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1992 JOINT SYMPOSIA

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URSI Radio Science Meeting

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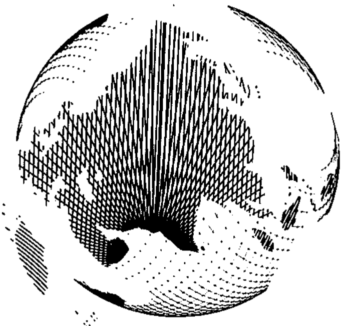

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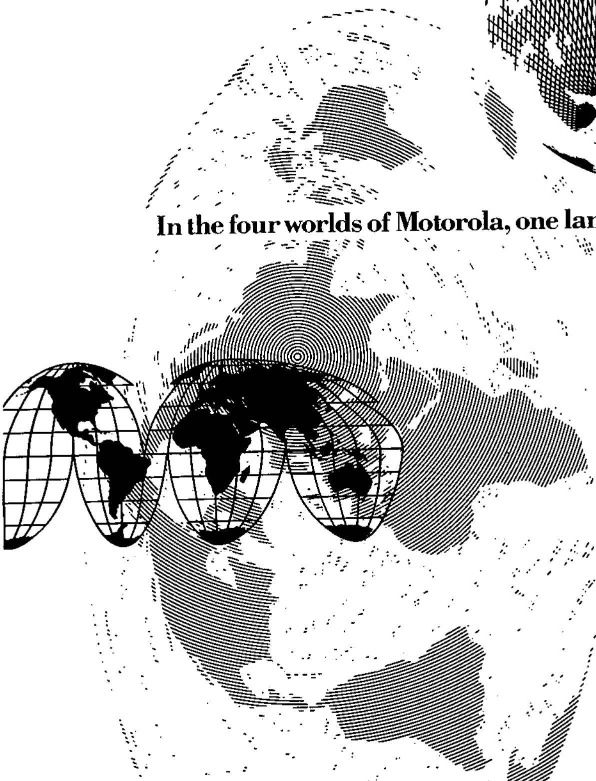

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Program and Digest

URSI Radio Science Meeting

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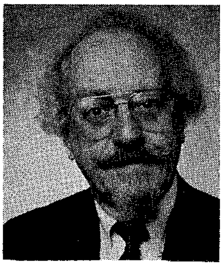
PREFACE



On behalf of the Steering Committee, welcome to the 1992 Joint Symposia (IEEE-APS International Symposium, URSI Radio Science Meeting, Nuclear EMP Meeting). The Joint Symposia are hosted by the University of Illinois at Chicago, in cooperation with the Illinois Institute of Technology, Northwestern University, the University of Illinois at Urbana-Champaign and local industry.

The US National Committee of URSI is participating in the Joint Symposia with Commissions A, B, D, E, and K. This digest contains the abstracts of the URSI technical sessions, sometimes held jointly with APS and/or NEM. In some instances, an abstract may not appear for a paper listed for presentation either because it was not timely received in proper format or because only an APS summary was available.

The preparation of this digest was made possible by the cooperation of my colleagues, Professors S.R. Laxpati and R.A. Schill, Jr., and the assistance of my graduate students J. Ali, S.F. Kawalko and J.T. Kish.

Piergiorgio L.E. Uslenghi
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LOCALIZED WAVE REPRESENTATIONS

I. M. Besieris and A. A. Chatzipetros
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Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Large classes of nonseparable space-time solutions of the equations governing many wave phenomena (e.g., scalar wave, Maxwell's, Klein-Gordon equations) have been reported recently and will be reviewed briefly here. When compared with traditional monochromatic, continuous wave (CW) solutions, these localized wave (LW) solutions are characterized by extended regions of localization; i.e., their shapes and /or amplitudes are maintained over much larger distances than their CW analogues. Such solutions represent pulses with highly localized transmission characteristics which may have potential applications in the areas of directed energy applications, secure communications and remote sensing. It has been shown that LW solutions can be obtained from a representation that employs a decomposition into bidirectional traveling plane wave solutions; i.e., solutions formed as a product of forward and backward traveling plane waves. The bidirectional representation does not replace the standard Fourier synthesis, but rather complements it, especially for the LW class of solutions.

An extension to the bidirectional traveling plane wave decomposition is presented. New basis functions are used in the superposition resulting in exact, nonseparable, acoustic (scalar-valued) and electromagnetic (vector-valued) wave solutions in a variety of environments (free space, dispersive media, lossy media, metallic waveguides, optical dielectric waveguides). In the bidirectional representation, some of the attractive solutions require smart choices of complicated spectra. In the new superposition, these attractive solutions can be obtained more easily due to the freedom of choice of the basis functions used. This is illustrated by a class of interesting pulses known as sling-shot pulses or X waves. An effort is also made to obtain these solutions by applying the above technique directly to the Fourier representation.

The complicated internal structure of LW solutions can be probed with techniques based on energy conservation principles. Illustrative examples of local energy speeds are given for three LW solutions to the scalar wave equation (Focus Wave Mode, Modified Power Spectrum, Sling-Shot).

APERTURE REALIZATIONS OF EXACT SOLUTIONS TO HOMOGENEOUS WAVE EQUATIONS

Richard W. Ziolkowski

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Several new classes of localized solutions to the scalar homogeneous wave and Maxwell's equations have been reported recently. Theoretical and experimental results have now clearly demonstrated that very good approximations to these acoustic and electromagnetic localized wave (LW) solutions can be achieved over extended near-field regions with finite-sized, indepedently-addressible, pulse-driven arrays. Nonetheless, questions concerning the causality of these solutions and, hence, their physical realizability still persist.

It will be shown that it is **only** the forward propagating (causal) components of any solution of the scalar homogeneous wave equation that are actually recovered from either an infinite- or a finite-sized aperture in an open region. The backward propagating (acausal) components result in an evanescent wave superposition that plays no significant role in the radiation process. The exact, complete solution can be achieved only from specifying its values and its derivatives on the boundary of any closed region. By using those LW solutions whose forward propagating components have been optimized over the associated backward propagating terms, one can recover the desirable properties of these LW solutions over the extended near-field regions of a finite-sized, independently-addressible, pulse-driven array. These results will be illustrated with an extreme example - one dealing with the original solution which is superluminal and its finite aperture approximation, a sling-shot pulse. The sling-shot pulsed-beam field is generated by driving an aperture with a superluminal solution and is characterized as a moving interference pattern whose peak intensity moves at a group speed $v_g > c$, even though its constituent signals are traveling at the characteristic wave speed c of the medium. The sling-shot effect is lost once the interference pattern reaches the far field of the aperture.

REAL TIME ARRAY LAUNCHING OF LOCALIZED WAVE PULSED BEAM ENERGY†

D. Kent Lewis

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Recent experiments have shown that it is possible to create the Localized Wave (LW) pulse real time in an acoustic environment. The resulting pulsed beam maintains its amplitude and beam width better than either conventional single frequency or wideband beams of comparable frequency content. The spectral bandwidth of the LW pulse is also well maintained. The characteristics of the LW pulses are compared to both Gaussian weighed beams and unweighed, or piston, beams.

The systems used individually addressable arrays and multi-channel source electronics. We launch all necessary source signals simultaneously. The two real time array systems fielded to date are 1) a 25 element Cartesian grid array with 0.5 mm diameter elements on 2.5 mm centers in a 5 by 5 arrangement and 2) a 2 mm diameter central spot with 10 concentric rings of 1 mm widths. The active array elements in both cases are of PVDF.

This presentation describes work done and results achieved at LLNL in the generation of localized wave pulse beams. The effective frequency concept (M. Johnson, Lawrence Livermore National Laboratory, private communication, 1989) will be briefly described as well as the criteria of the effective Rayleigh distance (R. W. Ziolkowski, Localized Wave Engineering and Physics, Phys. Rev. A, vol. 44(6), 3960-3984, 1991) for a pulsed array. Based on these ideas, the LW pulse has achieved better efficiency than the other control beams and has extended its near-field out to 10 times the expected Rayleigh distance.

SPHERICAL SCATTERING OF SUPERPOSITIONS OF LOCALIZED WAVES

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The behaviour of an acoustic plane wave or point source field when scattered from a sphere is well understood; in these cases the incident field is monochromatic. The so-called focussed wave mode [FWM] localized wave [LW] solution of the homogeneous wave equation [HWE],

$$e^{i\beta(z+ct)} \frac{e^{-\beta\rho^2/[z_0+i(z-ct)]}}{4\pi i[z_0 + i(z+ct)]},$$

where $\beta > 0$ and $z_0 > 0$ are arbitrary parameters, can represent a concentrated travelling pulse, for large values of β. Taking a particular superposition of FWM pulses, with respect to the parameter β, leads to the so-called modified power spectrum [MPS] LW HWE solution,

$$\frac{1}{z_0 + i(z-ct)} \frac{1}{(s/\beta + a)^\alpha} e^{-bs/\beta},$$

where $s = \rho^2/[z_0 + i(z-ct)] - i(z+ct)$, and where a, α, b, & β are arbitrary positive parameters. Acoustic approximations to the MPS pulse have been launched by investigators and the LW transmission effect has been verified.

Here we present theoretical and experimental results on the acoustic scattering of the MPS pulse from hard spheres. We synthesize the effect of launching and approximation to the MPS pulse from a finite array of transducers by superposing the results obtained from a single transducer when it transmits an appropriate signal from a particular location. In this way we synthesize the array launching of a number of different MPS pulses, and measure the backscattered signal from steel spheres of various sizes. We show how the backscattered data may be used to determine the characteristics of the scatterer. We also indicate how the backscattered data from two spheres may be used to determine the separation of the scatterers. We present a video of a computer graphical simulation of the actual MPS pulse approximation that we launch acoustically; this clearly demonstrates the near field/far field transitional behaviour of the LW pulse.

LOCALIZED WAVE SOLUTIONS IN OPTICAL FIBERS: WAVEGUIDE CONSTRAINTS AND TECHNOLOGY ISSUES

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(908) 582-4538

In a recent paper (A. M. Vengsarkar et al., J. Opt. Soc. Am. A, 9, June 1992) we demonstrated the existence of localized wave (LW) solutions in optical fiber waveguides. Despite the waveguide constraints introduced by the fiber structure, solutions that resemble nondecaying free-space solutions were obtained using broad bandwidth spectra. In this presentation, we discuss in detail the effect of waveguide constraints on the solution methodology and describe two approaches toward solving the problem. A detailed study of the modified power spectrum is performed, practical issues regarding source spectra are addressed, and distances over which such localized wave solutions maintain their nondecaying nature are quantified. The waveguide structure used for the analysis did not incorporate the effects of losses or the dispersive nature of silica-based glasses. We show by analogy that the presence of material dispersion may not affect the localization of the solutions by considering the case of a plasma-filled metallic waveguide.

One of the notable features of all spectra that give rise to LW solutions is that they are broadband in the optical sense. This leads to the possibility of exciting the higher order LP_{11} mode within the fiber and thus adding to the noise in the system. We will evaluate the behavior of the LP_{11} mode in the fiber for the modified power spectrum (MPS) pulse. We will also direct our attention to the problem of sources - the requirements imposed on them by the spectra, the need for arrays for effective transmission and the robustness of spectra to minor deviations in implementation. Present day state-of-the-art technology is not capable of meeting requirements that will make practical implementation of LW solutions a reality. We address futuristic technology issues and briefly describe efforts that could lead to an efficient LW-solution based fiber optic system.

LOCALIZED ELECTROMAGNETIC FIELDS IN NONDISPERSIVE MEDIA I

Michael C. Moldoveanu and Arthur K. Jordan*
Research Laboratory of Electronics, Massachusetts Institute of Technology
*Permanent Address: Naval Research Laboratories, Washington, D.C., U.S.A.

We present a direct scattering theory for localized electromagnetic fields in three dimensions. Many localized solutions to the three dimensional time dependent wave equation can be derived from group-theoretical considerations. These solutions can be generalized to the vector wave equation to obtain solutions to the classical electromagnetic field equations. The work presented will relate such solutions to Maxwell's equations to the long-standing problem of finding an adequate linear wave formalism to describe relativistic particles. In particular, vector fields satisfying $E = h\omega$ and $\vec{p}$ and $h\vec{k}$ simultaneously are derived, and related to the directive model of atomic radiation (Nadelstrahlung), without recourse to nonlinearities to explain the localization phenomenon.

The inverse problem related to the synthesis of sources for launching localized electromagnetic waves. We present novel analytic solutions to the antenna synthesis problem when the far field in the family of directive waveforms introduced above. Our solutions relate both to paraxial and plane wave approximations to the localized pulses, and to the possibilities of launching these pulses from spatially oscillating sources.

Engineering applications derived from our approach include the synthesis of miniaturized superdirective antennas, and the launching of electromagnetic waves that can approximate with arbitrary precision the localization properties of particles in free space and in linear dispersive media.

RADAR EQUATION AND SIGNAL DESIGN FOR THE ELECTROMAGNETIC MISSILE

Xuegang Zeng *Weigan Lin*

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ABSTRACT

It has been found that the energy of certain electromagnetic pulses reaching a receiver far away can decrease with distance much more slowly than r^{-2}. Such slowly decreasing electromagnetic pulses are referred to as Electromagnetic Missile (EMM) (Wu, Jour. Appl. Phys., 57(7), 2370(1985)). Many practical EMM sources have been investigated both analytically and experimentally (Shen, Jour. Appl. Phys., 66(9), 4025(1989)). Recently, Myers(Proc. SPIE, Vol. 1226, 290(1990)) and Wen(Jour. Appl. Phys., 70(1), 1(1991)) have reported the backscattered field of the EMM by a plate as well as a sphere, and their analyses show that the backscattered energy decreases still slower than the ordinary case r^{-4}. When these important results are contrasted with the conventional radar, one finds that a large radar return may be obtained if choosing the EMM as a radar signal.

In this paper, the radar equation and the signal design for the EMM are presented based on the characteristics of the EMM. A range-velocity resolution function or Woodward's ambiguity function is obtained analytically, and several plots for range-velocity resolution function are shown. It shows that the radar equation, the signal design and the range-velocity resolution function are different from those for the ordinary radar.

- The concept of radar cross section is changed for the EMM.
- The radar equation is modified for the EMM.
- A suitable radar signal for the EMM is the pulse-position coding differing from the ordinary radar signal.
- The range-resolution is about several centimeters for the EMM.
- The range-velocity resolution function approaches the ideal thumback function.

Monday AM AP-S, URSI-B, NEM Session MA07

Room: Columbus A *Time*: 0820-1140

Inverse Methods

Chairs: L. A. Wegrowicz, MITEK Electronics Ltd.; W. C. Chew, University of Illinois, Urbana-Champaign

0820 **SIMULTANEOUS NONLINEAR INVERSION of PERMEABILITY and PERMITTIVITY in TWO DIMENSIONS USING TIME-DOMAIN DATA**
M. Moghaddam*, Jet Propulsion Laboratory; W. C. Chew, University of Illinois, Urbana-Champaign

0840 **INVERSION of REAL TRANSIENT RADAR DATA USING the DISTORTED-BORN ITERATIVE ALGORITHM**
William H. Weedon*, J. E. Mast, W. C. Chew, University of Illinois, Urbana-Champaign; H. Lee, Univ. California at Santa Barbara; J. P. Murtha, Univ. of Illinois at Urbana-Champaign

0900 **RECONSTRUCTION of CONTINUOUS and DISCONTINUOUS REFRACTIVE INDEX PROFILES from POWER MEASUREMENTS of REFLECTED FIELDS**
G. Mazzarella*, G. Panariello, Universita di Napoli

0920 **COMPARISON of OPTIMIZATION PROCEDURES for RADAR SCATTERING MATRICES**
Xin Zhang*, Chuan-Li Liu, Yoshio Yamaguchi, Wolfgang-M Boerner, University of Illinois at Chicago

0940 **SYNTHESIS of UNEQUALLY SPACED ARRAYS AS INVERSE PROBLEM**
L. A. Wegrowicz*, MITEK Electronics Ltd.; N. Rao Atluri, McGill University; F. Bardati, University of Rome "Tor Vergata"

1000 **Break**

1020 **POLYNOMIAL CHARACTERIZATION of INHOMOGENEOUS MEDIA and THEIR INVERSION USING NON-PLANE WAVE SOURCES**
Masoud Mostafavi*, San Jose State University; Wen-Chin Lan, Taiwan Microwave Company

1040 **DIRECTION FINDING of MAGNETOSPHERIC VLF/ELF WAVES BASED on the SIMULTANEOUS MEASUREMENT of MULTIPLE FIELD COMPONENTS**
Masashi Hayakawa*, The University of Electro-Communications; Shin Shimakura, Chiba University; Masaki Shimizu, K. Hattori, Nagoya University; Naofumi Iwama, Toyama Prefectural University

1100 **APPLICATIONS of the NEW GENERALIZED FORM of MAXIMUM ENTROPY METHOD to SOLVING INVERSE PROBLEMS**
Anisa T. Bajkova*, USSR Academy of Sciences

1120 **TARGET FEATURE EXTRACTION of FREQUENCY DOMAIN DATA with OPTIMAL RATIONAL APPROXIMATION**
Supeng Liao*, D. G. Fang, X. G. Li, East China Institute of Technology

COMPARISON OF OPTIMIZATION PROCEDURES FOR RADAR SCATTERING MATRICES

Xin Zhang, Chuan-Li Liu, Yoshio Yamaguchi and Wolfgang-Martin Boerner

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Basic principles of radar polarimetry are introduced and various optimization procedures for the propagation (scattering) range operator equation and the received power expressions are presented and compared. It is assumed that the radar is a complete coherent dual orthogonal (A,B) transmit/receive antenna system of high channel isolation and antenna side-lobe reduction, where in the case of wave interaction with a discrete stationary point target the propagation (scattering) matrix is given by the 2x2 coherent Jones (Sinclair) matrix [S(A,B)] and/or the 3x3 or 4x4 complex covariance matrix [Σ(A,B)], and the 4x4 Mueller (Kennaugh) power density matrix [M] for the symmetric (monostatic reciprocal: $S_{AB} = S_{BA}$) or the asymmetric (general bistatic, monostatic non-reciprocal: $S_{AB} \neq S_{BA}$) partially coherent cases, respectively. Separate optimization procedures are here introduced for the symmetric case, demonstrating that for the coherent (deterministic) scattering scenario the solutions are identical, and so approximately also for the partially polarized case, whereas for the partially coherent case a more elaborate optimization procedure for the 3x3 covariance and/or 4x4 Mueller matrices is employed. It is shown that there exist in total five unique pairs of characteristic polarization states for the symmetric scattering matrix of which two pairs, corresponding to the cross- polarization (x-pol) null and co-polarization (co-pol) maxima, are identical; whereas the x-pol max and x-pol saddle point pairs are distinct. These three pairs of orthogonal characteristic polarization states are also mutually at right angles to one another on the polarization sphere. The fifth pair, the (in general) non-orthogonal co-pol null pair, lies in the plane spanned by the co-pol max, or equivalently the x-pol null, and the x-pol max pairs which determine the 'target characteristic plane (circle) of Kennaugh'; and together with the orthogonal x-pol saddle point pair, being at right angles to this plane, they re-establish Huynen's 'polarization fork' concept. The various approaches are compared by two illustrative examples in which, besides the 'polarization forks', also the co-pol and x-pol power density plots and the relative co/cross-polarization phase (polarimetric correlation coefficient) plots are presented.

Monday AM1 URSI-B Session MA08

Room: Columbus C/D *Time*: 0820-0940

Numerical and Experimental Rough Surface Scattering

Chairs: Leung Tsang, Yasuo Kuga, University of Washington

0820 **MONTE CARLO SIMULATIONS and BACKSCATTERING ENHANCEMENT of RANDOM METALLIC ROUGH SURFACES at OPTICAL FREQUENCIES**
L. Li*, C. H. Chan, Leung Tsang, K. Pak, University of Washington; S. H. Lou, Jet Propulsion Laboratory

0840 **A CONFORMAL FINITE-DIFFERENCE TIME-DOMAIN APPROACH for MONTE CARLO SIMULATIONS of RANDOM ROUGH SURFACE SCATTERING**
C. H. Chan*, L. Li, J. T. Elson, Leung Tsang, University of Washington

0900 **WAVE SCATTERING from PERFECTLY CONDUCTING ROUGH SURFACES USING the FDTD METHOD**
John B. Schneider*, S. L. Broschat, Washington State University

0920 **MILLIMETER WAVE EXPERIMENTS on BACKSCATTERING ENHANCEMENT from ONE- and TWO- DIMENSIONAL VERY ROUGH SURFACES**
Phillip Phu*, Akira Ishimaru, Yasuo Kuga, University of Washington

MONTE CARLO SIMULATIONS AND BACKSCATTERING ENHANCEMENT OF RANDOM METALLIC ROUGH SURFACES AT OPTICAL FREQUENCIES

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Pasadena, CA 91109

With the advent of modern computers, there has been increasing interest in the numerical exact solution to the random rough surface scattering problem. The most common ones are the integral equation method and the extended boundary condition method. Recently, we have utilized the finite-element and finite-difference methods for the Monte Carlo simulations of random rough surface scattering. In this paper, we extend our finite-element formulation to the case of plane wave scattering from random metallic surfaces at optical frequencies and to study the backscattering enhancement associated with these rough surfaces. The finite conducting surfaces are modeled as lossy dielectric random rough surfaces backed by a perfect electric conducting (PEC) plane and a perfect magnetic conducting (PMC) plane for the TE and TM incident plane waves, respectively. In the construction of the full matrix leading to the solutions of the modal amplitudes of the scattered field, sine and cosine transforms of the normal derivative of the modal fields are evaluated simultaneously using the Fast Fourier Transform algorithm (FFT) to enhance the numerical efficiency of the method. Convergence of the method is demonstrated by varying the surface length L.

In this paper, two cases are investigated. For Case 1, the random surfaces have a correlation length of 3 wavelengths and a root-mean-square height of 1.7 wavelengths. For Case 2, these quantities are smaller and are, respectively, 1 wavelength and 0.6 wavelength. Numerical results are presented for both the TE and TM plane wave scatterings by the lossy random rough surfaces at various incidence angles from the normal. Both the TE and TM incidences show backscattering enhancement at all three incident angles. It is also found that while the TE and TM responses are very similar in Case 1, they are different in Case 2 at large incident angles. The TE incidence yields stronger backscattering enhancement in both cases, in contrast to the scattering from surfaces with small roughness where backscattering enhancement is observed only for the TM waves. In all the numerical simulations, the lossy surfaces absorb more power for the TM incidences than that of the TE.

A CONFORMAL FINITE-DIFFERENCE TIME-DOMAIN APPROACH FOR MONTE CARLO SIMULATIONS OF RANDOM ROUGH SURFACE SCATTERING

C.H. Chan*, L. Li, J.T. Elson, and L. Tsang
Electromagnetics and Remote Sensing Laboratory
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University of Washington
Seattle, WA 98195

Monte Carlo simulation of random rough surface scattering in the frequency domain using the integral equation method has been reported extensively in the literature. Reduction in computational time and computer memory using the finite-difference and finite-element methods has also been reported. Last year, we presented a finite-difference time-domain (FDTD) approach to the Monte Carlo simulation of random rough surfaces. The advantage of the FDTD approach is that the need of matrix inversion of any kind has been completely eliminated. In addition, one can also study transient scattering by random rough surfaces. To replace the Gaussian surface profile by a stair-case approximation, we used a discretization of 30 sample points per wavelength. Finer discretization may be required when the surface slope is large.

In this paper, we present a conformal FDTD approach to the Monte Carlo simulation of random rough surfaces. This conformal FDTD allows us to impose boundary conditions along the exact profile of the rough surface thus reducing the number of discretization points required as compared to the stair-case approximation. The basic idea of this conformal FDTD is that two finite-differencing grids are needed, namely, a master grid and a local grid. The master grid is a conventional Yee's grid and the local grid is a triangular grid which follows the same contour as the surface profile. This local grid extended from the surface profile into the master grid for a few grid zones. FDTD calculations are performed for both the master grid and the local grid with the information from the master grid transferred to the outer boundary of the local grid by a simple bilinear interpolation. Boundary conditions are then enforced on the local grid and interpolation is done again to update the boundary of the master grid that is located within the local grid. The FDTD cycle is then repeated. This interpolation of information between the master and local grids was first proposed by K.S. Yee *et al.* (June, 1991). It should be noted that in our local grid, we choose to time step the integral form of Maxwell's equation as the grid is not rectangular.

In this paper, both plane wave and tapered wave incidence will be investigated. Results will be presented for both one-dimensional and two-dimensional rough surfaces.

WAVE SCATTERING FROM PERFECTLY CONDUCTING ROUGH SURFACES USING THE FDTD METHOD

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Currently there is much interest in wave scattering from rough surfaces, which has diverse applications in both science and engineering. For example, rough surface scattering is important in integrated optics, microwave remote sensing, underwater acoustics, and silicon MOSFET physics.

A number of researchers have performed exact numerical experiments using Monte Carlo integral equation methods to solve the problem of scattering from randomly rough surfaces with both Gaussian and power law spectra. In this paper we present an alternate solution using a Monte Carlo Finite Difference Time Domain method. Like the integral equation method, the FDTD method is exact and bistatic radar cross sections can be calculated; however, it has four major advantages: (1) the three-dimensional problem is more readily implemented, (2) volume scattering can be easily included, (3) both pulsed and CW illumination can be used, and (4) propagation of both the total and scattered fields in the time domain can be observed.

The results presented in this paper are limited to scattering from one-dimensional, perfectly conducting surfaces with a Gaussian spectrum, and the incident field has TE polarization. Both transient and steady state (cross sections) results are presented, and the cross section results are compared to those found using the integral equation method as well as several different approximate methods.

MILLIMETER WAVE EXPERIMENTS ON BACKSCATTERING ENHANCEMENT FROM ONE- AND TWO-DIMENSIONAL VERY ROUGH SURFACES

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Backscattering enhancement from one-dimensional (1-D) very rough surfaces has been studied in recent years because of its importance in remote sensing. Until recently, experimental studies of backscattering enhancement have been limited to the optical region. However, since accurate determination of the exact surface roughness characteristics at optical frequencies is still difficult, controlled millimeter wave experiments in which the surface roughness statistics are known accurately should provide good comparisons for exact numerical calculations. Furthermore, in the two-dimensional (2-D) case, very little work has been done on the enhancement effects from very rough surfaces. Therefore, new experimental data obtained under well controlled conditions are essential to provide accurate information for comparison with numerical or analytical calculations.

In this paper, we will present experimental results on the scattering of millimeter waves from 1-D and 2-D very rough perfectly conducting surfaces with known statistics. One-dimensional surface profiles with roughness $h=l=3$mm (slope=1) and $h=3$mm,$l=9$mm (slope=1/3) are constructed with fast drying cement covered with several layers of highly conductive paint. Copolarized scattering cross sections of the rough surfaces are measured using a millimeter wave system based on the HP8510B network analyzer in the 75-100 GHz frequency range. Both transmitting and receiving antennas are beam-limited and many independent scattering samples are obtained by taking measurements at different locations along several surfaces. Bistatic experiments are performed at incident angles of 0, 20 and 40 degrees for both TE and TM incident polarizations. Strong backscattering enhancement is observed experimentally for both polarizations. Monte-Carlo numerical simulations based on the exact integral equation method for 1-D rough surfaces are compared with the experimental results. In the simulations, the calculations are based on cylindrical beamwave antennas because of the beam-limited patterns of both the transmitting and receiving antennas. The measured bistatic scattering cross sections are compared directly with the numerical simulations and the agreement between measurements and numerical results is good over a large range of incident angles and scattering angles. Experimental results on the enhancement from 2-D very rough surface are also discussed. 2-D rough surfaces which obey Gaussian roughness statistics are fabricated by machining plastics using a computer numerical control (CNC) milling machine. Bistatic measurements are performed for both TE and TM polarizations at different incident angles.

Monday AM AP-S, URSI-B Session MA09

Room: Columbus E/F *Time*: 0820-1200

Numerical Simulation and Modeling in Guided Wave Optics

Organizers: Sujeet K. Chaudhuri, University of Waterloo; Korada Umashankar, University of Illinois at Chicago

Chairs: Sujeet K. Chaudhuri, University of Waterloo; Korada Umashankar, University of Illinois at Chicago

0820 **BEAM PROPAGATION METHODS**
David Yevick*, Witold Bardyszewski, Queen's University; Bjorn Hermansson, Swedish Telecom; Moses Glasner, Penn State University

0840 **MODELING of GUIDED-WAVE OPTICAL COMPONENTS with EFFICIENT FINITE-DIFFERENCE BEAM PROPAGATION METHODS**
Youngchul Chung*, Nadir Dagli, University of California, Santa Barbara

0900 **MODELING and SIMULATION of VECTORIAL WAVE PROPAGATION in OPTICAL GUIDED-WAVE DEVICES by BEAM PROPAGATION METHOD**
W. P. Huang*, C. L. Xu, Sujeet K. Chaudhuri, University of Waterloo

0920 **VECTORIAL ANALYSIS of OPTICAL WAVEGUIDES by the METHOD of LINES**
R. Pregla*, Fern Universitat Hagen

0940 **ANALYSIS of OPTICAL GUIDED-WAVE DEVICES with the FINITE-DIFFERENCE TIME-DOMAIN METHOD**
S. T. Chu*, Sujeet K. Chaudhuri, W. P. Huang, University of Waterloo

1000 **Break**

1020 **FINITE-DIFFERENCE TIME-DOMAIN SIMULATIONS of LINEAR INTEGRATED PHOTONIC DEVICES**
Raymond J. Hawkins*, Lawrence Livermore National Lab; Robert McLeod, University of Colorado at Boulder

1040 **FDTD SIMULATION of OPTICAL SOLITON PROPAGATION and SCATTERING in 2-D WAVEGUIDES**
Peter M. Goorjian, NASA Ames Research Center; Allen Taflove*, Rose M. Joseph, Northwestern University

1100 **A STUDY of OPEN DIELECTRIC WAVEGUIDE PROBLEMS USING the GENERALIZED INTEGRAL EQUATION METHOD**
Kazem Sabetfakhri, Linda P. Katehi*, The University of Michigan

1120+ **VIDEO PRESENTATION of the RESULTS by SOME of the AUTHORS**

BEAM PROPAGATION METHODS

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While the split-step fast Fourier transform propagation method has for many years been applied to waveguide modeling, the computation of optical losses in strongly-guiding rib waveguide structures has recently motivated the study of other algorithms. We discuss the application of Fourier transform, finite difference, finite element, real space, multioperator and Lanczos approaches to paraxial electric field propagation problems in guided-wave optics. While these methods are generally applied to the Fresnel equation, we also consider a class of solution algorithms for wide-angle equations. The results of these techniques is then employed to estimate the accuracy of the Fresnel in guided-wave contexts for both continuous and discontinous refractive index profiles. We discuss further the relative advantages and disadvantages of the various methods with regard to either numerical convergence or computation time. We finally consider reflection at an inhomogeneous dielectric interface for which we present a rapid split-operator procedure. The computational formalisms are illustrated for integrated optic microlenses and semiconductor rib waveguide bends and Y-junctions both numerically and by direct comparison with experiment.

MODELING OF GUIDED-WAVE OPTICAL COMPONENTS WITH EFFICIENT FINITE-DIFFERENCE BEAM PROPAGATION METHODS

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ABSTRACT

In this paper very efficient finite difference beam propagation methods (BPM) to model guided-wave optical components are described. If the index profile is two-dimensional the BPM can be formulated by employing the unconditionally stable and unitary Crank-Nicholson algorithm. This requires the solution of a system of tridiagonal linear equations at each propagation step, which can be performed very efficiently. Stability and numerical efficiency of this approach is found to be superior to conventional BPM that employs fast Fourier transform (FFT). For the modeling of structures with three dimensional index profiles an explicit finite difference beam propagation method (EFD-BPM) is found to be a very efficient technique. However, being explicit this scheme has to meet certain conditions for stability and power conservation, which are derived. In EFD-BPM at each propagation step only a sparse matrix multiplication is required. As a result of this, the computational effort per propagation step is reduced by an order of magnitude compared to the conventional BPM based on FFT. Furthermore, contrary to the conventional BPM, a non-uniform mesh can be simply incorporated into the algorithm, enhancing the efficiency further. As an ultimate test on the accuracy, experiments on deeply etched semiconductor waveguide zero-gap couplers were performed and the experimental results are found to be in very good agreement with the modeling results confirming the accuracy of the EFD-BPM. It is demonstrated that vectorial wave equation can also be easily solved using explicit finite difference scheme resulting in a vectorial BPM. A semi-vectorial explicit finite difference BPM, where coupling between orthogonal polarizations are ignored but a polarization correction term is included, is found out to be comparable in accuracy to the full-vectorial EFD-BPM. A non-iterative bidirectional BPM is also described. This approach can handle the backward traveling wave as well as the forward traveling wave. The coupling between the counter traveling waves at the discontinuities is modeled by a transmission matrix, while the counter traveling waves in the longitudinally invariant medium are propagated independently. The simulation results of the volume index grating agree very well with those calculated using finite difference time domain method.

MODELING AND SIMULATION OF VECTORIAL WAVE PROPAGATION IN OPTICAL GUIDED-WAVE DEVICES BY BEAM PROPAGATION METHOD

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Modeling and simulation of electromagnetic wave propagation in optical guided-wave devices by the beam propagation method (BPM) are presented and discussed. The vectorial properties of the propagating waves that are pertinent to many practical optical guided-wave devices are emphasized and illustrated by a newly developed vector beam propagation method (VBPM). The characteristics of the electromagnetic waves propagating in the optical guided-wave devices are first reviewed and the commonly adopted approximations in the guided-wave optics are discussed. Subsequently, the newly developed vector beam propagation method is described. The vectorial nature of the propagating waves are taken into account in the new scheme. The polarization dependence and coupling are modeled, and applications of the VBPM to various typical optical guided-wave devices are presented. Comparisons between the scalar and the vector BPMs are presented and discussed. Some comparisons between the effective-index 3-D and the full 3-D BPMs and the coupled-mode theory (CMT) and the BPMs are also made and discussed. Finally, some comments on the future directions of the modeling and the simulations of the electromagnetic wave propagation in guided-wave optics are given.

VECTORIAL ANALYSIS OF OPTICAL WAVEGUIDES BY THE METHOD OF LINES

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In this contribution it will be shown that the Method of Lines (MoL), a special finite difference method is especially suited for the analysis of waveguides for integrated optics. The guiding structure is modelled through a set of single layers. The refractive index of each single layer is only a function of the lateral direction. This function is varying from layer to layer. Steps are also possible. Therefore e.g. strip loaded film guides, channel guides and also diffused guides are included in this model. Because the wave equations are discretized only as far as necessary, namely in one direction, most of the calculation is done analytically, and accurate results are obtained with comparatively less computational effort.
It will be shown, that

- the analysis procedure is straight forward and does not need apriori information about the field distribution,
- the convergence behaviour is monotonic and hence extrapolation is possible and gives accurate results,
- the calculation of the field distribution is very accurate beause of the relation of the MoL to the Discrete Fourier Transformation,
- the MoL does not yield spurious modes and the relative convergence phenomenon is not observed.

The following work has been done and results will be presented:

- Dispersion curves and field distribution for fundamental and higher order modes for various optical waveguides have been calculated with high accuracy.
- Radiation losses have been calculated for circular bends.
- The efficiency is improved by using higher order approximations for the difference operators.
- Open cross sections have been modelled by using absorbing boundary conditions.

Analysis of Optical Guided-Wave Devices with the Finite-Difference Time-Domain Method

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ABSTRACT

Although the Finite-Difference Time-Domain (FDTD) method has for many year been one of the popular methods used in microwave and millimeter wave research, only recently it has been applied to solve optical waveguide problems. One obvious reason for the lack of popularity of the FDTD method in guided-wave optics is economic. Unlike most structures in microwave and millimeter wave research where wave interaction with the geometries are strong and wave phenomena such as, coupling and radiation, take place within a few wavelengths. Most wave interactions in optical structures are weak, structures with length in the orders of hundred and thousand of wavelengths are required to perform functions such as, power routing and filtering. At this moment, the computational power required to simulate thousands of wavelengths long structure using the FDTD method are not widely accessible.

The FDTD method does offer versatility and accuracy that are superior to many other approaches. As the size of the optical devices become more compact and the computational power become less expansive, the FDTD method will be commonly used by the optical engineers. However, in order to improve the appeal of the method to the researchers in the optical community, the following should be considered. First, identify the type of geometries that are difficult to analyze with the common optical guided-wave theories, but are possible with the FDTD analysis. This would demonstrate the power of the method and will enchance its use in the analysis of these problems. Second, improve the efficiency of the FDTD algorithm. One way of achieving this is to understand the properties of the optical guided-wave devices, and exploit these properties to improve the computational efficiency of the FDTD scheme.

In this presentation, our views on the above considerations along with suggestions of alternate approaches to the full vector FDTD algorithm such as, semi-vectorial and scalar FDTD will be presented.

Finite-Difference Time-Domain Simulations of Linear Integrated Photonic Devices

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*** University of Colorado, Boulder, CO 80309*

The development time of new photonic integrated circuits and systems can be reduced significantly if predictive computational design techniques are used. We have developed a number of such techniques, for photonic integrated circuit/device design, and will discuss our experiences with them. Currently we are studying the use of complete Maxwell solvers for predicting the broadband response/behavior of complex optical interconnects.

Interest has recently grown in applying microwave modeling techniques to optical circuit modeling . One of the simplest, yet most powerful, microwave simulation techniques is the finite-difference time-domain algorithm (FDTD). We have also been using, and will discuss (using simulation video results) the FDTD in integrated optics design. With this versatile technique we are able to predict the broadband behavior of geometrically complex optical interconnects. A typical example of such a structure is a Bragg grating used to couple light into (out of) a waveguide. The ability to accurately treat coherent effects, reflections, and wide spectral variations in material properties has made the study of grating-based devices and other complex structures a comparatively straightforward task. We find that the finite-difference time-domain method gives designers insights only revealed by complete vector EM fields. Combining the FDTD algorithm with graphical pre- and post-processing tools can lend new insight in to simple problems, such as couplers and gratings, and provide valuable information on the operation of proposed hardware.

Because virtually no assumptions are made in the development of the FDTD method, the algorithm is able to represent a wide-range of physical effects. Waves can propagate in any direction, multiple reflections within structures can cause resonances, multiple modes of various polarizations can be launched, each of which may generate within the device an infinite spectrum of bound and radiation modes. The ability to model these types of general physical effects is what makes the FDTD method interesting to the field of optics. Since photonic devices are an essential element of wideband communications systems, we expect that FDTD will play an important role in their development.

FD-TD SIMULATION OF OPTICAL SOLITON PROPAGATION AND SCATTERING IN 2-D WAVEGUIDES

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Experimentalists have produced all-optical switches capable of 100-fs responses. To adequately model such switches, nonlinear effects in optical materials (both instantaneous and dispersive) must be included. However, until our previous work [1], the nonlinear Maxwell's equations had not been solved. Rather, approximations had been made that result in a class of generalized nonlinear Schrodinger equations (GNLSE) that solve only for the *envelope* of the optical pulses, discarding the optical carrier. However, engineered inhomogeneities in nonlinear optical circuits will likely be at distance scales in the order of 0.1 - 10 optical λ, violating assumptions regarding slowly-varying parameters (which run throughout NLSE theory).

In this paper, we extend to 2-D the FD-TD approach we presented in [1] for solving the 1-D Maxwell's equations for materials having linear and nonlinear instantaneous and Lorentz-dispersive effects in the electric polarization. This takes into account such quantum effects as the Kerr and Raman interactions. Again, the innovation is the treatment of the convolution integrals which describe the dispersions as new dependent variables. By time-differentiating these convolutions, an equivalent system of coupled, nonlinear, second-order ordinary differential equations is derived. These equations together with Maxwell's equations form the complete system. Backstorage in time is limited to only that needed by the time-stepping algorithm for the ODE's (2 time steps), rather than that needed to store the time-history of the kernel functions of the convolutions.

The novel approach discussed here is robust. It assumes nothing about: (a) the homogeneity or isotropy of the optical medium; (b) the magnitude of the nonlinearity; (c) the nature of the material's ω - β variation; and (d) the shape, duration, and polarization of the optical pulse(s). The new method solves for *fundamental field quantities* rather than a nonphysical envelope function. It has the potential to provide an unprecedented modeling capability for millimeter-scale integrated optical circuits having sub-micron engineered inhomogeneities.

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[1] P. M. Goorjian and A. Taflove, "Direct time integration of Maxwell's equations in nonlinear dispersive media for propagation and scattering of femtosecond electromagnetic solitons," *Optics Letters* **17**, 180-182 (1992).

A Study of Open Dielectric Waveguide Problems Using The Generalized Integral Equation Method

by

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Theoretical studies on geometrically simple optical and microwave dielectric waveguides have been presented in the past decade using approximate or numerical methods. The approximate methods are represented by an analytical approximation introduced by marcatili and by the effective index method. The numerical methods are divided into variational methods, mode matching methods, finite element methods and integral equation methods using volume polarization currents. These methods have been exclusively applied to two-dimensional problems with most of the existing techniques performing a fine discretization of the cross section. Such discretization introduces many unknowns and strong numerical instabilities. Consequently, an extension of these methods to three-dimensional problems faces many practical limitations and requires special care.

This paper presents a novel formulation which can be applied to two- and three-dimensional open dielectric waveguide problems. This powerful method transforms complex problems to simplified equivalent planar ones which are then solved using known planar integral equation techniques. At first, the electric field in the dielectric waveguide is expressed in terms of a volume polarization dipole moment from which a planar polarization dipole moment is defined. Further, generalized boundary conditions on the surface of the dielectric waveguide are enforced to make the introduced planar dipole moment equivalent to the original volume polarization dipole moment. In this manner, a simplified planar integral equation is derived which is then solved in the spectral domain to provide very satisfactory results. In this presentation, for the sake of simplicity, the above formulation will be applied to a variety of infinite as well as finite dielectric slab waveguides and the merits and numerical attributes of the technique will be extensively discussed.

Monday AM URSI-B Session MA11

Room: Columbus H *Time*: 0820-1200

Numerical Methods for Scattering

Chairs: K. A. Michalski, Texas A&M University; David M. Le Vine, NASA Goddard Space Flight Center

0820 **OBLIQUE INCIDENCE SCATTERING by LARGE, COATED CYLINDERS of ARBITRARY CROSS SECTION**
P. Bonnemason*, R. Le Martet, B. Stupfel, CEA, Centre d'Etudes de Limeil-Valenton

0840 **RADAR CROSS SECTION SYNTHESIS USING the METHOD of MOMENTS**
David C. Jenn*, Naval Postgraduate School

0900 **SCATTERED FIELD on the AXIS of an OPEN-ENDED CONDUCTING TUBE**
Robert W. Scharstein*, Anthony J. M. Davis, The University of Alabama

0920 **A MAGNETIC FIELD INTEGRAL EQUATION FORMULATION for SCATTERING from THREE-DIMENSIONAL SURFACES USING CURVED TRIANGULAR PATCHES**
Debra L. Wilkes*, Chung-Chi Cha, Syracuse Research Corporation

0940 **VALIDATION of MMP3D CODE for RCS PREDICTION**
S. Keiner*, University of Ottawa; S. R. Mishra, C. Larose, David Florida Laboratory

1000 **SCATTERING by ARBITRARY SECTION CYLINDER COMPUTED by MULTI-CENTER CYLINDRICAL HARMONICS FUNCTIONS EXPANSION**
C. C. Wei*, Yan-ming Xiao, Weng-bin Wang, Xi-yuan Zhang, Xi'an Jiaotong University

1020 **SCATTERING of ARBITRARILY-POLARIZED EM WAVE by DISCONTINUITY in GROUNDED DIELECTRIC LAYER**
J. Song*, Dennis P. Nyquist, K. M. Chen, E. J. Rothwell, Michigan State University; S. Ohnuki, Tokyo National College of Technology

1040 **RADAR CROSS-SECTION of PARALLEL CIRCULAR CYLINDERS: a COMPARATIVE STUDY of DIFFERENT TECHNIQUES**
Atef Z. Elsherbeni*, University of Mississippi

1100 **A SIMPLE SCATTERING MODEL for THIN MATERIAL WIRES**
Keith W. Whites*, University of Kentucky

1120 **ELECTROMAGNETIC PLANE WAVE SCATTERING by a TROUGH on the GROUND**
Hiroshi Shirai*, Kazuhiro Hirayama, Chuo University

1140 **SCATTERING AMPLITUDE of a THIN LOSSY DIELECTRIC DISC by the INTEGRAL EQUATION METHOD**
S. Selim Seker*, Roger H. Lang, George Washington University; David M. Le Vine, NASA Goddard Space Flight Center

OBLIQUE INCIDENCE SCATTERING BY LARGE, COATED CYLINDERS OF ARBITRARY CROSS-SECTION.

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In this paper, we consider the problem of computing the surface currents and the Radar Cross Section (RCS) of coated cylindrical structures of arbitrary cross-section, illuminated by an obliquely-incident plane wave. The cylinders under consideration may be either open or closed, and they may even be disjointed. Our emphasis in this paper is to consider scatterers that are large compared to the wavelength and to investigate the reliability of the Leontovich boundary condition for modeling imperfect conductors. In addition, our objective in this work is to achieve a high degree of numerical accuracy even in the angular range where the RCS is low. This is an important issue in the design of low observable targets.

Two approaches to solving the RCS problem are presented in this paper. The first of these employs an integral equation technique based on the Method of Moments (MoM), associated or not (perfectly conducting case) with the Leontovich boundary condition prescribed on the outer boundary of the scatterer. Formulations eliminating the spurious internal resonances have been systematically implemented, and an original discretization of the surface currents have been used so as to reduce the memory storage requirements.

The second approach is based upon the use of the finite element method (FEM), applied in conjunction with an integral equation formulation. The finite element formulation is employed within the inhomogeneous domain that contains the scatterer. The integral equation formulation, applied to the outer boundary of the body, ensures that the Sommerfeld's radiation condition is fulfilled. An important problem that must be successfully resolved in the process of deriving the high frequency solution of the scattering problem is the suppression of the spurious internal resonances. An approach to circumventing this problem is described in the paper.

A vectorized computer program has been developed for the CRAY YMP/8128 using the two approaches described above. This paper presents representative numerical results for a variety of large geometries, including an assembly of several coated cylinders of arbitrary cross-section, an open cavity, and a cylinder of triangular cross-section coated with low and high index materials. These results are subsequently interpreted in terms of edge and creeping waves contributions. In each case, we compare the results obtained with the integral equation approach to those obtained with the combined FEM/Integral equation method, and demonstrate that excellent agreement is obtained when the Leontovich boundary condition is used in a legitimate manner. We also include some examples illustrating the failure of this condition when it is employed inappropriately.

RADAR CROSS SECTION SYNTHESIS USING THE METHOD OF MOMENTS

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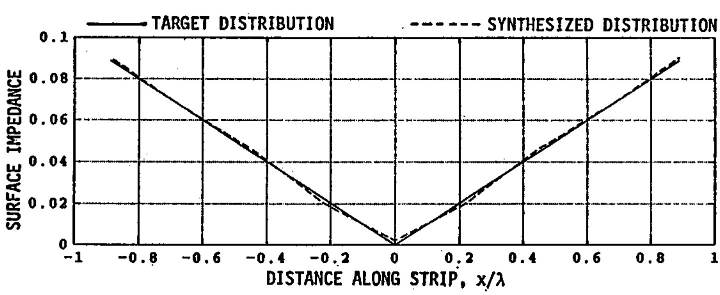
A synthesis procedure is described that yields the surface impedance at every point on the surface of a body for a specified radar cross section (RCS) pattern. The solution parallels the standard method of moments (MM) technique in that the surface impedance is expanded into a series of basis functions with unknown coefficients. An approximate impedance function is obtained by assuming a current (e.g., physical optics) and solving the integral equation for the expansion coefficients. A rigorous solution to the problem requires that both the surface current and impedance be expanded into series. In the first case, the approximation for the current and the properties of the basis functions will determine whether the resulting set of simultaneous equations will be linear or not. In the second, a nonlinear set of simultaneous equations must be solved.

In this presentation the coupled set of integral equations will be derived for the surface impedance and current on an arbitrary body. As an example of how MM is applied to reduce the integral equations to matrix form, the solution for a thin strip is examined in detail. A typical result is shown in the accompanying figure for a TM_z polarized plane wave incident on a $.1\lambda$ by 2λ strip. The exact impedance distribution is shown by the solid line, and that recovered by the synthesis method by dashed. As expected, the synthesized distribution was sensitive to several parameters, among them the sampling increment in angle, range of impedance values synthesized, and the approximations made to linearize the equations, all of which will be discussed.



SCATTERED FIELD ON THE AXIS OF AN OPEN-ENDED CONDUCTING TUBE

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AND

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The fields on the axis of an open-ended conducting cylinder of finite length are evaluated following the Galerkin expansion of the surface currents induced by an incident plane wave. All scattered fields and hence surface currents are expressed as Fourier transforms in the axial (z) dimension. Naturally, the circular symmetry of this body of revolution preserves the orthogonality of the azimuthal modes which are the basis of a trigonometric series in azimuthal angle ϕ. Only the modes with azimuthal index $n = 0$ or $n = 1$ contribute to the on-axis fields. The spectral functions are given in terms of Chebyshev series with edge-condition weighting. Special function properties are used to transform the infinite range Fourier integrals to finite range integrals with simple $(1 - x^2)^{\pm 1/2}$ integrand factors, suitable for direct computation via a Chebyshev-Gauss quadrature. Total on-axis electric field in the deep interior of the tube is on the order of 10^{-5} for a tube of electrical girth $ka \approx 1$, relative to an incident electric field of unit amplitude. This gives a measure of the accuracy of the computations, since a null field exists in the deep interior of this cutoff circular waveguide. Numerical results for several combinations of geometry, frequency, and excitation are presented and studied. The standing waves of near-field E_z are different for the TM exterior back scatter (entrance) and forward scatter (exit) regions. Preliminary investigation indicates that the asymmetrical trends in both the surface currents and the axial fields are plausible in view of the coupling between the incident plane wave and the normal surface modes of the circular pipe.

A MAGNETIC FIELD INTEGRAL EQUATION FORMULATION FOR SCATTERING FROM THREE-DIMENSIONAL SURFACES USING CURVED TRIANGULAR PATCHES

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The scattering from closed surfaces can be computed using the method of moments formulation of the magnetic field integral equation. When the surface is curved, it can be modeled using curved triangular patches which conform exactly to the original surface. A basis function on these curved triangular domains has previously been used in an electric field formulation (Wilkes & Cha, 1991 IEEE AP-S Symposium).

The magnetic field integral equation is obtained by enforcing the boundary condition which relates the tangential component of the total magnetic field ($\underline{H}$) to the surface current ($\underline{J}$):

$$\hat{n} \times \underline{H} = \hat{n} \times (\underline{H}^i + \underline{H}^s) = \underline{J} \qquad on\ S^- \tag{1}$$

where the total magnetic field is the sum of the incident and scattered fields. The scattered H-field is given by the curl of a vector potential ($\underline{A}$):

$$\underline{H}^s = \nabla \times \underline{A} = \nabla \times \int_S \underline{J}\, G(\underline{r},\underline{r}')\, da' \tag{2}$$

where $G(\underline{r},\underline{r}')$ is the free-space Green's function.

When evaluating the above integral on a curved surface, the extraction of the proper singularity and the effects of the curvature must be carefully treated. A term is subtracted from the integral which renders the resulting integral non-singular, and can be evaluated numerically to yield the proper singularity as well as the higher-order effects of the curvature.

Numerical results are shown which compare the scattering from various objects using the magnetic integral equation formulation and the electric field integral equation formulation for curved triangular patch basis functions, as well as their flat triangular patch counterparts.

VALIDATION OF MMP3D CODE FOR RCS PREDICTION

S. Kiener *

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The MMP (Multiple Multipoles) codes in 2D and 3D are based on direct expansion of fields in a series of multipole functions and solving the resulting matrix equation with a generalized point matching technique. RCS predictions using these codes to not involve any integration and thus are computationally efficient.

To validate the predictions checks are made to ensure that the resulting solution satisfies the boundary conditions. Previous validation of these codes for some benchmark targets have been carried out using computed results from other solutions (such as method of moments) or by consistency checks. This paper provides an 'external' validation by comparing the computed RCS results with measured data.

In particular, predicted RCS of "hot-dog" shaped (cylinder with hemispherical caps) targets with different length to diameter ratio (L/d = 10, 5, 2.5) and over a wide range of frequency L/λ = .4 to 4 are compared to precisely measured data.

The measurements were made using a HP-8510 network analyzer based system in an anechoic chamber. The computations were carried out using a 386-PC. Since MMP3D code does not support rotational symmetry, the treatment of bodies of revolution is similar to 3D objects.

It is concluded that the multiple multipole method provides an efficient technique to predict both monostatic and bistatic far field RCS. Bulk properties of materials such as conductivity and dielectric properties can also be easily modeled.

Scattering by Arbitrary Section Cylinder Computed by Multi-center Cylindrical Harmonics Functions Expansion

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A new method: Multi-center Cylindrical Harmonics Functions Eexpansion Method (MCHFEM) is introduced for formulating the 2-dimensional scattering problems in which the scattered fields (and the interior fields in the case of a dielectric scatterer) are represented in an expansion in terms of the cylindrical harmonics functions at some proper points, the coefficients of which are unknowns. The boundary conditions are applied at the surface of the scatterer and are satisfied using point-matching. The Generalized Multipole Technique (GMT) and the Cylindrical Harmonics Functions Expansion Method (CHFEM) are two special cases of this method. It was derived that the convergence is no long governed by the distribution of singularities in the analytic continuation of the exterior scattered fields. So this method overcomes the drawbacks of GMT and CHFEM. In this paper, the method is applied to the scattering of two-dimensional cylindrical scatters of arbitrary cross section and only the TM polarization of the excitation is concidered. The solution for the coefficients of the series are obtained by inversion of an overdetermined matrix equation by least square method. The method is illustrated using perfectly conducting elliptic cylinders with semiaxes a, b ($a>b$, $ka=6.28$, $a=4b$) and elliptic dieletric cylinder with semiaxes a, b ($a>b$, $ka=5.024$, $a=4b$) (The two cases can not be solved by CHFEM). Solution to the problem of multiple scattering by two conducting scatterers is also obtained. all of these numerical results demostrates the validity of this method.

SCATTERING OF ARBITRARILY-POLARIZED EM WAVE BY DISCONTINUITY IN GROUNDED DIELECTRIC LAYER

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The 2-D interaction of impressed fields with a longitudinally invariant discontinuity in an infinite grounded dielectric sheet is investigated. Impressed electric fields consist of either plane waves incident from space above the dielectric sheet or surface waves supported by that layer; both TE and TM polarizations, having electric fields parallel and perpendicular, respectively, to the discontinuity axis, are considered. A polarization electric-field integral equation (EFIE) for the electric field induced in the discontinuity region is formulated and solved numerically. The scattered fields maintained by excess induced polarization currents include surface waves bound to the dielectric layer and radiation fields in the space region; both are evaluated, the latter by the steepest-descent integration approximation.

A coordinate system is chosen with y parallel to the discontinuity axis, while x is normal and z tangential to the dielectric/space interface in the transverse plane. The y-invariant electric field induced in the discontinuity region satisfies the EFIE

$$\vec{E}(x,z) - \frac{jk_0}{\eta_0}\int_{LCS} \delta n^2(x',z')\,\vec{G}(x|x';z-z')\cdot\vec{E}(x',z')\,dx'dz' = \vec{E}^i(x,z)$$

for all (x,z) in LCS, where δn^2 describes the index contrast between coating and discontinuity dielectrics and LCS designates the longitudinal cross section where $\delta n^2 \neq 0$. $\vec{E}$ has only a y component for the TE polarization, but both x and z components for the TM illumination. The dyadic Green's function is

$$\vec{G}(x|x';z-z') = \sum_{\alpha=x,z}\sum_{\beta=x,z} \hat{\alpha}\, G_{\alpha\beta}(x|x';z-z')\,\hat{\beta} + \hat{y}G_{yy}(x|x';z-z')\hat{y}$$

in which the $G_{\alpha\beta}$ have Sommerfeld-type integral representations obtained by a direct-field approach. Alternative integral representations for the latter are obtained using real-line and branch-cut integration contours.

MoM numerical solutions for the induced electric field are implemented, and the induced-field profiles are investigated. The amplitudes of surface waves excited by excess discontinuity-region polarization currents are calculated, as well as the radiation scattering pattern which they maintain and the associated scattering width. An important physical phenomenon appears to be the conversion of power from incident plane-wave radiation to surface-wave power bound to the dielectric layer.

RADAR CROSS-SECTION OF PARALLEL CIRCULAR CYLINDERS: A COMPARATIVE STUDY OF DIFFERENT TECHNIQUES

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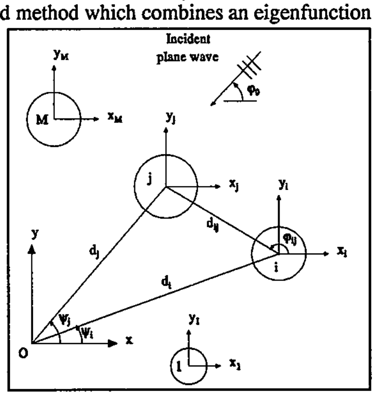
Numerous electromagnetic and antenna applications require accurate analysis for predicting the radar cross-section of parallel cylinders. Among these applications is the modelling of reflecting and absorbing surfaces by an array of circular cylinders. The problem of the scattering by many cylinders has been under continuous investigation for decades using different techniques. In this paper, the analysis of selected techniques will be outlined along with numerical comparisons for the far and near fields for an array of circular cylinders. These techniques include an asymptotic high frequency method, a boundary value approach, an iterative scattering method and a hybrid method which combines an eigenfunction expansion solution with the method of moments. The parallel cylinders are arbitrarily located as shown in the figure and are made of perfectly conducting, imperfectly conducting, or homogeneous dielectric materials or combinations. The validity and accuracy of each technique are demonstrated by illustrative numerical examples. The limitations of the associated computer codes when using a personal IBM-PC or compatible computer are also outlined. The effects of various parameters (cylinder to cylinder coupling, type of the incident electromagnetic wave, angle of incidence, mode of excitation (TE or TM), shadowing effects, spacing between the cylinders and the physical parameters of each cylinder) on the radar cross-section of the array of cylinders are also investigated.



A SIMPLE SCATTERING MODEL FOR THIN MATERIAL WIRES

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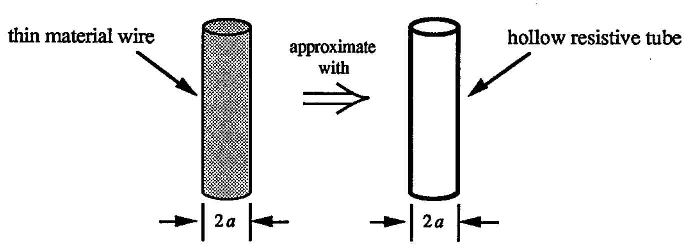
An analysis of the electromagnetic scattering by an arbitrarily shaped dielectric/magnetic (material) structure can be numerically performed using a number of well-known methods which include surface- and volume-equivalence techniques. However, for thin material wires the cost of computation becomes prohibitively expensive, thus severely limiting the overall length of the target which can be analyzed.

A new model is proposed here whereby the thin material wire is approximated by a resistive sheath or hollow tube, as shown in the figure, where the boundary conditions $\hat{n}\times(\bar{E}^+ - \bar{E}^-) = 0$ and $\hat{n}\times(\bar{E}^+ + \bar{E}^-) = 2R_s\hat{n}\times\hat{n}\times(\bar{H}^+ - \bar{H}^-)$ (T. B. A. Senior, *IEEE AP*, pp. 577-579, May 1985) are satisfied everywhere on the surface of the tube. The "+" and "-" affixes refer to surfaces just outside and inside the tube, respectively, $\hat{n}$ is the unit outward normal and R_s is the (complex) surface resistance. In this approximate model, the effective R_s is calculated from the equivalent 2-D scattering problem and hypotheticated to pertain in kind to the 3-D case, provided the radius is small with respect to the length. Comparisons made to date with other solutions (E. H. Newman, *IEEE AP*, pp. 1488-1496, Oct. 1991 and personal communication) have been very favorable.

There are two principle advantages to using such a model when the usual assumptions made for perfect electrically conducting (pec) wires are also incorporated. First is the enormous reduction in the computational expense compared to the more rigorous numerical methods, with little sacrifice in solution accuracy. Second is the simplicity of the model. It can be easily integrated into existing pec wire codes with only a slight modification of the moment method impedance matrix fill routine. A number of validating results will be shown to delineate the precise boundaries in which this model remains accurate.



ELECTROMAGNETIC PLANE WAVE SCATTERING BY A TROUGH ON THE GROUND

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Recently, attention have been made for measuring radar cross section from open-ended cavities and many investigations have been reported. When an electromagnetic wave impinges on such open structure, its scattering pattern often exhibits singular characteristics. This is due to the re-radiation contribution from the internal guiding or resonance structure.

In this paper, electromagnetic plane wave scattering by a trough will be discussed. The conventional approach to analyze the scattering field from such structure may be numerical schemes such as the moment method, which are effective for small scatterers, but not for large objects compared with the wavelength. The method used here is the high frequency asymptotic ray technique, which serves an attractive alternative scheme. It is customarily useful to use the modal description for the interior guiding structure region, and ray description for the exterior region. Accordingly, in order to calculate the scattered field efficiently, each description should be retained in the suitable region. Ray-mode conversion between the above two alternative descriptions has to be considered at the opening. Such conversion can be established by rigorous Poisson summation formula. Thus, one can construct the solution with keeping the advantages of both descriptions. In order to take account of the effect of multiple internal reflections, modal couplings at the opening are also considered.

Numerical calculation has been done and these obtained results are compared with those by the boundary integral method (BIM) (T.M. Wang & H.Ling, *J. Elect. Waves and Appl.* 5, 301-314, 1991). Agreement seems to be excellent even for pretty shallow case.

SCATTERING AMPLITUDE OF A THIN LOSSY DIELECTRIC DISC BY THE INTEGRAL EQUATION METHOD

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The electromagnetic scattering from an arbitrarily shaped lossy dielectric disc is being studied. An exact integral equation for the internal field in the disc is formulated and is solved by employing perturbation theory. After performing a transverse Fourier transform on the integral equation, a regular perturbation series is developed with the electrical thickness of the disc used as a small parameter. Once the internal fields are known the scattering amplitude is obtained by a Green's theorem relationship.

Using this methodology, the zeroth and first order solutions for the internal field are found explicitly. They are then used to find an approximation to the scattering amplitude which is accurate to second order in the electrical thickness of the disc. To verify the correctness of the solution, energy conservation is checked for first and second orders in electrical thickness. As expected the conservation equation of first order terms contains contributions from the total and absorption cross sections; no scattering terms appear. The second order conservation equation has contributions from both scattering and absorption cross sections. It is interesting to note that the second order solutions for the total and absorption cross sections depend on a spectrum of propagating, as well as, evanescent waves within the dielectric disc.

The results show that second order terms must be used to account for scattering effects in the total cross section. The theoretical development is complemented by numerical examples where the importance of the second order terms is examined as a function of the disc parameters and frequency.

Monday AM URSI-E, NEM Session MA12

Room: Columbus I/J *Time*: 0820-1200

Coupling to Cables

Chairs: R. L. Gardner, Phillips Laboratory, USAF; Jack Bridges, IIT Research Institute

0820 **CALCULATION of TYPICAL RESPONSES of AERIAL LINES to a HEMP**
F. Arreghini, M. Ianoz*, Ecole Polytechnique Federale de Lausanne; W. Radasky, K. Smith, Metatech Corporation

0840 **TRANSIENT COUPLING to BURIED BARE and INSULATED CABLES**
G. E. Bridges*, The University of Manitoba

0900 **SIMPLIFIED APPROACH for the DETERMINATION of DISTURBING VOLTAGES INDUCED on CABLE BUNDLES**
B. Demoulin*, C. Poudroux, M. Rifi, P. Degauque, Universite de Lille

0920 **SUSCEPTIBILITY of HIGH VOLTAGE MULTICONDUCTOR OVERHEAD LINES (EDF) to FAST TRANSIENT ELECTROMAGNETIC PERTURBATION**
Ch. Dumond*, O. Dafif, M. Besse, Bernard Jecko, IRCOM URA CNRS No 365, Equipe "EM"; N. Recrosio, F. Morillon, E.D.F. Lab d'Essais a Haute Tension; R. Ott, Electricite de France

0940 **TRANSFER IMPEDANCE SETUP for MULTICONDUCTOR SHIELDED CABLES**
R. Boucheteau, M. Cazajous*, Commissariat a l'Energie Atomique; B. Demoulin, Univ. des Sciences et Tech. de Lille

1000 **Break**

1020 **COMMON and DIFFERENTIAL MODE INJECTION in SHIELDED MULTICONDUCTOR TRANSMISSION LINES**
J. L. ter Haseborg*, Technical University Hamburg-Harburg; F. Wolf, C. Plath GmbH

1040 **A NEW ALGORITHM for ANALYSIS of COMPLEX GROUNDING STRUCTURES**
Han Fang*, Northern Jiaotong University

1100 **NONLINEAR RESPONSES for IMPULSE CURRENTS on FERROMAGNETIC SHIELDS**
W. J. Croisant*, C. A. Feickert, M. K. McInerney, US Army CERL

1120 **TRANSFER IMPEDANCE of USER-INSTALLED CONDUIT TERMINATIONS**
Llewellyn Jones*, Ahmed Abdelgany, William Slauson, Raytheon Company

1140 **ELECTROMAGNETIC COUPLING CALCULATIONS USING SPREADSHEET PROGRAMS on PERSONAL COMPUTERS**
Lothar O. Hoeft*, BDM International, Inc.

CALCULATION OF TYPICAL RESPONSES OF AERIAL LINES TO A HEMP

by

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Calculations of the response of above-ground conductors such as power or communication lines to HEMP are needed to translate any incident HEMP environment waveform to currents and voltages at a facility entry point. These values can then be used for designing an appropriate protection philosophy. The calculation approach is important because: (1) long lines are able to collect a substantial amount of the HEMP energy and direct it toward a single entry point of the system, and (2) it is not feasible to develop a HEMP field simulator capable of illuminating a sufficient length of a line in a threat-relatable fashion (high-level plane wave field over several hundred meters of line). For these reasons accuracy of the HEMP coupling calculations is very important.

This paper will discuss recent efforts in Lausanne , Switzerland and Metatech Corporation in Goleta, California to perform a set of calculations of typical responses of aerial lines to a HEMP with the aim to provide peak current and voltage values of conducted disturbances for the new IEC HEMP standard that is now currently under development in TC 77, Working Group 10. These calculations were performed using the "Longmire" incident electromagnetic field pulse which is considered more realistic than the classical "Bell-Laboratory" waveform.

Comparisons between time and frequency domain calculations will be provided, showing results in good agreement. In addition, a recent experiment performed at the Centre d'Etudes de Gramat (France) has provided the opportunity to perform a code/data comparison which shows also a good agreement between measured and computed values (fig. 1). The paper will discuss the advantages of the various methods used and the reasons for the differences observed.

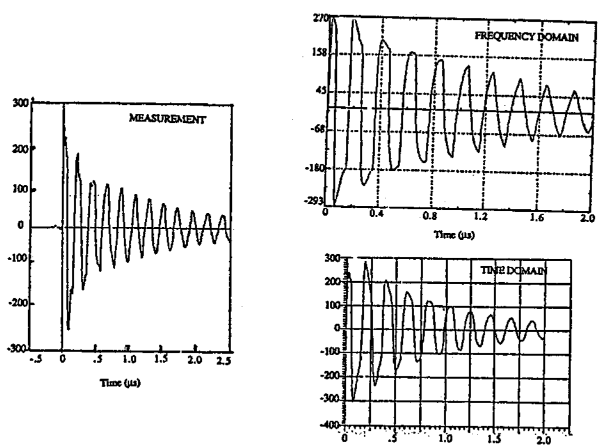

Figure 1 Current (A) measurements and calculations for a 30m long single line, 3 meters above the ground. Observer position at midpoint.

TRANSIENT COUPLING TO BURIED BARE AND INSULATED CABLES

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The coupling of transient sources to buried cables and pipes is important for the study of EMP and lightning effects as well as having many remote sensing applications. In this work, the current induced on infinitely long bare and insulated cables buried in a lossy half-space is formulated. For this problem a quasi-TEM transmission line approach is commonly employed as a solution technique. Here the cable is modeled by its equivalent circuit parameters and the incident field is modeled as a distributed source along its axis. This approach is relatively simple and only requires the accurate determination of the cable parameters. Unlike overhead cables, the propagation characteristics of a buried cable is strongly dependent on the electrical parameters of the earth, the burial depth when compared to the skin depth, and the insulating properties of the cable. Insulated and bare (grounded) cables have a dramatically different behavior. Further, the transmission line approach assumes the discrete modes dominate the induced current, ignoring the surface wave and radiation spectral contributions. Several of these issues have been examined in the frequency domain (D.A. Hill, IEEE Trans. Geoscience Remote Sensing, 720-725, 1988).

In order to study the accuracy of the transmission line approach, an exact solution is developed for determining the current induced on a buried cable system. A spectral domain formulation is used (K. Tsubota and J.R. Wait, Geophysics, 941-951, 1980) where a solution is given in the standard integral form, with time domain results obtained using the Fourier transform. Examples are presented for typical cable geometries and earth parameters. The simple result formulated by Vance (E.F. Vance, *Coupling to Shielded Cables*: Wiley, 1978) giving the induced current on a buried cable due to an exponential transient incident plane wave is compared to the more accurate theory.

SIMPLIFIED APPROACH FOR THE DETERMINATION OF DISTURBING VOLTAGES INDUCED ON CABLE BUNDLES

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If a transient electromagnetic wave impinges on cable assemblies, one of the problems is to determine the voltages at the ends of the cable bundle. However, in most practical cases, only on or two cables or wires inside the bundle are connected to very sensitive equipments which must be protected.

The calculation of the disturbing voltages can be made by using the coupled transmission line theory. In a first step, the analytical solution in the frequency domain depends on the matrix inductance and on the matrix capacitance. Each element of these matrices characterizes the lineic parameters of the coupled lines. In the general case, it is necessary to make numerous measuremrents to get each inductance and capacitance coefficient. From these datas, it is possible to deduce the propagation constants corresponding to the various eigenmodes propagating along the cable assembly and which are needed to compute the voltage amplitude induced on the various wires.

We propose, in the scope of this paper, to simplify this method by using another approach for which the inductance coefficients are calculed approximately from the well-known formulas given by the theory of coupled lines situated in a homogeneous dielectric medium. Then we assume that the equivalent permittivity of the dielectric medium can be deduced from the velocity of the common mode propagating on the cable and which can be measured very easily. From the knowledge of the inductance coefficients and of the equivalent dielectric permittivity, the capacitance coefficients are determined.

A comparison between the voltages predicted by the rigorous method and those got with this simple approach will be described. The shift in the resonance frequencies will be considered and the error margin on the disturbing voltage amplitudes is given both at low and high frequencies.

Lastly an application of these results into the time domain is given. The peak amplitude and the energy on the loads are calcuted through the rigourous modal theory and with the simplified approach.

SUSCEPTIBILITY OF HIGH VOLTAGE MULTICONDUCTOR OVERHEAD LINES (EDF) TO FAST TRANSIENT ELECTROMAGNETIC PERTURBATION

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This article presents the theoretical and experimental study of high voltage large multiconductor overhead lines susceptibility to a nuclear electromagnetic pulse (NEMP).

This study aims to determine induced currents (rise time, amplitude) on lines, taking into account their geometrical configurations (height, sagged wires...), their endings (loads in high voltage substations) and the electrical properties of soil. So, currents and overvoltages propagating in the sensitive devices of line endings could be calculated.

These currents are obtained by a space-time integral equation which is solved by the "moments method" joined to a second order polynomial representation (the chosen interpolation is Lagrange's one).

Two applications will be presented:

- Experimental simulation by a strip-line simulator (EDF) excited by an electromagnetic pulse generator. The small-scale line is located in the test zone above a perfectly conductive ground. A comparison between theory and experimentation is systematically done. A rigorous method is used for the theoretical study.

- Theoretical study of coupling between a nuclear electromagnetic pulse and high voltage loaded lines. This study will be performed in real size with the electrical properties of soil defined by (ε_r, σ). The currents on the line above the surface are driven by the total electric field (incident plus reflected) calculated without approximation. However, Fresnel approximations are used to compute fields reradiated by the line.

Coupling NEMP - high voltage lines (EDF) will be presented for differents parameters:

- line's height
- conductors number and radius
- electrical properties of soil
- angle of incidence

This study will be performed in order to determine the most penalizing cases.

TRANSFER IMPEDANCE SETUP FOR MULTICONDUCTOR SHIELDED CABLES

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Transfer impedance (T.I.) is an useful parameter for determining the electromagnetic field penetration into a shielded cable. For several years, methods and test setups have been developed for coaxial or shielded twisted pairs. Accurate and reliable measurements for these kinds of cables can be performed in many laboratories.

This paper presents an original setup built in our NEMP laboratory for the measurement of the T. I. of multiconductor cables. Its main characteristics are the following : number of conductors inside the cable (up to nineteen), length of the tested cable (2 m) and frequency bandwidth (from 10 kHz up to 15 MHz). T. I. can be measured for two configurations : single common mode (one conductor/shield) and total common mode (all the conductors linked together)

The quadriaxial structure of the setup avoids the use of a Faraday cage. Wires commutation is made by means of miniature relays located inside two screened boxes at both ends of the line. Instrumentation consists in a frequency generator coupled with a broad band power amplifier and a selective voltmeter fed with a battery. The commutation principle could be extended for the measurement of the T.I. in differential mode.

Setup calibrations were achieved with initial measurements of wellknown shielded cables such as coaxial with a solid outer conductor and shielded twisted pair. Good results were obtained for frequencies up to 10 MHz, beyond this bandwith, perturbations arose at the ends of the cable. The resolution of the measurements is about $10^{-5}\Omega/m$.

The first tests performed on a nineteen conductors cable show that there are differences between single common mode and total common mode measurements. Furthermore, the position of the conductor inside the cable is a significant parameter in the case of an helicoïdal shield, but not in the case of a solid outer conductor or a braided shield.

In addition to this, the setup enables the measurements of the lineic impedance Z_{ii} of each conductor and of the coupled lineic impedance Z_{ij} of two conductors i and j. These parameters can be used to determine the signal induced inside a cable by mutual coupling.

COMMON AND DIFFERENTIAL MODE INJECTION IN SHIELDED MULTICONDUCTOR TRANSMISSION LINES

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Abstract

In order to protect electronic systems against transients, nonlinear protection circuits are necessary. In case of multiconductor transmission lines connected with sensitive electronic systems, a lot of protection circuits have to be installed. By application of nonlinear filter pin connectors it is possible to arrange the filters for the complete number of line conductors within a plug.

Beside the suppression of interfering transients in multiconductor transmission lines by nonlinear filter pin connectors the influence of these protective devices on the transmission of the signals is of interest. In case of RF- and data lines the transmission and reflection behaviour as well as the RF-coupling between individual filter pins are of special significance.

While in previous papers (e.g. NEM'90) the transient response and transmission characteristics of nonlinear filter pins have been discussed exclusively, in this publication results will be represented showing the behaviour of nonlinear filter pin connectors installed in special plugs in connection with shielded multiconductor transmission lines. Concerning the transient response, the test pulses have been injected on the line shield by means of a current probe. Dependent on the individual line conductors, (outer and inner conductors), connected with different filter pins on the inside of the plug it exists a common mode as well as a differential mode excitation.

Measurement results in the time domain will be represented showing the transient response for linear and nonlinear filter pin connectors dependent on different line terminations. Measurement results in the frequency domain will show the influence of the line and the plug, containing the filter pins, on the RF-characteristics.

A NEW ALGORITHM FOR ANALYSIS OF COMPLEX GROUNDING STRUCTUES

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It is often involved to design and analyse various kinds of grounding structure in order to ensure normal operation, or safe protection, of power system and communication system against electromagnetic pulse (T. Nagono, Electr. and Comm. Jpn. pt.1, 68, 109–116, 1985). The resistance of the grounding structure is one of the most important parameters in analysing its EMP response. With the rapid development of computer technology, many numerical algorithms are becoming available (R. P. Nagar, IEEE Trans. PAS–104, 1985).

In this paper, the finite element approach is used and a new algorithm is presented to calculate ground resistance and leakage currents. This algorithm could be applied to treat various kinds of complex grounding structure composed of conductive grids and rods. Furthermore, the distribution of the earth potential, touch voltage, and step voltage caused by EMP currents in the ground could be also calculated by the algorithm.

In the algorithm, the image effect of the grounding structure is taken into account in addition to that of the ground itself. For a complex grounding structure, the average current distribution could not be assumed as in the case of a single conductive rod, because the leakage currents in all element are not the same. In the paper, it is assumed that if the wavelength is much greater than maximum size of a complex grounding structure, the ground would be equipotenial, i.e., the potentials on all the elements segmented from the ground are the same with that of the whole grounding system. Furthermore, it is assumed that the potential in each element is equal to the potential at its central point, and that the leakage current is uniformly distributed. It is shown that the element resistance matrix [R], element current matrix [1], ground voltage V_g, EMP current I in the ground, and ground resistance R_g satisfy the following relations

$$[\mathbf{R}][\mathbf{I}] = V_g[1] \tag{1}$$

$$V_g = R_g I \tag{2}$$

$$R_g = \frac{1}{[1]^T[\mathbf{R}]^{-1}[1]} \tag{3}$$

For higher accuracy, each element could be further subsegmented into a number of subelements. Two examples are given, and compared with the experiment results which are in good agreement with the computation.

NONLINEAR RESPONSES FOR IMPULSE CURRENTS ON FERROMAGNETIC SHIELDS

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An approximation to a thin-walled cylindrical geometry problem considers a planar ferromagnetic sheet of thickness d with electrical conductivity σ, differential magnetic permeability $\mu_d(H)=dB(H)/dH$ (assumed to be a scalar function of the magnetic field intensity H), and saturation magnetization B_s subjected to an impulse sheet current with total charge per unit length Q_o applied transversely along the outer surface and a vanishing magnetic field intensity condition at the inner surface. Mathematical analysis in conjunction with numerical analysis is used to characterize the peak value of the transient electric field response induced at the inner surface E_{peak} and the time of the peak t_{peak}.

A dimensionless formulation of the nonlinear problem for an arbitrary relative differential permeability $\mu_{rd}(H)=\mu_d(H)/\mu_o$ reveals a fundamental combination of the nonmagnetic parameters:

$$\beta = \frac{Q_o}{\sigma d^2}, \tag{1}$$

which defines an applied pulse parameter for the problem. If E_{peak} and t_{peak} are referenced to the constant permeability that would give the same result from the solution to the linear problem, then one can express E_{peak} in terms of an effective permeability $\mu_E(\beta)$

$$E_{peak} = 5.9220537270 \frac{Q_o}{\mu_o \mu_E(\beta) \sigma^2 d^3} \tag{2}$$

and t_{peak} in terms of an effective permeability $\mu_T(\beta)$

$$t_{peak} = 0.091751715 \mu_o \mu_T(\beta) \sigma d^2, \tag{3}$$

where the functions $\mu_E(\beta)$ and $\mu_T(\beta)$ corresponding to a given $\mu_{rd}(H)$ are calculated numerically. Numerically, $\mu_E(\beta)$ and $\mu_T(\beta)$ exhibit the following behavior: for very small pulses both approach the initial value of the relative permeability so that to a good approximation $\mu_E(0)=\mu_T(0)=\mu_{rd}(0)$; near $\beta=B_s/2$ both exhibit the onset of saturation, which is in close agreement with that predicted by the limiting nonlinear theory for a step magnetization curve; and for extremely large pulses both approach the permeability of free space so that to a good approximation $\mu_E(\infty)=\mu_T(\infty)=\mu_{rd}(\infty)=1$.

An applied pulse parameter that includes B_s can be inferred from a dimensionless formulation for $\mu_{rd}(H)=B_s exp(-H/H_c)/\mu_o H_c$

$$\zeta = \frac{Q_o}{\sigma d^2 B_s}. \tag{4}$$

Moreover, the same combination of parameters is found in the analytical solution obtained using the limiting nonlinear theory for a step magnetization curve. Preliminary numerical results indicate that ζ is also applicable to other permeability representations.

TRANSFER IMPEDANCE OF USER-INSTALLED CONDUIT TERMINATIONS

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Flexible conduits are used on many systems to provide better shielding than that obtainable with a standard double overbraid. However, in many designs the flexible conduit is terminated in the field with user-installable terminations. A test program was conducted to evaluate the transfer impedance of conduits with user-installed terminations. Four vendors provided user-installable fittings for their own conduit. All conduits were 1 meter long and had a 0.75 inch inner diameter. Each of the vendors use different termination methods but they all rely on threaded connections to terminate the conduit to the connector.

The transfer impedance measurements were made with a standard quadraxial fixture. Calibration of the fixture was performed using a known solid and perforated tube. Data was obtained from 5 Hz to 200 MHz using the HP 3577 network analyzer.

The transfer impedance was measured and recorded for three different torque values (85 inch-pounds, 45 inch-pounds, and 20 inch-pounds). The transfer impedance is strongly dependent on the torque value. Typically the difference between hand-tightening and torquing to 45 inch-pounds is approximately 10 dB at 10 MHz with little improvement at higher torque values. The transfer impedance is relatively flat out to 100 KHz and then exhibits a slight diffusion dip before increasing above 1 MHz. This increase is characteristic of leakage through apertures. Differences in the transfer impedance for the four vendors are shown. The transfer impedance with the user-installed terminations is compared to data for factory terminations. In general, the data shows that the transfer impedance for the conduit is dominated by the termination method.

ELECTROMAGNETIC COUPLING CALCULATIONS USING SPREADSHEET PROGRAMS ON PERSONAL COMPUTERS

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The advent of personal computers with sophisticated spread sheet programs has given the engineer or scientist a powerful tool for quickly and accurately calculating the electromagnetic coupling in systems. The spreadsheet computational technique emphasizes how electromagnetic energy flows from the source or culprit to the receiver or victim. Each step in the computational process is represented by a relatively simple, easily understood coupling model. This allows the analyst to see the results of all the intermediate steps in the calculation, and gain a much clearer insight into the coupling process than can usually be obtained from more elaborate special purpose computer codes.

The computational technique is based on the concept that an electromagnetic coupling calculation can represented as a product of transfer functions. In the frequency domain these are phasors, have a magnitude and phase. Each of these can usually be broken down into quite simple formulations. Each is calculated by one column of the spread sheet. Frequency, with either a linear or logarithmic distribution, is represented by the rows of the spreadsheet. The plotting capabilities of the spread sheet can be used to present the data in graphical form. As in most EMC calculations, the magnitude only can be calculated if desired. If phase is also calculated, the results can be used to transform time domain waveforms.

This paper will explain the technique and present an example of coupling through cable shields. The common mode currents and voltages on the overbraid, the twisted pair shield and the twisted pair wires were calculated.

The use of a spread sheet frees the electromagnetic analyst from the computational housekeeping and allows attention to be focused on the physics of the situation.

Monday AM2 URSI-B Session MA14

Room: Columbus C/D *Time*: 1020-1200

Adaptive and Non-Cartesian Space/Time Discretization

Chairs: Wolfgang J. R. Hoefer, University of Ottawa; Raymond Luebbers, The Pennnsylvania State University

1020 **USING ADAPTIVE SPATIAL DOMAIN with the FINITE-DIFFERENCE TIME-DOMAIN METHOD**
Xiaohua Wu*, David Conn, McMaster University

1040 **CURVED SURFACE MODELING with the FINITE-DIFFERENCE TIME-DOMAIN TECHNIQUE**
Michael B. Gedera, Kenneth R. Demarest*, University of Kansas

1100 **CONFORMAL FDTD MODELING of the RCS of THREE DIMENSIONAL OBJECTS**
T. G. Jurgens*, Fermi National Accelerator Laboratory; Allen Taflove, Northwestern University

1120 **MATRIX APPROACH to IMPLEMENTING the NON-ORTHOGONAL FINITE DIFFERENCE TIME DOMAIN ALGORITHM**
Jin-Fa Lee*, Worcester Polytechnic Institute; Omar M. Ramahi, R. Mittra, University of Illinois, Urbana-Champaign

1140 **SOLVING LARGE UNSTRUCTURED GRID TIME DOMAIN EM PROBLEMS USING MIMD PARALLEL COMPUTERS**
Niel K. Madsen*, Lawrence Livermore National Lab

Using Adaptive Spatial Domain with the Finite-Difference Time-Domain Method

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A new technique using an adaptive spatial domain with the finite-difference time-domain (FD-TD) method is developed. In this technique, the spatial computation domain is gradually expanded to whole region while the excitation wave propagates. The major advantage achieved is significant saving in computation time for field analysis.

The FD-TD method has been used extensively for the electromagnetic field analysis. One of its major limits is that it requires a very long computation time. This is due to the fact that the space steps must be small enough to describe different physical structures in a reasonable number of meshes and to guarantee the accuracy of the difference approximation of Maxwell equations. Furthermore, the time steps used is limited by the stability restriction of the finite difference equations.

In most cases of field analysis using FD-TD method, impulse response, characteristics impedance and effective dielectric constant are concerned. This analysis only requires transmission response of systems and at most one time reflection response. It is obvious that the excitation wave does not affect the field anywhere before it reaches there. As well known, the effective speed of the wave is considerably lower than speed of light, specially in case of the electro-optic devices where GaAs ($\epsilon_r = 13.2$) is often used as substrates. Therefore, an adaptive spatial computation domain can be gradually expanded to the whole region of the interest according to the time when the wave propagates through the region. In this way, before excitation wave reaches to the nodes, the time to calculate fields at these nodes can be saved.

In this paper, an impulse response of a coplanar waveguide on GaAs substrate is calculated using FD-TD method in an adaptive spatial domain. The computational domain is defined by $93\Delta x * 21\Delta y * 180\Delta z$. The time step is chosen such that the wave goes through one space step in five time steps. For transmission analysis, the results have shown that computation time can be saved by more than 35% compared to the time used in the FD-TD method using fixed spatial domain. For reflection problem, 18% saving in computing time has been achieved. This technique can significantly improve computation efficiency for field analysis using the FD-TD method. It is applicable to many other field problems involving transmission and one time reflection analysis.

Curved Surface Modeling with the Finite-Difference Time-Domain Technique

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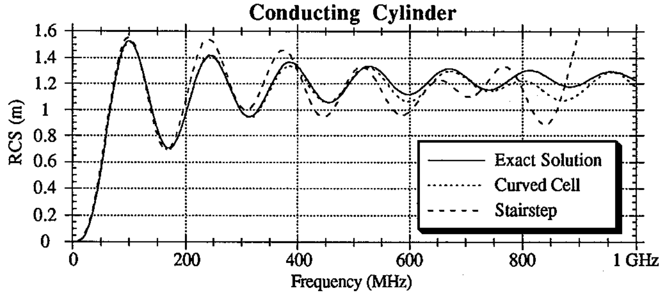
One of the most serious limitations of the standard finite-difference time-domain (FDTD) technique has been its inability to accurately model objects whose surfaces do not conform to the rectangular grid. The square cell FDTD technique models curved boundaries with a stairstep approximation to the shape of the object. By using a very fine grid, reasonable results can be obtained, but only at the expense of increased computer modeling costs.

A code has been developed that utilizes a curved cell formulation of the standard FDTD technique. The algorithm locally deforms cells that are cut by the surface of the scatterer so that the resulting mesh conforms to the true shape of the surface. A combined cell-linking and near-neighbor field approximation technique is used to perform the contour integrations required to update fields in distorted cells. Both the mesh generation and subsequent field advancement stages are performed automatically by the code, with the user only providing a functional description of the scatterer. The user is not required to change any field equations when the geometry is changed.

The purpose of this presentation is to compare the results of this method with those of the stairstep technique in terms of solution accuracy and computational savings. The results presented are for TE mode scattering from two-dimensional, perfectly conducting objects. By comparing with both closed form and moment method solutions, the results demonstrate a substantial improvement in solution accuracy over the stairstep technique.

Backscatter from Two-Dimensional Conducting Cylinder



CONFORMAL FDTD MODELING OF THE RCS OF THREE DIMENSIONAL OBJECTS

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A. Taflove
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Traditional FDTD algorithms are based on Maxwell's curl equations. The resulting computer codes represent an object's curved surface with a stair-stepped approximation. This limitation has been remedied with the development of the Contour FDTD (CFDTD) algorithm. This algorithm, based on the integral form of Maxwell's equations, models curved surfaces conformally. Previously published results for two dimensional scattering problems (T.G. Jurgens, et al., IEEE Trans. APS, March 1992) have shown that the technique enhances the accuracy of the FDTD code for metal, dielectric and permeable objects. In some cases the accuracy of the CFDTD formulation exceeded the traditional FDTD formulation even when the spatial resolution of the traditional method was four times greater than the contour method.

This presentation reports on the extention of the CFDTD algorithm for the modeling of three dimensional electromagnetic scattering problems. Since the Ampere and Faraday contours of Maxwell's equations encircle a surface, the CFDTD code represents a three dimensional object as a series of two dimensional contours. These contours are computed in a manner similar to that used for two dimensional scattering problems.

Validations for several canonical objects are presented. Single-body scattering results include the illumination of a sphere and a truncated right circular cylinder. Multiple-body scattering validations are shown for a system of two spheres. Various sphere separations are investigated. Illustrations of the near fields' structure are shown.

The CFDTD data is compared to the traditional FDTD algorithm, series solutions, the Generalized Multipole Technique and the Method of Moments. Point by point agreement between data sets (excluding the traditional FDTD algorithm data) is generally in the 0.1 dB range, with a few data points approaching 1 dB. The CFDTD algorithm maintains accuracy over a dynamic range exceeding 45 dB. This underlines its suitability for the modeling of low observable objects. Since the code computes field values in the entire volume immediately surrounding the scatterers, detailed near field information is available. High current and charge accumulation areas can be identified thus leading better understanding of the scattering physics.

A MATRIX APPROACH TO IMPLEMENTING THE NON-ORTHOGONAL FINITE DIFFERENCE TIME DOMAIN ALGORITHM

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Worcester Polytechnic Inst.

Omar Ramahi & Raj Mittra
ECE Dept.
University of Illinois

A non-orthogonal finite difference time domain (FDTD) algorithm, that utilizes the covariant and contravariant components of the electric and magnetic fields as the state variables, has been described previously (J. F. Lee, R. Palandech, & R. Mittra, IEEE MTT, Apr. 1992). The finite difference equations for the non-orthogonal FDTD algorithm can be written as follows:

$$\begin{aligned} E^{1,n+1}_{i,j,k} &= E^{1,n}_{i,j,k} + \frac{\delta t}{\epsilon\sqrt{g}}\left[h^3_{i,j+1/2,k} - h^3_{i,j-1/2,k} - h^2_{i,j,k+1/2} + h^2_{i,j,k-1/2}\right]^{n+1/2} \\ h^1_{i,j,k} &= g_{11}H^1_{i,j,k} \\ &+ \frac{g_{12}}{4}\left[H^2_{i+1/2,j-1/2,k} + H^2_{i-1/2,j-1/2,k} + H^2_{i+1/2,j+1/2,k} + H^2_{i-1/2,j+1/2,k}\right] \\ &+ \frac{g_{13}}{4}\left[H^3_{i+1/2,j,k-1/2} + H^3_{i-1/2,j,k-1/2} + H^3_{i+1/2,j,k+1/2} + H^3_{i-1/2,j,k+1/2}\right] \quad (1) \end{aligned}$$

where E is the contravariant component of the electric field, and h and H are the covariant and contravariant components of the magnetic field, respectively. The difference equations for the other components can be derived readily via index permutations.

The direct implementation of Eq. (1) has two major drawbacks:

1. The adoption of the (i, j, k) coordinate system makes the mesh generation task very difficult, for all but the simplest of scatterer geometries.
2. A 3 by 3 metric tensor has to be stored for each grid point to make the computation more efficient. Consequently, the non-orthogonal FDTD algorithm is considerably more storage intensive than the conventional Yee algorithm.

In this paper, we propose a matrix formulation of the FDTD algorithm to circumvent the above two difficulties. The approach makes use of the concept of the element matrix in the finite element methods. In the present approach, the electric and magnetic fields are updated through the multiplication of four global matrices $[\mathcal{A}]$, $[\mathcal{B}]$, $[\mathcal{C}]$ and $[\mathcal{D}]$. Furthermore, these matrices are assembled from the element matrices in exactly the same manner as is done in the finite element (FEM) implementations. For instance, the recursion equations are written as:

$$\begin{aligned} E^{n+1} &= E^n + \frac{\delta t}{\epsilon_o}[\mathcal{A}][\mathcal{D}]H^{n+1/2} \\ H^{n+1/2} &= H^{n-1/2} - \frac{\delta t}{\mu_o}[\mathcal{B}][\mathcal{C}]E^n \quad (2) \end{aligned}$$

The numerical procedure based on (2) has been integrated with a commercially-available mesh program, via., PATRAN, and has been used to analyze a number of three-dimensional electromagnetic problems. Representative numerical results will be presented in the paper.

Solving Large Unstructured Grid Time Domain EM Problems Using MIMD Parallel Computers

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The solution of electromagnetically large 3D EM problems in the time domain is still a challenging problem for even the most powerful computers. Parallel computers with large numbers of processors and large amounts of memory are seen as the only viable approach for successfully solving these types of problems - particularly when algorithms allowing the use of unstructured finite element type grids are used.

We will describe our efforts in creating a massively parallel version of the Discrete Surface Integral 3D code (DSI3D) which solves Maxwell's curl equations in the time domain using unstructured grids. The massively parallel computer that we have used is the 128-processor Intel iPSC/i860, which is a Multiple Instruction Multiple Data (MIMD) type of parallel computer. The primary goal of our work has been to produce a parallel DSI3D code that runs efficiently on this type of parallel computer. By running efficiently, we are referring to efficient use of memory and execution speeds which scale approximately linearly with the number of processors.

The distribution of the problem among the processors is a critical choice in determining the overall efficiency. We will describe a recursive spectral bisection technique [H.D. Simon, *Comp. Sys. Engr.*, Vol. 2, 135-148, 1991] which is broadly applicable, easily implemented, and seems to distribute the problem among the processors in such a manner that a good work-load balance is achieved and inter-processor communication is minimized. The use of this technique together with several general purpose reuseable software modules allows the construction of an efficient MIMD parallel code in a relatively straightforward manner. Solutions of several very large scattering and propagation problems requiring the use of unstructured grids consisting of millions of cells will be presented.

Monday AM2 URSI-A Session MA15

Room: Columbus G *Time*: 1020-1200

Antenna and Cavity Measurements

Chairs: Motohisa Kanda, NIST; Y. Kim, Jet Propulsion Laboratory

1020 **A COAXIAL CAVITY METHOD for MEASUREMENT of ELECTROMAGNETIC PROPERTIES of MATERIALS**
Ching-Lieh Li*, K. M. Chen, Michigan State University

1040 **INFRARED DETERMINATION of ELECTROMAGNETIC FIELDS COUPLED THROUGH LONGITUDINAL and TRANSVERSE SLOT APERTURES in CYLINDRICAL CAVITIES**
John D. Norgard*, Ronald M. Sega, Univ. of Colorado at Colorado Springs; Michael G. Harrison, Hugh H. Pohle, USAF Phillips Laboratory

1100 **SIR-C ANTENNA PATTERN PREDICTION USING FIELD PROBE MEASUREMENTS**
Y. Kim*, Jet Propulsion Laboratory; Dennis L. Coombs, Ball Aerospace Systems Group

1120 **INVESTIGATION of TEM CELL TECHNIQUE**
Bin Song*, Junmei Fu, Xi'an Jiaotong University

1140 **RADIO HOLOGRAPHY IMAGE RECONSTRUCTION in the VPA FRESNEL REGION**
V. Khaikin*, V. Morozova, USSR Academy of Sciences

A COAXIAL CAVITY METHOD FOR MEASUREMENT OF ELECTROMAGNETIC PROPERTIES OF MATERIALS

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When an open-ended coaxial probe is used to non-destructively measure the EM properties of a thick material layer, the EM fields excited inside the material layer are localized around the probe aperture. Thus the scheme of using open-circuit input impedance (material backed by air) and short-circuit input impedance (material backed by a metallic plate) to quantify both complex permittivity and permeability of the material would fail because these two impedances are almost identical.

To overcome this difficulty, the center conductor of the coaxial probe is extended into the material such that the EM fields are extended into the material. To accommodate this arrangement, a coaxial probe is terminated by a coaxial cavity with a movable backwall. When the cavity is partially filled with a material, two input impedances of the cavity can be measured by setting the backwall at two different locations. From these two input impedances, the EM parameters, including the complex permittivity and permeability, of the material can be determined.

Theoretical analysis of this coaxial cavity is mainly based on cavity mode expansion of the electric field at the discontinuity. The aperture electric field is determined by Galerkin's method. After that the input impedances of the cavity can be expressed implicitly as functions of EM parameters of the materials, which can be determined inversely by a numerical Newton's method.

A series of experiments has been conducted to measure the input impedances of the cavity filled with various materials using a network analyzer. Experimental results were compared with numerical results.

INFRARED DETERMINATION OF ELECTROMAGNETIC FIELDS COUPLED THROUGH LONGITUDINAL AND TRANSVERSE SLOT APERTURES IN CYLINDRICAL CAVITIES

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Michael G. Harrison and Hugh H. Pohle, USAF Phillips Laboratory PL/WSM, Kirtland AFB, NM 87117-6008

An enhanced infrared (IR) detection technique using IR focal plane array technology (FPA) is applied to the mapping of two-dimensional cross-sectional views of electric and magnetic field distributions inside a waveguide or a cavity when excited by an aperture.

The IR measurement involves the observation of microwave/millimeter wave (mw/mmw) energy deposited into an electrically lossy detection screen. Joule heating results in IR emissions which can be detected by an IR imaging system. The detection screen material is calibrated such that a given temperature rise (above the ambient temperature of the material) corresponds to a particular electric field intensity level. The FPA system allows for increased sensitivity of detection and, therefore, greater dynamic range of the electromagnetic field measurements.

The effect of cavity geometry on the energy coupled through a slot aperture is investigated through the use of planar mappings of the internal field. The IR technique is used to map the cross-sectional and longitudinal energy profiles of the electromagnetic field both in the vicinity of the aperture and along the length of the cylinder. The energy profiles of the fields are determined as a function of the frequency above and below the cutoff frequencies of the waveguide and the aperture. The dominant mode and several higher order modes are mapped inside the cavity over several cross-sectional cuts through the aperture and on either side of the aperture. Through use of these cross-sectional positions of the detection material, a three-dimensional field profile can be obtained.

Thin, rectangular slot apertures are excited in a circular, cylindrical cavity. The long axis of the aperture slots are oriented along the axis of the cylinder (longitudinal) and orthogonal to the axis (transverse). The aperture geometry is 10 centimeters in length and 0.0635 cm (25 mils) in width. The copper cylinder is one meter in length and 10.16 cm (4 inches) inner diameter. The cylinder is closed at both ends with a copper mesh screen which will act as a conducting shield at mw/mmw frequencies but is transparent to IR and will allow infrared thermograms to be made inside the cavity. Measured electric and magnetic field distributions are compared to theoretically established values.

SIR-C ANTENNA PATTERN PREDICTION USING FIELD PROBE MEASUREMENTS

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SIR-C (Shuttle Imaging Radar-C) is a SAR (Synthetic Aperture Radar) with simultaneous multi-frequency and multi-polarization capability. The SIR-C antenna is composed of 18 L-band and 18 C-band microstrip panels. The dimensions of antenna are 12.0 m X 2.9 m and 12.0 m X 0.7 m for L- and C- band, respectively. Due to the large sizes of the antennae, it is difficult to directly measure the far-field pattern. In this talk, we will present a method of indirectly measuring the far-field pattern of a physically large antenna.

Since the SIR-C antenna is a microstrip array antenna, it is useful to measure the radiation pattern of a single radiating element. Since a single radiator is small, the pattern can be measured in an anechoic chamber. This measured pattern will be compared with the transmission line model predictions. The physics of a blind spot in the pattern will be illustrated using the conservation of momentum. We also need to know the amplitude and phase relations between the radiating elements to predict the antenna pattern. These complex field quantities, including mutual couplings, can be measured using a field probe.

The electromagnetic field probe is an electrically small loop which is placed extremely close (less than 1/50 of wavelength) to the microstrip antenna. Even though the probe itself introduces some disturbances to the antenna, it is verified that we can accurately measure the relative field values between different radiating elements. The details of the probe and the advantages of using this probe for the microstrip array will be presented. The predicted patterns of SIR-C antenna (both L- and C-band) using the suggested technique will also be given.

The research described in this abstract was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

INVESTIGATION OF TEM CELL TECHNIQUE

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Xi'an Jiaotong University, Xi'an, Shaanxi, P.R.China)

With the development of electronic and electromagnetic techniques, the number of various electronic and electromagnetic instruments increase sharply . In order to make these instruments work compatibly, their anti-interferences must meet certain specific requirement. Recently, the TEM cell technique has become a main way for the measurement of sensitivity.

A TEM cell is essentially a large section of rectangular coaxial transmission line used to establish an isolated known test environment. High field levels can be achieved with minimal power requirements and without interfering with nearby equipment. The useful frequency range of the TEM cell for EMI measurements is limited by the cut-off frequencies of the higher order TE and TM modes and the appearance of resonances due to reflections at the taper sections. The higher order mode resonances appear at sharply defined frequencies. Thus, there may exist frequency windows between resonances where field variations become predictable and TEM cell usage is still quite valid. The results of cut-off frequencies may be used to predict the frequencies of higher order TEM cell resonance. This problems have been investigated with a variety of technique. But there is some disagreement among the published results. The purpose of our study is to show that the boundary-element method(BEM) is suited for the evaluation of cut-off frequencies for the large number of higher order modes in the TEM cell. The results obtained by this method are compared with those obtained by other authors and discussion are made to show that the BEM is a very powerful method for finding cut-off frequencies of higher order modes in the TEM cell. The basis analytical approach leading to the cut-off frequency is to convert the wave equation into a matrix equation and find the eigenvalues. Our results show that the first resonance TE_{011} is found to be very weak and becomes pronounced when a discontinuity is placed horizontally at the middle of the vertical sidewall. Moreover, resonance effects also become pronounced for the TE_{10} and TE_{11} modes when some perturbation is given at the center line of the cell. Thus for small test objects like PCB's and components, the TEM cell could be used above the TE_{101} resonance within the predetermined frequency windows.

RADIO HOLOGRAPHY IMAGE RECONSTRUCTION IN THE VPA FRESNEL REGION

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The technique and equipment of a holography recording in one of the Variable Profile Antenna(VPA) foci have been described formerly (V.Khaikin:Proceedings of XIV ESA Workshop on Antenna Measurement in Noordwijk, Netherland, 1991; Abstacts of URSI-Meeting/APS-Symposium in London, Canada, 1991).

In this report we consider the process of holography image reconstruction in the VPA Fresnel region.

If $\dot{E}(u,v)$ is VPA aperture field given in the region $[\Delta U,\Delta V]$ and $H(x,y)$ is the Far field hologram calculated in $[\Delta X,\Delta Y]$, the aperture field $\ddot{E}(u',v')$ with $u'=k_U u, v'=k_V v$ can be reconstructed in $[\Delta U',\Delta V']$ region by the inverse Fourier transform(FT) or DFT/FFT.

We simulated this process for our method of the holography recording and image reconstruction in which the position of $\ddot{E}(u'-u_o,\ v'-v_o)$ in the aperture plane is determined by the space frequency of linear phase shift of the reference wave u_o, v_o and an unwanted autocorrelation function $\ddot{E}_{aut}\sim\ddot{E}(u',v')\circledast\ddot{E}^*(u',v')$ is suppressed down to residual $\ddot{E}^{res}_{aut}$. The results of this simulation for different VPA configurations, wavelengths and sizes of holgraphy data array $[\Delta X,\Delta Y]$ in conditions of real S/N, nonlinearity of phase shift, atmosphere influence and other disturbing factors of a radio holography experiment are presented. The limitations of the reconstructed surface accuracy ε_Σ and resolution $\Delta u'_{min}$, $\Delta v'_{min}$ are given for the whole VPA and a single VPA element.

Fortunately, we can apply the same FT/DFT to reconstruct a hologram recorded by our method in the VPA Fresnel region with rather a small error $\varepsilon_F=\Sigma\varepsilon_{FT},\varepsilon_{DFT},\varepsilon_{FFT}$. As the result we obtain ε^e_Σ=50 µm after reconstruction of 22 GHz hologram measured at RATAN-600 radio telescope in real atmosphere conditions. An atmosphere contribution ε^e_{atm} is dominating in the experimental ε^e_Σ over ε^e_F, ε^e_{aut}(error caused by $\ddot{E}^{res}_{aut}$), $\varepsilon^e_{U,V}$(transfer error u'->u, v'->v) and others. The extreme size of holography data array $[\Delta X^e, \Delta Y^e]_{max}$ limits mainly the achievable surface resolution by 2 m for the whole antenna and by 10 cm for a single RATAN-600 element.

Monday PM URSI-B Session MP03

Room: Grand C *Time*: 1320-1700

Nonlinear Optical Phenomena

Organizer: Richard W. Ziolkowski, University of Arizona
Chairs: Richard W. Ziolkowski, Ewan M. Wright, University of Arizona

1320⁺ **ULTRA LONG DISTANCE TRANSMISSION USING ERBIUM-FIBER AMPLIFIERS and SOLITONS**
L. F. Mollenauer*, AT&T Bell Laboratories

1400⁺ **NUMERICAL EXPERIMENTS in NONLINEAR OPTICAL PULSE PROPAGATION**
Raymond J. Hawkins*, Lawrence Livermore National Lab

1440 **COMPUTATIONAL MODELING of MAXWELL'S EQUATIONS in NONLINEAR DISPERSIVE MEDIA for PROPAGATION and SCATTERING of FEMTOSECOND ELECTROMAGNETIC SOLITONS**
Peter M. Goorjian*, Alex C. Woo, NASA Ames Research Center; Allen Taflove, Northwestern University

1500 **Break**

1520⁺ **HIGHLY NONLINEAR PHENOMENA in OPTICAL WAVEGUIDES**
Ewan M. Wright*, University of Arizona

1600⁺ **FULL-WAVE, VECTOR MAXWELL EQUATION MODELING of SELF-FOCUSING of ULTRASHORT OPTICAL PULSES in a NONLINEAR KERR MEDIUM**
Richard W. Ziolkowski*, Justin B. Judkins, University of Arizona

1620⁺ **DISCUSSION**

Ultra Long Distance Transmission Using Erbium-Fiber Amplifiers and Solitons

L. F. Mollenauer

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Ultra long distance fiber optic transmission systems using inexpensive, broad-band, erbium-fiber optical amplifiers to replace expensive, rate-limiting, electronic regenerators are now under development. The highest bit rates are obtained in such an all-optical system by using the special, nondispersive pulses known as solitons. Indeed, we have demonstrated error free (measured bit error rate $\leq 10^{-10}$) soliton transmission over paths as long as 15,000 km at 5 GBit/s, and the same over more than 12000 km at 10 GBit/s. The latter result, based on a two channel (2x5 Gbit/s) *wavelength division multiplexing* (WDM), is possible because solitons of different optical frequencies (unlike other pulses) are transparent to each other. As promising as it is, this result represents only the beginning: single-channel bit rates (for the trans-oceanic paths) are soon expected to reach, or even to exceed, 10 Gbit/s, while remaining fully compatible with extensive WDM.

The physics underlying these practical results will be sketched in a tutorial manner. In particular, the following topics will be addressed: 1) the nonlinear Schrödinger equation and the robustness of solitons in fibers; 2) lumped amplifiers and solitons based on *path-average* values of pulse power and fiber dispersion; 3) effects of amplifier spontaneous emission noise on soliton amplitude and timing jitter, and hence on error rates; 4) the use and benefits of frequency guiding fibers in the transmission line; 5) soliton-soliton interactions in WDM; 6) how solitons maintain a high degree of polarization, and the potential for polarization division multiplexing.

Numerical Experiments in Nonlinear Optical Pulse Propagation

Raymond J. Hawkins

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Numerical experiments have provided great insight both for result interpretation and experimental design in the field of nonlinear optics. In this talk I will give an overview of the use of the Beam Propagation Method (BPM) in the ***predictive*** treatment of nonlinear optical pulse propagation problems in optical fibers. The BPM is a pseudospectral technique used to solve the principal equation of nonlinear fiber optics: the nonlinear Schrodinger equation. Efficient solution using BPM coupled with a history of predictive results (i.e. no adjustable parameters) has made this approach a standard in the study of nonlinear guided-wave optics.

An example of the predictive power of the BPM is found in the simulations studies of the optical dark soliton. (W.J. Tomlinson, R.J. Hawkins, A.M. Weiner, J.P. Heritage, and R.N. Thurston, "Dark optical solitons with finite-width background pulses", J. Opt. Soc. Am. B. 6, 329-334, 1989) This highlights the use of the BPM in predicting how the interplay between group-velocity dispersion and self-phase modulation results in a stable optical pulse and demonstrate how deviations from the analytic solution encountered in the laboratory can be successfully accounted for. The success in predicting the low-power dark soliton behavior led to the study of higher-power dark solitons. Prediction of the properties of these solitons required the addition of a broad-band Raman-response term. (A.M. Weiner, R.N. Thurston, W.J. Tomlinson, J.P. Heritage, D.E. Leaird, E.M.Kirschner, and R.J. Hawkins, "Temporal and self-shifts of dark optical solitons," Opt. Lett. **14** , 868-870, 1989). Extension of the BPM to account for the Raman-response of the medium has enabled the prediction of pulse propagation behavior both for solitons as well as non-soliton pulses.

The BPM has also been employed extensively in the study of bright solitons as will be described by others in this session. In keeping with the theme of predictive numerical experiments, I will review the prediction of the collision of two optical solitons and show the BPM predictions of the observed behavior of these solitons during and after the collision.(S.R. Friberg, W. Jiang, Y.Sakai, and R.J. Hawkins, "Observation of soliton collisions in optical fiber," in ***Ultrafast Phenomena VII*, Springer Series in Chemical Physics**, Vol. 53, edited by C.B. Harris, E.P. Ippen, G.A. Moreau, and A.H. Zewail (Springer-Verlag Berlin, Heidelberg, 1990), pp. 184-186)

COMPUTATIONAL MODELING OF MAXWELL'S EQUATIONS IN NONLINEAR DISPERSIVE MEDIA FOR PROPAGATION AND SCATTERING OF FEMTOSECOND ELECTROMAGNETIC SOLITONS

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and
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A new algorithm is presented that can solve the time dependent, nonlinear Maxwell's equations. This algorithm is a finite-difference time-domain (FDTD) algorithm and it is used for calculations of the propagation and scattering of femtosecond electromagnetic solitons. The modeling of the material includes linear dispersive effects and nonlinear instantaneous and dispersive effects, thereby permitting the modeling of optical solitons that have very large instantaneous bandwidths. This new algorithm should provide a modeling capability for millimeter-scale integrated optical circuits beyond that of existing techniques that use the generalized nonlinear Schrodinger equation (GNSE), since it retains the optical carrier wave and can rigorously treat the electromagnetic field physics of inhomogeneous nonlinear dispersive media in the context of a vector field boundary value problem.

The fundamental innovation of the present approach is to notice that it is possible to treat the linear and nonlinear convolution integrals, which describe the dispersion, as new dependent variables. Using this observation, a coupled system of nonlinear second-order ordinary differential equations can be derived for the evolution of the linear and nonlinear convolution integrals, by differentiating them in the time domain. These equations, together with Maxwell's equations form the system that is solved to determine the electromagnetic fields in nonlinear media. Using this approach, the level of storage is reduced by a factor of 10,000 in comparison to an approach that implements the direct evaluation of the convolution integrals over the time interval of the calculation. For 2-D or 3-D calculations the level of storage is reduced from an order of 1000 Gwords to an order of 1 Gword.

Using this algorithm, results are presented of first-time calculations in one dimension of the propagation and collision of femtosecond electromagnetic solitons that retain the optical carrier. The nonlinear modeling takes into account such quantum effects as the Kerr and Raman interactions. The present approach is robust and should permit the modeling of 2-D and 3-D optical soliton propagation, scattering, and switching directly from the full-vector, nonlinear Maxwell's equations.

The algorithm will be presented in full detail in the presentation. Also a video will be shown of the propagation and collision of femtosecond electromagnetic solitons.

HIGHLY NONLINEAR PHENOMENA IN OPTICAL WAVEGUIDES

Ewan M. Wright

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ABSTRACT

An exciting aspect of nonlinear integrated optics is the prediction that the properties of guided waves can become power-dependent when one or more of the guiding media is nonlinear. It is useful to classify these effects as either weakly or highly nonlinear, depending on the ratio of the nonlinear change in refractive-index to the linear index difference between the guiding media. In the weakly nonlinear regime where the ratio is small, the field profiles can be approximated by the linear guided modes and only the propagation constants are power-dependent. This is the regime of operation of, for example, the usual directional coupler. In contrast, in the highly nonlinear regime the ratio is larger than or equal to one and both the propagation constants and field profiles become power-dependent, and a variety of fascinating new phenomena emerge. The simplest of these is *soliton emission*, which occurs in a one-dimensional slab waveguide with a nonlinear self-focusing cladding. As the input power is increased the nonlinear change in refractive-index can counter the linear index difference between the film and cladding. Beyond this threshold the incident power radiates into the nonlinear cladding medium, and self-focusing causes the field to form into a *spatial soliton* which propagates away from the film.

In this talk I shall describe the basic physics and potential applications of highly nonlinear phenomena in optical waveguides. Particular emphasis shall be placed on the use of spatial solitons for all-optical switching.

Full-wave, vector Maxwell equation modeling of self-focusing of ultrashort optical pulses in a nonlinear Kerr medium

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The University of Arizona
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There is continuing and ever increasing interest in the propagation of optical pulses in nonlinear media. This interest has been driven by the anticipation of enormous technological dividends which include potential revolutionary device concepts in military, computer, telecommunications, detection, and medical technologies. The nonlinear optics area is being pursued vigorously by university, government laboratory and industrial concerns.

With this continuing and heightened interest in nonlinear semiconductor and optically integrated devices, more accurate and realistic numerical simulations of these devices and systems are in demand. Numerical modeling offers the potential of encouraging multiple device and system design iterations as well as of providing frameworks in which one can interpret complex experimental results and suggest further diagnostics or alternate protocols. Current calculational capabilities in the optics community include approximate scalar models solved with analytical approaches and parabolic beam propagation (numerical) codes. These scalar models, however, can not model a variety of physical situations which are intimately dependent on the vector nature of the electromagnetic fields. Although they have been extremely successful in microwave applications, full-wave, vector Maxwell equation approaches have not been used in general in the nonlinear optics community.

The adaptation of a standard time domain two- and three- dimensional vector, linear Maxwell's equations discrete solver to the problems of beam propagation in nonlinear media will be discussed in detail. In particular, a nonlinear generalization of a linear finite difference time domain (FDTD) Maxwell's equations solver in two spatial dimensions and time will be described that is being used to study the interaction of femtosecond optical pulses with a Kerr nonlinear material. The numerical simulator has been constructed by incorporating into the FDTD solver a vector extension of a currently used nonlinear materials model. This time-dependent model of the Kerr medium exhibits self-focusing (linear diffraction offset by spatial dispersion), nonlinear compression (temporal dispersion), and nonlinear damping and growth. We have found that the full-wave, vector Maxwell equation approach fully encompasses the effects generally contained in the conventional scalar models of self-focusing in a Kerr medium as well as several others. Self-focusing results will be presented which emphasize those vector properties. These include the behavior of the transverse power flow which arises from the interaction between the focusing mechanisms and the growth of the longitudinal electric field component; and the reflection of wave energy from the nonlinear focusing region. Typical examples of the applications of this approach to the study of pulse scattering from a linear-nonlinear interface will also be presented.

Monday PM AP-S, URSI-A Session MP07

Room: Columbus A *Time*: 1320-1700

Polarization Radar Calibration

Chairs: W. Wiesbeck, Universitat Karlsruhe; Y.M. M. Antar, Royal Military College of Canada

1320 **A FULL RCS CALIBRATION TECHNIQUE USING a DIHEDRAL CORNER REFLECTOR**
Jiahn-Rong Gau*, Walter D. Burnside, The Ohio State University

1340 **LIMITATIONS of MULTIPLE FEEDS in a POLARIMETRIC-RADAR COMPACT RANGE**
K. W. Sorensen*, W. H. Schaedla, B. C. Brock, Sandia National Laboratories

1400 **A SIMPLE POLARIMETRIC CALIBRATION METHOD WHICH UTILIZES a REFERENCE TARGET**
B. C. Brock*, Sandia National Laboratories

1420 **CALIBRATION of POLARIMETRIC RADAR SYSTEM USING THREE PERFECTLY POLARIZATION-ISOLATED CALIBRATORS**
Tzong-Jyh Chen, Tah-Hsiung Chu*, National Taiwan University

1440 **A NEW TIME DOMAIN and POLARIMETRIC MEASUREMENT ALGORITHM for COMPLEX TARGET RECONSTRUCTION**
Laurent Desclos*, Gerard Chassay, LCST - INSA

1500 **Break**

1520 **COMPLEX TARGET POLARIMETRIC MODELIZATION and MEASUREMENT**
Laurent Desclos*, Gerard Chassay, LCST - INSA

1540 **ANALYSIS of SHAPED DIHEDRAL REFLECTORS APPLICATION to POLARIMETRIC S.A.R CALIBRATION**
Jean-Claude Souyris*, P. Borderies, ONERA/CERT; P. F. Combes, Universite Paul Sabatier; H. J. Mametsa, ONERA/CERT

1600 **COHERENT POLARIMETRIC SAR MEASUREMENTS of DIHEDRALS and TRIHEDRALS CHARACTERIZING the PROPAGATION PROPERTIES of a FOREST CANOPY**
J. S. Gwynne*, Jonathan D. Young, The Ohio State University

1620 **VHF/UHF ULTRA-WIDEBAND MEASUREMENTS of SCATTERING TARGETS in FOLIAGE**
Jonathan D. Young*, Michael Poirier, The Ohio State University; Bruce Ferrell, Loral Defense Systems

1640 **ULTRA-WIDEBAND POLARIMETRIC IMAGING of CORNER REFLECTORS in FOLIAGE**
D. J. Blejer*, S. M. Scarborough, C. E. Frost, H. R. Catalan, MIT Lincoln Laboratory; K. H. McCoin, D. M. Mukai, Wright Laboratory

Coherent Polarimetric SAR Measurements of Dihedrals and Trihedrals Characterizing the Propagation Properties of a Forest Canopy

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Department of Electrical Engineering
Columbus, Ohio 43212

Calibrated coherent polarimetric ultra-wide bandwidth (UWB) synthetic aperture radar (SAR) measurements of simple scatterers such as dihedrals and trihedrals provide insight into the more complicated problem of characterizing and predicting the interactions of complex real world targets with the forest canopy and individual nearby trees. This in turn will lead to the ability to detect, locate, and identify man-made targets concealed in woodlands.

The HP8753 based radar used to perform these measurements collected 200-2000 MHz data during the late summer and again in the fall of 1991. The radar, mounted 100 feet above the ground, overlooked a woodlot typical of the forested areas found throughout the central and northeastern United States. This includes such trees as black cherry, sugar maple, American elm, red oak, and bitternut hickory with an average canopy height of 60 feet. In the foreground was located a small 2 foot dihedral used to determining the calibration transfer function (CTF) of the radar. This, in conjunction with antenna patterns and free space loss compensation, is sufficient to calibrate RCS measurement of down range targets concealed in the forest. Located on the forest floor where numerous dihedrals and trihedrals ranging in size from 4 to 8 feet on edge, and the calibrated measurements of these targets provided the means to extract foliage propagation properties of the forest.

The presented data will described the attenuation and phase dispersion resulting from the propagation through the overhead canopy as calculated from the known scattering of the concealed dihedrals and trihedral. Interactions between these targets and nearby trees will be identified and measured data will be presented in the frequency, time, and image domains.

VHF/UHF Ultra-Wideband Measurements
of
Scattering Targets in Foliage

by

Jonathan Young* and Michael Poirier
Ohio State University
ElectroScience Laboratory

Bruce Ferrell
Loral Defense Systems: Arizona

This paper discusses a system which was designed to investigate several performance parameters of UWB (Ultra-Wide Band) foliage penetration and radar scattering in the VHF-UHF frequency range. The goals of the experiment include: 1)a study of UWB radar propagation through foliage, including both attenuation and dispersion of this coherent wideband energy, 2) study of the clutter scattering from the woods under wideband coherent illumination, 3) study of the distortion in the target impulse signature caused by interactions with nearby trees and foliage, and 4) study seasonal and possibly diurnal changes for the UWB case.

The system uses the "Big Ear"radio telescope as a support structure for SAR images. One portion of this telescope is a tilting reflector, 100 ft. high by 340 ft. long. The top edge of the tilting reflector provides a 340 ft. long track for a dual polarized UWB rhombic antenna cart assembly which is used to provide SAR imaging of the woods 150 ft. beyond, and targets concealed therein. The SAR image system provides data at declination angles from 10 degrees to 50 degrees, over the frequency range of 200 to 2000 MHz. Data were gathered over both 120 ft. and 240 ft. scan lengths, and for downrange distances up to 350 ft.

The stepped frequency radar system is based on a Hewlett Packard 8753 Network Analyzer, but the transmit signal has a pulse modulator and amplifier just before the transmit antenna. There is a matching pulse modulator and low-noise preamplifier in front of the receive input of the network analyzer. The system is typically operated with a 170 nsec pulse length, a pulse rep rate of 1 MHz, and a frequency step increment of 1.25 MHz.

Coherent SAR images have been generated for the woods with several targets included in the scene. The data provides information over 200 MHz to 2000 MHz and for HH, HV and VV polarizations. The measurements were performed with full summer foliage (August) and under fall foliage (October) conditions.

Monday PM URSI-B Session MP08

Room: Columbus C/D *Time*: 1320-1700

Conformal Antennas

Chairs: Dipak L. Sengupta, University of Detroit; Jeffery T. Williams, University of Houston

1320 **RADIATION EFFECTS of a SLOT in the GROUND PLANE of a MICROSTRIP LINE**
A. B. Kouki*, R. Mittra, A. Khebir, University of Illinois, Urbana-Champaign

1340 **ANALYSIS of a TWO-LAYERED MICROSTRIP ANTENNA USING the MULTIPORT NETWORK MODEL**
Patrick Perini*, Jet Propulsion Laboratory; K. C. Gupta, University of Colorado at Boulder

1400 **DESIGN of SLOT COUPLED MICROSTRIP PATCH ANTENNAS USING OPTIMIZATION TECHNIQUES**
K. Leblebicioglu, G. Dural*, Middle East Technical University

1420 **MULTIMODE SPIRAL-MODE MICROSTRIP ANTENNAS for WIDEBAND WIRELESS TELECOMMUNICATION**
J. J. H. Wang*, G. D. Hopkins, V. K. Tripp, Georgia Institute of Technology

1440 **DESIGN and CHARACTERIZATION of RESISTIVELY and REACTIVELY LOADED MICROSTRIP DIPOLES for BROADBAND, TRAVELING WAVE APPLICATIONS**
Richard R. Grzybowski*, United Technologies Research Center; Rajeev Bansal, University of Connecticut

1500 **Break**

1520 **RESISTIVELY LOADED PRINTED SPIRAL ANTENNAS**
Nathan J. Champagne II*, Jeffery T. Williams, D. R. Wilton, University of Houston

1540 **ELECTROMAGNETICALLY FED ANNULAR PATCH ANTENNAS**
M. Orefice, P. Pirinoli*, G. Vecchi, Politecnico di Torino

1600 **FD-TD ANALYSIS of VIVALDI FLARED HORN ANTENNAS**
Eric T. Thiele*, Melinda Piket-May, Ann Komaromi, Allen Taflove, Northwestern University

1620 **AN EFFICIENT ANALYSIS of the MUTUAL COUPLING in a LARGE FINITE ARRAY of SLOTS in a MATERIAL COATED GROUND PLANE**
G. A. Somers*, Prabhakar H. Pathak, The Ohio State University

1640 **ACCURATE NUMERICAL SYNTHESIS of ARBITRARY CONFORMAL ANTENNA ARRAYS**
J. C. Olivier*, Potchefstroom University for CHE

RADIATION EFFECTS OF A SLOT IN THE GROUND PLANE OF A MICROSTRIP LINE

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The assessment of spurious radiation and EMI shielding effects of a thin slot in the ground plane of a microstrip line (See Figure 1) is an important problem and is examined in this paper using a spectral domain approach. The conventional approach to solving aperture problems is to regard the slot electric field as the unknown and to solve the resulting integro-differential equation for this field using the method of moments in the spatial domain (C. M. Butler, Y. Rahmat-Samii & R. Mittra, IEEE Trans. Antennas Propagat., vol. AP-26, pp. 82-93, 1978) and (C.M. Butler & K. R. Umashankar, Radio Sci., vol. 11, pp. 611-619, 1976). Because in this approach two equivalent half-space problems are constructed on either side of the shorted aperture, this method is limited to slots separating homogeneously filled half-spaces for which the expressions for the spatial domain Green's function are easily obtainable.

The proposed spectral domain approach combines the decomposition of the original problem into equivalent half-spaces with simple equivalent transmission-line analysis. This way, dielectric layers can be accounted for on either side of the slot in a straight forward manner. Results for the amount of radiated power as well as radiated field patterns are obtained for different slit sizes and dielectric constant values. It is observed that the presence of thin slots in printed circuits, which might be necessary out of several design necessities, can be a significant source of electromagnetic leakage and consequently may cause considerable interference and compatibility problems.

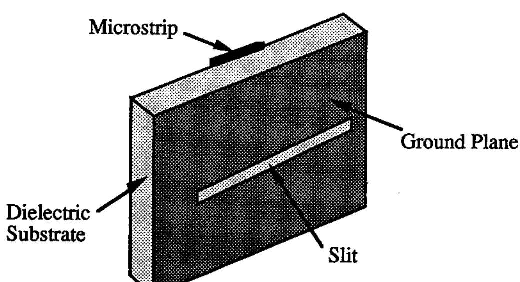

Figure 1. Geometry of a thin slot in the ground plane of a microstrip line.

Analysis of a Two-Layered Microstrip Antenna
Using the Multiport Network Model

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Vertically stacked multiple microstrip resonators have been used to increase the bandwidth of inherently narrowband microstrip antennas. Realization of such antennas has been accomplished mostly by experimental iteration or full wave analysis techniques. Experimental iterations are expensive and time consuming, while full wave analysis methods are computationally intensive, and hence inconvenient for CAD of arrays. To overcome these deficiencies, a multiport network model (MNM) is proposed for a two-layered microstrip antenna. This model allows the use of network methods for CAD of such antennas.

The MNM uses separate network models to represent the internal and external fields associated with the stacked patches. The internal fields consist of uniform two dimensional fields in two regions - those underneath the lower patch, and those in between the stacked patches. The external fields are considered in three parts - one, fringing fields between the patches and the ground plane; two, fringing fields coupling between the two patches; and three, radiation fields in the far zone. Network models have been developed for modeling all these components.

To obtain the internal field networks, the Z-matrix is computed using the two dimensional Green's function for rectangular segments. The two internal field networks are interconnected by enforcing continuity at the edges. To obtain the external fringing and coupling networks, multi-conductor coupled line analysis is used to calculate fringing capacitances and inductances. The radiated fields are represented by a generalized radiation conductance network. Network methods are used to match the internal and external fields at their interface. The network analysis yields input impedance which determines the resonant frequency and overall bandwidth. The analysis also yields the edge voltages for a given input excitation, which are used for evaluating the radiation field.

Modeling details and verification shall be presented.

DESIGN OF SLOT COUPLED MICROSTRIP PATCH ANTENNAS USING OPTIMIZATION TECHNIQUES

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Recently, excitation of microstrip antennas using a slot on the ground plane has become popular (Aksun, Chwang and Lo, IEEE AP-38, No.8 August 1990, pp.1224-1230). Analysis is based on the cavity model (Lo, Solomon and Richards, IEEE AP-27 No.3, March 1979, pp.137-145) and the slot is represented by an equivalent magnetic current source. The electric field under the patch is then obtained in terms of a set of cavity modes. The location of the slot is an important parameter because it considerably effects the polarization and the input impedance of the antenna.

In this paper the design of a certain microstrip patch antenna is accomplished by an optimization method. The basic design variables are taken to be the slot width, length, position and orientation, the requirement for circular polarization which is the main objective is considered to be the constraint function. There are other constraints on our design parameters as well. The input impedance is relatively less important with respect to the circular polarization and is taken to be the main objective function.

The resultant optimization problem has been solved by an optimization technique called augmented Lagrangians. (Luenberger, "Introduction to linear and nonlinear programming" Addison Wesley, 1973). While evaluating the cost function at a particular point certain approximations in field computations have been made in order to simplify the problem and decrease the computer time. Numerical results are presented in tabular form corresponding to various choices of: a-) weights in the optimization problem, b-) initial points, c-) constraints on design parameters. The method is tested or different microstrip patch antenna configurations.

MULTIMODE SPIRAL-MODE MICROSTRIP ANTENNAS FOR WIDEBAND WIRELESS TELECOMMUNICATION

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The spiral-mode microstrip antenna (J. J. H. Wang and V. K. Tripp, *IEEE AP Trans.*, 39, 332-335, March 1991; patents pending) has been shown to be wideband, with performance comparable to that of the cavity-loaded spiral and sinuous antennas, while having high efficiency and low profile like the microstrip patch antenna. This class of antenna is uniquely suitable for wireless personal/mobile communication systems in which a broader bandwidth is desired and whenever low profile and conformability are needed. So far we have only published experimental results for mode-1 models only. In this paper, we present measured results for this class of antenna operating in mode-2 and in a hybrid of mode-1 and mode-2. It is shown that a moderate antenna gain, as well as beam and null steering, can be achieved by combining mode-1 and mode-2 with proper phasing. The beam and null steering feature of the multimode version is desirable when adaptive interference suppression is important.

Techniques were also developed to reduce the size of the spiral-mode microstrip antennas by up to 70% or so. One form of these compact spiral-mode microstrip antennas is of the phased array type, instead of the spiral or sinuous geometries employed in regular models. However, this size reduction is achieved at a sacrifice of bandwidth and/or efficiency. As a rule of thumb, the smaller the antenna, the narrower the bandwidth and the lower the efficiency. However, this reduced bandwidth, now down to, say, 100%, is still adequate for many applications, and is of course a significant improvement over the 6% bandwidth of the typical microstrip patch antenna.

Both the regular and the compact spiral-mode microstrip antennas can be constructed by printed circuit technology, and are potentially of low cost and high reliability.

Design and Characterization of Resistively and Reactively Loaded Microstrip Dipoles for Broadband, Traveling Wave Applications

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It is well known that the current distribution on dipole antennas exists primarily as standing waves. For this reason, the input impedance of a dipole antenna is a strong function of frequency. In contrast, a traveling wave antenna possesses an input impedance that is comparatively frequency independent. An important result of this reduced frequency dependence is the decrease in VSWR and an increase in bandwidth for a given antenna. In the past, free standing, traveling wave dipoles have been realized by the incorporation of distributed resistive loading along the length of the antenna. This type of loading permits the rapid attenuation of a traveling wave current as it proceeds toward the feed point. These experiments were performed at frequencies of several hundred megahertz. Resistive loading, however, reduces the radiation efficiency of the antennas by dissipating some of the input power as heat. This dissipative power loss may be overcome by utilizing reactive loading. Several authors have demonstrated cylindrical antenna structures with bandwidths of 3:1 by loading a dipole at equally spaced intervals with lumped capacitive elements.

This paper describes a design and characterization effort to obtain broadband traveling wave behavior on printed microstrip dipole antennas at X-band. Both resistive and reactive loading schemes were employed on these metal dipoles which ranged in length from one quarter wavelength to over five wavelengths at 20 GHz. Surface current magnitude and phase data obtained from a special magnetic field sensing device designed for this purpose will be presented.

RESISTIVELY LOADED PRINTED SPIRAL ANTENNAS

Nathan J. Champagne II*, Jeffery T. Williams,
and Donald R. Wilton

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Traditionally, spiral antennas are backed by large, absorber-filled cavities to eliminate backside radiation and preserve free space radiation characteristics on their front side. The costs associated with the design and fabrication of such antennas are quite high. In addition, these antennas are bulky and thus difficult to incorporate into support vehicles. To counter these difficulties, spiral antennas printed on conductor-backed substrates have been investigated. Initial studies demonstrated that such antennas have undesirable large axial ratios and poor frequency performance. However, recent experimental studies (J. J. H. Wang & V. K. Tripp, *IEEE Trans. Antennas and Propag.* AP-39(3), pp. 332–335, 1991) in which the arms of the printed spiral are loaded with absorbing or resistive material have demonstrated that printed spirals can produce broad radiation patterns with low axial ratios. In these studies, the printed spirals were shown to have efficiencies greater than or equal to equivalent cavity-backed spiral antennas. However, it was also suggested that for these antennas the impedance bandwidth of the antenna was reduced.

In this presentation the numerical modeling of printed spiral antennas will be discussed, and numerical results will be presented which demonstrate the effects of loading. Results will be shown which compare the impedance and radiation characteristics of ideal cavity-backed spirals (free-space spirals) with loaded, printed spirals. It will be shown that resistive loading significantly reduces the ground plane effects, and, when properly designed, printed spiral antennas have radiation and impedance characteristics rivaling their cavity-backed counterparts.

Electromagnetically Fed Annular Patch Antennas

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Multi-layer radiating elements, with patches electromagnetically coupled to microstrip line feed, present some advantages over other configurations of microstrip radiators. Among various possible shapes, the annular one seems particularly interesting.

The employed method of analysis, valid also for radiators of arbitrary shape, may assume either an excitation with a voltage gap generator, or with an incident field suitably represented by the dominant (quasi-) TEM mode of the microstrip line: in this latter case the scattered field has a contribution due to the reflected TEM and another due to the continuous portion of the spectrum, that is considered as a "disturbance" vanishing away from the discontinuity region.

By application of the equivalence theorem, a double integral equation is obtained for the equivalent currents on the microstrip line and on the patch. This equation is trasformed into a linear system via the Method of Moments, conveniently modified when TEM terms on the line are considered. The matrix entries are evaluated in the plane-wave spectral domain.

Neglecting the transverse component on the narrow microstrip line, the current, or its disturbance (non-TEM) term, is expanded in longitudinally piecewise triangular basis functions with static-like transverse behaviour (weakly divergent on the edge).

The basis functions on the patch are defined over the entire domain. The usual trigonometric expansion is used for the azimuthal dependence, while first and second kind Chebyshev polynomial have been employed for the radial dependence of the azimuthal and radial component, respectively, multiplied by their weight functions. The latter closely represent the expected field behaviour at the edge. Convenient analytical expressions have been found for the Fourier transform of these basis functions.

The results of the theoretical analysis will be presented, toghether with measured data.

FD-TD Analysis of Vivaldi Flared Horn Antennas

Eric T. Thiele, Melinda Piket-May,
Ann Komaromi, and **Allen Taflove**
EECS Department, McCormick School of Engineering
Northwestern University, Evanston, IL 60208

A current trend in antenna design is towards a class of antennas employing integrated circuit technology. The slotline antenna is a member of this class. Some issues to be considered in the design of such an antenna are radiation patterns, directivity, sidelobe levels, input impedance, and aperture efficiency. Certain of these antenna performance criteria were met with the introduction introduction by Gibson of the Vivaldi tapered slot antenna. The Gibson design produces a symmetric beam across a 3:1 bandwidth. It has the characteristics of appreciable gain, low sidelobes, and symmetric endfire radiation. No other well-known planar design is capable of this.

As there are limited analytical models to study a tapered slot antenna, and none known to include the effects of a stripline feed, the finite-difference time-domain (FD-TD) model has been implemented to augment empirical designs. This method naturally accounts for the complex interactions needed to model this type of problem, such as diffraction effects due to finite ground planes, variations in phase velocities, frequency-dependent impedance, and detailed feed structures. It also allows for straightforward calculation of far field radiation patterns.

The FD-TD methodology is demonstrated to be a useful predictive tool in assessing these antenna types. Comparisons are made with measured data for a stripline-fed, electrically small Vivaldi tapered slot antenna. These Vivaldi tapered slot antennas are often configured in arrays in order to produce a desired radiation pattern. FD-TD results are presented for sub-array element pairs and for full arrays of the Vivaldi tapered slot antenna. On the Cray YMP/8 we can model an array consisting of 4-5 cross-pair Vivaldi antennas. We show good correlation between computed and measured data for the primary features of the antenna patterns. We will also report computational studies of the driving-point impedance of a single cross-pair module as a function of the phasing of the elements of the array.

AN EFFICIENT ANALYSIS OF THE MUTUAL COUPLING IN A LARGE FINITE ARRAY OF SLOTS IN A MATERIAL COATED GROUND PLANE

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Department of Electrical Engineering
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The evaluation of mutual impedance between slots in a grounded dielectric slab is typically done by numerically evaluating a Sommerfeld type integral for the grounded slab Green's Function. However, in moderately sized to large arrays this numerical integration is very time consuming when considering the distant elements and hence can be prohibitive. By applying equivalence principles, the calculation of the mutual impedance is transformed to a reaction of the field emanating from an equivalent magnetic current (which replaced the transmitting slot) with the equivalent magnetic current (which replaced the receiving slot).

An asymptotic representation of the grounded dielectric slab Green's Function was developed in closed form to facilitate an efficient calculation of the fields radiated by a magnetic current in the presence of a grounded material slab. This Green's Function is asymptotically rigorous and incorporates the effects of all relevant modes of radiation, i.e. space wave, surface waves, and leaky waves and their coupling within the so called transition regions. This representation is asymptotic with respect to a large parameter which involves the lateral separation between the source and field points. It remains uniformly valid for observation points and source points separated by distances as small as two tenths of a wavelength. This representation is extremely useful for large finite array computations. Unlike the Sommerfeld representation, the computation time of the asymptotic Green's Function is independent of the source and observation point separations.

The mutual coupling trends for dominant mode rectangular waveguide slots are examined for various substrate thicknesses, material parameters and relative positionings of the transmitting and receiving slots. Additionally, a comparison of the computation times of the asymptotic Green's Function and the numerical evaluation of the exact Sommerfeld integral representation of the Green's Function will be presented.

ACCURATE NUMERICAL SYNTHESIS OF ARBITRARY CONFORMAL ANTENNA ARRAYS

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The synthesis of antenna arrays has been an active field of research for the better part of 5 decades. Most classical synthesis techniques however only treat linear equispaced arrays. Recent trends are to employ numerical algorithms to achieve synthesis of arbitrary arrays.

This paper presents a numerical algorithm capable of the synthesis of an arbitrary conformal array. The array may consist of radiating elements with arbitrary individual radiation patterns. These elements need not be located in a flat plane; i.e. the elements may be alloyed to conform to an arbitrary surface. It is however assumed that the individual radiation element patterns used correspond to the element patterns when located on the actual array but with the other elements removed. The algorithm is able to synthesise an arbitrary far field pattern if the number of elements are sufficient. If the number of elements used is insufficient, the algorithm will converge to the optimal solution for the given array.

The method presented in this paper is based on an iterative scheme developed in [1]. The method uses adaptive array theory. A large number of artificial interference signals are introduced in the array sidelobe region. The adapted pattern is then used in a recursive feedback scheme until the ideal interference spectrum is attained. The method will be used to determine the array weights for a 10 element array on a parabolic curve. Various levels of curvature in the curve are introduced, and in each case the excitation weights are determined using the algorithm. These numerical results will indicate the method's versatility and accuracy.

[1] C.A. Olen and R.T. Compton, "A numerical pattern synthesis algorithm for arrays", IEEE Trans. Antennas Propagat., Vol. 38, No. 10, 1990, pp. 1666–1676.

Monday PM URSI-B Session MP09

Room: Columbus E/F *Time*: 1320-1700

Bridging the Gap Between Low and High Frequency Regimes

Organizer: T. B. A. Senior, The University of Michigan
Chairs: T. B. A. Senior, The University of Michigan; R. E. Kleinman, University of Delaware

1320 **INTRODUCTION to FREQUENCY DOMAIN SCATTERING**
T. B. A. Senior*, The University of Michigan

1340 **ITERATIVE METHODS for INTERMEDIATE FREQUENCIES**
R. E. Kleinman*, University of Delaware; Peter M. van den Berg, Delft University of Technology

1400 **JUDICIOUS CHOICE of the SEM REPRESENTATION for SCATTERED FIELDS**
Carl E. Baum, Phillips Laboratory; T. H. Shumpert*, M. A. Richards, Auburn University

1420 **BASIC CONSTRAINTS on the FUNCTIONAL BEHAVIOR of SCATTERED FIELDS, with APPLICATIONS**
K. M. Mitzner*, Northrop Corporation

1440 **AN INTEGRAL EQUATION in TERMS of CHARGE for TE SCATTERING by CURVED OPEN SURFACES**
K. M. Mitzner, Northrop Corporation; John L. Volakis*, Jian-Ming Jin, Leo C. Kempel, D. Ross, The University of Michigan

1500 **Break**

1520 **HYBRID TECHNIQUES in ELECTROMAGNETICS REVISITED**
L. N. Medgyesi-Mitschang*, McDonnell Douglas Research Laboratories

1540 **ON the BEHAVIOUR of UNIFORM RAY SOLUTIONS at LOWER FREQUENCIES**
Prabhakar H. Pathak*, R. J. Marhefka, The Ohio State University

1600+ **PANEL DISCUSSION (1600-1700)**

INTRODUCTION TO FREQUENCY DOMAIN SCATTERING

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In the case of scattering from a body with at least one dimension finite, it is possible to distinguish three regions as a function of frequency. Low frequencies where the wavelength is much greater than a significant body dimension; high frequencies, where the wavelength is much less; and the region in between, generally referred to as the resonance region. At low frequencies, analytical techniques are available to determine the field from the solution of static problems, and in the case of a finite body, the resulting expression for the far zone scattered field is a Taylor series in integer powers of the frequency whose finite radius of convergence is often used to define the onset of the resonance region. At high frequencies, optical or ray techniques are applicable. In general, the scattering can be attributed to one or more isolated portions of the body, and by including more of these contributions and the interactions between them, it is often possible to achieve substantial penetration of the resonance region from above. However, except in the pathological case of a perfectly conducting paraboloid viewed on axis, there is always a (lower) part of the resonance region which is not covered, and here numerical (e.g. integral equation) techniques are appropriate. Examples are given illustrating the behavior as a function of frequency and showing what can be achieved.

In order to bridge, or at least narrow, the gap between the low and high frequency regions, and to set the stage for the later papers in the session, some of the mathematical problems that must be addressed are described.

Iterative Methods for Intermediate Frequencies

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Scattering problems in the frequency domain are most often formulated as integral equations involving either boundary or domain integrals. Various methods have been devised to solve these equations or discrete versions thereof. Iterative methods are prominent in this regard and may be considered as a natural framework in which to extend low frequency expansions. The simplest iterative technique, the Neumann series, is closely related to the low frequency or Rayleigh series and has the same limitations on convergence. More sophisticated iterative methods may be viewed as methods for extending the range of frequencies for which convergence is assured.

In this paper we describe the essential features of the Neumann series, over-relaxation methods, Krylov subspace methods, and the conjugate gradient methods. These methods are shown to be derivable from an error minimization principle using various error criteria. Convergence of these methods is discussed and shown to be obtainable in the unifying framework of error minimization. The success of these methods in penetrating the resonance region and achieving convergent results at intermediate to high frequencies is demonstrated in some numerical examples.

The integral equations which arise in electromagnetic problems almost always involve non-selfadjoint operators which lead to non-Hermitian matrices. One drawback of the conjugate gradient method is the implicit symmetrization (operating with the adjoint) which squares the condition number. It is this fact which has motivated the investigation of alternatives such as the biconjugate gradient and conjugate gradient squared methods. These methods are also discussed and convergence problems are described as are numerical successes and failures.

JUDICIOUS CHOICE OF THE SEM REPRESENTATION FOR SCATTERED FIELDS

C.E. Baum, Phillips Laboratory, U.S. Air Force, Kirtland AFB, NM
T.H. Shumpert* and M.A. Richards, Elect. Eng., Auburn University, AL

A number of previous investigators have noted that the most general form of the Singularity Expansion Method (SEM) representation for the transient scattering response of a finite extent object admits a variety of forms (C.E.Baum, L.W.Pearson, *Electromagnetics* 1, 209-228, 1981). Each of these forms serves to accentuate some desirable property or mitigate some undesirable property of the behavior of the solution in either the time and/or frequency domain(s). Previous investigations into determining accurate and efficient forms for the input admittances or impedances of simple radiators have employed the "so-called" modified pole series expansion with reasonably good success (L.W.Pearson, D.R.Wilton, *IEEE AP*-29, 697-707, 1981).

This paper presents several specific examples of the many possible forms available for the representation of the far scattered fields of finite objects through the use of a more general form of the modified pole series expansion. Through the use of these forms for the far scattered field, an efficient and meaningful representation for the scattering length (or radar cross section) can be determined with explicit definition of the terms representing the asymptotically high- and/or low-frequency extrema. Thereby, a minimum number of terms can be used to represent the scattering object over a broad range of frequencies, at least from low frequencies well up into the resonance region. The most judicious form for determining the far scattered field in the desired frequency regime is proffered. A discussion is included as to the "best" choice of the type of SEM coupling coefficient (i.e., Class 1 or 2) which is most appropriate to use in the modified pole series expansion for various far field applications (target discrimination, radar cross section, etc.). Calculated results for the scattering length of several simple scatterers are presented and discussed.

BASIC CONSTRAINTS ON THE FUNCTIONAL BEHAVIOR OF SCATTERED FIELDS, WITH APPLICATIONS

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A body that scatters linearly and passively can be considered as a passive linear filter that transforms one function of time and space, the incident field, into another, the scattered field. One way to characterize the filter behavior is to express the far-field scattering of a plane wave as a function of complex frequency s and of the angles of incidence and of scattering, also taken complex.

The physics of the problem imposes basic constraints on the filter response. For any fixed real angles of incidence and scattering, causality requires that the frequency response not have singularities in the right half of the s-plane. For forward scattering, which is extinction, both causality and conservation of energy impose constraints on the frequency response. The angular dependence of the response is constrained by the requirements that the forward scattering theorem hold for all real angles of incidence and that an appropriate reciprocity relationship hold for every pair of real angles. Additionally, the angular spectrum of the response at fixed frequency is dependent on the maximum dimensions of the scatterer.

This paper reviews previous work in which the author and his associates made use of s-plane constraints to obtain simple but accurate empirical formulas for the frequency response of a rounded conducting wedge. New results are presented showing that the approach can be extended to the case of exterior wedge angle greater than 2π, for which the flat faces are spreading apart as they approach the rounded edge. This extension was obtained by taking advantage of another type of constraint, namely that the scattering response tends to change smoothly as a parameter characterizing the body geometry (in this case, the wedge angle) is changed smoothly.

AN INTEGRAL EQUATION IN TERMS OF CHARGE FOR TE SCATTERING BY CURVED OPEN SURFACES

K.M. Mitzner[1], J.L. Volakis*[2], J.M. Jin[2], L.C. Kempel[2] and D. Ross[2]

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A new integral equation (IE) has been developed for transverse electric (TE) scattering by open two-dimensional surfaces such as curved resistive strips. The new equation is written in terms of charge density, which is the natural quantity of interest for low frequency applications, and reduces in the limit to a known IE for statics. Consequently this charge integral equation (CIE), unlike the standard electric field integral equation (EFIE) in terms of the current, remains useful numerically at arbitrarily low frequencies even when pulse basis functions are used.

The CIE is of the form

$$\frac{1}{Z_0}E_s^{inc}(s) = \frac{j\omega\hat{R}}{4}\int_C\left(\frac{L-2\delta}{L}\right)[\rho(s+\delta)-\rho(s-\delta)]\,d\delta + j\frac{\omega^2}{c_0}\int_C\rho(s')\,G_I(x,y;x',y')\,ds' - \frac{j}{4}c_0\int_C\rho(s')\frac{\partial}{\partial s}H_0^{(2)}(k_0 r)\,ds' ,$$

with

$$G_I(x,y;x',y') = \int_0^{s'}(\hat{s}\cdot\hat{s}'')\,H_0^{(2)}(k_0\tilde{r})\,ds'', \qquad \tilde{r} = [(x-x'')^2+(y-y'')^2]^{1/2} ,$$

where s is the arc length along the surface contour of total length L, $\rho(s)$ is the charge density, $H_0^{(2)}$ is a Hankel function, c_0 is the speed of light, k_o is the wave number, Z_0 is the wave impedance of free space, and $\hat{R}\frac{Z_o}{2}$ is the resistivity of the strip (so that $\hat{R}$ is a normalized quantity). In order to obtain a unique solution, the CIE must be supplemented by an equation for conservation of charge. Much of the advantage over the standard EFIE arises from the less singular behavior of the kernels, which makes it possible to obtain an accurate and efficient numerical implementation of the CIE using pulse basis functions and point matching. It is important to offset the matching points properly rather than take them at the centers of the pulse segments. The first integral on the right hand side of the CIE can be evaluated analytically for the pulse basis functions, and G_I can be calculated progressively as s' is increased.

Details of the CIE derivation and implementation, numerical results, and comparisons with standard EFIE results are presented.

HYBRID TECHNIQUES IN ELECTROMAGNETICS REVISITED

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Deeper understanding of electromagnetic radiation and scattering phenomena from complex objects and rapid advances in computer technology have led to a synthesis of methods, generally designated as hybrid techniques. The principal feature of these techniques is that they combine high frequency (asymptotic) methods with the low frequency (numerical) ones.

Of the former, the primary ones are the Geometric Theory of Diffraction (GTD), its derivatives such as the Uniform Theory of Diffraction (UTD), and the Physical Theory of Diffraction (PTD). These methods provide efficient, rapid computation of localized EM phenomena associated with canonic geometries such as edges, wedges, cylinders, and other shapes. Except under special conditions, these methods cannot handle surface wave phenomena (such as traveling waves) from coated surfaces. For these and non-canonic geometries, other methods must be used, often called numerical methods.

While the high frequency methods describe EM phenomena from localized features (such as edges), numerical methods can provide solutions incorporating globally all the EM effects on a body. Because of the computational requirements, they are generally applicable for frequencies where the objects are electrically small. Hence, they are denoted as low frequency methods. Some of these methods are: the method of moments (MM), the uni-moment methods, the finite element (FE) and the finite difference (FD) methods. For problems involving conducting or layered objects formulated in terms of surface integral equations (SIE), the MM technique is widely used. For objects with gaps, apertures, or highly inhomogeneous penetrable regions, partial differential equation (PDE) formulations are used, solved by FE or FD techniques.

In the hybrid approach, the high and low frequency methods are combined in a mathematically consistent way. In this manner, the best features of these methods are retained to solve classes of problems not amenable to one group of methods alone. In this presentation, the advantages as well as limitations of various hybrid methods involved SIE and PDE formulations will be discussed. The representative methods will be compared for computational efficiency and accuracy. Suggested directions for future research in this area will be given.

On the Behaviour of Uniform Ray Solutions at Lower Frequencies

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Uniform ray solutions can provide accurate asymptotic high frequency (HF) estimates for the fields of radiating objects. Due to the local properties of HF fields, simpler canonical geometries can be analyzed using HF asymptotics to obtain the relevant uniform ray coefficients (i.e. UTD coefficients) to describe the corresponding reflection/diffraction processes. The radiation/scattering from a complex object is then built up from a superposition of the fields arising from these local radiation/scattering centers. Accuracy of the HF analysis pertaining to complex objects is therefore directly dependent on the accuracy of the canonical HF solutions. As the frequency decreases so does the electrical separation between the scattering centers and it then becomes necessary to include multiple wave interactions between them to maintain accuracy. Indeed, uniform ray solutions can be employed in conjunction with self-consistent procedures for incorporating multiple interactions as, for example, in the scattering from strips, polygonal cylinders, etc. This technique is found to remain surprisingly accurate even for separations between neighboring scattering centers as small as a quarter wavelength. Improvements to such analysis can be incorporated via a spectral extension of uniform ray methods. This allows the field arriving from one scattering center when it illuminates a nearby second scattering center, to be expressed in terms of a superposition of simple ray optical fields. This is essential because the fields arriving from the first center are not purely ray optical unless they are observed sufficiently far from it, whereas, the UTD coefficients require the excitation to be ray optical. The use of spectral extension of ray methods can yield accurate results for scattering by strips as small as a tenth of a wavelength. Also, one may need to include higher order terms in the UTD coefficients as one goes lower in frequency. For example, an analysis of the the scattering by a smooth closed convex body may need corrections to geometrical optics reflection along with a sufficient number of multiply encircling surface diffracted ray terms when pushing ray methods to lower frequencies. It must be kept in mind that higher order terms present in the UTD coefficients, as well as those resulting from multiple interactions, constitute an asymptotic series which is typically only semi-convergent. Thus, the HF approximations will fail at low enough frequencies when scattering centers can not be isolated or localized, straining the asymptotic HF series beyond its limits of validity. Nevertheless, if the analysis is done carefully, users of ray methods can generally expect reasonable engineering results for complex radiating objects almost down to the first resonance. Examples illustrating some of the above concepts will be presented.

Monday PM URSI-B Session MP10

Room: Columbus G *Time*: 1320-1700

Propagation and Scattering in Complex Media

Chairs: Raymond Luebbers, The Pennnsylvania State University; Akira Ishimaru, University of Washington

1320 **PASSIVITY CONDITIONS for the CONSTITUTIVE PARAMETERS of LOSSY CHIRAL MEDIA**
J. H. Cloete*, University of Stellenbosch

1340 **PREDICTION of CHIRALITY PARAMETER for CHIRAL COMPOSITES**
H. Scott Langdon*, Raymond Luebbers, Craig Bohren, The Pennsylvania State University

1400 **DIELECTRIC and MAGNETIC PROPERTIES of CARBONYL IRON POWDER LOADED SILCON RUBBER SHEETS**
D. Ghodgaonkar*, V. K. Varadan, Vasundara V. Varadan, The Pennnsylvania State University

1420 **A NUMERICAL INVESTIGATION of SCATTERING from DIRECTIONALLY CONDUCTING SURFACES**
Lars Lindskov Pedersen*, Technical University of Denmark

1440 **VELOCITY of ELECTROMAGNETIC WAVES in DISORDERED MEDIA**
Yasuo Kuga*, Akira Ishimaru, Daniel Rice, University of Washington

1500 **PROPAGATION of PLANE WAVES in a DISSIPATIVE RANDOMLY INHOMOGENEOUS MEDIUM**
Sasan S. Saatchi*, Jet Propulsion Laboratory

1520 **3D FINITE ELEMENT-INTEGRAL EQUATION FORMULATION for SCATTERING and RADIATION of DOUBLY PERIODIC ARRAY of CAVITY ELEMENTS**
Habib Massoudi*, John D'Angelo, General Electric Co.

1540 **WAVE PROPAGATION in a LAYERED MEDIUM with SMOOTHLY VARYING TRANSVERSE INHOMOGENEITIES**
Chenhong Huang*, Zuoguo Wu, R. D. Nevels, Texas A&M University

1600 **MUTUAL COUPLING BETWEEN LOOP ANTENNAS in CYLINDRICALLY STRATIFIED MEDIA**
W. D. Rawle*, Technical University of Nova Scotia

1620 **VISUALIZATION of INCLUSIONS in LAYERED MEDIA: 2D MODEL BASED on SOURCE-TYPE INTEGRAL EQUATIONS**
Dmitry O. Batrakov*, Nikolay P. Zhuck, Kharkov State University

1640 **POLARIMETRIC EVOLUTION of CHAFF MEDIA**
Laurent Desclos*, LCST - INSA; P. Pouliguen, CELAR

Passivity Conditions for the Constitutive Parameters of Lossy Chiral Media

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Physically necessary conditions on the complex plane behaviour of the constitutive parameters, $\epsilon = \epsilon' + i\epsilon''$ and $\mu = \mu' + i\mu''$, of non-chiral passive materials are well known. Assuming that the fields have $\exp(-i\omega t)$ harmonic time dependence the passivity conditions are $\epsilon'' \geq 0$ and $\mu'' \geq 0$. (The superscripts $'$ and $''$ identify the real and imaginary parts of a variable in this abstract.)

The paper will present a generalization of these conditions for lossy, homogeneous chiral materials. Constitutive relations in the form advocated by Jaggard and Engheta (e.g. N. Engheta & D.L. Jaggard, *IEEE Antenna & Propagation Society Newsletter*, 6–12, October 1988) will be used. Thus $\mathbf{D} = \epsilon\mathbf{E} + i\xi\mathbf{B}$ and $\mathbf{H} = i\xi\mathbf{E} + (1/\mu)\mathbf{B}$, with ξ the chirality admittance, ϵ the permittivity, and μ the permeability of the chiral medium. All may be complex to account for energy dissipation in the material.

The conditions imposed by passivity on the intrinsic wave impedance, $\eta_c = \mu/(\sqrt{\mu\epsilon + \mu^2\xi^2})$, and the left-circularly and right-circularly polarized wave numbers, $k_r = \omega(\sqrt{\mu\epsilon + \mu^2\xi^2} + \mu\xi)$ and $k_l = \omega(\sqrt{\mu\epsilon + \mu^2\xi^2} - \mu\xi)$, will also be investigated.

The work is based on the conservation principles for energy and momentum, and the complex Poynting theorem which states

$$\nabla \cdot (\mathbf{S}) = \nabla \cdot (\mathbf{E} \times \mathbf{H}^*) = i\omega(\mathbf{B} \cdot \mathbf{H}^* - \mathbf{E} \cdot \mathbf{D}^*).$$

The real parts of the chiral medium Poynting's vectors are

$$\mathbf{S}'_{r,l} = \hat{z}2(1/\eta_c)' \exp(-2k''_{r,l}z),$$

with the subscripts $_r$ and $_l$ associated with left and right circularly polarized eigenwaves propagating in the $+z$-direction.

Thus electromagnetic momentum conservation imposes the condition $(1/\eta_c)' > 0$ on the real part of the intrinsic impedance.

The left hand side of the theorem yields

$$(\nabla \cdot \mathbf{S}_{r,l})' = -4k''_{r,l}(1/\eta_c)' \exp(-2k''_{r,l}z)$$

for the real part of the divergence. Passivity requires $(\nabla \cdot \mathbf{S}_{r,l})' \leq 0$, thus the imaginary parts of the wave numbers must satisfy

$$k''_{r,l} \geq 0.$$

The right-hand side of Poynting's theorem yields

$$(\nabla \cdot \mathbf{S}_{r,l})' = -\omega \left[\frac{\mu''}{|\mu|^2} \frac{2|k_{r,l}|^2}{\omega^2} + 2\epsilon'' + \frac{4\xi''}{\omega} \left\{ \begin{array}{c} +k''_r \\ -k''_l \end{array} \right\} \right] \exp(-2k''_{r,l}z).$$

The implications of this result on the complex domain properties of μ, ϵ, and ξ will be discussed.

PREDICTION OF CHIRALITY PARAMETER FOR CHIRAL COMPOSITES

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Artificial chiral materials have been fabricated by randomly suspending identical conducting helices in a dielectric medium (eg. V. K. Varadan, V. V. Varadan, and A. Lakhtakia, "On the possibility of designing anti-reflection coatings using chiral composites," Journal of Wave-Material Interactions, Vol. 2, No. 1, January 1987). In this paper a method for predicting the chirality of such material from the geometry and conductivity of the helical inclusions, their concentration, and the permittivity of the matrix material is presented.

Assuming that the suspension of helices is dilute, that is, single scattering dominates, an equation is derived which predicts the chirality parameter, beta, from the co- and cross-polarized forward scattered electric field for a single helix and the constitutive parameters of the matrix. The approach follows that of C. Bohren and D. Huffman in Absorption and Scattering of Light by Small Particles, Wiley, 1983. The forward-scattered fields for a single isolated helix inside the lossy medium are determined by application of a Method of Moments code.

While this approach is limited to dilute composites, it can be applied to most radio frequency composite chiral materials reported in the literature except at the highest concentrations. To illustrate this a composite chiral material consisting of conducting helices suspended in a lossy epoxy dielectric with loss tangent on the order of 0.03 and a relative dielectric constant of approximately 2.5 is considered. The predictions of chirality parameter beta are in good agreement with those measured (R. Ro "Determination of the electromagnetic properties of chiral composites using normal incidence measurements," Ph.D. dissertation, The Pennsylvania State University, 1991) for wire concentrations of 0.8% and 1.6%. Comparisons are also made with measurements of beta for a composite chiral material slab fabricated by the authors and coworkers in a similar matrix material.

DIELECTRIC AND MAGNETIC PROPERTIES OF CARBONYL IRON POWDER LOADED SILICON RUBBER SHEETS.

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Carbonyl iron loaded silicon rubber (or, other low-loss and low-dielectric constant materials such as epoxies, urethanes, plastic resins) sheets are used as a lossy microwave materials for free-space microwave absorbers and EMI shielding applications. In bar and rod form, this material is also suitable for microwave attenuators and terminations in waveguide, coaxial and stripline transmission media. For these applications, it is necessary to know the dielectric and magnetic properties of carbonyl iron loaded silicon rubber (CIPS) sheets for different concentrations of carbonyl iron powder. A free-space method (Ghodgaonkar *et al*, IEEE Trans. I and M, April 1990) was employed for the dielectric and magnetic measurements in the frequency range of 8.6 to 13.4 GHz. In this method, relative complex permeability (μ^*) and relative complex permittivity (ε^*) are simultaneously calculated from free-space S_{11} and S_{21} measurements of CIPS sheets. The measured results are reported for five CIPS sheets with carbonyl iron powder concentration varying from 0 to 57.2 % by volume. The normalized free-space impedance (Z_i) and attenuation coefficient (α (dB/ cm)) for different concentrations are calculated which will be useful for attenuator and termination applications. Reported results in this paper include measured ε^*, μ^*, Z_i and α values for CIPS materials. An empirical relationship will be developed for predicting ε^* and μ^* values for any concentration between 0 and 57.2 % by volume by using dielectric and magnetic mixture theories.

A NUMERICAL INVESTIGATION OF SCATTERING FROM DIRECTIONALLY CONDUCTING SURFACES

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In this study we consider electromagnetic scattering from a surface having directional conductivity, ie., a surface that in each point is perfectly conducting in one direction whereas the conductivity perpendicular to this direction is zero. For this structure the current is thus constrained to flow in certain paths, referred to as the 'lines of conductivity'. An integral equation for the current induced by a given incident field may be derived by demanding that the component of the total electric field parallel to lines of conductivity vanishes on the surface. Applying the method of moments to this 'single component electric field integral equation' for the directionally conducting surface we can set up a system of linear equations for the current expansion coefficients. It can be shown that under certain circumstances this matrix equation will be closely related to the matrix equation for the current expansion coefficients in the corresponding perfectly conducting case.

This investigation has been concentrated on plane wave scattering from a directionally conducting spherical shell. The cases that have been considered are infinite conductivity along either the 'latitude'-lines (a ϕ-conducting spherical shell) or the 'longitude'-lines (a θ-conducting spherical shell). For these rotationally invariant directionally conducting structures both the generalized impedance matrix (the system matrix) and the excitation vector (the right hand side) can be easily constructed from the impedance matrix and the excitation vector, respectively, pertaining to the perfectly conducting surface. Hence, already developed software for bodies of revolution can be used to a very high extent.

Numerical results have been obtained for the induced current as well as the bistatic and back scattering cross sections for these two directions of conductivity.

For the ϕ-conducting spherical shell severe numerical problems seem to occur. We find that the results depend critically on the discretization in the moment method approach and only by careful segmentation of the generating curve we obtain reasonable convergence with respect to the number of expansion functions. Comparisons to an array of circular loops indicate that the problems arise from the use of a subdomain basis in modelling the current behaviour perpendicular to the lines of conductivity. This conclusion is further supported by the fact that no anomalies are encountered for the θ-conducting spherical shell. Here, the subdomain basis is used to model the current behaviour along the lines of conductivity.

It is expected - but not yet investigated - that some of the above mentioned problems might occur also for other directionally conducting surfaces.

VELOCITY OF ELECTROMAGNETIC WAVES IN DISORDERED MEDIA

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Backscattering enhancement (also known as *Anderson localization*) has attracted considerable interest in both the remote sensing and solid state physics communities. Backscattering enhancement is caused by the constructive interference of two waves traversing though identical randomly distributed particles in opposite directions. Physicists also recognized that the transport of electrons in a strongly disordered material is governed by multiple scattering leading to *weak Anderson localization*. When the wavelength and particle size are chosen to be the highest peak of the Mie resonant region and the volume fraction of particles is appreciable, the multiple scattering becomes extremely large and the wave becomes trapped within a small volume. The diffusion coefficient which is related to the propagation of the incoherent wave also decreases sharply. This phenomenon is known as *strong Anderson localization*. In this region it is believed that the energy velocity becomes much less than that of a medium without scatterers.

We have studied the velocity of electromagnetic waves in the *strong Anderson localization* region using a microwave system and densely distributed glass beads. The phase, group and energy velocities are obtained as a function of frequency and path length. The energy velocity that is equivalent to the pulse arrival time is obtained by taking the Fourier transform of the frequency domain data. It is shown that the energy velocity decreases significantly when the frequency is changed from the Rayleigh region to the Mie region.

Propagation of Plane Waves in a Dissipative Randomly Inhomogeneous Medium

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In this paper, the propagation of plane waves in a layer of one-dimensional dissipative random medium is considered. The medium is modeled by a complex permittivity whose real part is a random function of position and the imaginary part is a constant representing the absorption. The one dimensional problem is mathematically equivalent to the analysis of a transmission line with randomly perturbed distributed parameters and a single mode lossy waveguide and the results can be used to study the propagation of radio waves through atmosphere and the remote sensing of geophysical media.

We assume, the scattering medium consists of an ensemble of one-dimensional point scatterers randomly positioned in a layer of thickness L with diffuse boundaries. A Poisson impulse process with density λ is used to model the position of scatterers in the medium. By employing the Markov properties of this process an exact equation of Kolmogorov-Feller type has been obtained for the probability density of the reflection coefficient. This equation has been solved by combining two limiting cases: 1) when the density of scatterers is small, and 2) when the medium is weakly dissipative. A two variable perturbation method for small λ has been used to obtain solutions valid for thick layers. These solutions, are then asymptotically evaluated for small dissipation.

To show the effect of dissipation, the mean and fluctuations of the reflected power are obtained. The results have been compared with a lossy homogeneous medium and with a lossless inhomogeneous medium and the regions where the effect of absorption is not essential have been discussed.

3D FINITE ELEMENT-INTEGRAL EQUATION FORMULATION FOR SCATTERING AND RADIATION OF DOUBLY PERIODIC ARRAY OF CAVITY ELEMENTS

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The problem of Electromagnetic(EM) scattering and radiation from an infinite planar array of cavity elements with complex geometry and material composition is treated in this paper. A computer code has been developed for analysis of both near- and far-zone EM fields in a doubly periodic array of cavity-backed apertures on a ground plane. The code is based on a hybrid 3D finite element-periodic integral equation formulation. The hybrid formulation is derived via utilization of EM equivalence principle and transformation of the original EM problem into coupled interior and exterior problems. The interior problem involving closed inhomogeneous medium, with/without radiating elements, is solved by finite element. The exterior problem is treated with integral equation method.

Integral equation methods treat unbounded EM problems very effectively but they become computationally intensive when complex inhomogeneities are present. On the other hand, bounded inhomogeneities are best handeled by finite methods. The hybrid FE-IE technique is computationally advantageous, since it combines and retains the most efficient characteristics of both finite element and integral equation methods. For periodic structures, the periodicity requirments are imposed and included in the integral equation part of the formulation. In addition, the efficiency of the code has been further improved by application of accelaration techniques to the summation of the series which arises in the integral formulation due to periodic array of EM sources and charges.

Numerical results for some 2D and 3D geometries will be presented and compared with other techniques, such as: method of moments, finite element method with absorbing boundaries, and mode matching technique. It is shown that the near-field distribution and induced currents are obtained to an excellent accuracy.

WAVE PROPAGATION IN A LAYERED MEDIUM WITH SMOOTHLY VARYING TRANSVERSE INHOMOGENEITIES

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Electromagnetic wave propagation through a layered media with an arbitrary smoothly varying inhomogeneous refractive index in each layer is considered in this paper. The layer boundaries are parallel and the geometric dimensions are large in terms of wavelengths. Wave profiles over a propagation distance which is many, perhaps several hundred, wavelengths from the origin is of interest in geophysics, acoustics, and fiber optics.

This paper describes a numerical technique for analyzing such a geometry. The propagation of electromagnetic waves is first formulated in terms of a path integral, which is then numerically evaluated by a stationary phase Monte Carlo (SPMC) method. A key technical challenge is to perform a multidimensional integration with a highly oscillatory integrand. To overcome this difficulty, a SPMC filter is constructed which is transparent only in those regions where the integrand is relatively stable, and is opaque elsewhere. The filter designed here does not have a strong dependence on a particular choice of the SPMC parameters and hence enables us to obtain a numerically efficient analysis technique. The entire formulation, as well as the numerical technique, is first justified by the two-dimensional free space propagation example, which is analytically soluble. Numerical results showing the diffracted field for a two-dimensional multimode graded-index optical waveguiding structure are presented. The fundamental mode of a monomode graded-index waveguide is also numerically calculated. Specific numerical and analytical features of the propagation model are also discussed. The results will be shown to be in good agreement with those computed by the Fourier transform path integral (FTPI) method, which is developed independently for the evaluations of the electromagnetic field.

MUTUAL COUPLING BETWEEN LOOP ANTENNAS IN CYLINDRICALLY STRATIFIED MEDIA

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This paper presents an analysis of the mutual coupling between loop antennas which are positioned concentrically on the interfaces of cylindrically stratified dielectric layers. The antennas are modelled, using the thin wire approximation, as $f(\phi)\delta(z)$ electric current distributions on the various dielectric interfaces. A Debye potentials based formulation is employed to obtain formal exact expressions for all electromagnetic field components resulting from the presumed current distributions. The formulation for the mutual coupling follows a standard development and relates the currents in the two antennas, for example, to their respective excitation voltages. This is accomplished by first introducing modal parameters, voltage, current, self and mutual impedance, to calculate the amplitudes of the antenna current Fourier components. In this work, the excitation voltage on the first antenna is set at 1.0 volts and the second antenna is short-circuited. The excitation voltage is modelled as a rectangular function in ϕ on the antenna conductor's surface.

A number of factors influence the mutual coupling between the antennas. The excitation of hybrid mode surface waves exhibits a significant impact on the coupling. An extensive investigation into these surface waves is presented and their relation to hybrid mode surface waves in other simpler geometries is considered. Radiation into the outermost dielectric layer will also have an impact upon the mutual coupling between these antennas and this will be discussed. Finally, the antenna radius - conductor radius factor Ω exhibits an impact upon the mutual coupling between the antennas and this will also be discussed.

This canonical geometry has many applications in the areas of antenna and microwave engineering. It is suggested that the results presented may be useful in the design of dielectric rod antennas and in the design of launching mechanisms for dielectric waveguides.

VISUALIZATION OF INCLUSIONS IN LAYERED MEDIA: 2D MODEL BASED ON SOURCE-TYPE INTEGRAL EQUATIONS.

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This report focuses on the visualization of a penetrable body burried in some inhomogeneous host medium with known properties. This topic is of obvious interest for geophysics, non-destructive testing, medicine. A novel feature of our approach is that all information about the host medium is totally absorbed into the proper Green's function for this medium at the very stage of posing the inverse problem.

We exploit a source-type integral equation linking the values of the electric field vector $\vec{E}$ ($\sim\exp(-i\omega t)$) at arbitrary point of space and within the scatterer's domain V. The arising system of linear relations for the induced electric current density $\vec{J}$ streaming within V and the unknown function $\hat{\xi}$- the difference between absolute permittivity distributions of the scatterer and the host medium- takes up the form:

$$u=u_0+\Phi\hat{G}_0\,\vec{J}, \qquad \vec{J}=-i\omega\hat{\xi}\,(\vec{E}_0+\hat{G}_0\,\vec{J}),$$

while a non-linear master equation for $\hat{\xi}$ reads as

$$u=u_0-i\omega\Phi\hat{G}_0\,(1+i\omega\hat{\xi}\,\hat{G}_0)^{-1}\,\xi\,\vec{E}_0.$$

Here, respectively, $\hat{G}_0$ and $\vec{E}_0$ are the electric Green's operator and the primary electric field corresponding to the host medium, with the scatterer being absent, Φ is the proper linear measurement functional, and $u=\Phi\vec{E}$ ($u_0=\Phi\vec{E}_0$) is the value of the informative parameter when the scatterer is present (absent).

The first formulation has been applied by us to the model of a slab of finite thickness hosting a 2-dimentional scatterer. The aim was to restore $\hat{\xi}$ via measurements of total field at the boundaries of a slab. The second one was implemented in the essentially 1D problem of retrieving $\hat{\xi}$ for radially inhomogeneous cylinder covered with a cladding with given permittivity profile via frequency range measurements. The inversion procedure in the later case was based on the Newton-Kantorovich iterative scheme.

POLARIMETRIC EVOLUTION OF CHAFF MEDIA

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In order to create, in a short time and in a large frequency band, a very high R.C.S., random distributions of resonating dipoles of different lengths are used since the world war II.

Since Van-Vleck's works , a lot of studies were published but none of them is able to give a good description of all the phenomena appearing during the diffraction in a cloud of Chaff.

One of this phenomena is the great difference of the reflectivity between the copolarization measurement in an Horizontal base HH or in a vertical base VV. Generally the HH level for the average R.C.S. is greater than the VV level by about 3 or 6 dB. It is very important to say that this phenomenon is a non stationnary one and that this difference can increase with the time.

In this paper, a new and rigorous polarimetric study of the diffracted field of cloud of dipoles or other simple objects is given.

A cloud of Chaff is in most of the case composed by many millions of dipoles which the positions and orientations are to be known in order to calculate the theoretical R.C.S. . So, there must be a modelization of the aerodynamic behaviour of the dipoles which is strongly depending on the atmospheric conditions.All the possible movements in the cloud can't be simply described by a determinist approach. It allows one to use the statistics to determine possible directions or orientations. Shielding and coupling of all elements are also studied in details. The modelization of the R.C.S. of a Cloud of objects is made in two times:

1) The positions and orientations of the N dipoles which are the constitution of the cloud are randomly distributed. These distributions are taken into account the possible nature of the cloud (or the possible application the cloud is made for).

2) The calculation of the R.C.S. for the media and the three dimensionnal polarimetric behaviour diagram in co or cross-polarization versus frequency, the angle of orientation or the angle of ellipticity of the base of polarization (emission-reception).

An other part of this study is the possible inclusion of simple objects in the studied media. Such a possibility is very interessant to modify the polarimetric behaviour of clouds in order to make modification of target signature or to imitate one

Monday PM1 URSI-B Session MP11

Room: Columbus H *Time*: 1320-1500

Combined Numerical - High Frequency Methods

Chairs: Gabriel F. Herrmann, Lockheed Palo Alto Research Laboratories; Giuliano Manara, University of Pisa

1320 **TWO-DIMENSIONAL IMAGE THEORY for the CONDUCTING HALF PLANE**
Ismo V. Lindell*, M. E. Ermutlu, Keijo I. Nikoskinen, Helsinki University of Technology

1340 **NUMERICAL DIFFRACTION COEFFICIENTS for SURFACE WAVE PHENOMENA**
M. P. Hurst*, McDonnell Douglas Research Laboratories

1400 **A HYBRID FD-FEM DESCRIPTION of the DIFFRACTION at an IMPEDANCE WEDGE**
Giuseppe Pelosi, Angelo Freni, R. Tiberio, Roberto Coccioli, University of Florence; R. D. Graglia*, Politecnico di Torino

1420 **TIME-DOMAIN SCATTERING by an IMPEDANCE WEDGE**
J.-M.L. Bernard, Le Centre Thomson d'Applications Radar; Giuseppe Pelosi, Angelo Freni, University of Florence; Giuliano Manara*, University of Pisa

1440 **DIFFRACTION by CONDUCTING PLANE ANGULAR SECTORS with SMALL ACUTE and LARGE OBTUSE ANGLES**
Leonidas P. Ivrissimtzis*, Radix Ltd.

TWO-DIMENSIONAL IMAGE THEORY FOR THE CONDUCTING HALF PLANE

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Diffraction of electromagnetic fields by a perfectly conducting half plane is one of the classical problems of electromagnetics, first solved by Sommerfeld in 1897 in noting that the earlier solutions of Fresnel and Kirchhoff were not exact but high-frequency approximations. Many solutions to the problem have emerged since then, involving different integral expressions, but as far as these authors know, no image source representations have been given for the diffracted fields. In the present paper, diffraction image of a two-dimensional line current parallel to the edge of a conducting half-plane is given, replacing the half plane by an image surface current located in complex space, much in analogy to the exact image theory given by the present author to treat problems in layered media.

The analytical expression of the image surface current is given in terms of simple trigonometric functions in contrast to the more complicated functions characterizing the true physical currents on the half plane. Also, in contrast to the nonphysical edge current applied in the physical diffraction theory, the present image current is exact, i.e., valid for any frequency. The diffraction image is quasi physical in being independent of the location of the point where the field is to be calculated. However, the range of the field point must be limited to a predetermined half space for a particular diffraction image source to allow a convergent field integral. Thus, the diffraction field in all points of the physical space can be obtained in terms of two diffraction images.

Computed diffraction patterns show the equivalence of the image method and the field integral method. The theory suggests itself for integral equation formulations of various problems involving a conducting half plane in addition to other structures. Also, being quasi-physical sources, the diffraction images can readily be approximated by applying physical intuition. The theory is extendable to three-dimensional problems and perfectly conducting wedges.

NUMERICAL DIFFRACTION COEFFICIENTS FOR SURFACE WAVE PHENOMENA

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Recently, ray-optics techniques have been applied to a broad class of previously untreated geometries through the use of diffraction coefficients in numerical form derived from moment method analysis of finite bodies. Numerical diffraction coefficients have been obtained for edge scattering from layered dielectric screens and finite frequency-selective surfaces (FSS), and for corner diffraction coefficients from lossy plates and finite FSS. Most treatments have been limited to first order diffraction because of the difficulty of extracting diffraction coefficients from data which includes significant higher order diffraction effects, such as coupling between edges. Such effects are typically suppressed through the introduction of loss in the canonical test objects. In many problems, however, higher order diffraction contributes significantly to the total field and must be included in ray-optics analysis. In particular, dielectric and periodic surfaces can support trapped waves which are guided by the surface and couple edges regardless of how distantly they are separated.

This paper will describe a method of determining the parameters necessary to include surface waves in the Numerical Uniform Theory of Diffraction (NUTD). The propagation constant of a surface wave and its reflection coefficient at discontinuities must be determined, as well as its coupling to space waves. In a few cases the surface wave propagation constant is known analytically, but usually must be found numerically. This can be accomplished by performing numerical analysis of a finite body and examining the fields near the surface. Since surface waves fields can be described by complex exponential functions, a decomposition of the total field near the surface into a sum of exponentials reveals the propagation constants of surface waves and the reflection coefficient at a discontinuity. Prony's method is used for this purpose. In the problem of bistatic scattering by a strip there remain three unknowns at each edge describing coupling between incident and scattered space and surface waves. These unknowns are determined by calculating (via the moment method) the scattered field from six strips of different widths and solving a sixth order linear system at the incident and scattered angles of interest.

Examples of near and far field scattering and antenna problems involving dielectrics and FSS will be presented with comparison to direct moment method calculations.

A HYBRID FD-FEM DESCRIPTION OF THE DIFFRACTION AT AN IMPEDANCE WEDGE

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An exact solution for the scattering by an impedance wedge illuminated by a plane wave perpendicularly incident on its edge ($\beta=\pi/2$) was given in (G.D. Maliuzhinets, *Sov. Phys. Dokl.*, Vol. 3, pp. 752-755, 1958) . This solution for the total field is represented by a Sommerfeld spectral integral. Later on, spectral integral solutions for the 3D case ($\beta \neq \pi/2$) have been obtained for some special configurations; *i.e.*, the half-plane, the two-part problem, the right-angled wedge and the wedge with a unitary normalized surface impedance. All those solutions involve the special functions introduced by Maliuzhinets himself. Rather efficient calculations of the scattered ray field may be performed by using numerical approximations of these special functions, within the high-frequency asymptotic expressions of these solutions. On the other hand, an efficient technique for evaluating the field in the near zone of the edge is not yet available.

In this communication, a quite different approach is used to contribute to the analysis of the more general case of skew incidence, when the fields that satisfy the Helmholtz equation are coupled by the impedance boundary conditions. First, in order to decouple the boundary conditions, we resort to a perturbative formulation which of course applies to small deviations from $\beta=\pi/2$. Next, the set of successive perturbed equations is solved by resorting to a numerical procedure, which exploits the fact that the diffracted field satisfies a system of parabolic equations. These equations, that are a special case of the transverse diffusion equations in ray coordinates, are solved by the method of finite differences (FD) taking into account the compatibility conditions at both the shadow and reflection boundaries.

This solution yields an accurate and efficient asymptotic evaluation of the field at a large but finite distance r_0 from the edge. Also, it is used to construct a proper boundary condition for the interior problem ($r \leq r_0$), which is solved by the finite element method (FEM).

It is found that this technique provides an efficient tool for investigating on the behavior of the field, even in the close vicinity of the edge. Furthermore, the effectiveness of this numerical solution of parabolic equations for reconstructing the asymptotic evaluation of the field is discussed, and its accuracy is assessed by comparison with the known high-frequency, analytic solutions.

TIME-DOMAIN SCATTERING BY AN IMPEDANCE WEDGE

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Time-domain field solutions are of relevant importance for a large variety of practical applications. For instance, they can be extremely useful in electromagnetic pulse (EMP) studies, when the effects of the exposition of a complex structure to a lightning flash or to a nuclear blast have to be evaluated. In particular, several time-domain analytical solutions have been derived for the canonical problem of electromagnetic wave scattering from perfectly and non-perfectly conducting wedges. Nevertheless, extensive numerical investigations on these solutions are not available in the literature, particularly in the non-perfectly conducting case.

The two-dimensional scattering of a time-dependent plane wave by a wedge with two different, isotropic impedance faces has been analyzed in (G. Pelosi, *et al.*, JINA' 90, Nice, France, November 13-15, 1990). There, the analysis is valid only when the surface impedances of the wedge are frequency independent.

In this communication a new approach to the problem is presented, that allows us also to treat the more general case of skew incidence. In particular, the hypothesis of frequency independence of the impedances of the faces of the wedge has been removed, enabling us to consider a wider class of practical problems. It can be noted that the proposed procedure is also valid when the boundary conditions are expressed in a more general form with respect to the Leontovich's one.

Suitable time-domain expressions are obtained by applying an inverse Laplace transform to the solution for the corresponding time-harmonic problem. It is worth pointing out that this latter solution in known for every value of the exterior wedge angle and of the surface impedances in the 2D case, and for some special wedge configurations in the 3D case, as for example: i) the half-plane; ii) the right-angled wedge; *iii*) the absorbing wedge with unit relative impedance. For all these problems the response of the wedge is expressed in the form of a Sommerfeld integral, involving the Maliuzhinets special functions (G.D. Maliuzhinets, *Sov. Phys. Dokl.*, Vol. 3, pp. 752-755, 1958).

The integral formulation for the field is then manipulated by simply considering the causality principle and the reality of the total field in the time-domain. The final expressions for the total field allow a useful physical interpretation of the solution and are suitable for efficient numerical evaluations. Several numerical results are presented, with emphasis to the viewpoint of energy distribution.

DIFFRACTION BY CONDUCTING PLANE ANGULAR SECTORS WITH SMALL ACUTE AND LARGE OBTUSE ANGLES

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A plane angular sector is a degenerate surface in the spheroconal system of coordinates. The separation of variables in this system results into an ordinary Bessel equation and a coupled Lamé partial differential equation, which involves a parameter $0<\kappa<1$ with direct dependence on the angle of the sector.

No closed form solutions for the eigenfunctions and eigenvalues of the coupled Lamé equation, subject to ordinary Neumman and Dirichlet boundary conditions, have been presented so far. Originally [*Satterwhite and Kouyoumjian; 1970*], a continued fraction method has been employed, which suffered from instability problems, especially, in the computation of larger eigenvalues. In this paper, a perturbation technique based on Feenberg's perturbation formula [*Morse and Feshbach; 1953*] which converges for limiting values of the angle parameter κ is investigated. It formally extends the approach developed by [*Sahalos and Thiele; 1983*], and overcomes some of the aforementioned difficulties. It may also allow theoretical assessment of the convergence of the eigenfunction solution.

The formulas for the eigenfunctions and eigenvalues can be reduced when κ is either small (small angle) or close to unity (large angle) by keeping the first terms in their series expansions. Then, the dyadic Green's function for the angular sector is merely a first order perturbation of the free space or half plane, respectively, Green's dyadic and can be easily manipulated, since it rather involves elementary operations.

The results can be utilized in the computation of the small corner correction in the case of blunt angle sectors, in addition to the dominant edge diffractions, or the corner effect in acute angle sectors. Possibilities of extending the formulas (via interpolation or higher order calculations) into more complete representations of the corner diffraction for more general cases is also discussed.

Monday PM URSI-A E, NEM Session MP12

Room: Columbus I/J *Time*: 1320-1700

EMP-System Test Results

Organizer: Hagen Schilling, WWD ABC-Schutz
Chairs: Hagen Schilling, WWD ABC-Schutz; C. D. Taylor, Mississippi State University

1320 **CONCLUSION of SYSTEM TESTS in the EMP-SIMULATOR of WWD ABC-SCHUTZ**
Hagen Schilling*, WWD ABC-Schutz

1340 **APPLICATION of the GERMAN STANDARDS for NEMP-SYSTEM TESTS**
J. Nedtwig*, Telefunken System Technik GmbH

1400 **THE SHIELDING EFFECTIVENESS of SEAMS and VENTS in TACTICAL SHELTERS**
R. A. Perala*, J. R. Elliot, R. S. Collier, Electro Magnetic Applications, Inc.

1420 **SHIELDING EFFECTIVENESS of METAL ENCLOSURES EXPOSED to DIPOLE FIELDS**
Nobert Esser*, ABB Management Services GmbH; Hagen Schilling, WWD ABC-Schutz

1440 **A SIMPLE MEASUREMENT METHOD for ESTIMATING the SHIELDING EFFECTIVENESS of UNDERGROUND BUILDINGS**
B. Z. Raisch*, Markus Nyffeler, Bruno Brandli, E. Dorr, B. Reusser, NC Laboratory

1500 **Break**

1520 **LOW LEVEL SIMULATION of the EMP ENVIRONMENT in a TELECOMMUNICATIONS TOWER**
Torbjorn Karlsson*, Sven Garmland, EMTECH

1540 **EMP COUPLING to SHIPS: ANALYSIS of DIFFERENT TECHNIQUES**
Herve Grauby*, GERAC; Jean-Pierre Percaille, Centre d'Etudes de Gramat

1600 **A SCALE-MODEL SIMULATOR for SYSTEM TESTS**
Christian Braun*, W. Graf, H. U. Schmidt, Fraunhofer Institut fur Naturwissenschaftlich-Technische Trendanalysen (INT)

1620 **SURFACE CURRENT DENSITY INDUCED on AIRCRAFT ILLUMINATED by EMP**
Chung-Hsuing Yeh*, Dau-Chyrh Chang, Chung Shan Inst. of Science and Tech.

1640 **MODAL EXCITATION of a LARGE AIRCRAFT USING MULTIPLE ANTENNAE**
Lothar O. Hoeft*, Joseph S. Hofstra, BDM International, Inc.; William D. Prather, Phillips Laboratory

CONCLUSION OF SYSTEM TESTS IN THE EMP-SIMULATOR OF WWD ABC-SCHUTZ

Hagen H. Schilling
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Since 1981 Germany has tested many systems and electric equipment in the EMP simulator of the WWD-ABC-Schutz which is located in Munster. This simulator is a bounded wave system for vertical polarized fields. The transmission line has a length of more than 100 m. In the working volume with the dimensions L = 20m, W= 12 m and H = 8 m EMP pulses with a field strength up to 75 kV/m and a rise time of less than 10 ns (10 - 90%) with a decay time of 10 µsec can be simulated. Pictures and technical details of this simulator with the two pulser systems and the data channels will be shown in the paper.

When we started in 1981 with our first system tests we applied the same test procedure which is used in many other EMP-test laboratories. Beginning with low field strength we measured the induced currents on most of the cabels. Then we extrapollated these measured values to the real threat and continued with upset and go-no-go tests. This test philosophy was changed because of the fact that we could reduce the total test time for systems by starting with a go-no-go test first and increasing the field strength up to the values where the permanent damages were found. In the next step we measure the induced currents and concentrate our measuring points to these cable connections where we have seen upsets or permanent damages. After analysing these results we develop and install hardening devices. At the end of the test we make a final acceptance test with 75 kV/m.

We have tested more than 90 different systems and smaller electric equipment. A conclusion of these test results of CC-systems, vehicles, tanks, aircraft-systems, NBC-protection equipment ect. will be shown in the paper. Some examples of these test results will be discussed in detail. We found that many systems even if they were not specially EMP hardened were not affected by EMP fields. In case of upsets or permanent damages the protection devices or hardening methods were not very cost effective. Finally some critical and unsolved problems like overtesting, safety margins, circuit analysis, cable coupling and international standardization of the test procedures will be discussed in the paper.

APPLICATION OF THE GERMAN STANDARDS FOR NEMP-SYSTEM TESTS

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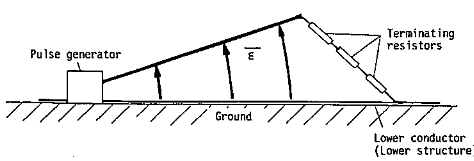
Abstract:
Since the early eighties german committees of standardization (NEA 760) for the german office of armement and procurement (BWB) define new standards for NEMP and LIGHTNING protection. These standards contain not only management rules, effective test procedures and protection measures but give also effective hints how to realize NEMP tests of "whole" systems. Since these new standards are nearly completed and in english available, Lit. /1/, it is the intention of the author (member and chairman of several committees) to give an overview of these standards and to present there advantages.

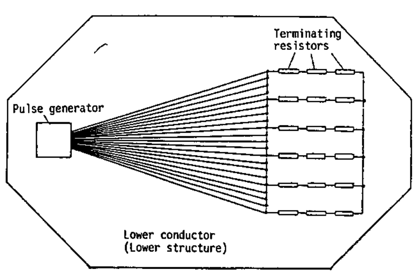
Before starting complete NEMP system tests several actions are to be carried out. First: Analyzing of all system functions, second: Definition of a test plan with definition of the test points, third: Selection of a suitable NEMP simulator, fourth: Low level tests in the simulator, fifth: Computer aided analises with calculations fo the expected distortions under threat levels, sixth: Threat level test and valuation of the damages, seventh: protection measures.

For all these activities the German NEMP Standards VG 96 900-907 offer helpful regulations. For an example the standard VG 96 903, part 50, NEMP tests in bounded wave guides, demand the definition of the field homogenity by a field mapping in the simulator.

The author gives not only an overview of the standards but presents the essentials of elected standards for NEMP testing and protections.

Lit. /1/: Book EMV3 (in English),
VDE-Verlag, Germany Berlin and Köln (DM 150)





THE SHIELDING EFFECTIVENESS OF SEAMS AND VENTS IN TACTICAL SHELTERS

by

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In this paper the SE of tactical shelters is described. The paper emphasizes a shelter without appendages. Also, the emphasis is on the shielding provided by the door seams, edge seams, and with some considerations of ECU vent openings.

Measurement techniques are described for determining the transfer impedances in-situ. It is shown that the SE of shelters can be completely specified in terms of the transfer impedances. It is shown how these transfer impedances are included in three dimensional numerical analysis techniques.

Experimental results are compared to numerical results for the SE of shelters for two important cases. These cases are for MIL-STD-285, and for EMP simulation in an EMP simulator. It is shown that the results generally agree within a factor of two. In addition, the relationship between MIL-STD-285 SE and EMP SE is described. The EMP field structure within a shelter is also described and interpreted. Both evanescent and propagating modes are discussed.

In the first example, a simulated Nuclear Electromagnetic Pulse (NEMP) plane wave from a U.S. Army NEMP Simulator was incident on a metallic tactical shelter having dimensions approximately 10' x 8' x 7'.

The main penetration into the interior is via seams around the edges of the door. Using a special measurement method which we developed (SIMM - Seam Impedance Measurement Method) under contract to Harry Diamond Laboratories (HDL) the impedances of the seams were measured. The impedances were input into our 3D Finite Difference solution of Maxwell's equations for the shelter interaction with the EMP, and internal EM fields and the response of an internal conductor were calculated and compared with measurements.

A second example, comparisons are made between numerically calculated results and MIL-STD-285 Se measurements. Excellent agreement is obtained.

SHIELDING EFFECTIVENESS OF METAL ENCLOSURES EXPOSED TO DIPOLE FIELDS

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Germany

The shielding effectiveness of metal enclosures is a well known solution of Maxwell's equations, if the incident electromagnetic field is assumed to be a plane wave. With respect to NEM problems this waveform is questionable for some applications. When considering the source region EMP for example, the assumption of a plane wave may be incorrect up to the Megahertz range, and when measuring the shielding effectiveness of a cabin, spherial waves may be incident on the shield over a wide frequency range due to the close distance of the antenna (MIL STD 285).

It could be misleading to compare these measurements with calculations based on an incident plane wave, and even more important, to use these measurements uncorrected for an incident plane wave such as the high altude EMP.

It is therefore important to understand analytically, if and to what extend the shielding effectiveness depends on the distance between source and shield.

This paper presents the analytical solution of Maxwell's equations for this problem and shows the influence of a variation of this distance on the calculated shielding effectiveness. An electric or magnetic dipole or a linear combination of both can be used as source, and all components of the electromagnetic field can be calculated at each detector point inside of the shield.

To allow an analytical solution the shield was assumed to be spherical. Radius, thickness and electrical parameters of the material as well as source distance and dipole parameters are the input data of the program.

Measurements of the shielding effectiveness of cabins at different detector points are compared with analytical predictions to contribute to experimental validation and discussion of accuracy and limits of the model.

A SIMPLE MEASUREMENT METHOD FOR ESTIMATING THE SHIELDING EFFECTIVENESS OF UNDERGROUND BUILDINGS

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In this paper, experimental techniques for determining the shielding effectiveness of a buried facility are discussed. The measurement method emphasizes simplicity, rather than a high dynamic range or accuracy. Requirements for shielding of buildings larger than 60 dB are, in most cases, unnecessary. A dynamic measurement range of 60 to 80 dB is reasonable from an engineering standpoint, and is sufficiently high for practical applications.

Shielding effectiveness of a buried building is measured by comparing signals received by two antennas: one located outside the underground building on the earth's surface, and the other located within the building. Signals can be received from either a controlled radiating source, or from existing broadcast stations.

When working with signals from a controlled source, the transmitting antenna should be located far from the receiving antennas, so that the incident field on the building appears as a plane wave. With this approach, the shielding behavior of the building can be evaluated at many different frequencies.

A simpler test approach is to use existing broadcast stations as a source. The first step in this procedure is to examine the radiating power and frequencies of local emitters near the facility. With these data, along with a knowledge of the transmitter distance, the signal strength received at the external antenna may be estimated. Similarly, with an estimate of the designed shielding effectiveness of the building, the internal antenna response may be roughly estimated. This provides initial information as to the feasibility of measuring an internal response from the broadcast source.

Regardless of the type of excitation source used, the shielding effectiveness of the building may be evaluated experimentally by means of a spectrum analyzer or by a HP3577A network analyzer. Large differences in the shielding effectiveness can be found for different polarizations and antenna locations. In practical cases, the shielding surface of the facility can be divided into smaller zones, and local shielding measurements made. Furthermore, for critical facilities, periodic testing of this kind may be conducted to evaluate the shielding degradation with time.

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LOW LEVEL SIMULATION OF THE EMP ENVIRONMENT IN A TELECOMMUNICATIONS TOWER.

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The effects of an electromagnetic environment that will be created by a high altitude EMP event have been investigated for observation locations inside the 150 m high Kaknäs tower in Stockholm, Sweden. The tower was illuminated with a low level CW field, and measurements were taken at a number of test points inside the tower. In order to obtain the properly extrapolated responses corresponding to a real incident EMP field, the simulation was carried out with several different considerations in mind. One concern of particular importance was how to perform simulation on a structure having the large dimensions of the Kaknäs tower.

The transfer function from a reference point to the test point was determined. Both amplitude and phase were measured. No nonlinear effects were taken into account. The reference outside the tower was chosen at a point where the incident field could be calculated.

First, the required plane wave quality of the simulated wave was studied. External currents induced on the tower were studied in a computer model by Dr F. M. Tesche, and different illuminations from a number of distances up to 500 meters were made. It was concluded that an illumination of the tower could be done from a location as close as around 140 m and still be correctly extrapolated. This was due to the fact that coupling into the tower was concentrated to a small number of entry points. The local coupling at each point of entry dominated over the propagated signal from other entry points.

A short dipole antenna was first used as an illuminator in order to cover the entire frequency range of 100kHz – 100 MHz. It turned out that this was insufficient below 1 MHz. An elegant solution to the problem was the infrequently used illuminator called the $\mathbf{p} \times \mathbf{m}$ -antenna, described by Carl E. Baum in the early 70's. This antenna is characterized by a near field that in one direction has exactly the ratio 377 Ω between the electric and magnetic field vector. Before the illumination was made a small study of the antenna was undertaken, and different scale models were tested.

The erected $\mathbf{p} \times \mathbf{m}$ -antenna was 60 meters high and was supported by a rope from the top of the tower. Because of its near field characteristics the antenna created a useful illumination of the tower at a distance of only 100 meters.

This paper will describe in more detail these measurements made on the Kaknäs tower and the test equipment configuration including the $\mathbf{p} \times \mathbf{m}$ antenna.

EMP COUPLING TO SHIPS :
ANALYSIS OF DIFFERENT TECHNIQUES

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EMP coupling assessment with a warship presents some difficulties, basically due to the dimensions of the system and to water. People concerned by these problems had to develop specific tools ; some of them are described in this paper and their performances compared.

The big pulse simulators (like EMPRESS II) are probably the most interesting devices for this application ; but they are very expensive, and they need the implementation of considerable ressources.

Scale model experiments and numerical studies do not need the immobilization of the ship. They remove the problems due to water and they allow to change easily the threat or other parameters.
Even if the precision is limited by the cost (numerical codes) or by the scale factor, even if it can be difficult to reproduce and measure the rise time, these two means give good results : some of them are presented and compared.

The next step consists in the evaluation of the internal transients : the limits of the tools described before induced the development of a CW method.

POSEIDON is the name of the experiment performed by the Centre d'Etudes de Gramat and the CERTEL

The principle of the experiment (which will be presented in detail) is to sweep the spectrum with a set of different antennae, amplifiers and sensors.
The ship under test (150 m long) is at anchor at 400 m from the emission point. The test is directed from a computer put on board ; a link allows the synchronization between the source on earth and the 5 spectrum analyzers (in the ship) which perform 5 measurements at the same time.
Different steps of signal assessment are necessary to go back to temporal signals.

Some examples of results are given and compared with signals coming from theoretical studies and scale model experiments.

The advantages of this method are numerous : stability of emission source, high dynamic range, low cost, easy moving and implementation.
The main problems come from the long signal assessment (minimum phase), the need of a reference and the spectrum weakness in the low frequencies. Some answers are given.

The conclusion shows the complementarity of all these tools.

A SCALE-MODEL SIMULATOR FOR SYSTEM TESTS

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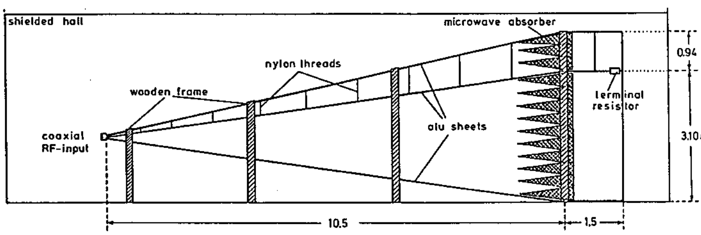
Our institute investigates electromagnetic effects on large structures and systems. For this purpose, we perform calculations with various computer codes (LIAN, NEC-2, MAFIA) as well as measurements with a self-developed field-coupling facility. With this TEM-simulator we perform scale- model measurements on conductive structures and systems.

The facility consists of a 10.5 m long asymmetric triplate transmission line, which widens from some cm at the source pyramidally to 4 m at the end. At low frequencies it is terminated with a network of resistors, at high frequencies a wall of absorbers placed across the output provides a non-reflecting termination. In a test volume of about 2x3x2 m scaled models of long wire antennas, shelters, aircraft etc. down to a scale factor of 1/50 can be tested. In general, we measure the complex transfer functions of the surface current density on the test object, $j(\omega)/E(\omega)$, and of the bulk and short circuit currents on a wire, $I(\omega)/E(\omega)$, in the frequency range between 1 and 2500 MHz. Folding the transfer function with the spectrum of an arbitrary stimulating pulse (NEMP for example) and Fourier transforming the product leads to the response of the system in the time domain.



Since 1985 we have conducted a great variety of tests of rather simple structures such as antennas and cylinders as well as of more complicated objects such as aircraft (1/20 scale-model of planned European fighter J 90 and 1/10 of TORNADO) and a 1/50 scale-model of the German frigate F 122.

In the last years there was an increasing demand for microwave coupling measurements up to the higher GHz-region, so we examined our simulator above the original bandwidth and improved its properties by some simple modifications. At present, we measure surface current densities on a slotted cylinder and the coupling onto wires behind these slots in the frequency range from 10 MHz up to 8 GHz.

SURFACE CURRENT DENSITY INDUCED ON AIRCRAFT ILLUMINATED BY EMP

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ABSTRACT

The surface current density induced on the aircraft illuminated by the nuclear electromagnetic pulse (NEMP) is discussed in this paper. Theoretical and experimental data are presented. The moment method and stick model of the aircraft were used to calculate the induced surface current. The electric field used for the calculation is the double exponential waveform :

$$E(t) = 52\,[\exp(-t/670) - \exp(-t/3.8)] \qquad \text{kV/m}$$

the unit of t is ns

The EMP simulator was constructed for the coupling experiment. The scale down Aluminum aircraft was used for this experiment. The length of the fuselage is 6 m, and the radius is 22.6 cm. Induced surface currents on the cylinder(only fuselage without wings) for different azimuth angles (0°, 45°, 90°. 125°, 180°) and different elevations(0.5m, 1.7m, 2.9m, 4.2m, 5.5m) were measured. These surface currents were calculated and compared with experimental results. Both results are pretty agreeable with each other. Surface currents induced on the scale down aircraft were measured and calculated. The peak of the surface current density is from 570 A/m to 1530 A/m. The peak value on the wing is from 210 A/m to 260 A/m. Resonant frequencies induced on the aircraft were also measured and discussed. The main resonant frequency is found from 8.5 MHz to 10.9 MHz for the different length of fuselage and wing, and the wing location with respect to the fuselage. Also, the second resonant frequency of the surface current induced on the aircraft depends on the length of the wing and the location of the wing. If the wing length is very short, the second harmonic will close to three times of main frequency. Results in this paper will be useful for the design of the protector due to the EMP in the aircraft.

MODAL EXCITATION OF A LARGE AIRCRAFT USING MULTIPLE ANTENNAE

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An aircraft is a compound electromagnetic scatterer, having various modes of oscillations, each mode having a characteristic frequency and damping constant. Modal excitation has been been explored extensively by innovative theorists, but has not been demonstrated experimentally in much detail. Modal excitation offers the hardness surveillance community a sophisticated tool of characterizing electromagnetic coupling to aircraft systems for at least two reasons: 1. Low level CW techniques are cheap and easy to implement and 2. Modal excitation reduces the uncertainties due to limited orientation of the aircraft. Results from earlier direct drive and antenna SPEHS (Single Point Excitation for Hardness Surveillance) development efforts suggested that these type of techniques could be used to modally excite an aircraft.

Modal excitation of a large aircraft was demonstrated by attaching electrically short monopole antennae to the aircraft's extremities (nose, tail, and wing tips) and feeding these antennae in-phase or out-of-phase using appropriate transformers and/or power amplifiers. The magnitude and phase of the magnetic fields on the surface of the aircraft was measured with MGL sensors, phase matched fiber optics systems and a computer controlled network analyzer. Measurements were made on the EMP Testbed Aircraft (EMPTAC), which is a Boeing 720 airframe and is similar to the aircraft on which much of the theoretical work was done.

Relatively pure single mode excitation was demonstrated for the lowest frequency modes. The resonances were much broader than those predicted by theory and the mode structure seems to disappear for frequencies greater than four times the lowest resonant frequencies. The resonant frequencies are significantly different than those predicted by theory.

Monday PM2 URSI-B Session MP14

Room: Columbus H *Time*: 1520-1640

Planar Waveguiding Structures

Chair: John Litva, McMaster University

1520 **DOMINANT LEAKY-MODE SOLUTIONS for MICROSTRIP LINES on ISOTROPIC SUBSTRATES**
David Nghiem, Jeffery T. Williams*, David R. Jackson, University of Houston; A. A. Oliner, Polytechnic University

1540 **A COMPARISON of the CIRCUIT PARAMETERS of a SINGLE MICROSTRIP SIMULATED with SEVERAL SPACE and SPECTRAL DOMAIN TECHNIQUES**
Niels Fache, Guy Coen, Krist Blomme, D. De Zutter*, University of Ghent

1600 **A PROPER SURFACE IMPEDANCE for DETERMINING LOSSES in PLANAR JUNCTIONS**
Christopher L. Holloway, John C. Moore*, E. F. Kuester, University of Colorado at Boulder

1620 **MODELING of IMAGE-TYPE SLOT LINES**
Youri V. Shestopalov*, Moscow State University

DOMINANT LEAKY-MODE SOLUTIONS FOR MICROSTRIP LINES ON ISOTROPIC SUBSTRATES

David Nghiem[†], Jeffery T. Williams[†*], David R. Jackson[†], and A. A. Oliner[††]

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It is well known that higher-order complex leaky modes can exist on an unshielded microstrip transmission line. These leaky modes correspond to higher-order propagating modes which become complex (with a complex longitudinal propagation wavenumber $\beta - j\alpha$) below the cutoff frequency. In the leaky region, these complex modes are improper with respect to the transverse directions, which means that the fields increase exponentially in those directions. Throughout most of the leaky region $\beta < k_0$, and also $\beta < k_{TM_0}$ (where k_{TM_0} is the wavenumber of the TM_0 surface wave), so that the attenuation constant α is interpretable as physical radiation of energy into the space region above the substrate and laterally into the TM_0 surface wave. These higher-order modes have a current distribution on the microstrip line which is quite different than that of the dominant (zero cutoff frequency) mode. Recently, it was observed that a *dominant* leaky mode could exist on microstrip if the substrate is anisotropic (M. Tsuji, H. Shigisawa, and A. A. Oliner, 1989 IEEE MTT-S Symp. Digest, pp. 783-786). This mode has leakage only into the TE_1 mode of the grounded substrate. This type of leaky mode is proper with respect to field variation in the vertical direction, but improper in the horizontal direction transverse to the strip.

The purpose of this presentation is to show, for the first time, that dominant complex leaky modes may also exist on microstrip lines with *isotropic* substrates. These dominant leaky modes are distinct from the conventional dominant microstrip mode, which always has a real propagation constant and a proper (bound) modal field. These new dominant leaky modes may leak energy into various guided-wave modes of the substrate, including the TM_0 and/or the TE_1 modes. These leaky modes do not require substrate anisotropy for leakage to occur. The leakage occurs primarily for thicker substrates, and could be responsible for unexpected and spurious high-frequency transmission line performance for microstrip circuits. Results obtained from a spectral-domain solution will be presented for the isotropic case to show the behavior of the new leaky mode solutions as functions of the strip and substrate geometry. These results will also be related to those for a microstrip line on an anisotropic substrate.

A COMPARISON OF THE CIRCUIT PARAMETERS OF A SINGLE MICROSTRIP SIMULATED WITH SEVERAL SPACE AND SPECTRAL DOMAIN TECHNIQUES

Niels Faché, Guy Coen, Krist Blomme (NFWO) and Daniel De Zutter (NFWO)

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The single microstrip line has been analyzed by a large number of authors in the last two decades. The behaviour of the microstrip is governed by an integral equation for the microstrip current. The integral equation is solved with the method of moments. We distinguish two different approaches in the solution techniques used for the microstrip and for more complicated multilayered structures with single and coupled strips. The first one is the spectral domain approach which is mostly combined with the method of Galerkin (for an overview see R.H. Jansen MTT-33, nr. 10, 1985). In the spectral domain approach the integral equation is solved in the spectral domain. The second, spatial approach solves the integral equation in the space domain and can be combined with the method of Galerkin or with pointmatching (N. Fache and D. De Zutter, MTT-36, nr. 4, 1988). In both approaches the unknown current is expanded into a finite sum of entire domain or subsectional basis functions. The method of moments transforms the integral equation into an eigenmatrix equation with as eigenmode the propagation constant of an eigenmode of the structure. The eigenvector consists of the amplitudes of the basis functions used in the current expansion. Both approaches yield very good results for the propagation constant of the eigenmode. However, the accuracy of the characteristic impedance strongly depends on the modelling of the current and the approximations made in the calculations of the matrix elements of the discretised integral equation.
The goal of this paper is to compare the accuracy, convergence and speed of different modelling techniques for both the propagation constant and the impedance of the microstrip line. We will also address some numerical difficulties and computational problems associated with the spatial and spectral techniques and with the use of complex basis functions such as the ones which include the edge singular behaviour.

A PROPER SURFACE IMPEDANCE FOR DETERMINING LOSSES IN PLANAR JUNCTIONS

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Integral equation based numerical codes provide a powerful means for accurately modeling microstrip junctions and discontinuities. Normally, the effects of metallization losses are modeled using a positionally independent surface impedance that is obtained from the bulk electrical properties of the metallization. However, this approach fails to account for geometry dependent loss effects such as metallization thickness, edge shape and surface roughness.

In this paper we present a positionally dependent equivalent surface impedance that accounts for metallization geometry loss effects. This equivalent surface impedance is obtained from a combination of asymptotic methods and a simple numerical finite element program. The proper equivalent surface impedance can then be tabulated and incorporated in a moment method code to provide accurate modeling of losses in general microstrip circuits. The results of this procedure will be compared to other theoretical values as well as experimental results.

MODELING OF IMAGE-TYPE SLOT LINES

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We consider the problems of normal waves and fundamental frequencies of the cylindrical slotted-type structures whose cross-sections are formed either by two different rectangular domains or by half-plane and rectangular domain. There are up to three dielectric layers in each bounded domain and several slots on the common parts of the boundaries.

The remarkable feature of these structures is in combination of open and bounded volumes connected by the slots which gives the possibility to use them as radiative elements of slot antennas. From the other side the well-developed technique for computation of the normal waves in transmission lines cannot be directly applied here also because the operators of the problems are complex-valued.

We prove the existence of point spectrum of the normal waves and apply analytical methods based on perturbation theory for solving the corresponding problems on characteristic numbers for multi-parameter summation-type or integral operator-valued functions and numerical algorithms for computation of the normal waves.

The basic results of this approach are published in *Mathematical Methods in the Applied Sciences*, vol.14, p.355–375 (1991).

Tuesday AM AP-S, URSI-B D, NEM Session TA03

Room: Grand C *Time*: 0820-1200

Photonic Systems for Antenna Applications

Organizer: Michael L. Van Blaricum, Toyon Research Corp.
Chairs: Michael L. Van Blaricum, Toyon Research Corp.; C. H. Cox III, MIT Lincoln Laboratory

0820+ **HIGH PERFORMANCE ANALOG FIBER-OPTIC LINKS for ANTENNA APPLICATIONS**
C. H. Cox III*, MIT Lincoln Laboratory

0900 **A CRITICAL LOOK at PHOTONICS for PHASED ARRAY SYSTEMS**
David D. Curtis*, Robert Mailloux, Rome Laboratory

0920 **REMOTE MULTI-OCTAVE ELECTROMAGNETIC FIELD MEASUREMENTS USING ANALOG FIBER OPTIC LINKS**
S. A. Pappert*, M. H. Berry, S. M. Hart, R. J. Orazi, S. T. Li, Naval Command, Control and Ocean Surveillance Center

0940 **OPTIMIZING ANTENNA DESIGNS WHEN USING INTEGRATED OPTICAL MODULATORS**
Michael L. Van Blaricum*, Michael P. Grace, Toyon Research Corp.; Thomas L. Larry, Toyon Research Corporation

1000 **LUNEBURG LENS ANTENNA with PHOTONIC SENSORS**
Don Hilliard*, Dean Mensa, Naval Air Warfare Center

1020 **HISTORY and the STATE of the ART of BULK MODULATORS for EM MEASUREMENTS**
Jerry C. Wyss*, Colorado Sensor Technology, Inc.

1040 **A SMALL WIDEBAND ANTENNA PRINTED on the SAME LiNbO3 SUBSTRATE AS the INTEGRATED OPTICAL MODULATOR**
Nobuo Kuwabara*, Tsuyoshi Ideguchi, NTT Telecommunications Networks Labs; Ryuichi Kobayashi, University of Electro Communications

1100 **WAVE-COUPLED W-BAND LiNbO3 MACH-ZEHNDER MODULATOR**
William B. Bridges*, Finbar T. Sheehy, California Institute of Technology; James H. Schaffner, Hughes Aircraft Company

1120 **PHOTONIC ELECTROMAGNETIC FIELD PROBES**
Motohisa Kanda*, Keith D. Masterson, David R. Novotny, NIST

1140 **SENSITIVITY ISSUES in PHOTONIC SENSOR SYSTEM DESIGN**
Gail T. Flesher*, General Research Corp.

HIGH PERFORMANCE ANALOG FIBER-OPTIC LINKS FOR ANTENNA APPLICATIONS

C. H. Cox III

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Optical fibers offer the potential for removing an often significant perturbation source from both the measurement of antenna patterns as well as the conveyance of RF to and from antennas. Unfortunately, this advantage has been masked by limitations in the RF-to-optical and optical-to-RF conversion processes needed to couple the RF into and out of the fiber, respectively. For example, these conversion processes typically result in a zero-length link transducer loss of 20 to 60 dB and noise figures of 30 to 70 dB. Recent progress in our understanding of the impact of various device parameters on link performance has permitted the design of links with net RF gain and noise figures as low as 6 dB.

In this talk simple analytic lumped-element small-signal models will be reviewed for the two most common link implementations: direct modulation of a diode laser, as shown in Fig. 1(a), and external modulation of a laser using a Mach-Zehnder integrated-optic modulator, as shown in Fig. 1(b). Although both modulation methods result in an intensity modulated optical carrier, the modeling reveals there are fundamental differences between the two in the dependance of various link parameters on device parameters. For example, Fig. 2(a) contrasts the RF gain and Fig. 2(b) shows the noise figure for both types of modulation versus average laser optical power. Analytical and experimental data show that passive impedance matching can be used to reduce loss and even achieve net RF gain in directly modulated links. A similar analysis for externally modulated links shows that the optical power, modulator sensitivity and impedance matching can be optimized to achieve net gain.

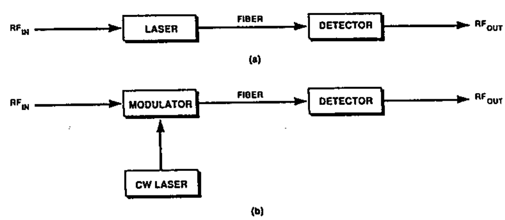

Fig. 1 Fiber-optic links using (a) direct and (b) external modulation

(a)

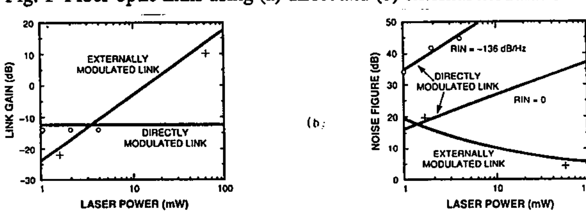

Fig. 2 Link (a) gain and (b) noise figure vs average optical power

A CRITICAL LOOK AT PHOTONICS FOR PHASED ARRAY SYSTEMS

David D. Curtis* and Robert J. Mailloux

Electromagnetics and Reliability Directorate
Rome Laboratory

Recent progress in photonics has focussed attention on control of phased array systems. Assessments range between the most avid proponents' optimistic view that the technology will soon replace most microwave analog scanning networks, to the pessimistic view that it will be too lossy, too costly, and too complex. This paper is an attempt to view photonic array control from the perspective of the array designer, to assess its potential in light of current array technology, and to suggest necessary developments.

Modern phased array technology provides accurate array control at relatively low cost. Passive analog systems cost hundreds of dollars per element, and with some added cost penalty can provide RF signals with a degree or two of phase error and tenths of a dB of amplitude error, as required for low sidelobe radiation. At higher frequencies efficiency can become a limitation, but solid state modules can improve efficiency, provide more power at the array, and improved signal to noise on receive. Solid state module arrays have traditionally been more expensive, but the costs are now competitive for some applications. Receive arrays using digital beamforming can provide the ultimate in low sidelobes and adaptively optimized pattern control.

Photonics has a difficult role to play against this existing technology, but brings some advantages that assure it a place in array control. In digital control signal distribution and RF power distribution, one can expect to see early applications of photonic technology. Control signal distribution complicates present day arrays, and is a relatively simple function to do photonically. RF signal distribution using photonics can, in principle, have the required accuracy, but losses in modulation and detection will require its use with solid state modules. The cost and reduction in dynamic range may limit this application for some systems. The use of photonics to provide time delay has great potential for wide band arrays, but is not without competition from digital beamforming systems, and does not readily admit to adaptive control. This paper addresses the state of developments in these areas, and highlights aspects of photonics research deemed critical to the deployment of photonics in array antenna systems.

REMOTE MULTI-OCTAVE ELECTROMAGNETIC FIELD MEASUREMENTS USING ANALOG FIBER OPTIC LINKS

S.A. Pappert*, M.H. Berry, S.M. Hart, R.J. Orazi, and S.T. Li

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Broadband electromagnetic field detection and monitoring systems have been investigated in the 30 MHz - 18 GHz frequency range. To minimize the intrusiveness of these field monitoring probes, fiber optic and electro-optic techniques have been employed to transmit the detected broadband information to a remote processing station. These short-haul (< 1 km) wideband fiber optic links possess no electrical or optical amplifiers to boost the detected antenna signal which increases the importance of constructing low noise figure transmission links. Both directly modulated (current modulation of injection laser diode) and externally modulated (voltage modulation of optical waveguide modulator) wideband optical systems have been developed.

Results of anechoic chamber tests of several electromagnetic field detection systems will be presented. The performance of a 2 - 18 GHz externally modulated system will be presented which consists of a broadband cavity-backed spiral antenna, an optical waveguide modulator, a 1.32 μm Nd:YAG solid state laser, single-mode optical fiber, and a high-speed photodiode. Operation with both III-V semiconductor based and lithium niobate based optical waveguide modulators have been investigated and compared for the externally modulated system. An rms electric field sensitivity of 15 μV/m and a spurious free dynamic range of 102 dB in a 1 Hz resolution bandwidth have been measured with this 2 - 18 GHz field detection system. The performance of a 30 MHz - 500 MHz directly modulated system will also be presented which consists of a broadband VHF/UHF antenna, a laser diode, single-mode optical fiber, and a photodiode. For each field sensing system, the frequency response, electromagnetic field sensitivity, dynamic range, as well as environmental stability are reported. The advantages and disadvantages of both the directly modulated and externally modulated electro-optic field detection systems will be discussed.

OPTIMIZING ANTENNA DESIGNS WHEN USING INTEGRATED OPTICAL MODULATORS

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The use of integrated-optical Mach-Zehnder interferometers (MZI) as the pick-up or modulation devices in optical antenna and sensor links allows a new set of options for the antenna designer to consider. Externally modulated optical links are inherently very broad-band. The bandwidth of optically based antenna links are therefore, usually limited by the antenna and matching network. In addition, the input impedance of integrated-optical modulators is capacitive with a small real part of a few Ohms. The modulator responds to the voltage induced across this capacitive reactance. Therefore, the design of antennas and matching networks to connect to external optical modulator links should not be limited to conventional or classical design considerations where typical 50 Ohms loads are used.

In this paper, we will investigate techniques for designing gain and bandwidth of a complete optical antenna link by optimizing antenna and matching network designs as a function of the sensitivity of the MZI. The newly written SCINW thin-wire antenna optimization code is used as the design tool to optimize the antenna and the matching network parameters. The FOLSIM (Fiber Optical Link SIMulator) code was used to predict the overall optical link gain, noise-figure, and dynamic range resulting from the optimized antenna and matching network designs when nominal optical device parameters are used.

Several typical antenna and matching network examples will be presented. It will be shown that the use of the optical modulator as a pick-up device will allow higher gain for a smaller effective aperture in cases where narrow band performance is desired. In addition, we will discuss approaches to broad-banding the antenna to take advantage of the optical link bandwidth.

LUNEBURG LENS ANTENNA WITH PHOTONIC SENSORS

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Standard approaches to sensing electromagnetic fields employ metallic antennas attached to transmission lines which couple the antenna to a receiver. A major disadvantage of this method is the perturbation in the measured field caused by the conducting materials used for the antenna and transmission lines. In addition, transmission lines are typically subject to attenuation and dispersion which limit the cable length at microwave frequencies, and are vulnerable to EMI and EMP sources. This paper describes a concept that eliminates these disadvantages by implementing an all-dielectric field sensing system composed of a Luneburg lens antenna and photonic sensors (U.S. Navy Patent Pending). The system measures the frequency, amplitude, phase, and angle-of-arrival of the fields. Tests have been conducted on a prototype version of this system. The photonic sensor used in these proof-of-concept tests was provided to the Navy by Colorado Sensor Technology, Inc. The Luneburg lens used in the tests was provided to the Navy by Rozendal Associates.

The Luneburg lens is a spherically-shaped, broad-band dielectic device that focuses an incident planar electromagnetic wave entering one side of the lens onto a spot on the opposite side of the lens (R.K. Luneburg, "Mathematical Theory of Optics", University of California Press, 1964, pp. 182-188). Photonic sensors are coupled with the Luneburg lens by positioning the electro-optic modulators on the focal surface of the lens. The field captured by the lens are focused onto the corresponding modulator, thus enhancing the sensitivity of the system by a factor proportional to the focusing gain of the lens. The angle-of-arrival of the fields can be determined by noting which sensors are most strongly modulated. Electro-optic modulators can be placed over the entire surface of the lens to provide 4π steradian coverage, Aperture blockage, that would occur with metal antennas is reduced because the modulators covering the lens surface on the side of field incidence are effectively transparent to the field thus allowing fields to penetrate into the lens and focus onto modulators on the opposite side.

Examples of applications for use of this system include: probing the fields of anechoic chambers; probing in areas of potential biological hazards; and as receiving antennas not susceptible to lightning, e.g, as a replacement to the parabolic satellite television antenna.

History and the State of the Art of Bulk Modulators for EM Measurements

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Abstract.

Eighty-four years ago, F. Pockels demonstrated the existence of the linear electrooptic effect in bulk crystals using an applied electric field. For the last forty-six years, various experimenters have been exploiting this effect to modulate light at progressively higher frequencies. In most of these applications, an electric signal is amplified and applied directly to a bulk crystal, with the main goal of efficiently modulating the light.

For the last fifteen years, a number of researchers have been applying the bulk crystal Pockels effect to construct antennas that can efficiently receive an electromagnetic (EM) signal without greatly perturbing the signal being measured. This paper will review the design parameters of such systems with particular emphasis on how these designs relate to the antenna characteristics. After briefly discussing some of the present problems in performing EM measurements with non-photonic techniques, this article will show how photonic sensors may solve some of these problems. In one application a system will be shown that has short metallic dipole antennas directly coupled to the bulk crystals. This configuration will be shown to have a minimum sensitivity of 1.7 mV/m per $Hz^{1/2}$ and a frequency bandwidth of 2.0 GHz.

Eliminating the dipoles and using the bulk crystal as the antenna element by itself, a more compact, ruggedized, practical system has been built which has a minimum sensitivity of 40 V/m per $Hz^{1/2}$, and a frequency bandwidth of greater than 2.0 GHz. Such a system has many applications including fast rise-time EMP measurements.

Wave-Coupled W-Band $LiNbO_3$ Mach-Zehnder Modulator

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Electro-optic modulators commonly use lithium niobate ($LiNbO_3$) as the substrate because of its high electro-optic coefficient. However, $LiNbO_3$ is dispersive, so the optical and electrical signals have different propagation times along the modulator electrodes. To prevent averaging of the signal in the modulator at high signal frequencies, the electrodes must be short, which gives low sensitivity.

We previously reported a method of cascading many short modulator electrodes, with the modulating signal coupled to the electrodes by antennas which were illuminated so that each electrode was driven in the proper phase. This makes it possible to construct sensitive modulators at high signal frequencies. In addition, since the modulator is radiatively coupled it is suited to waveguide-based systems and field sensing applications. We demonstrated X-band (10 GHz) and V-band (60 GHz) prototype phase-modulators at 633 nm optical wavelength. Our demonstration was restricted to phase-modulation because we used dipole antenna elements, and there was no convenient way to apply DC bias to the elements. A Mach-Zehnder amplitude modulator needs DC bias in order to operate in its linear region.

More recently we designed Mach-Zehnder amplitude modulators for W-band operation (94 GHz), at 1.3 μm optical wavelength. These modulators use bow-tie antennas, which are relatively insensitive to DC bias connections made to the ends of the antenna elements. The bow-ties should also give a greater bandwidth than the dipole antennas. The design and performance of these new modulators will be presented.

PHOTONIC ELECTROMAGNETIC FIELD PROBES

Motohisha Kanda, Keith D. Masterson, and David R. Novotny

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ABSTRACT

We describe optically sensed probes designed to accurately measure electromagnetic fields. The probes use passive electro-optic modulators of Pockels cell or integrated optics designs to transfer the electromagnetic signal to an optical carrier propagating in an a fiber optic link. This approach eliminates the need for active components or power sources in the probe head. It minimizes the distortion of the field being measured and is immune to EMI pickup on the lines leading to the signal processing electronics. Fiber optic systems are also capable of bandwidths up 100 GHz, while preserving both signal amplitude and phase over lines 100's of meters long. We describe an approach to modeling system performance using cascaded transfer functions. We also describe several probe systems that have been fabricated at NIST over the last few years. They include an isotropic probe consisting of three orthogonal dipoles, a probe for EMP measurements up to 200 kV/m, a probe using an integrated optics modulator for frequencies to above 3 GHz, and a probe to simultaneously measure both the electric and magnetic fields and their relative phases. The latter holds the potential of determining the Poynting vector in a plane wave, or of measuring the radiation emitted over the entire 4π steradians from a device placed at the center of three orthogonal, concentric loops. Field strengths down about 10 $\mu V\ m^{-1}\ Hz^{-1/2}$ are detectible using these techniques. Well designed photonic probes with passive electro-optic modulators have linear dynamic ranges of above 70 dB.

SENSITIVITY ISSUES IN PHOTONIC SENSOR SYSTEM DESIGN

by

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Abstract

Use of photonic technology in antenna or sensor systems is receiving close scrutiny for various applications where some aspect of photonic signal handling is superior to the equivalent rf technique. At the same time, the other aspects of photonic usage must not be allowed to substantially degrade other system performance goals. This paper addresses the important issue of sensitivity of photonic rf sensors or antenna elements compared to the usual non-photonic types, when no rf preamplifier is used.

The use of photonic techniques bring in new signal responsivity factors and new noise sources. Their effects on S/N ratio through the parameters of the overall system are presented. A number of different modulation techniques will be presented. The photonics sensor or photonic probe will be used as a comparison system because of its advantageous lack of need for metal coaxial cable for carrying signals. Coaxial cable causes reflections and field re-distribution to occur, highly perturbing the fields being measured. Use of optical fiber for signal transmission can eliminate most of this disturbance.

The more sensitive systems currently require optical phase or frequency control. To avoid this increase in complexity, the parameters to be targeted for improvement through research will be highlighted. Chip integration of the feedback control functions may also prove to be a feasible goal as optical components improve in performance and control aspects.

Photonic rf sensitivity is steadily approaching non-photonic sensitivity and is adequate for many applications now. Future system design will use photonic techniques as the advantages begin to outweigh the diminishing disadvantages.

Tuesday AM AP-S, URSI-B Session TA06

Room: Grand F *Time*: 0830-1130

In honor of Robert S. Elliott

Organizer: D. G. Dudley, University of Arizona
Chairs: D. G. Dudley, University of Arizona; Edmond S. Gillespie, California State University, Northridge

0830 **OPENING REMARKS by D. G. DUDLEY**

0840 **A FUNDAMENTAL THEOREM on the MAXIMUM FREQUENCY of COHERENT OSCILLATIONS by ROBERT S. ELLIOTT**
C. T. Tai*, The University of Michigan

0900 **LEAKY SURFACE WAVES on CURVED SURFACES**
Akira Ishimaru*, University of Washington

0920 **SCATTERING PROPERTIES of BROAD WALL SLOTS in RECTANGULAR WAVEGUIDE**
Sembiam R. Rengarajan*, California State University, Northridge

0940 **AN IMPROVED DESIGN PROCEDURE for SMALL ARRAYS of SHUNT SLOTS (JANUARY 1983, ROBERT S. ELLIOTT): a REPRISE**
Jon J. Gulick*, Hughes Aircraft Company

1000 **Break**

1020 **ANTENNA PATTERN SYNTHESIS**
L. Josefsson*, Ericsson Radar Electronics AB

1040 **HISTORICAL PERSPECTIVES - ROBERT S. ELLIOTT'S CONTRIBUTIONS**
Edmond S. Gillespie*, California State University, Northridge

1100 **R.S. ELLIOTT and HIS IMPACT at UCLA**
N. G. Alexopoulos*, University of California, Los Angeles

1120 **CLOSING REMARKS by D. G. DUDLEY**

A Fundamental Theorem on the Maximum Frequency of Coherent Oscillations by Robert S. Elliott

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The Unviersity of Michigan
Ann Arbor, MI 48109-2122

Abstract

In 1952, Elliott (J. Appl. Phys. 23, 812-818, August 1952) enunciated an important theorem on the maximum frequency limit for electron beam oscillators. The theorem is based on several physical laws. The first law states that the average power supplied by an electron beam to the field must be equal to the total average power lost by the resonant structure, including the useful output power and the ohmic loss. The second law states that the product of the frequency of oscillation and the average stored energy of the device must be greater than the average output power. The third law invokes the quantum theory of radiation. It implies that the minimum stored energy should be at least equal to the average noise energy level. With these laws at his disposal, the then young scientist was able to formulate his beautiful theorem.

In this talk, I will review this historical paper, showing the key formulation, and the proof of the theorem and its application to the design of klystrons and magnetrons, pointing out the inherent limitations of these devices to generate coherent oscillations in the optical spectra. It is, by no means, a coincidence that the invention of the laser in the late fifties could be viewed as a consequence of the limitations as revealed by Elliott's powerful theorem. The advance of many scientific breakthroughs is often guided by some profound studies of the existing limitations. Elliott's work is certainly one of the monumental corner stones in the field of microwave electronics. If his theorem had been fully appreciated many fruitless researchers probably would never have been attempted. Some anecdotes to support this conclusion will be told. After all, a twelve page Ph.D. dissertation must be a record at The University of Illinois or elsewhere. It is, indeed, my honor to share with you this magnificent story of a scientist to whom this session is dedicated.

LEAKY SURFACE WAVES ON CURVED SURFACES

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In the early 1950's, renewed interest was shown in the study of trapped surface waves following investigations on flat corrugated surfaces, axial surface waves on corrugated circular cylinders, and dielectric coated cylindrical conductors. However, Professor Elliott was the first to give an extensive analytical treatment of "azimuthal surface waves" on cylinders. This work published in 1955 has some unique features. It involved calculation of Hankel functions of the complex order which was extremely difficult in the pre-computer age. The complex order represents the propagation constant in the azimuthal direction. Floquet's theorem was applied to an azimuthal periodic corrugated structure. The surface wave propagates along the curved surface, and the power is not completely trapped on the surface but leaks out continuously. Professor Elliott was also the first to calculate the leakage rate correctly. This leaky surface wave concept was successfully applied to produce end-fire antennas at Hughes. By proper choice of the radius of curvature and length of the arc, the main beam can be positioned at end-fire and the nulls of the pattern can be filled in. The pattern also approximates a desired $CSC^2\theta$ response. These desirable features can also be obtained by corrugated spherical surfaces. Professor Elliott in his 1956 paper gave an indepth study of spherical surface waves which led to a successful beacon antenna. Once again, the curvature controlled the placement of the main beam and the fill-in. This paper summarized Professor Elliott's pioneering work on leaky surface waves and their significance, together with some anecdotes concerning controversies relating to his work.

SCATTERING PROPERTIES OF BROAD WALL SLOTS IN RECTANGULAR WAVEGUIDE

Sembiam R. Rengarajan*
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California State University, Northridge
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This paper will focus on Elliott's contributions to the understanding of the scattering properties of broad wall slots in rectangular waveguides. Their significance in the analysis and synthesis of slot arrays will also be discussed. Stevenson originally presented an analysis for resonant slots in terms of an integral equation. With the use of an approximate distribution for the aperture electric field, and from power balance consideration, the resonant slot conductance or resistance was obtained. Oliner employed a variational procedure to determine the susceptance or reactance of a slot near resonance. Khac presented a moment method solution for the aperture E-field from which scattering properties of the slot were deduced.

Elliott's design procedure for a linear or planar array requires input data for the resonant length and the normalized slot admittance. The resonant length data were previously obtained from carefully performed experimental measurements. It was noted that Khac's moment method model did not predict the resonant length accurately since the design of a high performance antenna requires resonant length data within a fraction of one percent accuracy. Such a requirement was fulfilled by Stern and Elliott with an accurate moment method model for a longitudinal slot. It was also shown that the shunt model, and a half-cosine equiphase distribution for the aperture field were poor under certain conditions.

Significant contributions of Elliott and others have led to the design of slot arrays without the need for any experimental data taking.

AN IMPROVED DESIGN PROCEDURE FOR SMALL ARRAYS OF SHUNT SLOTS

(JANUARY 1983, ROBERT S. ELLIOTT):

A REPRISE

Jon J. Gulick
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In 1983 a new procedure for the design of waveguide-fed longitudinal (shunt) slots was introduced. The paper titled "An Improved Design Procedure for Small Arrays of Shunt Slots," which appeared in the January issue of the transactions of the Antennas and Propagation Society, quickly became the definitive work on this important topic. Although the author of the paper, Professor Robert S. Elliott of the University of California at Los Angeles, seems to have suggested by the title that his procedure is in some way limited to arrays of relatively few elements, it has proved to be equally effective for the design of large as well as small arrays. Moreover, the relevant literature of the last decade indicates that Elliott's procedure can be readily extended to arrays which are comprised of other radiating elements as well.

This presentation commences with a discussion of the principal differences between the new method and the earlier design procedure which it replaced. An outline of the development used by Professor Elliott to arrive at a pair of coupled design equations follows. A critical examination of the two design equations, which serves to highlight the implications of mutual coupling between radiating elements, is then undertaken. Finally, the algorithm suggested by Elliott for array design is revisited. Based on the two design equations developed in the paper, this algorithm culminates in the required length/offset couplet for each slot in the array subject to a desired set of excitation coefficients and input match requirement.

ANTENNA PATTERN SYNTHESIS

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The impact of antenna pattern characteristics on system performance in e.g. radar is well understood. Antenna pattern synthesis has therefore been an important area for research. Early contributions include methods for synthesizing a prescribed, constant side lobe level while maintaining a narrow main beam (Dolph, Taylor). Several approximate methods for synthesizing a shaped beam, such as a $\csc^2$ pattern, have also emerged.

Ideally, one would like to control the amplitude of each sidelobe individually, and at the same time have the main beam shape match a desired shape to within an arbitrary maximum error. Such a method was indeed developed by R.S. Elliott for equispaced linear arrays. The method is based on modifying the roots of the array factor polynomial, a process that is well illustrated by the location of the roots with respect to the Schelkunoff unit circle. In an extension of the method together with Orchard and Stern (*IEE Proc. Part H,* Feb. 1985), a computationally efficient iterative method to find the optimum root locations for shaped beam pattern synthesis was described.

The pattern synthesis method has also been extended to planar apertures. It has been validated experimentally in a number of cases.

In the talk, the advances in the field of antenna pattern synthesis due to Professor Elliott will be reviewed including linear and planar arrays, and continuous planar apertures. The Elliott-Orchard method will be described in some detail. A few illustrations of results achieved with the method will also be presented.

HISTORICAL PERSPECTIVES - ROBERT S. ELLIOTT'S CONTRIBUTIONS

Edmond S. Gillespie
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In 1960, Professor Elliott's text entitled "Electromagnetics" (McGraw Hill, Publisher) appeared. It was a rather revolutionary treatise in terms of content and presentation. One of the unique features that set it apart from other texts was its detailed historical presentation. While critically acclaimed, it did not enjoy wide spread adoption as a textbook. Now out of print, it has moved into the realm of a classic work which is still referenced by other authors. Many generations of university students have "rediscovered" the book and have been enthralled and inspired by it. Evidence of this at my university is the fact that Professor Elliott's text is one of the most worn and tattered of all the books on electromagnetic theory in our library,indicating heavy usage over the last 30 years.

The reason for this, I believe, is the detailed historical presentation. Professor Elliott states it best in the preface of the book,

> "----Without the historical background, the reader of a technical exposition often is left with a bland reaction to his first encounter with a new physical concept. Yet, more often than not, there is behind this concept a rich heritage of thought, as outstanding human minds have struggled to identify the concept and clarify it. Awareness of this heritage instills added respect for each new principle and reveals an important lesson which all scientific history teaches - that complete understanding is rarely attained and that the struggle for clarity is still going on."

As our field has grown more mature, we all have become more interested in our scientific and technological history. The Hertz Centennial was evidence of this. That celebration lasted two years. Professor Elliott played a key role with the presentation of his paper "Electromagnetic Theory as Hertz Would Have Known It." No tribute to Professor Elliott would be complete without recognition of his contributions to the history of electromagnetics - this paper will review those contributions.

R.S. Elliott and His Impact at UCLA

Nicolaos G. Alexopoulos, Chairman, Electrical Engineering Department, University of California, 58-121 Engr. IV, 405 Hilgard Avenue, Los Angeles, CA 90024-1594

This presentation is an attempt to project the significance of an exceptional multifaceted individual; Robert Stratman Elliott. Dr. Elliott's career, particularly since he joined UCLA, will be the focus of this presentation. His impact in establishing an Electromagnetics group and in founding the Electrical Engineering department will be discussed, with an emphasis on Dr. Elliott's academic and professional achievements.

Dr. Elliott was the catalyst and the prime mover in creating a strong Electromagnetics group at UCLA. His book "Electromagnetics" (McGraw Hill, 1966) set by example the highest standards of intellectual pursuit amongst his colleagues. His exposition of Electromagnetic theory as developed from a single experimental postulate, Coulomb's law, was unique, elegant and brilliant. In this book he also educates us with a historical perspective of the scientific and engineering aspects of Electromagnetism.

Another significant impact to our Department has been Professor Elliott's philosophical approach as to what Engineering Education should be. He has managed to drive sophisticated theoretical methods to practical highly accurate design tools. This approach helps the engineer to develop microwave products (e.g. Antenna arrays) at a low cost. Dr. Elliott's contributions to Engineering education include the significant book "Antenna Theory and Design" (Prentice Hall, Inc., 1981) and a long list of journal publications. The importance of his work has culminated in numerous awards including IEEE best paper awards, IEEE Fellow, several IEEE Award Citations and membership to the National Academy of Engineering.

Professor Elliott's lifelong contributions at UCLA will be presented during this talk. The conclusion will be that Dr. Elliott is an outstanding individual as a scholar, educator, researcher, historian, writer and friend, that he is a rare human being who approaches life and work in a very serious, deep and pragmatic manner, that he avoids the superfluous and that he has a rare quality in that whatever he touches "it turns into gold".

Tuesday AM AP-S, URSI-B Session TA07

Room: Columbus A *Time*: 0820-1200

Polarimetric Radar Theory

Chairs: Shi-Ming Lin, Northwestern Polytechnical University; Masashi Hayakawa, The University of Electro-Communications

0820 **ON CHARACTERISTIC POLARIZATION STATES in the CROSS-POLARIZED RADAR CHANNEL**
Yoshio Yamaguchi*, Niigata Unviersity; Wolfgang-M Boerner, University of Illinois at Chicago; Hyo J. Eom, Korea Advanced Inst. of Science & Tech.; Masakazu Sengoku, Takeo Abe, Niigata University

0840 **POLARIMETRIC RADAR BACKSCATTER ALGORITHMS for PARTIALLY POLARIZED WAVES**
Y.M. M. Antar*, J.D.A.G. Kingbury, Royal Military College of Canada

0900 **OBSERVATIONS of POLARIMETRIC MILLIMETER-WAVE BACKSCATTER MEASUREMENTS from SNOWCOVER at 225, 95 and 35 GHZ**
Paul S. Chang*, Philip Langlois, Eric Knapp, R. E. McIntosh, University of Massachusetts at Amherst

0920 **POLARIMETRIC SCATTERING MODEL for GRASSY TERRAIN**
James M. Stiles*, K. Sarabandi, Fawwaz Ulaby, The University of Michigan

0940 **THE POLARIMETRIC MATCHED IMAGE FILTER: APPLICATION to SPECKLE REDUCTION & OPTIMAL BACKGROUND CLUTTER DISCRIMINATION in MICROWAVE SENSING and IMAGING**
Matthias Walther, Andrew C. Segal, University of Illinois at Chicago; Hyo J. Eom, Korea Advanced Inst. of Science & Tech.; Wolfgang-M Boerner*, University of Illinois at Chicago

1000 **A NEW CLASSIFICATION METHOD of the RADAR TARGETS by USING the GERSHGORIN DISKS of the MUELLER MATRIXES**
Shi-Ming Lin*, Northwestern Polytechnical University

1020 **FEATURES of POLARIMETRIC TERRESTRIAL WAVE PROPAGATION**
D. J. Cichon*, Th. Kurner, W. Wiesbeck, Universitat Karlsruhe

1040 **POLARIMETRIC SIGNATURES of a FORESTED CANOPY**
Mostafa A. Karam*, F. Amar, A. K. Fung, University of Texas at Arlington

1100 **REAL-TIME POLARIZATION-DIVERSE FEATURES EXTRACTION and AUTOMATED TARGET IDENTIFICATION USING NEURAL NETWORKS**
Liang-jie Zhang*, Weng-bing Wang, Xi'an Jiaotong University

1120 **THE INVERSE SCATTERING PROBLEM in the POLARIZATION PARAMETERS DOMAIN: SOLUTION VIA NEWTON-KANTOROVICH ITERATIVE TECHNIQUE**
Dmitry O. Batrakov*, Nikolay P. Zhuck, Kharkov State University

1140 **KENNAUGH'S OPTIMAL POLARIZATION for the MULTISTATIC RADAR**
Jian Yang*, Northwestern Polytechnical University

Observations of Polarimetric Millimeter-wave Backscatter Measurements from Snowcover at 225, 95, and 35 GHz

Paul S. Chang, Philip Langlois, Eric Knapp, and Robert E. McIntosh

University of Massachusetts
Microwave Remote Sensing Laboratory
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Measurements at 225, 95, and 35 GHz on various types of snowcover have been made at a site on the University of Massachusetts campus. The measurement setup consisted of a 20 foot gantry mounted on the roof of a 26 meter high building. The radar systems were mounted on an elevation over azimuth positioner on the gantry that was computer controllable. This radar platform overlooked a level snow field that was ideal for our measurements. The geometry permitted measurement of backscatter at incident angles of 25 degrees and 60-80 degrees. The measurements were automated so that a Polarimetric Radar Control and Data Aquisition (PRACDA) system and corresponding algorithms automatically positioned the radar system and aquired data for the full range of desired incident angles. PRACDA was also used to precisely position the radar beams during the calibration procedure.

The 225 GHz radar is a noncoherent system that transmits a peak power of 60 watts. The transmitted polarizations are varied utilizing two computer controlled quarter-wave plates. The Mueller matrix was obtained noncoherently using six independent polarizations. The 95 GHz polarimeter is a fully coherent radar system capable of measuring the scattering matrix of a target. This system has a peak transmitted power of 1.5 kilowatts. The polarizations of the 95 GHz system are changed with a ferrite polarization switch and two quarter-wave plates. This setup allows us to coherently and/or noncoherently measure a target's Mueller matrix.The 35 GHz radar is a FM-CW system. This radar is capable of measuring only the co-polarized and cross-polarized backscatter from a target. The average power transmitted by the 35 GHz radar is approximately 6 milliwatts.

Our in-situ ground truth data consisted of measuring the snow water content, temperature, density, surface roughness, depth, particle size, and particle type. This information was correlated with the radar measurements. The dependence of the radar cross-section and polarimetric measurements on the physical parameters of the snow and incident angle were studied. In this paper, we will show how snow parameters affect various terms of the Mueller matrix.

Polarimetric Scattering Model For Grassy Terrain

James M. Stiles, Kamal Sarabandi and Fawwaz T. Ulaby

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Abstract

Information obtained from the polarimetric scattering response of a rough, bare soil surface can lead to an accurate estimate of the soil moisture content of that surface. Assuming proper selection of sensor parameters (incidence angles and frequencies), polarimetric scattering data can provide the information required to infer each soil parameter on which the scattered response is dependent. However, soils are most commonly covered by vegetation, adding another collection of physical parameters which affect the surface polarimetric scattering response. Possible vegetation covers include members of the grass family such as wheat, hay and other plants exhibiting long, thin leaf and stalk structures. In addition to major factors such as total biomass and moisture content, scattering from grasses is also dependent on the finer features of a plant structure, including leaf cross section geometry and leaf curvature.

A scattering model has been developed which provides an exact numerical solution to scattering from stalks and leaves of arbitrary cross sections, orientations, and lengths. Because the constituent cross sections are assumed to be electrically small, a two dimensional Rayleigh scattering approximation was employed and polarizability tensors were determined numerically. The dipole moments per unit length were then calculated, and integrating these values over the length of each constituent resulted in an expression for the total scattered field. These results were combined with a statistical description of a grassy vegetation cover to provide the phase and extinction matrices required for a first order, vector radiative transfer scattering model of the grassy vegetation cover. This model was used to investigate the dependence of the total polarimetric scattering response on both soil and vegetation parameters. Eventually, this model will be used to determine the scattering data necessary to invert the model and obtain an estimate of the moisture content of the soil surface and the biomass of the vegetation cover.

THE POLARIMETRIC MATCHED IMAGE FILTER: Application to Speckle Reduction & Optimal Background Clutter Discrimination in Microwave Sensing and Imaging

Matthias Walther, Andrew C. Segal, Hyo Joon Eom and Wolfgang-Martin Boerner

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During the past decade, polarimetric radar technology reached the state of developing true coherent dual orthogonal polarization channel radar (POL-RAD) systems enabling the quasi-instantaneous recovery of the coherent 2x2 complex scattering matrix $[S(A,B = A_{\perp})]$ and/or associated 3x3 complex covariance matrix $[\Sigma(A,B = A_{\perp})]$ and 4x4 real Kennaugh (Mueller) power density matrix [M] on a bin-by-bin or, in the case of POL-SAR systems, pixel-by-pixel basis, respectively.

Based on this advanced performance level, it is now possible to introduce 'Polarimetric Matched Signal/Image Filters [PMSF/PMIF]' which utilize complete information of the electromagnetic wave scatterer interaction process. As a result of this rapid recovery of the scattering matrix information, at short time-intervals well under the decorrelation periods of moving and vibrating scatterer, very essential 'vector wave scattering information', inprinted during the "wave polarization state transformation" process are retained which, otherwise, would be lost by 'statistical averaging'; and a more complete description or recovery of the scattering process is therefore possible.

Utilizing novel results of a comparative approach of scattering matrix optimization procedures for [S], [Σ] and [M], and their Lie SU(n = 2,3,4)-group theoretic expansions, it was possible to derive a set of more robust target detection, speckle reduction and clutter suppression algorithms. Utilizing the polarimetric invariants of Trace{[Σ]} = Span{[S]} = invariant and Span{[Σ]} = invariant, the 'covariance matrix invariance ratio', (cmir) = (Span{[Σ]}/Span{[S]}) = invariant, is introduced and found to provide a good measure on "speckle reduction" as well as for obtaining an optimal high resolution image. Thereafter, the PMSF/PMIF filter process is introduced which is based on the target/clutter characteristic polarization state plus optimal stochasticity coefficient (optimal degrees of polarization and of coherency) approaches combining rigorous electromagnetic theory with basic principles of advanced vector signal estimation and detection theory.

Results are presented for POL-SAR image data sets collected with the air-borne NASA-JPL(P/L/X)-band SAR Polarimeter system over the San Francisco Bay area.

Tuesday AM URSI-B Session TA08

Room: Columbus C/D *Time*: 0820-1200

Antennas & Radiation I

Chairs: K. C. Gupta, University of Colorado at Boulder; O. M. Bucci, Universita di Napoli

0820 **COMPUTER SIMULATION of FAR-FIELDS of INDIVIDUAL ANTENNA ELEMENTS and CIRCULAR ARRAYS AROUND CONDUCTING CYLINDERS**
Arsenio Vargas*, MITRE Corp.; Rajeev Bansal, University of Connecticut

0840 **ANTENNA PATTERN SYNTHESIS USING NEURAL NETWORKS**
W. T. Smith*, T. R. Damarla, University of Kentucky

0900 **RADIATION PATTERN of MULTI-SLOTTED DIELECTRIC-COATED ELLIPTIC CYLINDER ANTENNAS**
A. Sebak*, The University of Manitoba

0920 **MUTUAL COUPLING EFFECTS in NEEDLE ARRAYS**
Roger H. Lang*, Omer Kavaklioglu, George Washington University

0940 **RADIATION and WIDE-BAND SCATTERING of PROBE-FED RECTANGULAR PATCHES INFINITE ARRAY on MULTILAYER DIELECTRIC SHEET**
P. Borderies*, Jerome Bruniquel, ONERA/CERT

1000 **Break**

1020 **ANALYSIS of MICROSTRIP DISCONTINUITIES in MULTILAYERED ANISOTROPIC SUBSTRATES**
R. R. Boix*, J. Martel, M. Horno, University of Seville

1040 **RIGOROUS ANALYSIS of a WAVEGUIDE-EXCITED MICROSTRIP PATCH ANTENNA of ARBITRARY SHAPE**
M.-H. Ho*, C.-I. G. Hsu, K. A. Michalski, Kai Chang, Texas A&M University

1100 **MULTIPORT NETWORK MODEL for TWO-PORT GAP-COUPLED RECTANGULAR MICROSTRIP PATCHES COVERED with a THICK DIELECTRIC LAYER**
A. Benalla*, K. C. Gupta, University of Colorado at Boulder; Seung-In Yang, Soongsil University

1120 **INFLUENCE of TAPERING COEFFICIENT on the RADIATION PATTERNS of a LINE SOURCE**
P. M. Rao*, G. S. N. Raju, K. R. Gottumukkala, Andhra University

1140 **RADIATION FIELDS from TWO-WIRE TRANSMISSION LINE ANTENNAS**
Ernest A. Bacca*, Kirtland AFB; Albert W. Biggs, University of Alabama in Huntsville

COMPUTER SIMULATION OF FAR-FIELDS OF INDIVIDUAL ANTENNA ELEMENTS AND CIRCULAR ARRAYS AROUND CONDUCTING CYLINDERS

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and

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The use of an electric surface current model for the microstrip antenna in front of or around a conducting cylinder has been successfully used in the efficient calculation of the far fields due to such a radiating structure (J. Ashkenazy et. al., *IEEE Trans. Antennas Propagat.*, AP-33, 295-299, 1985.) The fields are constructed in the Fourier domain using the Fourier components of the scalar functions which generate the TE and TM modes. The microstrip antenna is accounted for using its electric surface current in the H-field boundary condition at the cylinder boundary. Published experimental results have demonstrated the reliability of the analysis approach (E. Levine et. al., *Microwave Journal*, 85-92, March 1987).

Individual elements analyzed thus far have been vertical and horizontal half-wavelength dipoles, axial patches, and wraparound, or ring, antennas. The results of our simulations have compared well with published results, as will be demonstrated in the presentation. In addition, circular arrays consisting of the vertical and horizontal dipole elements have also been analyzed and will be presented. The utility of the developed computer code in analyzing the far field modes from a circular array has also been achieved. The use of the cardioid to represent the element pattern of a vertical-dipole circular array around a conducting cylinder has been validated by our work and will be compared with the exact pattern.

A strong focus of the computer simulation work has been the radiation patterns resulting from single tilted half-wavelength dipoles and also circular arrays of these elements. Verification for the approximately vertical and horizontal cases has been done. However, comparison of our results for intermediate tilt angles has not occurred partly due to the lack of open-literature results for these configurations. Results for intermediate, as well, as extreme tilts of the dipole elements will be presented.

ANTENNA PATTERN SYNTHESIS USING NEURAL NETWORKS

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Antenna design usually entails picking a certain class of antenna with known radiation characteristics for a given current distribution. The selected radiator is then modified to satisfy pattern and system specifications. Antenna pattern synthesis is the inverse design problem. Pattern synthesis is a process by which an antenna current distribution is determined given certain specifications for the radiation pattern. After finding the required current distribution, the antenna type is then designated.

There are several antenna pattern synthesis techniques. The choice of technique depends on the design pattern characteristics. Synthesis methods usually fall into two categories depending on the desired pattern type: shaped beam or narrow main beam with low side lobes. In general, for finite antennas, the solution for the pattern synthesis problem produces a current distribution whose radiation properties approximate the desired radiation pattern. Different synthesis techniques produce varying degrees of match.

In this presentation, the term neural network refers to a parallel computing algorithm that is somewhat based on biological neural network processes. The parallel algorithm is constructed by interconnecting nonlinear computing elements. There are many different types of neural networks. Choice of a particular type depends on the application and the data being analyzed. Neural networks can be "trained" to efficiently perform tasks that are often time-consuming when conventional computing methods are employed.

The objective of this presentation is to evaluate the use of neural networks in pattern synthesis design of antennas. The type of neural network chosen for this study is a multilayered network employing the Backpropagation learning paradigm. The algorithm is trained using data simulated by conventional pattern synthesis techniques for array antennas and line sources. The trained net is then used to synthesize the antenna parameters for given patterns. Results are compared with the parameters generated by neural network analysis and those generated by conventional methods.

RADIATION PATTERN OF MULTI-SLOTTED DIELECTRIC-COATED ELLIPTIC CYLINDER ANTENNAS

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The radiation pattern of slots located on cylinders has attracted the attention of many investigators due to their wide-ranging applications. This paper is concerned with the radiation characteristics of a finite array of axial slots on a non-confocal dielectric-coated elliptic cylinder. We assume that the aperture field, i.e. the excitation voltage, is a specified function on each slot. The theoretical analysis is based on the eigenfunction technique and the addition theorem for the Mathieu functions. The fields in the dielectric coating and exterior regions are expanded in terms of the Mathieu and modified Mathieu functions with unknown expansion coefficients. These unknown coefficients are determined by enforcing appropriate boundary conditions at the interface between the dielectric and free space regions and at the slotted elliptic cylinder. The result is an infinite system of simultaneous equations. In order to generate numerical results and from a practical point of view the series solution must be truncated in a suitable fashion to obtain a finite size matrix. The order of such a matrix depends on the electrical size and property of the coating region as well as the degree of required accuracy from the solution. This technique has been used to extend the formulation for a single slot antenna on an elliptic cylinder coated with a confocal dielectric layer (J. H. Richmond, IEEE Trans Antennas Propagat., vol. AP-37, pp. 1235-1241, 1989) to the present general case of a single slot or array of slots with a non-confocal coating.

The theory and quantitative results of the radiated far-field for different core and coating sizes will be presented to illustrate the effect of coating material on the radiation pattern of the antenna.

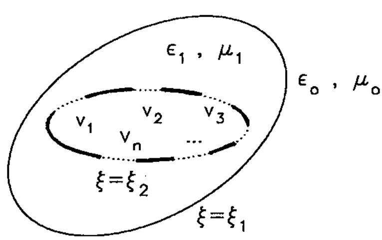

Fig. 1: Array of N axial slots on elliptic cylinder with dielectric coating.

MUTUAL COUPLING EFFECTS IN NEEDLE ARRAYS

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Past work has shown that scattering from a random collection of arrays of needles differ dramatically from scattering by an equivalent random collection of single needles. The results indicate that the spatial correlation between needles in each array leads to an increased backscatter. This finding shows that the correlation effects between needles in conifer canopies must be taken into account.

In the previous, work mutual coupling effects between array elements have not been considered. These effects will be accounted for here. The needle array is modeled by a periodic structure consisting of finite circular lossy dielectric cylinders. The field inside the individual cylinders is found by analyzing an infinite array of infinitely long dielectric cylinders by Floquet techniques. The methods employed follow closely those used by Twersky (IRE Trans. AP-10, 737-765, 1962) but have been generalized to three dimensional incidence wave configurations. The formulation leads to a pair of infinite systems of equations for the unknown coefficients. These equations are solved by approximate techniques in the limit where the array period is small compared to the wavelength.

Scattering amplitudes for the needle array are calculated by approximating the internal fields in the needle array by those in the infinite array of infinitely long cylinders. Calculations are made is the frequency range between L and X bands. The importance of accounting for mutual coupling is discussed. In addition, the approximation of the array by an equivalent dielectric disc will also be commented upon.

RADIATION AND WIDE-BAND SCATTERING OF PROBE-FED RECTANGULAR PATCHES INFINITE ARRAY ON MULTILAYER DIELECTRIC SHEET

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There is, at present, a trend toward use of "skin" antennas, among which patches are certainly the most popular. Accurate calculation of the scattering diagram of such an antenna in a much wider frequency band than its operating one should be taken into account in the design step for purpose of its coupling evaluation with nearby scatterers.

Here we deal with probe-fed rectangular patches laid out in a plane, infinite, periodical in two dimensions phased array. Probes are assumed infinitely thin and much shorter than wavelength. The substrate and the superstrate (above the patches) are multilayered dielectric sheet. In the radiation problem, quantity of interest is input impedance versus scanning angle and frequency. In the scattering problem, the array is loaded by a given impedance and illuminated by an incident plane wave. Relevant outputs are power absorption by the load and scattering diagram of the array, keeping in mind that the higher-order grating modes get the latter very complex with their frequency scanning.

Moments method is used. Current on the patches is expanded on a set of trigonometric basis functions. Scattered field, through Poisson formula, is expressed with series induced by the discretization of dyadic spectral Green functions the terms of which are similar to Floquet modes.Total electric field in all space and particularly on the patches includes fields scattered by both patches and probes and incident plus reflected fields which would exist if the patches were absent and which are directly calculated by transmission line theory. Equating to zero its tangential components on the patches results in a linear system the solution of which is a set of unknown current expansion coefficients from which all the relevant quantities will be yielded.

Software is validated through power balance, convergence and reciprocity tests. Typical curves of scattered power versus frequency, including specular reflection and higher order diffractions, are shown and analysed. In the analysis, we will emphasize the influence of the substrate and the superstrate properties on the radiation and scattering diagram, and will show comparisons between theory and measurements.

MULTIPORT NETWORK MODEL FOR TWO-PORT GAP-COUPLED RECTANGULAR MICROSTRIP PATCHES COVERED WITH A THICK DIELECTRIC LAYER

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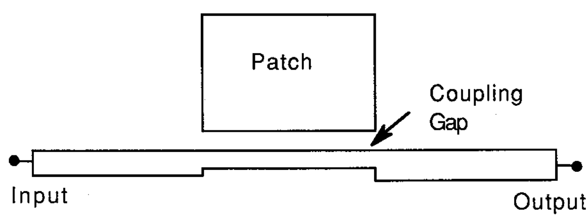
Two-port rectangular microstrip patches have been widely used as elements of series-fed arrays. The power radiated by individual patches is often controlled by varying the width of the patch. For series-fed arrays with low side lobe levels, the first few elements are required to radiate a very small fraction of the input power. For these elements, the width of the patch becomes very small. However, the smallest width that can be used is limited by fabrication techniques. Furthermore, the conductor loss associated with narrow patches is high and reduces the overall efficiency of the array. An alternative configuration which yields low values of power radiated without reducing the width of the patch is the gap-coupled two-port rectangular microstrip patch (shown in the Figure below).

The multiport network model (MNM) for radiating microstrip patches has been used for the analysis and design of two-port gap-coupled rectangular microstrip patches without a dielectric cover layer (A. Benalla and K. C. Gupta, IEEE AP-S Symposium 1991, London, Canada). In this paper, this multiport network model is extended to the analysis of such patches with a dielectric cover layer. In this case, the edge admittance and mutual coupling networks are derived from the electromagnetic analysis of a magnetic current element on a ground plane and covered with a dielectric layer. The MNM procedure developed for gap-coupled patches has been verified by comparing the calculated results with the moments method approach.



INFLUENCE OF TAPERING COEFFICIENT ON THE RADIATION PATTERNS OF A LINE SOURCE

P. Mallikarjuna Rao*, G.S.N.Raju and K.R.Gottumukkala, College of Engineering, Andhra University, Visakhapatnam-530 003, India.

The radiation patterns of an aperture is shaped depending on the application. For instance, the radiation patterns with minimum beam width of the mainlobe and low side lobes are generated from high range resolution radars. These types of beams are also used in point-to-point communication systems. The beam width as well as the sidelobes are controlled by the aperture distribution consisting of both amplitude and phase functions. It is already established in the literature that a linear and uniformly excited array yields a radiation pattern with the first sidelobe level of about -13.5dB. This is found to be reduced using tapered amplitude distributions. However, each type of tapering results in a radiation pattern with different sidelobe structure. It is, therefore, useful to study the radiation characteristics of an aperture for different tapered distributions.

In the present work, a cosine on pedastal type of distribution with a tapering coefficient varying from 0 to 1 is considered to study the nature of the variation of the beam width of the mainlobe and different sidelobes and their levels in the entire visible region. The radiation patterns are computed numerically for different array lengths and tapering coefficients. The beam width of the mainlobe, first, second and last sidelobe levels are presented in the following table as a function of array length and tapering coefficient. The results of this paper are extremely useful for the design of an array antenna for any type of application which demands a specific radiation pattern. The amplitude distribution considered in this work is useful and simple in the sense that the nature of tapering is entirely controlled simply by a coefficient instead of complex mathematical functions.

Radiation Characteristics

	Array Length = 25 λ				Array Length = 50 λ			
Tapering Coefficient	1st side lobe [dB]	2nd side lobe [dB]	Last side lobe [dB]	Beam-width	1st side lobe [dB]	2nd side lobe [dB]	last side lobe [dB]	Beam-width
0.0	-13.45	-18.09	-37.75	0.08	-13.45	-17.90	-44.06	0.037
0.2	-17.3	-20.26	-39.74	0.09	-17.3	-20.26	-45.64	0.046
0.4	-23.60	-23.6	-42.49	0.101	-23.6	-23.60	-48.4	0.078
0.6	-28.72	-29.90	-45.64	0.161	-28.72	-29.90	-51.93	0.078
0.8	-38.75	-39.15	-51.93	0.161	-38.75	-39.15	-57.84	0.078

RADIATION FIELDS FROM TWO-WIRE TRANSMISSION LINE ANTENNAS

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The family of antennas analyzed and described in this paper are fabricated from two parallel linear perfectly conducting, infinitely thin wires. Spacing between antenna elements is much less than the source wavelength. The excitation current is constant along the wires, and is flowing in opposite directions.

The family of these antennas are generated by varying the length of the pair of parallel wires. When their lengths are very short compared with the source wavelength, the antennas are known as a pair of infinitesimal dipoles, or Hertzian dipoles. With intermediate lengths, the antenna are similar to wave antennas ([1] H.H. Beverage, C.W. Rice, and E.W. Kellogg, "The Wave Antenna," AIEE Transactions, Vol. 42, pp. 215-266, 1923) developed by H.H. Beverage, transmission line antennas, and horizontal antennas buried in Antarctica ice and snow ([2] A.W. Biggs, "Radiation Fields from an Electric Dipole in Homogeneous Antarctic Terrain," IEEE Transactions, Vol. AP-16, pp. 201-208, March 1968). The wave antenna, or Beverage antenna, is a single long low wire over an earth ground plane. It was erected both on Long Island and in Fife, Scotland, in 1923.

Transmission line antennas are single wires above perfectly ground planes so that the single lines and their images form a parallel two wire transmission line. These are encountered with coaxial feeds on aircraft, where the outer conductors terminate on the aircraft surface and the inner conductor continues slightly and then bends to be parallel with the surface. The terminations may be short circuits, open circuits, mismatched, or matched loads. Matched loads simulate the constant current excitation, while the other loads introduce standing waves.

When the lengths increase to several wavelengths, the broadside or main lobe increases in magnitude, side lobes also increase in both number and magnitude, and both mainlobe and sidelobe beamwidths decrease. As the antenna lengths approach infinity, the mainlobe and sidelobe beamwidths approach zero, and the mainlobe increases in the form of a Dirac Delta function. Infinite wire antennas are included for comparison only, since the infinite wire pair cannot currently be realized in practice.

Antenna patterns are presented for the varying finite lengths described above.

Tuesday AM URSI-B Session TA10

Room: Columbus G *Time*: 0830-1200

Symmetry, Scaling and Groups I

Organizer: Dwight L. Jaggard, University of Pennsylvania
Chairs: Dwight L. Jaggard, University of Pennsylvania; Ross A. Speciale, General Dynamics Company

0830 **INTRODUCTORY COMMENTS**

0840 **SYMMETRIES of DUALITY, RELATIVITY, and THEIR COMBINATION**
Carl E. Baum*, Phillips Laboratory

0900 **APPLICATIONS of GROUP THEORY in SCALAR DIFFRACTION and ARRAY THEORY**
James E. Richie*, Marquette University

0920 **A CONJECTURE on the POLARIZABILITIES of a PLANAR APERTURE**
K. S. H. Lee*, Kaman Sciences Corporation

0940 **ON KNOTS, BRAIDS and ELECTROMAGNETISM**
Dwight L. Jaggard*, University of Pennsylvania

1000 **Break**

1020 **TOPOLOGY of KNOTS and LINKS and CAVITY RESONATORS**
Mamdouh M. I. Saadoun*, Nader Engheta, University of Pennsylvania

1040 **SECTORED CYLINDRICAL CAVITY RESONATORS**
Ross A. Speciale*, General Dynamics Company

1100 **SCALED ELECTROMAGNETIC PROPAGATION: NON INTEGER DERIVATVE and HYPERBOLIC GEOMETRY**
F. Heliodore*, Alcatel Alsthom Recherche; P. Riot, STCAN; A. Le Mehaute, Alcatel Alsthom Recherche

1120 **ON the ROLE of NON-INTEGRAL (FRACTIONAL) CALCULUS in ELECTRODYNAMICS**
Nader Engheta*, University of Pennsylvania

1140 **NONLINEAR DYNAMICAL BEHAVIOR of FIELDS and CURRENTS in TED'S at MICROWAVE FREQUENCIES**
Clifford M. Krowne*, Naval Research Laboratory; Clement W. Skorupka, Susquehanna University

SYMMETRIES OF DUALITY, RELATIVITY, AND THEIR COMBINATION

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Besides the symmetries present in an electromagnetic object (antenna, scatterer, etc.) there are symmetries inherent in the Maxwell equations themselves (C.E. Baum and H.N. Kritikos, Symmetries in Electromagnetics, Physics Note 2, December 1990). These latter symmetries are important in themselves and can be used in combination with the geometric symmetries. One of these symmetries is that of duality, the symmetry on interchange of electric and magnetic quantities. This is formally represented in the combined field, $\vec{E}_q = \vec{E} + qjZ_o\vec{H}$ with $q = \pm 1$, and similar combined quantities (current densities, etc.). This leads to various concepts such as dual forms of the equivalence and reciprocity theorems. It also leads to the Babinet equivalence by simple multiplication by the imaginary (j), and to the generalized form of self-complementary antennas and scatters.

In special relativity the 4-dimensional coordinate can be written in the form $\underline{r}_p = (\vec{r}, pjct)$ with $p = \pm 1$, and the 4-current density and 4-potential can be similarly written. The skew-symmetric 4x4 field tensor can be written using the combined field using both separation indices p and q. This gives a field tensor with only three distinct elements which is pq ($=\pm 1$) times its own dual and has eigenvalues $\pm[E_q \cdot E_q]^{1/2}$ (with zero trace), thereby giving a more simple and compact representation. Reversal of the signs of q and p corresponds to space (or magnetic field) and time reversal respectively. The combination pq gives a higher symmetry combining these, and considerably simplifies the formulas.

APPLICATIONS OF GROUP THEORY IN SCALAR DIFFRACTION AND ARRAY THEORY

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The solution to electromagnetics problems has been simplified through the application of symmetry principles pertaining to simple physical symmetry. More recently, self-similar symmetry has been developed into a useful analytical tool. The vehicle necessary to formalize symmetry relations is group theory. The use of group theory has the potential to expose information essential to the solution of a problem. For example, space groups have been extensively used in quantum mechanics for the crystalline solid state. Energy band calculations rely on group theory to make solutions possible. The use of group theoretical concepts, however, has not been extensively studied for electromagnetic applications. Valuable qualitative insight regarding the solution to a complex problem may be obtained using group concepts. In addition, placing symmetry concepts within the initial formulation of the problem may lead to further insight pertaining to a particular problem.

The symmetries inherent in Maxwell's equations allow for the effective use of group theory. In electro-magnetics, our predominant application will be to bridge this mathematical symmetry with the physical geometry. In this paper, the essential concepts for group theory will be presented. Scalar diffraction theory will be cast in a group theory format by applying the concepts introduced. Examples will be provided that illustrate the bridge between the mathematical and physical symmetries. Finally, array theory will be presented as a specific case of scalar diffraction theory.

A CONJECTURE ON THE POLARIZABILITIES OF A PLANAR APERTURE

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Abstract

The conjecture is, the inverse of the electric polarizability, α_e, is equal to or greater than the sum of the inverse of the two principal magnetic polarizabilities, α_{mxx} and α_{myy}, namely

$$\frac{1}{\alpha_e} \geq \frac{1}{\alpha_{mxx}} + \frac{1}{\alpha_{myy}} \tag{1}$$

The equality sign is shown to hold for elliptic and circular apertures.

This paper first reviews the background that has led to this conjecture: a suggestive example offered by a cross aperture and the numerical work of Latham and De Smedt and Van Bladel on apertures of shape other than elliptic. The conjecture is then proved, by virtue of the variational principle, for apertures with two axes of symmetry . Finally, by an application of the optical theorem and the causality principle a weaker conjecture is proved, namely

$$\frac{2}{\alpha_e} \geq \frac{1}{\alpha_{mxx}} + \frac{1}{\alpha_{myy}} \tag{2}$$

The derivation of (2) is based on the exact solution to the boundary-value problem of calculating the total energy transmitted by a step-function plane wave through an aperture of arbitrary shape. It can be shown that the transmitted energy is equal to twice the difference between the magnetic energy stored in the induced magnetic dipoles and the electric energy stored in the induced electric dipole. With this exact solution one can immediately deduce (2).

ON KNOTS, BRAIDS AND ELECTROMAGNETISM

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The blending of electromagnetic theory with concepts of knots and braids appears to have its origins in the mid nineteenth century when the question of flux linkages by circuits was first addressed. In that case, the question of the magnetic flux captured by a wire helix was investigated. More recently, the topology of knots and braids has become linked with a number of concepts in pure and applied science. These range from the knotted path of of the periodic orbit of the Lorentz attractor, to quaternions, the structure of DNA, and quantum field theory.

Here be briefly review selected portions of the history of knots and braids and introduce Artin's theory of knots and the Jones algebra for describing knots and appropriate concepts of groups for knots and braids. This will be followed by an examination of several braided and knotted structures and their interaction with electromagnetic fields.

As an example, consider the knots shown below. A knot is chiral, if it is topologically distinct from its mirror image. (Are these knots chiral or achiral?) By an examination of the forces induced in chiral knots through direct currents, it appears that these structures become less chiral under the influence of an external field. Thus we conjecture that the chirality of knots tends to decrease under the influence of static external fields in a similar manner that of braids [for the latter, see D. L. Jaggard, A. R. Mickelson and C. H. Papas, "On Electromagnetic Waves in Chiral Media," *Appl. Phys. 18*, 211-216 (1979)].

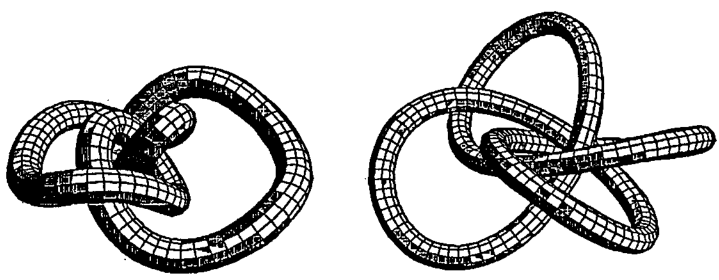

Figure eight knot (left) and torus knot (right) as examples of common knots.

Likewise we consider the effect of time-varying fields on knotted and braided structures with respect to propagation and scattering. The relation of scattered fields to the topology of these objects is explored here, perhaps for the first time.

TOPOLOGY OF KNOTS AND LINKS AND CAVITY RESONATORS

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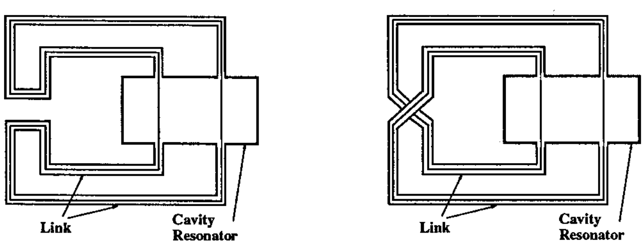
The theory of *knots* and *braids* has been an active branch of topology in mathematics. There has been a considerable amount of work done in this area with regard to various representations of knots and braids and group theoretical approach to such topological problems [R. H. Crowell and R. H. Fox, *Introduction to Knot Theory*, Blaisdell Pub., 1963]. The mathematical foundations built for the knot theory have been shown to be very fruitful in describing several phenomena in physics and there have been interesting connections between these two fields [L. H. Kauffman, *Knots and Physics*, World Scientific Pub. 1991]. In general, these mathematical tools can have potential applications in those branches of physics involving topology. One such branch is electrodynamics. There has been great interest in exploring the role of general topology of structures in electromagnetic interaction of complex systems [F. C. Yang & C. E. Baum, Electromagnetic topology: Measurements and norms of scattering parameters of subshields, *Electromagnetics*, 6, 1986]. However it would be interesting to examine how the geometry of knots and links can be connected to electromagnetic phenomena and how their mathematics can be applied to electromagnetic problems.

In this talk, we examine the role of another form of topology, namely topology of knots and links in electrodynamics and present certain examples in which such topology plays a major role. As an illustrative example, we consider a circular cavity resonator which is connected to a closed-loop transmission line to form a knot. The connecting link can have several different configurations as shown in Figure below. We study the effects of different configurations (topology) of this link on such electromagnetic phenomena as cavity field distributions, resonance frequency, stored energy, etc. The connections between the mathematics of knots and these electromagnetic phenomena are explored and addressed. Potential applications of this study in the design of microwave devices and components are also mentioned.



Cavity resonator connected to a closed-loop of transmission line to form a knot. Two possible configurations of the link (or two different knots) are shown here. Relations between the topology of knots and electromagnetic properties of the cavity are discussed.

SECTORED CYLINDRICAL CAVITY RESONATORS

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ABSTRACT

Cylindrical cavity resonators, with either four or six external ports symmetrically located around the cylinder axis, are analyzed as sectored ring-resonators. Circuit models are used, that include either four or six mutually identical cylindrical cavity-sectors, with either 90° or 60° azimuthal angular span, that are sequentially connected around the cylinder axis.

Each of the cylinder sectors is represented as a reciprocal, and symmetric three-port black-box network, and includes one of the resonator external ports on its radial reflection-symmetry plane.

A classical linear multiport network analysis treatment of the problem leads to: a) An independent confirmation of prior results, and b) A very extensive set of new mathematical expressions, that fully describe the propagation of guided electromagnetic waves through electrically-large, two-dimensional clusters of identical, directly-coupled, cylindrical cavity resonators, with either a square or an hexagonal cluster lattice.

Each of the four or six sectors of either a four-port or of a six-port cylindrical cavity resonator, one that exhibits both rotational and reflection-symmetries (Speciale, ACES 1989 & 1991), is represented as a reciprocal, and symmetric (but not necessarily lossless) three-port black-box network (Fig. 1). The ports of all sectors are sequentially numbered, in cyclic order around the cylinder axis, with port 2 of each sectors representing one of the resonator external ports. The ports 1 and 3 of each resonator represent the internal, radial reference planes through the cylinder axis, that: a) Define the azimuthal location and angular span of each sector, b) Are azimuthally spaced by either 90° or 60°, halfway between external ports, and c) Are axial reflection-symmetry planes for the whole cylindrical resonator.

The assumed reciprocity and symmetry of the sectors implies a doubly-symmetric structure for the otherwise unknown 3 x 3 impedance matrix Z_S of each sector. This symmetry, with respect to both matrix diagonals, reduces the number of different matrix-entries from nine to only four. The Z-matrices of the resonators are circulant.

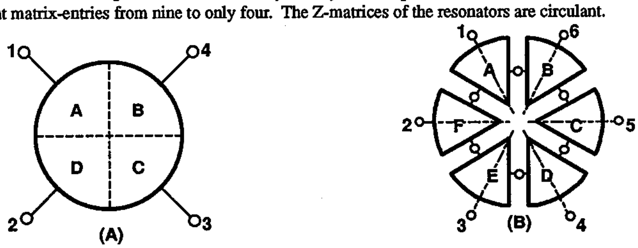

Figure 1 – Sectored, Reciprocal, Four-Port, C_{4V}-Symmetric, and Six-Port, C_{6V}-Symmetric Cavity Resonators.

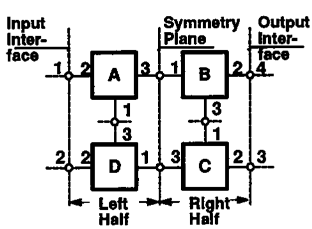

Figure 2 – Network Interconnection of the Four Sectors of a C_{4V}- Symmetric Cavity Resonator.

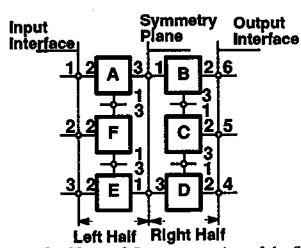

Figure 3 – Network Interconnection of the Six Sectors of a C_{6V}- Symmetric Cavity Resonator.

SCALED ELECTROMAGNETIC PROPAGATION: NON INTEGER DERIVATIVE AND HYPERBOLIC GEOMETRY

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The main assumptions which allow one to describe wave phenomena both in relativistic and non-relativistic cases will be reviewed. The limitation of the Maxwellian formalism will be shown in the case of fractal geometry and the origin of the discrepancy will be given.

The mathematical foundations of electromagnetic theory will be established in terms of differential geometry. The use of exterior algebra allows one to summarize electromagnetic phenomena in a concise point of view through diagrams revealing, in particular, the links with co-homology spaces.

In relation with algebraic topology, it will be shown how the parameterization of a fractal space can be described using Schwartz generalized functions which lead, in reciprocal space, to the introduction of the non-integer derivative.

A functional analysis, based on adequate operators, is developed which may open a timely new point of view to analyze wave propagation in heterogeneous media and give new electromagnetic invariants taking in account the non-integer characteristics of the dimension of the space.

A clear relationship will be made between hyperbolic geometry and non-integer derivative. It will be finally shown that the imaginary radius of curvature of this geometry is related to the imaginary time vectorial component already designed as the expression of the irreversible time and more generally speaking, leads to the introduction of new relativistic concepts associated with scale dependence.

ON THE ROLE OF NON-INTEGRAL (FRACTIONAL) CALCULUS IN ELECTRODYNAMICS

Nader Engheta

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The idea of non-integer or fractional differentiation and integration has been around for many years and has been shown to have important applications in formulation of certain electrochemical problems [K. B. Oldham and J. Spanier, *The Fractional Calculus*, Academic Press, New York, 1974.]. Since in electrodynamics, we deal with differential and integral operators on vector field quantities **E**, **B**, **D** and **H**, it would be interesting to explore the concept of non-integer (fractional) calculus in electrodynamics, and study the possible implications of use of such mathematical techniques in electromagnetic problems. For instance, the idea of impedance with non-integer dimension was introduced by Le Méhauté and Heliodore to describe interaction of waves with fractal interface, and this idea has suggested some fractional differentiation between electric and magnetic fields [Le Méhauté A. and Heliodore, F., "Introduction to Fractional Derivatives in Electromagnetism: Fractal Approach of Waves/Fractal Interface Interactions," *Proc. of Progress in Electromagnetics Research Symposium (PIERS,89)*, p. 183, 1989]. Furthermore, a fractional differential relation between electric and magnetic field was also discussed for electromagnetic wave propagation in lossy media [N. Engheta, Continuous Dimensionality in Electrodynamics: Non-integer Vector Calculus in Electromagnetic Problems and Its Potential Applications," *Proc. of Progress in Electromagnetics Research Symposium (PIERS,89)*, p. 183, 1991]. The idea of continuous dimensionality was also considered extensively in von Neumann algebras, which has played an important role in the mathematical structure of quantum physics, and also in relating certain areas of abstract mathematics, such as the knot theory with statistical mechanics.

The motivation behind this study, besides the academic curiosity, is to explore new ways of describing and analyzing electromagnetic properties of materials and heterogeneous composites with fractal properties. In this talk, the concept of fractional calculus will be reviewed, and the role of such mathematical tools in electrodynamics will be explored and discussed. A possible extension of the definition of vector operators such as gradient, divergence, and curl with non-integer (fractional) operators will be mentioned. Potential applications of this technique in wave propagation in composite media will also be addressed.

NONLINEAR DYNAMICAL BEHAVIOR OF FIELDS AND CURRENTS IN TED'S AT MICROWAVE FREQUENCIES

Clifford M. Krowne and Clement W. Skorupka

Code 6850.3 Microwave Technology Branch, Electronic Science and Technology Division, Naval Research Laboratory, Washington, D.C. 20375-5000, and Dept. of Physics and Astronomy, Susquehanna University, Selinsgrove, PA 17870

Microwave devices are nonlinear dynamical systems. In the past decade an array of powerful time-series-analysis techniques have emerged to model, characterize (T.S. Parker and L.O. Chua, IEEE Proc. vol. 75 no. 8 p. 982-1008, aug 1987), and exploit (T.L.Carrol and L.M. Pecora, IEEE Trans. on Circuits and Systems, vol. 38, no. 4, April 1991 p. 453 - 456) a range of nonlinear behavior in simulations as well as experiment. Many simple physical systems such as the pendulum exhibit such strongly nonlinear behavior as chaos. Semiconductor microwave materials and devices have no lack of nonlinearities, and the field is wide open for the identification and possible exploitation of a variety of previously unobserved or overlooked behaviors.

We will present a brief introduction to nonlinear dynamical behavior of driven, dissipative systems. Topics to be discussed will include strange attractors, fractal dimension, sensitivity to initial conditions, and Lyapunov exponents. The recently experimentally realized phenomenon of strange nonchaotic behavior will be discussed (W.L. Ditto, M.L. Spano, et al, Physical Review Letters, v65 p. 533, 1990).

We will then bring the methods of nonlinear systems theory to bear on our specific problem of interest: the electron transport, electromagnetic fields, and terminal current and voltages for a transfered electron device (TED). We have developed a time dependent model of the TED, derived from drift, continuity, and Gauss's law applied to a one-dimensional semiconductor. The main source of nonlinearity is the velocity-electric field characteristic. We perform a mode expansion of the electric field and develop a set of coupled ordinary differential equations. We study the time behavior of a truncated set of the electric field modes by numerical integration. The model is subjected to a variety of external drives (time dependent boundary conditions), and we characterize the behavior using fractal dimension and Lyapunov exponents.

We will discuss some of the guidelines for experimental studies of time series behavior of microwave systems, and factors that limit estimates of fractal dimension and Lyapunov exponent such as noise, and sampling rate and precision of commercially available Analog to Digital Converters.

Tuesday AM URSI-B Session TA11

Room: Columbus H *Time*: 0820-1200

Finite Element/Hybrid Methods

Chairs: Y. Rahmat-Samii, University of California, Los Angeles; T. Cwik, Jet Propulsion Laboratory

0820 **APPLICATION of PHYSICAL OPTICS HYBRID METHOD (POHM) : MULTI ELEMENT RADIATORS on LARGE BODIES**
R. E. Hodges*, Y. Rahmat-Samii, University of California, Los Angeles

0840 **COUPLING FINITE ELEMENTS and INTEGRAL EQUATIONS to MODEL THREE DIMENSIONAL SCATTERING and RADIATING STRUCTURES**
T. Cwik*, V. Jamnejad, Jet Propulsion Laboratory

0900 **COUPLING of FINITE ELEMENT and MOMENT METHODS for ELECTROMAGNETICS MODELING in TIME DOMAIN**
L. J. Bahrmasel*, McDonnell Douglas Research Labs; D. S. Wang, McDonnell Douglas Research Laboratories

0920 **EFFICIENT IMPLEMENTATION of EXACT BOUNDARY OPERATORS for the FINITE ELEMENT METHOD**
Stephen D. Gedney*, University of Kentucky

0940 **FINITE ELEMENT MESH GENERATION on MIMD COMPUTERS for EM SCATTERING PROBLEMS**
R. D. Ferraro*, Barbara A. Zimmerman, Jet Propulsion Laboratory

1000 **Break**

1020 **AN ELEMENT-BY-ELEMENT A POSTERIORI ERROR ESTIMATION and IMPROVEMENT APPROACH for the FINITE ELEMENT ANALYSIS of THREE-DIMENSIONAL ELECTROMAGNETIC BOUNDARY VALUE PROBLEMS**
U. Pekel*, Robert Lee, The Ohio State University

1040 **CONVERGENCE ACCELERATION by PRECONDITIONING a BLOCK QUASI MINIMUM RESIDUAL METHOD for a FINITE ELEMENT FORMULATION of ELECTROMAGNETIC SCATTERING**
W. E. Boyse, A. A. Seidl*, Lockheed Palo Alto Research Laboratories

1100 **AN ITERATIVE SOLVER for MULTIPLE RIGHT HAND SIDES BASED on the BLOCK LANCZOS ALGORITHM**
W. E. Boyse*, A. A. Seidl, Lockheed Palo Alto Research Laboratories

1120 **AN EXAMINATION of TIME INTEGRATION TECHNIQUES for MAXWELL EQUATIONS**
L. J. Bahrmasel*, R. A. Whitaker, McDonnell Douglas Research Labs

1140 **A ONE DIMENSIONAL NUMERICAL STUDY on the EFFECT of BOUNDARY CONDITIONS on DISCRETIZATION ERROR for FEM**
Y. S. Choi*, Robert Lee, Ri-Chee Chou, The Ohio State University

APPLICATION OF PHYSICAL OPTICS HYBRID METHOD (POHM): MULTI ELEMENT RADIATORS ON LARGE BODIES

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One of the most difficult problems in electromagnetics is the analysis of electromagnetic radiation and scattering in the presence of large complex bodies. In many practical radiation problems one finds a complex radiating structure, such as a Yagi antenna, mounted on a curved but relatively smooth object such as an airplane fuselage. In earlier work we have demonstrated that a hybrid technique which combines the strength of PO and MM is capable of providing an accurate solution to this class of problems. However, there is still a need for further refinement of the technique so that it provides better accuracy in regions which are not adequately described by PO and is still too large to be handled by the Moment Method. The most common example of this is the region of an object which lies on the boundary between the complex antenna (analysis by MM) and a large, smooth region which is adequately characterized using PO.

This paper presents an overview of our work on improving the accuracy of the Physical Optics Hybrid Method (POHM). There are two aspects to this. First, since the computer time required for solution of an n by n matrix increases as n^3 while fill time increases as n^2 it is clear that solution time dominates over fill time. More significant is the fact that the stability of the matrix equation degrades as the matrix size increases. For finite precision computer arithmetic, the maximum size of the Moment Method region may be extended using Canning's Impedance Matrix Localization (IML) method. This paper shows the results of our efforts to employ IML in the transition region between the "pure" Moment Method and the PO regions. Finally, some example calculations are presented to further demonstrate the potential of POHM. We will present results to show multi-element wire antennas mounted on a finite ground plane and a truncated cone structure.

Coupling Finite Elements and Integral Equations to Model Three-Dimensional Scattering and Radiating Structures

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The usefulness of finite element modeling follows from the ability to accurately simulate the geometry and three-dimensional fields on the scale of a fraction of a wavelength. To make this modeling practical for engineering design, it is necessary to integrate the stages of geometry modeling and mesh generation, numerical solution of the fields, and display of field information. The stages of geometry modeling, mesh generation, and field display are commonly completed using commercially available software packages. Algorithms for the numerical solution of the fields need to be written for the specific class of problems considered. Interior problems, i.e. simulating fields in waveguides and cavities, have been successfully solved using finite element methods. Exterior problems, i.e. simulating fields scattered or radiated from structures, are more difficult to model because of the need to numerically truncate the finite element mesh. To practically compute a solution to exterior problems, the problem domain must be truncated at some finite surface where the Sommerfeld radiation condition is enforced, either approximately or exactly. Approximate methods attempt to truncate the mesh using only local field information at each grid point, whereas exact methods are global needing information from the entire mesh boundary. This paper outlines a method that couples three-dimensional finite element solutions interior to the bounding surface with an integral equation solution that exactly enforces the Sommerfeld radiation condition.

The use of surface integral equations to truncate the computational mesh used in finite element modeling is proving to be a useful method to model electrically large and inhomogeneous objects. The finite element model is used in inhomogeneous or irregular regions to provide a local description of the fields and material parameters. The surface integral equation is used to model fields in the homogeneous region exterior to the object and incorporates the radiation condition exactly. The surface is taken to reside directly on the object, and the surface tangential fields are the unknown quantities in the integral equation. By matching field boundary conditions through the surface, fields are coupled from the interior to exterior regions, and a system of equations is formed which can be solved by various means. Radiated or scattered fields are easily computed from the calculated surface fields. Depending on the type of problem considered, computational requirements vary.

Work is currently underway to model frequency selective surfaces (FSS's), waveguide horn systems, and arbitrary scatterers. When examining FSS's, which could include dichroic plates made of apertures in metal plates, the region modeled by finite elements consists of one periodic cell and is typically on the order of one cubic wavelength. The bounding mesh surface is on the order of two square wavelengths. Waveguide horn systems can be somewhat larger, especially when many waveguide components are modeled simultaneously with the horn, and, the bounding mesh surface is also larger. Scatterers can be arbitrarily large, simply depending on the size of the object in wavelengths. Results of this modeling will be presented.

COUPLING OF FINITE ELEMENT AND MOMENT METHODS FOR ELECTROMAGNETICS MODELING IN TIME DOMAIN

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Many physically meaningful electromagnetic problems require knowledge of time-varying solutions to Maxwell's equations. Among these are problems in the areas of remote sensing, electromagnetic interference, and of course transient electromagnetic scattering. Due to the geometric and material complexities, partial differential equation methods such as the finite element method (FEM) are the most common choices for adequate modeling. However, the application of these methods to scattering problems requires the enforcement of a radiation boundary condition (RBC) on a finite computational domain. Typical radiation boundary conditions, either exact (J. B. Keller, D. Givoli, *J. Comput. Phys.*, 82, 172, 1988) or approximate (A. Bayliss, E. Turkel, *Commun. Pure and Appl. Math.*, 33, 707, 1980) require the extension of the computational domain from the target to a contour which circumscribes the target as well as a region that consists solely of free space. The size of the free space region may be quite large, especially for electrically large scatterers and hence the use of FEM methods can be computationally prohibitive.

Recently, we have developed a hybrid time-domain analysis in which we combined the FEM with a time-domain method of moments (TDMM) which enforces exact boundary conditions on the boundaries which coincide with the physical boundaries of the scatterer. This hybrid analysis substantially reduces the mesh domain required by the FEM analysis when the RBC is applied. The equivalence principle is used to separate the original problem into an exterior and an interior problem. The exterior problem dealing with a homogeneous region can be solved using a TDMM technique, while the interior problem with the geometric and material complexities is solved effectively with the FEM. Results will be presented comparing results from use of the hybrid scheme with previously published data.

EFFICIENT IMPLEMENTATION OF EXACT BOUNDARY OPERATORS FOR THE FINITE ELEMENT METHOD

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The finite element method (FEM) has proven to be a very robust technique for the computation of the electromagnetic fields radiated from or scattered by complex structures situated in an unbounded space. To practically treat such a class of problems using the FEM, the volume of discretization must be truncated to a finite domain via the introduction of an artificial boundary. Consequently, to uniquely solve for the radiated or scattered fields, a boundary operator which properly ensures the continuity of the electromagnetic fields across the artificial boundary must be introduced. A class of approximate boundary operators that have been successfully used are referred to as absorbing boundary conditions (ABC). However, when treating highly irregular shaped or multiple body structures, the separable boundaries often required by ABCs do not conform to the structure's surface, which results in a significantly large volume of discretization. This can lead to a substantial increase in the order of the sparse FEM matrix, as well as an increase in the discretization error. An alternate class of boundary operators, often referred to as global operators, are based on exact integral equation formulations. The advantage of these operators, is that the artificial boundary surface can exactly conform to the complex structure. Furthermore, multiple body systems can easily be treated using non-overlapping domains. The disadvantage of global operators, however, is that the sparsity of the FEM matrix can be disrupted.

In this paper, efficient methods for implementing global boundary operators based on surface integral equation (SIE) formulations are presented. It is assumed that the fields within the global domain are represented uniquely via finite elements. Therefore, an exact SIE operating on fields lying on an interior boundary can be used to compute the fields on the artificial boundary surface. The fields computed by the SIE are then enforced as a Dirichlet boundary condition on the artificial boundary. With this constraint, the FEM operator can be manipulated such that it results in a symmetric matrix that is largely sparse, except for the coupling between unknowns on the interior and the artificial boundaries. The solution of the symmetric matrix expression is then computed using an iterative method based on the preconditioned conjugate gradient (PCCG) method. It is shown that a highly effective and efficient preconditioner is the matrix representing the interior region of the global domain. An approximate solution of this highly sparse matrix is sufficient for the rapid convergence of the PCCG. It is shown that this method is quite computationally efficient and is well suited for multiprocessor super-computers. Furthermore, for large problems, methods to efficiently compute the dense block of the matrix due to the global boundary operator, which reduce the overall memory requirements, are discussed.

Finite Element Mesh Generation on MIMD Computers for EM Scattering Problems

Robert D. Ferraro and Barbara A. Zimmerman

Jet Propulsion Laboratory / California Institute of Technology

MIMD Computers such as the Intel iPSC/860 Gamma and Delta machines, and the NCUBE2 allow the solution of extremely large EM scattering problems using the finite element method. These machines consist of a collection of processors, each with their own compliment of main memory, connected together by a communication network. Due to the large compliment of memory available on such machines (on the order of Gigabytes), scattering problems involving millions of mesh points can now be solved in core. However, generating a finite element mesh of that size on a sequential computer and then inputing it to the parallel machine represents a serious I/O problem which limits the effectiveness of using parallel computers. The computer time required to construct the mesh on a fast workstation (if it is, in fact, possible) actually dwarfs the time to solve the problem on the parallel computer. Additionally, the I/O facilities available for transfering the mesh from the workstation to the parallel machine are inadequate to deal with the volume of data.

In order to avoid the problem, we are generating our scattering computation meshes on the MIMD machine. We have implemented, as a first step, parallel mesh refinement on an Intel iPSC/860 Gamma machine in conjunction with our Finite Element scattering codes. The domain of the scattering problem is coarsely meshed on a workstation at the density necessary to reproduce the geometry of the problem. Using quadratic elements, the number of elements required in the coarse mesh can easily be less than one per wavelength. This minimal mesh is then input to the parallel mesh refinement software. Each element is subdivided into a sufficient number of new elements to meet the mesh density required for accurate solution of the scattering problem. Use of isoparametric quadratic elements allows the curvature of the scattering geometry to be accurately retained during the subdivision process. The subdivided mesh is then repartitioned among the processors to achieve optimum load balance for the scattering computation.

We will describe the mesh refinement method and illustrate its usefulness on several finite element EM scattering problems. Parallel efficiency of the mesh refinement, and the overall efficiency and execution time to solution for large scattering problems will be presented.

Parallel mesh refinement has two drawbacks: a coarse mesh is required to begin with, and mesh density transitioning (as required, for example, in crossing boundaries between dielectrics of different permittivity) is problematic. We have also begun work on complete mesh generation in parallel, starting from only the geometry description. Progress on this project will also be reported.

AN ELEMENT-BY-ELEMENT A POSTERIORI ERROR ESTIMATION AND IMPROVEMENT APPROACH FOR THE FINITE ELEMENT ANALYSIS OF THREE-DIMENSIONAL ELECTROMAGNETIC BOUNDARY VALUE PROBLEMS

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The main cause of numerical errors in the finite element analysis of three-dimensional electromagnetic boundary value problems is the fact that the finite element method is based on the concept of discretization. This concept implies the expansion of the solutions for the electromagnetic fields in terms of a set of linearly independent shape functions, which are exclusively defined at the nodes of a particular master element. Although it is possible to improve the accuracy of the field solutions by increasing the nodal density or the order of the shape functions, these modifications will unavoidably result in a drastic decrease in the computational efficiency of the finite element analysis technique.

Instead, an element-by-element a posteriori error estimation and improvement approach (H. Ohtsubo and M. Kitamura, Int. J. Num. Meth. Eng. 29, 223-244, 1990) can be employed to improve the accuracy of the field solutions. In this approach, the element-wise computation of the error is based on the concept of self-equilibration of the residuals inside the elements, which results in a relatively simple procedure for the allocation of discontinuities in the relevant field components across interelement boundaries. The approach does not provide explicit asymptotic expressions for the error as the element size approaches zero, and also does not lead to theoretically valid upper bounds on the energy norm of the error, because the compatibility conditions between neighbouring elements are neglected. However, the numerical advantage of this approach is that once the error has been estimated on an element-by-element basis, it is simply added to the standard three-dimensional finite element solutions for the electromagnetic fields in order to improve the accuracy of those solutions, without the need to employ adaptive mesh refinement procedures which require a repetition of the entire solution process with the newly generated mesh. Consequently, the a posteriori error estimation and improvement approach does not require excessive additional amounts of computer memory or computational time.

CONVERGENCE ACCELERATION BY PRECONDITIONING A BLOCK QUASI MINIMUM RESIDUAL METHOD FOR A FINITE ELEMENT FORMULATION OF ELECTROMAGNETIC SCATTERING

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Using several preconditioning strategies we study the convergence properties of a block Quasi Minimum Residual (QMR) method for the sparse stiffness matrices resulting from a Finite Element (FE) formulation of electromagnetic scattering. The indefinite nature of these complex symmetric matrices makes the QMR method, which has a stable factorization algorithm for indefinite matrices, an attractive alternative to the more widely used Bi-conjugate Gradient method.

The preconditioners we examine consist of various incomplete factorizations of the FE stiffness matrix. These include two methods for dropping terms from the factor as it is computed. One drops all terms not within the structure of the original matrix while the second drops terms which are small compared to the diagonal. The former method has the advantage of using a static data structure. The latter method requires a dynamic data structure, since the structure depends on the numerics, but attempts to retain the more significant terms of the factor.

To monitor the convergence properties of the algorithm we compute at each iteration the equation residual and the solution residual as well as a quasi residual computed as part of the iteration. The solution residual is computed by comparing the iterated solution with a direct solution of the problem. A strong correlation of the quasi residual or, if necessary, the equation residual with the solution residual gives us confidence in using one or the other in stopping the iteration. Plots of residuals as a function of iteration number for various preconditioners will be presented to illustrate the convergence acceleration as well as the correlation among the residuals.

In order to choose a objective stopping point for the iteration we compare the far field cross section resulting from the QMR iteration with the cross section resulting from a direct solution of the same matrix problem. This comparison, for various stopping criteria, allows us to estimate the earliest iteration stopping point while maintaining accuracy in the far field cross section.

AN ITERATIVE SOLVER FOR MULTIPLE RIGHT HAND SIDES BASED ON THE BLOCK LANCZOS ALGORITHM

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Finite element discretizations of Maxwell's equations are becoming more prevalent for scattering applications. While iterative methods of solving the resulting large sparse systems work well for generating a few solutions, the computation of a monostatic radar cross section (RCS) involves the solution for many right hand sides and is the major numerical burden.

The Quasi Minimum Residual (QMR) method, developed by R. Freund, is an iterative solver of particular merit in solving the large sparse matrices occurring in the discretization of Maxwell's equations. It specifically addresses the complex symmetric indefinite nature of the matrices generated and provides for nearly monotonic residuals, facilitating the termination of the algorithm.

An extension of the QMR method is presented, based on the block Lanczos algorithm, which solves multiple right hand sides simultaneously in such a way that convergence is accelerated. The Lanczos algorithm is the basis for many iterative solution and eigenvalue methods. It's block generalization has been used to accelerate the convergence of eigenvalue problems. The adaptation of the block Lanczos algorithm to the QMR method involves converting vectors to matrices and scalars to matrices. The algorithm changes slightly due to the fact that matrices, unlike scalars, do not commute and the required block QR factorization differs significantly from the scalar case.

Numerical examples, showing acceleration of convergence with increased number of simultaneous solutions, are show. These examples come from finite element discretizations of Maxwell's equations in a hybrid finite element method code.

AN EXAMINATION OF TIME INTEGRATION TECHNIQUES FOR MAXWELL EQUATIONS

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During the past decade, much progress has been made in solving the time dependent Maxwell equations. From a numerical perspective, most of the emphasis has centered around the finite-difference-time-domain methods following the work of Yee (K. S. Yee, AP-14, 302-307, 1966). In performing the time integration, the most common method which has appeared in the literature has been the "leap-frog" method which is an explicit, central difference scheme with second-order accuracy. During the past twenty years, much work has gone into the development of robust, accurate and efficient ordinary differential equation solvers. It is this technology which we hope to take advantage of in the solution of the time dependent Maxwell equations.

To obtain a system of ordinary differential equations in time from Maxwell's curl equations, the method of lines is used. This is accomplished by spatially discretizing the curl operators which appear in Maxwell's curl equations leading to a system of coupled ordinary differential equations. The method of spatial discretization is independent of the choice of ordinary differential equation solver and is left to the discretion of the researcher. In our work, we have chosen to make use of the finite element method and have followed the lead of previous researchers by staggering the placement of the electric and magnetic field vectors within the mesh.

In this paper, we will examine the application of several methods of time integration of the ordinary differential equations which arise from applying the method of lines to Maxwell's curl equations in two-dimensions. Each will be evaluated in terms of robustness, accuracy, and efficiency. A number of problems amenable to analytic solutions will be used for comparison.

A ONE DIMENSIONAL NUMERICAL STUDY ON THE EFFECT OF BOUNDARY CONDITIONS ON DISCRETIZATION ERROR FOR FEM

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It is well known that one of the major sources of error in a finite element solution is discretization error (R. Lee, Radio Science Meeting, London, Ontario, 1991). In this earlier study of discretization error for the two dimensional wave equation, it was shown that the accuracy of the solution depends on the nodal density per wavelength, the electrical size of the medium, the choice of interpolation function, and the boundary condition. For the problem of electromagnetic scattering, the implementation of a boundary condition is complex and often inaccurate so that it is difficult to decouple the errors inherent in a given boundary condition from the discretization error. For the one dimensional wave equation, the boundary conditions are exact; therefore, we consider the one dimensional problem of a plane wave propagating in free space.

In this paper, we study the effects of five boundary conditions on the discretization error for the finite element method. These boundary conditions correspond to commonly used ones for the two and three dimensional wave equation. The essential (Dirichlet) and the natural (Neumann) boundary conditions are considered though they have limited applications to scattering problems. We also implement two types of exact absorbing boundary conditions, which are degenerate forms of boundary conditions in two and three dimensions. One is analogous to approximate absorbing boundary conditions such as the Bayliss-Turkel boundary condition, and the other is analogous to a hybrid integral equation/finite element boundary condition. The final boundary condition is the implementation of the bymoment method.

To show the effects of different boundary conditions on the discretization error, numerical solutions are generated for each boundary condition as a function of electrical size ($a = 1.2\lambda$, 3.6λ, 10.8λ), nodal densities ($\lambda/h = 5$, 10, 15, 20, 25, 30), and interpolation function (linear, quadratic, or cubic function).

Tuesday AM1 URSI-E, NEM Session TA12

Room: Columbus I/J *Time*: 0900-0940

EMP Environments and Extrapolation

Chair: W. Radasky, Metatech Corporation

0900 **A COMPLETE EMP ENVIRONMENT GENERATED by HIGH-ALTITUDE NUCLEAR BURSTS**
K.-D. Leuthauser*, Fraunhofer Institut fur Naturwissenschaftlich-Technische Trendanalysen (INT)

0920 **EXTRAPOLATION of EMP RESPONSES: an EXPERIMENTAL and ANALYTICAL STUDY**
C. L. Gardner*, S. Kashyap, M. R. Lauzon, J. S. Seregelyi, Defence Research Establishment Ottawa; J. J. A. Klaasen, TNO Physics and Electronics Laboratory

A COMPLETE EMP ENVIRONMENT GENERATED BY HIGH-ALTITUDE NUCLEAR BURSTS

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ABSTRACT

Very few papers are available in the open literature on high-altitude nuclear EMP fields offering detailed quantitative results for the whole variety of weapon related input parameters (i. e. gamma yield, energy and pulses shape) and scenario oriented quantities (i. e. height of burst, observer location with regard to Ground Zero).

Recently, the EXEMP code developed by the author was extensively employed for systematic variation of the above mentioned parameters. The present version of the code is self-consistent, i. e. solves the equation of motion of the Compton electrons in the presence of EMP generated electric and magnetic fields. Moreover, it comprises the following features

- exact energy-angle correlation for the Compton electrons (Klein-Nishina)
- exact ionization loss (Bethe-Bloch equation)
- inclusion of multiple ionization scattering effects (obliquity) in equation of motion
- electron mobility and avalanching dependent on air density-scaled electric fields
- ionization time lag for build-up of conductivity
- dipole earth magnetic field
- curved earth surface

The basic approximation is still the high frequency or outgoing wave approximation of the Maxwell equations in retarded time which are thus reduced to ordinary differential equations.

Equations of motion of Compton electrons, electron density rate equations and Maxwell equations are solved numerically by means of a fourth order Runge-Kutta algorithm.

The influence of the various input parameters on the incident electromagnetic fields will be extensively discussed, including 'smile-face' diagrams and plots showing pulse width, power per unit area and polarization dependent on observer location.

Extrapolation of EMP Responses:
An Experimental and Analytical Study

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ABSTRACT

Recently Klaasen (J.J.A.Klaasen, DREO Report 1076, May, 1991) has proposed a time-domain extrapolation technique based on the singularity expansion method (SEM). In the method developed by Klaasen, the experimentally measured EMP response of a system is extrapolated to that which would have been measured if the incident field had been a true double-exponential (Bell Laboratories) waveform.

In recent years, the double-exponential waveform has been criticised as being unrealistic at early times because the first derivative of this waveform is discontinuous at the onset of the pulse. This discontinuity is inconsistent with the physics of the fission process and the generation of prompt gamma rays during a nuclear explosion. To overcome this difficulty, other waveforms have been proposed of which the "new NATO" pulse (NATO EMP Engineering Practices Handbook, File No. 1460-3, 1989) is one of the most commonly used. Depending on the type of simulator used for experimental measurement and whether the equipment being measured is intended to be airborne or ground based, it may also be necessary to include or remove the effects of ground reflections during the extrapolation process.

In this paper we examine the extension of the method developed by Klaasen to allow extrapolation to more complicated incident waveforms such as the new NATO curve. We will present the results of various analytical studies that have been carried out and, in addition, the results of experimental studies exploring the extrapolation of measured responses from one input waveform to another.

Tuesday AM2 URSI-E, NEM Session TA16

Room: Columbus I/J *Time*: 1000-1200

EMP Interaction

Chairs: K. S. H. Lee, Donald P. McLemore, Kaman Sciences Corporation

1000 **ON the COUPLING of MICROWAVE RADIATION to WIRE STRUCTURES**
C. D. Taylor*, Mississippi State University; Charles W. Harrison, Jr.,

1020 **A SPECTRAL DOMAIN APPROACH to ELECTROMAGNETIC COUPLING THROUGH APERTURES**
A. B. Kouki*, A. Khebir, R. Mittra, University of Illinois, Urbana-Champaign

1040 **ELECTROMAGNETIC COUPLING THROUGH a ROW of AIRCRAFT WINDOWS for FREQUENCIES LESS THAN 100 MHZ**
Lothar O. Hoeft*, Joseph S. Hofstra, Ronald Karaskiewicz, BDM International, Inc.

1100 **FREMP COUPLING THROUGH an AIRCRAFT WINDOW**
Lothar O. Hoeft, Joseph S. Hofstra*, Ronald Karaskiewicz, BDM International, Inc.

1120 **RESPONSE of TYPICAL AIRCRAFT ANTENNNAE to FAST RISETIME EMP**
Lothar O. Hoeft*, David E. Thomas, Joseph S. Hofstra, Robert L. Hutchins, Ronald Karaskiewicz, BDM International, Inc.

1140 **ATTENUATING EM WAVE PENETRATION INTO a RESONANT CAVITY by AUGMENTING MULTIPLE MONOPOLES**
Gu Zeji*, Beijing Broadcasting Istitute

ON THE COUPLING OF MICROWAVE RADIATION TO WIRE STRUCTURES

by

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ABSTRACT

The general aspects of the interaction of wire structures with microwave radiation are considered. Receiving antenna theory is used for structures whose characteristic dimension is a few wavelengths or less. And transmission line theory is used for electrically long wire configurations.

A simple procedure is presented for bounding the response of wire structures that are not electrically long. This is achieved through using the receiving cross section. The maximum receiving cross section and radiation resistance are presented for obtaining the bounds on the general responses of a few canonical configurations - the center-loaded dipole, the circular loop antenna, the impedance loaded monopole, and the transmission line antenna. This formulation is valid until the structure dimensions approach several wavelengths.

The analysis of electrically long wire structures is accomplished by using transmission line considerations. Results are obtained for a terminated single wire oriented parallel to a nearby ground plane and for a two-wire transmission line. In both cases plane wave illumination is considered. Both simple formulas and data from a numerical analysis are provided. It is shown by comparing results from a general numerical solution to results obtained from transmission line theory that the TEM mode current is a suitable approximation for the wire current with line separations up to and exceeding a wavelength.

Measured results are also discussed. Coupling data for both shielded and unshielded wire configurations are analyzed. Finally, coupling to general wire configurations inside enclosures is discussed. This requires that coherence effects be considered.

A SPECTRAL DOMAIN APPROACH TO ELECTROMAGNETIC COUPLING TROUGH APERTURES

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The problem of electromagnetic coupling through apertures in perfectly conducting screens has received considerable attention ever since the early days of the electromagnetic era. Kirchhoff in 1891 used a scalar approach that was based on Huygen's principle and Green's theorem and concentrated on the high-frequency range where the aperture field was assumed to be essentially the same as the incident field. On the other hand, Lord Rayleigh in 1987, with his calculation of the fields in the vicinity of the aperture, postulated a wavelength approaching infinity, and thus provided the low-frequency counterpart to Kirchhoff's work.

During 1970s, when significant advances in computer technology started taking place, more insight into the aperture coupling problem was gained through the application of numerical techniques (C.M. Butler & K. R. Umashankar, Radio Sci., vol. 11, pp. 611-619, 1976) and (C. M. Butler, Y. Rahmat-Samii & R. Mittra, IEEE Trans. Antennas Propagat., vol. AP-26, pp. 82-93, 1978). The approach used was based on an integro-differential equation formulation in the spatial domain and involved the decomposition of the original problem into equivalent half-spaces. The spectral domain method is used in a similar fashion (i.e., with equivalent half-spaces) but results instead in a pure integral equation that is solved in the transform domain. In addition to being more appealing in the formulation process, the spectral domain technique also covers a wider class of structures than its spatial domain counterpart. In particular the inclusion of dielectric layers on either side of the slot can easily be incorporated in the analysis.

Results for the aperture field distribution in slots of variable sizes are obtained and compared to previously published results by Butler *et al.* The extension of the present formulation to other slot structures will be discussed.

ELECTROMAGNETIC COUPLING THROUGH A ROW OF AIRCRAFT WINDOWS FOR FREQUENCIES LESS THAN 100 MHZ

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The electromagnetic coupling through the 29 forward windows of a commercial aircraft was measured as part of program to estimate the internal EMP coupling into large aircraft. A parallel plate transmission line was installed on the surface of the aircraft over the windows. A computer controlled network analyzer and two MGL magnetic field sensors allowed measurement of the magnetic field coupling between the surface of the aircraft and interior points. Replacing the interior sensor with a current probe allowed transfer functions to be measured between the surface of the aircraft and representative cable bundles. Measurements were made between 10 kHz and 100 MHz.

For frequencies up until 60 MHz, the magnetic field transfer function was independent of frequency. These measurements showed that the magnetic field from this array of apertures decreased as $1/r^2$. One meter from the window centerline, the magnetic field transfer function was 45 dB below the surface magnetic field. Off axis test points were lower, as would be expected.

The transfer function between the aircraft fuselage and the current on vertical cables near the windows was about -90 dB for frequencies between 0.5 and 10 MHz. For 6 kA of fuselage current, the coupled currents due to the windows would be about 200 mA.

This initial electromagnetic coupling survey allowed the electromagnetic vulnerability of the aircraft to be estimated on the basis of measured transfer functions. This reduced the uncertainties in the internal coupling calculations.

FREMP COUPLING THROUGH AN AIRCRAFT WINDOW

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In order to obtain a better understanding of how fast risetime electromagnetic pulse (FREMP) waveforms couple through aircraft windows and to nearby wiring, a controlled experiment was conducted on a large commercial aircraft and on a surrogate aperture that had the same dimensions as an aircraft window. This aperture was excited with a tangential electric field produced by a 1 ns risetime 10 kV square wave pulser and a horn type exciter placed against the aircraft surface. All measurements were made with appropriate time domain instrumentation.

These measurements demonstrated that the aperture affected the exciting pulse in a number of ways. One of the principal effects was that the aperture reduced the fall time of the transmitted pulse. For an aperture the size of a passenger window, the width of the transmitted pulse was about equal to the risetime. The second effect demonstrated by these measurements was that the peak amplitude of the field inside of the aperture along a line normal to the surface decreased as $1/r^3$. This suggests that for the time regimes of the excitation pulse, the electromagnetically excited aperture acted like a dipole.

Quantitative measurements were made of the FREMP coupling to cables in the vicinity of the window. The amplitude of the current pulse on these cables decreased rapidly at locations on the cable only a fraction of a meter away from the aperture, indicating a loss mechanism was involved. The most likely loss mechanism was radiation and/or a dispersive propagation medium on the surface of the cable.

RESPONSE OF TYPICAL AIRCRAFT ANTENNAE TO FAST RISETIME EMP

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Deliberate antennae, by their very nature, collect and transmit to the system large transients when exposed to an electromagnetic pulse (EMP). Except for a few HF antennae, most of the deliberate antennae on an aircraft are designed to operate above 100 MHz. Most antennae behave like a derivative sensor (response proportional to frequency until resonance). Thus, while these antennae may have a nominal response to the relatively slow risetime of the "traditional double exponential" pulse, their response to a faster risetime pulse could be significantly higher. Because of questions concerning the applicability and availability of analytical models, it was decided to measure the response of all of the antennae from an aircraft and calculate the transient that resulted from exposure to fast risetime EMP.

The voltage response of 15 antennae was characterized by installing them in the wall of a Transverse Electromagnetic (TEM) cell and measuring the voltage response from 500 kHz to 1 GHz using a computer controlled network analyzer.

The transient response was estimated by calculating the response to the Heaviside unit step function, fitting the unit step function frequency domain response with damped sine waves using a Prony technique, summing the damped sines to get the unit step time time domain response, and obtaining the Bell Labs time domain response by convolving with the time derivative of the double exponential surface electric field or obtaining the full amplitude unit step response by multiplying by twice the incident field.

The two waveforms were selected in order to bound the problem. The "traditional double exponential" pulse was selected because it represented a well known waveform and thus served as a point of departure. The Heaviside unit step function was selected because it represented the worst possible waveform. Two types of stimulus surface electric fields were used for the calculations: Twice the incident field and twice the incident field plus the scattered field due to the aircraft response.

These experimental and calculational studies showed that the response of the antenna to the incident field was much more significant (by almost an order of magnitude) than the response to scattered surface electric field of the aircraft. Thus a good estimate of the antenna response could be obtained by using twice the incident field as the forcing function.

Sensitivity studies carried out by varying the number of poles used to fit the frequency domain response showed that the exact form of the response was relatively unimportant in estimating the peak voltage response of the antenna to FREMP. Thus future studies can use simplified models with increased confidence.

This study showed that transient voltages as high as a few tens of kilovolts could appear at the antenna terminals when the aircraft is exposed to a typical Fast Risetime EMP (FREMP).

Analysis of the measured antenna responses with respect to their physical dimensions showed that a reasonably good estimate of the antenna's transfer function could be obtained from its overall physical dimensions.

ATTENNUATING EM WAVE PENETRATING INTO A RESONANT CAVITY BY AUGMENTING MULTIPLE MONOPOLES

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It has been found that multiple monopoles which symmetrically straddle the two sides of a slot can greatly reduce EM wave coupling into a resonant cavity. It is demonstrated by moment methods that under the resonant condition, the maximum field amplitude in the cavity is reduced from 85 times without monopoles to 10^{-2} times with monopoles compared with that of incident wave, and the penetration power is attenuated by 10^{-6} times compared with that when the monopoles are not present.

When we study the effect of a strong EM pulse produced by nuclear explosion or lightning on electric equipment or when we study EM shielding and EM compatibility, the phenomenon we often see is EM coupling into a cavity through a slot. Of particular interest is the maximum field amplitude in the slot and inside the cavity exclosure under resonant conditions. D.B. Seidal (IEEE Trans., AP-30, No. 4, 1982) and David K. Cheng (IEEE Trans., MTT-26, 914, 1978) have analyzed the problem. To date, only undertaking theoretical analysis of the problem has been carried out. It does not appear that anyone has attempted to find an efficient approach to solve the problem. The significance of this paper is in having found an efficient approach by which the field inside the resonsant cavity and EM coupling to the resonant cavity can be reduced greatly. Therefore, the shielding effect due to the resonance can be eliminated. From Maxwell' equations and by introducing the boundary conditions, we first establish exact integral equations which consider the effect of the monopole length, the slot length and width, the mutual distance between monopoles, the distance from the bottom of the monopole to the center line of the slot, the thickness of the conducting screen and the wall loss. Then with the help of computer, we obtain the electric currents on the monopoles, magnetic currents on the slot, the field inside the cavity and EM wave coupling power. Further, we obtain the optimum configuration by which the EM coupling is the smallest. The maximum number of monopoles we augment with is 12.

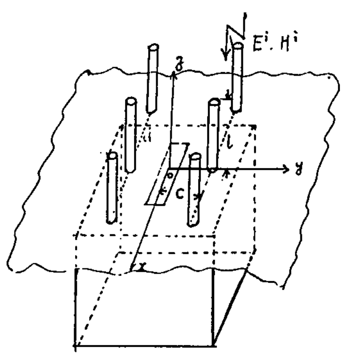
We conclude:

1. If the length l and the distance d are given, the smaller the distance c, the larger the attenuation is obtained. (See figure).

2. There is an optimum length l corresponding to the given distance c and d in which the attenuation is the largest. Also there is an optimum distance d corresponding to the given distance c and length l.

3. The larger the distance c, the shorter the resonant length l is needed, in which the attenuation is the largest.

4. Increasing the number of monopoles does not increase the attenuation. We obtain large attenuation using only 2 monopoles.



Tuesday AM URSI-D Session TA13

Room: Columbus K/L *Time*: 0820-1140

Modelling of High Frequency Circuits

Chairs: A. C. Cangellaris, University of Arizona; Jim Mink, ARO

0820 **DEVELOPMENT of a GENERALIZED HIGH-FREQUENCY MODEL for SURFACE-MOUNT MICROELECTRONIC PACKAGES**
H. Astrain, Motorola SPS; D. R. Bridges, P. C. Cherry*, University of Utah; G. Davis, Motorola SPS; M. L. Gundersen, K. R. Hulse, M. F. Iskander, B. M. Prestwich, University of Utah; R. Sundstrom, Motorola SPS; M. S. Talbot, University of Utah; W. Valentine, Motorola SPS

0840 **MODELLING of ELECTROMAGNETIC PACKAGING and COAX-TO-MICROSTRIP TRANSITION EFFECTS by FD-TD METHOD**
Ke-Li Wu*, Chen Wu, Zheqiang Bi, John Litva, McMaster University

0900 **TIME DOMAIN MEASUREMENTS and MODELING of MIMIC PACKAGES**
Imran A. Bhutta*, Monty B. Hayes, Aicha Elshabini-Riad, Sedki Riad, Virginia Polytechnic Inst. & State Univ.

0920 **A COMMON PROBLEM with PRINTED CIRCUIT BOARD RADIATION MODELS**
Todd H. Hubing*, University of Missouri-Rolla

0940 **CHARACTERIZATION of ACTIVE CPW CIRCUITS with LOCAL S-PARAMETERS**
Vesna Radisic, Dag R. Hjelme, Zoya B. Popovic*, Alan R. Mickelson, University of Colorado at Boulder

1000 **Break**

1020 **A COMPREHENSIVE APPROACH to HIGH-FREQUENCY OSCILLATOR DESIGN and IMPLEMENTATION USING CAD TOOLS**
Nebil Tanzi*, Illinois Istitute of Technology; Thomas T. Y. Wong, Illinois Institute of Technology

1040 **A PHYSICAL MODEL for GRID OSCILLATORS**
Kuang Yi Chen, Alan R. Mickelson, Zoya B. Popovic*, University of Colorado at Boulder

1100 **ELECTROMAGNETIC MODELING in HIGH-RATE DATA SYSTEMS**
Zorica Pantic-Tanner*, San Francisco State University; David R. Tanner, Lockheed Company

1120 **A COMPARISION BETWEEN TWO GaAs MONOLITHIC TRANSIMPEDANCE AMPLIFIERS for HIGH SPEED OPTICAL COMMUNICATION SYSTEMS**
J. A. Casao, P. Dorta, J. L. Caceres, M. Salazar-Palma*, J. Perez, Universidad Politecnica de Madrid

DEVELOPMENT OF A GENERALIZED HIGH-FREQUENCY MODEL FOR SURFACE-MOUNT MICROELECTRONIC PACKAGES

H. Astrain,**† D. R. Bridges, P. C. Cherry,* G. Davis,** M. L. Gundersen,
K. R. Hulse, M. F. Iskander, B. M. Prestwich, R. Sundstrom,**
M. S. Talbot, and W. Valentine**

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Integrated circuit packages are becoming a major limitation in meeting performance requirements for high-speed integrated circuits (ICs). Signal degradation due to the physical parameters of the packages are limiting the production of ICs that operate at frequencies exceeding 1-3 GHz. Discontinuities from bond wires and input pins introduce frequency-dependent reflections, and cross talk as well as ohmic and radiation losses produce additional signal degradation.

This paper describes the development of a generalized high-frequency model for surface-mount packages of various sizes, pin counts, and pin placement. This model will be used by the project sponsor to characterize various packages, examine the causes of signal degradation within a specific package type, and help develop guidelines towards improved package designs for high-frequency ICs. Packages of interest to the project sponsor (Motorola Inc.) include the plastic lead chip carrier (PLCC) 20-, 44-, and 68-pin packages; the small-outline integrated circuit (SOIC) 8-, 16-, and 24-pin packages; and the super-small-outline package (SSOP) 8-, 20-, and 28-pin packages. The developed high-frequency model for all these packages is based on measured and/or simulated S parameters. It is based on a detailed equivalent circuit with elements that vary depending on the pin count and placement and other package design parameters such as the width and length of lines and separation distances between them. The S parameters for some packages were measured using a high-frequency probe station on an HP 8510 network analyzer, while S parameters for other packages were calculated using simulation software such as EMSIM by EEsof and HFSS by Hewlett Packard. In identifying the trends in the variations of the inductance [L] and capacitance [C] matrices versus the geometrical and physical parameters of all packages, Xgeom and EM (by Sonnet Software) as well as LINPAR (by Artech House) were used. Results illustrating the simulation of the high-frequency performance of a wide variety of packages will be presented and data showing the accuracy of the developed generalized model for frequencies up to 10 GHz will be presented.

†Authors' names are arranged alphabetically.

Modelling of Electromagnetic Packaging and Coax-to-Microstrip Transition Effects by FD-TD Method

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Abstract

With the development of microwave integrated circuits (MIC) and monolithic microwave integrated circuits (MMIC), the packaging and transition effects have recently become a hot topic of wide interest. The problems related to packaging effects have been investigated in the spectral domain by a number of papers. But the study has not been completed in these early models. The latest model is based on an integral equation approach, which is derived by an application of the reciprocity theorem and is then solved by the moment method. Although in this model the microwave circuits can be simulated in a package environment, the simulation still deviates from practice. For example, the higher order modes near the coax-to-microstrip transition have not been completely taken into account because the coaxial feed is described by a magnetic frill current which involves only the TEM mode in the coaxial line. So that, the model is restricted to the low frequency range. On the other hand, like other spectral domain models, the relative convergence of the Green's function makes it difficult to obtain a reliable solution.

A direct three-dimensional finite-difference time-domain (FD-TD) method is applied to the full-wave analysis of packaging and transition effects of microwave circuits. The model is shown to be an accurate tool for modelling shielded microwave circuits which are connected to coaxial connectors. The packaging effect and the transition effect between the coaxial line and microstrip will be automatically included in the system function in frequency domain. This system functions of microwave circuits can be determined by simulated time-domain waves that are reflected and transmitted down the coaxial line. As an example, a microstrip line in a metal box which is connected with coaxial line, is analyzed and measured. The comparison between experimental and numerical results shows very good agreement. The details will be presented in the conference.

TIME DOMAIN MEASUREMENTS AND MODELING OF MIMIC PACKAGES

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In this work, time domain techniques are used to investigate the parasitic effects of a Millimeter wave and Microwave Integrated Circuit (MIMIC) package. Time domain measurement can help in the identification process of the different regions of the package and the effect of these regions on the high frequency electrical performance. Time domain measurements have also demonstrated that in order to develop a package that does not incorporating any significant noise or does not cause a significant reduction in the overall signal bandwidth, the effect of these regions on the high frequency signal must be minimized.

Time domain measurements of a typical MIMIC package illustrate that when the high frequency signal line transitions from a microstrip to a stripline or from a stripline to a microstrip, the change in the signal line strip-width results in the introduction of a parasitic capacitance, referred to as the transition capacitance.

Computer simulations of the MIMIC package show the cause of the transition capacitance. The electromagnetic field around a microstrip or a stripline varies only in the normal direction. However, in the transition region as the strip-width is changing, the change results in not only a normal variation in the electromagnetic field but also an axial variation. This additional electromagnetic variation results in an additional flux component and thus appears as a capacitance associated with the transition region.

Based on the computer simulations, a new MIMIC package design is also proposed. This new design is based on a signal line with constant strip-width. In the constant strip-width design, there is no variation of the electromagnetic field in the axial direction. Computer simulation of the new design predict a reduction of over 90% in the transition capacitance value. Actual realization of the designed package is achieved using a low temperature, cofireable, multilayer, ceramic tape system. Evaluation of the electrical performance of the package is conducted as part of the work.

A COMMON PROBLEM WITH PRINTED CIRCUIT BOARD RADIATION MODELS

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Electromagnetic radiation from printed circuit cards and cables is a topic of great concern to many industry and government organizations. A considerable amount of attention has been devoted to this topic in the literature. Historically, efforts to model practical printed circuit card configurations have been based on analytical techniques that greatly over-simplify the problem in order to obtain a solution. More recently, there has been a great deal of interest in using numerical modeling techniques for this purpose.

Printed circuit cards present a formidable electromagnetic modeling environment. A detailed 3-dimensional, full-wave analysis is beyond the capabilities of existing modeling codes. One common method of simplifying the problem is to combine transmission line analysis techniques with a full-wave numerical technique. Transmission line theory is used to calculate the signal currents on individual traces. Numerical models use these currents as the *source* and calculate the fields and currents coupled to other conductors. At first glance, this approach appears to achieve a significant reduction in the complexity of the problem at only a minor cost in solution accuracy. Unfortunately, for most printed circuit card configurations, the impact on solution accuracy is far from minor.

This paper will show that any printed circuit board radiation model that attempts to constrain the current on the traces prior to performing a full-wave analysis is unlikely to yield an accurate result. The problem lies in the fact that the current on two-conductor transmission lines will generally have two components.

1. A differential-mode (or signal) component that flows in opposite directions on each conductor.
2. A common-mode (or antenna) component that flows in the same direction on both conductors.

The differential-mode component is usually an order of magnitude or more greater than the common-mode component and it is the differential-mode component that is calculated using transmission line theory. The differential-mode current value is usually very close to the total current and therefore it is often considered to be a good approximation. This presentation will show that, although it is relatively small, the common-mode component has the greatest impact on the radiated fields. The transmission line approach artificially constrains this component to be zero and the resulting error is significant.

It is still possible to get useful information from a transmission line analysis of the circuits on a printed circuit card. However, it is very important that the current on individual traces not be constrained prior to performing the full-wave analysis.

CHARACTERIZATION OF ACTIVE CPW CIRCUITS WITH LOCAL S-PARAMETERS

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Parasitic reactances due to active device electrodes become a hard problem at millimeter wave frequencies with respect to analysis and scaling. Rigorous characterization of these parasitics require a full-wave analysis. However, generally the line dimensions are such that the local field distributions are dominated by the static field. A characterization technique based on these local static fields is advantageous when compared to a full-field technique due to its simplicity and computational speed. It should be most attractive when extended to three-dimensional structures. In this paper we will report on progress towards characterization of active CPW circuits using local, continuously varying, S-parameters defined in a region very small compared to the wavelength.

The formulation is based on the quasi-static arguments presented above. In this formulation the circuit performance is described by the Riccati equation (can be obtained from a Riccati transformation on the transmission line equations). The parameters in the Riccati equation are related to the local static field distribution. This characterization technique is fully verifiable from local two-dimensional surface potential measurements using electrooptic sampling (D. Hjelme et. al., National Radio Science Meeting, Boulder, CO. 1992). Device parasitics are characterized as deviations of the quasi-static field distributions from the idealized TEM distributions close to the device. We have applied the technique to passive coplanar waveguide (CPW) structures such as impedance steps and bends. We are currently applying these principles to active CPW structures. Coplanar waveguide circuits are promising candidates for the millimeter-wave region and the optical sampling technique is easily implemented on them. The validity and accuracy of the technique will be discussed by comparing the results to electrooptic measurements, network analyzer measurements, as well as to results from full-field models.

A COMPREHENSIVE APPROACH TO HIGH–FREQUENCY OSCILLATOR DESIGN AND IMPLEMENTATION USING CAD TOOLS

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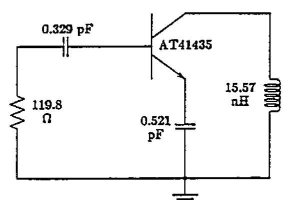
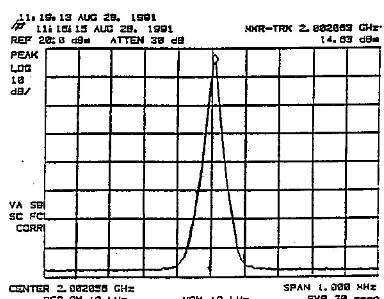
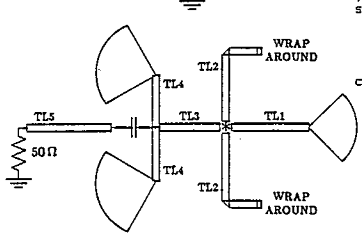
In this work we implemented a systematic methodology for designing high–frequency oscillators with both series and parallel configurations. It is based on the quasi-linear design technique introduced by Vehovec et al., and further developed in more recent years by a number of research groups. A special feature of our approach is the provision to allow the reference planes of the active device to be adjusted so that one may have greater flexibility in realizing the circuit with a practical layout, while reconciling the oscillation criterion with impedance matching requirements. The incorporation of linear computer-aided design program into the design procedure enables one to enforce the set of equations for the embedding elements upon a physical circuit layout, thus minimizing further iterations in the realization process.

The active device is characterized by a set of two-port parameters obtained either by measurement or from an appropriate equivalent circuit under the desired bias conditions, signal level and termination conditions. The oscillation equations for the chosen configuration are then solved to obtain the embedding network in terms of lumped elements. Realization of these lumped elements are accomplished with microstrip transmission line sections, which are further refined with linear CAD tools to satisfy the oscillation conditions. The design procedure has been verified and tested with the construction of oscillators using both series and parallel configurations. The lumped circuit prototype, refined microstrip layout and the output spectrum of an oscillator implemented using this design procedure are shown in the figures below.







A PHYSICAL MODEL FOR GRID OSCILLATORS

Kuang Yi Chen, Alan R. Mickelson, Zoya B. Popović*

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A planar grid oscillator coherently combines the output power from a large number of microwave oscillators into an angularly narrow radiated microwave beam. In this study, we approach the modeling of this device from the viewpoint of well developed laser models. The device is quite similar to a maser or a laser in that random emissions of photons are combined via cavity feedback in order to generate coherent stimulated cavity modes. We have modeled the oscillator using an active surface, a coherent feedback model and plan to experimentally verify this model both by microwave field measurements and in situ optical sampling measurements on a linear transistor array built on a GaAs substrate.

The oscillator array with a mirror placed at a certain distance away from the grid forms a resonant cavity. As bias is applied to the devices, noise starts oscillation in each device, which generates a propagating field in the cavity. The field reflected from the mirror induces currents in the gate leads of the transistors, which are then amplified and radiated by the drain lead. After a short dynamic transient, locked oscillation is established in the cavity for a certain cavity length. This process is equivalent to stimulated emission, since the feedback field causes the carrier recombination to be coherent with the carrier recombination one round trip time earlier. The model presented here takes into account the fact that the fields inside the cavity are neither near field nor far field and can be used to find the mode frequencies as a function of the biases. In addition, the model gives relative amplitude and phase relationship in the cavity. The general character of this model will enable us to understand the dynamical behavior of this device, and therefore the injection locking transients.

ELECTROMAGNETIC MODELING IN HIGH DATA RATE SYSTEMS

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High-speed digital circuits are widely used in communication systems. In order to minimize the costs of design and production of digital systems it is necessary to develop CAD tools for their accurate simulation. An important step in the simulation process is electromagnetic modeling. First, an electromagnetic model is developed. Second, lumped or distributed parameters of an equivalent electric circuit are extracted. The lumped parameters are capacitance and inductance matrices and the distributed parameters are characteristic impedance matrices and propagation constants. For low rate systems in the 1 MBPS range (where the pulse-rise times are relatively long) the quasi-TEM model is accurate. However, the next generation of communication equipment will be much faster, in the range of 1.0 to 3.0 GBPS. The harmonics in the high rate clock and data signals exceed the range in which quasi-TEM models are valid. Hence, it is necessary to develop a full-wave electromagnetic model for the new generation of high-speed digital circuits.

In this paper a full-wave model based on a variational functional for the propagation constant, rather than the free-space wave number, is developed. The functional is formulated in terms of the transverse components of the magnetic and/or electric field (T. Angkaew et al., T-MTT, 35, 117-123, 1987). The functional is solved using a finite element method. Tangential vector finite elements (J. Nedelec, Numer. Math. 35, 315-341, 1980, D. Tanner & A. Peterson, Microwave & Opt. Tech. Let., 2, 331-333, 1989) are employed. This approach has two distinctive advantages over the standard FEM procedure. First, the propagation constant can be directly calculated for a given frequency. Second, non-physical, spurious modes are easily identified with the use of edge (tangential) elements.

Based on the described electromagnetic model, a general computer program for electromagnetic modeling of high data rate systems has been developed. It consists of three modules. The first module is used for semi-automatic mesh generation. The second module solves for the propagation constant and the field distribution. The third module calculates the parameters of the equivalent circuits. Numerical results for the parameters of some typical structures are presented in the paper.

A COMPARISON BETWEEN TWO GaAs MONOLITHIC TRANSIMPEDANCE AMPLIFIERS FOR HIGH SPEED OPTICAL COMMUNICATION SYSTEMS

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Both at the receiver and the repeater stations of most fiber-optic communication systems the optical signal is transformed to an electrical signal by means of a photodiode and then amplified before passing through an equalizer for regeneration. Among the options for optical preamplifiers the transimpedance one has shown to be the most suitable configuration in high bit rate systems. Its MMIC construction is commercially preferable for reproducibility, reliability and cost reasons.

This paper compares two different GaAs MMIC transimpedance amplifier designs, both of them having as basic configuration a simple cascode one (Bahl et al., IEEE 1986 Microwave Millimeter-Wave Monolithic Circuits Symposium, pp.35-38) followed by a buffer stage for matching purposes. The second design is a novel and enhanced version in terms of bandwidth and noise. Figs. 1a) & 2a) show their schematics. The first design is AC coupled; the capacitors C_2, C_3 are included for DC decoupling purposes. The second design is a DC-coupled one in which shift-level diodes are included in the bias network to fix the working point of each FET. Nevertheless the principal difference between both designs is the introduction, in the second one, of two peaking inductors (Kikuchi et al., IEEE Trans. MTT, Dec. 1990, pp.1916-1923), one in series with the input FET (to produce a high frequency peak in order to increase the bandwidth), and the second one in a feedback loop (to improve the high frequency noise behavior).

Both designs were constructed employing the GaAs half-micron F20 process of GEC Marconi Materials and Technology. The chips were tested on-wafer and on-carrier in the facilities of the Polytechnic University of Madrid, showing good agreement with the simulated behavior. Figs. 1b) & 2b) allow a comparison between the transimpedance gain results of both designs. The second one show excellent performances for speeds higher than 1.5 Gb/s with high transimpedance gain (63 dB Ω), wide bandwidth (from DC to 1.6 GHz), low power consumption (0.5 W), low equivalent noise current (5 pA/$\sqrt{Hz}$) and negligible sensitivity of the behavior with the temperature and the bias point variations. It is the authors believe that state of the art results have been obtained for this simple configuration, showing the effectiveness of the improvements done over the first design.

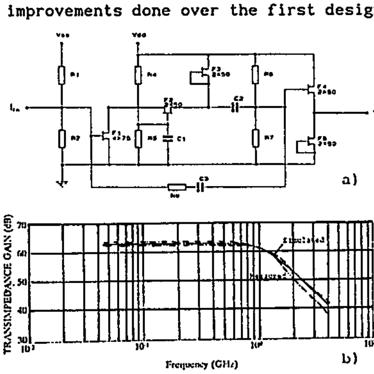

Fig.1

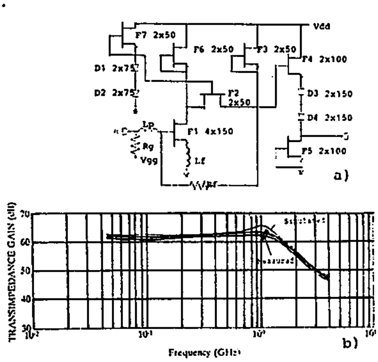

Fig.2

Tuesday AM2 URSI-B Session TA14

Room: Grand D *Time*: 1020-1200

Propagation II

Chair: A. R. Webster, University of Western Ontario

1020 **ANALYSIS and SIMULATION of MULTIPATH FADING for BASIC EXCHANGE RADIO (BEXR) SYSTEMS**
Jean-Fu Kiang*, Sing H. Lin, Bell Communications Research

1040 **DUAL-WAVELENGTH RADAR STUDIES of SNOWFALL**
S. Y. Matrosov*, R. A. Kropfli, NOAA Wave Propagation Lab

1100 **CALCULATIONS of SIGNALS DISTORTIONS and FIELDS of the ELECTROMAGNETIC WAVES REFLECTED from STRATIFIED MEDIA**
V. E. Kunitsyn*, A. B. Usachev, Moscow State University

1120 **INFLUENCE of RANDOM INHOMOGENEITIES UPON RAYS PATHS in REFRACTIVE MEDIA of the IONOSPHERE TYPE**
S. M. Golynski*, Moscow State University

1140 **A NEW METHOD of WAVE FIELD DESCRIPTION in an AREA of REFLECTION**
S. M. Golynski*, V. D. Gusev, Moscow State University

ANALYSIS AND SIMULATION OF MULTIPATH FADING FOR BASIC EXCHANGE RADIO (BEXR) SYSTEMS

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Basic exchange radio (BEXR) system is an economic facility to provide rural area telecommunication services. However, the performance and reliability of a BEXR system can be deteriorated by multipath fadings which are caused by terrain scattering and atmospheric refraction. Although empirical models are available for multipath fading on microwave radio links above 2 GHz, these models can not be directly applied to BEXR links due to significant differences in antenna beamwidth and antenna height. Hence, understanding the mechanisms of signal fading in BEXR links is critical to engineer BEXR systems.

In this work, we propose a method to calculate a scaling factor to account for the differences between microwave links and BEXR links. First, we study the terrain scattering by using a rough surface model and the atmospheric refraction by using a ray tracing approach. Then, we calculate the received signal powers of a microwave link and two BEXR links on the same path under the same propagation condition. We find that the magnitude of terrain scattered signal is comparable to that of the refracted signal. The fading distributions for all the three links are obtained by simulations over different possible propagation conditions. From the simulation results, we derive a scaling factor to modify the existing microwave multipath fading models for BEXR applications.

The predictions by the modified model agree well with two sets of measured results conducted by BellSouth engineers. This modified model indicates that the probability distribution of fading signal on BEXR links is a strong function of antenna height and of antenna beamwidth.

DUAL-WAVELENGTH RADAR STUDIES OF SNOWFALL

S.Y. Matrosov* and R.A. Kropfli
NOAA Wave Propagation Laboratory

Recent studies of snowflake size distributions indicated that, though these distributions can be often described in terms of the melted equivalent diameter D by an exponential function of the Marshall-Palmer type i.e. $N_0 \exp(-aD)$, there is no significant correlation between the two parameters of this size distribution, namely N_0 and a, as there is for rain. So it is obvious that measurements of radar reflectivity at one wavelength are generally insufficient for estimating parameters of snowfall. One of the possible ways to raise the information content of radar measurements of snowfall is to use dual-wavelength radar techniques.

Theoretical modeling the backscattering properties of snowflakes shows that radar reflectivities of snowfall can be satisfactory described by the Rayleigh-Gans approximation. These reflectivities in the millimeter and centimeter wavelength regions are quantitatively different. Backscattering of dry snowflakes in the millimeter region is sufficiently non-Rayleigh due to the scatterers' sizes, however, backscattering at wavelengths $\lambda \geq 3$ cm approaches the Rayleigh regime. Differences between reflectivities in these two regions are detectible and can reach several decibels (from 1 to approximately 8 dB). These differences can serve as a relatively good indicator of a characteristic size of falling snowflakes (i.e. of parameter a in the snowflake size distribution). Having two independent types of radar measurements (radar reflectivities and reflectivity differences) we generally are able to get information on both parameters of the size distribution and obtain more accurate estimates of the snowfall rate.

Theoretical results about snowflake backscattering properties were found to be generally consistent with the experimental data obtained during the Winter Icing Storm Project (WISP) in which the NOAA Wave Propagation Laboratory participated during the winter season of 1991. These data were collected by the collocated NOAA X-band (λ = 3.2 cm) and Ka-band (λ = 8.6 mm) radars with the matched antenna pointing angles during the snowfall events and by corresponding ground measurements of snowfall rates and snowflake sizes near the radar site.

CALCULATIONS OF SIGNALS DISTORTIONS AND FIELDS OF THE ELECTROMAGNETIC WAVES REFLECTED FROM STRATIFIED MEDIA

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We suggest a new method for calculation of electromagnetic wave fields and signals distortion either for isotropic stratified media or magnetoactive ones. The method is based on the algorythms for calculations of matrix of complex reflection (r) and transparency (t) coefficients. The main advantage of this approach compared with the methods developed earlier is connected with the taking into consideration the overbarrier reflection and the tunnel-effect. We are not restricted with the model of the dielectric constant profile. It can be arbitrary and it's thickness can reach more than million of wavelengths. The method is equally suitable for the ionospheric plasma, where effect of gyrotrophy is essential, for the plasma in solid dielectrics and also for waves reflected from anisotropic crystals.

To solve the problem we reduce the initial matrix Helmholtz equation for the column E components of field to the matrix Riccati equation that describes the auxiliary matrix V: VE = E', namely the matrix analog of field logarythmic derivative

$$dV/dz + V^2 + k^2 \hat{\varepsilon}(z) = 0.$$

Here $\hat{\varepsilon}(z)$ is the dielectric constant matrix. Solving numerically this equation one can easily find the reflection r and transparency t complex coefficients for every of field components. Calculations of signals distortions passing through magnetoactive media is realized by means of expansion to the Fourier spectrum and using r and t for every component. Fields calculations are carried out with the help of signals expansion into the angle spectrum. The method was checked by different ways.

Application of the method is illustrated in the report by a set of examples for the case of ionospheric plasma. Calculations of ionograms presented allow us to explain quantitative and qualitative such effects as multiple reflections, the wide semitransparency range of sporadic Es layers, the nonmonotonous reflection coefficient modulus dependence on the frequency, the resonances of group delays and some others, which can be observed in experiments. The software package is created for the calculations of reflection and transparency coefficients, signals distortions and fields of the waves, reflected from stratified media. The software package can be used on IBM-370 type computers as well as on personal computers IBM PC AT.

INFLUENCE OF RANDOM INHOMOGENEITIES UPON RAYS PATHS IN REFRACTIVE MEDIA OF THE IONOSPHERE TYPE

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The rays statistics in refractive media with random inhomogeneities can be described in the Markov diffusion approximation under the certain conditions. A solution of the corresponding Fokker-Planck equation (FPE), defining the probability of the transition of the process $X(\sigma)=\{\theta(\sigma),\varphi(\sigma)\}$ (θ and φ are polar and azimuth angles of scattering rays after passing the distance σ in the medium) from an initial state $X_i = X(\sigma_i)$ to a final state $X_f = X(\sigma_f)$, can be represented in the form of the path integral

$$P(x_f,\sigma_f/x_i,\sigma_i)\,dx_f = \iint D\{x(\sigma)\}\exp\left\{-\int_{\sigma_i}^{\sigma_f}\mathcal{L}\left[x(\sigma),\dot{x}(\sigma)\right]d\sigma\right\}.$$

Here $D\{X(\sigma)\}$ is the invariant measure providing the normalization of the transition probability and the function $\mathcal{L}$ named the Onsager-Machlup lagrangian (OML) defines the most probable path of the process in question. The OML is fully defined by the convection and local dispertion coefficients of the initial FPE and for the case of wave propagation in refractive media with random isotropic inhomogeneities has the following form

$$\mathcal{L}(\theta_p,\dot{\theta}_p,\varphi_p,\dot{\varphi}_p) = \frac{n^2}{4B}\left[\dot{\theta}_p+\frac{1}{n}\frac{dn}{dz}\right]^2-\frac{1}{n}\frac{dn}{dz}\cos\theta_p+\frac{n^2\sin^2\theta_p(\dot{\varphi}_p)^2}{4B}-\frac{B}{2n^2},$$

where $n = n(z)$ is the regular part of the refractive index of the medium under consideration; B is the diffusion coefficient, which depends on the random inhomogeneities correlation function; $\theta_p(\sigma)$ and $\varphi_p(\sigma)$ are the most probable values of the polar and azimuth angles defining the most probable rays path.

As examples we investigate two models of the refractive medium, namely, the linear and the parabolic approximations of the refractive index regular part. It is shown that in the case of reflection from the medium the most probable rays trajectiries are asymmetrical with respect to the point of reflection and can be described by the integral law of refraction. In conclusion we discuss the vertical displacement of the reflection point, the horizontal displacement of the exit point and the deviation of the most probable polar exit angle of rays compared with the corresponding parameters of the undisturbed trajectory in the medium without refraction, which satisfies the Snell's law.

A NEW METHOD OF WAVE FIELD DESCRIPTION IN AN AREA OF REFLECTION

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We consider a new approach to problems of wave propagation and scattering in inhomogeneous and random-inhomogeneous media. According to this method the wave field with the harmonic dependence on time can be represented as a superposition of two linear-independent progressive waves. These waves propagate in opposite directions and do not interact with each other. For example, in the case of wave propagation in stratified media the wave field has the following form (the factor $\exp\{-i\omega t\}$ is omitted)

$$U(z) = C_1 m^{-1/2} \exp\{i\kappa\Phi\} + C_2 m^{-1/2} \exp\{-i\kappa\Phi\},$$

$$\Phi = \int_0^z m(s)\,ds,$$

where C_1 and C_2 are integration constants defined by the boundary conditions; κ is the free-space wave number; $m = m(z)$ is the only unknown function, which plays a role of the effective refractive index of the medium considered and satisfies the nonlinear differential equation of the second order (or the linear integral equation of the Volterra type).

For some definite models of refractive media of the Ionosphere type the effective refractive index can be found exactly under given initial or some other additional conditions connected with physical reasons. In general, including the wave propagation in random media, for solution the nonlinear differential equation defining m it is necessary to use different asymptotic methods, the choice of which depends on the problem in question.

According to the definition the effective refractive index m is positive in the whole area of the progressive waves existence up to a level of reflection that is identified with the upper boundary of the medium. This is one of the main advantages of the approach under consideration because it is possible to describe the wave field in the area of reflection unlike the geometrical optics approximation and its different modifications.

As an example we consider the exact solution of the problem for the stratified medium, the dielectric constant of which has the linear dependence on height. In conclusion we discuss the solution of the same problem in the presence of random isotropic inhomogeneities.

Tuesday PM AP-S, URSI-D Session TP03

Room: Grand C *Time*: 1320-1640

Superconductivity and Applications

Organizer: Linda P. Katehi, The University of Michigan
Chairs: Linda P. Katehi, The University of Michigan; Samir El-Ghazaly, Arizona State University

1320 **HIGH Tc SUPERCONDUCTING DEVICES DEVELOPMENT at DU PONT**
Zhi-Yuan Shen*, Charles Wilker, Philip S. W. Pang, Daniel B. Laubacher, William L. Holstein, Dean W. Face, Dennis J. Kountz, Amy L. Mathews, Julia M. Meriwether, Charles F. Carter, DuPont Central Research and Development

1340 **EXPERIMENTAL RESULTS on a 12-GHZ 16-ELEMENT MULTI-LAYER MICROSTRIP ARRAY with a HIGH-Tc SUPERCONDUCTING FEED NETWORK**
Jeffrey Herd, J. P. Kenny, Rome Laboratory; K. G. Herd, General Electric Corp.; W. G. Lyons*, Alfredo C. Anderson, MIT Lincoln Laboratory; P. M. Mankiewich, M. L. O'Malley, AT&T Bell Laboratories

1400 **A Ka- BAND ELECTROMAGNETICALLY-COUPLED SUPERCONDUCTING MICROSTRIP ANTENNA**
Mark A. Richard*, Case Western Reserve University; K. B. Bhasin, NASA Lewis Research Center; Paul C. Claspy, Case Western Reserve University

1420 **A 4-ELEMENT SUPERCONDUCTING MICROSTRIP ARRAY**
Mark A. Richard*, Case Western Reserve University; K. B. Bhasin, NASA Lewis Research Center; G. Koepf, Ball Communication Systems Division; Paul C. Claspy, Case Western Reserve University

1440 **FULL-WAVE ANALYSIS of HIGH-Tc SUPERCONDUCTOR PATCH ANTENNA on LOSSY BI-ANISOTROPIC SUBSTRATES**
Zhenglian Cai*, Jens Bornemann, University of Victoria

1500 **Break**

1520 **HTc SUPERCONDUCTIVE INTERCONNECTIONS SPICE MODELING for MICROWAVE APPLICATIONS**
Thanh Vu Dinh, Beatrice Cabon*, J. Chilo, LEMO-ENSERG

1540 **3D-TLM ANALYSIS of HIGH-Tc SUPERCONDUCTING COUPLED-COPLANAR WAVEGUIDE**
M. Vanselow, B. Isele, R. Weigel*, Peter Russer, Technische Universitat Munchen

1600 **HTc SUPERCONDUCTIVE INTERCONNECTIONS for ULTRA FAST LOGIC CIRCUITS**
Beatrice Cabon*, Thanh Vu Dinh, J. Chilo, LEMO-ENSERG

1620 **SPECTRAL DOMAIN FORMULATION for SUPER-COUNDUCTING MICROSTRIP LINES with ARBITRARY STRIP THICKNESS**
A. T. Shalaby*, Menoufia University

HIGH T_c SUPERCONDUCTING DEVICES DEVELOPMENT AT DU PONT

Zhi-Yuan Shen*, Charles Wilker, Philip S. W. Pang, Daniel B. Laubacher, William L. Holstein, Dean. W. Face, Dennis J. Kountz, Amy L. Matthews, Julia M. Meriwether, Charles F. Carter

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Abstract

This paper is a summary of high T_c superconducting (HTS) devices developed at Du Pont over the past two years. We have designed, fabricated and tested a number of HTS devices such as a 5 GHz microstrip line resonators; 3-pole, 5-pole, 7-pole microstrip line bandpass filters; a 11-nanosecond coplanar delay line; a 0.5-4.5 GHz 7-section Chebyshev microstrip line power splitter/ combiner; 5.55 GHz HTS-sapphire resonators with extremely high Q-value, and III-V semiconductor-HTS hybrid amplifiers and oscillators, etc. The thin film HTS materials used for fabricating these devices are: YBaCuO(123), TlBaCaCuO(2212) and TlPbSrCaCuO(1212) with very low surface resistance and high power handling ability.

These HTS devices have superior performances compared to those of their counterparts made of normal metals such as copper or gold. As an example of the high performance, the 5.552 Ghz HTS-sapphire-HTS resonator achieved Q-values of $3x10^6$ at 80 K and $1.4x10^7$ at 4 K and its power handling ability ranging from 10^4 to $0.5x10^6$ watts depending upon the operating temperature.

The design, fabrication, performance and the applications of these devices and circuits are presented. In addition, how to integrate these devices into a microwave system will also be discussed. An X-band dual channel receiver front end will be presented as an example. It consists of an amplifier, a power splitter/combiner, two local oscillators, two balanced mixers, two low pass filters and two video detectors with over forty components on a three inches wafer.

EXPERIMENTAL RESULTS ON A 12-GHz 16-ELEMENT MULTILAYER MICROSTRIP ARRAY WITH A HIGH-T_c SUPERCONDUCTING FEED NETWORK

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The design, fabrication, and measurement of a 4 × 4 multilayer microstrip array are described. The power distribution to the individual elements has been accomplished with a high-T_c superconducting microstrip feed network. The development of multilayer microstrip phased-array antennas is attractive because of the broad-bandwidth scanning properties of stacked microstrip patches. Furthermore, this multilayer structure lends itself to integration with a high-T_c superconducting feed network because one of the layers in the structure is a vacuum gap (for thermal isolation at cryogenic temperatures). Superconducting planar power-distribution networks can greatly reduce the distribution losses and corresponding reduction in gain that a normal metallic planar feed network would experience.

The structure consists of three dielectric layers which are, from top to bottom, a quartz superstrate, a vacuum gap, and a $LaAlO_3$ substrate. Patches made of silver were deposited on the top surface of the quartz. A network of power dividers and lower microstrip patches was patterned on the top surface of the $LaAlO_3$ from a thin film of the high-T_c superconductor $YBa_2Cu_3O_{7-x}$, while a silver ground plane was deposited on the bottom surface of the $LaAlO_3$. A multilayer, infinite-array spectral-domain Green's function was used with the method of moments to design the microstrip feed network and proximity-coupled elements. For simplicity, the analysis assumed that the superconducting film had infinite conductivity. The approach using an infinite-array dyadic Green's function models all mutual coupling effects including surface-wave resonances.

Measurements on elements at 12 GHz in a waveguide simulator have been used to replicate an infinite array environment. Silver, superconducting niobium, and superconducting $YBa_2Cu_3O_{7-x}$ were used for the lower patch and feed line in three waveguide simulator tests. The results indicate a bandwidth of 8%. For the phased array, both E- and H-plane antenna patterns were measured at 12 GHz, indicating a gain of approximately 15 dBi.

A Ka-BAND ELECTROMAGNETICALLY-COUPLED SUPERCONDUCTING MICROSTRIP ANTENNA

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ABSTRACT

The recent discovery of the ceramic high-temperature superconductors (HTS) has generated much speculation into their use in microwave antennas systems because of their potential to dramatically reduce feed network losses. Experimental investigations of passive microwave devices such as delay-lines, resonators, and filters have shown that HTS provides a substantial loss reduction over identical circuits fabricated with metals. One of the drawbacks of using HTS for microstrip antennas, however, is the fact that HTS is unavailable on low-permittivity substrates. The use of a high-permittivity substrate for microstrip antennas leads to undesireable characteristics such as narrow bandwidth and reduced radiation efficiency due to surface wave generation.

To overcome this difficulty and effectively use HTS in microstrip antenna systems, a two-layered electromagnetically-coupled microstrip patch has been investigated. This configuration allows the patch to be patterned with gold on a lower permittivity substrate while still using HTS for the feed network. For this work, a lower (feed) substrate of 250 μm thick lanthanum aluminate (ϵ_r=23) was used. A YBCO microstrip feed line is patterned on one side with a gold ground plane on the reverse side. The upper substrate is 125 μm thick alumina. A circular patch 760 μm in radius is patterned on this substrate. The two substrates are held together with a thin layer of Shipley photoresist. A second antenna, identical but with a gold feed line, was also fabricated for comparison purposes. The input impedance, efficiency and far-field antenna patterns are presented and compared with the gold antenna.

HTc SUPERCONDUCTIVE INTERCONNECTIONS SPICE MODELING FOR MICROWAVE APPLICATIONS

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Introduction

An original modeling concept describing superconducting material through an equivalent circuit is proposed. It allows superconducting interconnections to be analyzed using any electrical nodal simulator (SPICE, for example).

Modeling concept

Using the Moment Method concept for parameter calculation (R. F. Harrington, "Matrix methods for field problems", Proc. IEEE, 55, 1967, pp 136-149), the cross section of the line is divided into subsections having constant current densities (Fig. 1). For any elementary subsection i, the voltage drop on a unit length is (J. Chilo et al: "Proximity effects of interconnection lines ...", 13th Euro. Microwave Confer., Sept. 1983, pp. 369):

$$u_i(r_o) = \frac{J_i(r_o)}{\sigma_i} + j\omega \sum_N \int J_j(r_c)\, G(r_o, r_c)\, dS_j$$

where σ_i, J_i and S_i are the conductivity, the current density and the area of the subsection i respectively, $G(r_o, r_c)$ is the 2-D Green function.

For a superconducting strip, the two-fluid model can be used with a complex conductivity : $\sigma = \sigma_n - j\sigma_s$. Then, from the circuit point of view, this voltage drop can be equated to a parallel circuit (normal resistance r_n and superconducting inductance L_s) in series with self and mutual magnetic inductances. Considering that the line current is composed of a set of elementary parallel currents and that the conductor cross section is an equipotential surface, we can build up an equivalent circuit of parallel branches including their mutual inductances M(i,j). The whole equivalent circuit of Fig. 2 may be simulated using SPICE, providing the variations of line parameters versus frequency .

Modeling results in frequency domain

A typical superconducting microstrip line (YBaCuO, w=2µm, t=0.5µm, h=1µm, ε_r=3.9) has been analyzed. The variations of the attenuation constant at 77 K versus frequency calculated by our equivalent circuit method and by the PEM method (H. Y.-Lee and al., "Phenomenological Loss Equivalence Method...", IEEE-MTT, Vol. 37, No. 12, Dec. 1989, pp. 1904) are shown in Fig. 3. A good agreement between these two results is observed. A next paper (this issue) will demonstrate the advantages in using superconducting interconnections in fast logic circuits.

Conclusion

Our new modeling concept for analyzing superconducting interconnections is based on a description of the material by an equivalent circuit. The great adavantages are the following :

- Simplicity of the description, suitability for any circuit simulator. Here, SPICE has both capabilities of frequency and time domain analyses.
- Extension of this concept to capacitive modeling of the line and investigations of coupling effects , already completed (T.Vu Dinh et al, "Equivalent circuit...", Electronics Letters, Vol. 27, No.9, April 1991, pp 710-712)
- Simulation of non linear circuits demonstrating spurious commutations of logic gates due to lossy and coupling effects of interconnections (this issue).

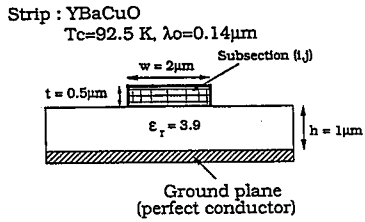

Fig. 1: Cross sectional division of a superconducting line.

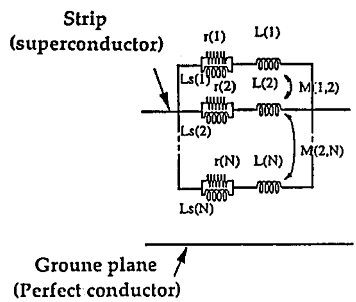

Fig. 2 : Equivalent circuit for a microstrip superconducting line.

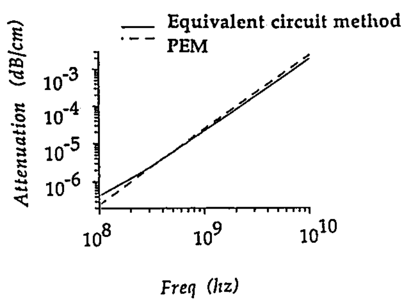

Fig. 3 : Frequency variations of line attenuation calculated by equivalent circuit method and PEM.

3D–TLM ANALYSIS OF HIGH–T_c SUPERCONDUCTING COUPLED–COPLANAR WAVEGUIDE

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We have investigated high–temperature (high–T_c) superconducting coupled coplanar transmission lines (CCPW) fabricated from high–quality aligned $YBa_2Cu_3O_{7-x}$ (YBCO) films on $LaAlO_3$ substrates. The coplanar waveguide (CPW) is a particularly suitable thin–film structure, requiring the coating of only one side of a substrate with a superconductor and thereby allowing the other side to be thermally anchored during deposition and in situ annealing of the superconductor. Recently, we have constructed high–T_c CPW resonators and oscillators made of YBCO on $LaAlO_3$ substrates (R. Klieber, R. Ramisch, R. Weigel, M. Schwab, R. Dill, A.A. Valenzuela, P. Russer, Proc. IEDM, 923–926, 1991). We have already investigated high–T_c coplanar waveguides using a partial wave synthesis (J. Keßler, R. Dill, P. Russer, IEEE Trans. MTT–39, 1566–1574, 1991).

This paper deals with the application of the three–dimensional transmission–line matrix (3D–TLM) method to CCPW circuit structures. We use the 3D–TLM algorithm with the symmetrical condensed TLM node. The circuits are investigated in the time domain by calculating the response for single–pulse exciation. From these results, the frequency characteristics are calculated by fast Fourier transform (FFT) using zero–padding. The circuit structures are embedded in domains bounded by absorbing walls. The absorbing boundary conditions are modelled by discrete Green's functions (John's matrices). We describe the surface impedance of the high–T_c superconducting material according to the two–fluid model and to the London theory by inductive and resistive stubs.

Fig. 1 shows the cross section of the coupled parallel coplanar waveguide structure to be analyzed with geometrical dimensions a, b, and D. Dimensions a and b are chosen to obtain a 50 Ω characteristic impedance of the uncoupled coplanar waveguide. The calculated line–to–line coupling is shown in Fig. 2 for various distances D. The substrate height and the ratio a/b were 500 μm and 0.2, respectively. An infinitely thin conductor was assumed in the simulation.

Fig. 1

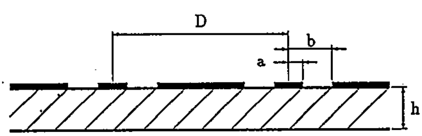
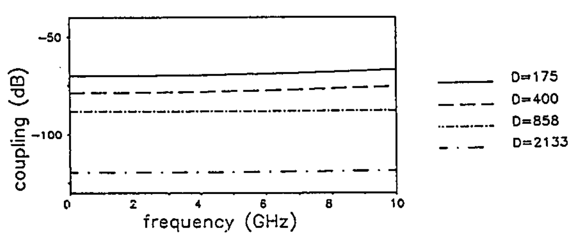


Fig. 2



HTc SUPERCONDUCTIVE INTERCONNECTONS FOR ULTRA FAST LOGIC CIRCUITS

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LEMO - ENSERG, 23 rue des Martyrs, B. P. 257, 38016 Grenoble Cedex, France

Introduction

HTc superconductors are be very attractive for applications to fast logic circuits: interesting microwave passive circuits and sophisticated packaging with multichips modules may be investigated. This paper presents modeling results in frequency domain and experimental validation of superconductive transmission lines. Time domain simulations are carried out demonstrating their interest, in a propagation point of view, for packaging applications.

SPICE simulation results and experimental validation in frequency domain

A microstrip YBaCuO transmission line has been analyzed using SPICE ("HTc interconnections SPICE modeling for microwave applications", URSI 92)(*). In order to validate our models, a broad band characterization (0-15GHz) of an YBaCuO line of 40mm length, 350nm thick deposited on a sapphire substrate of 250mm thick has been performed (1990 Applied Superconductivity Conference, Dallas, USA Sept.90). Propagation parameters (attenuation coefficient, phase velocity,...) have been extracted and their frequency variations compared with modeling results. A good agreement has been achieved when taking into account radiation. At this step, the simulation shows major effects on superconductive line performances concerning:

- Influence of the nature of the ground plane: the use of a normal conductive ground plane induces much larger losses (e. g. 3 times higher at 10GHz)
- Influence of the upper conductive layer: to ensure the contacts at the two ends of the line, a silver layer was deposited on top of it. Due to proximity effects, the presence of thi upper layer is responsible for losses dramatically higher (100 times higher on the whole frequency range).

Applications to high speed circuits

In fast logic interconnections, clock signals having rise time of approximate 100ps are very usual. Therefore, interconnections must be considered as propagating lines, in this case inserted between logic gates. An equivalent circuit of the superconductive line has been developed (*) and a SPICE simulation of the whole circuit including logic gates (Fig. 1) has been performed in time domain. When a normal conductive line is used, distorsion of the waveform and attenuation in signal amplitude occur (Fig. 2A). In this case, the signal reaching point c is at the commutation threshold of gate ECL B. This may result in mulfunctions of the logic circuit. Fig. 2B shows the evolution of the same signal, but propagating on an YBaCuO transmission line (length $\mathcal{L}$=10cm). In this case, a perfect transmission is obtained.

Conclusion

SPICE simulations have demonstrated the advantages in using HTc superconductive interconnections for applications to fast logic circuits and their integration in multichips modules. Low losses of these materials enables new promising devices to be studied (delay lines, devices with controlled dispersion...)

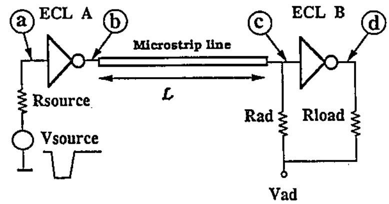

Fig. 1: Superconductive transmission line inserted into two logic gates.

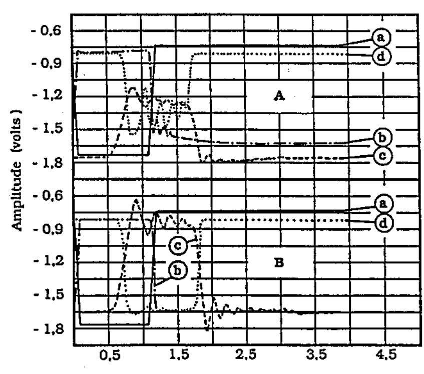

Fig. 2: Time domain signals at points a, b, c, d
A/ Normal conductor
B/ Superconductor

Tuesday PM AP-S, URSI-A Session TP07

Room: Columbus A *Time*: 1320-1700

Imaging Radar

Chairs: Gilles Y. Delisle, Laval University; Yoshio Yamaguchi, Niigata University

1320 **CROSS-RANGE VELOCITY COMPUTATION for ISAR IMAGING**
Gilles Y. Delisle, H. Q. Wu*, D. Grenier, Laval University; R. M. Turner, Defense Research Establishment Ottawa

1340 **AN APPROACH to ANGULAR MOTION COMPENSATION in ISAR IMAGERY**
Benjamin C. Flores, Alberto Ugarte*, University of Texas at El Paso

1400 **FULL 3D MICROWAVE QUASI-HOLOGRAPHIC IMAGING**
Juan-Carlos Castelli*, Francios Tardivel, ONERA

1420 **A NEAR FIELD SPHERICAL WAVE INVERSE SYNTHETIC APERTURE RADAR TECHNIQUE**
A. Broquetas*, L. Jofre, Angel Cardama, ETSE Telecomunicacio - UPC

1440 **HIGH-RESOLUTION IMAGE FORMING with BISPEKTRAL DATA PROCESSING**
A. V. Totsky*, Aviation Institute; V. Ye. Morozov, Ukrainian Academy of Sciences

1500 **SYNTHETIC APERTURE FM-CW RADAR APPLIED to the DETECTION of OBJECTS BURIED in SNOWPACK**
Yoshio Yamaguchi*, Masashi Mitsumoto, Masakazu Sengoku, Takeo Abe, Niigata University

1520 **A HYBRID APPROACH for 2-D RCS IMAGING**
M. M. Giray*, Royal Military College of Canada; S. R. Mishra, David Florida Laboratory

1540 **WIDEBAND POLARIMETRIC RADAR IMAGING**
Glafkos Kyriakos Stratis*, Vivek Naik, Wolfgang-M Boerner, University of Illinois at Chicago

1600 **VHF/UHF ULTRA-WIDE BAND SAR IMAGING of SCATTERING TARGETS in FOLIAGE**
Bennett Chan*, Jonathan D. Young, The Ohio State University

1620 **WAVELET DECOMPOSITION of UWB RADAR SIGNALS**
Ismail Jouny*, The Ohio State University

1640 **WIDEBAND ISAR SIGNATURES of GROUND VEHICLES at UHF FREQUENCIES**
Joseph W. Burns*, Environmental Research Inst. of Mich.; Donald F. Herrick, Environmental Research Inst. of Michigan; M. A. Ricoy, The University of Michigan

WIDEBAND POLARIMETRIC RADAR IMAGING

Glafkos Kyriakos Stratis, Vivek Naik and Wolfgang-Martin Boerner

THE UNIVERSITY OF ILLINOIS AT CHICAGO
Department of Electrical Engineering and Computer Science
THE COMMUNICATIONS AND SENSING LABORATORY
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Although the concept of the electromagnetic wave polarization state is strictly defined for the coherent case in the frequency domain, a "time-domain" extension of the polarization descriptors for the wide-band spectral radar target and clutter analysis is yet to be developed. The relationship of the polarization dependence of the corresponding radar cross-section matrices in the frequency domain with that of the target eigen-resonance maps is demonstrated leading to the concept of polarimetric wavelets, which offers a useful interpretative tool for polarimetric UWB target versus clutter discrimination and analysis. Utilizing available sets of multi-band (CW) spectral polarimetric scattering matrix [S] data sets in the (30) 300 MHz to 3(30) GHz region, the relevance of a "polarimetric extension" of the UWB impulse radar approach will be demonstrated with the specific aim of identifying the important wide-ranging applications of future UWB (non-carrier frequency) polarimetric impulsive radar (POL-RAD), SAR(POL-SAR), and ISAR (POL-ISAR) systems not only to Low-RCS-target analysis but much more so to under-burden (foliage/poorly conductive media) penetration for detecting hidden conducting objects (tanks, mines, etc.) and in wide area site/environmental security monitoring (due to non-detectability of carrier-free impulses by narrow-band carrier systems).

For simplicity only the monostatic reciprocal propagation and scattering cases are considered for which the resulting scattering matrices are symmetric. It is assumed that the UWB radar is a complete (coherent source) dual orthogonal $(A, B = A_\perp)$ transmit/receive antenna system of high channel isolation and high antenna sidelobe reduction. First the CW single/multiple separated carrier frequency, then the narrow and broadband and finally the purely UWB (impulsive: non-carrier) polarimetric radar cases are considered. The complete scattering matrix optimization solutions for the 2x2 complex Jones (Sinclair) $[S(A, B = A_\perp)]$, the 3x3 complex Covariance $[\Sigma(A, B = A_\perp)]$ and the 4x4 real Mueller (Kennaugh) power density matrix solutions are presented for the symmetric case $(S_{AB} = S_{BA})$. Assuming that the propagation medium is only slightly disturbed and that the polarimetric signatures are obtained at high repetition rates so that the quasi-coherent, partially polarized scattering conditions are satisfied, the solutions are extended to the multi-spectral carrier cases.

VHF/UHF ULTRA-WIDEBAND SAR IMAGING OF SCATTERING TARGETS IN FOLIAGE

Bennett Chan* and Jonathan Young
Ohio State University
ElectroScience Laboratory

The radar response, of foliage at selected narrow bands, has been studied and statistically modelled, while the wideband response behavior is not as well known. Measurements were taken of a medium-sized woodlands with a basal area of 106 sq. ft./acre, in a bandwidth from 200 MHz to 2000 MHz. The woodland was located in a temperate climate, and consisted of 100% deciduous vegetation. The data were taken in both summer and autumn. The autumn measurements were done with an estimated 10% leaf coverage. Corner reflectors were placed into the target range to study absorption.

The image process will be described. Coherent focused images are generated using an adaptation of a projection slice algorithm. Since the resolution is on the same order as the effective center frequency, the polarity of the focused image is meaningful. Plots which preserve this information will be presented.

This paper describes the results of these measurements by presenting waterfall plots and Synthetic Aperture Radar (SAR) images. Image data for VV, HH, and VH linear polarizations are presented.

Tuesday PM URSI-B Session TP08

Room: Columbus C/D *Time*: 1320-1640

Discontinuities in Waveguiding Structures

Chairs: R. F. Harrington, Syracuse University; E. F. Kuester, University of Colorado at Boulder

1320 **FINITE ELEMENT ANALYSIS of THREE-DIMENSIONAL WAVEGUIDE DISCONTINUITIES USING an EDGE ELEMENT APPROACH**
G. Wilkins*, IBM; Jin-Fa Lee, Worcester Polytechnic Institute; R. Mittra, University of Illinois, Urbana-Champaign

1340 **RESONANT PROPERTIES of the I-TYPE SLOT on WAVEGUIDE EDGE WALLS**
B. E. Pauplis*, C. J. Alexander, L. F. Kuegler, D. C. Power, Raytheon Company

1400 **ANALYSIS of CENTERED LONGITUDINAL SHUNT SLOT EXCITED by L-SHAPED POST**
S. Hashemi-Yeganeh*, Arizona State Unversity

1420 **FULL WAVE SCATTERING ANALYSIS of the JUNCTION of a CIRCULAR WAVEGUIDE and a SMALLER RECTANGULAR WAVEGUIDE**
R. H. MacPhie*, R. Deleuil, A. K. Daoudia, Universite de Provence

1440 **DETERMINATION of the SCATTERING MATRIX of CYLINDRICAL POSTS in the FOUR WALLS of RECTANGULAR WAVEGUIDES**
Odilon Maroja Filho, Luiz Costa da Silva*, Catholic University of Rio de Janeiro

1500 **Break**

1520 **DUAL BAND CORRUGATED CIRCULAR WAVEGUIDE POLARIZERS**
J. M. Rebollar*, J. Esteban, Universidad Politecnica de Madrid

1540 **EFFICIENT ANALYSIS of TRUE ARBITRARILY SHAPED IRIS with ANY THICKNESS in CIRCULAR WAVEGUIDE**
J. Garcia*, L. Valor, J. Zapata, ETSI Telecomunicacion

1600 **SINGULAR ELEMENT for EFFICIENT ANALYSIS of HOMOGENEOUS WAVEGUIDES with SHARP METAL EDGES**
J. M. Gil*, J. Zapata, ETSI Telecomunicacion

1620 **BANDWIDTH PROPERTIES of TUNER BETWEEN RECTANGULAR WAVEGUIDE and DIELECTRIC-LOADED RECTANGULAR T-SEPTUM WAVEGUIDE**
Vadim V. Yakovlev*, Russia Academy of Sciences

FINITE ELEMENT ANALYSIS OF THREE-DIMENSIONAL WAVEGUIDE DISCONTINUITIES USING AN EDGE ELEMENT APPROACH

G. Wilkins*	J. F. Lee	R. Mittra
IBM	EE Dept.	ECE Dept.
E. Fishkill Facility	Worcester Polytechnic Inst.	Univ. of Illinois

The modeling of arbitrary, three-dimensional discontinuity problems in waveguides is an important problem which lends itself to convenient analysis via the Finite element Method(FEM). One major concern in the application of the conventional FEM analysis to these problems is the appearance of the spurious modes which arise as a result of improper modeling of the null space of the *curl* operator. Bossavit and Mayergoyz (A. Bossavit & I. D. Mayergoyz, IEEE, MAG-25, 1989) have shown that the use of the edge element totally eliminates the spurious mode problem, and yet allows the satisfactory implementation of the boundary conditions. As a preamble to carrying out the waveguide analysis, it is convenient to analyze the inhomogeneously-filled cavity problem, which differs from the waveguide problem only by the way the boundary conditions are applied at the input and output ports. After presenting some representative results for the cavity problem we proceed to discuss waveguide discontinuities such as the one shown in Fig. 1. Numerical results are shown in Fig. 2 and are compared with those derived by other approaches.

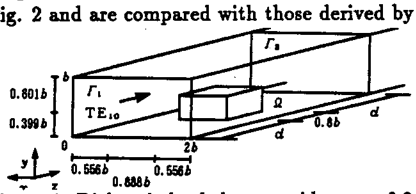

Figure 1: Dielectric-loaded waveguide: $\epsilon_r = 6.0$.

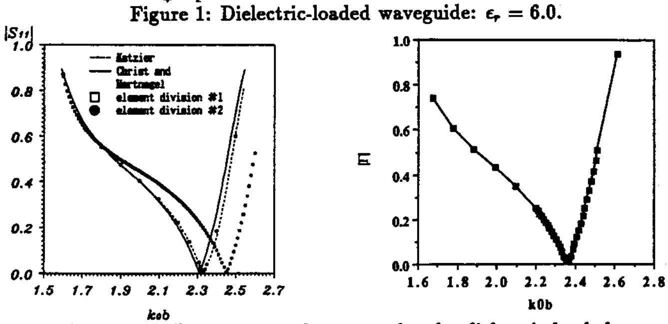

Figure 2: Reflection coefficient versus frequency for the dielectric-loaded waveguide obtained by the edge-element technique along with other approaches.

FULL WAVE SCATTERING ANALYSIS OF THE JUNCTION OF A CIRCULAR WAVEGUIDE AND A SMALLER RECTANGULAR WAVEGUIDE

R.H. MacPhie*, R. Deleuil and A.K. Daoudia
Laboratoire de Radioélectricité - Université de Provence
Avenue Escadrille Normandie-Niemen
13397, Marseille, France

This paper considers the problem of electromagnetic scattering at the junction of a circular waveguide of radius R and a smaller rectangular guide of width a and height b. As indicated in Fig.1 the two guides are aligned along the same z-axis of symmetry. This configuration is the dual of a large rectangular-to-small circular guide junction for which a full wave solution (J.D. Wade and R.H. MacPhie, IEEE Trans. MTT-34, 1085-1091, 1986) was obtained using the conservation of complex power technique (CCPT).

As before, the electric fields in each guide are expanded in terms of TE(h) and TM(e) modes and the E-fields are matched at junction :

$$E_2 = \begin{cases} E_1 \text{ , in aperture} \\ 0 \text{ , on wall} \end{cases} \quad (1) \quad \text{where : } E_i = \sum_{mn} A_{i\,mn}\, e^h_{i\,mn} + \sum_{pq} B_{i\,pq}\, e^e_{i\,pq}\ , \ \ i=1,2 \quad (2)$$

The modal orthogonality in the circular guide (guide 2) permits us to obtain the following E-field mode matching matrix equation :

$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = \begin{bmatrix} [H] & [K] \\ [Q] & [E] \end{bmatrix} \begin{bmatrix} A_1 \\ B_1 \end{bmatrix} \quad \text{or } C_2 = [M]\,C_1 \qquad (3)$$

The CCPT (R. Safavi-Naini and R.H. MacPhie, IEEE Trans. MTT-29, 337-343, 1981) is then applied to deduce the scattering matrix $[S]$ of the junction . In particular :

$$[S_{11}] = \left([Y_1] + [Y_{L1}]\right)^{-1} \left([Y_1] - [Y_{L1}]\right) \qquad (4)$$

where $[Y_i]$ is the diagonal modal admittance matrix of guide i and $[Y_{L1}] = [M]^T [Y_2] [M]$ is the load admittance matrix "seen" by guide 1 at its junction (z=0) with the larger circular guide.

Of particular interest is the evaluation of the elements of $[M]$ wherein the Bessel-Fourier fields of the circular guide are matched to Fourier-Fourier fields in rectangular guide. This is facilitated by the following "plane wave" expansion :

$$J_p(h\rho)\, e^{jp\phi} = \frac{j^p}{N} \sum_{q=0}^{N-1} e^{jq\frac{2p\pi}{N}}\, e^{-jh\left[x\cos\left(\frac{2q\pi}{N}\right) + y\sin\left(\frac{2q\pi}{N}\right)\right]} \qquad (5)$$

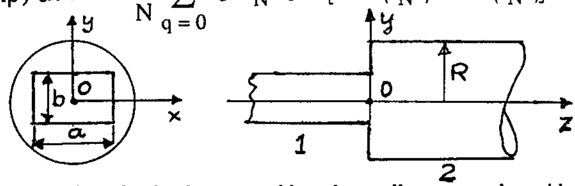

Fig. 1. Junction of a circular waveguide and a smaller-rectangular guide.

Determination of the Scattering Matrix of Cylindrical Posts in the Four Walls of Rectangular Waveguides

Odilon Maroja Filho and Luiz Costa da Silva*
Pontifícia Universidade Católica do Rio de Janeiro
Rua Marquês de São Vicente, 225-Gávea - RJ - BRAZIL

A model was developed for the determination of the scaterring matrix of cylindrical posts in the four walls of a rectangular waveguide (filter cell for circularly polarized signals), as shown in Fig.1.

As an intermediate step it was analysed the case of only two vertical posts. The scattering matrix was obtained solving an equivalent problem, where the gap between the posts was replaced by a metallic wall and magnetic current densities. The electric currents induced on the post, and the magnetic current densities, were determined by the moment method. The scattered fields were calculated using images and the diadic Green's function for the cylindrical cavity internal to the gap .

For the case of posts in the four walls of the waveguide, the moment method was applied again. The current induced on the vertical posts were calculated using the same technique described above and ignoring the presence of the horizontal posts. The currents on the horizontal posts were determined in a similar way, but assuming incident on them the wave incident in the waveguide and the wave scattered by the vertical posts.

Numerical results show very good agreement with measurements. An example is shown in Fig. 2 (four posts with radius of 3.17mm, height of 10mm in a square waveguide of 45.8mm). Discrepancies between theory and experiment (for post heights of 5, 10 and 15mm) are less than 5% in the amplitude and less than 4^{o} in the phase of the reflection and transmission coefficients.

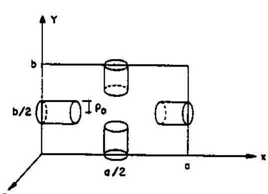

Fig. 1. Geometry of the posts

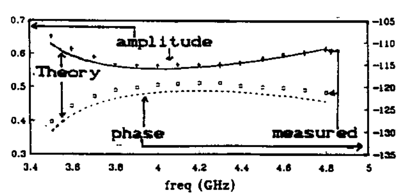

Fig. 2. Reflection coefficient as a function of frequency

DUAL-BAND CORRUGATED CIRCULAR WAVEGUIDE POLARIZERS

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ETSI Telecomunicación. Universidad Politécnica de Madrid
28040-Madrid. España.

Antennas with circular polarization are widely employed in satellite communications (TT & C antennas, Direct Broadcast TV, etc). The waveguide polarizer is the device which provides the required circular polarization in these antennas. Different structures have been employed as polarizers in square and circular waveguides depending on the type of horn. For example, corrugated square waveguide polarizers are used for pyramidal horn antennas, meanwhile pin circular waveguide and corrugated circular waveguide polarizers are used for conical horns.

The design of dual-band polarizers in circular waveguide becomes a very difficult task, independently of the chosen structure, when the frequency distance between the both bands is large. A corrugated structure containing rectangular and circular waveguide sections is considered in this paper to design dual-band polarizers with input and output circular waveguides. The basic discontinuity of the proposed structure, i.e. the circular-to-rectangular waveguide discontinuity, is analyzed by mode-matching in order to obtain its Generalized Scattering Matrix (GSM). Since all the integrals to be evaluated are analytical, the GSM is efficiently and accurately computed.

Modal dispersion characteristics of this corrugated structure are calculated using the admittance multimode parameters and the Floquet's theorem. A computer program has been developed to calculate the dispersion diagram ß-f for the two fundamental modes (vertical $ß_v$ and horizontal $ß_h$ polarization) as a function of the geometrical dimensions of the corrugated structure. The initial design rule is that the dimensions of the corrugated structure satisfy the following relationship: $ß_v(f_1)-ß_h(f_1) = ß_v(f_2)-ß_h(f_2)$, where f_1 and f_2 are the central frecuencies of the two desired bands. The geometrical dimensions of the polarizer, containing a finite number of corrugations, are obtained by means of an optimization program, that minimizes an error function which takes into account the reflection coefficients for the two polarizations and the differential phase shift $\pm 90^o$, at a finite number of frecuencies in both bands. In order to improve the electrical performances of the polarizer, additional degrees of freedom are introduced allowing the dimensions of the corrugations to be different.

Dual-band polarizers in K_u band have been designed. Excellent electrical performances have been predicted and some examples will be presented.

EFFICIENT ANALYSIS OF TRUE ARBITRARILY SHAPED IRIS WITH ANY THICKNESS IN CIRCULAR WAVEGUIDE

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Until this time the equivalent susceptance of a transversal iris to a waveguide has been broadly solved by means of polarizability concept based on Cohn's measurement, or static aproximations from several authors, for a number of different shapes. Only a few shapes has close-form solution.

Recently (J. Zapata *et alt.*,URSI SYM. 1991, London,Canada) it has been proved that a hybrid Finite Element Method - Mode Matching (FEM/MM) procedure is a suitable and very eficient tool for the analysis of discontinuities between arbitrarily shaped hollow waveguides.

In this work is presented the application of that FEM/MM procedure to solve the iris type problem taking properly into acount the non zero thickness of the transverse wall and the frequency dependence of the susceptance of any true arbitrarily shaped aperture.

In order to test the above method, it has been applied to calculate parameters of a number of iris with differents shapes. In all the cases a very good agreement with measurement, or with parameters obtained by other methods, has been found. As a sample can be presented the following data:

In fig. 1 the VSWR of a rectangular slot, with non zero thickness, beetween a rectangular and a circular waveguide is conmpared with measured data (B. N. Das, *et alt.*, MTT-39, Feb. 1991, pp. 357-359).

A rounded end slot in circular waveguide has been analyzed for several thickness. In fig. 2 is shown its susceptance for zero thickness, comparing our computed values with obtained by means Cohn's approach and Eastham's formulas (G. Eastham, *et alt.*, MTT-39, Apr. 1991, pp. 718-723).

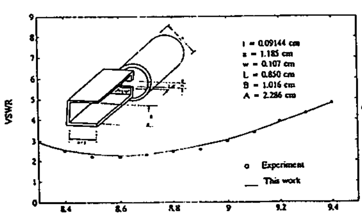

fig. 1

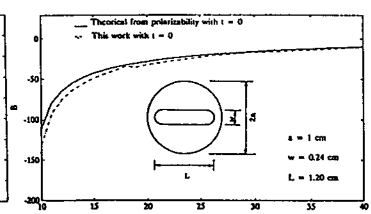

fig. 2

SINGULAR ELEMENT FOR EFFICIENT ANALISYS OF HOMOGENEOUS WAVEGUIDES WITH SHARP METAL EDGES

* J.M.Gil, J.Zapata
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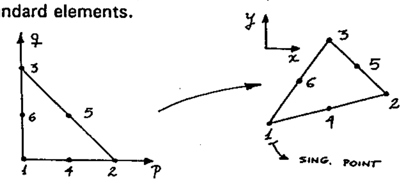
28040 Madrid Spain

In problems with field singularities due to the presence of reentrant corners, as it is well known, convergence rate for a Finite Element Method (FEM) solution for Helmholtz's equation, depends on nature of the solution near the singular points. Waveguides with sharp metal edges may be analyzed more efficiently by using singular elements that allows take into account more properly such field singularities.

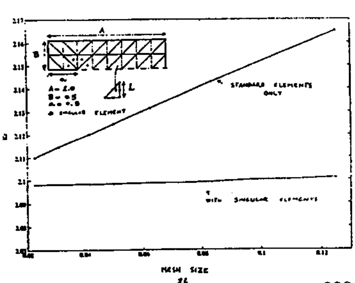
This work is concerned with the improvement of the convergence rate for a FEM solution when employing singular elements to the analysis of homogeneous waveguides when the cross-section has sharp metal edges. The singular elements used in this work are based on the modification of the geometrical transformation for a standard isoparametric finite element, obtaining elements for which the Jacobian vanishes at the singular points (see figure). Such approach can be applied to field singularities of any order.(Wait, R. Comp. Meth. Appl. Mech. Engineering 13 1978 141-150).

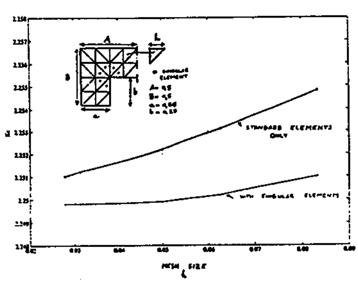
Following the above procedure, it has been analysed several homogeneous waveguides with reentrant corners of angles 2π, and $3\pi/2$, which has field singularities. The eigenvalue for several singular modes has been obtained. As an example, in the figures it can be seen some results obtained using this approach. In order to show the dramatic improvement on the convergence rate for K_c of the first TE singular modes, in the figures has been present also the values computed by means of standard elements.



$$x-x_1 = [(x_2-x_1)p+(x_3-x_1)q]\,(p+q)^{m-1}$$

$$y-y_1 = [(y_2-y_1)p+(y_3-y_1)q]\,(p+q)^{m-1}$$





BANDWIDTH PROPERTIES OF TUNER BETWEEN RECTANGULAR WAVEGUIDE AND DIELECTRIC-LOADED RECTANGULAR T-SEPTUM WAVEGUIDE

Vadim V. Yakovlev
Institute of Radioengineering and Electronics, Russia Academy of Sciences, 18 Marx Ave., GSP-3, Moscow 103907 Russia

Rectangular T-septum waveguide (RTSW) is known as an efficient element of microwave technology because of increased values of cutoff wavelengths, bandwidth and electric-field strength. Practical using of RTSW is rather difficult without mode matching of it and ordinary standard waveguide - in particular, rectangular waveguide (RW). Furthermore, a lot of real devices made on the basis of RTSW such as attenuators, absorbing loads, microwave ovens, etc contain dielectric filling in the region of capacity gap. Then the problem of matching RW and partially loaded RTSW is to be solved.

In the report two stages of solving are considered. The first actual configuration of linear (or nonlinear) tuner between the two hollow system of RW and RTSW is chosen by graphoanalytical operations on a special nomogram (Kolomeytsev, Yakovlev, Telecomm.Radio Engng.2, Radio Engng. 45(2), 1990). Fig.1 shows normalized cutoff wavelengths of dominant (λ_{c1}) and first higher (λ_{c2}) modes versus longitudinal coordinate z in linear tuner with length L. On it a and b are an internal sizes of RTSW, a_o is a wide wall of RW, and t, d are the width and height of RTSW capacity gap. It is clear from these curves that both the cutoff regime and the multimode one may appear. Only nonlinear variation at least one of tuner dimension can provide a transmission of dominant band from RW to RTSW.

Afterwards regular RTSW unit with nonregular dielectric load between the wide wall and the top of T-septum is to be taken into consideration. An original program based on finite-element method was built and used to obtain the bandwidth properties of the structure. So in spite of impossibility to transmit a hollow RTSW band without any changing it may be create a conditions for single mode regime. To do it the permittivity of material should not prevaile any value ε_m. In Fig.2 these values are plotted against d/b. Note that ε_m is increased as a result of increasing the sizes of capacity gap.

The results could be used in the design of efficient microwave devices on the rectangular T-septum waveguide.

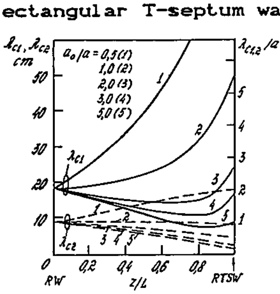


Fig.1

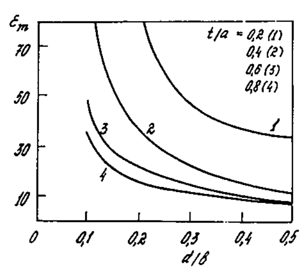


Fig.2

Tuesday PM1 URSI-B Session TP10

Room: Columbus G *Time*: 1320-1500

Symmetry, Scaling and Groups II

Organizer: Dwight L. Jaggard, University of Pennsylvania
Chairs: Dwight L. Jaggard, University of Pennsylvania; A. Le Mehaute, Alcatel Alsthom Recherche

1320 **AN INTRODUCTION to WAVELETS**
Benjamin B. Wells*, Science Applications International Corp.

1340 **WAVELET REPRESENTATIONS for SELF-SIMILAR SIGNALS and SYSTEMS**
Gregory W. Wornell*, Massachusetts Institute of Technology

1400 **DIFFRACTION by CANTOR TARGETS: THEORY and EXPERIMENT**
T. Spielman*, Dwight L. Jaggard, University of Pennsylvania

1420 **SCATTERING and ABSORPTION of ELECTROMAGNETIC RADIATION by RANDOM FRACTAL CLUSTERS of PARTICLES**
Kung-Hau Ding*, New Mexico State University

1440 **RENDERING DIFFRACTION in GRATINGS and FRACTALS**
Dan Sandin*, Craig Barnes, University of Illinois at Chicago

AN INTRODUCTION TO WAVELETS

Benjamin B. Wells
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The recent popularization of wavelets has caused a stir in several engineering, physical sciences, and mathematics communities. Applications that involve traditional Fourier analysis are being reviewed to determine whether wavelet analysis might improve the outcomes, or at least increase computational efficiency. For some applications the results of this review have been favorable.

One of the reasons for the interest in wavelet analysis is the number of diverse subjects that it touches and incorporates into a single framework. A few that come to mind are: Shannon sampling, the uncertainty principle, the coherent states of mathematical physics, and time-frequency analysis. Many traditional expansions both orthogonal and non-orthogonal have many of the properties of a wavelet expansion. For example, expansions in terms of the Hermite functions, the prolate spheroidal functions, and the Gabor functions are in the spirit of wavelet expansions.

The recent history of the subject is generally acknowledged to have begun in 1982 with an analysis of seismic data by J. Morlet. The subject was then taken up by a group of French mathematicians, notably A. Grossmann and Y. Meyer, and incorporated into the body of mathematics known generally as harmonic analysis. In 1985 Y. Meyer constructed a continuous wavelet whose associated wavelet family forms an orthonormal collection of functions. The subject was then "rediscovered" by engineers and physicists who have been working out the applications.

The definiton of a wavelet family begins with a function $w(t)$ defined on the real line and having total energy equal to one. It is assumed that w has good localization in both time (or space) and frequency. The wavelet family generated by w is obtained by successive translations of w by an integer followed by dilations by an integer power of two. The wavelet family is double indexed by the successive operations:

$$w_{m,n}(t) = 2^{m/2} w(2^m t - n) ; \; m,n = 0, \pm 1, \pm 2, \dots .$$

The interesting and sometimes difficult part of the construction is to determine w such that the wavelet family $\{w_{m,n}\}$ is orthonormal and allows for the efficient representation of some class of functions. Orthonormality is a convenience and allows for easy calculation of the wavelet coefficients in the traditional way. We shall present examples of wavelet families and illustrate data compression and signal filtering by wavelet analysis.

Wavelet Representations for Self-Similar Signals and Systems

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Orthonormal wavelet bases, i.e., orthonormal bases in which the basis functions are all dilations and translations of a single prototype function, are in many respects, ideally suited for the synthesis, analysis, and processing of some broad classes of self-similar signals and systems.

For the $1/f$ family of self-similar random processes, orthonormal wavelet basis expansions are effectively Karhunen-Loève-type expansions. The $1/f$ processes—processes whose sample functions exhibit both statistical scale-invariance and a special kind of stationarity—model an extraordinarily broad range of natural and man-made phenomena. Because the coefficients of wavelet expansions of such processes are virtually uncorrelated, extremely efficient algorithms can be developed for analyzing and processing $1/f$ data. For example, a number of fundamental problems of detection and estimation involving $1/f$ processes can be addressed using a wavelet-based framework.

Orthonormal wavelet bases also provide highly efficient representations for classes of self-similar signals characterized by a *deterministic* scale-invariance relation. In particular, through wavelets it is possible to derive orthonormal self-similar bases for these signals. Synthesis of such signals, which generalize the well-known homogeneous functions, is potentially important in a range of engineering applications, including remote sensing and communications. In fact, in the communications context, wavelet expansions lead to an efficient strategy for embedding information into a self-similar signal on all time scales. The resulting "fractal modulation" strategy is naturally suited for use with noisy channels of unknown duration and bandwidth.

Many classes of self-similar signals can be described in terms of the outputs of self-similar systems driven by random or deterministic inputs. Wavelet transformations also lead to canonic representations for an important family of self-similar systems—specifically, linear systems that are jointly scale-invariant and translation-invariant. In turn, such representations play an important role in understanding, characterizing, and implementing these systems.

DIFFRACTION BY CANTOR TARGETS: THEORY AND EXPERIMENT

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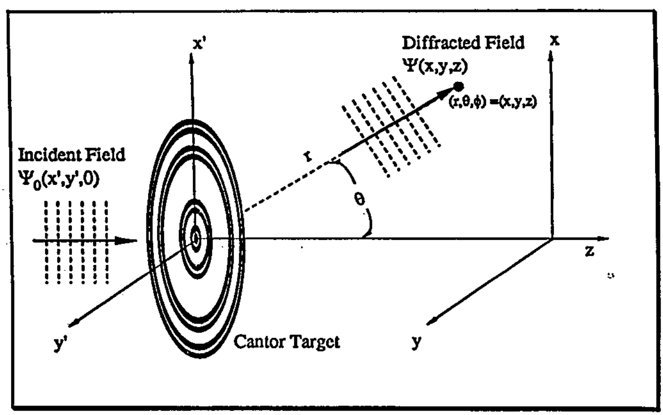
Fractal electrodynamics combines classic electromagnetic theory with the recursive properties of fractal geometry [see e.g., D. L. Jaggard, "Fractal Electrodynamics," in *Recent Advances in Electromagnetic Theory,* H. N. Kritikos and D. L. Jaggard, eds., Springer-Verlag (1990)]. Electromagnetic waves can be used to remotely gather information on the fractal nature of a surface via observation of the scattered fields. Here, the wavelength of the incident fields is used as a variable yardstick to interrogate the multi-scale nature of the fractal surface or aperture.

We investigate the Fraunhofer diffracted fields for a target with azimuthal symmetry whose radial transfer function is a hybrid of the classic Cantor Set. Examination of the diffraction patterns for various stages of growth and differing fractal dimension provide the variable-length yardstick needed to fully describe fractal geometries. Closed-form, recursive solutions are given for the diffracted fields as well as some nonrecursive solutions for a specified subset of these Cantor targets. Numerical solutions are also examined as substantiation of the analytical solutions. Experiments in the optical regime provide further verification of the solutions.



Problem Geometry: Diffracted field Ψ from a fractal aperture as a function of scattering angle θ for a time harmonic incident plane wave Ψ_0.

SCATTERING AND ABSORPTION OF ELECTROMAGNETIC RADIATION BY RANDOM FRACTAL CLUSTERS OF PARTICLES

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Fractal clusters of particles result from a variety of physical processes, such as aggregation, solidification, and polymerization. Generally, the fractal objects have the porous, ramified, and tenuous structures, and the important properties of noninteger dimension and invariance under scale transformation. The aerosols in atmosphere are often random clusters of small primary particles with ramified and connected appearance. They are considered to be fractal aggregates and the essential fractal morphology has already been demonstrated for soot and smoke.

The aggregation process of small primary particles is simulated by applying the cluster-cluster aggregation (CCA) algorithm. In this model, the primary particles undergo random walk simultaneously to form small clusters initially, and subsequent collisions will lead to their aggregation. The fractal dimensions of resultant agglomerates are determined by finding out the power form relationship between the number of primary particles and the cluster gyration radius. The self-similarity characteristics are analyzed by considering the pair correlation among positions of monomers. In spite of the low density of aggregates, the close proxmity of primary particles may impose strong interactions among them. To study the scattering and absorption behavior of electromagnetic waves by such fractal aggregates, a rigorous T-matrix approach together with the translation addition theorem for vector spherical waves, taking into account the features of discrete primary particles, is employed to solve the aggregate scattering problem.

Rendering Diffraction in Gratings and Fractals

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A large part of computer graphics deals with the generation, or "rendering" of images. One way of rendering an image, is to determine how light interacts with a "scene". Even though this technique is used almost exclusively, the wave properties of light have almost been completely ignored.

The two most common approaches to "realistically" render a scene are ray tracing and radiosity. Ray tracing as the name implies, treats light as rays, which are shot into a scene, and return color information based on the interaction of the rays with the scene. The second method, radiosity subdivides a scene into segments, call patches, then at each patch, the incoming energy from every other patch in the scene is computed. While both methods can produce strikingly realistic images, both completely ignore the wave properties of light, raytracing by treating light as rays, and radiosity by considering only energy.

Diffraction is a case that requires consideration of light as waves, as a result the traditional methods must be modified or scrapped completely to produce correct results. Diffraction exists in both biological (butterfly wings, bird feathers) and manufactured (compact disc, gratings) materials, in addition diffraction can be considered when rendering fractals.

Our approach to rendering diffraction has been two-fold. One approach has been to modify ray tracing to use analytic solutions for simple cases such as diffraction gratings. For other cases, such as fractals, we integrate Frenel's equations by extreme subsampling and summing the magnitude and phase of the rays. Both methods take into account the wave properties of light in order to render diffraction and interference more correctly.

Tuesday PM URSI-B Session TP11

Room: Columbus H *Time*: 1320-1700

Finite Element Analysis of Complex Bodies

Chairs: A. F. Peterson, Georgia Institute of Technology; Robert Lee, The Ohio State University

1320 **A FINITE ELEMENT TECHNIQUE for SOLVING an ELECTRICALLY LARGE TWO DIMENSIONAL ELECTROMAGNETIC SCATTERING PROBLEM**
V. Chupongstimun*, Robert Lee, The Ohio State University

1340 **A PARTITIONING APPROACH to the ELECTROMAGNETIC CHARACTERIZATION of LARGE TWO-AND THREE DIMENSIONAL STRUCTURES**
C. T. Spring*, A. C. Cangellaris, University of Arizona

1400 **AN EFFICIENT FINITE ELEMENT METHOD for DETERMINING the SCATTERING from LOSSY CYLINDERS USING the IMPEDANCE BOUNDARY CONDITION and an ABSORBING BOUNDARY CONDITION**
R. K. Gordon*, Ahmed A. Kishk, University of Mississippi

1420 **FINITE ELEMENT ANALYSIS of INHOMOGENEOUS, AXIS-SYMMETRIC RADOMES**
R. K. Gordon, University of Mississippi; R. Mittra, University of Illinois, Urbana-Champaign

1440 **A FINITE ELEMENT FORMULATION for TREATING ELECTROMAGNETIC SCATTERING by ANISOTROPIC BODIES of REVOLUTION**
A. Khebir*, A. B. Kouki, F. M. Ghannouchi, Renato G. Bosisio, Ecole Polytechnique de Montreal

1500 **Break**

1520 **FINITE ELEMENT ANALYSIS of 2D HETEROGENEOUS SCATTERERS INCORPORATING QUADRATIC TANGENTIAL-VECTOR BASIS FUNCTIONS and a LOCAL RADIATION BOUNDRY CONDITION**
A. F. Peterson*, Georgia Institute of Technology

1540 **CHARACTERIZATION of a CLASS of AXIALLY SYMMETRIC RADOMES USING a FINITE ELEMENT - BOUNDARY INTEGRAL TECHNIQUE**
J. D. Collins*, John L. Volakis, The University of Michigan

1600 **FULL WAVE ANALYSIS of ARBITRARILY SHAPED STRUCTURES USING the FINITE ELEMENT METHOD**
Jean Dallaire*, A. Khebir, Renato G. Bosisio, Ecole Polytechnique de Montreal

1620 **MODIFIED BOUNDARY ELEMENT TECHNIQUE for EIGENVALUE PROBLEMS**
Bin Song*, Junmei Fu, Xi'an Jiaotong University

1640 **APPLICATION of MODIFIED INDIRECT BOUNDARY ELEMENT METHOD to ELECTOMAGNETIC FIELD PROBLEMS**
Bin Song*, Junmei Fu, Xi'an Jiaotong University

A FINITE ELEMENT TECHNIQUE FOR SOLVING AN ELECTRICALLY LARGE TWO DIMENSIONAL ELECTROMAGNETIC SCATTERING PROBLEM

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Finite element analysis has become a powerful numerical technique in the study of electromagnetic wave problems. In the two dimensional electromagnetic scattering problem, for an electrically large body, the number of unknowns becomes excessively large. This fact makes the problem computational intensive and often inaccurate. One technique for solving a very large matrix is the conjugate gradient method. However, with this method, the matrix can become ill-conditioned even with a pre-conditioning scheme. Instead, a new technique has been developed to solve this problem accurately and efficiently.

In the new approach, the electrically large body is divided into many quadrilateral segments. Each segment will be solved independently using the original finite element method where the interior boundaries are expanded as the summation of cosine and sine series with the unknown coefficients. Applying the continuity of the tangential magnetic fields at each interior boundaries reduces the numbers of unknown coefficients. Since each interior boundary is shared by two segments, the solutions at the boundary obtained by these two segments must be equal. This generates a set of equations which couples the segments. Integrating these equations with a set of weighting function at the boundary will generate a matrix equation. A large banded matrix (associated with all the unknown coefficients) can be generated from the multiple interior solutions at the boundaries. This matrix is solved by the use of riccati transform. The scheme mentioned above is first tested on an elongated body with X uniform segments and $X-1$ interior boundaries. A modified formulation is then implemented to handle an arbitrary two dimensional body. The advantage of this technique is that it takes less computational time. Based on the LU decomposition of a full matrix, the computational time is $O(N^3)$ (N=number of unknown). However, for this technique assuming that the body is divided into X uniform segments, the computational time is $O(\frac{N^3}{X^2})$. Since FEM has a banded matrix, the computational time is $O(NB^2)$ (B=bandwidth). This will further improve our computational time because B for the segment is small. Consequently, this approach will be able to solve a large two dimensional electromagnetic scattering problem efficiently.

A PARTITIONING APPROACH TO THE ELECTROMAGNETIC CHARACTERIZATION OF LARGE TWO- AND THREE-DIMENSIONAL STRUCTURES

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A partitioning method is proposed for the electromagnetic modeling of electrically large structures. The total structure under consideration is partitioned appropriately into smaller regions for which solutions to Maxwell's equations can be obtained subject to Dirichlet and/or generalized Neumann boundary conditions on the physical and artificial (partition) boundaries. Since the subregions are decoupled, the associated boundary value problems can be solved in parallel. Finally, by invoking appropriate field continuity relations at the partition boundaries, a linear system of equations is formed which is solved for the fields throughout the entire structure. The partitioning of the structure is such that the final matrix is banded and can be inverted efficiently using the Ricatti transform method.

The advantages of the proposed method are improvements in flexibility, accuracy, and timesavings over conventional methods. Gains in flexibility are made by being able to model each region using the most appropriate numerical method and by simplifying the task of numerical grid generation by working with smaller, less complicated regions. Gains in accuracy are made by reducing numerical phase error, since the electrical size of the regions for which a numerical solution is obtained using discrete methods is controlled. Furthermore, the ill-conditioning associated with very large matrices is avoided. Gains in timesavings are made by inverting smaller matrices and by avoiding multiple analysis of subregions which have the same geometry and media characteristics. Finally, the solution algorithm for the proposed method is ideally suited for parallel processing.

Two-dimensional studies of parallel-plate waveguiding structures with multiple discontinuities demonstrate the advantages of the proposed technique. For a parallel-plate waveguide, thirty wavelengths long, a timesavings of a factor of ten was obtained (without utilizing the parallel-processing features of the method) when the proposed method in combination with finite elements was used instead of a standard finite element solution of the entire structure. Further studies are performed in three dimensions to illustrate the suitability of the method for the electromagnetic analysis of large structures of high complexity.

AN EFFICIENT FINITE ELEMENT METHOD FOR DETERMINING THE SCATTERING FROM LOSSY CYLINDERS USING THE IMPEDANCE BOUNDARY CONDITION AND AN ABSORBING BOUNDARY CONDITION

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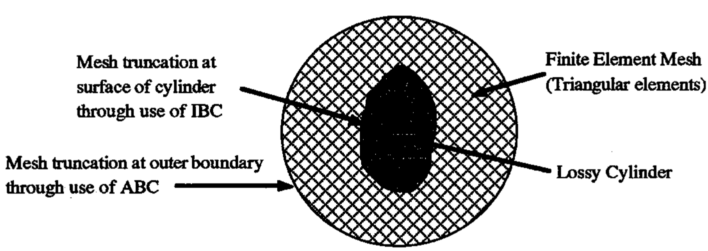
The concept of the impedance boundary condition (IBC) has been used extensively in numerical techniques based on integral equation formulations. In those cases where the IBC closely approximates the exact boundary condition, its use can result in a dramatic reduction in the number of unknowns needed in the numerical solution procedure. In this paper we discuss the use of the IBC concept in a partial differential equation formulation. We will present a technique for solving electromagnetic scattering problems that is based on the use of a finite element method that employs the IBC and an absorbing boundary condition (ABC). Such a technique is particularly attractive for problems in which both inhomogeneous and large, lossy objects are in the problem domain; the presence of the inhomogeneous objects makes the use of the finite element method advantageous; the use of the IBC at the surface of the large lossy objects obviates the extension of the finite element mesh into the interior of these objects and thus dramatically reduces the number of unknowns; and the use of the ABC allows mesh truncation without an increase in the bandwidth of the finite element matrix.

We will present results for the use of this technique in the determination of the scattering from lossy cylinders. It will be shown that through the use of both the IBC and an ABC it is possible to determine the scattering from large, lossy targets in an efficient manner. Numerical results for both TE and TM scattering from several geometries will be presented to demonstrate this method.



FINITE ELEMENT ANALYSIS OF INHOMOGENEOUS, AXIS-SYMMETRIC RADOMES

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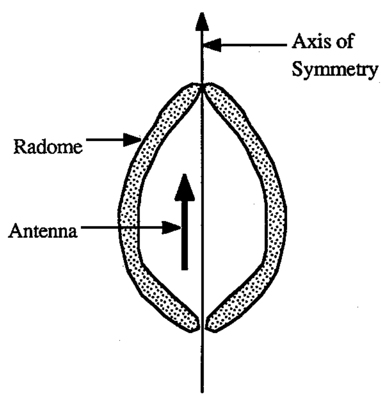
The problem of predicting the radiation pattern distortion introduced by a dielectric radome of arbitrary profile is an important one that arises frequently in the design process of the radome, but has not been addressed numerically rigorously until quite recently. Gordon & Mittra (URSI Symposium Digest, 1991) presented a technique for using the finite element method (FEM) in conjunction with the reciprocity theorem to analyze inhomogeneous, axis-symmetric radomes. In this approach, the finite element method is used to solve a pair of partial differential equations satisfied by the coupled azimuthal potentials (CAPs) introduced by Morgan and Mei. Because the Bayliss-Turkel type of absorbing boundary condition does not lend itself to generalization to these potentials, an asymptotic boundary condition obtained from Wilcox's expansion for the scattered field is used to truncate the finite element mesh.

The initial step in the procedure is to use the finite element method to find the fields in the vicinity of the radome when it is illuminated by a distant source. Then, using these fields along with the current distribution on the antenna, the far-field pattern of the antenna within the radome is determined via an application of the reciprocity theorem.

In the above-mentioned paper, the algorithm just described was used to determine the far-field pattern of a single test dipole located inside an axisymmetric radome. In this paper, we generalize the procedure and illustrate its application to more general antenna configurations including arrays.



A FINITE ELEMENT FORMULATION FOR TREATING ELECTROMAGNETIC SCATTERING BY ANISOTROPIC BODIES OF REVOLUTION

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A three-component finite element formulation for solving electromagnetic scattering by isotropic bodies of revolution was developed and, successfully, applied for various objects with complex shapes and material properties including those having sharp edges, curved surfaces, and high aspect ratios (A. Khebir, J. D'Angelo, and J. Joseph, IEEE-AP to appear). In this work, we extend the formulation to include objects made of, or coated with anisotropic materials. This formulation avoids the use of the so called coupled azimuthal potentials (CAP's) introduced by Morgan, Chang, and Mei (M. A. Morgan, S. K. Chang, and K. K. Mei, IEEE-AP 25, 413-417, 1977). It directly solves for all three components of either the electric or magnetic field using a node-based finite element approach. Hence, it avoids the use of numerical derivatives to determine the non-azimuthal components of the field, and lends itself to the use of a direct vector absorbing boundary condition which does not increase the bandwidth of the matrix. In addition, since all field components are solved for at once, a harmonic expansion, based on Stratton spherical wave functions, is used to accurately determine the radar cross section for scattering problems or antenna gain for radiation problems.

The formulation is based on the following decomposition of the field and the weighting function,

$$\mathbf{H}(\rho,\phi,z) = \sum_{m=-\infty}^{\infty} \mathbf{H}_m(\rho,z)\, e^{jm\phi} \tag{1}$$

$$\mathbf{W}(\rho,\phi,z) = \sum_{m=-\infty}^{\infty} \mathbf{W}_m(\rho,z)\, e^{-jm\phi} \tag{2}$$

Further details of the formulation as well as results for various scatterers made of, or coated with anisotropic materials, will be presented.

FINITE ELEMENT ANALYSIS OF 2D HETEROGENEOUS SCATTERERS INCORPORATING QUADRATIC TANGENTIAL-VECTOR BASIS FUNCTIONS AND A LOCAL RADIATION BOUNDARY CONDITION

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Recently, vector interpolation functions ("edge elements") of various polynomial orders have been proposed for the finite element discretization of the vector Helmholtz equation. These basis functions permit a systematic realization of the mixed-order function spaces introduced by Nedelec (J. C. Nedelec, *Numer. Math.*, vol. 35, pp. 315-341, 1980). When used to discretize the curl-curl form of the vector Helmholtz equation, these basis functions separate the nullspace of the operator from the desired solutions and therefore eliminate spurious modes in cavity and waveguide formulations. Although the lowest-order tangential-edge vector basis functions have zero divergence, this is not a general property of the higher-order polynomials and is not directly related to the ability to eliminate spurious modes. The linear-order edge elements have been described by many authors; quadratic tangential-edge vector basis functions have only recently appeared in the literature (J. -F. Lee, D. -K. Sun, and Z. J. Cendes, *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1262-1271, Aug. 1991).

This paper presents a 2D scattering formulation incorporating quadratic tangential-vector basis functions to discretize the curl-curl form of the vector Helmholtz equation. A local vector radiation boundary condition is imposed on a circular boundary surrounding the scatterer. The theoretical formulation will be described, including the development of the basis functions and the radiation boundary condition. Numerical results for cavities illustrate the complete absence of spurious eigenfunctions that can corrupt scattering formulations. Scattering results obtained using linear and quadratic vector basis functions will be used to demonstrate the superior accuracy of the quadratic functions. Vector basis functions have discontinuous normal components at cell boundaries, prompting past questions regarding the behavior of numerical solutions in homogeneous regions and at material interfaces. Results demonstrate that the quadratic vector basis functions closely approximate continuous fields in homogeneous regions and accurately model jump discontinuities at interfaces. Finally, we discuss the performance of a complex-valued version of the sparse matrix algorithm Y12M when used to treat the finite element system arising from the vector formulation. Computational requirements are often similar for a given number of linear and quadratic basis functions, suggesting that the extension to the quadratic case can produce improved accuracy with minimal additional cost.

CHARACTERIZATION OF A CLASS OF AXIALLY SYMMETRIC RADOMES USING A FINITE ELEMENT – BOUNDARY INTEGRAL TECHNIQUE

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A class of axially symmetric radome structures are analyzed using the Finite Element – Boundary Integral technique (FE–BI). By virtue of the finite element method, this formulation permits the characterization of composite bodies of revolution comprised of metal and material sections, possibly anisotropic. Moreover, by terminating the finite element mesh with our exact boundary integral, there is no compromise in accuracy.

The FE–BI method is implemented by discretizing the Coupled Azimuthal Potential (CAP) equations [Morgan et. al., *IEEE Trans. Antennas Propagat.*, pp. 413-417, May 1977] in the usual manner leading to a sparse matrix. The mesh is terminated on an artificial right circular cylindrical enclosure on which a discrete version of the Stratton–Chu integral equation is imposed to ensure the outgoing nature of the fields. The employed enclosure ensures that some of the integrals are convolutional and are thus amenable to evaluation via the FFT in an iterative solution scheme. Use of the FFT also permits a reduction in the storage requirement of the full matrix to $O(N)$.

The interior resonances associated with the integral equation are eliminated by two simple methods. One involves a simple reformulation of the problem in terms of the scattered field, instead of the usual total field formulation. The second involves a "complexification" method [Murphy et. al., *J. Appl. Phys.*, pp. 6061-6065, 1990] where a small loss is introduced in the otherwise free space medium. The performance of the two methods are compared and discussed.

This method is employed to characterize multilayered radomes with metallic bulkheads. Also included are resistive cards and impedance boundary conditions. Finally, the method's attributes are discussed.

FULL WAVE ANALYSIS OF ARBITRARILY SHAPED STRUCTURES USING THE FINITE ELEMENT METHOD

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The present work consists mainly in analyzing non-homogeneous, anisotropic and lossy microwave transmission structures where the physical shape of the circuits and the number of conductors and dielectrics are arbitrary. The finite element method (FEM) is able to support the above constraints, and it has therefore been chosen for the present study. An unresolved problem with the FEM is the treatment of interfaces (dielectric to dielectric, dielectric to electric or magnetic wall) having an arbitrary direction. In a cartesian coordinate system, it is well known that such interfaces are problematic when they are not aligned with the X-Y axes. The present study assumes no such alignment.

Different formulations are available to perform a full wave analysis. The first used is called $E_z - H_z$; it was introduced by Daly in 1971. In this case, one represents the fields E_z and H_z by simple scalar potentials, but the results contain spurious solutions. Later the vectorial Helmholtz-like formulation was proposed by Konrad in 1976 to solve for all components of the electric or magnetic field. Hermitian polynomials were then used with this formulation by Israel et al. in 1990. This approach guarantees a divergence-free electromagnetic field in each element because of the continuity of the field derivatives and consequently the spurious solutions disappear. However, this formulation is complex and problematic near the boundaries. Another way to eliminate spurious solutions is the use of tangential vector FEM developed by Jin-Fa Lee in 1990. The difficulty to increase the order of the interpolation polynomials and the large space to store them, as compared to the node-based formulation, was a sufficient reason to reject the choice of a vector-based formulation. Two methods are available to eliminate the spurious solutions and still keep the simplicity of the node-based FEM: the penalty method and the reduction method. The penalty method has the disadvantage of involving an arbitrary scalar number called p. This number p multiplies the divergence-free term added in the global formulation and gives a relative importance to this term in the functional. In spite of recent work by Paulsen and Lynch in 1991 using the above approach, p is not known a priori and we found the method non-attractive. The second method to eliminate spurious solutions, in the node-based FEM, is to represent H_z in term of H_x and H_y with the divergence-free equation, $\nabla \cdot \vec{B} = 0$, in the magnetic vectorial Helmholtz formulation. The method was proposed by Hayata (K.Hayata et al., IEEE-MTT, Vol.34, No.11, november 1986) and it has been chosen for the present work.

We present a new approach to treat boundaries and interfaces with an arbitrary normal in conjunction with the functional developed by Hayata et al. The consideration of interfaces and boundaries requires to find the normal and the tangential components of the field to apply the well known continuity conditions afterwards. The simplicity of Lagrange polynomials in the node-based FEM is used to easily increase element order. It is then very easy to represent any curved shape and to solve for full wave without any spurious solution.

MODIFIED BOUNDARY ELEMENT TECHNIQUE FOR EIGENVALUE PROBLEMS

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Boundary Element Method(BEM) has already been accepted as a powerful analytical tool, because it requires only the boundary of the domain to be discretized, thereby reducing the data preparation efforts considerably. But the direct application of the BEM to the eigenfrequency analysis is difficult because the matrices themselves implicitly contain the frequency parameter in them. Consequently, the problem could not be cast in the form of either a standard or a generalized eigenvalue problem.

Recently the Dual Reciprocity Method(DRM) and the Complementary Function-Particular Integral Method(PIM) were proposed for the eigenvalue problems. In the two approaches, the free vibration differential equation are separated into two components, one, free of a frequency parameter, leading to the system mass matrix. The former is transformed into the boundary integral equation using a fundamental solution, independent of the frequency. On the other hand, the latter becomes a volume integral just like a body force term in the boundary element method. But both DRM and PIM require inversion of a matrix of size at least as large as the system matrices before the equations can be cast in the form of generalized eigensystem.

In the present paper, a simple but effective technique is presented via the use of either DRM and PIM, in which no matrix inversion is necessary, especially for the most important case of the pure Neumann problem. The idea is to temporarily retain the fictitious density functions as the system variable instead of the original dependent variable. The eigenvalue remain unchanged under the change of variables; the eigenvectors in terms of the original variables can also be retrieved very easily. In case of a part of the boundary wall is of the Dirichlet type, only a small size matrix needs to be inverted. So the new technique retains all the advantages of these methods, but removes the need to invert a large matrix in the formulation of the eigenproblem. This paper focuses attention only on 2-D electromagnetic eigenvalue analysis, and cases linear as well as quadratic boundary elements. A number of simple problems with known analytic and experimental results are presented in order to show the validity of the proposed technique.

APPLICATION OF MODIFIED INDIRECT BOUNDARY ELEMENT METHOD TO ELECTROMAGNETIC FIELD PROBLEMS

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The boundary element method(BEM) consists of direct boundary element method(DBEM) and indirect boundary element method(IBEM). The DBEM is generally represented as being based on Green's identity, while in IBEM, the integral equations are expressed in terms of a unit singular solution (or source) which satisfies the governing differential equation. This singular solution is distributed at a certain density over the boundary of the domain of the given problem. Compared with the DBEM, the IBEM has a few merits, i.e., the required size of the computer memory being small, the computation time being short, however, it has a serious drawback when used in its conventional form. When the boundary has geometric discontinuities (corners), there is no guarantee that the proposed fictitious source density distribution exist. If it does, it is likely to become infinity at the corners and makes modelling in this regions very difficult, leading subsequently to errors. This inherent feature of the IBEM has limited its applications. Some earlier workers have approximated the geometry by representing corners by two independent nodes placed slightly away from the actual corner. Although this approach has the effect of rounding off the corner(thereby approximating the source density to take finite value), it has a disadvantage , i.e., it results in poor solutions at the corners and edges for all problems.

The main purpose of our study is to present a modified indirect boundary element method(MIBEM) . The MIBEM , which relocates the surface of the source distribution at a certain distance outside the physical domain of the problem, eliminates the consistent singular behaviour of the source density at the corners. In addition, it also relieves the need to apply the special and careful treatment required for the evaluation of singular integrals in the neighborhood of the singular point. Therefore, the MIBEM enhances the capability and range of application of the IBEM. In this study, the MIBEM is applied to the investigation of electromagnetic field problems, such as the case of electromagnetic waveguide discontinuities, multi-media problems.

Tuesday PM1 URSI-A E, NEM Session TP12

Room: Columbus I/J *Time*: 1320-1500

High Power Electromagnetics Instrumentation

Chair: I. N. Mindel, IIT Research Institute

1320 **ACTIVE SENSORS : HIGH BAND, DYNAMIC and SENSITIVITY INSTRUMENTATION for PROGRESSIVE NEMP and HPM TESTS and EMC**
Gregoire Eumurian*, Fabrizio Pampalone, THOMSON-CSF/DSE

1340 **THE CERENKOV RESPONSE of LUCITE and QUARTZ to GAMMA RADIATION**
F. A. du Chaffaut*, D. Croteau, Centre d'etudes de Bruyeres le Chatel

1400 **DEVELOPMENT of a PROTOTYPE, HIGH SENSITIVITY, WIDEBAND ANALOG FIBER-OPTIC LINK**
Eduardo Saravia*, InterScience Inc.; Bruce T. Benwell, U. S. Army Laboratory Command

1420 **EFFECT of INDUCTIVE COUPLING DEVICES on COUPLED WAVEFORMS**
Charles E. Goldblum*, James L. Press, Ed Damerau, Moshe Netzer, R&B Enterprises

1440 **SWEPT FREQUENCY SINGLE POINT EXCITATION TECHNIQUE for MEASURING the SHIELDING of AIRCRAFT**
Lothar O. Hoeft*, BDM International, Inc.; Donald P. McLemore, Bruce Burton, Stan Kokorowski, Kaman Sciences Corporation; John Pratt, William D. Prather, Phillips Laboratory

ACTIVE SENSORS : HIGH BAND, DYNAMIC AND SENSITIVITY INSTRUMENTATION FOR PROGRESSIVE NEMP AND HPM TESTS AND EMC

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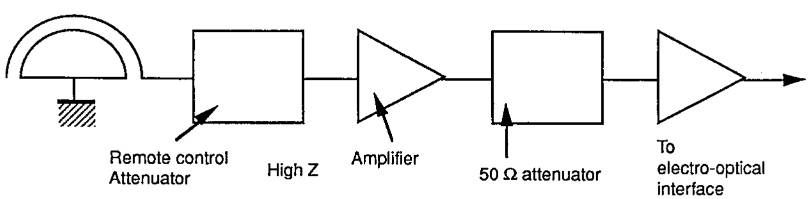
NEMP, EMC and HPM tests require instrumentation with a very broadband ranging from a few kHz to several GHz. Conventional sensors, passive sensors, cover this frequency band. However their large size and lesser sensitivity, requiring electro-magnetic fields at very high levels, do not allow tests on small objects and can only be used at high field levels approaching qualification levels.

Conversely, active sensors, measuring a few centimeters, are able to provide a sensitivity that is almost a thousand times higher ; thereby, enabling test at low levels and gradual rise to the qualification level. This type of test offers the advantages of not being destructive and of costing less than conventional tests. We describe instrumentation based on the use of active sensors for NEMP and EMC tests. The most advanced level of work enables extending this concept to include 1.5 GHz with instantaneous dynamic range > 60 dB for field levels ranging from 50 mV/m to over 1 MV/m. We also show evidence of the feasibility of very broadband active photonic sensors for microwave reseach at a few tens of GHz.

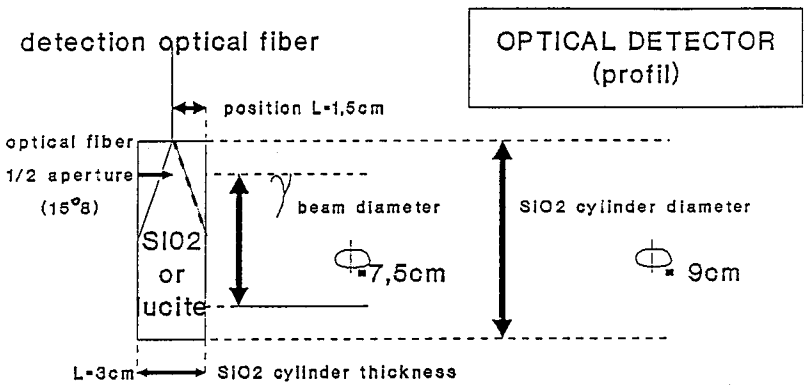


TYPICAL E FIELD NON DERIVATIVE ACTIVE SENSOR

CERENKOV RESPONSE OF LUCITE AND QUARTZ TO Γ RADIATION

*F.Amaudric du Chaffaut (Service C.E.M B.P.12 - 91680 Bruyéres-le-Châtel FRANCE)
D.Croteau

We have tried to elaborate a relevant theory for evaluating the effectiveness of Lucite and Quartz as CERENKOV materials for "all optical fast "gamma" detectors.We study the theoritical response of such materials to gamma radiations from 0.5 to 10 Mev.The detection of "CERENKOV" light is done with an optical fiber.The following picture shows treated problem geometry.



The topic of this study is the response of the sensor itself We suppose the optical fiber protected enough in order to get no variation in the transmission factor coming from a direct effect from gamma radiation on the fiber.

We are interested in the number of "cerenkov" photons created upon the absorption of a gamma ray of energy Eγ.So we take in consideration: photoelectric effect,pair production,compton effect,and we assume a single scattering event for the "γ" radiation.secondary electrons and Bremstrahlung during the stopping of the primary electron are not studied.

We compute sucessevely :

the electron ranges in SiO2 and Lucite detector
the detection of "CERENKOV" light in an optical fiber
the response of this system versus the "γ" radiation energy.

The path of electrons is studied with the aid of "MOLIERE theory and the computation of electron ranges is done with a MONTE-CARLO method.Electron ways can be traced with a specific graphical program

The hard problem of "CERENKOV" photons collection by optical fiber is solved by a geometrical method.

Finally we compare our theoritical results with these of J.E.DOYLE and W.C.DICKINSON (:UCRL-7032 ,1962).

DEVELOPMENT OF A PROTOTYPE, HIGH SENSITIVITY, WIDEBAND ANALOG FIBER-OPTIC LINK

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Although digital transmission over fiber-optic links is now common, the ability to handle analog signals with arbitrary modulation in photonic systems is only now being developed. With the anticipated advanced high-altitude electromagnetic pulse (HEMP) simulators, there is now the need for a high-sensitivity, wideband, miniature transmitter/data link that can be used to isolate the output signal of electric and magnetic field sensors (during transmission to remotely located instrumentation) from the intense electromagnetic (EM) environment produced over the simulators test volume.

In cooperation with Harry Diamond Laboratories (HDL), InterScience, Inc., is developing an analog optical link based on the direct modulation of an ultrahigh-speed miniature diode laser with the rf signal generated by an EM sensor. The link specifications are an operational bandwidth from 10 KHz to 2 GHz, a sensitivity of 20 μV, and a dynamic range of 40 dB. A small size (<7.5 cm^3) is necessary to minimize the perturbation to the EM fields being measured. The specifications of this link are well beyond those of present commercially wideband optical links. More specifically, the system consists of an InGaAsP miniature laser diode as a source, a single-mode optical fiber, and an InGaAsP PIN photodiode. Pre-amplification of the input signal is needed to drive the laser diode and cover the entire dynamic range, i.e., input signals from 20 μV at the tangential noise level to 2 mV at the 1 dB compression point. Other important features of the laser transmitter include bias and network matching of the rf input, monitoring and automatic control of the dc power to keep the laser bias optical power constant and a built-in calibration capability. A fully operational breadboard prototype system was assembled and subjected to extensive testing, both as individual components and as an integrated system. The results have demonstrated that the proposed analog optical link can be fully implemented with present technology to meet all performance requirements.

EFFECT OF INDUCTIVE COUPLING DEVICES ON COUPLED WAVEFORMS

Dr. Charles E. Goldblum, James L. Press, Ed Damerau, Moshe Netzer
R & B Enterprises, 20 Clipper Rd. W. Conshohocken PA 19428

This paper uses a unique technique for determining the transfer function of a coupling device as a function of frequency and load. At the present time, typical test procedures for EMP and lightning testing as well as some recent developments in CW radiated susceptibility testing utilize a calibration procedure consisting of a coupling device and a generator driving a known low inductive load. After calibration on this know load, the coupler is placed round the cable under test and the injection onto the cable is performed while monitoring the current and/or voltages. The output of the generator is then increased until either the calibrated setting is achieved or the required voltage/current is reached. Due to the differences between the known load and the cable under test, the waveforms may be radically different. These differences are typically caused by cable impedances and the complex load impedance of the unit under test. The technique presented here will allow the test planner or test engineer to predetermine the shape of the waveform on the cable and determine the optimal waveform norms that are applicable to the unit under test. Comparison will be made between a theoretical waveform and data taken in the laboratory. Typical EMP and lightning waveforms will be used such as double exponential, damped sine wave and trapezoidal. A discussion of various standards and test procedures will be presented detailing the importance of this work on future test methods and standards.

This technique for predeterming the coupled waveform will consist of the following algorithm:

1. A fast Fouier transform (FFT) is performed on the signal waveform to determine its frequency content.

2. A measurement of the scattering parameters of the coupling device (S_{11}, S_{12}, S_{22}, and S_{21}) is performed. These measurements will be made using a vector network analyzer (HP8753C) and the coupling device as a two port network.

3. Transformation of the scattering parameters into a set of ABCD parameters typically used in impedance measurements.

4. The transmission line is then represented as a two port network and its S parameters are measured and transformed into the ABCD space.

5. An analysis is performed using existing software to determine the transfer function of the coupling device, transmission line, generator, and load impedances.

6. Convoluting the signal spectrum derived in step #1 with the transfer function derived in step #5. This will determine the frequency response of the coupled and measured waveform.

7. Perform an inverse Fourier transform on the convoluted spectrum calculated in step #6 to retrieve the time domain waveform of the coupled waveform.

Data will be presented showing the transfer function for various loads ranging from 50 ohms to 10 kilohms. The paper will discuss the advantages of this technique and discuss its impact on future specification and standards for conducted susceptibility testing. With the support of data taken using standard measurement techniques, such as signal generators, oscilloscopes and spectrum analyzers, the paper will illustrate the effectiveness of this technique for determining waveform norms that are essential for the engineer who is attempting to design transient protection devices for electronic devices that are required to meet various conducted susceptibility requirements. The paper will then conclude with various examples of the utility of this new technique for determing coupled waveform characteristics.

SWEPT FREQUENCY SINGLE POINT EXCITATION TECHNIQUE FOR MEASURING THE SHIELDING OF AIRCRAFT

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A swept frequency single point excitation technique was recently demonstrated which show great promise for measuring the exterior field to cable current transfer functions of well shielded aircraft without using special facilities. Measurements were made for frequencies between 100 kHz and 200 MHz using a computer controlled network analyzer, a 15 W power amplifier, fiber optic links and appropriate sensors.

These measurements showed that good signal-to-noise ratios could be maintained when measuring currents on the cores of well shielded cables using only 15 W of power. Reproducibility of the measurements was good up to 80 or 100 MHz. Above these frequencies, the magnetic fields on the surface of the aircraft depended to some extent on the ground return configuration. Above 80 MHz, the magnetic fields on the surface of the aircraft and the current coupled to the cable cores showed evidence of several broad resonances. However, when the cable core measurements were referenced to the surface magnetic fields, these broad resonances were removed.

Comparison of the peak current induced by the EMP simulator to the current transfer function measured using the swept frequency single point excitation showed that the two techniques displayed the same trends, however, there was some scatter in the data (about a factor of 2 or 3). The peak current response obtained using the EMP simulator appeared to be directly proportional to the magnitude of the current transfer function at 2.7 MHz. At 80 MHz, the peak current appeared to be proportional to square root of transfer function.

The effect of inserting degradations in the cables and apertures could be seen in certain cases. In most cases, the significant coupling path was not the cable shield at the test point. Therefore, degrading the shield did not significantly increase the coupling.

The significance of this work is that it demonstrated that transfer functions between the surface magnetic fields on the fuselage and currents on second level conductors (wires within shielded cables) were able to be measured over a wide frequency range with simple equipment and without special facilities.

Tuesday PM URSI-B D Session TP13

Room: Columbus K/L *Time*: 1320-1700

Electromagnetic Analysis of Particle Accelerators

Organizers: T. G. Jurgens, Fady A. Harfoush, Fermi National Accelerator Laboratory
Chairs: T. G. Jurgens, Fady A. Harfoush, Fermi National Accelerator Laboratory

1320 **APPLICATION of FDTD MODELING to PARTICLE ACCELERATORS**
Fady A. Harfoush*, T. G. Jurgens, Fermi National Accelerator Laboratory

1340 **HIGHER ORDER MODE STUDIES of the 352 MHZ TM010 ACCELERATING CAVITY for the ADVANCED PHOTON SOURCE (APS)**
J. F. Bridges*, R. L. Kustom, T. L. Smith, Y. W. Kang, Argonne National Laboratory

1400 **HIGHER ORDER MODE DAMPING in an ACCELERATING RADIO FREQUENCY CAVITY**
Y. W. Kang*, J. F. Bridges, R. L. Kustom, Argonne National Laboratory

1420 **APPLICATION of TIME-DOMAIN DISPERSIVE MEDIA MODELS to WAKE POTENTIAL CALCULATION**
J. F. DeFord*, C. C. Shang, Lawrence Livermore National Lab

1440 **THE 3D, ELECTROMAGNETIC, PARTICLE-IN-CELL CODE, QUICKSILVER**
M. L. Kiefer*, D. B. Seidel, R. S. Coats, T. D. Pointon, J. P. Quintenz, Sandia National Laboratories

1500 **APERTURE COUPLING MEASUREMENTS in a TEST CHAMBER for the ADVANCED PHOTON SOURCE**
J. J. Song*, J. H. Zhou, Argonne National Laboratory

1520 **MEASUREMENT and MODELING of WAVE PROPAGATION in FERRIMAGNETIC MATERIALS for KICKER MAGNETS**
C. C. Jensen*, J. A. Dinkel, T. G. Jurgens, Fermi National Accelerator Laboratory

1540 **STUDYING THREE-DIMENSIONAL EFFECTS in RF STRUCTURES**
M. Jean Browman*, Los Alamos National Laboratories

1600 **EXPERIMENTAL STUDY of BEAM IMPEDANCE for the 7-GeV ADVANCED PHOTON SOURCE (APS) - the COAXIAL WIRE METHOD with the SYNTHETIC PULSE TECHNIQUE**
J. J. Song*, R. L. Kustom, Argonne National Laboratory

1620 **COMPUTER MODELING of CHERENKOV WAKEFIELD ACCELERATOR STRUCTURES**
Paul Schoessow*, Argonne National Lab

1640 **ACCELERATING CAVITIES for the POSITRON ACCUMULATOR RING of the ADVANCED PHOTON SOURCE**
Y. W. Kang*, R. L. Kustom, J. F. Bridges, L. Emery, Argonne National Laboratory

APPLICATION OF FDTD MODELING TO PARTICLE ACCELERATORS

F. A. Harfoush and T. G. Jurgens
Fermi National Accelerator Laboratory
Batavia, Illinois 60510

The FDTD code has been used to model many physical phenomena such as electromagnetic scattering and interaction, biological effects. Here we report on the extension of the FDTD methodology to model electromagnetic phenomena in particle accelerators. The associated electromagnetic field of a bunched charged particle beam travelling in an accelerator induces currents on the surrounding surfaces which in turn excite secondary fields. These fields are referred to as wake fields. The presence of such wake fields can deleteriously affect the path of subsequent particle bunches and lead to their destruction upon collision with the accelerating structure. Various normalized integrals of field components on a given path are used to define impedances of a given structure. These impedances are a measure of the efficacy of an accelerating device.

Our starting point in the FDTD analysis is the integral form of Maxwell's equations. To incorporate the physics of the moving particle bunch an extra term is added to Ampere's law.

$$\oint_C \vec{H} \cdot \vec{dl} = \iint_S \sigma \vec{E} \cdot d\vec{S} + \frac{\partial}{\partial t} \iint_S \vec{D} \cdot d\vec{S} + \iint_S \rho \vec{v} \cdot d\vec{S} \qquad (1)$$

The $\rho\vec{v}$ term accounts for the movement of charge through the FDTD lattice. The FDTD formulation used here incorporates contour modeling of curved surfaces (T.G. Jurgens, et al., IEEE Trans. APS, March 1992) as opposed to the traditional stair-stepped approximation.

The code has been validated for the case of a beam travelling at the speed of light through an empty circular cylindrical pipe with perfectly conducting walls. The next geometries investigated are a pillbox cavity in a beam pipe with and without flat plates. The flat plates can represent either beam signal pickups or electrostatic beam separators. The presence of the flat plates necessitates the use of a 3-D FDTD code. Illustrative examples of the above simulations showing the time evolution of the wake fields and resonances will be presented.

HIGHER ORDER MODE STUDIES OF THE 352 MHz TM_{010} ACCELERATING CAVITY FOR THE ADVANCED PHOTON SOURCE (APS)

J. F. Bridges*, R. L. Kustom, T. L. Smith and Y. W. Kang
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Argonne, IL 60439

Beam instabilities in particle accelerators are caused by spurious resonances in the beam vacuum chamber, accelerating cavities and other devices which either monitor the beam or guide it through the accelerator. Beam particles are in bunches which approximate Gaussian or $\cos^2$ shapes in time with typical duty cycles of one to ten percent.

These pseudo-delta functions energize resonances along the beam path, particularly in the radio frequency accelerating cavities which are designed for optimum operation at the accelerating frequency but have higher order modes due to the cavity geometry. In high current accelerators, high order modes can cause beam instabilities. These instabilities occur because the beam bunches are acted upon by higher order modes voltages which are generated by previous beam bunches passing through the cavity. The beam bunches then oscillate about their canonical position in time (phase around the circulator accelerator. If the amplitude is large enough, the bunches can be lost by hitting either the beam vacuum chamber or the "dynamic aperture" of the magnetic guide fields. Instabilities occur in both the longitudinal and transverse directions to the beam path. Therefore, higher modes having both longitudinal and transverse impedances must be damped (or eliminated) to a level which is below a threshold beam current.

The threshold currents for each mode are calculated using computer programs. Then those modes which can cause instabilities are measured in the cavity using perturbation techniques for measuring the fields along the beam path through the cavity. Once these modes are found and their fields "mapped" using either dielectric or metal "beads" (of various shapes), they are damped using voltage probes and current loops to couple to a convenient field of the higher order mode. Modes from 352 MHz to 1.6 GHz are discussed along with the hardware and damping ratios. The fundamental (accelerating) mode frequency is 352 MHz. All modes which can cause beam instabilities are investigated up to 1.6 GHz which is the cutoff frequency of the beam chamber. Above 1.6 GHz modes excited by the beam in the cavity travel out of the cavity via the beam chamber. These modes will be damped by devices coupled to the beam chamber outside the cavity.

HIGHER ORDER MODE DAMPING IN AN ACCELERATING RADIO FREQUENCY CAVITY

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In radio frequency (RF) accelerating cavity structures of particle accelerators, spurious resonances exist due to interaction between the bunched particle beam and the cavity. The higher order modes (HOMs) other than the fundamental accelerating mode frequency can cause beam instabilities and eventual loss of beam. These HOMs are eliminated or reduced by using the dampers on the cavity. A damper is a properly terminated transmission line section, (such as the aperture coupled hollow waveguide or a coaxial E- or H-field probe antenna), which can couple to the cavity mode(s). One damper may be used for coupling to more than one mode.

Analytical prediction and control of the property of dampers in an accelerating cavity are investigated. At each HOM frequency, the input impedance to each damping device terminal is determined and then used to predict the damping ratios. The cavity system with N-ports for HOM damping is treated as an N-terminal network. The scattering parameters [S] of this N-terminal network are measured in frequency domain by using a standard network analyzer. The open circuit impedance matrix [Z] and then the short circuit admittance matrix [Y] are found from the matrix [S]. The input impedances at each terminal is determined from the result. The reflection coefficient and the damping ratio at each frequency are determined and compared with measurement results.

If a terminal input impedance at a mode frequency is much different from the characteristic impedance of the transmission line, terminating the transmission line alone may not provide sufficient damping. Using the impedance matching network for damping certain mode(s) is also discussed.

Application of Time-Domain Dispersive Media Models to Wake Potential Calculation

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Lawrence Livermore National Laboratory
L-626, Livermore, CA, 94550

The wake potential, as used to characterize the interaction of a charged particle bunch with a structure such as an accelerator beampipe insertion, is defined by the expression

$$\vec{W}(s) = \frac{1}{Q} \int_{z=-\infty}^{\infty} \left[\vec{E} + \vec{v} \times \vec{B}\right]\Big|_{t=\frac{z+s}{v}} dz.$$

The potential is the integral of the Lorentz force on a unit test charge produced by the diffracted fields of a source charge (Q) as the two charges transit the structure with fixed, identical velocities $\vec{v}$. The wake potential is an extremely useful quantity in the study of beam dynamics in accelerators, and as such it plays a central role in the design of many modern accelerator components.

The most efficient method for computing the potential is through use of a time-domain technique, as its calculation involves broadband information about the electromagnetic characteristics of the structure. Although potentials have traditionally been required only for metal-vacuum structures, for which existing finite-difference time-domain (FDTD) codes such as TBCI and MAFIA are sufficient, there is now significant interest in accelerator components containing a variety of dispersive media. In particular, there is a strong need for capabilities to model devices such as ferrite-loaded kicker magnets and RF booster cavities, induction modules, and ferrite beamline insertions.

To address this need we have developed Debye models of several soft ferrites (Ferrite-50 (TransTech), PE11B (TDK), PE11BL (TDK)), using data generated at LLNL by G. Kamin, and at Cornell University by W. Hartung. An efficient technique to compute the temporal convolutions necessitated by the Debye model that does not require the storage of the time-histories of the field quantities was found (but not published) by Yee in 1974, and has recently been rediscovered by Luebbers, et al. (IEEE-EMC, **32**, Aug., 1990, pp. 222-227). As reported last year at this meeting, this technique has been implemented in the FDTD wakefield code AMOS. In this talk we will present the application of AMOS to several problems of current interest involving the ferrites listed above, including a high-order mode absorber in the superconducting RF booster for the Cornell B-factory, and the ETA-II induction module. The former consists of thin ferrite insertions in a relatively large beampipe, and we will show potentials and impedances of this structure, as well as comparisons with experimental data obtained by L. Walling (SSCL). The ETA-II module is a rotationally symmetric device that consists of a gap in the beampipe wall connected to a radial line which is backed by a large ferrite toroid. The module has been studied previously with non-dispersive models, and we will show comparisons between these calculations, those obtained using the Debye model of the ferrite, and experimental measurements (L. Walling).

THE 3D, ELECTROMAGNETIC, PARTICLE-IN-CELL CODE, QUICKSILVER

M. L. Kiefer*, D. B. Seidel, R. S. Coats, T. D. Pointon, and J. P. Quintenz
Sandia National Laboratories, Albuquerque, New Mexico

The QUICKSILVER suite of codes has been developed at Sandia National Laboratories for performing simulations in three dimensions using time-domain, finite-difference, electromagnetic techniques. Simulations can be performed with or without charged particles; when charged particles are included, particle-in-cell (PIC) techniques are used. The suite includes a preprocessor and several postprocessors and may be licensed for commercial or government use.

QUICKSILVER, the member of the suite for performing the physics simulations, has been designed to make efficient use of vector, multiple-CPU computers with large central memory and fast, out-of-memory storage. Using a Cray Y-MP computer, it has been used to simulate many diverse applications with and without charged particles. A long-term project to port QUICKSILVER to a massively parallel computing platform is in progress so that even more ambitious simulations may be attempted.

Integral to QUICKSILVER's use are a user-friendly preprocessor, MERCURY, and several postprocessors for displaying various types of data produced by QUICKSILVER. The MERCURY preprocessor is designed to allow the rapid setup of complex 3D simulations while minimizing the errors that might be associated with that setup. MERCURY supports all the modeling capabilities of QUICKSILVER, as well as limited support (e.g., finite-difference mesh generation) for other codes. Several postprocessors are used to analyze the wealth of data that can be produced by QUICKSILVER and other simulation codes. For example, AVS and a related postprocessor, QSAVS, are used to display 3D graphics images and animation on high-performance, 3D graphics workstations. A support package for automated recording/playback of animations to/from a videodisk unit is also available. The PLOTPFF postprocessor has been developed to provide detailed analysis of fields and particle snapshot data, as well as limited analysis of time-history data. The IDR postprocessor provides a full-range of time-history analysis capabilities.

QUICKSILVER and its associated pre- and postprocessors reside on several different machines. This has necessitated the development of a Portable File Format (PFF) which allows data to be transported among the various machines in an efficient, machine-independent binary file format. This format has been designed to be easily extensible and is currently being used by several other Sandia codes which allow them to directly use the postprocessors in the QUICKSILVER suite.

This paper will include a brief overview of the components of the QUICKSILVER suite and its current modeling capabilities. As time and space permit, sample applications will be shown and future development plans will be described.

APERTURE COUPLING MEASUREMENTS IN A TEST CHAMBER FOR THE THE ADVANCED PHOTON SOURCE (APS)

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The beam energy loss due to the various parasitic modes in the 7-GeV APS storage ring should be estimated. It is impractical to do computer simulation to estimate the parasitic mode loss on some vacuum components on the APS ring, because of the nature of the complexity. For example, there should be a RF shielding structure between the photon absorber and circulating beam, so that the beam is not disturbed by the photon absorber.

In order to determine and minimize beam impedance due to the RF shielding structure, aperture coupling chambers were set up. The transverse electromagnetic wave (TEM), which propagates in one rectangular chamber, couples through the aperture and radiates into the other identical chamber. A common wall between them has various sizes, thicknesses, shapes, and the number of the holes.

The 4x4 S parameters (transmission, reflection, forward coupling, and backward coupling) were measured, while the case of the "large" aperture coupling was emphasized (i.e. when aperture dimensions are larger than the wavelength). The results are to be compared with any available theories (the diffraction model, the radiating model, etc.) and applied to the detail design of the photon absorber.

MEASUREMENT AND MODELING OF WAVE PROPAGATION IN FERRIMAGNETIC MATERIALS FOR KICKER MAGNETS

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Batavia, Illinois 60510

In colliding beam physics, bunched beams of charged particles are accelerated to relativistic velocities and made to collide. One measure of the efficacy of this collision is luminosity, which is the interaction rate per unit cross section. In order to increase luminosity with existing facilities, an increase in the interaction rate and requisite improvements in the particle beam steering equipment is needed. In particular the transfer of beams between circulating accelerators requires a fast, high intensity and uniform electromagnetic field which bends, or kicks, the beam. Soft ferrimagnetic materials, primarily NiZn, and pulsed power supplies are used to supply energy for bending the beam. A better understanding of these materials and their use in beam line devices is needed to accomplish this task. Here we report on the combined use of experimental measurements and numerical simulations to gain insight into the physics of kicker operation and thus improve its performance.

Measurements were made on a coaxial test fixture as well as a kicker magnet. Low frequency measurements with the test fixture provided verification of the manufacturer's material characterization data. High frequency characterization data beyond that supplied by the manufacturer were also extracted from test fixture measurements. This data provided validation for the numerical simulation code. Time and frequency measurements were made on the kicker magnet and compared to numerical data.

The Contour Finite Difference Time Domain algorithm (T.G. Jurgens, et al., IEEE Trans. APS, March 1992) was used to model the ferrimagnetic loaded structures. The frequency dispersive nature of the material and its high permittivity were accounted for in the computer code. The code computes field values in the entire volume, permitting the creation of detailed field illustrations. Identification of high magnetic and electric field regions aids in better understanding of the magnet's physics.

Studying Three-Dimensional Effects in RF Structures

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Los Alamos, NM 87545

Major breakthroughs in the electromagnetic modeling of three-dimensional radio-frequency (RF) structures have been made during the last decade. Researchers now have the tools to study important three-dimensional effects in such structures. This presentation will discuss three such studies made using release 2 of the family of electromagnetic field solvers called MAFIA plus some special postprocessors:

- A study of the end regions of radio-frequency quadrupoles (RFQs)
- A study of the feasiblity of extending the usefulness of RFQs by building longer, compensated structures, and
- A study of the effect of asymmetric slots on RF fields in the beam region of coupled-cavity linear accelerators.

In the investigation of the end regions of RFQs we (Browman, Spalek, Barts, "Studying the End Region of RFQs," *Proc. of the 1988 Linear Accelerator Conference*) found that (1) undercutting the vane is essential, and (2) the slope of the undercut affects the peak current flow and the power dissipation at the ends of the vanes. In particular it was found that in designing such an end region a tradeoff must be made between minimizing the peak power loss density and reducing the total power loss.

RFQs use strong electrostatic focussing in a narrow channel, thus allowing high-current beams. They also combine the functions of acceleration and bunching, which means these functions can be accomplished in a compact, lightweight structure. Unfortunately, the amount of acceleration given to a particle depends on the length of the RFQ used. Problems of mode coupling and field uniformity multiply as the length of the RFQ increases, so until now RFQs have been used only for low-energy acceleration. We (Browman and Young, "Coupled RFQs as Compensated Structures," *Proc. of the 1990 Linear Accelerator Conference*) have investigated a scheme by Dr. Lloyd Young to couple together short, e.g., one-meter long, sections of RFQs, thus making a longer, compensated structure with improved mode separation and longitudinal stability.

Finally, we will examine a method of studying the asymmetry caused by the orientation of coupling slots in coupled-cavity linacs. More specifically, we will look at the difference between the fields in the cavity with slots and the corresponding cavity without slots.

EXPERIMENTAL STUDY OF BEAM IMPEDANCE FOR THE 7-GeV ADVANCED PHOTON SOURCE (APS) - THE COAXIAL WIRE METHOD WITH THE SYNTHETIC PULSE TECHNIQUE

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The circulating beam in a storage ring induces electromagnetic fields in the vacuum chamber elements. The induced EM fields, which are proportional to the impedance seen by the particle beam may drive instabilities for the beam. The instabilities would cause a beam energy loss, an emittance growth, and could limit a beam current, and eventually the lifetime.

The beam coupling impedance of the storage ring vacuum chamber components was measured with a coaxial wire method using a synthetic pulse technique. By sending rf power through a thin wire in the reference chamber and in the device-under-test (DUT), 2x2 S-parameters can be measured and a synthetic pulse can be generated via Fast Inverse Fourier Transformer (FFT). The S-parameter contains some information on the EM field distribution which is perturbed by any discontinuity of the DUT.

The experimental results on the longitudinal and transverse impedances in the frequency domain and their corresponding loss parameters in the time domain with the synthetic pulse will be presented, compared with the real-time pulse method, and analyzed with the computer simulation whenever possible.

COMPUTER MODELING OF CHERENKOV WAKEFIELD ACCELERATOR STRUCTURES

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A potential high gradient accelerator technology for future high energy linear colliders is based upon the electromagnetic wakefield excited by Cherenkov radiation of an intense relativistic drive beam in a dielectric loaded slow wave structure. The wakefield is then used to accelerate a second, less intense witness bunch to high energies. Simulations using the ARRAKIS codes will be presented which relate specifically to dielectric device experiments planned for the Argonne Wakefield Accelerator (AWA).

The ARRAKIS codes are a set of 2D time domain finite difference codes developed to model various classes of Cherenkov wakefield devices. A great deal of freedom in specifying dielectric properties is provided. In particular, problems involving nonlinear, anisotropic, and conductive media can be treated. The codes have been implemented on a number of parallel computer architectures. The ARCHON subset was specifically developed for the Connection Machine and is well suited for problems requiring very large mesh sizes and fast computational turnaround.

The Coupled Wake Tube Accelerator (CWTA) is a promising variant of the basic Cherenkov wakefield accelerator which utilizes a noncollinear drive-witness beam geometry. The wakefield generated by the drive bunch in a large diameter dielectric structure is coupled to a small diameter structure (accelerating tube) with the same TM_{01} mode frequently through a quarter-wave transformer section. This technique provides a gradient set-up by geometric compression of the drive beam's wakefield. The larger bore drive tube reduces beam breakup effects on drive bunch, and noncollinear geometry makes staging easier. In general parasitic HEM_{mn} modes excited by the drive beam will not be luminal in the accelerator tube.

ARCHON calculations of the time evolution of TM and HEM modes in optimized CWTA structures will be presented, including visualizations of CWTA device wakefields.

ACCELERATING CAVITIES FOR THE POSITRON ACCUMULATOR RING OF THE ADVANCED PHOTON SOURCE

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The Advanced Photon Source (APS) at the Argonne National Laboratory consists of four accelerators: Linac, Positron Accumulator Ring (PAR), Synchrotron, and Storage Ring. The PAR has two RF systems, one at 9.8 MHz and the other at 118 MHz, the twelfth harmonic. Each system consists of one cavity, one amplifier and control circuitry.

The cavities are designed using the computer codes MAFIA and URMEL-T. These finite difference codes use a mesh to compute the electromagnetic fields supported by the geometry of the structure. For each cavity, a two-dimensional model of the cavity is used to determine the higher order modes up to 1.6 GHz using the URMEL-T code. MAFIA is used with a three-dimensional model of the cavity for 118 MHz. The cavity for the first harmonic frequency is a folded coaxial re-entrant type cavity. This design is chosen to reduce the axial length of the cavity. The cavity for the twelfth harmonic frequency is half-wavelength coaxial cavity. Both cavities have openings of 4.8" diameter through the center conductor for the beam to travel through. Cylindrical alumina ceramic windows are used across the accelerating gap for isolating the vacuum in the beam chamber from the air in the cavity.

The cavity shapes are optimized for high Q-factor and short length. The frequency and the Q-factor of the higher order modes are both calculated using the programs and measured in the cavity using perturbation techniques. Comparisons between the computed results and the measurement are discussed.

Tuesday PM2 URSI-E, NEM Session TP15

Room: Columbus I/J *Time*: 1520-1640

Device Characteristics

Chair: J. P. Castillo, Logicon RDA

1520 **USING the R2SPG to CHARACTERIZE and EVALUATE EMP UPSET THRESHOLDS**
Lothar O. Hoeft*, William H. Cordova, Ronald Karaskiewicz, Gerald A. McArthur, Bradley Spalding, Joseph S. Hofstra, BDM International, Inc.

1540 **FLASH X-RAY EFFECTS on MMIC**
Daniel C. Yang*, K. Vu, T. Lunn, E. Rezek, L. Fletcher, TRW Inc.

1600 **MODELING SATURABLE MAGNETICS for EMP ASSESSMENTS**
Joseph Miletich*, Llewellyn Jones, William Slauson, Raytheon Company

1620 **USING ESD DAMAGE DATA to PREDICT EMP FAILURE THROUGH the WUNSCH-BELL MODEL**
Thomas L. Fowler*, Arthur J. Wan, Texas Instruments

USING THE R^2SPG TO CHARACTERIZE AND EVALUATE EMP UPSET THRESHOLDS

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The Repetitive Random Square-wave Pulse Generator (R^2SPG) was designed and built as one of a series of tools available for S/V engineers to use in system hardening programs. It is a small, simple, battery operated pulser that produces broadband fast rise-time (2.5 ns), controllable, high-amplitude transients at an average rate of 30 pulses per second. Its small size allows the same equipment to be used in the laboratory and on operational systems. It was designed to be an "electronic hammer" that could be used to excite the cable systems of a aircraft, ship, or ground system while they are installed using peak currents up to those associated with specification level EMP plus a safety factor of approximately 20 (26 dB). The R^2SPG, in itself, does not replace full-scale testing, as global illumination is not provided. However, in situations where complex digital upset testing is required, or where full-scale system tests cannot be done (for reasons such as system unavailability, schedule or cost), the R^2SPG provides a good alternative technique for electromagnetically stressing hardened systems. Because the R^2SPG produces a broadband transient, it excites the cable under test at its resonant frequencies. Thus the coupling is similar to EMP field to cable coupling. Comparison measurements using the EMP Testbed Aircraft (EMPTAC), demonstrated that the R^2SPG produces cable currents that are similar to those produced by EMP simulators.

Initially, the usefulness of the R^2SPG for upset testing was demonstrated on an AT class digital computer. This was followed by upset testing on a number of operational systems, including: a large digitally controlled communication system, a data display sub-system, and two radar sets. The first radar used 1960's analog technology retrofitted with digital computers. The second radar set was of 1970's vintage and made more extensive use of digital computers.

The small size of the R^2SPG made it convenient to take it to the operational systems for a short but meaningful test. The upset threshold was quickly established and its severity or impact on mission performance was evaluated. If necessary, temporary hardening fixes or procedural work-arounds could be developed on the spot and test. In addition, confidence was gained in the conservative nature of the original damage assessment.

If the upset threshold was within the limits of the test program and the capabilities of the R^2SPG, significant upsets generally required 3 to 10 A, even in unhardened systems. "Snow" on visual displays occurred at smaller currents. As expected, more modern systems had lower thresholds and more frequent upsets than older systems with less digital technology. None of the systems were damaged by the test. This tentatively confirms the statement that "upset occurs before damage."

FLASH X-RAY EFFECTS ON MMIC

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A study was made on dose rate radiation effects for four different types of MMIC processing technologies including 0.25 μm ion implanted GaAs MESFET, 0.25 μm MBE GaAs MESFET, 0.2 μm pseudomorphic AlGaAs/InGaAs HEMT and GaAs/AlGaAs HBT. The exposures were made with the Vulcan Flash X-Ray machine which has a half-max pulse width of 45 nanoseconds. All four types of MMICs were tested from $1x10^{10}$ rads/sec to approximately $1x10^{12}$ rads/sec. The operating frequency range of the circuits tested is from 3 GHz to 35 GHz. All circuits passed the radiation test without failure. A description of the test circuits and test results are presented as follows.

The HBT test circuit is an amplifier divider which consists of 138 transistors, and takes an input signal from 3.0 to 4.5 GHz and perform a divide-by-4 operation. Two samples were tested. The first was exposed up to $8.7x10^{11}$ rads/sec. The disturbances lasted from approximately 1 microsecond at low level to slightly less than 2 microseconds at high level. A second sample was also tested and displayed similar result.

A two-stage 6 to 10 GHz low noise amplifier was used as the 0.5 μm ion-implant MESFET test circuit. Each stage consists of a 0.5 x 300 μm transistor. It exhibits 15 dB gain and 5 dB noise figure. The test sample was exposed up to $9.5x10^{11}$ rads/sec and the results showed a complete initial dropout and returned to normal CW operation in 15 to 20 microseconds over the entire test range.

The 0.25 μm MBE MESFET test circuits is a 35 GHz two-stage balanced power amplifier with two 0.25 x 150 μm and two 0.25 x 300 μm MESFETs. It has 7 dB gain and +20 dBm output power. The test circuit was exposed up to $8.7x10^{11}$ rads/sec. It was observed that after an initial complete dropout, recovery to normal levels occurs in approximately 2 microseconds.

For 0.2 μm pseudomorphic HEMT a 26 to 40 GHz two stage balanced low noise amplifier consisting of four 0.2 x 100 μm HEMT devices was used as the test circuit. It has a nominal gain of 15 dB and 4 dB noise figure. It was exposed up to $1x10^{12}$ rads/sec and the recovery time was approximately 2 to 3 microseconds.

The flash X-Ray radiation hardness characteristics of four different types of GaAs MMICs were investigated. Good results were obtained on all of them. Further studies on total dose and neutron radiation effects are necessary to fully utilize the MMICs in the radiation environments.

MODELING SATURABLE MAGNETICS FOR EMP ASSESSMENTS

Joseph Miletich*, Llewellyn Jones, William Slauson
Equipment Division, Raytheon Co.

EMP protection circuits often utilize inductors with ferromagnetic cores. Recent assessments have shown the necessity of evaluating saturation of filters and inductors when assessing EMP protection circuits. Current versions of circuit simulation codes include models for non-linear magnetics. These models allow the EMP engineer to accurately model blocking inductors and EMI power line filters.

The response of the following typical hardening designs have been simulated using the Jiles-Atherton model in PSPICE®: an inductor isolating a large MOV from downstream clamping components, an EMI power line filter, and a small pin filter. With the Jiles-Atherton model, it is possible to model the B-H hysteresis curve, effects of DC bias current and frequency permeability roll-off.

The case of an inductor being used to isolate downstream components from an MOV is examined in detail. The Jiles-Atherton model values with resulting B-H curves are given for typical molypermalloy powder cores. The SPICE circuit simulation is presented for two cases, with clamping components and with power filters downstream. It is shown that saturation effects of downstream filters is possible even when the isolating inductor does not saturate. The results show the importance of frequency and damping factor in the EMP pin specification and the importance of looking at the entire system when conducting an EMP assessment.

EMI power line filters are too often ignored or treated very cursorily in standard EMP assessments. It is shown that with the Jiles-Atherton model it is possible to accurately predict the EMP transient response of power line filters. Test responses of filters to typical damped sinusoids are compared to model predictions. In addition, standard CW insertion loss curves are compared to SPICE model predictions. Other examples, such as typical pin filters are examined to show the utility of this approach of modeling magnetics in SPICE. The results of the assessments show that it is possible and in many cases important to model the magnetics in typical protection designs.

USING ESD DAMAGE DATA TO PREDICT EMP FAILURE THROUGH THE WUNSCH-BELL MODEL

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and
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Abstract

The Wunsch-Bell component damage model is a widely-used method of assessing the damage thresholds of semiconductor devices. Testing of components for Wunsch-Bell parameters is usually performed using a pulse generator which delivers a contant power to the device under test. Sources which may damage the device during operation in a circuit deliver a time-varying power to the component and cannot be directly related to the Wunsch-Bell parameters.

In the early 1970's, work was performed by Miletta, Peden, and Tasca to relate arbitrary power v.s. time waveforms to the time invariant power pulses used to generate the Wunsch-Bell characterization data. The work performed in this paper is a continuation of that effort. Electro-Static Discharge (ESD) damage threshold information has been related to EMP damage. This allows the system EMP analyst to take advantage of any ESD characterization data which may be available on components.

During the 1980's, Mil-Std-883 and Mil-Std-750 were revised to include an ESD hardening assessment test. The ESD waveform is similar in form to the Mil-Std-461C RS05 pulse, and can be represented with a similar double-exponential approximation. Competition among Integrated Circuit (IC) manufacturers has resulted in continuous improvement in ESD performance for new product lines, but the older product lines have remained essentially unchanged. ESD performance data for the newer ICs is generally available from most IC manufacturers and is often included in the data sheets.

The method described in this paper applies classical linear systems theory to the problem. First, the thermal impulse response of the device is obtained from the ESD damage data with the convolution integral. Next, the impulse response is represented in the frequency domain using the Fourier transform. Linear systems theory predicts that the convolution of the impulse response with arbitrary forcing functions gives the temperature rise of the IC junction (Wunsch-Bell theory). In the frequency domain, this convolution simplifies to a point-by-point multiplication. The EMP-induced forcing function is treated as a variable and determined through power spectrum integration of the respective Fourier transforms. In this manner, an EMP threat equivalent to the known ESD damage level is derived.

With a few simplifying assumptions, the results can be tabulated and used to evaluate system damage at the component level.

Tuesday PM2 AP-S, URSI-A Session TP16

Room: Columbus G *Time:* 1500-1720

Material Characterization

Chairs: Dennis P. Nyquist, Michigan State University; Morris Brodwin, Northwestern University

1500 **AN ALGORITHM for SOLVING ROBERTS-VON HIPPEL EQUATION: SEPARATION of CLOSE SOLUTIONS**
Teresa P. Iglesias, Anselmo Seoane*, Universidad de Vigo; Jose Rivas, Universidad de Santiago

1520 **MICROWAVE DIELECTRIC MEASUREMENTS of CERAMIC COMPOSITES at HIGH TEMPERATURES**
Octavio Andrade*, Shane Bringhurst, Magdy F. Iskander, University of Utah

1540 **FREE-SPACE MEASUREMENT of DIELECTIC CONSTANTS and LOSS TANGENTS of LOW-LOSS MATERIALS USING a MICROWAVE INTERFEROMENTER TECHNIQUE**
D. Ghodgaonkar*, Vasundara V. Varadan, V. K. Varadan, The Pennnsylvania State University

1600 **BROADBAND MATERIAL CHARACTERIZATION USING MICROSTRIP/ STRIPLINE FIELD APPLICATOR**
J. M. Grimm*, Dennis P. Nyquist, M. Thorland, Michigan State University

1620 **COMPLEX WAVES EXCITED by an OPEN-ENDED COAXIAL PROBE in LAYERED MEDIA**
Ching-Lieh Li*, K. M. Chen, Michigan State University

1640 **INTERCOMPARISON of PERMITTIVITY MEASUREMENTS USING the TRANSMISSION/REFLECTION METHOD in 7-mm COAX**
Eric J. Vanzura*, National Inst. of Standards and Tech.

1700 **A STUDY of ELECTRICAL CHARACTERISTICS of a MESH REFLECTING SURFACE**
T. Takano*, E. Hanayama, S. Araki, Inst. of Space and Astronautical Science

AN ALGORITHM FOR SOLVING ROBERTS-VON HIPPEL EQUATION: SEPARATION OF CLOSE SOLUTIONS.

Teresa P. Iglesias - Dpto. Física Aplicada
Anselmo Seoane* - Dpto. Tecnología de las Comunicaciones
Universidad de Vigo

José Rivas
Universidad de Santiago

The short-circuited line method for the determination of the complex dielectric permittivity requires solving a transcendental equation of the form $(\tanh z)z = c$ on the complex plane, with c a constant obtained from experiment. Although this equation possesses infinite solutions, it is enough in practice to consider only a few of them, with small values of the real part. Several methods for its resolution have been developed, such as Dakin-Works's approximation, which is not applicable for samples with loss-tangent $\tan\delta > 0.1$ due to the great errors that can arise. There are also graphical methods like Roberts-von Hippel's or Delbos-Demau's. Computers have allowed the use of iterative numerical methods; of them, the more commonly used is Newton-Raphson's one. This method converges from a good initial approximate value to one single root so that if there were two roots close to each other, one of them might be ignored. Gelinas et al. use also Newton's method for the case $Re(c) \leqslant 0$. It is necessary to distinguish the close roots when studying, for instance, the effect that the sample thickness has on the uncertainty in ε due to errors that the measurement of the VSWR and the position of the minimum of the standing wave.

The present work describes a numerical procedure to solve that equation thich allows to distinguish close solutions. It finds any desired number of solutions without needing a previous survey in order to select initial approximations to the roots, it is easy to implement, it does not require a large computational power and execution times are reasonably low. The algorithm has been tested both numerically and against experimental results with several organic liquids.

MICROWAVE DIELECTRIC MEASUREMENTS OF CERAMIC COMPOSITES AT HIGH TEMPERATURES

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High-temperature permittivity measurements of ceramic materials at microwave frequencies have received considerable attention in recent years, particularly since advances in the microwave sintering process of these materials have indicated some superior attributes like improved microstructure, reduction of internal stress, lowering of thermal gradients, and reduction of the sintering temperature. A comprehensive understanding of this complex process, however, requires that a complete database of the dielectric properties of ceramic materials of interest be available over a broad frequency range and up to sintering temperatures.

Various methods and techniques are available in the literature for permittivity measurements of solid and low-density (powder) materials which are adequate for ceramics. However, extension of these methods to accurate measurements at sintering temperatures (up to 1500°C) and over a broad frequency band require consideration of various tradeoffs, such as sample holder thermal expansion, minimization of heat transfer to the measuring equipment, handling of the sample, accurate temperature readings, and selection of suitable materials for the sample holder design.

This paper describes ongoing efforts for broadband, high-temperature characterization of materials at the University of Utah. For narrow-band measurements at S and X bands the cavity perturbation method is used, and the rectangular cavity designs and high-temperature measurement techniques using a fused silica sample holder and a modern network analyzer are explained. Considerations of accuracy are addressed, and experimental results for Zirconia and Alumina are presented for temperatures up to 1200°C.

Broadband measurements at high temperatures are obtained using the open-ended coaxial line technique. For these measurements, a novel probe using metallized, low-thermal expansion ceramics was designed and constructed. The coaxial probe design and details of the experimental arrangement are described, and a simple and accurate analytical procedure to calculate the complex permittivity of the sample from the measurement of the probe admittance is explained. Experimental results for some selected ceramic samples will also be presented for temperatures up to 1200°C.

Free-Space Measurement of Dielectric Constants and Loss Tangents of Low-Loss Materials using a Microwave Interferometer Technique

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Free-space techniques have been used for the measurement of dielectric constants and loss tangents using short-circuited-line method (Ghodgaonkar *et al* , IEEE Trans. I & M, 38, 1989, pp. 789-793), reflection and transmission coefficient method (Ghodgaonkar *et al* , IEEE Trans. I & M, 39, 1990, pp. 387-394) and transmission coefficient method (Varadan *et al* , IEEE Trans. I and M, 40, October 1991) which is similar to the method described by R. M. Redheffer (Techniques of Microwave Meas., C. G. Montgomery, Ed., Vol. 2, p. 592). For microwave materials with loss tangents less than 0.006, these free-space methods can not be used for accurate measurements.

A microwave interferometer technique (proposed by W. Culshaw, Proc. Phys. Soc., 66B, 1950, pp. 597-608) is implemented on the free-space microwave measurement system consisting of transmit and receive spot-focusing horn lens antennas, a network analyzer , mode transitions and a computer. A planar sample (15.2 cm × 15.2 cm in cross-section) is sandwiched between two composite reflectors for measurement of free-space S-parameters. Composite reflectors are made from 6 to 9 (depending on the dielectric constant) quarter-wavelength planar sheets of teflon or fused quartz which are a quarter-wavelength apart in free-space. Dielectric properties will be calculated from the changes in resonant frequency and Q-factor due to the planar sample. The measurement system, calibration technique and the design of composite reflectors will be described. Experimental results will be reported at 16 GHz for several low-loss materials including polyvinyl-chloride, boron nitride and borosilicate glass.

COMPLEX WAVES EXCITED BY AN OPEN-ENDED COAXIAL PROBE IN LAYERED MEDIA

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When an open-ended coaxial probe is used to measure EM properties of an infinite material medium, the EM fields excited inside the material medium are localized around the probe aperture, and quasi-static theory may be sufficient to predict the probe characteristics. However, when the material medium is a layered medium then a full-wave analysis is required to predict the probe characteristics.

In case an open-ended coaxial probe is placed against a material layer which is backed by air, surface wave modes can be excited in the layer. In case the probe is placed against a material layer which is shorted by a metallic plate, radial guided waves can be excited in the layer. The excitation of these guided EM waves may affect the input impedance of the probe, thus influences the quantification of EM properties of materials.

Excitation of the complex waves by a probe in a layered medium was theoretically analyzed. A series of experiments was conducted to measure the input impedance of an open-ended coaxial probe placed against a layered medium. The effects of the excitation of complex waves on the probe input impedance and its consequences on the quantification of EM properties of the layered material were studied.

INTERCOMPARISON OF PERMITTIVITY MEASUREMENTS USING THE TRANSMISSION/REFLECTION METHOD IN 7-MM COAX

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The Transmission/Reflection (T/R) method is frequently used by those interested in dielectric and magnetic properties measurements at RF and microwave frequencies, but suffers from a lack of standard procedures, algorithms and materials. To aid in standardizing the T/R method, the National Institute of Standards and Technology (NIST) organized a nationwide intercomparison of permittivity measurements in the 50 MHz to 18 GHz frequency range. The T/R method involves calculation of relative permittivity (ϵ_r) and permeability (μ_r) from transmitted and reflected scattering parameters measured by a network analyzer. This intercomparison focuses on permittivity only, and a permeability measurements intercomparison is presently being organized.

Three sample kits have been circulated among fifteen participating organizations. Each kit will be circulated to five different participants. All three sample kits contain four materials with ϵ_r ranging from approximately 5 to 20, and one sample kit contains a fifth, higher-permittivity sample with ϵ_r somewhere between 35 and 60.

Measurement results are compared with each other and with high-accuracy cavity resonator measurements made by NIST. The differences in reported values of ϵ_r are primarily due to differences in data-reduction algorithms and air-gap corrections. The commonly implemented Nicholson/Ross algorithm is shown to be less accurate and much more unstable than the Baker-Jarvis algorithm, especially when the sample is longer than a half wavelength. This half-wavelength problem has been avoided through the use of short samples. However, this approach often leads to other uncertainties such as sample alignment, length, location and geometry that are difficult to quantify or correct. The inevitable presence of air gaps between the sample and the transmission line's inner and outer conductors biases permittivity results low. The required air-gap correction increases as permittivity increases. Suggested ways of eliminating the air gap problem include the use of rectangular waveguide or larger-diameter coax, and the application of a conductive paste to fill in the air gaps.

A Study of Electrical Characteristics of a Mesh Reflecting Surface

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Electrical reflection and transmission characteristics are experimentally studied. Special cares are taken to isolate two measuring horns in the measurement system, and the data are processed to extract the reflection and transmission coefficient of the mesh out of the standing wave phenomena.

The results showed the significant dependence on the polarization and incidence angle of the incident field, though the mesh is composed of tangled wires.

As the wire runs in one direction keeping contacts with neighboring wires, the electro magnetic characteristics are anisotropic. The reflection loss is 0.1 and 0.3dB with electrical field in the direction of the wire running and in the orthogonal direction, respectively.

The anisotropy and the dependence on the incident angle and polarization are modelled well by the model of apertures in a conductor plane. The polarization conversion effect is analyzed using the model. The maximal polarization shift angle of 15 degrees is possible.

The residual loss which can not be attributed to reflection and transmission losses is derived from the measured data. The loss is about 0.05 dB and is considered to include scattering loss, conduction loss of the wire metal and the conduction loss at the wire contacts.

The antenna composed of this type of mesh surface may have the gain dependence on the polarization angle so that the ellipticity of circularly polarized wave may be degraded up to 0.2 dB.

Tuesday PM1 URSI-B Session TP17

Room: Columbus B *Time*: 1320-1500

Miscellaneous Contributions I

Chairs: Doren Hess, Scientific-Atlanta Inc.; M. Plonus, Northwestern University

1320 **BEYOND the BORN APPROXIMATION: TWO NEW NONLINEAR ESTIMATORS for ELECTROMAGNETIC SCATTERING in CONDUCTING MEDIA**
T. M. Habashy*, Schlumberger-Doll Research; R. W. Groom, Queen's University; B. R. Spies, Schlumberger-Doll Research

1340 **AN EXAMINATION of the RYTOV APPROXIMATION for LOW-FREQUENCY 3D SCATTERING with LARGE CONDUCTIVITY CONTRASTS and an EXTENDED RYTOV APPROXIMATION**
R. W. Groom*, Queen's University; T. M. Habashy, Schlumberger-Doll Research

1400 **MIXED BOUNDARY VALUE PROBLEM for the SURFACE CURRENTS on an OPEN-ENDED CONDUCTING TUBE**
Anthony J. M. Davis*, Robert W. Scharstein, The University of Alabama

1420 **A NUMERICAL TECHNIQUE for COMPUTING SPHERICAL BESSEL FUNCTONS of COMPLEX ARGUMENTS**
George T. Shoemaker*, Pennsylvania State University, Erie

1440 **THEORETICAL and EXPERIMENTAL STUDY of DIELECTRIC and MAGNETIC PROPERTIES of MIXTURES**
Caiming Qui*, Shuzhang Liu, Weigan Lin, Univ. of Elect. Science & Tech. of China

BEYOND THE BORN APPROXIMATION: TWO NEW NONLINEAR ESTIMATORS FOR ELECTROMAGNETIC SCATTERING IN CONDUCTING MEDIA

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The Born approximation, widely used for solving scattering problems, is of limited utility for low-frequency electromagnetic scattering where the principal contributor to scattering is conductivity variation. The Born approximation is an extremely poor estimator for the scattered field, even for moderate conductivity contrasts. Not only is the magnitude of the internal field not estimated correctly, but no information is obtained on the phase of the total internal field if it is anomalous to the background field. These are severe limitations, since the entire scattering problem can be described in terms of the internal field, and hence invalidates the Born approximation for many applications where conductivity can vary over many orders of magnitude.

We present two relatively simple nonlinear approximations. The first, termed the Static Localized Nonlinear approximation, is designed specifically to correct the magnitude of the internal electric field. To account for induction effects when the scatterer's scale size is of the order of or larger than one wavelength, an additional correction was developed. This correction, termed the Localized Nonlinear approximation, improves the estimate of the phase of the scattered field and includes some of the cross-polarization effects due to scattering.

Although these approximations are nonlinear in conductivity, they are generally much faster to compute than the full forward problem employing a purely numerical approach, and are as computationally efficient as the Born approximation. The effectiveness, scope of application, and geometric dependence of these approximations are demonstrated with two simple but important geometries: the sphere and the rectangular prism.

AN EXAMINATION OF THE RYTOV APPROXIMATION FOR LOW-FREQUENCY 3D SCATTERING WITH LARGE CONDUCTIVITY CONTRASTS AND AN EXTENDED RYTOV APPROXIMATION

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The Born and Rytov approximations are two commonly used approximations for solving scattering problems both of which are valid for small contrasts between the scatterers and the background medium. However, for a given contrast, the Rytov approximation is valid for a larger size scatterer than is the Born approximation. Conversely, for a certain size scatterer, the Rytov approximation is a better estimator than the Born approximation for a larger contrast. In this paper, we examine the limitations of these two approximations for 3D scattering in conducting media at low to moderate frequencies. To do so, we utilize two basic geometries for the scatterers; the sphere via an analytical solution and the rectangular prism using full numerical modeling solutions.

Due to the fundamental limitations of both of these estimators, we extend an earlier nonlinear estimator (presented in a companion paper by Habashy, Groom and Spies) to incorporate additional phase effects via a first-order phase correction termed the Localized Non-Linear Rytov approximation. This estimator attempts to overcome some of the limitations of the Born and Rytov by partially summing the secular terms appearing in the Born series thus resulting in an approximation that have a much wider range of validity than both the Born and Rytov approximations but is equally rapid in computation.

The greater accuracy obtained with the newly developed Localized Non-Linear Rytov approximation over the standard approximations (Born and Rytov) is illustrated again with the use of the spherical and rectangular scatterers.

MIXED BOUNDARY VALUE PROBLEM FOR THE SURFACE CURRENTS ON AN OPEN-ENDED CONDUCTING TUBE

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AND

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A mixed boundary value problem is formulated for the surface currents that are induced by a time-harmonic plane wave incident upon an open-ended conducting tube of finite length. Scattered fields are represented by spatial Fourier transforms in the axial dimension for each of the uncoupled azimuthal Fourier modes of this body of revolution. Numerically efficient mathematical expressions having explicit physical significance are derived to solve the set of linear equations from a Galerkin expansion of the currents in terms of Chebyshev polynomials with edge-condition weighting. Resultant surface currents and axial fields are calculated for several combinations of scatterer geometry and frequency. All coefficients in the linear equations are expressed in terms of a common integral of the product of four Bessel functions. Upon subtraction of the static contribution, the required integral is written as the sum of a triple Fourier coefficient of a regular function and the integral of the simplest combination of the Bessel functions. Induced vector currents on the hollow tube can exhibit extreme variation over the conducting surface, in both the azimuthal and axial directions. The numerical implementation of this mathematical analysis yields a complete and accurate solution for both the circumferential and axial currents, as a function of electrical length, cylinder aspect ratio, and the polarization and orientation of the incident plane wave. The standing wave nature of the surface currents indicates that the interaction between the exciting plane wave and the tube ends occurs via the external surface modes of the conducting cylinder.

A NUMERICAL TECHNIQUE FOR COMPUTING SPHERICAL BESSEL FUNCTIONS OF COMPLEX ARGUMENTS

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For the last several years I have been working to develop techniques for modeling open region low frequency scattering in a conductive medium such as seawater. The technique I have developed is based upon the Unimoment Method as proposed by Mei. The technique relies upon subdividing the solution region into two subregions. The first of these subregions contains the scatterer and is of finite extent. The solution in this region is carried out using a finite element technique to generate a set of numerically generated basis functions. The second subregion is of infinite extent and encompasses the rest of the solution region. This second subregion may be considered to be source free and homogeneous and therefore a standard multipole solution is used. The general solutions in the two subregions are coupled by a moment integral. The results of this work have been previously reported.

Essential to the generation of accurate solutions is the accurate calculation of the multipole fields used in the second subregion. This requires the accurate calculation of spherical bessel functions of a complex argument. In the previously reported work the recurrence relations were used to compute the spherical bessel functions. The stability of this technique is always questionable and I have found accurate results are particularly difficult to obtain when the argument is complex. This paper reports the results of a study undertaken to develop a more accurate technique for computing spherical bessel functions of complex arguments.

It can be shown that if the function shown below is expanded in a Fourier series the Fourier coefficients are proportional to the spherical bessel functions of the complex argument, z. The calculation of the spherical bessel functions therefore consists of determining the Fourier coefficients.

$$\cos\left(z \sqrt{1-k\, e^{it}} \right)+\sin\left(z \sqrt{1-k\, e^{-it}} \right)=\sum_{n=-\infty}^{\infty} C_n(z)\; e^{int}$$

THEORETICAL AND EXPERIMENTAL STUDY OF DIELECTRIC AND MAGNETIC PROPERTIES OF MIXTURES

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The microscopically complicated mixtures containing random dielectric and magnetic ellipsoids or coated ellipsoids are often meeted, such as in snow, soil, rocks, forests, and various electromagnetic wave absorbers. The previous mixing formulas are only for dielectric scattering particles or magnetic cases, and also for scatterers of high dielectric or magnetic constant they are not accurate enough to explain the data.

In this paper the apparent permittivity theory for only dielectric ellipsoids(A.H.Sihvola & J.A.Kong, IEEE Trans. Geosci. Remote Sens. 26, 420-429, 1988) has been generalized to the dielectric and magnetic ellipsoids or coated ellipsoids. Like Sihvola & Kong's method, we here assume the dipole moment of one scatterers is not embedded in infinite background material(ε,μ), but in the 'apparent material'(ε_h,μ_h). We have $\varepsilon_h=\varepsilon+ h\ (\varepsilon_{eff} -\varepsilon)$, $\mu_h=\mu+ h\ (\mu_{eff} -\mu)$. The generalized Maxwell-Garnet, QCA-CP, and Polder-van Santen mixing formulas for the dielectric and magnetic mixing coated ellipsoids may be derived, resp., with $h=0$, $h=1$, and $h=1-L_i$ (L_i is depolarization factor).

In the experimental study, the ferite mixtures as well as Al_2O_3 mixtures are carried out for various particle shapes(sphere, rod, plate). we find newly, the mixing formulas with $h=1$ is better than the case of $h=0$ and $h=1-L_i$ to explain the measured data when the dielectric permittivity or magnetic permeability is high. The depolarization factors should be corrected accordingly in the theoretical analysis. Most important, when the permittivity or permeability changes greatly, h can be replaced with different values to make the resulted mixing formulas accurate enough to explain various cases. Also h can be determined experimentally, especially for metal scattering particles, which are strong scattering problems that are almost hardly analized accurately by existing theories.

Wednesday PM AP-S, URSI-A B E, NEM Session WP01

Room: Grand E *Time*: 1320-1700

Transient Radar

Organizers: Carl E. Baum, Phillips Laboratory; Ivan J. LaHaie, Environmental Research Inst. of Mich.
Chairs: Carl E. Baum, Phillips Laboratory; Ivan J. LaHaie, Environmental Research Inst. of Mich.

1320 **STATUS of ULTRAWIDEBAND (UWB) RADAR and ITS TECHNOLOGY**
Merrill Skolnik*, Naval Research Laboratory

1340 **APERTURE EFFICIENCIES for IRAs**
Carl E. Baum*, Phillips Laboratory

1400 **ANALYSIS of the IMPULSIVE RADIATING ANTENNA**
Everett G. Farr*, EMA Inc.

1420 **OVERVIEW of the HDL IMPULSE SYNTHETIC APERTURE RADAR**
John W. McCorkle*, U. S. Army Laboratory Command

1440 **SELECTED SEA CLUTTER and TARGET MEASUREMENTS with a 0.2-1.0 GHZ ULTRA-WIDEBAND RADAR**
Michael A. Pollock, Vincent P. Pusateri, Thomas E. Tice, Robert J. Dinger*, Naval Ocean Systems Center

1500 **Break**

1520 **ULTRA-WIDE BANDWIDTH, MULTI-DERIVATIVE RADAR SYSTEMS**
Richard W. Ziolkowski*, University of Arizona

1540 **TRANSIENT RADAR for TARGET IDENTIFICATION and DETECTION**
K. M. Chen*, Dennis P. Nyquist, E. Rothwell, P. Ilavarasan, J. Ross, Michigan State University

1600 **BAYESIAN PROBABILTY THEORY APPLIED to the PROBLEM of RADAR TARGET DISCRIMINATION**
Lloyd S. Riggs*, Auburn University; C. Ray Smith, AMSMI-RD-AS-RA

1620 **A REVIEW of CURRENT GROUND PENETRATING RADAR CONCEPTS**
Jonathan D. Young, M. Poirier, Leon Peters, Jr.*, The Ohio State University

1640 **PANEL DISCUSSION on FUTURE of TRANSIENT RADAR (CHAIR: M. SKOLNIK)**

STATUS OF ULTRAWIDEBAND (UWB) RADAR AND ITS TECHNOLOGY

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An ultrawideband radar (which is somewhat arbitrarily defined as one with a relative bandwidth greater than about 25%) is of current interest because of its successful application for ground probing radar and the challenge of working in an area where the commonly invoked assumption that signals are narrowband is not necessarily valid. It is also of interest because of the importance of bandwidth in many radar applications. This paper describes some of the major differences between UWB and narrowband radar; such as the transient nature of radiation and scattering, the need to account for dispersive effects when propagation is over a wide frequency range (especially at low elevation angles), the effects of UWB in the Fresnel region, the limitations of the narrowband assumption widely used in signal processing theory, the complexity of signal processing when the target cannot be considered as a point source, the time-dependent nature of sea scatter when viewed with high spatial resolution, and the opportunity to process the actual UWB RF signal waveform rather than its envelope. Examples of some of these differences are given, including the radiation of a single cycle from a dipole (which is relatively broadband) and the nature of the Fresnel region when a single cycle is radiated (both examples are due to S. Samaddar). The current status of UWB radar technology for transmitters, antennas, and signal processing is briefly reviewed. The role of the laser-actuated semiconductor switch transmitter is discussed and compared with more conventional tube technology and with solid state modules. The possibility of analog or digital signal processing for area MTI to detect moving targets in clutter is also reviewed.

APERTURE EFFICIENCIES FOR IRAs

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In a previous paper (C.E. Baum, Radiation of Impulse-Like Transient Fields, XXIII URSI General Assembly, Prague, 1990, p. 277) it was shown that a suitable antenna for use as part of an impulse radar consists of a paraboloidal reflector fed by conical TEM wave launcher with termination impedances at the junction with the reflector edge. With a step-like (fast rising) wave on the feed, the radiated field has a narrow impulsive part with time integral (or area of waveform) proportional to 1/r times the integral of the electric field over the effective aperture illuminated by the reflector. The antenna pattern is reinterpreted in time domain in the form of pulse width or amplitude as a function of angle off the center of the beam.

This paper considers the characteristics of the aperture shape and size for launching the impulsive portion of approximate impulse-radiating-antenna (IRA) waveforms. Using complex-variable techniques the electric field on the aperture plane (early time) is assumed to have the distribution of a TEM plane wave (inhomogeneous) on the aperture and is formulated as a complex field given by the derivative of the complex potential with respect to the complex coordinate (two dimensional). The surface integral is converted to a contour integral around the aperture for ease in evaluation. This is used to define appropriate characteristic lengths for the aperture which can be maximized for best impulsive operation. Some convenient shapes (e.g. circular) are evaluated in closed form which can be directly used in the design of such antennas. The aperture optimization is applied to both TEM horns and TEM-fed reflectors, which are shown to have complementary structures on the aperture plane.

ANALYSIS OF THE IMPULSE RADIATING ANTENNA

Everett G. Farr

There has been a growing interest in the radiation of broadband pulses of electromagnetic energy. One candidate for such an antenna is the Impulse Radiating Antenna (IRA) (C.E. Baum, Sensor and Simulation Notes 321, 327, and 328). The purpose of this paper is to analyze further the properties of the IRA, and to provide a basis for comparison to other candidate antennas.

A diagram of the IRA is shown in Figure 1. It consists of a paraboloidal reflector fed by a 400-Ω spherical transmission line. Our design called for a 1.2 m dish with a F/D ratio of 0.4. At the junction of the feed and the dish are 2 200-Ω terminations that provide an approximately matched load at low frequencies. The spherical transmission line feed is a variant of a Balanced Transmission-line Wave (BTW) feed (E.G. Farr, IEEE Trans. Electmag. Compat. Vol. 33-2, pp. 105-112, 1991). The BTW feed provides a measure of directionality at low frequencies, and reduces late-time ringing of the radiated waveform.

The analysis proceeds along a two-pronged approach. At low frequencies, the structure is analyzed with the Method of Moments (MoM) using the Numerical Electromagnetics code. At high frequencies, we used Geometrical Optics (GO). It is shown that the GO results overlap the MoM results over a certain portion of bandwidth. After obtaining frequency domain results, one can drive the antenna with a step-function like time domain waveform in order to see the radiated waveform in the far field. We chose an inverse double exponential with a 10-90% risetime of 250 ps. and time to decay to 10% of the peak of 500 ns.

A graph of the radiated field on axis is shown in Figure 2. Note that for a step function input, we expect an impulse function to be radiated, with artifacts both before and after the peak. This is what is seen in Figure 2. Furthermore, we know exactly the size and shape of the artifact on the leading edge of the waveform, so we can gauge the accuracy of the calculations. Preliminary calculations suggest that the BTW feed successfully reduces the ringing in an IRA. Since that is one of the important requirements for successful Ultra Wideband systems, it appears that the IRA will be a leading candidate for the antenna of such a system.

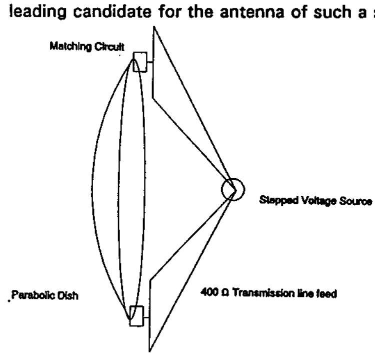

Figure 1. The Impulse Radiating Antenna.

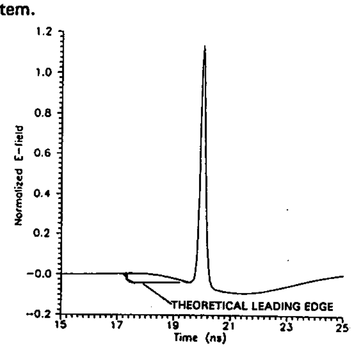

Figure 2. Waveform Radiated on Boresight.

OVERVIEW OF THE HDL IMPULSE SYNTHETIC APERTURE RADAR

JOHN W. MCCORKLE
U.S. ARMY HARRY DIAMOND LABORATORIES

Historically, the relative bandwidth of radars has been sufficiently small that a target's echo is adequately modeled by a single number, σ, the Radar Cross Section (RCS) – usually given in square meters. As a corollary, historically, radar systems have not measured target ringing. In the ultra-wide bandwidth (UWB) case where $.5 < \Delta F/F_0 < 2$, however, a single number does not adequately describe a target's RCS. First, σ is a function of frequency. The well known plot of the RCS of a sphere showing Rayleigh, resonant, and optical regions is an example. Second, in addition to the magnitude characteristic plotted, there is also a phase characteristic. These two frequency-domain characteristics can also be represented as a time domain signature containing a ringing or resonant response. In either case – time domain or frequency domain – the plots can be referred to as the impulse response of the target.

The process of obtaining images of the reflectivity or density of target areas that are rotating and translating with respect to a sensor such as a monostatic or bistatic radar, a sonar, or an x-ray CAT scanner has been studied for the past 40 years. Dale A. Ausherman , Adam Kozma, Jack L. Walker, Harrison M. Jones, and Enrico C. Poggio ("Developments in Radar Imaging" IEEE Trans. Aerosp. Electron. Syst. AES-20, No.5, pp. 363-400: Jul. 1984) give an excellent review of the work done in this area. Until now, however, implementation and study of image formation processing has been limited to isotropic point scatterers. Most radar targets, however, are anisotropic, resonant, and dispersive scatterers. Treatment of these cases becomes important when the sensor spectrum covers the Rayleigh, resonant, and optical regions of a family of targets. For example, discrimination between scatterers can be based on the unique signature of each target - but only if the information in the signature is preserved in the image formation process. Inclusion of anisotropic features become even more important when the aperture covers large angles.

This paper describes an impulse radar built on a railroad track on top of the main building at the U. S. Army's Harry Diamond Laboratories facility in Adelphi Maryland. The radar operates over a Ultra-Wide Bandwidth (UWB) of 50-1000 MHz and is fully polarimetric. Coherence is maintained across the aperture by a coherent-on-receive system. The pulse repetition interval (PRI) is jittered by a code with a spike autocorrolation. A 384 foot railroad track is used to collect data over a synthetic aperture. The radar includes a 480 MFLOP array processor that is used to do pulse-to-pulse interference filtering followed by a backprojection focusing algorithm. Since the bandwidth of the radar is greater than that of real targets, both the range resolution and azimuthal resolution are a constrained by the target scattering characteristics rather than the radar. Azimuthal resolution is further degraded since the target RCS is not constant for all positions on the synthetic aperture. The backprojection algorithm works in the time domain. It is modified to preserve natural resonance energy reflected by targets. Measurements to be carried out by the radar include clutter backscatter, foliage penetration loss, foliage penetration group delay, signatures of dispersive targets in the presence of clutter, and signatures of anisotropic targets in clutter.

SELECTED SEA CLUTTER AND TARGET MEASUREMENTS WITH A 0.2-1.0 GHZ ULTRA-WIDEBAND RADAR

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Impulse generators that can produce very short pulses (less than one nanosecond) and a very high peak powers (a few gigawatts) have been developed in recent years for the simulation of electromagnetic pulse (EMP) effects. The availability of such sources has naturally led radar designers to consider their use in radar systems: Instead of generating a high range resolution waveform by conventional pulse compression means, the notion is to simply transmit the ultra-short pulse in a brute force manner to achieve the desired range resolution. The advantages proposed for such an ultra-wideband (UWB) impulse radar range from better detection of low flying aircraft to exploitation of nonlinear target scattering effects. To explore the potential of UWB radar for over-the-ocean surveillance applications, we began a program at the Naval Ocean Systems Center (NOSC) to design and assemble an UWB radar in 1991 at a test site located along the Pacific Ocean near San Diego. The source generated a pulse with a 0.5-nsec pulsewidth and a 0.2-nsec rise time, yielding a waveform with energy concentrated in the 0.2 - 1.0 GHz portion of the spectrum. Incidence angles to the ocean of 0.35 to 7.0 degs were possible. In this paper we will describe the radar and a few of the first measurements with it. In particular, we present the first calibrated measurements ever reported of sea clutter made over a bandwidth of 0.2-1.0 GHz.

Ultra-Wide Bandwidth, Multi-Derivative Radar Systems

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The characteristics of the beams generated by ultra-wide bandwidth electromagnetic systems are central to their practical applications. These characteristics include the rate of beam divergence, the beam intensity, and the energy efficiency. Analytical bounds on the characteristics of beams generated by an arbitrary pulse-driven array have been derived and supported with numerical calculations. (R. W. Ziolkowski, "Localized Wave physics and engineering", Phys. Rev. A, vol. 44(6), 3960-3984 (1991); R. W. Ziolkowski, "Properties of Electromagnetic Beams Generated by Ultra-Wide Bandwidth Pulse-Driven Arrays", to appear in IEEE Trans. Antennas and Propagat., 1992) These bounds will be briefly reviewed; they extend the meaning of near-field distances or diffraction lengths to the situation where the array driving functions can be broad-bandwidth signals. Particular attention will be given to transmitting and receiving array systems which consist of elements that are not large in comparison to the shortest wavelength of significance contained in the signals driving them. The output signals of such systems are multiple time derivatives of the input driving functions. They constitute multi-derivative beam systems whose coherence properties are degraded more slowly by diffraction than lower-order systems. The bounds define the extent of these extended near-field enhancements.

It has also been shown that for certain measures of performance involving these beam characteristics, a localized wave pulse-driven array can outperform similar continuous-wave-driven arrays. A new type of array is required to realize these localized wave effects - one that has independently addressible elements. The enhanced localization effects are intimately coupled to the proper spatial distribution of broad-bandwidth signals driving the array; i.e., by controlling not only the amplitudes, but also the frequency spectra of the pulses driving the array. These enhancements have been verified with an array of ultrasound transducers in water. (R. W. Ziolkowski and D. K. Lewis, "Verification of the localized-wave transmission effect", J. Appl. Phys., vol. 68, pp. 6083-6086, 1990) Possible photo-conductive switch based realizations of these independently addressible arrays and multiple derivative systems will be discussed.

A brief discussion of a preliminary analysis of the potential applicability of multi-derivative, localized wave arrays to radar and to other remote sensing systems will be given. It will include the effects of having a target within the extended near-field region of a localized wave array. Comparisons between a localized wave pulse driven array system and the corresponding conventional continuous wave system will be used to illustrate these results.

TRANSIENT RADAR FOR TARGET IDENTIFICATION AND DETECTION

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A radar system using narrow interrogating EM pulses can provide capabilities of target identification and detection. When a target is illuminated by a narrow EM pulse, the scattered response from the target consists of an early-time response and a late-time response. The late-time response has been utilized to discriminate and identify the target based on the E-pulse (Extinction-pulse) and the S-pulse (Single-mode extraction pulse) techniques. These techniques are aspect-independent and their basic principles have been developed at Michigan State University. Our present effort on these techniques is to study the effectiveness of these techniques in the presence of sea clutter and noise.

We have initiated a study on the utilization of the early-time response of the target for target identification. The early-time response of a target consists of a series of sharp peaks representing specular reflections from discontinuities of the target structure. The locations and amplitudes of these peaks can be determined from the measured early-time response through a theoretical technique. The target is then identified by correlating its early-time response with that stored for a group of targets for various aspect angles. This procedure necessitates the storage of vast amounts of data. We have developed a method for reducing the amount of stored data based on the observed behavior of the early-time response. The scheme of using the early-time response has an advantage of high energy content but a disadvantage of aspect dependency leading to the need for predetermining the target's aspect angle.

We have also initiated a study to develop effective schemes to enhance the target response without increasing the noise and clutter levels for the purpose of target detection using narrow EM pulses. Possible schemes include the waveform shaping of interrogating pulses and coherent response processing utilizing the relative motion of the target against the background.

Bayesian Probability Theory Applied to the Problem of Radar Target Discrimination

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In this paper the task of discriminating among a set of N known targets based on their radar returns is viewed as a problem of information processing, calling for a full application of probability theory. Two distinct problem areas will be investigated.

In the first, Bayesian probability theory is used to derive an expression for an enhanced discrimination waveform which, in the two target case, maximizes the log odds in favor of one target over the other. Target transfer functions are computed in the resonance region (target linear dimensions on the order of a wavelength) using the singularity expansion method. Numerical results are provided which show that best discrimination, in the simple two target case, occurs when the incident waveform has its energy concentrated near the frequency where the difference in the impulse response of the two targets reaches a maximum. Changes in the enhanced discrimination waveform with target aspect will be discussed.

In the second part of this presentation probability theory is employed to discriminate among a set of targets based on their high-range-resolution (HRR) radar returns. An expression for the back-scattered field from a triangular-patch model of a perfectly conducting radar target (without apertures) is derived using the usual physical optics (PO) approximation for the currents induced on the target by the incident field. The frequency domain expression for the back-scattered far field is inverse Fourier transformed to obtain the target's HRR radar return. Example calculations show that for the four target case the Bayesian algorithm identifies the unknown target correctly greater than 90% of the time for signal-to-noise ratios as low as 2 (3 dB).

Wednesday PM AP-S, URSI-B D E Session WP02

Room: Columbus E/F *Time*: 1320-1700

Electromagnetic Aspects of VLSI Packaging

Organizer: R. Mittra, University of Illinois, Urbana-Champaign
Chairs: A. E. Ruehli, IBM; R. Mittra, University of Illinois, Urbana-Champaign

1320* **ELECTRICAL MODELING and SIMULATION ISSUES in ULSI PACKAGING**
J. L. Prince*, University of Arizona

1400* **THREE DIMENSIONAL CIRCUIT ORIENTED ELECTROMAGNETIC MODELING for VLSI PACKAGING**
A. E. Ruehli*, H. Heeb, IBM

1440 **DISCUSSION**

1500 **Break**

1520* **ELECTROMAGNETIC CHARACTERIZATION of HIGH-SPEED VLSI INTERCONNECTS with PERFORATED REFERENCE PLANES**
A. C. Cangellaris*, University of Arizona

1600* **A REVIEW of TECHNIQUES for ELECTROMAGNETIC MODELING of ELECTRONIC PACKAGES**
R. Mittra*, University of Illinois, Urbana-Champaign

1640 **DISCUSSION**

ELECTRICAL MODELING AND SIMULATION ISSUES IN ULSI PACKAGING

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Predicted (and predictable) trends in leading-edge electronic packaging and chip technology indicate that pressure on ULSI packaging design capabilities will increase. Modeling and simulation capabilities are key components of the ULSI Design System which has yet to be developed. Issues in the modeling and simulation area revolve around the critical ability to perform "efficient" simulation. Here, "efficient" means the simulation with the *least real time delay* before *acceptably accurate* results are available to the design engineer in an information format (in contrast to a *data* format). Implicit in this is the premise, based on observation and experience, that there is never enough computational and information management capability to "fully" analyze (no approximations or truncations) real designs in times consistent with human design engineering practice.

An example of one critical issue is the exploration and definition of the boundaries between different electrical analysis domains, for example quasi TEM-mode and full-wave, or lossless quasi TEM-mode and lossy quasi TEM-mode, etc. Another example of a critical issue is design data manipulation and information management, which is critical even now for systems involving a few dozen chips with a few thousand I/O's and a few tens of thousands of interconnect lines, but will become more of an issue when the chip I/O count and interconnect line count increase by one or two orders of magnitude in the next few years. Other issues such as experimental/simulation interactions and limits on electrical signal transmission technology will also be identified and discussed.

THREE DIMENSIONAL CIRCUIT ORIENTED ELECTROMAGNETIC MODELING FOR VLSI PACKAGING

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The clock rate of VLSI digital systems is rapidly increasing and the switching transients contain frequencies in the GHz range. The emphasis in the past has been on improving the speed of the VLSI semiconductor circuits. However, in high end systems, the packaging parasitics are limiting the system performance. Hence, a spectrum of requirements exits for the for the analysis of the contribution of the packages to the performance of VLSI systems.

Here, we concentrate on the electrical analysis and modeling of high performance packages. For several aspects of the electrical analysis, the three dimensional nature of the geomtries must be taken into account. This makes both the modeling programs and the solver aspects much more comnplicated. First, the total number of subdivisions or cells is $O(n^3)$, where n is the number of cells per side. Surface formulations like integral equation solutions as opposed to diffential equation type solutions may reduce this by n for homogeneous regions. The cost for this reduction is usually at the expense of the higher cost for computing the matrix coefficients.

In this talk we will give an overview of circuit oriented approaches for the solution of interconnect problems. We will consider new issues for partial element equivalent circuit modeling like retardation and dielectrics. This corresponds to a full wave electromagnetic solution of the problem. A further issue which will be discussed is potential circuit solver methods for the solution of these problems. Mainly, the solution of these problems is very time consuming due to the couplings and exact as well as approximate solution techiques may be appropriate in some cases.

ELECTROMAGNETIC CHARACTERIZATION OF HIGH-SPEED VLSI INTERCONNECTS WITH PERFORATED REFERENCE PLANES

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As the complexity and speed of integrated circuits increases, high-speed, high-density interconnection networks are required to support propagation of very broadband signals with frequency content extending to at least 10 GHz. To secure signal integrity and acceptable speed, multichip module (MCM) configurations have been proposed where, by placing multiple chips on a single substrate, interconnection distances are reduced. Mesh reference planes are required in order to facilitate the connection between chip and the signal line as well as connections between different signal layers. Undoubtedly, these mesh planes perturb the propagation characteristics of the interconnections from the values they would have if the planes were solid. Furthermore, through-mesh coupling between lines situated on either side of a mesh plane becomes possible, especially at higher frequencies.

From a system analysis point of view, it is desirable to obtain transmission-line equivalents for the aforementioned interconnections which can be used in conjunction with extended SPICE-like simulators to facilitate the analysis of the complete nonlinear circuit. A brief review of frequency-domain and time-domain techniques used for the extraction of such transmission-line equivalents is given. Emphasis is placed on the utilization of these full-wave, vectorial electromagnetic simulation tools for establishing upper frequency limits for the quasi-TEM modeling of such interconnections. Furthermore, within the limits of the quasi-TEM approximation, the validity of a simple dispersive model for the electrical analysis of interconnections with perforated reference planes is examined. The advantage of this model is that simple two-dimensional transmission-line parameter extraction programs are mainly uitilized and, combined with an appropriate electromagnetic analysis of the periodic interconnect geometry, lead to a computationally efficient prediction of the transmission line characteristics of the interconnections. The proposed model is extended also to the electrical characterization of coupled interconnects, as well as interconnects located on either side of a perforated plane. Comparisons with experimental results and results obtained using rigorous full-wave techniques are used to demonstrate the validity of the proposed model.

A REVIEW OF TECHNIQUES FOR ELECTROMAGNETIC MODELING OF ELECTRONIC PACKAGES

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Urbana, IL 61801-2991

Accurate simulation of cross-talk noise in interconnections is important in the design of electronic packages containing high-speed digital devices, lossless or lossy transmission lines and discontinuities, as for instance bends, vias and tapered etches. In this talk we review some techniques for the electromagnetic modeling of interconnections that lead to equivalent circuits suitable for incorporation into circuit simulation programs, e.g., SPICE.

Uniform transmission line etches on planar substrates, for example microstrip lines and striplines of rectangular cross-section, are most conveniently and efficiently modeled using the integral equation method employed in conjunction with the Method of Moments. However, the Finite Element Method (FEM) is better-suited for this task when the cross-section of the line configuration is arbitrary, and the dielectric substrate is non-planar. Recently, it has been shown that direct Maxwell solvers in the time domain, e.g., the Finite Difference Time Domain Method (FDTD), can also be used to compute the propagation characteristics and characteristic impedance of general transmission line configurations in a convenient manner.

One of the the most challenging problems in package modeling is that of deriving the equivalent circuit of discontinuities in single or multiple lines, for instance bends, cross-overs, and vias. Quasi-electrostatic and quasi-magnetostatic analyses of these problems are typically carried out by using the integral equation method. However, once again, the general purpose programs are often direct Maxwell solvers. This is because these methods have the capability of incorporating automatic mesh generators for convenient description of the problem geometries, and, hence, are potentially useful as CAD tools.

In this paper, we briefly review various computational modeling approaches mentioned above, comment on their relative merits, and point out some of their drawbacks.

We include a number of representative numerical examples of discontinuity modeling, extraction of their circuit parameters, and the incorporation of these equivalent circuits in time domain simulation algorithms.

Wednesday PM AP-S, URSI-B D Session WP03

Room: Columbus C/D *Time*: 1320-1700

MMIC Devices and Applications

Organizers: David C. Chang, University of Colorado at Boulder; Tatsuo Itoh, University of California, Los Angeles

Chairs: David C. Chang, University of Colorado at Boulder; Tatsuo Itoh, University of California, Los Angeles

1320 **MONOLITHIC PHASED ARRAYS: an OVERVIEW**
Robert Mailloux*, Rome Laboratory

1340 **RECENT PROGRESS on MICROWAVE and MILLIMETER WAVE DEVICE and CIRCUIT TECHNOLOGY**
Chente Chao*, Hughes Aircraft Company

1400 **MODELING MICROWAVE CIRCUITS: LINEAR, NONLINEAR and SYSTEM SIMULATION**
Anthony M. Pavio*, Texas Instruments, Inc.

1420 **TESTABILITY and YIELD of MMICS**
Barry R. Allen*, TRW Electronics Systems Group

1440 **ANTENNA/MMIC PACKAGING TECHNIQUES for COMMERCIAL APPLICATIONS**
Hugh R. Malone*, Motorola Inc.

1500 **Break**

1520 **ELECTROMAGNETIC SIMULATION METHODS for MMIC DESIGN**
K. C. Gupta*, University of Colorado at Boulder; Roberto Sorrentino, Universita Degli Studi di Perugia

1540 **OPTICALLY-BASED TESTING of CIRCUITS and DEVICES**
John F. Whitaker*, The University of Michigan

1600 **NEW DEVICE/CIRCUIT INTEGRATION**
Karl D. Stephan*, University of Massachusetts at Amherst

1620* **DISCUSSION**

MONOLITHIC PHASED ARRAYS: AN OVERVIEW

Robert J. Mailloux
Electromagnetics and Reliability Directorate
Rome Laboratory

The last decade has seen significant developments toward "monolithic" phased arrays at EHF frequencies. Although there are yet no fielded arrays, there is a capability that can now be exploited.

The term monolithic is not really applicable to phased arrays. There are monolithic circuits, but monolithic scanning arrays are not yet practical, and perhaps not even a reasonable goal. The assembly of arrays including microwave or millimeter wave monolithic integrated circuit technology has resulted in viable, but not monolithic, solutions. Among the first attempts were several very high risk subarray developments at 20 and 44 GHz, that placed microstrip elements , phase shifters and amplifiers in complete subarrays on GaAs substrates. These monolithic subarrays were designed for incorporation into arrays with multiple layer printed circuit boards for microwave, DC, and logic distribution. This multi-layer fabrication is termed "tile" construction, and has the primary advantage of being very thin. Of the several subarrays designed and built in this manner, the first suffered yield problems, and were not fully successful. Other problems with this tile construct are that it is difficult to remove heat and to arrange for the large number of vertical interconnects necessary to provide bias and control to each subarray. This "back plane" technology proves to be one of the key issues in development of arrays with tile construction.

A second construction approach that has found favor if the array can be made somewhat thicker is called the "brick" construct. In this architecture, the array is fabricated on multi-layer circuit boards that are mounted perpendicular to the aperture. With this construct there is more room for heat removal, and for signal and bias line distribution.

With either architecture, the array design is dominated by thermal constraints, and so device efficiency and noise figure have become the primary design tradeoffs. This has resulted in recent developments of subarrays and circuits with pseudomorphic HEMT and Indium Phosphide substrates.

This paper summarizes progress in array architecture and device development toward "monolithic" arrays, and presents examples to illustrate the state of the art.

Recent Progress on Microwave and Millimeter Wave Device and Circuit Technology

Chente Chao
Hughes Aircraft Company

This presentation will summarize the recent progress in the development of GaAs- and InP-based microwave and millimeter wave device, circuit, and component technologies. State of the art in MESFET, HBT, and HEMT device technologies for applications in both low-noise amplification and high-efficiency power generation will be reviewed. Ultra low-noise amplification using GaAs-based pseudomorphic and InP-based, lattice-matched HEMTs with gate length down to one-tenth of a micron will be highlighted. High-efficiency microwave power generation based on improved MESFET design, as well as recently developed microwave HBT technology, will be discussed.

The development of monolithic integrated circuits for high-performance transmit/receive module, broadband receiver, and low-cost sensor applications will be summarized and highlighted with circuit examples of single- and multiple-function MMICs. Advanced circuit design techniques, including design centering for higher circuit yield and chip compaction for minimum chip size, will be illustrated.

Recent progress on the development of the advanced components based on the integration of these MMICs will also be presented. Package design criteria for the complex multi-chip components will be discussed in terms of RF performance, size, weight, thermal conductivity, and cost constraints. Methods for integration of passive circuits into the multi-layer module to achieve built-in circuit structures and to meet demanding module performance and size requirements will be highlighted.

MODELING MICROWAVE CIRCUITS: LINEAR, NONLINEAR AND SYSTEM SIMULATION

Dr. Anthony M. Pavio
Texas Instruments, Inc.
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For many years the microwave design community has focused its CAD activities toward the linear simulation of hybrid circuits. This trend prevailed through most of the past decade. However, it is now possible and quite practical to simulate most performance aspects of hybrid and monolithic circuits and systems.

This presentation will focus on the aspects of simulating practical microwave circuits with real world constraints such as modeling errors, process variations, layout effects and circuit size. Simulation examples which integrate linear and nonlinear problems as well as system simulation requirements will be presented. Typical circuit topologies included are multi-stage monolithic power amplifiers, passive baluns structures and digital FM receivers. The application of time-domain versus frequency-domain simulation techniques will also be discussed. In addition, the use of EM simulators to evaluate critical circuit aspects will be included. Whenever possible, commercially available software products will be used in the illustration of simulation techniques and results. Included with the design examples is a discussion of the capabilities and limitations of the available software tools.

TESTABILITY AND YIELD OF MMICS

Barry R. Allen
TRW Electronic Systems Group, Redondo Beach, CA

The complexity and performance expectations of MMICs has increased to the point where testing will be a major cost driver if testing strategies and procedures are not optimized. The testing problem has grown as the complexity and functionality of MMICs has increased. Previously gain or gain and noise figure were sufficient to fully verify the operation of MMICs. Many chips now contain several functions on a chip to form a small sub-system resulting in a more complex test problem. The level of testing required to identify good die depends on the performance requirements and the design margins for individual specifications. The verification of chip performance and yield through 100% test of every specification is not always practical or necessary, if the fabrication process is repeatable and there are sufficient design and process margins.

Present MMICs may contain up to several hundred devices. As the complexity of MMICs has grown, it is no longer practical to verify the DC performance of every active device in a circuit to derive circuit yield. Our approach to MMIC yield measurement is to provide on-wafer functional testing. On-wafer RF testing, combined with minimum DC testing, provides the necessary testing of individual chips with minimum costs. The on-wafer tests required to verify chip performance may include any tests that would be associated with verification of a microwave subsytem. The on-wafer tests used to screen MMICs for yield currently include measurements of output power, complex gain, return loss, noise and spurious outputs. To provide effective on-wafer screening of MMICs, testability must be included as part of the design. The design issues that influence on-wafer testability include: pad placement, stability, number of connections, and thermal resistance.

The testing required to identify good die may range from full functional testing of every specification to simple DC screening. The required level of testing is usually related to the performance requirements of the chip and the design margins. For example gain and DC current measurement is usually sufficient to verify noise figure performance if the noise figure margin is high. Unless the process and design are well characterized, initial testing of MMICs may include more extensive testing than necessary for production testing. Once the critical test parameters are identified, the production die screening tests can be made more efficient by elimination of tests that have high yield and are highly correlated with other test parameters.

ANTENNA / MMIC PACKAGING TECHNIQUES FOR COMMERCIAL APPLICATIONS

Hugh R. Malone
Motorola Inc.

The purpose of Microwave Monolithic Integrated Circuits (MMIC) in commercial systems is to make the antenna design practical. MMIC's allow systems to operate at frequencies where directional antennas can be small and cost effective. Even in this important role, the cost of MMIC's must not dominate the system cost. More specifically, the package for the MMIC and the manner it connects to the antenna must be very cost effective. This paper will present an overview of low cost techniques that can be used to insert an MMIC between a cost effective antenna and the rest of the system.

Many excellent packages have been developed for use with MMIC's for applications that range up to 26 GHz. Most of these packages are designed to contain a high performance MMIC for use in a military or aerospace application. In these applications, the MMIC may replace a module that costs several thousand dollars and thus a $25 MMIC package is affordable.

In many commercial applications $25 is unaffordable. An example of this is found in the Motorola Altair™ wire-less in-building communication system. The purpose of the Altair™ system is to replace computer network cables that are routed throughout a building. A long coax cable cost only a few dollars, but installation and/or re-installation adds some additional cost. The MMIC's, the package and the total assembly must be cost competitive with the cable approach.

Injection molded plastic parts are cost effective. Many children's toys are made using metalized, injection molded plastic parts. This same technique can be used for certain microwave applications. The loss of a microstrip line made on injection molded polyetherimide (PEI) is less than 1.0 dB per inch through X-band. This is acceptable for many systems such as Altair™ where line loss can be over come with the gain of the MMIC's. Injection molded, metalized PEI housings are also compatible with automated die bonding and wire bonding techniques if the thickness of the PEI is greater than 0.025". Thin sections of PEI are not consistently flat enough for high yield wire bonding techniques. Motorola has developed an injected molded, metalized waveguide to microstrip transition that operates in Ku-band. With this technique, the transition between an MMIC and a low cost waveguide antenna is nearly cost free.

Today's technology can provide MMIC die for less than a dollar. Injection molded plastic packaging techniques are cost effective. The combination of low cost MMIC technology and injection molded packages will be applied to many new and unexpected commercial and/or consumer applications.

ELECTROMAGNETIC SIMULATION METHODS FOR MMIC DESIGN

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Accurate computer-aided design techniques are a necessary prerequisite for first-pass success and the resulting economic feasibility of monolithic microwave integrated circuit technology. Traditionally, microwave circuit designers have used a transmission-line circuit approach with quasistatic and two-dimensional planar modeling for characterization of various passive components like junctions, discontinuities, resonators, etc. Full-wave electromagnetic simulations provide the most accurate approach with a minimum of analytical approximations in the characterization process for various passive components. Three important applications of EM simulators for MMIC design are: (a) Accurate characterization of junctions and discontinuities, (ii) evaluation of parasitic coupling among various parts of MMICs, and (iii) the effect of packages on MMIC performance. None of these items can be characterized with satisfactory accuracy using conventional transmission line and quasistatic approached. For example, it has been shown that electromagnetic simulation is necessary for incorporation of spurious coupling effects in MMICs (see Goldfarb and Platzker, *International Journal of Microwave and Millimeter-Wave Computer-Aided Engineering*, Vol. 1, No. 1, January 1991, pp. 38-47). Similarly, electromagnetic analysis has shown that the spurious coupling may be enhanced considerably, by as much as 50 dB, if package resonances occur in the operating frequency range. (For example, see Sabban and Gupta, *International Journal of Microwave and Millimeter-Wave Computer-Aided Engineering*, Vol. 1, No. 4, pp. 403-411.)

This presentation will review various integral equation-based and differential equation-based electromagnetic simulation methods used for MMIC modeling and design. Integral equation-based methods solve for electric current distributions on the conductors located on the top surface of a microstrip circuit and/or for equivalent magnetic current distributions on the slots in coplanar line circuits. Differential equation-based techniques include finite element, finite difference, edge elements and TLM approaches implemented either in frequency or in time domain. In addition to the analysis algorithms employed, the usefulness of EM simulators depends on the ease of input procedure for geometrical layout and techniques used for extraction of useful circuit parameters (e.g. S-matrix characterization).

Discussion will include areas wherein further research is needed in order to make electromagnetic simulation more useful for MMIC design.

OPTICALLY-BASED TESTING OF CIRCUITS AND DEVICES

John F. Whitaker
Center for Ultrafast Optical Science
University of Michigan

The ability to measure very short time-duration electrical waveforms, and thus very high frequency signals, is limited when using conventional all-electronic instruments. Since modern analog devices now have predicted cutoff frequencies in the multi-hundred-gigahertz regime, and digital electronic components which have picosecond switching characteristics are being fabricated, alternatives to the currently used test and measurement techniques must be considered. In addition, there is mounting interest in the development of the capability to measure waveforms at internal nodes of integrated circuits, particularly with high temporal resolution (or high frequency response) and without the constraints of electron-beam testing. A variety of techniques which utilize short-duration laser pulses and fast optoelectronic sampling gates are now being applied to such test and measurement problems. This paper will introduce and address the progress of two of the principal optically-based techniques in this field, electro-optic and photoconductive sampling.

The various embodiments of the optically-based measurement techniques have bandwidths that approach or exceed one terahertz. They have been used to perform network analysis for the small-signal characterization of HEMTs and other high-frequency devices, acquiring *S*-parameters up to frequencies greater than 100 GHz. Furthermore, since single-picosecond-rise-time step functions with significant voltage amplitudes can be routinely generated using short laser pulses, large-signal switching measurements have also been made using optical methods. Current efforts are concentrating on increasing the performance and accuracy of measurements and applying them more directly to MMIC and VLSI.

NEW DEVICE/CIRCUIT INTEGRATION

Karl D.Stephan
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University of Massachusetts
Amherst, MA 01003

Abstract

As monolithic integration of conventional microwave and millimeter-wave circuits has become almost routine, several groups have advanced the frontier of integration further toward larger-scale circuits with novel operating modes. Many of these developments tend to blur the distinction between antennas and circuits to yield better performance in terms of total effective isotropic radiated power (EIRP), power density, or power-handling capability.

In the field of microwave control circuits, arrays of interconnected diodes have been demonstrated to be useful in quasioptical systems for applications as diverse as switching, phase shifting, and frequency multiplication. An integrated 464-diode W-band switch reported by Stephan and Goldsmith will be described, and the work by Rutledge et al. on diode-grid phase shifters, frequency multipliers, and high-dynamic range mixers will be reviewed.

Two-terminal active devices such as Gunn diodes are featured prominently in several power-combining schemes. York, Compton et al. have demonstrated a 16-element Gunn-diode array that produces 22 W EIRP at 9.6 GHz. In addition, they have discovered that under the right conditions, arrays of Gunn diodes can mode-lock together, giving rise to novel pulse effects.

Turning to transistor circuits, Itoh et al. have developed several interesting and useful circuits, including one that allows both external injection-locking and quasioptical power-combining. The future will tell how system designs will be affected by these novel developments.

Wednesday PM AP-S, URSI-B E Session WP04

Room: Grand F *Time*: 1320-1700

Wireless Communication

Organizer: T. M. S. Heng, Motorola Inc.
Chairs: T. M. S. Heng, Q. Balzano, Motorola Inc.

1320⁺ **IN-BUILDING WIRELESS COMMUNICATION - ALTAIR**
T. Freeburg*, Motorola Inc.

1400⁺ **LOW-EARTH ORBIT GLOBAL CELLULAR COMMUNICATIONS NETWORK**
Raymond J. Leopold*, Motorola Inc.

1440 **DISCUSSION**

1500 **Break**

1520⁺ **PERSONAL WIRELESS COMMUNICATION**
Don Cox*, Bellcore

1600⁺ **INTELLIGENT VEHICLE HIGHWAY SYSTEM**
Alan Kirson*, Motorola Inc.

1640 **DISCUSSION**

ALTAIR - TRUE WIRELESS IN-BUILDING NETWORKING

Thomas A. Freeburg
Motorola Inc.

Despite the advances in power and performance we now enjoy thanks to modern solid-state electronics, we're still shackled with the problems -- physical, logistical, and financial -- of wire- and cable-based communications within buildings. Anyone familiar with installing, maintaining, and changing building cabling doesn't have to be convinced that it's a nightmare crying for a viable wireless alternative. Needed: a high-performance, easy-to-deploy, user-transparent, reliable wireless in-building communications network technology to complement, extend, or replace current hard-wired communications. Such a system must also be compatible with present and future cable-based voice/data communications performance, standards, and protocols.

In a five-year engineering effort, Motorola's Wireless Enterprise Systems group (WES) has developed the technology to make such a system truly practical, cost effective, and achievable. The system technology is based on a microcellular communications network architecture using low-power 18-gigahertz (GHz) radio technology as the transmission medium.

This paper describes the basic set of problems which this technology addresses, the minimum performance and features required of a viable in-building wireless technology, the range of options available in selecting a design approach for such a system and, finally, the considerable technical problems Motorola engineers faced in developing a system using 18-GHz radio technology and how they solved them.

To illustrate and clarify the specific problems and technical tradeoffs involved in the development process, some discussion of the fundamental design and operation of a baseline generic microcellular wireless in-building system is included.

MOTOROLA'S IRIDIUM™ SYSTEM:

LOW-EARTH ORBIT GLOBAL CELLULAR COMMUNICATIONS NETWORK

Dr. Raymond J. Leopold
Chief Engineer
Motorola Satellite Communications

The technical parameters which led to Motorola's announced IRIDIUM™ system are discussed. The Iridium system is a worldwide, satellite-based, cellular, personal communications system primarily intended to provide commercial, low-density, mobile service via portable, mobile, or transportable user units, employing low-profile antennas, to millions of users throughout the world. Calls can be made and received anywhere in the world with a personal, portable unit. Small smart satellites are internetted to form the network's backbone. Small, battery-powered, cellular-telephone-like user units communicate directly to the satellites. Gateways (earth stations) interface from the satellites to the individual Postal, Telephone and Telegraph Authorities (PTTs). The system is intended to be compatible with terrestrial cellular telephone systems installed, or being installed, in densely populated areas by providing a similar service everywhere else in the world. Iridium is much more than the technology that allows it to be built -- the Iridium program is a vision, a reliable vision, for a worldwide portable, personal communications system -- a vision whose greatest realization, like the telephone of a century ago, is beyond today's imagination.

PERSONAL WIRELESS COMMUNICATIONS

Donald C. Cox
Bellcore, Red Bank, NJ 07701

Interest in "Personal Communications" in the United States and worldwide has increased to a level unexpected several years ago. Recently, the terms Personal Communication Network (PCN) or Services (PCS) have become telecommunication industry buzzwords. Several approaches to tetherless personal communications encompass: a) derivatives from low-power cordless telephones including CT-2 and Phonepoint/Telepoint in the United Kingdom, Europe, and the Far East. Digital European Cordless Telephone (DECT) in Europe, cordless PBXs and Handiphone in Japan, Universal Digital Portable Communications at Bellcore and ISM-band products being developed; b) second generation higher power digital cellular mobile radio, e.g., Global Standard Mobile (GSM formerly Special Group Mobile of ETSI) in Europe, TIA and CTIA (IS-54 and proposed E-TDMA and CDMA technologies) in the United States and the Japanese Digital Cellular standard (JDC); c) both low-power wireless local area networks (LANs) for data and higher power wide area radio data networks in the United States and Europe; and d) medium power PCNs in the United Kingdom. These different approaches are aimed at different specific applications as well as being at different stages of definition, development, and evolution. Other activity includes regulatory initiatives by the FCC in reaction to petitions for spectrum and requests for experimental licenses and starting activities in several standards bodies, including TIA, committee T1, CCIR, CCITT, and IEEE. Low-power digital radio could be integrated as an access technology into an intelligent local telephone exchange network to provide ubiquitous PCS.

This talk will provide a brief overview of these worldwide activities, followed by discussion of wireless access technology alternatives, and recent activities related to frequency allocation. Some technical challenges and a proposed personal communications system based on low-power digital radio access to intelligent local exchange networks will be discussed.

Wednesday PM AP-S, URSI-A B D E K, NEM Session WP05

Room: Columbus I/J *Time*: 1320-1700

Computers in Electromagnetics Education

Organizers: R. E. Collin, Case Western Reserve University; Magdy F. Iskander, University of Utah
Chairs: R. E. Collin, Case Western Reserve University; Magdy F. Iskander, University of Utah

1320 **INTEGRATION of the PERSONAL COMPUTER INTO UNDERGRADUATE ELECTROMAGNETICS COURSE**
Warren L. Stutzman*, Virginia Polytechnic Inst. & State Univ.

1340 **COMPUTER AIDS in CHEMICAL ENGINEERING EDUCATION- an ASSESSMENT of CACHE - 1971-1991**
Warren D. Seider*, University of Pennsylvania

1400 **THE USE and IMPACT of VISUAL ELECTROMAGNETICS SOFTWARE in the CLASSROOM**
R. W. Cole*, Curtis Brune, University of California, Davis

1420 **COMPUTER SIMULATIONS in the CHEMICAL ENGINEERING LABORATORY**
P. K. Andersen*, R. G. Squires, G. V. Reklaitis, Purdue University

1440 **INTERACTIVE COMPUTER MODULES for UNDERGRADUATE CHEMICAL ENGINEERING INSTRUCTION**
H. Scott Fogler, Susan M. Montgomery*, The University of Michigan

1500 **Break**

1520 **PROGRESS in COMPUTATIONAL ELECTROMAGNETIC MODELING for EM COURSEWARE: a PERSONAL PERSPECTIVE at PENN STATE**
Karl S. Kunz*, The Pennnsylvania State University

1540 **REFLECTIONS on CAEME SOFTWARE and NEW DEVELOPMENTS TOWARDS SOFTWARE IMPLEMENTATION in CLASSROOM TEACHING**
Magdy F. Iskander*, University of Utah

1600 **INTEGRAL EQUATIONS in ELECTROMAGNETICS for UNDERGRADUATES**
Chalmers M. Butler*, Clemson University

1620+ **DISCUSSION/DEMONSTRATIONS**

COMPUTER AIDS IN CHEMICAL ENGINEERING EDUCATION -- AN ASSESSMENT OF CACHE -- 1971-1991

Warren D. Seider
Chemical Engineering Department
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Philadelphia, PA 19104-6393

Abstract

Since its inception in 1971, the CACHE Corporation has concentrated on promoting cooperation among universities, industry, and government in the development and distribution of computer-related and/or technology-based educational aids for the chemical engineering profession. This article assesses the success of several projects designed to provide aids for individual courses, as well as for a broader segment of the curriculum. The projects include: (1) the provision of 125 computer assignments for the core courses, (2) the preparation of teaching materials for, and the distribution of, Monsanto's FLOWTRAN program for use in the design courses, (3) the preparation of PC modules for many courses, leading to the Michigan project on the Development of Innovative Engineers and the Washington project on Graphical Computer Aids, for fluid flow and reaction, in the design of chemical reactors, and (4) the development of the MICROCACHE courseware delivery system. Also considered are the CACHE recommendations concerning the minimum requirements for computing in the undergraduate curriculum, presented to the AIChE Education and Accreditation Committee. The CACHE Corporation has facilitated several research conferences, the impact of which is assessed.

THE USE AND IMPACT OF VISUAL ELECTROMAGNETICS SOFTWARE IN THE CLASSROOM

Rodney Cole, Curtis Brune*
Department of Physics
Learning Skills Center
University of California, Davis

Abstract

Electromagnetic radiation, involving non-local retarded solutions to Maxwell's equations, has long been difficult to teach and frustrating to learn. It often takes years of study to be able to conceptually understand a solution without using the powerful mathematics of Maxwell's theory. This steep learning curve is a major contribution to the decrease in the number of students choosing electromagnetics as a career. In response to this state of affairs, we have developed software that runs on a MacIntosh microcomputer and helps students visualize the fields and electromagnetic effects. The software consists of a field simulator that maps the electric, scalar potential, vector potential, and magnetic fields around distributions of point charges. The charges may be static, moving, and accelerating. It allows radiation patterns to be simulated from the charge distributions. It supports contour, pseudo-color, and fieldline maps of the fields. In addition, there are several HyperCard tutorials that accompany the simulation program, and span an introductory course in electromagnetics. The HyperCard tutorials point out useful features in classic field problems and relate the field maps to the fundamental laws of electricity and magnetism. They feature animated field sequences and animated equations. After a brief description of the software, we will present a video tape showing it being used in the introductory calculus physics class at the University of California, Davis, both by the instructor in lecture, and by the students in classroom discussion sections. You will be able to see how students are interacting with the software. Finally, results on how the software has affected student performance will be presented. We will analyze the impact computer instruction has had on the students.

Computer Simulations in the Chemical Engineering Laboratory

P. K. Andersen
Department of Freshman Engineering

R. G. Squires and G. V. Reklaitis
School of Chemical Engineering

Purdue University
West Lafayette, IN

A number of computer-based modules have been developed for the senior chemical engineering here at Purdue University. Each module comprises a sophisticated simulation and a videotaped "plant tour" of an actual chemical plant, produced with the technical assistance of an industrial sponsor. To date, six companies (Air Products, Amoco, Dow, Ethyl, Mobil, and Tennessee Eastman) have sponsored modules.

The process simulations are written for Sun workstations running under UNIX and X Windows. The simulations are designed to be "user-friendly," employing a graphical user interface, pull-down menus, and extensive on-line help. A typical simulation consists of 10,000 lines of C and FORTRAN code, and closely models the behavior of an existing chemical plant.

These simulation modules have been used at Purdue and other universities for several years, and have proven to be an attractive alternative to traditional laboratory experiments. Using a simulation, students can investigate processes that would be not be feasible to operate in the university lab. Furthermore, the simulation programs are flexible, and can be used in courses other than the senior lab.

The Purdue modules provide a sense of realism that is unusual in the undergraduate laboratory. The students are given their assignment letters on official company letterhead. The assignments include an imaginary research budget from which the students must pay their experimental expenses. Nearly any action that the students take has a cost that must be paid from the budget. Additional "labor costs" are charged for overtime and weekend runs. (The professor even charges a "consulting fee" to answer students' questions.) This forces the students to plan carefully and to exercise good engineering judgement.

INTERACTIVE COMPUTER MODULES FOR UNDERGRADUATE CHEMICAL ENGINEERING INSTRUCTION

H.Scott Fogler, Susan M. Montgomery *
Department of Chemical Engineering, University of Michigan
Dow Building, 2300 Hayward, Ann Arbor, MI 48109-2136

The goal of the computer modules component of the project "A Focus on Developing Innovative Engineers", funded by the National Science Foundation, is to develop a complete set of interactive computer modules for courses in the undergraduate Chemical Engineering curriculum, where each computer module reinforces one of the key course concepts. Modules are then to be distributed free to all educational institutions. Modules for the Introduction to Chemical Engineering course have been tested and distributed, and modules are currently being tested in the Fluids/Transport, Separations, and Chemical Reactor Design courses.

The computer modules generally consist of a brief review of the material, followed by an interactive problem solving session. The optional review benefits a student who may not have understood the material by providing an additional, self-paced, presentation of the key concept. Some of the modules expose the student to new technologies (e.g. drug patches, chemical vapor deposition) and allow the student to learn by induction using a computer simulation of the processes involved. This provides a different experience than the typical classroom or homework experience. In addition, many of the problems to be solved are presented as part of an overall scenario, to capture the student's interest. This portion of the module also includes hints and reference screens to guide the student through the problem. Other modules provide for interactive testing of the subject matter, enhancing the learning experience for the student.

The development of modules has advanced to such an extent that module developed during the summer 1991 have been successfully used in the fall and spring semesters at the University of Michigan, with few adjustments suggested, either in the technical content or in the organization of the modules. Response to the modules from other universities has also been positive, with nearly 40 requests for even the testing versions of some of the modules at a recent national meeting.

PROGRESS IN COMPUTATIONAL ELECTROMAGNETIC MODELING FOR EM COURSEWARE: A PERSONAL PERSPECTIVE AT PENN STATE

Karl S. Kunz
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Penn State University
University Park, PA 16802

Recent advances in computational electromagnetic modeling makes it possible to provide students with interactive, color visualization of complex three dimensional phenomena on personal workstations in real time at reasonable cost.

The advances are: 1) the computational engines available, where we have found the finite difference time domain (FDTD) techniques to be most advantageous; 2) the availability of powerful workstations with extensive color graphics support, operating in the multi-megaflop regime; and 3) an emerging environment of courseware development support from a host of groups and agencies, including at Penn State, CAEME, and ECSEL, which permits development of student friendly interfaces or shells.

In our work the interface provides multiple problem types with a hierarchical level of problem sophistication ranging from demonstrations-to tutorials-on up to independent student design efforts. The student selects the problem type (a waveguide for example), the level of difficulty or interactivity suitable to his or her experience, inputs the required variables then watches as the system responds in time to the selected stimulus in the form of real time graphical display of the fields and interaction object.

The level of capability in computational modeling for EM courseware has evolved rapidly over just a few years, proceeding from one dimensional modeling then two dimensional, and now three. The need for color graphical display of the modeling results was apparent even in the early stages of development and has grown rapidly along with computational speed. At present there is still more to be obtained from increases in speed and graphical sophistication, however the greatest challenge is to lower costs making this approach to teaching more attractive.

INTEGRAL EQUATIONS IN ELECTROMAGNETICS FOR UNDERGRADUATES

Chalmers M. Butler
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Undergraduate courses in electrical engineering dwell on differential equation methods, yet much of the practicable analysis of today in electromagnetics is based on integral equation techniques. To be prepared for demands on engineers of the future, a student should be exposed to integral equations and to simple methods for solving them, at least to the extent that an appreciation of what an integral equation is and how it differs from a differential equation can be acquired. If for no other reason, one can justify a brief study of integral equations on the basis that a young engineer should have some understanding of the principles that underlie the many computer codes that he/she will be expected to utilize in everyday engineering practice.

Instructional materials and attendant computer software have been developed to serve as aids to students who wish to learn methods for formulating and solving simple integral equations applicable to problems in electromagnetics. The materials, which are highly tutorial and suitable for self-study, comprise a general discussion of integral equations, step-by-step derivations of integral equations, and development of numerical methods for solving these equations. They include numerous examples illustrating the formulations and solution techniques, all supported by discussions of applications of these methods to sample problems of practical interest and by computer codes that enable a student to observe an implementation of the numerical solution method. The codes provide the opportunity for the student to view the solution and to test the sensitivity of the solution to changes in problem parameters. Exercises (problems) are provided which will give the student the opportunity to test his/her mastery of the material and to extend the material to current applications. A student may either write all code needed for solving the exercises or may take advantage of all or parts of blocks of code provided in the form of subroutines.

The notes describe derivations of integral equations and developments of numerical methods for solving many types of problems including: charged parallel conducting cylinders, isolated and coupled microstrip and stripline structures, charged thin-wire conductors, wire scatters and antennas (including simple arrays), and scattering of TM waves by conducting cylinders. All these examples are supported by computer codes.

Selected portions of the instructional aids and supporting computer codes will be described in the presentation and sample examples will be illustrated.

Wednesday PM AP-S, URSI-B, NEM Session WP06

Room: Columbus K/L *Time*: 1320-1700

Modern RCS Computation

Organizer: S. W. Lee, University of Illinois, Urbana-Champaign
Chairs: S. W. Lee, University of Illinois, Urbana-Champaign; Alex Woo, NASA Ames Research Center

1320 **MODERN RCS COMPUTATIONS - a PRACTICAL APPROACH**
Thomas A. Blalock*, U. S. Army Missile and Space Intelligence Center

1340 **RCS COMPUTATION at the SYRACUSE RESEARCH CORPORATION**
Chung-Chi Cha*, Syracuse Research Corporation

1400 **ELECTROMAGNETICS ANALYSIS CODES**
Dennis M. Elking*, Scott D. Alspach, Dwayne D. Car, Kirk E. Castle, Janice L. Karty, James H. Knehans, McDonnell Douglas Corp.; Ronald A. Pearlman, James M. Roedder, McDonnell Douglas Corporation

1420 **ELECTROMAGNETIC CODE CONSORTIUM**
James H. Kirkland*, US Army Missile & Space Intelligence Ctr

1440 **EFFICIENT SIGNATURE ESTIMATIONS in an ADVANCED GRAPHICS ENVIRONMENT**
Richard A. Shepherd, T. Olson, Charles S. Liang*, General Dynamics

1500 **Break**

1520 **RCS with TSAR FDTD CODE**
Scott L. Ray, S. T. Pennock*, Lawrence Livermore National Laboratory

1540 **RADAR CROSS SECTION COMPUTATIONAL TECHNIQUES**
Hung B. Tran*, Rockwell International

1600 **BENCHMARKING of RCS CODES**
Helen T. G. Wang*, Michael L. Sanders, Naval Air Warfare Center; Alex Woo, Michael Shuh, NASA Ames Research Center

1620 **RADAR CROSS SECTION COMPUTATION and VISUALIZATION by SHOOTING-AND-BOUNCING RAY (SBR) TECHNIQUE**
C. Long Yu*, Pacific Missile Test Center; S. W. Lee, University of Illinois, Urbana-Champaign

1640 **DISCUSSION**

MODERN RCS COMPUTATIONS - A PRACTICAL APPROACH

Thomas A. Blalock
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ABSTRACT

Today, Radar Cross Section (RCS) calculations are being used for a variety of applications. Among these are design of low observable vehicles, missile fuzing studies, intelligence signature estimates, and determining material characteristics. Today's demand for RCS computations is increasing due to the high costs and limited budgets for RCS range measurements. RCS predictions require a variety of tools to be at the disposal of the analyst. Some of these tools exist and some are being developed.

The most important requirement of an RCS analyst is an understanding of the electromagnetic scattering mechanisms of the object to be modeled. This understanding is vital if one is to build good RCS models. In today's world of low observable targets, the RCS analyst can no longer use simple primitives (cones, spheres, ellipsoids, facets, etc.) to describe the surface curvature. A computer-aided-design (CAD) software package is required along with the ability to output geometry in a standard, widely recognized format. To act upon this geometry, a variety of RCS codes employing different methodologies are needed to cover the frequency range of interest. For so called "high frequency" cases where the wavelength is smaller than the object's smallest dimension, a physical optics, geometrical optics, uniform theory of diffraction code is needed. For "low frequency" cases where the wavelength is of the same order as the object's smallest dimension, a 2-d or 3-d method of moments code, a k-space code, or other low frequency code is required. Different codes are needed depending on far-field or near-field applications. Special codes are needed to deal with inlets, cracks, gaps, edges, wedges, and materials. Finally, after RCS has been calculated, a robust set of post-processing codes are required so that meaningful conclusions can be reached.

This paper addresses these requirements and describes a modern practical approach to the prediction of RCS.

RCS COMPUTATION AT THE SYRACUSE RESEARCH CORPORATION

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RCS Computation has been a main area of research work at the Syracuse Research Corporation (SRC) for a number of years. Sponsorships of projects in a variety of application areas over the years have enabled continuous research work in the field of electromagnetic scattering and the accompanying simulation software development. This paper will summarize SRC's work to date in this area.

Of quite some significance in SRC's history of RCS computation work was its pursuit in the late 1970's of an "active library" concept for the purpose of target identification. A critical element in this approach is a theoretical RCS prediction model which can accept an appropriate geometrical description of a target and relevant radar parameters, and accurately and quickly predict the target signatures. This motivation and other related projects resulted in, by the early 1980's, an RCS prediction software named SRCRCS, and an accompanying CAD modeling package named SCAMP. The theoretical prediction in SRCRCS is based on the theories of physical optics (PO) and the physical theory of diffraction (PTD), and the geometrical modeling in SCAMP is performed by using a combination of flat facets and a special class of canonical shapes.

The simulation software found a variety of applications. Besides assessment of target cross sections, and identification experiments, it also served as a very useful tool in many other problems. For example, it provided realistic data for use in the development of new signal processing algorithms. In the development of a training simulator of a ship identification system, it also provided realistic signatures in place of measurement data. To suit the variety of radar applications encountered, the computed RCS is post-processed and displayed in a variety of forms. This includes the CW angular display, wideband range profile, range-time or Doppler-time intensity plots, and two-dimensional image display.

Throughout the 1980's and the early 1990's, a number of capabilities were also added to the simulation system:

- Bistatic signatures.
- Absorber coated targets.
- 3-Dimensional method of moments solutions for metallic and dielectric materials
- Curved surface patch modeling.
- Multiple bounce.

ELECTROMAGNETICS ANALYSIS CODES

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Introduction: In recent years a requirement has emerged in the aerospace industry to analyze and design air vehicles with significant emphasis on reducing radar cross section (RCS). Typically both low frequency codes, such as method of moments (MOM), and high frequency codes, which use the physical theory of diffraction (PTD), are required to cover the design space. RCS computations are only made on the exact computer aided design and drafting (CADD) geometries, embodying vehicle design at various stages of development and used by automated machinery to mill components to precision tolerance. Connections exist to multiple geometry systems as well as the Initial Graphics Exchange Specification (IGES) standard.

RCS Codes: CADDSCAT has extensive capability to analyze these geometries at high frequencies, including the recently developed bistatic and near field options. MULTIRAY addresses high frequency multiple bounce combining ray tracing with PTD. CAVERN analyzes cavities such as inlets and ducts, combining ray tracing with modal solutions using a reaction integral. PLATE3D is a specialized MOM code for analyzing material treatments on rectangular plates. CLOAK is a recent innovation at MCAIR that provides generalized 3D MOM analysis directly from CADD patches, with an impedance boundary condition (IBC) option. Unique basis functions achieve an accuracy with only 4 unknowns per wavelength for which other codes, such as TSP, require as many as 15 to 20 unknowns per wavelength. All of these codes are linked to their geometry interface with IGES standard as a minimum.

The Electromagnetic Code Consortium
by James H. Kirkland

Abstract

In 1987, an initiative was made to consolidate radar cross section (RCS) code development sponsored by the Tri-Services, and NASA. An RCS Code Consortium was formed, consisting of a government steering group, and members from the industry/academic community. Since the formation of the Consortium, significant progress has been made to advance code development work sponsored by the U.S. government. This paper is intended to make the RCS community aware of the Electromagnetic Code Consortium, so that potential contributors to code development can become involved with the Consortium.

The objective of the Electromagnetic Code Consortium is to significantly advance the state-of-the-art in basic EM scattering research and to produce the computer codes necessary for prediction of military platform signatures. This shall be accomplished by determining the current state-of-the-art, and avenues for further advancement of electromagnetic radiation and scattering prediction codes. After developing the technology roadmap, the roadmap will be implemented through the development of highly efficient, modular computer codes, which form the basis for advanced RF, IR, and EO scattering and radiation analytical techniques. To assure compatibility, these modular codes shall share a common geometry package, allowing any or all of the individual modules to be linked and shared as required. A support contractor will be available to maintain a codes/documentation repository, to provide training, to insure distribution of software and documentation to consortium participants, and to provide assistance to operation maintenance and upgrades of codes in support of the Electromagnetic Code Consortium.

EFFICIENT SIGNATURE ESTIMATIONS IN AN ADVANCED GRAPHICS ENVIRONMENT

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AN ADVANCED TECHNIQUE HAS BEEN DEVELOPED FOR THE COMPUTATION OF PHYSICAL OPTICS BACKSCATTERING FROM LARGE, COMPLEX TARGETS OVER MULTIPLE FREQUENCY BANDS WITH UNPRECEDENTED SPEED. IT TAKES FULL ADVANTAGE OF THE POWER OF THE PRESENT (AND FUTURE) HIGH PERFORMANCE GRAPHICS ENGINES FOR SURFACE RENDERING AND SHADOWING. THIS METHOD HAS BEEN IMPLEMENTED WITH A FIRST-GENERATION CODE LABELLED VISAGE (VISUAL INVESTIGATION OF SCATTERING IN AN ADVANCED GRAPHICS ENVIRONMENT) ON THE SILICON GRAPHICS IRIS 4D SERIES WORKSTATIONS. THE COMPUTATION THROUGHPUT HAS SHOWN TO BE ESSENTIALLY INDEPENDENT OF THE TARGET COMPLEXITY AND THE DESIRED NUMBER OF FREQUENCIES. IN ADDITION, GEOMETRICAL SHADOWING OF TARGET COMPONENTS IS AUTOMATICALLY HANDLED.

THE TREMENDOUS AMOUNT OF DATA VISAGE IS CAPABLE OF GENERATING CAN BE EASILY INTERPRETED THROUGH THE USE OF MULTI-DIMENSIONAL COLOR GRAPHICS. THE VISAGE CODE INCLUDES VISUAL COMPUTATION WITH INTERACTIVE DISPLAYS. IN ADDITION, THE DATA FORMAT IS PERFECTLY SUITED FOR USE WITH MANY SOPHISTICATED POST-PROCESSING SCHEMES SUCH AS ISAR (INVERSE SYNTHETIC APERTURE RADAR) IMAGING FOR SCATTERING CENTER DIAGNOSTICS.

TARGET MODELS ARE GENERATED WITH THE GENERAL DYNAMICS ACAD (ADVANCED COMPUTER AIDED DESIGN) PROGRAM WHICH HAS BEEN DESIGNATED AS THE STANDARD GEOMETRY GENERATION CODE BY THE JOINT SERVICES ELECTROMAGNETICS CODE CONSORTIUM (EMCC). THE SYSTEM SUPPORTS DESIGN TECHNIQUES THAT INTEGRATES WIREFRAME, SURFACE, AND SOLID MODELING COMMANDS WITH OVER 900 OPTIONS. THE THREE MODELING TECHNIQUES ARE INTEGRATED THROUGH USE OF GEOMETRIC ASSOCIATIVITY TO ENABLE RAPID MODIFICATIONS IN A TYPICAL DESIGN ENVIRONMENT. ACAD PROVIDES MANY UNIQUE INTERFACE OPTIONS TO SUPPORT THE VARYING REQUIREMENTS OF SIGNATURE PREDICTION, AERODYNAMIC ANALYSIS, STRUCTURAL ANALYSIS, AND COMPUTATIONAL FLUID DYNAMICS.

RADAR CROSS SECTION COMPUTATIONAL TECHNIQUES

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We shall focus our discussion on 3 representative approaches for 3 classes of techniques used to perform radar signature calculations: (1) Asymptotic techniques: Physical Theory of Diffraction (PTD) approach. If the wavelength $\lambda = \frac{2\pi}{k}$ of a radar beam is small in comparison with the characteristic size of a scatterer, Maxwell's Eqs. can be solved approximately. Such a solution simulates accurately the specular and edge diffraction contributions to the scattered field for perfectly conducting and coated objects (E.Bleszynski, M.Bleszynski, H.B.Tran, *Physical theory of diffraction for scattering of electromagnetic waves of an arbitrary incidence angle from an impedance wedge*, Rockwell Int. report 1988). Radar signatures of 3-dim configurations are obtained within seconds on 20MIPS workstations. However, calculated radar signatures are insensitive to details of scattering structures of the order of λ or smaller, surface wave diffraction and multiple scattering effects are not included and electromagnetically penetrable regions can be modeled only approximately by the first (impedance) or higher order boundary conditions. (2) Techniques of solving Maxwell's Eqs. in the differential form: Finite-Volume Time-Domain (FVTD) approach. (3) Techniques of solving Maxwell's Eqs. in the integral form: Adaptive Integral Method (AIM) approach. The last two approaches provide exact numerical solutions to Maxwell's Eqs. They are expected to capture all relevant details of the scattering structure in a single computational framework. They both utilize algorithms in which memory and execution time scale linearly with the number of computational elements and are very well suited for massively parallel computational environment. In the FVTD (V.Shankar, W.Hall, A.Mohammadian, *A CFD-based finite volume procedure for computational electromagnetics - interdisciplinary application of CFD methods*, AIAA CFD Conference, Buffalo, New York 1989) approach Maxwell's Eqs. are written in the equivalent conservation-law form in the curvilinear body-fitted coordinates. The Lax-Wendroff integration scheme and the Riemann theory of characteristics are used to evaluate solution vectors in each computational cell. Curvilinear coordinates allow to divide the entire configuration into zones of different electromagnetic properties and to set up curvilinear grids of optimal density determined by local material properties in every zone.They assure high accuracy in implementing boundary conditions on zonal interfaces. The AIM (M.Bleszynski, T.Jaroszewicz, *An Adaptive Integral Equation Solver for Large Scale Electromagnetic Computations*, National Radio Science Meeting, Boulder, Co 1992) method is designed for solving Maxwell's Eqs. in the integral representation. The major advantage of an integral method is that the outer boundary conditions are inherently built into the formulation. Hence solving Maxwell's Eqs. outside the scattering body which often consumes dominant portions of CPU time and memory in partial differential equation solvers is not required. Numerical solutions for the currents induced on a target are sought on a multilevel nonuniform rectangular grid by solving the corresponding system of linear equations; the discrete fast Fourier transforms are applied to carry out fast and memory reduced matrix operations.

We shall present some applications of the discussed above approaches.

BENCHMARKING OF RCS CODES

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ABSTRACT

As the control and prediction of the electromagnetic (EM) signatures of air vehicles become more and more important, the electromagnetic scattering codes are facing more and more difficult problems. Unlike the conventional targets which consist of cylinders, frustums and plates, the targets with low radar cross-section have either stealthy smooth surfaces or radar absorbant material (RAM) coatings. Also the interest of observation angle is more towards grazing instead of broadside. Thus the secondary phenomena like surface waves, edges, and surface discontinuities are dominate. The accuracy of the prediction codes at low levels are far more important than before and a good set of measurement data is needed to validate the prediction codes.

Several sets of targets were built and measured for validating the computational electromagnetic codes as they apply to different problems. The problems include 3D metallic, and coated targets, 3D bulk dielectric material, 2D metallic targets, cavities, and plates close to grazing for edge waves.

It is our intent to publish all the data we obtained and distribute to the EM community for diagnostic and validation purpose. We hope this stimulates more research and improvement of the computational electromagnetic codes.

RADAR CROSS SECTION COMPUTATION AND VISUALIZATION BY SHOOTING-AND-BOUNCING RAY (SBR) TECHNIQUE

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In the course of analyzing the radar cross section (RCS) of a complex target, the accurate prediction and determination of the scattering mechanisms as well as the identification of the electromagnetic scattering centers on a complex platform often pose a great challenge to the RCS analysts/engineers. Especially when the backscattering returns are due to the multiple reflections among target airframe, stores and engine inlets, it is almost impossible to pin-point the exact causes and locations of the scattering mechanisms. Although the high-resolution radar imaging technique has widely been used in many test facilities to perform RCS diagnostic studies, the effectiveness of this method is still limited in accurately determining and explaining the causes of the scattering phenomena.

An effort is currently being conducted to develop an analysis model with sophisticated graphic capability for analyzing and visualizing the electromagnetic scattering from a complex radar target. This analytical model employed a hybrid technique of the shooting and bouncing ray (SBR) method and the Physical Theory of Diffraction (PTD). The proposed SBR/PTD method employes rigorous use of theoretical foundations of Geometric-Optics (GO) and PTD by including the following four steps in the electromagnetic calculations: (1). The divergence factor of a ray pencil, (2). A rigorous wavefront integration technique at the exit point, (3). The first order edge diffraction, and (4). Radar absorbing material characteristics.

Coupled with computer-aided design (CAD) graphics, the model provides a new capability for visualizing, analyzing, and interpreting the complex radar scattering phenomena via dynamic ray-picture displays on a computer graphic terminal. With its sophisticated capability to rapidly conduct visual diagnostic studies of radar scattering sources and multiple reflections form a complex target, the SBR model provides RCS engineers an efficient and cost-effective way of performing many practical RCS analysis, design and reduction applications that are not feasible in the past. In addition, this method can be used to complement the experimental measurements in maintaining the quality assurance of the test data measured.

Thursday AM1 AP-S, URSI-B Session RA03

Room: Grand C *Time*: 0820-1000

EM Applications of Neural Networks

Organizers: Akira Ishimaru, Leung Tsang, University of Washington
Chairs: Akira Ishimaru, Leung Tsang, University of Washington

0820 **APPLICATION of ARTIFICIAL NEURAL NETWORK (ANN) TECHNIQUE to ROUGH SURFACE INVERSE SCATTERING PROBLEMS**
Akira Ishimaru*, Jenq-Neng Hwang, University of Washington; Kuniaki Yoshitomi, Kyushu University; Jei S. Chen, Lockheed Palo Alto Research Laboratory

0840 **REAL-TIME ADAPTIVE WAVEFRONT CONTROL by an ARTIFICIAL NEURAL NETWORK at the MULTIPLE MIRROR TELESCOPE**
M. LLoyd-Hart*, R. Dekany, B. McLeod, P. Wizinowich, D. Colucci, D. Wittman, D. McCarthy, R. Angel, University of Arizona

0900 **MULTI-PARAMETRIC INVERSION in MICROWAVE REMOTE SENSING with an ARTIFICIAL NEURAL NETWORK TRAINED with MULTIPLE SCATTERING THEORY**
Leung Tsang*, Jenq-Neng Hwang, Daniel T. Davis, Zhengxiao Chen, University of Washington

0920 **MULTILAYERED FREQUENCY SELECTIVE SURFACE DESIGN USING ARTIFICIAL NEURAL NETWORKS**
C. H. Chan*, Jenq-Neng Hwang, Daniel T. Davis, University of Washington

0940 **RADOME DESIGN by SIMULATED ANNEALING TECHNIQUE**
Kuan-Kin Chan*, Po-Rong Chang, Fang Hsu, National Chiao Tung University

APPLICATION OF ARTIFICIAL NEURAL NETWORK (ANN) TECHNIQUE TO ROUGH SURFACE INVERSE SCATTERING PROBLEMS

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In recent years, artificial neural network (ANN) technique has been applied to many engineering problems. This paper gives an introduction to an ANN multilayered perceptron technique and its application to rough surface inverse scattering problems. A multilayered perceptron has one or more layers of hidden neurons between the input and output layers. For our rough surface scattering problem, the values of the spectral correlations of the scattered intensities are the input and the desired roughness parameters, rms height and correlation distances are the output. We first solve the forward problem, apply the input, and use arbitrarily chosen initial weights and bias to obtain the output. We then find the error between the target and the output. We use backpropagation technique to change the weight and bias to reduce the error. The above learning procedure is repeated many times to train the ANN. Once the ANN is trained, the measured inputs are applied to the ANN and the desired outputs are obtained quickly.

This paper examines the forward problem of calculating the spectral correlations of speckle patterns of two different wavelengths in the backward and specular directions. A beam wave is incident on the surface and the scattered fields are calculated using the surface integral equation and the Monte Carlo simulation. The surface is one dimensional, the Dirichlet condition is satisfied on the surface, and the surface spectrum is Gaussian. This forward problem is used to determine the range of parameters which are effective for inversion.

Next, the inverse problem of finding the surface parameters, σ and ℓ, from the measurement is considered. Here we use the artificial neural network (ANN) technique. The calculated spectral correlations for given surface parameters are used to train the ANN. An advantage of the ANN technique is that even though it may take a large amount of computer time to train the ANN, once the ANN is trained, the inverse problem of finding the surface parameters from the measured spectral correlations can be accomplished quickly. Numerical examples are given to show the effectiveness of the method.

Real-Time Adaptive Wavefront Correction by an Artificial Neural Network at the Multiple Mirror Telescope

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Turbulence in the atmosphere causes distortion of the optical wavefront from astronomical sources, resulting in severe degradation of the resolution and signal-to-noise ratio of focal plane images formed by a large telescope. Typically, resolution is limited to 0.5 - 1 arcsecond (2.5 - 5 μrad), which compares very poorly to the theoretical limit set by diffraction of around 0.03 arcseconds for existing large telescopes in the visible region of the spectrum. Diffraction-limited resolution can be recovered with the techniques of adaptive optics in which an equal aberration with opposite sign is applied to the wavefront by a deformable mirror. We have previously demonstrated in computer simulation that the aberration can be derived by a trained artificial neural network from a pair of simultaneous in- and out-of-focus focal plane images (Angel *et al. Nature* **348**, 221). In this paper, we report the first results from an adaptive system operating on line at the Multiple Mirror Telescope (MMT), in which the wavefront is sensed by a neural network, implemented on an array of twenty transputers. Star images were formed at a wavelength of 2.2 μm by two coherently phased apertures of the MMT, and analysed by the net. Outputs from the net were used to drive piezo-electric actuators on two segments of an adaptive mirror in the optical beam train, controlling five degrees of freedom of the wavefront. These are the mean slopes in x and y across each of the two mirrors, and the relative piston between them. With the servo loop in operation, the corrected image shows significant power at the diffraction limit of 0.1 arcseconds (0.5 μrad), and a much improved peak intensity.

MULTI-PARAMETRIC INVERSION IN MICROWAVE REMOTE SENSING WITH AN ARTIFICIAL NEURAL NETWORK TRAINED WITH MULTIPLE SCATTERING THEORY

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An objective of microwave remote sensing is the mapping and retrieval of useful geophysical parameters, such as, physical temperature and snow-water equivalent, from remote sensing measurements. However, remote sensing measurements are also dependent on a large number of unknown physical parameters, such as, snow mean-grain size, snow density, and snow layering. In volume scattering problems in remote sensing, the forward scattering models are that of vector radiative transfer theory and dense media radiative transfer theory which include multiple scattering effects. Thus, the inversion problem in remote sensing consists of multi-parametric inversion from multi-frequency and polarimetric remote sensing measurements. We have performed such inversions with artificial neural networks (ANN) and constrained iterative inversions trained with multiple scattering theory.

The iterative inversion of the network generates the parameters from a trained forward mapping, Φ, that gives a network output as close as possible to a desired measurement vector. By taking advantage of the duality between the weights and the input activation values in minimizing the mean squared error, E, the iterative gradient descent algorithm can again be applied to obtain the desired input vector. We have performed the inversion of four snow parameters from passive microwave remote sensing measurements with a neural network trained with the dense media radiative transfer theory. The four parameters are snow-water equivalent (or snow depth), mean-grain size of ice particles in snow, snow density, and snow temperature. The basic idea is to use the input-output pairs generated by the dense media scattering theory to train the neural network. The inversion is from passive microwave remote sensing measurements of five brightness temperatures: 19 GHz V polarization, 19 GHz H polarization, 22 GHz V polarization, 37 GHz V polarization and 37 GHz H polarization. It is shown that the neural network works very well on synthetic testing data. We have demonstrated mapping of an entire region based on synthetic data and the inversion technique. The incorporation of ground-truth information is also considered by a minimum disturbance principle in fine-tuning the approximated ANN.

MULTILAYERED FREQUENCY SELECTIVE SURFACE DESIGN USING ARTIFICIAL NEURAL NETWORKS

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Frequency selective surfaces (FSSs) have widespread applications over much of the electromagnetic spectrum. They exhibit total reflection or transmission over a frequency band dictated by their unit-cell geometries, spacings, skew angles, dielectric constants and thicknesses of supporting dielectric layers, etc. There is no closed form solution directly available from a given desired frequency response to the corresponding surface. The conventional trial and error design procedure is too laborious and human dependent, an alternate design procedure using an artificial neural network can alleviate these difficulties.

Two design approaches of a single-layered FSS surface using artificial neural networks have been reported. The first one uses a bitmap model to represent the unit-cell geometry and the second one uses a parametric representation. While the former one allows more freedom in choosing the unit-cell geometry, it also requires a much larger training database and more iterations for a convergent design than the latter one which only works for a fixed geometry. Both approaches require the training and inversion of a multilayer perceptron, a feed-forward neural network which has one or more layers of hidden neurons between the input and output layers. When the network is trained, it is used to generate the frequency responses to the input test surfaces parameters. The inversion process is to generate input surface parameters corresponding to a given desired frequency response. The learning phase of the multilayer perceptron uses the back-propagation algorithm to determine the weights of the network to minimize the mean squared error between the desired values and the actual output values. By taking advantage of the duality between the weights and the activations, the inversion algorithm back-propagates the error signals down to the input layer to update the activation values of input units so that the output error is decreased.

When extending the artificial neural network approach for the design of multilayered FSSs, the parametric representation can reduce the number of variables significantly and thus reduce the size of the neural network and the number of iterations required in the network inversion. In this paper, designs of multilayered FSSs using dipole and tripole patches and slots will be presented.

Thursday AM AP-S, URSI-B Session RA06

Room: Grand F *Time*: 0820-1200

In Honor of Robert G. Kouyoumjian

Organizer: Prabhakar H. Pathak, The Ohio State University
Chairs: Prabhakar H. Pathak, Leon Peters, Jr., The Ohio State University

0820 **HISTORICAL REVIEW of ELECTROSCIENCE LABORATORY with an EMPHASIS on CONTRIBUTIONS of R. G. KOUYOUMJIAN**
Leon Peters, Jr.*, The Ohio State University

0840 **A BRIEF HISTORY of the UTD - FOCUS on EDGE DIFFRACTION**
R. G. Kouyoumjian*, The Ohio State University

0900 **FREQUENCY and TIME DOMAIN HYBRID RAY-MODE-RESONANCE GTD for LAYERED, CAVITY-COUPLED and PERIODIC CONFIGURATIONS**
L. B. Felsen*, Polytechnic University

0920 **ON the QUESTION of TIME CAUSALITY for HF RAY FIELDS TRAVERSING CAUSTICS**
Prabhakar H. Pathak*, Robert J. Burkholder, The Ohio State University

0940 **A DYADIC DIFFRACTION COEFFICIENT for a VERTEX**
S. Maci*, R. Tiberio, L. Giorgi, University of Florence

1000 **Break**

1020 **PHYSICAL OPTICS IMPULSE RESPONSE from FACETED TARGETS**
S. W. Lee*, S. K. Jeng, University of Illinois, Urbana-Champaign; C. Long Yu, Pacific Missile Test Center; Charles S. Liang, Richard A. Shepherd, General Dynamics

1040 **UTD ANTENNA CODES THROUGH the YEARS**
Walter D. Burnside*, The Ohio State University

1100 **DESCRIPTION of a GENERAL COMPUTER PROGRAM for RCS COMPUTATION of COMPLEX SHAPES DESCRIBED by a CAD SYSTEM, FOUNDED on GTD/UTD**
F. Molinet*, Th. George, MOTHESIM; J. M. Brun, L. P. Untersteller, CORETECH

1120 **ANALYTICAL SOLUTIONS from CURRENT INTEGRALS in BACKSCATTERING PROBLEMS**
M. Martinez*, Consejo Superior de Invest. Cientificas

1140 **DISCUSSION**

HISTORICAL REVIEW OF ELECTROSCIENCE LABORATORY WITH AN EMPHASIS ON CONTRIBUTIONS OF R.G. KOUYOUMJIAN

L. Peters, Jr.
Dept. of Electrical Engineering
The Ohio State University
Columbus, Ohio

The Antenna Laboratory (now the ElectroScience Laboratory) was created during World War II under the supervision of George Sinclair.

After the war years it continued to grow and prosper. It was joined in 1950 by Bob Kouyoumjian as one of a group of graduate students. These graduate students (including Bob) under Prof. Rumsey formed the technical nucleus that has since rippled through a variety of EM and related organizations. At least nine of these early student members of the Antenna Laboratory have in subsequent years been elected as Fellows of the IEEE. At the present time eight members of the ESL are Fellows in the IEEE or nearly half of the senior staff.

With the advent of the launching of Sputnik and the Korean war, the Antenna Laboratory experienced an area of unprecedented growth. A number of the above graduate students became faculty members including Bob. With the exception of a static period in the early 70's the Antenna Laboratory, by now the ElectroScience Laboratory, continued to grow and its technical breadth had increased substantially resulting in the above name change.

By the 80's, Bob had become firmly entrenched as a "guru" having taught the advanced Electromagnetics course sequence since 1956. He is always willing to discuss any electromagnetics problem any student would care to bring up.

The ESL has completed more than 600 contracts covering a variety of topics and sponsors. Approximately 400 M.Sc. theses and 240 Ph.D. dissertations have been completed and 700 archival journal papers have been published. As a final comment, I ran a citation index for ESL authors in AP-S only for a five year period in 1988. Bob's work was cited 135 times.

A Brief History of the UTD — Focus on Edge Diffraction

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This paper presents a brief history of the UTD for the diffraction by edges in perfectly-conducting surfaces. In this theory diffraction coefficients must be found so that the diffracted field is valid at shadow and reflection boundaries when the edge is illuminated by an arbitrary ray-optical field. In the mid 1960's I began to work on this problem using the ordinary wedge as a canonical geometry. At the time I was fortunate in having a series of excellent graduate students. First, working with D.L. Hutchins, the scalar diffraction coefficients for the two dimensional problem were found. Crucial to the success of this work was the correction of an error in W. Pauli's earlier solution of the canonical problem.

Next, P.H. Pathak and I investigated the three-dimensional case for the perfectly-conducting wedge. A remarkably simple form of the dyadic diffraction coefficient was found which greatly enhanced the practical importance of our result. When the incident field has a rapid spatial variation at the edge, the preceding solution must be augmented by slope diffraction. Working with Y. Hwang a dyadic slope diffraction coefficient was obtained, and later a different expression for this diffraction coefficient was derived in work with T. Verrutipong. These two slope diffraction coefficients are being compared at the present time.

Early in 1980 O.M. Buyukdura and I re-examined the solution to the canonical wedge problem. By retaining higher order terms in the asymptotic solution, improved expressions for the ordinary and slope diffraction coefficients were obtained which made it possible to calculate the field of a dipole close to the edge of a wedge. In further work with Buyukdura a wave guided by the edge of the wedge was identified and used to calculate the radiation from scatterers located at the edge.

In 1976 Professor Roberto Tiberio and I began to study double diffraction, where a second edge is illuminated by a field from the first edge which is not ray optical. Later G. Pelosi and G. Manara were involved in this research. The problem was solved using spectral theory, and the new expressions for double diffraction were applied to numerous examples to demonstrate their accuracy.

In conclusion, some thoughts on recent and future developments in edge diffraction are mentioned.

Frequency and Time Domain Hybrid Ray-Mode-Resonance GTD for Layered, Cavity-Coupled and Periodic Configurations

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The geometrical theory of diffraction (GTD) with its various uniformized improvements has become a principal analytic modeling tool of high frequency scattering from structures with complex shapes. In this modeling, account has been taken of smoothly curved and sharply discontinuous (edge-connected) perfectly conducting and finite impedance surfaces. In more recent studies, the GTD methodology has been extended to scatterers with surfaces that contain dielectric layers, periodic structures and aperture coupling to interior cavities. These features require the inclusion of dispersive traveling and resonant mode phenomena in the catalog of the traditional GTD ray species. The outcome is a self-consistent hybrid ray-(traveling mode)-(resonant mode) GTD in the frequency domain, and its wavefront-resonance counterpart in the time domain. The building blocks for this enriched GTD are provided by studies of canonical configurations that include dielectric-covered plane and cylindrical surfaces, infinite and finite periodic arrays, and cavity-backed apertures. The results can be phrased in terms of strongly dispersive surface-guided ray fields, diffracted multiple Floquet-mode ray fields due to global, periodicity, edge scattered ray fields with diffraction coefficients that bear the signature of truncated periodicity, and slit scattered ray fields with diffraction coefficients modified by interior loading. Numerical examples in the frequency and time domains illustrate these concepts.

On the Question of Time Causality for HF Ray Fields Traversing Caustics

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The development of analytical solutions for the transient radiation or scattering of EM pulses from complex objects is desirable because not only are they more efficient but they also provide more physical insight than the corresponding numerical solutions. However, exact analytical solutions can be obtained only for a very limited number of transient radiation/scattering boundary value problems. On the other hand, it appears feasible, in general, to analytically invert into time domain the corresponding asymptotic high frequency ray solutions such as those based on the uniform geometrical theory of diffraction (UTD); this has been shown for some special cases by Kouyoumjian & Verrutipong. Such analytical inversion of frequency domain (FD) based UTD solutions into the time domain (TD) are valid for early to intermediate times after the arrival of the wavefronts corresponding to the different FD ray mechanisms. Such early time analytical solutions can, in principle, be combined into a hybrid scheme whereby the late time response may be found via numerical solutions of the governing space-time integral or differential equations. While the development of an early to intermediate time response for radiation and scattering by analytically inverting the FD based UTD solutions into TD is clearly useful so that a progressing wave or TD-UTD can be developed for complex objects, there remains an underlying difficulty in such a procedure which needs to be resolved before it can be implemented to deal with general situations. This difficulty arises from the fact that a FD based UTD ray field undergoes a constant phase jump of $\pm\frac{n\pi}{2}$ for all $\left(\begin{smallmatrix}\text{positive}\\ \text{negative}\end{smallmatrix}\right)$ frequencies whenever it passes through an odd number $(=n)$ of caustics, thereby violating the Hilbert transform relationship, and provides upon inversion to TD a transient field which is non-causal! A preliminary study has been performed which develops an exact, causal analytical solution to the physical options (PO) approximation for the on axis transient scattering from a two-dimensional parabolic cylinder whose concave face is illuminated by an axially incident impulsive plane wave. This analytical time domain PO (or TD-PO) solution indicates upon comparison with the corresponding TD-UTD solution that the TD-UTD is non-causal for observation points beyond the focus (caustic) as expected; however, the causal part of the early TD-UTD solution compares very well analytically as well as provides numerical results which agree extremely well with the TD-PO solution, indicating that the causal part of the TD-UTD is not really affected by the non-causal portion of the response. Additional examples which bear the latter behavior will also be indicated and some conclusions will be drawn.

A DYADIC DIFFRACTION COEFFICIENT FOR A VERTEX

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An approximate and yet efficient description of the scattering by a vertex interconnecting two or more edges, is relevant to several practical applications. Although several authors contribuited to this important subject, still there are well grounded motivations for further investigations. In this paper, a formulation is presented for evaluating the asymptotically, dominant contribution to the field scattered by the tip of two or more interconnected wedges, illuminated by an electromagnetic plane wave. The field is represented as the sum of contributions from each planar angular sector between two adjacent, joined edges.

Our approximate description of the interaction between edges 1 and 2, is constructed as the superposition of two analogous mechanisms; a field contribution emanating from edge 2 (21) when it is illuminated by the edge 1, and that from 1 when it is illuminated by 2 (12). The procedure for deriving a solution for the scattering phenomenon (21) from edge 1 to edge 2, consists of three basic steps that are sumarized herein after. i) First, the total field scattered from the edge 1 is represented by its plane wave spectrum. ii) Next, each plane wave, after impinging on the edge 2, provides the contribution in the direction of observation, which is evaluated by resorting to an ILDC formulation. iii) Then, this plane wave response of the semi-infinite edge 2 is used to weight the spectrum from edge 1 to yield an integral representation, which can be evaluated in a closed form.

For the sake of convenience, the solution of the field scattered in the far zone is presented first for a scalar, plane wave illumination. Next, the scalar formulation is used to construct the solution for an arbitrarily polarized, plane electromagnetic wave. It is shown that the solution can be cast in a simple, compact and symmetric, dyadic form that explicitely satisfies reciprocity. Also, it is shown that the solution possesses the proper behaviour to account for scattering phenomena including contributions of the order of doubly diffracted fields. Finally, this plane-wave, far-field response of the vertex is used to weight the plane wave spectrum representation of a source, located at a finite distance from the tip. This double spectral representation of the field is asymptotically evaluated to find the desired uniform, dyadic diffraction coefficient.

DESCRIPTION OF A GENERAL COMPUTER PROGRAM FOR RCS COMPUTATION OF COMPLEX SHAPES DESCRIBED BY A CAD SYSTEM, FOUNDED ON GTD/UTD

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In this paper, a description of a general computer program is given which calculates the Radar Cross Section of complex targets modeled by CAD systems. It is founded on the Uniform Theory of Diffraction of Kouyoumjian and Pathak |1, 2| and comprizes two main parts : a general computer library for GTD applications called PROMETHEE which manages the asymptotic solutions and calculates the diffracted field and a general ray tracing code on CAD targets. In caustic directions, the GTD/UTD is replaced by PO.

For each diffraction process, the space is divided into regions corresponding to the most efficient asymptotic solutions available. Once the ray path is known, the choice of the correct asymptotic solution is managed by PROMETHEE which determines also the characteristics of the wavefront after each diffraction process and calculates the field at the observation point.

The geometry of the target is modeled by a biparametric polynomial representation with restrictions (Bezier polynomials).

The ray searching techniques comprize elimination procedures in order to optimize the combinatory analysis on the Bezier squares. In a pretreatment, a list of visibility is constructed which identifies all the Bezier squares which are seen from one of them. In addition, a framing technique is used to delimit the beam of rays after each interaction.

This procedure is very efficient for searching of multiply reflected rays and combination of reflected and diffracted rays.

An algorithm for the determination of the geodesic curves followed by the creeping rays which cross the limits of the Bezier squares has also been developed. Fig.1 and 2 illustrate some outputs of this algorithm.

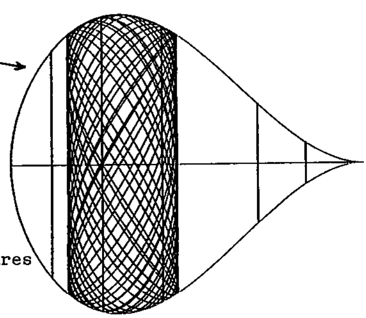
As an example, the application of the computer program to a missile modeled by 45 Bezier squares will be presented.

References

|1| R.G. Kouyoumjian and P.H. Pathak, "A Uniform Geometrical Theory of Diffraction for an Edge in a Perfectly Conducting Surface", Proc. IEEE, Vol. 62, pp. 1448-1461, November 1974.

|2| R.G. Kouyoumjian and P.H. Pathak, "A Uniform GTD approach to EM Scattering and Radiation", in Acoustic, Electromagnetic and Elastic Wave Scattering - High and Low Frequency Asymptotics, Vol. II, edited by Varadan and Varadan, North Holland Publishers, 1986.

Fig. 2 : geodesics on a water drop



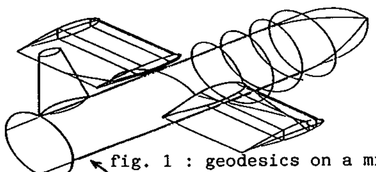


fig. 1 : geodesics on a missile modeled by Bezier squares

ANALYTICAL SOLUTIONS FROM CURRENT INTEGRALS IN BACKSCATTERING PROBLEMS

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The geometrical theory of diffraction (GTD) and its uniform extension (UTD) (Kouyoumjian and Pathak, IEEE Trans. Antennas Propag., AP-62, Nov. 1974), have been largely used for analyzing high frequency electromagnetic scattering problems. One of the major problems of the GTD-UTD is the infinite fields at and near the caustics. In the case of backscattering of plane waves, caustics occur, for example, along the specular direction of flat plates, axis of bodies of revolution and specular directions of singly curved surfaces. The high frequency approaches based on current integrals are useful in those cases.

This paper presents a summary of some analytical solutions for analyzing high frequency backscattering problems, based on the physical optics (PO) and equivalent current methods (ECM) (E.F. Knott and T.B.A. Senior, IEEE Trans. Antennas Propag., AP-21 Sep. 1973). The equivalent currents in the ECM integral are found via GTD, using a modified concept of currents, or via the physical theory of diffraction (PTD) when they are used to improve the PO solution.

Analytical and uniform expressions can be found in some cases from direct evaluation of these integrals, from asymptotic evaluations by the stationary phase method with end points contributions, using special functions, etc.

Results for backscattering from conducting polygonal plates, discs, cones and singly curved bodies of arbitrary cross section with edges , tips or inflection points, will be discussed.

Thursday AM URSI-B Session RA07

Room: Columbus A *Time*: 0820-1200

Method of Moment Analysis of Large Bodies

Chairs: D. S. Wang, McDonnell Douglas Research Laboratories; D. R. Wilton, University of Houston

0820 **APPROXIMATE SCATTERING from ELECTRICALLY LARGE STRUCTURES**
John Stach*, SRI International

0840 **ANTENNA ANALYSIS in COMPLEX ENVIRONMENT**
Jonathon Veihl*, Eric Michielssen, R. Mittra, University of Illinois, Urbana-Champaign

0900 **IMPEDANCE MATRIX LOCALIZATION (IML): FURTHER IMPROVEMENTS for EVEN LARGER MOM PROBLEMS**
Francis X. Canning*, Rockwell International Science Center

0920 **THE SOLUTION and NUMERICAL ACCURACY of LARGE MOM PROBLEMS**
T. Cwik*, J. E. Patterson, Jet Propulsion Laboratory

0940 **MASSIVELY PARALLEL HYBRID (MOM/UTD) SOLUTIONS of COMPLEX ELECTROMAGNETIC PROBLEMS**
Wallace Bow, Adrian S. King*, Sandia National Laboratories

1000 **Break**

1020 **SPATIAL DECOMPOSITION METHODS for OPEN CYLINDRICAL CAVITIES**
Raphael Kastner*, Yigal Twig, Tel Aviv University

1040 **MODELING of THREE DIMENSIONAL SCATTERING USING LARGE CURVILINEAR TRIANGULAR PATCHES and WAVELET EXPANSION FUNCTIONS**
D. S. Wang*, McDonnell Douglas Research Laboratories; Grant Welland, Shiying Zhao, University of Missouri, St. Louis

1100 **INDUCED CURRENTS in SURFACES DESCRIBED by BEZIER'S PATCHES USING MOMENT METHOD**
J. F. Rivas*, M. F. Catedra, Universidad de Cantabria

1120 **NUMERICAL SIMULATION of a VIRTUAL MATCHED LOAD for the CHARACTERIZATION of PLANAR DISCONTINUITIES**
Hany Ghali*, M. Drissi, J. Citerne, LCST - INSA; Victor Fouad Hanna, Centre National d'Etudes Des Telecomm.

1140 **EMLIB: an INTERNET SERVER for ELECTROMAGNETICS SOFTWARE**
T. Cwik, Jet Propulsion Laboratory; Scott L. Ray*, Lawrence Livermore National Laboratory

APPROXIMATE SCATTERING FROM ELECTRICALLY LARGE STRUCTURES

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The application of accurate scattering simulations such as finite element moment and moment methods to electrically large structures is limited by computational speed and accuracy. This is due to the small element size needed to accurately model boundary conditions and simplify element characteristics. However, for a large class of problems in which a good approximate solution is acceptable, fewer, more complex elements can provide surprisingly accurate results.

An approach to the scattering solution of any structure is to (1) form a grid to represent a target, (2) compute the self and mutual impedance terms for the grid elements, (3) compute the admittance matrix by inverting the impedance matrix, and (4) apply the scattering geometry to the admittance matrix to solve for the scattered fields. For large structures, it is convenient to choose a sparse grid such that each sparse element coincides with many elements of an existing moment-method or finite-element grid. Then the self and mutual impedance terms of the sparse grid (meta-elements) can be computed by using small sections of the dense model. In this solution, only scattering data is used. Therefore, there is a sign ambiguity which is easily resolved by additional scattering computations of small sections of the dense model. The angle and polarization characteristics of each sparse element also can be computed by using sections of the dense model. Note that since scattering alone is used to compute impedances, any scattering prediction including measurements can be substituted for the dense model.

Equations for the computation of sparse grid impedances from scattering data will be presented. Then an example of the method applied to the scattering of an electrically large train using the NEC code will be shown. In this application, there is more than 50:1 reduction in the number of elements used without significant loss of accuracy.

ANTENNA ANALYSIS IN COMPLEX ENVIRONMENT

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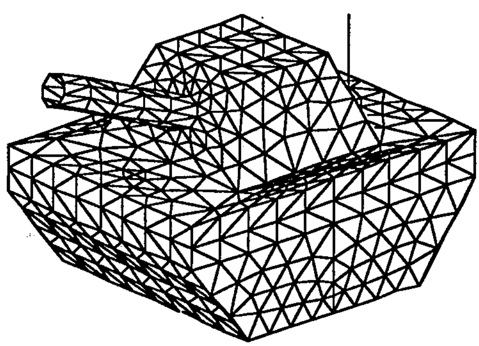
An antenna is often designed for optimal performance in an ideal environment, for instance over a perfectly conducting ground plane. However, performance characteristics such as impedance and radiation pattern can significantly change when it is placed in the actual operating environment. This situation can often be handled by modeling an antenna attached to an arbitrarily-shaped perfectly conducting body, and the entire complex structure can be considered as the radiating system. In this paper, a method of moments computer program based on a triangular patch model of the antenna platform is used to calculate the surface and wire currents by solving the electric field integral equation. From these currents, input impedance and the radiation pattern are calculated. An automatic mesh generating algorithm, viz., PATRAN, is employed to model the geometry of the complex structure in terms of triangular surface patches. A specific application of this general analysis tool is the study of monopole antennas mounted on a complex vehicle such as a tank. In this paper, results are presented for the effect of a monopole antenna position on the input impedance and the radiation pattern of the antenna mounted on a representative military tank. To restrict the number of unknowns to a tractable number, the largest dimension of the object is typically limited to approximately twice the wavelength. However, larger sizes can also be handled by using out-of-core solvers that permit the number of unknowns to go up to several thousand.



IMPEDANCE MATRIX LOCALIZATION (IML): FURTHER IMPROVEMENTS FOR EVEN LARGER MOM PROBLEMS

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The method of moments solves a problem with N unknowns using memory and execution times that are proportional to N^2 and N^3 respectively. As is well known, these requirements can easily become unreasonably large. The impedance matrix localization method allows much larger MoM problems to be run on a given computer. It uses directional basis and testing functions to localize all of the significant interactions within the impedance matrix to a small (~N) number of "clumps" of large numbers, while all the other numbers can be approximated by zero. Thus, the memory it requires is proportional to N, rather than to N^2 as for the usual MoM. Consequently, in an iterative solution the number of operations required per iteration is also reduced to be proportional to N, rather than to N^2.

Previous papers have shown that for 2D problems, the number of significant matrix elements is almost always less than 100N, and that the condition number of the IML matrix is somewhat (but not greatly) larger than that of the standard MoM matrices. Improvements are presented here which decrease the 100N to a much smaller number times N and which make the condition number of the IML matrix equal to that of the corresponding MoM matrix. This allows a solution with less storage, fewer operations per iteration, and fewer iterations. In addition, the pattern of non zero elements will be changed in several ways which allow more efficient preconditioners (approximate inverses to the matrix) which will further decrease the number of iterations required. (One newly developed preconditioner is described in a related talk by this author in an AP session at this meeting.)

THE SOLUTION AND NUMERICAL ACCURACY OF LARGE MoM PROBLEMS

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The evolution of computing hardware and software has allowed the solution of electromagnetic problems of ever increasing electrical size. This advancement has been a stimulus to the development of partial differential techniques such as finite difference or finite element methods, as well as permitting the use of existing integral equation techniques to solve larger problems in shorter amounts of time. Last year we reported on integral equation solutions for fields scattered from objects modeled by over 7,000 discretized current basis functions. This year we will report on solutions to problems with at least 30,000 discretized current basis functions. The calculations are completed on high-performance distributed memory parallel computers using optimized library routines to solve the matrix equation which results in the method of moment (MoM) formulation.

The successful parallelization of integral equation codes has been reported previously. A time consuming component of these codes is the solution of the dense, complex matrix equation resulting from the discretization of an integral equation. An LU factorization of the matrix is produced and used to complete the solution for a number of right-hand-side excitations. In this talk we report on the use of out-of-core and in-core routines to complete the matrix solution. An OOC routine, ProSolver DES (D. Scott, Intel Supercomputing Systems Division), is used on the Intel i860 64-node GAMMA hypercube and 512-node DELTA mesh. An electric field integral equation problem discretized with 30,000 unknowns has been demonstrated, executing in 6.2 hours total machine time on the 512-node DELTA. The OOC factorization was performed in 2.84 hours, sustaining 6.2 gigaflops performance during this component of the computation. The 30,000 order complex matrix results in over 14 gigabytes of storage of the LU matrix factors. A 50,000 unknown problem is also being studied, a size which results in 40 gigabytes of storage. With a total of 90 gigabytes disc storage on the DELTA machine, a problem of over 70,000 unknowns is possible and planned.

Concurrent with the numerical solution of the integral equations is a study of the resulting numerical accuracy. The results of this study will also be reported during this talk.

MASSIVELY PARALLEL HYBRID (MOM/UTD) SOLUTIONS OF COMPLEX ELECTROMAGNETIC PROBLEMS

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The ability to accurately predict the radiation and scattering from complex targets illuminated by various modulation schemes is critically important for the design, analysis, development, and deployment of many military systems. This is driven by advancements in low observable technology, antenna technology, communication technology, and radar technology. Cut-and-try methods are too costly and time consuming for modern electronic systems. Many electromagnetic codes fail to accurately predict the electromagnetic performance of complex systems in a timely manner due to their failure to account for such effects as diffraction and mutual coupling, use of only a single analysis technique such as physical optics, geometrical optics, or the method of moments (MOM) as opposed to the most appropriate technique for the given part of the complex target, and computational limitations such as memory requirements and impractical computing times. For instance, consider a target comprised of electrically large structures with small-to-medium sized electrical perturbations. Modeling such a target with MOM alone is intractable because of the overwhelmingly large impedance matrix. The use of high frequency methods to model the target sacrifices the detail required for the small-to-medium sized electrical perturbations. Accurate yet efficient methods to model targets comprised of electrically small and large regions are obtained by combining two or more solution techniques. These methods are referred to as hybrid methods. This talk presents a hybrid solution for electromagnetic scattering problems involving electrically large complex platforms with electrically small regions utilizing MOM and the uniform theory of diffraction (UTD). In addition, this talk also presents a massively parallel computation strategy as well as performance data. A radar model utilizing the MOM/UTD predicted fields is also presented.

SPATIAL DECOMPOSITION METHODS FOR OPEN CYLINDRICAL CAVITIES

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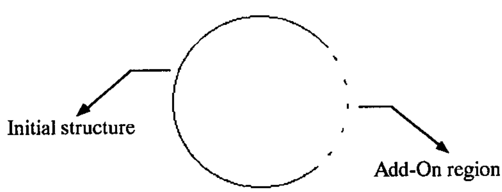
Spatial decomposition methods are characterized by high numerical efficiency, coupled with the unique ability to utilize previously acquired solutions of portions of the scatterer as a part of the analysis of the large scatterer. The process of adding the remainder of the solution is a relatively economical one, assuming that the initial stage of the sub-problem has been performed. The "Add-On" technique (R. Kastner, *IEEE Trans. AP* 37, 353-361, 1989) is an efficient example of the spatial decomposition idea. It has been applied to planar structures using the concept of the equivalent incident current which has helped reduce the total number of operations to $O(n^{2.5})$ for general plate problems. The use of the equivalent incident current can be extended to cylindrical structures, thereby arriving at the cylindrical "Add-On" approach presented in this work. In general, this source representation is defined over an entire coordinate surface, such as the plane as in the original "Add-On" case or a full circular cylinder as in the present case. The scatterer, though, occupies a portion of this surface and is not separable. The open cylindrical cavity treated in this work is the analog of the plates treated before. The problem is solved for large cylinders in three ways: 1. A straightforward Moment Method (MoM) solution (where possible), 2. A direct spatial decomposition solution based on the MoM matrix and invoking the matrix partitioning technique, 3. A cylindrical "Add-On" scheme. In the spatial decomposition cases, the cavity surface is being built up from incremental subdomain basis functions, starting at a single basis function and building the structure through the successive structures, until the closed cylindrical shell structure is reached. It is instructive to see the change in the current distribution as the last subdomain increment is added and the cavity becomes a smooth scatterer. This final stage is quite abrupt compared with the gradual changes in the current up to that stage. The two spatial decomposition techniques coincide throughout the process, and they also agree with the MoM solution wherever performed. However, the computational advantage of the "Add-On" technique is quite apparent. In the cylindrical case, the computational efficiency is also enhanced by the fact that the surface over which the equivalent incident current is defined is finite in nature, unlike the planar case, thus requiring no truncation.



Modeling of Three Dimensional Scattering Using Large Curvilinear Triangular Patches and Wavelet Expansion Functions

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Application of method of moments (MM) techniques for studying electromagnetic (EM) scattering of 3D arbitrary-shaped bodies requires sophisticated geometric modeling techniques for the boundary surfaces that support currents to be used in the integral equations. Most of these techniques employ planar-faceted models for the surfaces. These planar facets must be small compared to the principal radii of curvature to accurately model the surface geometry. The expansion functions commonly used for the surface currents are roof-top bases that vary linearly within each facet. Consequently, the size of each facet must also be small compared to the incident wavelength to accurately model the interactions of the EM waves with each facet. It has been shown that a minimum of 100 facets per λ^2 is required. This requirement severely limits the applicability of the MM techniques in treating scattering from 3D arbitrary-shaped bodies. Only bodies with surface areas less than $10\lambda^2$ can be treated. Recently, investigations have been carried out to develop a 3D MM technique that employs curved triangular patches for surface-geometry modeling (for example, D. L. Wilkes and C. C. Cha, 1991 North American Radio Science Meeting, p. 1512). As a result, fewer patches are needed for accurate surface modeling. However, the reduction in the number of patches is limited because the roof-top bases are still used resulting in the same requirement of small patches in comparison with the wavelength.

In this presentation, we report the development of an MM technique incorporating large triangular curved patches and non-linear bases. This technique provides not only accurate geometry modeling but also efficient representation of highly oscillatory surface currents. As a point of departure in our approach in comparison with the usual MM technique, the matrix equation resulting from the Galerkin technique is transformed according to the wavelet theory to form a sparse matrix. The unknown surface currents will also be expressed in terms of a set of wavelet expansion functions generated from the original non-linear bases. Our discussion will emphasize the accuracy and computational efficiency of the present formulation.

INDUCED CURRENTS IN SURFACES DESCRIBED BY BEZIER'S PATCHES USING MOMENT METHOD.

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This communication presents a technique for the analysis of the induced current on a conducting surface using the Moment Method, and describing the geometry by Bezier's patches. This technique allows to work with bodies of arbitrary shape.

The geometry description by means of Bezier's patches provides a better representation than using triangular patches. Bezier's patches are not restricted to be planar or to have straight contours. Also from computational geometry lots of analytical expressions can be found to compute parameters (surfaces, derivatives, integrals, etc) of bodies modelled by Bezier's patches. Other advantage is that meshings using Bezier's patches are avalaible for many structures since the are required for other studies (mechanical, technical, visualization, etc).

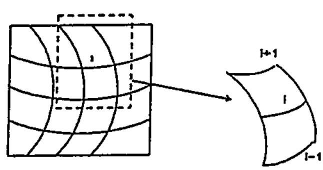

Figure 1

In the present Moment Method formulation, the Electric Field Integral Equation is solved by expanding the current in terms of modified rooftop functions. These rooftops are defined over pairs of contiguous Bezier's patches,in the common wedge, and the shape is such that induces a constat density of charge over each surface (figure 1).

Preliminary scattering results shown that the method is accurate and efficient.

NUMERICAL SIMULATION OF A VIRTUAL MATCHED LOAD FOR THE CHARACTERIZATION OF PLANAR DISCONTINUITIES

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**CNET/PAB, 92131 ISSY - LES - MOULINEAUX, FRANCE

ABSTRACT

One of the main problems encountered with discontinuities scattering parameters extraction techniques is the evaluation of the magnitude and position of the current or the electric field minimum especially for discontinuities having high reflection coefficients. A mixed technique, based on the association of the integral equation solved by the method of moments to the theory of loaded scatterers, is shown to be useful for simulating virtual matched loads for charcaterizing planar discontinuities. The theory of loaded scatterers is used to include the effects of either localized or distributed loads through which the matching can be achieved resulting in a modified integral equation. The main advantage of this technique, with respect to other existing ones, is that the obtained standing wave pattern is rather smooth which leads to a more precise determination of the reflection coefficients and also to an accurate phase evaluation due to the elimination of the sharp minimum of either current or electric field distributions. Obviously, this technique is able to characterize both symmetrical and asymmetrical discontinuities. Moreover, when using this technique for shielded discontinuities, the scattering parameters are obtained from the knowledge of only current or electric field maxima and hence, the errors associated with the accurate determination of the current or the electric field minimum evaluation encountered in other existing techniques are avoided. On the other hand, for open structures, this technique provides an estimation of the radiation and surface wave losses due to the discontinuity itself or due to the feeding line.

EMLIB: An Internet Server for Electromagnetics Software

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A long-standing problem in numerical electromagnetics research is software distribution. Successful general-purpose codes are typically maintained and distributed by their developers or are handled by a commercial firm. However, there is a second tier of electromagnetic (EM) software for which no effective distribution mechanism exists. This category includes highly specialized codes, test-bed codes that are used to investigate or demonstrate a particular algorithm, EM-specific mathematical subroutines, and programs that calculate analytic solutions to canonical problems. While such codes have great utility to the EM community, they have relatively little commercial value and are thus not distributed or archived. Consequently, researchers are forced to reinvent codes that have been written dozens of times in the past by other (unknown) individuals.

This problem has been addressed in other communities through the use of large scale computer networks combined with automated electronic mail and anonymous ftp servers. A notable example is NETLIB, a source of current numerical analysis software, maintained by workers at AT&T and Oak Ridge National Lab. These types of services simplify the distribution of software from both the maintainers' and the users' point of view. The maintainers are freed from the burdens of answering the mail and writing tapes in user-specific formats; they need only park the codes on disk and make them accessible to network users. Users can retrieve software whenever they need it and can browse through the catalog of available tools at any time.

A server has now been established at JPL for the distribution of EM software and information. This server, called EMLIB, will be maintained by a handful of volunteers who will actively solicit and catalogue software. This software will be voluntarily contributed by workers in the field, and should be appropriate for public domain distribution. It is expected that the software be written in standard languages, be documented and, if appropriate, come with associated sample input and output data.

In this talk we will describe how to use the EMLIB server for both retrieving and depositing software, along with a description of currently available software. Our policies and goals for the effort will be discussed. We acknowledge the support of JPL and NASA for contributing the needed resources. Specifically, appreciation is extended to Rob Hartop of the Microwave Engineering Group, JPL, where the server will reside, as well as Jean Patterson and William Rafferty also of JPL. ← send EMail to EMSTAFF@ MICROWAVES.JPL.NASA.GOV

Thursday AM URSI-B Session RA08

Room: Columbus C/D *Time*: 0820-1140

Guided Waves

Chairs: Ezekiel Bahar, University of Nebraska; Todd H. Hubing, University of Missouri-Rolla

0820 **NOISE TEMPERATURE COMPUTATIONS for BEAMWAVEGUIDE SYSTEMS**
W. Imbriale*, Alan G. Cha, T. Y. Otoshi, Jet Propulsion Laboratory

0840 **REFLECTION and SCATTERING of PLANE SURFACE WAVES**
V. P. Cable*, Lockheed Advanced Development Company

0900 **FINITE-ELEMENT TECHNIQUES for the ANALYSIS of TWO-DIMENSIONAL TRANSMISSION SYSTEMS**
C. F. Bunting*, W. A. Davis, Virginia Polytechnic Inst. & State Univ.

0920 **SURFACE INTERGRAL FORMULATION for CALCULATING CONDUCTOR LOSS in DIELECTRIC FILLED WAVEGUIDE**
Tanmoy Roy, Peter Petre*, Tapan K. Sarkar, Madhavan Swaminathan, Syracuse University

0940 **COAXIAL WAVEGUIDES with ANISOTROPIC IMPEDANCE WALLS**
Atef Z. Elsherbeni*, S. Zeng, University of Mississippi

1000 **Break**

1020 **COMPUTATION of CUTOFF WAVENUMBERS for PARTIALLY FILLED WAVEGUIDES of ARBITRARY CROSS SECTION with IMPEDANCE SURFACES**
Paul M. Goggans*, S. Shu, Ahmed A. Kishk, University of Mississippi

1040 **A NEW TYPE of WAVEGUIDE for MICROWAVE MEASUREMENT and POWER APPLICATIONS**
P. J. Luypaert*, Nianci Wang, Katholieke Universiteit Leuven

1100 **RADIATION SPECTRUM for INTEGRATED DIELECTIC OPTICAL WAVEGUIDES**
J. M. Grimm*, Dennis P. Nyquist, Michigan State University

1120 **ON the COUPLED-MODE FORMULATION of PARALLEL DIELECTRIC WAVEGUIDES**
Kiyotoshi Yasumoto*, Kyushu University

NOISE TEMPERATURE COMPUTATIONS FOR BEAMWAVEGUIDE SYSTEMS

W. A. Imbriale*, A. G. Cha, and T. Y. Otoshi
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Large beamwaveguide (BWG) type ground station antennas are generally designed with metallic tubes enclosing the beamwaveguide mirrors. The common methods used for computing performance of these systems are physical optics (PO) and Gaussian mode analyses. The weakness of these analyses is that they do not shed any light on the effect of the metal tube. A new and fundamentally more correct BWG analysis which considers the presence of the metal tube was developed. This analysis computes the scattered field from a BWG mirror using a PO integration procedure with a Green's function appropriate to the circular waveguide geometry. In this manner, the circular waveguide modes that are propagating in the oversized waveguides are determined. The analysis is cascaded from mirror to mirror by using the waveguide fields incident on the next mirror to compute the physical optics currents induced on the mirror.

Comparison of computed and measured scattered field results from several test models, as well as a comparison of predicted and measured gain from a full scale 34-meter antenna, have verified the accuracy of the new analysis with respect to scattered field computations. In addition to the gain and radiation patterns, the noise temperature contribution of the BWG is an important design parameter. There are thought to be two major contributors to noise temperature in a BWG system: the spillover past the mirrors and the conductivity loss in the walls. To date, there is no generally accepted technique for determining the conductivity loss in a BWG. Thus, the new analysis was extended to compute the conductivity loss in the walls of the waveguides. Since all the modes in the waveguide are known, it is a simple matter to use the standard approximations to determine the attenuation constant and thus the conductivity loss once the conductivity of the wall material is known. Experiments were done to determine the conductivity of the steel used to construct the BWG system. Using the measured conductivity and the computed modes in the BWG system, a conductivity loss was computed and converted into a noise temperature prediction. A comparison was then made with the measured noise temperature results from a 34-meter antenna BWG system. Unfortunately, the predicted noise temperature was significantly higher than the measured noise temperature. Subsequent tests using absorbing materials on the waveguide walls confirmed the inaccuracy of the computation. The most probable cause of the discrepancy is that the "standard approximations" used to determine the attenuation constants in waveguide are inaccurate for large-diameter systems.

REFLECTION AND SCATTERING OF PLANE SURFACE WAVES

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The descriptions and structure of plane surface waves have been given, interpreted, argued, and catalogued by many authors since the time of Sommerfeld. The reflection and scattering of these waves have received considerably less attention. The excitation problem, which has a direct relationship to the scattering of surface waves, is found in the literature. However, the focus has tended to be on the form of the launched fields, rather than on the boundary conditions which lead to free space radiation as well as surface waves. In those cases where boundary conditions are exploited to the extent of finding the Green's function for the problem, only solutions which require a scalar Green's function are found, i.e., problems where only transverse currents can flow. Such solutions are of little help if the surface waves are scattered by objects which extend in the direction of surface wave propagation.

This paper describes the investigation of plane TM surface wave scattering by an object with finite dimension in the direction of propagation; a tilted metallic strip. A nonscalar Green's function is derived and used to form an integral equation for the conduction current on the strip. The integral equation is solved via the Method of Moments, and these results are used to predict the scattering coefficient S_{11} for the backscattered surface wave. Computed results are also compared to measurements taken on a planar wave guiding structure. The initial agreement between numerical results and measurements is encouraging enough to suggest that this numerical model could be successfully applied to more complex surface wave structures, and the applicability of this model to scattering of planar TM surface waves by a loaded strip-dipole and an impedance strip is considered.

FINITE-ELEMENT TECHNIQUES for the ANALYSIS OF TWO-DIMENSIONAL TRANSMISSION SYSTEMS

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The goal of this paper is present the development of finite-element techniques for use in characterization of two-dimensional transmission line systems. As a specific example, propagation in a rectangular waveguide will be considered as bench-mark problem for which the exact solution is well known. This problem will be developed in the full-field form, rather than the more restrictive quasi-static form. Several aspects of using finite-element techniques will be considered, including random grid generation, sparse matrix storage, and storage efficient solution techniques. However, more fundamental to the consideration will be the differences in solution using different weighting constraints with and without conjugation. The results will be compared to the classic solution.

An important aspect of the solution to waveguide propagation analysis is the solution of a quadratic eigenvalue matrix problem. This solution is easily obtained through iterative methods, though not commonly discussed in the applied literature. The incorporation of lossy boundaries will also be discussed as a additional aspect of practical problems. The loss associated with a relatively good conductor is typically treated by a surface boundary condition. Alternatives to the boundary problem will be discussed along with implications for a two region treatment of the conductor-dielectric interface and the related element shapes one might expect.

SURFACE INTEGRAL FORMULATION FOR CALCULATING CONDUCTOR LOSS IN DIELECTRIC FILLED WAVEGUIDE

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Abstract

The power-loss method along with a surface integral formulation has been used to compute the attenuation constant in dielectric filled waveguides of arbitrary cross-section. Using the surface equivalence principle the waveguide walls are replaced by equivalent electric surface currents and dielectric surfaces are replaced by equivalent electric and magnetic surface currents. Enforcing the appropriate boundary condition an E-field integral equation(EFIE) is developed for these currents. Method of moments with pulse expansion and point matching testing procedure is used to transform the integral equation into a matrix one. The next step in the calculation of the attenuation constant is to obtain a relationship between the propagation constant and frequency. For this purpose the matrix equation is rearranged into a different from which contains the minimum eigenvalue of the moment matrix.

An iterative technique,i.e. Muller's method is used to find the frequency at which the minimum eigenvalue goes to zero which gives relation between the propagation constant and frequency.

From the above relation the fields inside and on the surface of the waveguide are calculated using the eigenvector pertaining to the minimum eigenvalue of the moment matrix. This is necessary to compute the attenuation constant. Normalized values of the attenuation constants have been made for a rectangular waveguide and it has been found that our results are in very good agreement with published data.

COAXIAL WAVEGUIDES WITH ANISOTROPIC IMPEDANCE WALLS

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ABSTRACT

The analysis of the propagating electromagnetic waves inside waveguides with impedance walls have received considerable attention due to its importance in the development of new microwave and millimeter-wave components. Meanwhile, the attenuation of an electromagnetic waves in a waveguide or acoustic pipe with an absorbing wall has been of recent interest due to its importance in the transmission of power at high frequencies and in the design of fixed-length signal attenuators.

Different methods have been developed for the solution of such boundary value problems. The solution of these electromagnetic problems using surface impedance concepts has been successfully applied to analyze circular waveguides and corrugated coaxial waveguides. The surface impedance is used generally to model a lossy dielectric, a dielectric coating or a corrugated surface. The use of the surface impedance concept greatly simplifies the solution of these problems. Circular waveguide with surface impedance and coaxial waveguide with corrugated surface are previously investigated.

In this paper, the analysis of the propagating electromagnetic waves inside cylindrical coaxial waveguides with arbitrary wall impedance and sectoral coaxial waveguides with perfect electric conductor (PEC) boundaries are presented using the concept of surface impedance. The waveguide surface impedances are considered anisotropic. The eigenvalues, cutoff frequencies, and wavenumbers of the TE, TM, and hybrid modes are calculated and discussed. The analysis and the associated computer codes are verified by comparing the numerical results of selected cases with previously published data. Pictorial displays of the transverse field components inside coaxial waveguides with impedance surfaces and sectoral coaxial waveguides with PEC boundaries are also presented. The effect of various parameters on the characteristics of the guided waves are also investigated.

COMPUTATION OF CUTOFF WAVENUMBERS FOR PARTIALLY FILLED WAVEGUIDES OF ARBITRARY CROSS SECTION WITH IMPEDANCE SURFACES

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This paper presents a procedure for determining the cutoff wavenumbers of partially dielectric-filled waveguides of arbitrary cross-section. At cutoff, the fields in a waveguide are either transverse electric or transverse magnetic to the direction of propagation in the guide (even for modes which are hybrid modes at frequencies above cutoff). The procedure presented here is based on the observation that, at cutoff, the fields in the guide are the same as the fields in a two-dimensional (2-D) resonator with the same cross section as the guide and that the resonant frequencies of the 2-D body are the cutoff frequencies of the guide. In this procedure, a numerical approach based on surface integral equation formulations and the method of moments is used to obtain a matrix equation for the 2-D body. Muller's method is then applied the matrix equation to determine the wavenumbers which cause its determinate to vanish. These are the cutoff wavenumbers.

On the conducting walls of the waveguide, perfect electric conductor surfaces, perfect magnetic conductor surfaces, and imperfect conductor surfaces (modeled using the impedance boundary condition) are considered. Consideration of these surfaces allows the matrix size to be reduced when an appropriate surface impedance can be calculated or when symmetric waveguides are considered.

An advantage of using the integral equation formulation approach is its ability of find all cutoff solutions and its freedom from spurious solutions. To validate the method, results for circular, partially-filled rectangular, and two walled corrugated rectangular waveguides are compared with analytical results. Results for T-septum rectangular, coaxial, and dielectric-loaded double-ridged waveguides are also presented.

A NEW TYPE OF WAVEGUIDE FOR MICROWAVE MEASUREMENT AND POWER APPLICATIONS

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In some applications of microwave technique it is highly desirable to find new types of waveguides which have superior properties such as less attenuation and higher power handing capacity than that of the conventional waveguides, while its exact wave functions can be easily determined. In this paper such a novel waveguide is found by using the nonseparable solution of the Helmholtz equation.

A nonseparable solution of the Helmholtz equation can be readily obtained from the well known separable solution $w^{(0)} = \cos(ax)\cos(by)$, by using the first order symmetry operator $M = y\frac{\partial}{\partial x} - x\frac{\partial}{\partial y}$ on it. (P.L.Overfelt, Electromagnetics, vol.9, pp.249-258, 1989.) Observing the combination of separable and nonseparable solution $F(x,y) = w^{(0)} + C_2M^2w^{(0)}$, a series of closed boundary shapes are found from $F(x,y) = 0$ with different constant C_2. These shapes can be used as the cross-section of a non-conventional waveguide. The TM mode field of the waveguide can be exactly determined from the field component $E_z = E_{z0}F(x,y)$ which satisfies the Helmholtz equation and boundary conditions. Fig.1 shows the cross-sections of the waveguide. It can be seen that they are smooth distortion of the boundary given by the separable solution alone. The characteristics of this kind of waveguide are studied in detail and the radiating properties of the open-ended waveguide is examined for a potential heating application in this paper. The analysis shows that it has better properties compared to that of the rectangular waveguide. Concerning the relative attenuation constant α_r and relative propagated power P_r (which are defined as the ratio of the attenuation constant and propagated power of the waveguide to those of rectangular ones) as well as the power handling capacity PHC, the results are shown in Table I, where $C_2 = 0$ corresponding to the rectangular waveguide determined from the separable solution. It is evident that this novel waveguide can propagate more power, have less attenuation constant and higher power handling capacity than that of the rectangular one. This is very attractive for microwave measurement and power applications.

Table I

C_2	0.000	0.015	0.025	0.035	0.045
P_r	1.000	1.143	1.182	1.199	1.184
α_r	1.000	0.898	0.864	0.844	0.839
PHC	.505	.511	.516	.522	.528

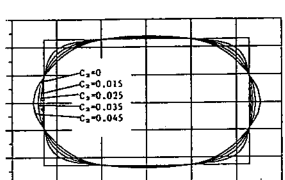

Fig.1 Closed boundary shapes for various C_2.
(A=2.286cm B=1.143cm)

RADIATION SPECTRUM FOR INTEGRATED DIELECTRIC OPTICAL WAVEGUIDES

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A major gap in the understanding of dielectric waveguiding structures exists. It is well known that a complete modal expansion for a dielectric waveguide involves both discrete bound modes and a continuous superposition of radiation spectral components. The bound modes for dielectric waveguides have been extensively investigated with both approximate and exact full-wave techniques. However, save for the simplest of cases, the radiation spectrum of dielectric waveguides has remained undetermined. Knowledge of this radiation spectrum is vital for modal description of EM wave excitation, coupling, or losses due to radiation at circuit discontinuities.

Full-wave analysis of practical integrated dielectric optical waveguides is accomplished by using an axial-transform domain EFIE based on Hertzian potentials supported by equivalent polarization currents arising from dielectric contrast, namely,

$$\vec{e}(\vec{\rho};\zeta) - (k_c^2 + \tilde{\nabla}\tilde{\nabla}\cdot)\int_{CS'} \vec{\vec{g}}(\vec{\rho}\mid\vec{\rho}';\zeta)\cdot\left\{\frac{\delta n^2(\vec{\rho}')}{n_c^2}\,\vec{e}(\vec{\rho}';\zeta)\right\}ds' = \vec{e}^{\,i}(\vec{\rho};\zeta)$$

for all $\vec{\rho} \in CS'$. The background environment is planarly layered, infinite in extent in the axial (z) and transverse (x) dimensions. The relevant scalar components of the Green's dyadic are one-dimensional Sommerfeld integrals on transverse wavenumber ξ, oscillatory and slowly convergent, and are dependent on the wavenumber parameter p_i, a square root quantity involving both spectral transform variables (ζ for z, ξ for x). Space-domain fields are recovered subsequent to a seemingly trivial inverse transform on axial wavenumber; yet, for the inverse axial transform to exist, the ζ-plane must be cut to assure analyticity.

The radiation spectrum for dielectric waveguides is identified with the branch cuts in the axial wavenumber (complex-ζ) plane that constrain the migration of branch point singularities in the transverse wavenumber plane. The inhomogeneous (forced) axial-domain EFIE is then solved for this restricted regime of ζ, utilizing a unit-source excitation, allowing for the determination of a radiation Green's dyad for the dielectric waveguide in terms of the spectral radiation fields.

ON THE COUPLED-MODE FORMULATION OF PARALLEL DIELECTRIC WAVEGUIDES

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The coupled-mode theory is one of the most commonly used approaches in the analysis of coupled optical waveguides. In this approach, the total wave fields of the coupled waveguides are expressed as a linear combination of the modal fields of the individual waveguides in isolation and a set of coupled differential equations for the modal amplitudes is derived by making use of various approximations. The well-known coupled-mode theory, which was first introduced in the analysis of optical waveguides, has now come to be known as the conventional coupled-mode theory. Recently the difficulties of the conventional theory have been criticized and much interest has been shown in obtaining a new theory, which is usually referred to as the improved coupled-mode theory. However the validity of the improved theory is not so self-evident as claimed.

In this paper, we discuss the coupled-mode formulation of parallel dielectric waveguides from the viewpoint of perturbation theory. We reexamine first the conventional and improved coupled-mode theories, and show that the conventional theory is equivalent to the first-order perturbation theory and the improved theory includes some corrections due to the higher order perturbation but in an improper manner. This explains the observation in several literatures that the improved theory yields significant errors in the strong-coupling regime. Next we present a new coupled-mode formulation based on a singular perturbation technique. In our approach, the original uncoupled-wave equation for the coupled waveguides are decomposed into an equivalent system of coupled-wave equations. The coupled-wave equations are expanded using the multiple-space scales and solved iteratively so as to satisfy the boundary conditions on the composite waveguide. Then the coupled equations between the modal amplitudes of the individual waveguides are systematically derived in the respective order of perturbation. The formulation is asymptotically correct and can be applied even in the strong-coupling regime.

Thursday AM URSI-E, NEM Session RA09

Room: Columbus E/F *Time*: 0820-1200

EM Topology

Organizer: P. Degauque, Universite de Lille
Chairs: Carl E. Baum, Phillips Laboratory; P. Degauque, Universite de Lille

0820 **INTEREST of a TOPOLOGICAL APPROACH for the STUDY of ELECTROMAGNETIC COUPLING**
J. P. Parmantier*, Dassault Aviation

0840 **TOPOLOGY BASED ELECTROMAGNETIC INTERACTIONS MODELLING**
Joe LoVetri*, University of Western Ontario; George I. Costache, University of Ottawa

0900 **AN APPLICATION of E.M. TOPOLOGY to a COMPLEX SYSTEM**
V. Gobin*, F. Issac, J. P. Aparicio, ONERA; I. Junqua, A. Madore, Centre d'Etudes de Gramat; J. P. Parmantier, Dassault Aviation

0920 **TREATMENT of NON-UNIFORM COUPLED LINES in a QUANTITATIVE TOPOLOGICAL APPROACH**
P. Besnier, P. Degauque*, B. Demoulin, Univ. des Sciences et Tech. de Lille

0940 **EQUALIZATION of LOSSY MULTICONDUCTOR TRANSMISSION LINES**
Jurgen Nitsch*, NBC Defense and Research Institute; Carl E. Baum, Phillips Laboratory; Richard Sturm, NBC Defense and Research Institute

1000 **Break**

1020 **NORM DETECTORS for MULTIPLE SIGNALS**
Carl E. Baum*, Phillips Laboratory

1040 **APPLICATION of NUMERICAL CODES to the STUDY of ELECTROMAGNETIC COUPLING**
X. Ferrieres*, V. Gobin, ONERA

1100 **ON the CONCEPTUAL FOUNDATIONS for DETERMINING the PROBABILITY of SURVIVAL for ELECTRONIC and COMMUNICATIONS SYSTEMS EXPOSED to EMP**
Ira Kohlberg*, Shawn C. Whetstone, Institute for Defense Analyses

1120 **CLASSIFICATION of ELECTROMAGNETIC ENVIRONMENTS for EMP HARDENING STANDARDS**
Torbjorn Karlsson*, EMTECH

1140 **PANEL DISCUSSION on FUTURE of EM TOPOLOGY**

INTEREST OF A TOPOLOGICAL APPROACH FOR THE STUDY OF ELECTROMAGNETIC COUPLING.

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Electromagnetic Topology is an original and powerful formalism developed in the seventies by C.E Baum et al. to solve internal electromagnetic problems on complex systems. The spirit of the method is to make the approximation that independent volumes can be defined in the structure to avoid a complete resolution on the whole geometry. The art of Topology then is, to bring together the elementary problems associated with each volume in order to obtain the response of the global system. To our knowledge, no application of this method had been published, till 1988, when ONERA, Dassault Aviation and Lille University decided to answer the question: can it be applied in aeronautics ? In 1992, after all the work we have done on the subject, we think that the application to industrial problems is feasible indeed.

Firstly, we present our personal view on the original formalism. Next, the benefits of the method will be shown. Particularly, a descriptive Topology and a quantitative Topology will be distinguished. The first one can be very useful to organize E.M coupling problems; employed as early as the design stage of an industrial product, the method allows for an optimization of the protections and the future maintenance, and makes all the certification studies easier.

Directly following the topological analysis, the quantitative Topology deals with the prediction of interference levels. The way to generalize a multiconductor line network formalism, specially well suited for lightning and EMP, will be dicussed.

Finally, examples dealing with the way to characterize a penetration path in a tological sense and the application of the method to a complete system will put forward the importance of the method.

TOPOLOGY BASED ELECTROMAGNETIC INTERACTIONS MODELLING

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The electromagnetically relevant attributes of an electrical system can be isolated by decomposing the system into an *electromagnetic shielding topology* and its dual graph or *interaction sequence diagram.* The interaction sequence diagram can be simply derived from a given electromagnetic topology. The electromagnetic topology consists of a description of the electromagnetically distinct volumes and their associated surfaces. The volumes define the *electromagnetic components* involved in the interaction. The interaction sequence diagram keeps track of the *interaction paths* throughout the system. The nodes in the topology are characterized as being either ***field nodes, circuit nodes*** or ***interaction path nodes*** (J. LoVetri & G.I. Costache, *IEEE Trans. on EMC*, vol. 33, no. 3, pp 241-251, Aug. 1991). Nodes are then given electromagnetic attributes which define the node's susceptibility and disturbance level (field and circuit nodes) or shielding effectiveness (interaction path nodes). These attributes are necessarily approximations to the processes which manifest the actual physical interaction problem. The form of these approximations as well as the operators which model the interaction between nodes will be discussed. Sources of error include: coarseness of the topological decomposition; type and approximation of attribute values; propagation of disturbances through the topology; and comparison of disturbance impinging at a node to the node's susceptibility level. A new formulation based on approximating the relevant attributes in the topology with trapezoidal fuzzy variables is also discussed. The implementation of these techniques into computer software simplifies the analysis and hardening process since, typically, a real system's topology consists of many nodes with many interaction paths. Future directions in this area of research will also be discussed.

AN APPLICATION OF E.M. TOPOLOGY TO A COMPLEX SYSTEM

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Since 1988, we tried to apply Electromagnetic Topology concepts to complex structures to give an evidence of its great help in industrial programs. All the work we performed led us to elaborate a numerical code named CRIPTE, originally inspired by the multiconductor transmission line network formalism, but generalized to E.M. Topology.

This tool and the concepts of the method have been validated on a common experiment performed in a collaboration between ONERA and CEG (Centre d'Etudes de Gramat). The structure under test was a caisson composed of five elementary subvolumes organized in the shape of a cross. Each volume was equiped with multiconductor lines running through the structure. Some paths could be considered as canonical, but others were more complex: indeed some cables were located near structural elements and geometical "defects". In particular an electronic equipment,connected to the internal wiring by means of shielded coaxial cables,has been simulated by a black box.

The external excitation was made by means of three apertures located in three of the elementary subvolumes. Several experimental methods of injection have been studied (direct injection on wiring; use of local strip-lines). A special one dealt with a coaxial cable unshielded at the aperture level. An experiment with the entire caisson under an EMP simulator (SSR) has also been performed.

The method to characterize the elementary subvolumes of the caisson in a topological way will be presented. We shall also show global frequency domain simulations dealing with the coupling on the whole structure. The use of transfer functions to predict the time response of the system will also be discussed.

TREATMENT OF NON-UNIFORM COUPLED LINES IN A QUANTITATIVE TOPOLOGICAL APPROACH

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In most cases, the calculation of electromagnetic disturbances induced on cable networks must take the non-uniformity of these cables into account. If we consider the simple example of cables parallel to a ground plane, a local non-uniformity occurs when either the height of the cable bundle above the plane varies continuously from one point to another one, or when this bundle divides into two or many parts. Applying the coupled transmission lines theory leads to second order differential equations with coefficients depending on the position of the cables.

For some configurations such as crossing wires or a wire whose height above the ground plane varies linearly... analytical solutions have been found and which are very useful for physical interpretation. However, these approaches cannot easily implemented into a numerical code based on the generalized transmission line equation used in the topological model and usually called B.L.T. equation (C. Baum, Transfer of norms through black boxes, Interaction Notes, Note 462, 1987). A solution consists in approximating a non-uniform structure by a series of small uniform structures separated by small discontinuities. The scattering parameters of this set of discontinuities are calculated and introduced into the B.L.T. equation formalism. S topological parameters have to be determined. Usually they are calculated from S_{50} parameters which are scattering parameters measured with respect to 50 Ohm. In case of ideal junction the matrix { [U] - [S_{50}] } where [U] is the unity matrix is singular. Then, the transformation of [S_{50}] into [S] is impossible. But one shows that topological S calculation is performed directly by defining some matrices which are combinations of rows and columns of general characteristic impedance matrix, depending on the way conductors are connected. The theoretical approach will be presented together with a comparison between theoretical and experimental results on few examples (crossing cables, non parallel cables...).

EQUALIZATION OF LOSSY MULTICONDUCTOR TRANSMISSION LINES

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Abstract

The exact analytical treatment of lossy multiconductor transmission lines (MTLs) is a very difficult task. The pairwise commutation of all relevant physical matrices occurring in the MTL equations can be used to decouple these equations by virtue of a diagonalization procedure. In this case an analytical solution is essentially simplified.

The requirement of commutativity on the other hand, of course, restricts the admitted classes of MTL configurations. In former publications (J. Nitsch, C. Baum, R. Sturm) we investigated circulant matrices and complex matrices which are the product of a real symmetric matrix times a complex valued function.

A special application of our general results to lossy MTLs over a lossy ground leads to an interesting aspect: It becomes possible to adjust the losses of the lines with those of the ground plane (reference conductor) such that the eigenvalues of the characteristic impedance matrix become those of a distortionless conductor system. Furthermore, for a chosen two - and three - multiconductor configuration we can match ground- and wire-losses in a way that the resulting eigenfunctions of the corresponding propagation matrix turn out to be equal to each other. This implies that all propagation modes of the conductor system have the same attenuation and the same velocity, in some cases even no dispersion occurring. The above procedure might become of some importance when one tries to transmit signals without distortion, in close analogy to the "equalization" of lossy telephone lines.

NORM DETECTORS FOR MULTIPLE SIGNALS

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One is often confronted with the problem of measuring a large number of electrical signals in some object (system) under test. These may be in either frequency or time domain. What is it about these signals that one can or should measure? For example, one might attempt to measure many thousands of time-domain signals, perhaps for each of several different orientations of the system in say some set of EMP simulators. This represents an enormous amount of time-sampled (or frequency-sampled) data to collect, store, and process before one attempts to draw conclusions from the test. Is there some way that one can compress or reduce the amount of data to be taken, stored, and processed while still being able to draw valid conclusions concerning the system performance? This paper addresses this question in terms of appropriate bounds on the signals in terms of norms. Norms provide a powerful concept for characterizing a set of waveforms as single, real, non-negative number. This can be used to give a bound on every waveform in the set. If one has a specification that all signals at a set of pins (in a system in some test electromagnetic environment) be less than some amount stated in such a norm sense, then a norm detector has the potential of simplifying the test.

The design of such a norm detector poses various technical problems. One of these concerns the perturbation of the voltages or currents to be measured. The actual sensor responding to each of the voltages (e.g. a parallel (to local ground reference) small admittance resistor) or currents (e.g. some small-insertion-impedance inductive coupling device) must give a negligible perturbation. For this purpose one needs to bound the appropriate eigenvalues of the source and input matrices (combined). Even the geometrical size of the devices in contact with or proximity to the pins or associated wires can be of concern because of the close packing of a large number of wires in a cable bundle or connector.

APPLICATION OF NUMERICAL CODES TO THE STUDY OF ELECTROMAGNETIC COUPLING

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In spite of the increasing performances of modern computers, it seems that the study of the electromagnetic coupling on a complex structure (such as an aircraft) is out of the capability of an only simulation taking into account all the interactions. The use of the Electromagnetic Topology formalism supposes that independant volumes can be defined in the structure and thus avoid the complete resolution of the whole problem. The numerical code CRIPTE based on a multiconductor lines network formalism can be used to connect elementary volume togather.

The objectif of this paper is to illustrate how electromagnetic numerical codes can help to fill a topological network with proper datas. Such a network can be descrided by means of 3 types of datas: **junctions** are represented by scatterring parameters, **multiconductor lines** are simulated by inductance and capacitance matrices (or speed and characteristic impedance), and the **sources** are applied by means of current and voltage generators on the lines. To complete experimental measurement of these parameters, various numerical codes can be used and some exemple are discussed:

- The first code is based on a quasistatic magnetic calculation of the current distribution on parrallel wires modelled by their mutual inductances. It can calculate some of the muticonductor lines parameter taking into account the return path of the currents.
- The second code is based on the Method of Moments solution of integral equations in the frequency domain. Exemples of the calculation of Thevenin equivalent generators are given.
- The last code gives a finite difference solution of the Maxwell Equation in time domain. Short-circuit fields on an aperture can be considered as the source terms to introduce in a complete network.

Most of the numerical results are discussed and compared to experimental datas obtained on a complex structure both in time and frequency domains.

ON THE CONCEPTUAL FOUNDATIONS FOR DETERMINING THE PROBABILITY OF SURVIVAL FOR ELECTRONIC AND COMMUNICATIONS SYSTEMS EXPOSED TO EMP

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The Institute for Defense Analyses, Alexandria, Virginia USA

This paper examines the concept of Probability-of-Survival, P_s, and the associated issue of confidence for electronic and communications systems exposed to the High Altitude EMP (HEMP) threat. *P_s is defined as the probability that all Mission Critical Functions (MCF) of the system will survive and that the system will complete its mission.* The determination of P_s is therefore a Bernoulli process with two outcomes: success (survival) or failure. The confidence, C, is a measure of the certainty ($0 \leq C \leq 1$) with which we can determine P_s.

The uncertainty in the prediction of P_s arises from the stochastic nature of the threat waveform $\vec{E}$. This randomness is embodied in the uncertainty parameters $\tilde{\eta}$, associated with the HEMP source mechanisms, and $\tilde{\Omega}$, associated with geometric factors and polarization. $\vec{E}$ is thus a random function $\vec{E}(t, \tilde{\eta}, \tilde{\Omega})$ from the sample description space defined by $\tilde{\eta}$ and $\tilde{\Omega}$. If $f_\eta(\tilde{\eta})$ and $f_\Omega(\tilde{\Omega})$ are the probability density functions for $\tilde{\eta}$ and $\tilde{\Omega}$ respectively (i.e. their assumed frequency of occurrence), we have

$$P_s = \iint f_\eta(\tilde{\eta})\, f_\Omega(\tilde{\Omega})\, d\tilde{\eta}\, d\tilde{\Omega}\,, \qquad (1)$$

where the domain of integration extends over all values of $\tilde{\eta}$ and $\tilde{\Omega}$ for which all the MCF survive.

P_s is difficult to determine purely analytically. In *principle*, it can be determined by simulation provided *all* possible values of $\tilde{\eta}$ and $\tilde{\Omega}$ are used. This is defined as ideal simulation, and it is not practical. Instead, we can select a finite set: ($\tilde{\eta}=\eta_1, \eta_2, \eta_3, \ldots \eta_N$; $\tilde{\Omega}=\Omega_1, \Omega_2, \Omega_3, \ldots \Omega_L$), and examine the number of times, M, that all the MCF survive. The approximate P_s is $\hat{P}_s = (M/LN)$ which is the ratio of the number of success to the total number of tests, N_0=LN. Confidence, C, is a measure of the degree to which $\hat{P}_s$ approximates P_s. C depends on the number of tests, N_0, and the desired degree of approximation defined by a small parameter, ε. We evaluate and compare the calculation of C as a function of N_0 and ε using Chebyshev's Inequality, a Bayesian approach, and Non-Parametric Statistics.

Methods for determining P_s are explored. The methods are based on the use of transfer functions that connect the excitation at each POE to a particular piece of mission critical equipment. Using topological considerations developed by Baum we show that the EMP-created stress (voltage or current) can be expressed as

$$\chi_\mu^{(j)}(t, \tilde{\eta}, \tilde{\Omega}) = \sum_k \vec{\varphi}^{(k)}(\tilde{\Omega}) \cdot \int_0^t \vec{g}_\mu^{(j,k)}(t-\tau)\, E(\tilde{\eta},\tau)\, d\tau\,, \qquad (2)$$

where $\vec{g}_\mu^{(j,k)}$ is a vector function that depends on the interior coupling between the k^{th} POE and pin μ of mission critical equipment j, $\vec{\varphi}^{(k)}$ is a vector function that depends on the orientation variables and location of the k^{th} POE, and $E(\tilde{\eta},\tau)$ is a scalar field.

Methods for independently determining, $\vec{g}_\mu^{(j,k)}$ and $\vec{\varphi}^{(k)}$ using combinations of EMP test facilities are examined. The net effect is that the EMP-created stress can be expressed in terms of the random variables, $\tilde{\eta}$ and $\tilde{\Omega}$. Using appropriate failure criteria, methods are presented for calculating P_s using Equation (1).

CLASSIFICATION OF ELECTROMAGNETIC ENVIRONMENTS FOR EMP HARDENING STANDARDS.

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Two sets of Swedish defense standards have been drafted, one containing immunity test methods and requirements on equipment, and another specifying the EMP environment into four different classes along with test procedures for determining the actual EMP response. Testing according to the immunity standards can be used to verify that equipment will function in a specified EMP environment. Testing according to the environment standard will be used to find the actual EMP response of a system inside a given topological volume, and after that classify the environment into one out of four classes.

In immunity standards test levels are specified for the succeptibility testing of equipment. Those levels have to correspond to an EMP environment that is specified in the environment standard. By establishing four specified EMP environment classes many advantages are gained, for example:

- Instrumentation for immunity testing is limited to few specified test levels and less costly than a more general test instrumentation.
- Environment specification is limited to a few levels — in practice only two EMP hardened levels — thereby facilitating decision making.

The environment classes are chosen to correspond as much as possible to certain types of practical facilities. In the long run, this makes it possible to perform a preliminary class determination by experience, rather than testing.

Four EMP environment classes have been suggested:

Class #1 is the unattenuated EMP field and unattenuated EMP induced currents in long lines.

This class is expected on all unhardened sites.

Class #2 is almost the same as class #1, except for a low frequency attenuation of currents. The raison d'être of this class is the prospective possibility of including lightning in the same environment classes.

This class is expected on unhardened sites with low frequency "lightning grounding" of cable shields and surge arresters.

Class #3 is an environment that is attenuated at least one order of magnitude from that of the EMP field, up to 200 MHz. Currents are low pass filtered.

This class corresponds to environments within volumes inside concrete buildings, which have all cable penetrations gathered at one entry plate that is well connected to the rebar structure.

Class #4 is an environment in which the EMP contribution is negligible.

This class will be found in all EMP protected facilities with high quality hardening.

Expected field strengths for the different environment classes have been calculated, and test currents for corresponding immunity classes have been determined. Damped sinusoidal test pulses of the same kind as in MIL-STD-461, CS 11-12 can be used. Examples of amplitudes at different frequencies for a given safety margin will be given in this paper.

Thursday AM URSI-B Session RA10

Room: Columbus G *Time*: 0820-1140

Chiral, Bianisotropic and Complex Media and Their Applications I

Organizers: Nader Engheta, University of Pennsylvania; A. Priou, DGA, Ministry of Defense
Chairs: Nader Engheta, University of Pennsylvania; A. Priou, DGA, Ministry of Defense

0820 **WAVE INTERACTION with COMPLEX MEDIA: a REVIEW**
Nader Engheta*, University of Pennsylvania

0840 **ON the RECIPROCITY of BI-ISOTROPIC MEDIA**
Ismo V. Lindell*, Helsinki University of Technology

0900 **THEORETICAL MODELIZATION and DIMENSIONING of CHIRAL MATERIALS**
Bernard Souillard*, X-RS

0920 **ON MODELLING and on NUMERICAL SIMULATION of ISOTROPIC CHIRAL MATERIALS**
A. Froger*, Centre d'Etudes du Ripault

0940 **MULTIPLE SCATTERING FORMALISM for PREDICTING EFFECTIVE PROPERTIES of CHIRAL COMPOSITES**
Vasundara V. Varadan*, Renuka Apparao, V. K. Varadan, The Pennnsylvania State University

1000 **Break**

1020 **DETERMINING CHIRAL PARAMETERS from MEASUREMENTS**
Markku Oksanen*, Helsinki University of Technology; Arto Hujanen, State Technical Research Center

1040 **EXPERIMENTALLY DETERMINED DESIGN CRITERIA for MICROWAVE CHIRAL COMPOSITES**
Vasundara V. Varadan*, R. Ro, V. K. Varadan, The Pennnsylvania State University

1100 **FARADAY-CHIRAL MEDIA: REFLECTION, PROPAGATION and DYADIC GREEN'S FUNCTION**
Dwight L. Jaggard, P. G. Zablocky, M. Mirotznik*, University of Pennsylvania

1120 **ELECTROMAGNETIC WAVE REFLECTION and TRANSMISSION at an ANISOTROPIC-ISOTROPIC INTERFACE**
Y. H. Lee*, J. K. Lee, Syracuse University

WAVE INTERACTION WITH COMPLEX MEDIA: A REVIEW

Nader Engheta

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U.S.A.

There has been a lot of research activities in the area of electromagnetic wave interaction with complex media in recent years. This is mainly due to potential applications of such materials in the design of novel devices and components, anti-reflection thin coatings, and microwave absorbers, and also due to the recent progress and development in making novel electromagnetic materials and composites. Complex materials include various classes of bianisotropic media. Such materials, which are described by one of the most general linear constitutive relations involving material parameters in tensor form, i.e.,

$$\mathbf{D} = \underline{\underline{\varepsilon}} \cdot \mathbf{E} + \underline{\underline{\alpha}} \cdot \mathbf{B} \qquad \text{and} \qquad \mathbf{H} = \underline{\underline{\delta}} \cdot \mathbf{E} + \underline{\underline{\beta}} \cdot \mathbf{B},$$

and their electromagnetic properties have been studied in detail by many researchers. As can be seen from the above constitutive relations, in these materials the electric and magnetic phenomena are coupled, and, in addition to conventional permittivity tensor $\underline{\underline{\varepsilon}}$ and permeability tensor $\underline{\underline{\beta}}$, there are other parameters given in the tensor form as $\underline{\underline{\alpha}}$ and $\underline{\underline{\delta}}$. The additional parameters introduced in the constitutive relations can provide new degrees of freedom in material synthesis. Therefore, a variety of novel applications and phenomena involving such materials may be resulted from these additional parameters.

These materials can themselves be divided into several subgroups. One such subgroup is the class of *biisotropic* media. For these media, the four material tensors reduce to four scalar quantities. More explicitly, they are characterized by

$$\mathbf{D} = \varepsilon\, \mathbf{E} + \alpha\, \mathbf{B} \qquad \text{and} \qquad \mathbf{H} = \delta\, \mathbf{E} + \mu^{-1}\, \mathbf{B}$$

One example of such media is chiral media which have been studied intensively in the past few years.

In this talk, a review of some of the physical principles of electromagnetic wave interaction with bianisotropic media are given and special cases such as biisotropic media, and chiral media are briefly discussed.

ON THE RECIPROCITY OF BI-ISOTROPIC MEDIA

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A bi-isotropic (BI) medium is defined for time-harmonic fields through four parameters ϵ, κ, χ, μ in the constitutive equations

$$\mathbf{D} = \epsilon\mathbf{E} + (\chi - j\kappa)\sqrt{\mu_o\epsilon_o}\mathbf{H},$$
$$\mathbf{B} = \mu\mathbf{H} + (\chi + j\kappa)\sqrt{\mu_o\epsilon_o}\mathbf{E},$$

where κ is called the chirality parameter and χ, the Tellegen parameter.
The nonreciprocity brought about by the Tellegen parameter χ was cited by the Dutch scientist Tellegen and can be easily demonstrated through the medium parameters by forming the following expression with two sets of sources $\mathbf{J}_1$, $\mathbf{J}_{m1}$ and $\mathbf{J}_2$, $\mathbf{J}_{m2}$ and the corresponding fields $\mathbf{E}_1$, $\mathbf{H}_1$, $\mathbf{E}_2$, $\mathbf{H}_2$:

$$\int_V \left[(\mathbf{E}_1, \mathbf{H}_1)\cdot\begin{pmatrix}\mathbf{J}_2\\ -\mathbf{J}_{m2}\end{pmatrix} - (\mathbf{E}_2, \mathbf{H}_2)\cdot\begin{pmatrix}\mathbf{J}_1\\ -\mathbf{J}_{m1}\end{pmatrix}\right] dV$$
$$= \int_V \left[(\mathbf{E}_1, \mathbf{H}_1)\cdot\begin{pmatrix}0 & -2j\chi k_o\\ 2j\chi k_o & 0\end{pmatrix}\begin{pmatrix}\mathbf{E}_2\\ \mathbf{H}_2\end{pmatrix}\right] dV.$$

In case of a reciprocal medium the integral should vanish for any field functions. This implies $\chi = 0$, which corresponds to the special case of a BI medium labeled as 'the isotropic reciprocal chiral medium' or, in short, 'the Pasteur medium'.
Although clearly seen from the above, the nonreciprocity of a BI medium is not straightforwardly seen by forming fields due to sources. In fact, it can be seen by experimenting that the BI medium is reciprocal for electrical or magnetic sources alone. This has caused some controversy as to whether the BI medium is really nonreciprocal or not.

In the present paper it is demonstrated with examples that the BI medium is truly nonreciprocal for the nonvanishing Tellegen parameter and the effect appears in cross-coupling of electric and magnetic sources. Some applications for nonreciprocal devices with the BI medium are suggested.

THEORETICAL MODELIZATION AND DIMENSIONING OF CHIRAL MATERIALS

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Abstract

We have considered chiral materials built with helices made of a conducting material placed in a matrix. We have developped a theoretical approach for the prediction of the electromagnetic properties of such a chiral medium knowing the electromagnetic properties of the matrix and the geometric as well as the electromagnetic parameters of the inclusions.

As a result we can dimension the parameters in order to obtain some specific effect, e.g. maximize absorption around some wavelength.

Some comparisons with experimental results will be presented and discussed.

The theoretical works have been achieved by A. RAMANI, Th. ROBIN and B. SOUILLARD. They are implemented in "REFLEXION" a commercial software for the computation of the electromagnetic properties of heterogeneous materials, which is operational since the beginning of 1989.

Our work is part of a joint program supported by DRET with MATRA DEFENSE (Team of D. JORDAN) who makes the materials and ONERA CERT (Team of A. PRIOU and S. BOLIOLI) who makes the electromagnetic mesaurements.

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ON MODELLING AND ON NUMERICAL SIMULATION OF ISOTROPIC CHIRAL MATERIALS

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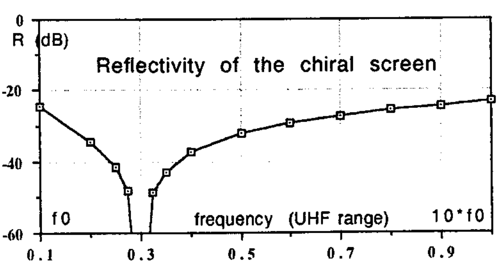
By analysing standard models of constitutives laws for isotropic chiral materials we derived a new one. This new constitutive law is physically equivalent or quasi-equivalent to the standard ones but is related directly with effective permitivity, effective permeability, and rotation rate of polarisation direction. Propagation in the material for an incipient linear polarised electromagnetic wave is interpretated in term of an "ordinary" propagation wave number (i.e. regardless the rotation) and in term of a rotation wave number. Propagation wave number is related in usual way with effective permitivity and effective permeability. Consequently this analysis gives the physical interpretation of formal parameters (ε,μ,chirality) of the standard models. This point is very important for numerical computations in order to obtain results with physical signifiance. It appears that potential interest of chiral materials is related to the variation of the effective permitivity with regard to the variation of the frequency. Both lossy and losseless materials have been studied.

Numerical simulations of anti-reflective screens are performed with materials made of chiral objects (Jaggard helix, and circular helix) embedded in organic matrix.



MULTIPLE SCATTERING FORMALISM FOR PREDICTING EFFECTIVE PROPERTIES OF CHIRAL COMPOSITES

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In modeling the effective properties of discrete random media using multiple scattering theory, it is traditional to set up the field formalism in terms of the propagation modes supported in the host material and treat the inclusion phase via a scattering operator such as the T– matrix. When the constitutive relations obeyed in the inclusion and host phases are different and the volume fraction of the inclusion phase is sufficiently large, then the effective medium should really be described with constitutive relations similar to that of the inclusion material. This phenomenon is similar to percolation and percolation thresholds. In a composite medium containing a random distribution of scatterers made of a chiral (handed) material that lacks reflection symmetry which are embedded in a host phase with reflection symmetry, the effective medium can lack reflection symmetry at higher volume fractions. Such materials find applications in microwave absorption and shielding.

A new multiple scattering formalism is presented which enables us to explicitly solve for the eigenvectors and eigenvalues associated with the dispersion equation for the effective medium and verify whether the effective constitutive behavior resembles that of the inclusion phase. Analytical expressions for the LCP and RCP wavenumbers of the effective medium are obtained in the long wavelength limit as a function of frequency, concentration of chiral inclusions and material properties of the host material and the chiral inclusions. At shorter wavelengths, the dispersion equation is solved numerically. Relationships to other effective medium models will be discussed. Analytical results are also compared with the predictions of mixing rules as well as experimental results.

DETERMINING CHIRAL PARAMETERS FROM MEASUREMENTS

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After the pioneer work of professor Lindman during and after the First World War, and the work done by Tinoco and his coworkers in 1950s, there has been no reports until recent years in the open literature about the measurement techniques and measured characteristics of chiral materials.

As it is well known, a chiral layer possesses two characteristic features as the eletromagnetic wave goes through the layer. These are: 1) rotation of the plane of polarization, called optical rotary dispersion (ORD) and 2) change of the polarization ellipticity due to losses, and referred as circular dichroism (CD). These effects depend on the amount of chirality in the material.

In the open litterature, there has been reports on how the angle of rotation and the polarization ellipticity can be determined. The basic method is very simple: a transmitted field is measured at two different angles - at the copolarized angle and at the arbitrary angle. Next the Stokes parameters are determined from the measurements, and the rotation angle and the axial ratio of the ellipse are calculated using these parameters.

In this paper, it will be shown how, using the κ-notation for the chiral material, the real and imaginary parts of the chiral parameter κ can be solved in a very simple way from knowing the rotation angle and axial ratio of the ellipse. Further, formulas for determing complex permittivity and permeability parameters of the chiral layer from the measured reflected and transmitted fields will be given.

The method will be applied to some chiral layers whose ORD and CD curves are available from the open litterature.

EXPERIMENTALLY DETERMINED DESIGN CRITERIA FOR MICROWAVE CHIRAL COMPOSITES

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A complete experimental study of chiral composite samples at microwave and millimeter wave frequencies (8 – 40 GHz) is presented. The electromagnetic field behavior in materials with a handed microstructure is readily described by the use of the constitutive relations $\mathbf{D} = \varepsilon (\mathbf{E} + \beta \nabla \times \mathbf{E})$ and $\mathbf{B} = \mu (\mathbf{H} + \beta \nabla \times \mathbf{H})$, where β is a new material parameter called the chirality parameter which results from the non-centro symmetric nature of chiral materials. The planar samples are prepared by embedding miniature helices in an epoxy host material. Right, left handed and racemic samples are made at three different volume concentrations, 0.8%, 1.6%, and 3.2%, to investigate effects of handedness and concentration. A free-space measurement system is employed to characterize the chiral composites. It is verified that the chirality parameter of the racemic samples has a value nearly equal to zero. Right and left handed samples have approximately the same values of the complex chirality parameter with opposite signs. The Cotton effect, has been observed in the region at which the maximum power absorption occurs. It is observed that the ratio L/λ_c of one turn length of the chiral inclusion to the wavelength in the chiral medium at frequencies where the maximum power absorption occurs is approximately a constant, independent of concentration. This is used as a design criterion for making broadband absorbers by optimally combining different helix sizes. Other useful design criteria are obtained using long wavelength theoretical models to invert the polarizability of a helix of given size from experimentally measured macroscopic properties.

FARADAY-CHIRAL MEDIA: REFLECTION, PROPAGATION AND DYADIC GREEN'S FUNCTION

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Faraday-chiral media blends the effects of Faraday rotation with those of chiral materials to form a nonreciprocal anisotropic chiral medium. Using this blend, we examine the control of electromagnetic chirality through the application of an external magnetic field. Plane wave propagation in and reflection from Faraday-chiral slabs are examined as a function of magnetic fields and degree of chirality for both chiro-ferrites and chiro-plasmas. These are characterized by the constitutive relations

$$\mathbf{D} = \underline{\underline{\varepsilon}}\,\mathbf{E} + i\xi_c\mathbf{B} \qquad \text{and} \qquad \mathbf{H} = i\xi_c\mathbf{E} + \underline{\underline{\mu}}^{-1}\,\mathbf{B}$$

among the four electromagnetic field quantities where the permittivity $\underline{\underline{\varepsilon}}$ and permeability $\underline{\underline{\mu}}$ may be anisotropic but the chirality is indicated by the scalar chirality admittance ξ_c.

This work was inspired by our initial investigation [N. Engheta, D. L. Jaggard and M. Kowarz, "Electromagnetic Waves in Faraday Chiral Material," to appear in *IEEE Trans. Ant. and Propagat.* (1992).] into unbounded anisotropic chiral material in which the two modes (right- or left-circular polarization) associated with electromagnetic chirality added to the two modes characteristic of Faraday media (propagation along the biasing magnetic field or against it) allowing Faraday-chiral materials to support four modes of propagation. These four eigenmodes each have their characteristic wavenumber. Since the Faraday effect can either reinforce or cancel the effect of rotation due to chirality, the former can be used as a mechanism to control the latter through variation of the biasing magnetic field. Here we examine wave interactions with Faraday chiral slabs of finite longitudinal extent which are both homogeneous and inhomogeneous. Our interest is to place in evidence the propagation, reflection and transmission properties of electromagnetic waves in such slabs and to investigate the interplay of Faraday and chiral effects. Reflection from and transmission through arbitrary inhomogeneous Faraday-chiral slabs is completely characterized by a matrix Riccati equation.

As a first step toward solving the source radiation problem, we also consider the dyadic Green's function for one-dimensional wave propagation in such media. As expected, all planar sources excite one or more of the four eigenmodes depending on the handedness of the source and direction of propagation. This places in evidence the four mode behavior of all sources in such media.

ELECTROMAGNETIC WAVE REFLECTION AND TRANSMISSION AT AN ANISOTROPIC - ISOTROPIC INTERFACE

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The reflection and transmission of electromagnetic wave incident from an isotropic medium upon an anisotropic medium has been studied (J. K. Lee, Progress in Electromagnetics Research Symposium Proceedings, p.714, July 1- 5, 1991). In this paper , we will consider the electromagnetic wave incident from an upper (lower) anisotropic medium upon a lower (upper) isotropic medium. The permittivity tensor of anisotropic medium is uniaxial with the optic axis tilted off the normal (z -) axis by some angle ψ . Knowing that inside the uniaxially anisotropic medium there exist two characteristic waves, i.e., an ordinary (*o*) wave and an extraordinary (*e*) wave (J. K. Lee and J. A. Kong, "Dyadic Green's function for layered anisotropic medium," *Electromagnetics*, Vol.3, 111-130, 1983) , one can formulate the field in the anisotropic region as a linear combination of two characteristic waves. Applying the boundary conditions at the anisotropic - isotropic interface, we find the *Fresnel reflection* and *transmission coefficients*, given the specific polarization of the incident wave which can be either ordinary (*o*) or extraordinary (*e*).

Results show that a wave incident with either *o* or *e* polarization transmits both the horizontally (*h*) polarized and vertically (*v*) polarized waves at the interface, hence the transmitted wave in general will be elliptically polarized. The reflected wave contains both the *o* - polarized and *e* - polarized components that propagate in different directions with different phase velocities. The phenomenon is known as *birefringence*. We derive the *Brewster Law* for the anisotropic - isotropic interface, by finding the conditions under which a wave of arbitary polarization or an unpolarized wave upon reflection becomes a linearly polarized wave (*o* or *e*) . The results will be compared with those of the isotropic - isotropic interface and the isotropic - anisotropic interface. The plots of the Fresnel reflection and transmission coefficients will also be given as a function of the incidence angles (zenith and azimuth) and polarization.

Thursday AM URSI-B Session RA11

Room: Columbus H *Time*: 0820-1200

Numerical Techniques for Guiding and Radiating Structures

Chairs: David C. Chang, University of Colorado at Boulder; M. P. Hurst, McDonnell Douglas Research Laboratories

0820 **NUMERICAL TESTBED for NOVEL DESIGN of MICROSTRIP ANTENNA**
Doris I. Wu*, Boulder Microwave Technologies, Inc.; David C. Chang, University of Colorado at Boulder

0840 **MODELING CASCADED SYSTEMS of CAVITY-BACKED APERTURES**
Robert M. Sharpe*, D. R. Wilton, David R. Jackson, University of Houston

0900 **EFFICIENT CALCULATION of RADIATION PATTERNS for FINITE-SIZE ONE-DIMENSIONAL LEAKY-WAVE ANTENNAS**
H. Ostner*, J. Detlefsen, Technische Universitat Munchen; David R. Jackson, University of Houston

0920 **RADIATION PATTERN SYNTHESIS for an ARRAY of LOG-PERIODIC ANTENNAS**
D. H. Werner*, R. D. Groff, J. K. Breakall, P. L. Werner, Pennsylvania State University

0940 **ANALYSIS and DESIGN of PLANAR WAVEGUIDE LONGITUDINAL SLOT ARRAY USING SCATTERING MATRIX APPROACH**
Karthikeyan Mahadevan*, University of Illinois, Urbana-Champaign; Charles E. Smith, University of Mississippi; Hesham A. Auda, Kato Group

1000 **ANALYSIS of SHIELDED MICROSTRIP-LIKE LINES with FINITE THICKNESS of STRIP CONDUCTORS**
Alexander Yakovlev*, Dniepropetrovsk State University

1020 **SYNTHESIS PROCEDURES for FINITE EMBEDDED ARRAYS**
J. M. Putnam*, L. N. Medgyesi-Mitschang, McDonnell Douglas Research Laboratories

1040 **ANTENNA DESIGN APPLICATIONS with an ELECTROMAGNETIC OPTIMIZATION CODE**
Thomas L. Larry*, Toyon Research Corporation

1100 **ANALYSIS of a WIDE RADIATING SLOT EXCITED by a MICROSTRIP LINE**
Masoud Kahrizi*, Tapan K. Sarkar, Zoran Maricevic, Syracuse University

1120 **THE MUTUAL COUPLING CHARACTERISTICS BETWEEN SLOT-MONOPOLE ANTENNA ELEMENTS**
Gu Zeji*, Beijing Broadcasting Institute

1140 **RESONANT BEHAVIOR of a PAIR of MONOPOLES STRADDLED on a SLOT-APERTURE BACKED by a CAVITY CONTAINING a WIRE**
Gu Zeji*, Beijing Broadcasting Institute

NUMERICAL TESTBED FOR NOVEL DESIGN OF MICROSTRIP ANTENNA

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Electromagnetic simulation of microstrip structures has played an increasingly important role in the design validation of monolithic microwave integrated circuits and antennas. In this talk, we will discuss the issues involved in extending the role of a simulation tool to serve as a testbed for novel microstrip antenna design. They include graphical user interface, geometry file structure, and sensitivity analysis, as well as computational efficiency for multi-frequency simulation and adaptability to different antenna and substrate compositions.

Our approach for the numerical engine is based upon a spatial-domain moment method with a mixed potential integral equation formulation. We will discuss not only the choice in the basis functions, but also the computational strategy for the Sommerfeld integrals and the associated moment integrals. Since the most computationally-intensive portion in this type of solvers is still the matrix fill time, we will discuss how one can improve the computational speed by evaluating the static portion of the moment integral analytically and storing it in a database while computing the dynamic portion approximately by interpolating data from pre-calculated look-up tables.

The robustness of a numerical testbed depends not only on an efficient solver but also on the ease in entering the geometries for simulation and sensitivity analysis. We will demonstrate how an early version of such a testbed helped in the development of wide band microstrip patches and circularly-polarized arrays.

Modeling Cascaded Systems of Cavity-Backed Apertures

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The problem of determining field penetration into a cavity backed aperture region is one of longstanding interest. Of particular interest in this presentation is the analysis of a more general structure that consists of a series of cavity sections coupled together via common apertures. In addition, each cavity section may contain either conducting obstacles such as wires or asymmetrical walls, or piecewise homogeneous dielectric regions.

In this work, we present a technique for efficiently modeling complex structures involving systems of cavities which are coupled together. An equivalent magnetic current is employed to model the aperture fields and a system of

... calculating the tangential aperture field in the space domain and setting this field to zero outside the physical aperture. This modified aperture field is then Fourier transformed to obtain the far-field pattern. The Fast Fourier Transform (FFT) can in principle be used for an efficient spectral integration calculation to get the aperture field of a one-dimensional leaky-wave antenna composed of a line source inside dielectric ... the FFT does not directly allow for arbitrary complex inte-

RADIATION PATTERN SYNTHESIS FOR AN ARRAY OF LOG-PERIODIC ANTENNAS

D. H. Werner* and R. D. Groff

... matrices. An expression for the driving point impedance of the array will be derived. Finally, techniques which can be used to characterize the active region of the array will be discussed.

ANALYSIS AND DESIGN OF PLANAR WAVEGUIDE LONGITUDINAL SLOT ARRAYS USING SCATTERING MATRIX APPROACH

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A scattering matrix approach to the analysis and design of planar waveguide longitudinal slot arrays is described in this paper. The array consists of N equally spaced slot modules (with a spacing "*d*" between the consecutive modules in the direction of the waveguide) in the broad wall of a set of M feed waveguides. The new method employs the scattering matrix for TE_{10} and TE_{20} (to the waveguide axis) modes of isolated longitudinal slot in the broad wall of a rectangular waveguide rather than the admittance of the slot derived from approximate shunt or series lumped element model for the slot. The method fully accounts for the external mutual coupling due to the TE_{10} and TE_{20} modes on the slots by using Kajfez and Wilton's scattering matrix representation for radiating elements [D.Kajfez and D.R.Wilton, "Network representation of receiving multiport antennas," *AEU*, Band 30, pages 450-454, November 1976), and can easily be extended to include the higher order waveguide modes by using the generalized scattering matrix of the slot. Thus the method takes into account the deviations in the slot aperture field distributions from a sinusoidal distribution that is normally assumed with a nearly resonant slot. Such a feature, along with the use of generalized scattering matrix, allows the method to be applicable for the analysis and design of arrays having a variety of modules such as, for instance, slots tuned by metallic posts, pairs of narrow slots, etc. The viability of scattering matrix approach is established by comparing the reflection coefficient and aperture field coefficient data obtained using the scattering matrix approach and a Method of Moments procedure. Numerical results for an example design of 2X3 planar array of longitudinal slots are presented.

ANALYSIS OF SHIELDED MICROSTRIP-LIKE LINES WITH FINITE THICKNESS OF STRIP CONDUCTORS

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the Ukraine, USSR

Resent developments require the correct information on dispersion and on the propagation of modes in transmission lines at high frequencies for designing specific waveguiding devises. The dispersion characteristics of dominant and higher order modes of microstrip-like lines at high frequencies have been reported by many papers. However, the mathematically correct solution of the problem with finite strip conductors thickness have not been obtained.

Rigorous numerical-analytical approach to hybrid-mode analysis of multiply connected structures with longitudinal dielectric layers and finite thickness of strip conductors is developed and mathematically grounded (Fig.1). The method is based on the integral representations for partial intersected regions by the use of dyadic Green-functions. An idea of the method goes as follows. A whole complicated region of determined field is subdivided into a number of simple regions. However, in contrast with the broadly used mode-matching method, the simple partial regions are intersected, i.e. have common parts. For each of considered regions a Sturm-Liouville boundary value problem is formulated to $\vec{E}$ vector of electromagnetic field. Using Gauss-Ostrogradsky tensor theorem and integral Fourier transform enables to obtain a Fredholm second type system of interconnected integral equations.

The system of integral equations is converted into a second type infinite system of linear algebraic equations: (L-I)A=0, where A - vector of unknown coefficients of the Fourier series expansion; L - matrix operator; I - idem-factor. For shielded microstrip-like transmission lines with finite thickness of strip conductors are shown, that Gölder space for functions defines l_1 space for coefficients A and

$A=\{a_n\} = O(n^t)$, $n \to \infty$; $t=-5/3$. The w-complete continuity for matrix operator L on pair of spaces : $l_1 \to l_1$ is proved.

The numerical results of dispersion characteristics of dominant and higher order modes of shielded microstrip line with finite thickness of strip conductor are obtained and compared with published results for microstrip line with negligibly thin strip conductor.

SYNTHESIS PROCEDURES FOR FINITE EMBEDDED ARRAYS

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The radiation characteristics of finite embedded arrays, scanned from broadside to endfire, are strongly dependent upon many interrelated parameters. Principal among these are: the choice of the array termination, the presence of superstrates (i.e., radomes) or substrates, ground plane curvature and termination, the excitation taper, and the distribution of active or parasitic elements in the array. To achieve desired synthesized patterns, these parameters must be taken into account in the synthesis procedure. Synthesis procedures are particularly sensitive to these parameters for endfire arrays. Array termination effects must be rigorously accounted for. The impact of superstrates and substrates in microstrip radiator structures in the endfire mode is paramount. In this presentation, we will examine various synthesis procedures for arrays composed of wire, patch, and microstrip elements. The choice of constraints and weights on the array feed topology will be described to achieve desired pattern optimality. Pattern synthesis sensitivity to array termination and superstrate and substrate effects will be discussed.

ANTENNA DESIGN APPLICATIONS WITH AN ELECTROMAGNETIC OPTIMIZATION CODE

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ABSTRACT

Electromagnetic (EM) computer codes have been taking on an increasingly important role in the design and development of antenna systems. The design role consists of finding the values of design variables (such as circuit elements, feed geometrics, and feed placement) which optimally satisfy the system requirements. Such a code called SCINW (SCattering and INteraction-Wire) has been developed to aid the design of systems whose antennas are wire structures. This paper will highlight the key features of SCINW. Examples of both transmission and reception applications will be shown.

The most important key features of SCINW are (1) accurate EM modeling at feeds and (2) a transfer function approach to formulating the EM problem. The wire structure is modeled using the method of moments. This produces linear (matrix) operators which are coupled to the feeds in a way that allows for complete flexibility in the positioning of feed points as well as accuracy in the calculation of the antenna impedance. Load impedances are accurately modeled by specifically accounting for the feed region geometry, cables, matching networks, and so forth. The transfer function structure allows the problem to be organized in such a way that the search for optimum design variables is as efficient as possible.

Some specific antenna designs will be shown in the examples. These designs will be optimized for various frequency bands using the requirements of maximizing partial and absolute gain.

Analysis of a Wide Radiating Slot Excited by a Microstrip line

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In this paper an analysis of a electrically wide radiating slot in a ground plane capacitively excited by a microstrip line is presented. The main advantages of radiating slots are wider bandwidth, less interaction via surface waves, better isolation of the feed structure and negligible radiation from the feed network. These kind of antenna have been found applications for a variety of radar and satellite communication. The slot is considered in an infinite ground plane. The ground plane is backed by a dielectric slab one surface of which is in contact with the ground plane. The printed microstrip line exciting the slot antenna is located on the other face of the dielectric slab.

In this analysis, the equivalence principle is applied to replace the slot by two oppositely directed magnetic currents. Hence the structure is decomposed into two isolated regions. Then the continuity of the tangential components of the fields is enforced to couple the field in these two regions. In addition to the electric field (magnetic current) in the slot, the surface electric current on the microstrip line is considered to be unknown. Therefore, unlike the other solutions for the slot problems no presumption for the surface electric current is assumed. Considering both components of the electric fields in the slot gives us the possibility to compute the radiation pattern for both polarizations.The method of moments is applied to solve the coupled integral equations obtained from the boundary conditions and find the current distribution on the microstrip line as well as the field distribution in the slot. In the next step the input impedance corresponding to the fundamental modes in the microstrip line is obtained utilizing the matrix pencil technique. This technique is used to decompose the current into its fundamental and higher order modes. The numerical results is obtained in the forms of the input impedance of the slot and the field distribution across the slot.

THE MUTUAL COUPLING CHARACTERISTICS BETWEEN SOLT-MONOPOLE ANTENNA ELEMENTS

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ABSTRACT: The mutual coupling between slot-monopole antenna elements is analyzed by MOM. In which both internal and external mutual coupling are considered. The mutual admittance and scattering parameters are presented, which show that the elements augmented with monopoles can indeed reduce mutual coupling than slot alone. The VSWR is measured and shows in good agreement with theoretical results.

COMPUTATIONAL AND EXPERIMENTAL RESULTS: Using field-equivalence principles and Imposing the boundary conditions results in simultaneous integral equations. By the moment method, which can be converted into a matrix equation. Then some important parameters can be obtained with the help of computers. Fig.2 shows mutual admittance, from which we can see the magnitude of oscillation of Clavin element is less than that of conventional slot. Fig. 3 shows the reflection and transmission coefficients. It is obvious that the element augmented with monopoles makes the reflection coefficients be less than that of slot alone. In other word, the transmission of the former is larger than that of the later. Fig.4 shows the experimental results and compared with theoretical one.

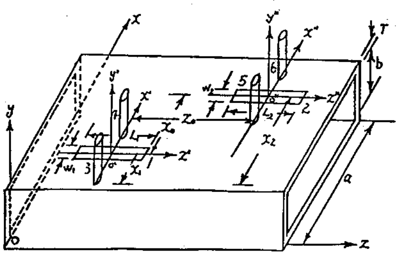

Fig.1.

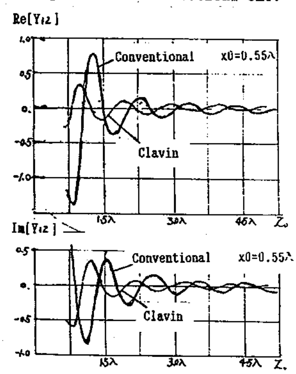

Fig.2

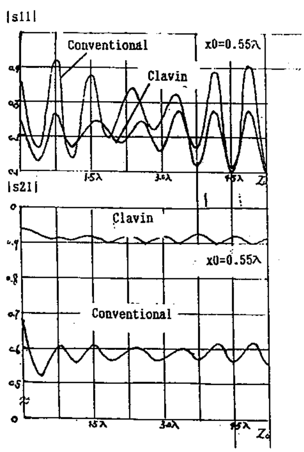

Fig.3.

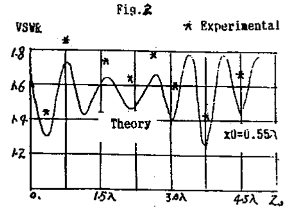

Fig.4.

Resonant Behavior of a Pair of Monopoles Straddled on a Slot-Aperture Backed by a Cavity Containing a Wire

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Abstract: The main purpose of this paper is to demonstrate the conclusion that 2 monopoles straddled symmetrically two sides of a slot-aperture can reduce EM wave penetration into a cavity may be not efficient if the cavity is not empty. It is shown by the moment method that the electric current on a wire in the cavity is from 8.6 times at aperture-cavity-wire resonance to 226 times at monopole-aperture-cavity-wire resonance than that of the same wire but with infinite length in a free space environment.

Recently, the author of this paper has purpose a new approach to reduce the incident electromagnetic wave penetration into a conducting cavity throuth a slot-aperture, which is mainly depend on a pair of monopoles. We do not know whether the approach is efficient if there is a conducting body in the cavity. The objective of this paper is just concerned with this problem. Of course, the most simple case is a thin wire in the cavity, which is parallel with one of the cavity and normal to the incident wave direction and that both ends of the wire are attached to the wall. The integral equations are established and numerically solved by the moment method, then the electric current on the wire and electric field distribution in the cavity are obtained, respectively.

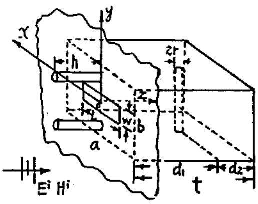

Fig.1. A pair of monopoles straddled on a slot-aperture backed a cavity containing a wire

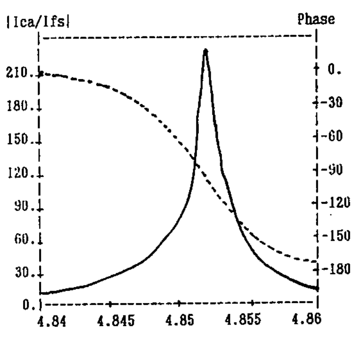

Fig.2. Ratio of the electric current on the wire at the resonance to that on the infinite length wire in a free space

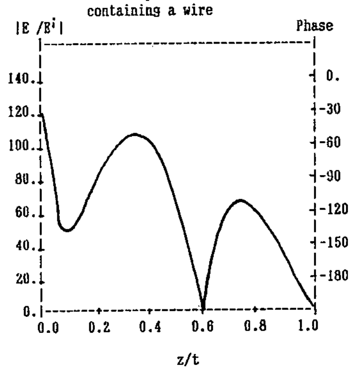

Fig.3. The electric field distribution at the resonance in the cavity as a function of z axis(x=y=0)

Thursday AM URSI-D Session RA12

Room: Columbus I/J *Time*: 0820-1200

Millimeter and Submillimeter Wave Active Devices and Circuits

Organizers: M. Salazar-Palma, Universidad Politecnica de Madrid; Roberto Sorrentino, Universita degli Studi di Perugia

Chairs: M. Salazar-Palma, Universidad Politecnica de Madrid; Roberto Sorrentino, Universita degli Studi di Perugia

0820 **RECENT DEVELOPMENTS in MILLIMETER-WAVE MONOLITHIC INTEGTRATED CIRCUITS**
H-L A. Hung*, COMSAT Laboratories

0840 **MILLIMETER-WAVE III-V INTEGRATED DEVICES**
Pierre Briere*, John Magarshack, THOMSON COMPOSANTS MICROONDES

0900 **SERIES IMPEDANCE of GaAs PLANAR SCHOTTKY DIODES**
Kaushik Bhaumik*, Boris Gelmont, Robert J. Mattauch, Michael Shur, University of Virginia

0920 **NEW GATE CURRENT MODELS for COMPLEMENTARY HETEROSTRUCTURE FIELD EFFECT TRANSISTORS (C-HFETs)**
E. Martinez*, Michael Shur, University of Virginia; F. Schuermeyer, Solid State Electronic Directorate

0940 **DESIGN ASPECTS for mm- and SUBmm-WAVE GaAs SCHOTTKY DIODES**
V. Krozer*, A. Grub, H. L. Hartnagel, Isnt. fur Hochfrequenztechnik

1000 **Break**

1020 **DESIGN and PERFORMANCE of a 640 GHz SUBHARMONICALLY PUMPED MIXER USING PLANAR GaAs SCHOTTKY DIODES**
Peter H. Siegel*, Imran Mehdi, Jet Propulsion Laboratory; William L. Bishop, Thomas W. Crowe, University of Virginia

1040 **EFFICIENCY of SINGLE BARRIER VARACTORS for SUBMILLIMETER WAVE POWER GENERATION**
S. M. Nilsen*, H. Gronqvist, H. Hjelmgren, A. Rydberg, Eric Kollberg, Chalmers University of Technology

1100 **A PLANAR SIS RECEIVER for ARRAY APPLICATIONS**
Philip Stimson*, Robert J. Dengler, Peter H. Siegel, Henry G. LeDuc, Jet Propulsion Laboratory

1120 **RADIATING SLOT-LINE RESONATORS for SIMMWIC TRANSMITTERS**
J. Hausner*, S. Moser, Peter Russer, Technische Universitat Munchen

1140 **6-ELEMENT PERIODIC and NON-PERIODIC LINEAR ARRAYS for QUASI-OPTICAL SPATIAL POWER COMBINER**
Shigeo Kawasaki, Tatsuo Itoh*, University of California, Los Angeles

Recent Developments in Millimeter-Wave Monolithic Integrated Circuits

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Abstract

Advances in GaAs- and InP-based technology have resulted in the realization of heterojunction transistor-type devices capable of operation at frequencies beyond 100 GHz. These achievements have also led to successful device/circuit integration and to the development of a large number of monolithic millimeter-wave integrated circuits (MMICs). Currently, MMIC technology is being further developed for potential insertions into various commercial and military systems, such as communications satellites, smart munitions, terrestrial communications links, and collision-avoidance systems for automobiles.

This paper presents an overview of current activities in the MMIC area. First, recent performance results are given for different devices including metal-semiconductor field-effect transistors (MESFETs), high electron mobility transistors (HEMTs), pseudomorphic-HEMTs (P-HEMTs), heterojunction bipolar transistors (HBTs), and Schottky barrier diodes (SBDs) for millimeter-wave applications. The advantages and disadvantages of using these devices for various component applications in millimeter-wave systems are addressed, followed by a discussion of recent accomplishments in MMIC development.

MMIC applications are grouped into three categories: small-signal and low-noise circuits, power amplifiers and large-signal circuits (including mixers and oscillators), and control circuits (such as phase-shifters, switches, and attenuators). Measured results for these MMICs, as well as for receivers, frequency converters, and transmitter subsystems, using both GaAs- and InP-based device structures for existing systems and future phased-array applications are summarized. The packaging aspect of these MMICs for millimeter-wave systems is also addressed. Finally, the limitations of current on-wafer MMIC characterization at millimeter-wave frequencies are discussed, and new approaches, including optical techniques, are presented.

MILLIMETER-WAVE III-V INTEGRATED DEVICES

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ABSTRACT

This paper will describe work that is being carried out in Europe on Civil Applications at millimeter-wave frequencies. There are many reasons why such frequencies are used. Compactness, directivity, such beams can be focussed without large antennas to the required surface (unlike I-R or optical sources which are too fine). A very important advantage at 60 GHz is its exponential absorption in air which allows the presence of a large number of users in a confined space without interference. Details of applications will be given especially those envisaged in Europe.

Such applications are only possible if reliable inexpensive components become available. There has been a considerable effort in recent years to provide such components in Europe particularly en CEE programmes as ESPRIT - RACE - and DRIVE. These are aimed at Wide-Band Communications and automobile applications for which the technological foundations have been prepared with programmes such as AIMS, CLASSIC, etc. Results of these programmes will be presented with examples of MMIC 60 GHz Jow-noise and power amplifiers, oscillators and mixers using pseudo-morphic hemt devices, and synthesizers based on HBT varactor tuned, VCO's.

A new age in transactions at a distance has come about due to the availability of these devices, and their industrialization is now well under way and should give rise to the reasonably priced components that are necessary before large quantity production applications become a reality.

Series Impedance of GaAs Planar Schottky Diodes

Kaushik Bhaumik*, Boris Gelmont*+, Robert J. Mattauch*, and Michael Shur*

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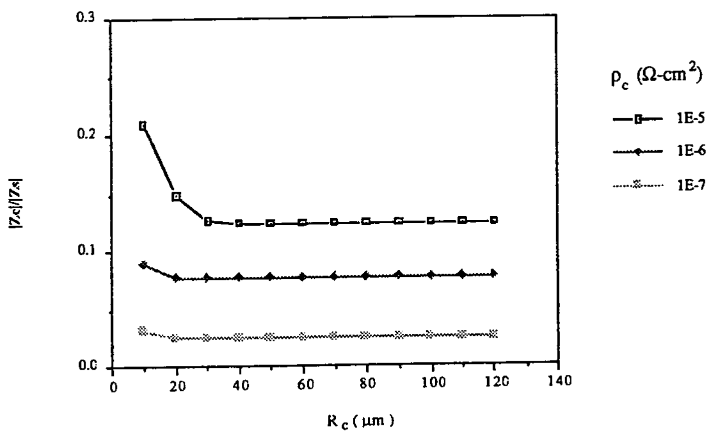
ABSTRACT

We discuss the impedance of ohmic contacts of a GaAs cylindrical planar Schottky diode. The impedance is estimated using a lumped element model for series impedance components: epilayer impedance, spreading impedance, substrate impedance and ohmic contact impedance. The expression for the high-frequency impedance of an annular ohmic contact is developed based on the solution of the equations of a novel transmission line model in the cylindrical coordinate system. Such a solution allows us to express the ohmic contact impedance as an analytical function of the specific contact resistance, transfer length, and device geometry. This formulation is used to ascertain the contribution of the ohmic contact impedance to the overall device series impedance at both DC and microwave frequencies up to 500 GHz. Diode impedance characterization indicates that, for a typical diode design, the ohmic contact impedance makes a relatively small contribution to the series impedance in comparison to the other components, both at DC and operational frequencies. Hence, the dimensions of the contact pads can be scaled down significantly without any appreciable increase in series impedance but with a decrease in the parasitic pad-to-pad capacitance. Finally, this modelling establishes theoretical guidelines regarding the allowable limits for specific contact resistance in small geometry diodes, so that device I-V characteristics are not significantly altered as a result of the ohmic contact impedance. The results are shown to be in a reasonable agreement with experimental data.



Ratio of absolute values of contact to series impedance versus anode radius for different values of specific contact resistance at 500 GHz.

NEW GATE CURRENT MODELS FOR COMPLEMENTARY HETEROSTRUCTURE FIELD EFFECT TRANSISTORS (C-HFETs)

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**Solid State Electronic Directorate,
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ABSTRACT

Complementary Heterostructure Field Effect Transistor (C-HFET) technology has matured to the point that the first high-density Static Random Acess Memories have been recently introduced, with extraordinary state-of-the-art circuit performance (Grider *et al., GaAs IC Symposium Technical Digest*, pp 143-146, 1990). This technology promises to surpass Complementary MOS technology in speed and power dissipation. However, circuit models specifically taylor for this technology, have not been implemented yet. The purpose of this work is to introduce new semi-empirical gate-current models that cover the entire range of gate voltages from below and above threshold, for n- and p-channel Heterostructure Insulated Gate Field Effect Transistors (HIGFETs) based on the AlGaAs/InGaAs/GaAs material system. Especial attention has been given to the subthreshold regions where gate leakage is important and affects the static power of the circuits.

These semi-empirical models are based on a new interpretation of the quantized energy levels at the AlGaAs/InGaAs heterointerface. In addition, the gate current is explained by the two diode model (Chen *et al. IEEE Trans. Electron Devices*, ED-35, No. 5, pp 570-577, May 1988). This model assumes that below threshold, the gate current is controlled by the Schottky barrier height, and the ideality factor is close to unity. Above threshold, the effective heterojunction band discontinuity controls the gate current and the ideality factor is then determined by the change in the interface potential with respect to change in the gate voltage. In our calculations, we use a modified Richardson equation to describe the gate current density as a function of gate voltage and temperature. Theoretical calculations have been also compared with experimental results at a wide temperature range with excellent agreement between theoretical and experimental data. The results will be presented in conjunction with the theoretical models and the implications involve in the theoretical calculations.

Design aspects for mm– and submm–wave GaAs Schottky diodes

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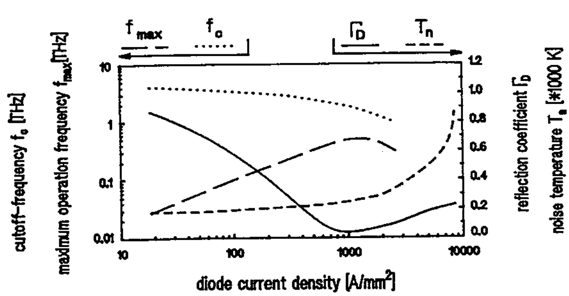
Abstract

Low–noise GaAs Schottky diodes have been used as nonlinear detectors for mixing applications at frequencies from 100 GHz up to the THz range. The higher the operation frequency of the mixer, the more careful has to be the diode design in order to achieve optimum mixer performance. For many years diode parameters have been optimized by minimizing the so called $R_S C_{j0}$ product. It will be shown that this optimization criterium leads to unphysical results and gives no information about the real maximum operation frequency of the Schottky diode. Instead of the cutoff–frequency $f_c = 1/(2\pi R_S C_{j0})$ the maximum operation frequency $f_{max} = 1/2\pi[(R_j + R_S)C_j]$ in combinaton with the diode reflection coefficient Γ_D and the diode noise temperature T_n should be used for the optimization of the diode parameters (doping concentration, diameter, epi–layer thickness). This optimization yields concurrently the proper operating region exhibiting minimum noise temperature and good matching of the mm–wave mixer, as indicated in fig.1. This has been accomplished by the use of a novel physical Schottky diode model. The principle feature of this model is the accurate determination of the mm–wave performance utilizing only DC meauserements. This model exhibits a very good agreement between measured and calculated DC –, C/V– and RF–noise characteristics. Schottky diodes with different diameters have been used to optimize the diode design for a certain frequency range.

fig.1:



DESIGN AND PERFORMANCE OF A 640 GHz SUBHARMONICALLY PUMPED MIXER USING PLANAR GaAs SCHOTTKY DIODES

Peter H. Siegel*
Imran Mehdi

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This paper presents design and performance data for a 640 GHz subharmonically pumped waveguide mixer using an antiparallel pair of planar air bridge type GaAs Schottky barrier diodes. The mixer is a prototype for a space qualified unit to be flown on the Earth Observing System Microwave Limb Sounder satellite instrument. The 640 GHz radiometer is one of four submillimeter and one millimeter wave channels which will be used to measure key chemical species in the Earth's upper and lower stratosphere and upper troposphere. Radicals, reservoirs and source gases in all chemical cycles now thought critical to our understanding of ozone depletion will be globally monitored on a daily basis. Additional measurements include molecular species involved in radiative forcing of climate change and the effects of volcanic injections into the lower stratosphere.

The 640 GHz mixer uses a split block rectangular waveguide design with a 2:1 width-to-height ratio throughout to simplify fabrication. In the space qualified design, the mixer filter circuitry and planar diodes are integrated onto a single substrate composed of a thin GaAs semi-insulating layer bonded to an electrically thick quartz carrier. A 200 GHz prototype laboratory receiver using a similar mixer configuration has already been completed and the measured mixer noise and conversion loss are below that of the best reported whisker contacted or planar diode mixers using the subharmonic pump arrangement at this frequency. In addition, the required local oscillator power was as low as 3 mW for the unbiased diode pair and significant LO noise suppression was observed.

EFFICIENCY OF SINGLE BARRIER VARACTORS FOR SUBMILLIMETER WAVE POWER GENERATION

S. M. Nilsen, H. Grönqvist, H. Hjelmgren, A. Rydberg, E. Kollberg
The Millimeter Wave Group
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High efficiency submillimeter wave multipliers can be designed from single barrier varactor (SBV) diodes, typically a mesa diode made from n^{++}-GaAs/200nm n-GaAs/20nm $Al_xGa_{1-x}As$/200nm n-GaAs/n^{++}-GaAs. The diode is contacted via an ohmic contact at both ends. Experiments have shown that the diode is capable of an efficiency equal to or better than the best Schottky varactor diodes .

This contribution addresses the design of the device for maximum efficiency. To asses experimental diodes, properties such as the IV-, and CV characteristics can easily be measured at DC and microwave frequencies, while multiplier characteristics can only be evaluated in a more complicated experiment for which an optimized waveguide structure must be designed and fabricated.

A low series resistance is an important factor for high efficiency. Although GaAs diodes have shown excellent efficiency, diodes based on InAs should be much better due to the higher mobility. We have designed several diodes based on GaAs, InGaAs and InAs. For the GaAs based diode we use a barrier of AlGaAs, in the InGaAs based diode we use AlInAs as a barrier. The latter diode is grown lattice matched on an InP substrate. For the InAs based diodes we use an AlSb barrier which gives a very high barrier. It should therefore be very efficient in blocking the current through the varactor. This device is grown on a GaAs substrate with a thick buffer layer. Current vs. voltage characteristics have been measured on large area diodes for all our materials and compared with theory.

Modelling multiplier efficiency shows that for a particular series resistance (R_s) and minimum capacitance (C_{min}) there is a maximum in the efficiency for a certain maximum capacitance C_{max}. We will point out some design rules where power handling, current saturation and the implication of the series resistance is taken into account.

Accurate modelling of experimental SBV multipliers for various epilayer designs is carried out in two steps. First, the semiconductor transport equations are solved simultaneously using a finite difference scheme in one dimension. Secondly, the calculated IV-, and CV characteristics are used as the input to a multiplier simulator which calculates the optimum impedances, and output powers at the frequencies of interest. Multiple barrier varactors are also modelled in this way.

A PLANAR SIS RECEIVER FOR ARRAY APPLICATIONS

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The quasiparticle superconductor-insulator-superconductor (SIS) mixer is the lowest noise detector in the millimeter-wave region and forms the basis of most high quality receivers for millimeter-wave astronomy. Conventional SIS receivers are of a waveguide block design, but quasi-optical devices with planar circuit mixers are an attractive approach for constructing array receivers. They suffer the disadvantage of being fixed tuned but provide the advantage of convenient monolithic fabrication.

We have constructed a novel planar, quasi-optical SIS receiver operating at 230 GHz which is suitable for array applications. The receiver consists of a 2×5 array of half wave dipole antennas with ten $0.7 \times 0.7\,\mu$m niobium–aluminum oxide–niobium SIS junctions fabricated on a 10 mil thick quartz wafer. The wafer is placed on the front, flat face of a quartz dielectric-filled parabola: a circular paraboloidal lens which is metalized on its curved (rear) surface. The parabola focuses the incoming radiation onto the antennas at the wafer center. The 1–2 GHz intermediate frequency is coupled from the mixer via coplanar strip transmission lines. An amplifier chain with a gain of 90 dB and a noise temperature of 6 K amplifies the IF before removal from the 4.2 K liquid helium immersion cryostat. The receiver noise temperature is measured using 77 and 4 K loads using the Y-factor method. The mixer noise temperature and conversion loss are extracted using a variable temperature IF blackbody load, which allows accurate calibration of the IF system. The mixer output reflection coefficient is measured directly by injecting a signal through a directional coupler.

The performance of single elements in the array was measured across the IF band at an LO frequency of 230 GHz. The best results were obtained at 1.2 GHz, where a mixer noise temperature of 148 K DSB, a receiver noise temperature of 259 K DSB and conversion losses of 10 dB (into a matched load) were obtained. The IF mismatch is approximately 2 dB. The mixer noise temperature and conversion loss are essentially constant across the IF band. The receiver noise temperature follows the noise behavior of the IF amplifier, rising substantially at the band edges. These noise temperature results are approximately a factor of 3 worse than those obtainable from the best waveguide mixers at this frequency which is encouraging. The conversion loss however, is considerably poorer, but expected, given the lack of tuning.

Radiating Slot-Line Resonators for SIMMWIC Transmitters

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Planar slot line resonators are of interest for applications in SIMMWIC (Silicon Millimeter Wave Integrated Circuits) transmitters since the function of resonator and antenna may be included in one structure. (J. Buechler, K.M. Strohm, J.F. Luy, T. Goeller, S. Sattler, P. Russer, "Coplanar Monolithic Silicon IMPATT Transmitter", European Microwave Conference, 1991) Slot lines are either characterized as dispersive and lossy transmission lines or as radiating antennas. (T. Itoh, R. Mittra, "Dispersion characteristics of slotlines", Electronics Letters, Vol.7, pp 364-365, 1971). We have investigated half-wavelength slot line resonators short circuited on both ends. These resonators have to optimized for center point mounting of low impedance IMPATT diodes as the active devices. We used scaled structures to handle with reasonable structure dimensions. Two different substrate materials were chosen, 25 mil RT-Duroid with an ϵ_r of 10.6 which is very close to the dielectric constant of high resistive silicon (ϵ_r =11.7) and 400 micrometer thick silicon. Since silicon millimeter wave integrated circuits usually are on substrates with a thickness of 100 micrometers we achieved two different scale factors namely 6.35 and 4 respectively. The calculated unscaled resonance frequency was 107 GHz. The substrate did not have a ground metallization on the back side. The radiated power was transmitted through the dielectric side of the substrate. The coupling of the slot line resonator to the coaxial port of a network analyser was done by using a coax to slot line transition. To comply with the small dimensions of the slot line structures we used a very thin semirigid cable. The slot width at the coupling point is about 90 microns in the downscaled case. For the first series resonance which will be used as the frequency determining resonance in conjunction with an IMPATT-diode the input impedance is figured with its real and imaginary part. Bias-lines contribute with additional resonances and a shift to lower resonance frequencies.

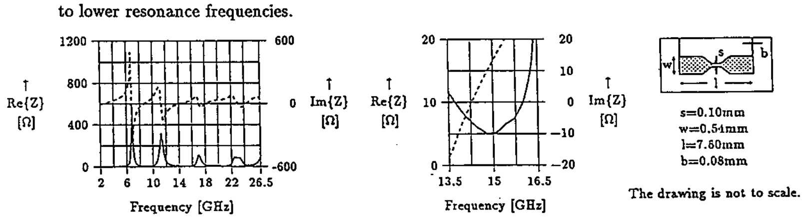

Figure 1: Scale-factor 6.35 on RT-Duroid, with bias-slots. Re{Z} — , Im{Z} - - - f_{res} = 90.5 GHz

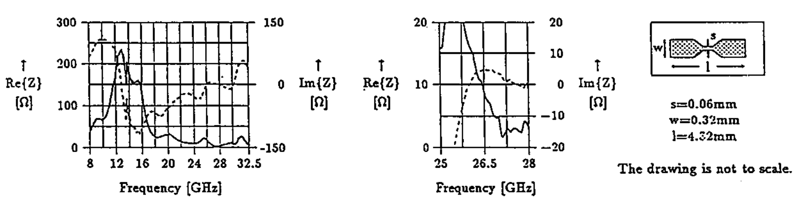

Figure 2: Scale-factor 4 on silicon. Re{Z} — , Im{Z} - - - f_{res} = 106 GHz

6-ELEMENT PERIODIC and NONPERIODIC LINEAR ARRAYS for QUASI-OPTICAL SPATIAL POWER COMBINER

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This paper describes quasi-optical spatial power combiners using 6 series slot radiators in a H-plane and 6 negative resistance oscillators. Two kinds of circuits are reported; one has a periodic structure and the other has a nonperiodic structure. The slots are embedded in the ground plane of the oscillator circuit in order to utilize the both sides of a substrate. The FET oscillators operated around 16.5 GHz are strongly coupled through a microstrip line. The structure can be scaled for use at much higher frequencies.

The circuit configuration with slots on the back side of the substrate is shown in Fig. 1. Each oscillator directly connected through a microstrip line with λ/4 impedance transformers generates an RF energy used for the locking signal to the adjacent oscillators and for the radiation through slot. In order to provide the slot with RF energy effectively, a λ/4 open-end circuit is adopted as a microstrip and slot line transition.

The center positions of the slots of one circuit are periodic. Since the feed lines from the oscillators are located at the centers of the slots in the other side of the substrate, the positions of the oscillators are also periodic. The distance between the two centers is 1λ. On the other hand, the center positions of the slots of the other circuit are nonperiodic. The increasing rate of the distance between two centers is 2%. Therefore, in this nonperiodic 6-element array, the slot length of the two outer slots is 4% longer than that of the two center slots. Since the oscillator provides the slot with RF energy from the center of the slot, the position of the oscillators are also shifted away with every 2% of the wavelength.

In the experiment of these two arrays, Σ patterns were obtained. The nonperiodic array exhibited a narrower beam width and a wider tuning range (almost double) by changing the applied DC voltages (V_{ds} and V_{gs}) than the periodic array had.

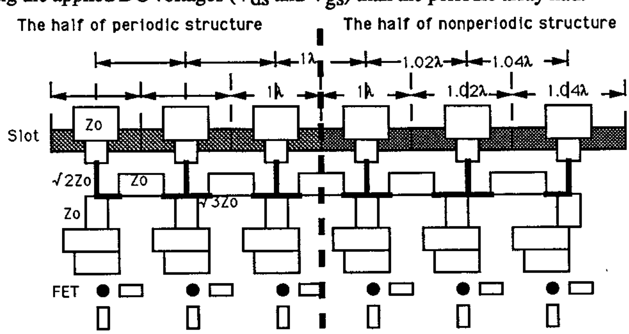

Fig. 1 Quasi-Optical Combiner Circuit Structure

Thursday AM URSI-B Session RA13

Room: Columbus K/L *Time*: 0820-1120

Rough Surface Scattering Theory

Chairs: L. W. Pearson, Clemson University; Gary S. Brown, Virginia Polytechnic Inst. & State Univ.

0820 **MICROWAVE SCATTERING from a RANDOM MEDIUM LAYER with a RANDOM INTERFACE**
Saba Mudaliar*, Rome Laboratory / ERCE

0840 **SCATTERING of a GAUSSIAN BEAM by a PERFECTLY CONDUCTING ROUGH SURFACE**
R. E. Collin*, Case Western Reserve University

0900 **SHADOWING CORRECTIONS for SCATTERING from NATURAL SURFACES**
E. Rodriguez*, Y. Kim, Jet Propulsion Laboratory

0920 **NUMERICAL EVALUATION of ROUGH SURFACE SCATTERING at NEAR GRAZING INCIDENCE**
Y. Kim*, E. Rodriguez, S. H. Lou, Jet Propulsion Laboratory

0940 **ROUGH SURFACE SCATTERING, INTEGRAL EQUATIONS, and the COMPOSITE SURFACE SCATTERING MODEL**
Gary S. Brown*, Virginia Polytechnic Inst. & State Univ.

1000 **Break**

1020 **SCATTERING from CYLINDERS with a PERIODICALLY CORRUGATED PERIPHERY USING a CURRENT-MODEL TECHNIQUE**
Amir Boag*, Yehuda Leviatan, Alona Boag, Technion-Israel Institute of Technology

1040 **BACKSCATTERING of the ELECTROMAGNETIC MISSILE on the ROUGH SURFACE**
Yi-Jun He*, Quan-Rang Yang, Southeast University Nanjing

1100 **A NEW SMALL PERTURBATION TECHNIQUE for the PROBLEM of SCATTERING from SIMPLE and COMPOSITE RANDOM SURFACES**
Ming-quan Bao*, Chang-bao Zhou, Second Institute of Oceanography

MICROWAVE SCATTERING FROM A RANDOM MEDIUM LAYER WITH A RANDOM INTERFACE

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In the field of wave propagation and scattering from layered media a problem of great practical interest and importance is the one where both medium parameters and interfaces have random fluctuations. Many natural objects are best represented and studied by this kind of a model. Not many works are reported in the literature on this topic.

In this paper we consider a layer of random medium sandwiched between two homogeneous media. The bottom interface of the random medium layer is planar while the top interface is randomly rough.

For a plane electromagnetic wave incident on this layer from above we are interested in the far-zone scattered field. The object is to seek a perturbation solution based on the assumption that the random fluctuations associated with the medium and the interface are small.

We first consider the situation where the boundary is unperturbed and obtain a first-order solution to the scattered field. This constitutes the first part of the solution. In the second part the actual boundary condition on the rough surface is replaced by an approximate boundary condition on the mean surface and the first-order scattered field is obtained as a surface integral. In both cases the unperturbed Green's function for the planar layered structure is used.

We next proceed to evaluate the bistatic scattering coefficients. These are calculated analytically and expressed in a compact and meaningful form. Using schematic scattering diagrams the various terms that constitute the scattering coefficients are identified. These terms may be grouped as surface scattering, volume scattering and volume-surface scattering. The special situation of backscattering is considered in some detail. On comparing our results with those in the literature we find that they are in agreement. Physically our first-order solution represents the single scattering case. However the present framework may be extended to study the more difficult case of multiple scattering.

SCATTERING OF A GAUSSIAN BEAM BY A PERFECTLY CONDUCTING ROUGH SURFACE

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In numerical calculations of scattering from a rough surface it is common practice to use a tapered field for the illumination in order to limit the area of the rough surface from which significant scattering occurs. In this paper we develop a full wave theory for the scattering of a gaussian beam by a perfectly conducting rough surface.

The incident field is assumed to be produced by a large aperture antenna having a gaussian electric field amplitude distribution. The field from this antenna is expressed as a specturm of incident plane waves. The full wave theory described previously by the author (Radio Sci. Meeting Abstracts, p224, London, Ont. 1991) is used to determine the scattered field for each incident plane wave. The total scattered field is synthesized by integrating over the spectrum of incident plane waves.

The theory developed will show that the total scattered field consists of a specular reflected gaussian beam with a local phase correction plus an additional scattered field that is given by an integral which has the same scattering coefficient and other factors as occurs for an incident plane wave but which also includes a gaussian tapered illumination function. It is also shown that the small perturbation results are only obtained when the integrated term, that results from integration by parts to eliminate the explicit dependence on the surface slopes, is retained.

SHADOWING CORRECTIONS FOR SCATTERING FROM NATURAL SURFACES

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California Institute Technology
Pasadena, CA 91109

To compensate for shadowing effects as the incidence angle approaches grazing, it has been the practice in the literature to introduce the ad hoc assumption that a shadowing correction based on geometrical optics may be applied. Two types of shadowing corrections may be considered: monostatic or bistatic shadowing. In monostatic shadowing, it is assumed that the surface current may be set to zero in all the areas where the incident field suffers from geometrical shadowing. In bistatic shadowing, one sets the current to zero in areas which are not visible in the bistatic scattering direction.

In this work, we test the validity of these shadowing approximations for surfaces whose height spectrum is a power law. We compute the current numerically using the method of moments and calculate the bistatic cross section. This current correctly includes all diffractive effects of shadowing. Next, we set the current to zero in all geometrically shadowed regions and again calculate the approximate bistatic cross section. By comparing the scattering cross sections, we show that the standard shadowing approximations are grossly inaccurate for natural surfaces, and the bistatic cross section is more inaccurate than the monostatic cross section.

As a better shadowing correction, we introduce the concept of a two-scale shadow: we seek to shadow only areas that are in deep shadows, not in regions where diffractive effects are important. To implement this idea, we shadow areas that are in the geometrical shadow of a smoothed surface. We show that by appropriately selecting the filtering cutoff, only minimal errors are produced in the bistatic cross section. We explore the selection of the two-scale separation as a function of surface height and slope.

Finally, we show how the two scale approximation may be incorporated in analytic scattering theories to significantly improve the prediction for the bistatic scattering cross section.

The research described in this abstract was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by Office of Naval Research through an agreement with the National Aeronautics and Space Administration.

NUMERICAL EVALUATION OF ROUGH SURFACE SCATTERING AT NEAR GRAZING INCIDENCE

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Several numerical techniques have been applied to rough surface scattering even though surface height variations are limited to one dimension. The most popular method has been MOM (Method of Moments). Recently, FEM (Finite Element Method) has been successfully utilized for the evaluation of rough surface scattering cross sections (S. H. Lou et al., JEWA Vol. 5, No. 8, 835-855, 1991). The results from both methods have been compared statistically for modest incidence angles. In this presentation, we compare these two techniques for near grazing incidence. Especially, the comparisons will be made in both deterministic and statistical ways. Here, we consider ocean-like surfaces which exhibit height power law spectra.

For MOM, the edge current is induced due to the finite size of the simulated scattering surface. Hence, this edge current must be removed to evaluate the scattering cross section, which is defined for an infinite surface. It is well known that the edge current can be suppressed by synthesizing an antenna pattern on the surface patch. Hence, a larger surface patch is desirable in order to obtain the scattered fields with correct statistics. We will address the requirements on the surface length, tapering, and sampling distance for near grazing incidence.

For FEM, the periodic boundary condition is utilized to apply the method to a surface with finite length. In this way, the edge current can be avoided automatically. Since it is possible to add the antenna pattern effects to FEM results using the method by Jordan and Lang (A.K. Jordan & R.H. Lang, Radio Sci. 14, 1077-1088, 1979), the scattering cross sections evaluated using both methods can be compared deterministically. It is noticed that the accuracy of FEM is not significantly affected by the scattering patch length unlike MOM. Based on these numerical results, we examine the scattering mechanism when the incidence angle approaches grazing.

The research described in this abstract was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by Office of Naval Research through an agreement with the National Aeronautics and Space Administration.

ROUGH SURFACE SCATTERING, INTEGRAL EQUATIONS, AND THE COMPOSITE SURFACE SCATTERING MODEL

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One of the most successful models for scattering of electromagnetic waves from rough surfaces is the so-called composite surface model in which the surface comprises small amplitude height perturbations are superimposed on top of a large, gently undulating height structure. The terms large and small are taken to be relative to the electromagnetic wavelength. The scattering from such a rough random surface is due to quasi-optical like reflection form the gently undulating substructure and the Bragg-like resonant scattering from the small height perturbations. The only effect of the large scale height substructure on the small scale scattering is to provide a tilt to the small scale scattering surface. This gives rise to a smearing of the Bragg wavenumber to a range of wavenumbers.

This composite surface scattering model exhibits a great deal of physical appeal in that it takes two asymptotic solutions and shows how they should be "patched" together to provide the total angular scattering model. Unfortunately, it is very difficult to derive this model using first principles scattering theories. The purpose of this paper is to show how such a derivation can proceed when starting from the integral equation for the current on the rough surface.

We start with the magnetic field integral equation for the current induced on a perfectly conducting surface that has both large and small scales of roughness perturbing the interface. Because of the large scale height, it would seem that we should be able to solve this integral equation by iteration and stationary phase asymptotics. That is, for each iteration we evaluate the integral by means of stationary phase since the height is large compared to a wavelength. However, we must remember that in the stationary phase approach it is assumed that the surface contains features which are large compared to the em wavelength. When the integration point is far from the point of observation, this restriction need not be enforced because of the dominance of the usual stationary phase effects (which lead to shadowing and multiple ray bounce). However, when the point of observation and the point of integration are close to each other, we cannot neglect the effects of the small scale structure because it is much more dominant in its effect than the stationary phase part (which is negligable in the vicinity of this point). Thus, we must split the range of the integral into two regions; one which is in the immediate neighborhood of the point of observation and one which includes all the rest of the surface. It will be shown that it it this split that leads to the composite surface scattering model. The small scale contribution comes from the small neighborhood while the shadowing comes from the remaining neighborhood.

SCATTERING FROM CYLINDERS WITH A PERIODICALLY CORRUGATED PERIPHERY USING A CURRENT-MODEL TECHNIQUE

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A current-model technique is presented for a complete analysis of electromagnetic scattering of a time-harmonic plane wave from a cylinder whose periphery is corrugated in a periodic fashion. In this technique, the scattering problem is formulated not in terms of equivalent surface current distributions applying standard formulations, but in terms of off-boundary located fictitious sources. As discussed below, this kind of approach offers a few attractive features.

In applying the current-model technique to the problem of scattering from a periodically corrugated dielectric cylinder, we simulate an equivalence for each one of the two homogeneous regions involved. One equivalence is for the free space region exterior to the cylinder while the other equivalence is for the interior of the cylinder. In each equivalence, the respective region is considered along with a complementary region of identical constitutive parameters. In turn the field in that region is approximated by means of a linear combination of fields due to a set of fictitious rotationally-periodic sources located outside the region. With an adjustable amplitude, each rotationally-periodic source consists of a group of strips of electric current properly modulated and distributed periodically on a circular mathematical surface concentric with the physical one. The radii of the various circular mathematical surfaces defining the locations of the rotationally-periodic sources involved are in general different. The groups of current-strips comprising the various rotationally-periodic sources are axially directed and curved to coincide with the respective mathematical surfaces defining their location. The current-strips are all characterized by a common Fourier-transformable electric current density profile. The field produced by each such a periodic source can be represented by a uniformly convergent series of cylindrical Floquet modes with analytically known coefficients. Furthermore, the expansion of the far-zone scattered field in terms of cylindrical Floquet modes, known as the space-harmonic representation for the scattered field, is analytically expressible in terms of the amplitudes of the sources. The ability to express these fields analytically is very useful as one can avoid the computationally intensive surface integrations when evaluating the fields. It may also be noted that since the sources are at some distance away from the boundary surface, their fields constitute a basis of smooth field functions on the boundary. In addition to the formation of a smooth field, the freedom in the choice of source locations also permits fitting of the actual fields on the boundary as per requirement. Finally, since we are using, though indirectly, a basis of field functions smooth on the boundary, the simulated fields can be forced to obey the continuity conditions in some simple sense. Here, the solution is effected by adjusting the amplitudes of the fictitious sources for the continuity conditions at a discrete set of points on the cylinder boundary. Once the desired source amplitudes are found, approximate values for the fields everywhere can be readily obtained by simple summations.

The suggested procedure is simple to implement. It has been applied to sinusoidally-corrugated cylinders, but it is by no means restricted to this special case. Perfectly conducting corrugated cylinders have also been treated within the general procedure as a reduced case. The convergence behavior and accuracy of the procedure have been studied. The procedure has been found to be efficient and the results have been shown to satisfy the boundary condition check within a very low error.

Backscattering of The Electromagnetic Missile On The Rough Surface

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State Key Laboratory of Millimeter waves
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Southeast University, Nanjing,210018,P.R.China

ABSTRACT

Up to now, there are many electromagnetic missile(EMM) lunachers that have been proposed and some backscatterings of EMM that have been studied. The backscattering of an EMM with an energy decreasing as $r^{-\epsilon}$ by a perfactly conducting plate has been studied and the analysis shows that the energy backscattered varies $r^{-\epsilon}$ with the same exponent as the incident EMM The backscatterings of EMM with energydecreasing as $r^{-\epsilon}$ by perfectly conducting circular cylinder , elliptical cylinder and sphere are studied The scattering of an EMM on the rough surface is left as an open question. In this paper, the backscattering of an EMM with energy decreasing as $r^{-\epsilon}$ by a perfactly conducting rough surface is studied.

We consider the Fourir transform of a transmitting current $\overline{J}(r,t)$ given by

$$\overline{J}_\omega(r) = \begin{cases} \hat{y} f(\omega)\delta(z - z_0) & x_0 - b/2 < x < x_0 + b/2 \\ 0 & otherwise \end{cases}$$

For a fast-rising puls, We can let $f(\omega) = \omega^{-(1+\epsilon)/2}$. We finally obtain that the EM pulse radiated by the current $\overline{J}(r,t)$ is an EMM whose energy decreases as $r^{-\epsilon}$, slower than r^{-1} .

If the high of the rough surface is normally distributed with the mean value $< \zeta >= 0.$, and the standard deviation σ $< exp(iv_z\zeta) >$ is given by the well-known characteristic function $\chi(v_z)$. We finally obtain that the mean backscattering power decreases as $r^{-\epsilon}$, which is the same as that for plate scattering.

A NEW SMALL PERTURBATION TECHNIQUE FOR THE PROBLEM OF SCATTERING FROM SIMPLE AND COMPOSITE RANDOM SURFACES

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P.R.C.

A new small perturbation technique is proposed in this paper, which consists of the following aspects: (1) Random integral equation of the surface source density is solved by an asymptotic method which uses Neumann series. Different order small-perturbation solutions to the equation can be obtained directly and conveniently. (2) The multivariate characteristic function of random variables and its partial derivatives are applied to SPM to evaluate coherent and incoherent scattering intensity in terms of the surface source density. The results of this method is more accurate than those of conventional SPM, especially when the roughness of surface is large. (3) Pade approximants is used to improve the convergence of small perturbation solution.

This algorithm extends the domain of validity of SPM, which can be applied to the case when the assumptions involved in the classical models are not satisfied, and when rms surface height is not small relative to radiation wavelength and reaches the partial domain of validity of Kirchhoff simulation and two-scale model. Coherent intensity and backscattering coefficient obtained by this algorithm agree with those obtained by numerical method which are taken as standard of comparison.

Thursday PM URSI-B E, NEM Session RP02

Room: Grand B *Time*: 1320-1700

High Power Microwaves

Organizer: D. Giri, PROTECH

Chairs: D. Giri, PROTECH; Albert W. Biggs, The University of Alabama at Huntsville

1320 **GENERAL CONSIDERATIONS in SPECIAL HPM**
Carl E. Baum*, Phillips Laboratory

1340 **TRENDS and BOUNDS in RF COUPLING to a WIRE INSIDE a SLOTTED CAVITY**
K. S. H. Lee*, F. C. Yang, Kaman Sciences Corporation

1400 **TIME-DOMAIN ELECTROMAGNETIC PENETRATION THROUGH ARBITRARILY SHAPED NARROW SLOTS IN CONDUCTING SCREENS**
Erik K. Reed*, KEMET Electronics Corp.; Chalmers M. Butler, Clemson University

1420 **CALCULATION of APERTURE COUPLING by MEANS of the ELECTRIC FIELD INTEGRAL EQUATION (EFIE)**
C. D. de Haan*, TNO Physics and Electronics Laboratory

1440 **CALCULATION of the BANDWIDTH BROADENING of HIGH-POWER MICROWAVE PULSES by AIR BREAKDOWN in a RECTANGULAR WAVEGUIDE**
D. J. Mayhall*, J. H. Yee, R. A. Alvarez, Lawrence Livermore National Lab

1500 **Break**

1520 **ANTENNA CONCEPTS for HIGH POWER MICROWAVE APPLICATIONS: SYNTHESIS, ANALYSIS and DESIGN ISSUES**
Y. Rahmat-Samii*, Dah-Weih Duan, University of California, Los Angeles; L. F. Libelo, Harry Diamond Laboratories; D. Giri, PROTECH

1540 **ANALYTICAL and EXPERIMENTAL STUDIES of a MAGNETICALLY INSULATED TRANSMISSION LINE OSCILLATOR**
Albert W. Biggs*, The University of Alabama at Huntsville

1600 **HIGH POWER NONRESONANT VIRTUAL CATHODE OSCILLATOR**
C. Leibovitz, A. Rosenberg, B. Mandelbaum, J. Shiloh*, RAFAEL

1620 **PHASE-LOCKING of STRONGLY COUPLED RELATIVISTIC MAGNETRONS**
H. Sze*, R. R. Smith, J. Benford, B. Harteneck, Physics International Company

1640 **ON the USE of the HILBERT TRANSFORM for PROCESSING MEASURED CW DATA**
Frederick M. Tesche*, Electromagnetics Consultant

GENERAL CONSIDERATIONS IN SPECIAL HPM

Carl E. Baum
Phillips Laboratory, Kirtland AFB, NM 87117-6008

In the evolution of EMP technology we have reached the point where people are considering how to produce similar effects by more conventional means and how to protect against such threats. This is the subject of special high-power microwaves (HPM). While, as a practical matter, we can consider the traditional type of EMP waveform as given, it is by no means an optimum waveform for interaction with electronic systems and producing EMP-like upsets and failures. This allows one to design a waveform which more efficiently interacts with the system via an appropriate transfer function resonance, i.e., an approximate sinusoid in the microwave region.

In designing such a special HPM device one must consider the overall problem from source to signal at the failure port of interest in the electronic system. This can be handled by considering each term in a product of transfer functions. For the source we need to characterize the power as a function of frequency which can be delivered into the lowest order mode $H_{1,0}$ of a standard rectangular waveguide (the useful power). This can be cast in the form of an effective voltage which in general is a decreasing function of frequency. This power is fed to a special reflector antenna which gives a transfer function to the far electric field which is an increasing function of frequency and is proportional to the aperture area of the reflector. For locations near the earth surface there is a breakdown field limitation in the MV/m range. Staying below this field will simplify the propagation (approximately no attenuation). At higher altitudes this attenuation consideration is more severe. Interaction with the system is a complex item, but a canonical response for unintentional interaction paths (back door) can be developed into low-frequency (differentiation), resonant-region, and high-frequency (integration) regimes. In this case the overall performance is optimized with a frequency chosen near the top of the resonance regime, or roughly a GHz. The pulse width should be on the order of a hundred cycles so that an appropriate system response can be rung up to get maximum internal response.

TRENDS AND BOUNDS IN RF COUPLING TO A WIRE INSIDE A SLOTTED CAVITY

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ABSTRACT

This paper considers how to bound the power picked up by a wire inside a cavity with a slot in its wall. The consideration is based on equivalent circuits and power conservation, and is general enough for applications to real-world systems. The calculations compare favorably with measurement data.

Recently some progress has been made on calculating the bounds of RF coupling to the interior of a system. The bounds are on the coupling cross section σ and the integral of it over all wavelengths, namely

$$\int_0^\infty \sigma d\lambda \le \pi^2 V(P_{11} + M_{22}) \tag{1}$$

Eq.(1) is useful in two ways. It bounds the behavior of σ at low and high frequencies. It can also be utilized to obtain some upperbound energy that an incident electromagnetic wave can penetrate into the interior of a system, given the geometries and the distribution of its POEs. Warne and Chen have skillfully applied (1) to bound EMP coupling problems (EMC Vol. 32, No. 3. pp. 217-221, August 1990). Noticing that the left-hand side of (1) is proportional to the total absorbed energy for a step function incident plane wave, they have shown that

$$2\int_0^\infty \sigma\, S_{inc}\, df \le \frac{1}{2}\mathbf{E}_o \cdot \mathbf{p} + \frac{1}{2}\mathbf{H}_o \cdot \mathbf{m} \tag{2}$$

The left-hand side is the energy absorption, and the right-hand side is the total energy stored in the induced electric and magnetic dipoles **p** and **m**. Making use of (2), one can also write down the exact solution to the boundary-value problem of calculating the total energy (Wt) transmitted by a step-function plane wave, $\mathbf{E}_{inc} = \mathbf{E}_o\, u(t - x/c)$, through an aperture in an infinite, perfectly conducting ground plane. The solution is

$$W_t = \mu_o\, \mathbf{H}_o \cdot \boldsymbol{\alpha}_m \cdot \mathbf{H}_o - \varepsilon_o\, \mathbf{E}_o \cdot \boldsymbol{\alpha}_e \cdot \mathbf{E}_o \tag{3}$$

where $\boldsymbol{\alpha}_e$ and $\boldsymbol{\alpha}_m$ are the electric and magnetic polarizability tensors of the aperture.

TIME-DOMAIN ELECTROMAGNETIC PENETRATION THROUGH ARBITRARILY SHAPED NARROW SLOTS IN CONDUCTING SCREENS

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A time-domain integral equation is presented that governs the unknown electric field, or equivalent magnetic surface current, in an aperture of general shape in a planar conducting surface of infinite extent. The equation is specialized to the case that the aperture is a narrow slot of arbitrary contour. An efficient and stable "marching in time" numerical method is developed for solving the general slot equation. From knowledge of the slot magnetic current, the shadow-side electric field that penetrates the slotted screen is computed. The solutions for magnetic current and shadow-side field are compared via Fourier transformation with those obtained by solving the corresponding time-harmonic integral equation. Results are further validated by demonstrating close correlation between values of the calculated field on the shadow side of the conductor and data derived from laboratory measurements. For numerous slot lengths and shapes, time- and frequency-domain data illustrating the behavior of the slot field and penetrated field are presented and compared with measured results. The general features of the computed and measured magnetic currents and fields are explained and are related to practical questions that may arise in shielding applications.

The stability of the time-domain solution technique is investigated and found to be very high. This is demonstrated by observing the data decay "naturally" to a small fraction of a percent of peak values and then on to "0" after several thousand time steps, without evidence of the usual behavior associated with instability. The steps taken to achieve such stability are discussed.

The apparatus and methods employed to measure shadow-side electric field are described, including a brief outline of the calibration procedure.

The responses of a slot to an EMP-type pulse and to a Gaussian pulse are presented as examples.

CALCULATION OF APERTURE COUPLING BY MEANS OF THE ELECTRIC FIELD INTEGRAL EQUATION (EFIE)

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Energy associated with electromagnetic (EM) radiation can penetrate into a metallic structure such as an aircraft, missile or a system connected with cables. The unintentional coupling of RF energy through apertures (back door coupling), such as windows, wheel bays and imperfections of the walls can have disruptive or damaging effects on a variety of electrical or electronic systems inside the enclosure.

An electric field integral equation (EFIE) computer program based on the Method of Moments is used to calculate the EM coupling of apertures in perfectly conducting bodies. The EFIE program calculates the EM-scattering by arbitrarily shaped objects. The program computes the induced surface current distribution and the electric or magnetic fields surrounding the body. The EFIE formulation is applicable to both open and closed surfaces, and is often used for RCS prediction techniques.

In this presentation a cylinder is modelled as a surface patch model. Rectangular and circular apertures were placed in the front and back surface of the cylinder. The dimensions of the apertures can be extended to a few wavelengths of the incident field. The results for several body configurations will be presented.

CALCULATION OF THE BANDWIDTH BROADENING OF HIGH-POWER MICROWAVE PULSES BY AIR BREAKDOWN IN A RECTANGULAR WAVEGUIDE

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Wideband, high-power microwave pulses are expected to have a number of important future applications. One convenient way to generate such pulses with fairly conventional, presently existing technology is to erode the tails of short (3–10 ns), high-amplitude (>0.5 MV/m) pulses in a low-pressure air cell. The pressure should be matched to the incident pulse characteristics so that sufficient air breakdown occurs to cause severe tail erosion. This erosion shortens the pulses and thereby broadens the bandwidths.

We have experimentally demonstrated that such tail erosion broadens the 3 dB bandwidths of 8 ns, 0.67–1.16 MV/m, 2.8608 GHz pulses in a WR-284 rectangular waveguide at the air pressure of 3.5 torr. Preionization from a ^{60}Co gamma source generated a localized background electron population, which ensured reproducible air breakdown from the incident pulses. The bandwidth was broadened from 0.147 GHz by 0.0097–0.039 GHz (0.34–1.4% relative to the incident carrier frequency). This broadening was simulated with a two-dimensional, electromagnetic, finite difference, electron fluid code, predicting broadening by 0.029–0.13 GHz (1.0–4.4%).

The code also predicts the bandwidth broadening of idealized incident pulses with an 0.5 ns linear rise and a 3.0 ns linear fall. These pulses enter a rectangular waveguide cell at 3.5 torr, containing a spatially Gaussian background electron distribution with an axial FWHM of 3 cm. The transverse FWHM in the waveguide "a" direction and the peak electron density are variable. The incident bandwidth is 0.342 GHz (12%). Calculations are performed for incident amplitudes of 1–18 MV/m, peak electron densities of $10–10^{11}$ cm^{-3}, and transverse FWHMs of 3 and 10^4 cm. The transmitted bandwidth varies from 0.352–3.214 GHz (12.3–112%), the transmitted center frequency varies from 2.87–4.72 GHz, and the transmitted amplitude varies from 1.10–12.7 MV/m at 54.6 cm from the cell input port. Because of the linearity of the empty waveguide, the transmitted bandwidth will remain constant with propagation down the waveguide. The transmitted amplitude will vary with axial position as the spectral components rearrange themselves due to dispersion. For a peak density of 10^9 electrons/cm^3, the amplitude at 54.6 cm from the input varies from 0.617–2.06 MV/m; whereas, that at 69.8 cm varies from 0.581–2.05 MV/m. For several values of incident amplitude, the amplitude at 69.8 cm exceeds that at 54.6 cm.

Air breakdown at low pressure should afford a promising, convenient method for generation of wideband, high-power microwave pulses with presently existing technology. The electron fluid code should provide a unique capability for investigation and design.

ANTENNA CONCEPTS FOR HIGH POWER MICROWAVE APPLICATIONS: SYNTHESIS, ANALYSIS AND DESIGN ISSUES

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There has been considerable amount of research activities in the areas of the optimum transformation of high power electromagnetics fields to different distances. One of the key elements in the overall system realization is the proper utilization of an optimized radiating antenna. The main task of this radiating antenna is to be able to focus the electromagnetic energy toward particular directions and distances in the most efficient manner.

In this paper, applications of different antenna systems to produce directive High Power Microwave (HPM) radiations are first reviewed. The overall system architecture including reflector antenna configuration, source, waveguide, and feeds is detailed. The key design issues are summarized and novel synthesis/analysis techniques utilizing a newly developed diffraction optimization synthesis technique are discussed. Representative design concepts are presented for an optimized dual shaped reflector antenna system in order to maximize the antenna performance for a 7-element feed array considering the air breakdown issues. Representative results will also be shown for the transient behavior of the radiated field.

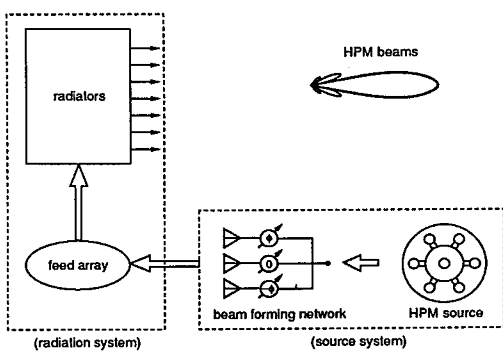

Figure 1: Basic functional units of an HPM antenna system.

ANALYTICAL AND EXPERIMENTAL STUDIES OF A MAGNETICALLY INSULATED TRANSMISSION LINE OSCILLATOR

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ABSTRACT

The magnetically insulated transmission line oscillator (MILO) is a coaxial transmission line (CTL) whose outer anode conductor is a set of periodically spaced corrugations, or cavities, aligned parallel to the axis of the center conductor, or cathode, axis. The slow wave structure are rectangular teeth with gap width B (1) = 0.7 cm, depth L (1) = 1.8 cm, period D (1) = 1.4 cm, cathode radius R (I) = 6.5 cm, and anode radius R(O) = 8.5 cm.

Anode corrugations or radial cavities allow the CTL to generate electromagnetic waves which propagate axially with phase velocities less than the velocity of light. These "slow waves" are like those in traveling wave tubes. The slow waves have phase velocities which increase to those of light as the serrations become shallower and wider, becoming smooth coaxial conductors when the antenna is reached.

High power microwave generation in MILO is achieved when operated as a magnetically insulated transmission line ([1] Raymond Lemke and Collins Clark, "Theory and simulation of high-power microwave generation in a MILO," J. Applied Physics, Vol. 62, pp. 3436-3440, 15 Oct. 1987). The applied voltage between electrodes is high enough to create field-emission-induced plasma at the cathode. Electron flow from cathode to anode is radial because of the high radial electrical field, but the magnetic field created by the power flow insulates the cathode by preventing electrons emitted by the cathode from reaching the anode ([2] Marco Di Capua, "Magnetic insulation," IEEE Trans. Plas. Sci., vol. PS-11, pp. 205-215, Sept. 1983). Electron trajectories are like those in magnetrons.

Magnetic insulation also assumes conductive paths at the ends of electrodes to allow electron current to flow from anode to cathode to complete the circuit.

The insulated electron flow (see [2] above) in the anode-cathode gap interacts with slow, transverse waves generated in the periodic rectangular corrugated CTL. With each cavity a shorted radial transmission line ([3] Leon Brillouin, "Wave guides for slow waves," J. Appl. Phys., Vol. 19, pp. 1023-1041, Nov. 1948).

HIGH POWER NONRESONANT VIRTUAL CATHODE OSCILLATOR

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Virtual Cathode Oscillators (Vircator) have been demonstrated to emit short pulses of very high power microwaves, ranged up to several gigawatts. The mechanism for the emission of the radiation has been attributed to both space and time oscillation of the virtual cathode and the oscillation of electrons in the potential well between the real and virtual cathodes (reflexing electrons). Vircators are also known to emit a wide band spectrum. Narrow band spectrum in Vircators can be achieved by a resonant cavity structure. Operation of Vircators is characterized by a single pulse of relatively low efficiency. However, its high power and relative simplicity makes the Vircator a useful source in HPM laboratories, for the study of HPM coupling to various systems.

In this paper we present detailed studies of a nonresonant Virtual Cathode Oscillator with extremely narrow band spectrum, which is an inherent property of the source. The device will be described along with measurements of the relevant parameters. The measurements were carried out in the S-band using a mildly relativistic electron beam with currents close to the critical current for pinching condition (0.5 - 1MV, 30-50 kA and pulse length of 50 nsec). Various techniques were used to measure the power and frequency of the microwave radiation. A high resolution pressurized calorimeter has been developed and used for measurements of the microwave power output. The calorimeter high sensitivity (50mV/J) and excellent signal to noise ratio makes it a very efficient tool for measurements of high power microwave. Maximum output power between 200-300 MW was achieved when the cathode surface design, charge voltage and anode-cathode gap are arranged to simultaneously maximize the diode voltage, satisfy magnetic insulation and avoid nonuniform and unstable electron emission.

Frequency measurements using a heterodyne mixer clearly indicate that the virtual cathode oscillates at a single frequency (~3 GHz) with a narrow bandwidth (<2%). The customary chirping behavior exhibited by a nonresonant Vircator oscillator is absent in these measurements. The central frequency follows roughly the beam plasma frequency and can be perfectly tuned by varying the diode voltage and anode-cathode gap. Microwave-induced gas breakdown indicates clearly that the dominant waveguide mode is TM_{01} mode.

Phase-Locking of Strongly Coupled Relativistic Magnetrons

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Abstract

Phase-locking of two strongly coupled S-band relativistic magnetrons in the gigawatt regime has been achieved. A single high voltage pulser drives the two relativistic magnetrons connected by a short waveguide of length $l \simeq n\lambda/2$. The time required to lock is $\simeq$ 7 ns. Phase-locking lasts for $\simeq$ 15-20 ns. Phase-locking in the π and 2π modes are demonstrated by direct phase measurement. The rms peak power is $\simeq$ 1.6 GW in the π mode and 400 MW in the 2π mode. Power density enhancement due to source coherence is directly measured in the radiation field. Locked phase measurements agree with phenomenological modelling of the experiment using a simple Van der Pol model.

ON THE USE OF THE HILBERT TRANSFORM FOR PROCESSING MEASURED CW DATA

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The Hilbert transform is a commonly used technique for relating the real and imaginary parts of a causal spectral response. It is found in both continuous and discrete forms, and is widely used in circuit analysis, digital signal processing, image reconstruction and remote sensing. One useful application in the area of high power microwave (HPM) technology is in correcting measured continuous wave (CW) transfer function data to insure causality in reconstructed transient responses. Another application of the Hilbert transform is in the area of complex spectral estimation using magnitude-only data.

In this paper, the theoretical basis for the Hilbert transform is briefly reviewed, and the numerical methods used for computing the transforms are discussed. In the evaluation of the Hilbert integral, there is an apparent singularity of the integrand, and this must be treated carefully.

Applications of the transform to several specific problems are then discussed. The so-called minimum phase reconstruction of a complex-valued spectrum using magnitude-only data is a common application of the Hilbert transform. This problem is examined for both real system data and analytically-derived spectral data, and possible errors in the resulting reconstructed transient waveforms are illustrated. It is shown that the minimum phase reconstructed transient waveform can be significantly different from the "real" waveform.

The use of the Hilbert transform for spectral filtering is also discussed. When measuring CW spectral data, or when computing CW responses using a measured transfer function, errors in the measurements can cause the resulting spectrum to correspond to that of a non-causal signal. The Hilbert transform may be used to filter the CW spectrum to insure causality in the reconstructed response. This technique is discussed and illustrated with examples.

Thursday PM URSI-B Session RP07

Room: Columbus A *Time*: 1320-1620

Inverse Scattering

Chairs: A. K. Jordan, Naval Research Laboratory; James R. Wait, Consultant

1320 **LOCAL BACKPROPAGATION and TIME DOMAIN INVERSE SCATTERING USING PULSED BEAMS**
Timor Melamed*, Tel-Aviv University; Ehud Heyman, A. J. Devaney Assoc., Inc.

1340 **ELECTROMAGNETIC PROFILE RECONSTRUCTION USING the RICCATI EQUATION APPROACH**
Jiqing Xia*, Massachusetts Institute of Technology; A. K. Jordan, Naval Research Laboratory; Jin A. Kong, Massachusetts Institute of Technology

1400 **AN INVERSE ELECTROMAGNETIC INDUCTION PROBLEM**
James R. Wait, ; K. A. Nabulsi*, University of Arizona

1420 **MULTI-FREQUENCY INVERSE SCATTERING of MULTIPLE CONDUCTING CYLINDERS**
Gregory P. Otto, W. C. Chew*, University of Illinois, Urbana-Champaign

1440 **INVERSION of 3-D CONDUCTIVITY VARIATIONS VIA a NONLINEAR APPROXIMATION to the SCATTERED ELECTROMAGNETIC FIELDS**
C. Torres-Verdin*, T. M. Habashy, Schlumberger-Doll Research; R. W. Groom, Queen's University

1500 **Break**

1520 **NEARFIELD MICROWAVE IMAGING of BURIED MOISTURE: DIFFRACTION EFFECTS**
J. Roussos, G. Tricoles*, P. Yasuhara, General Dynamics Electronics Division

1540 **A THREE DIMENSIONAL FEM/BEM FORMULATION for ELECTROMAGNETIC PROBLEMS**
R. Andre*, N. Wang, A. Dominek, The Ohio State University

1600 **SOLUTIONS of INVERSE SCATTERING PROBLEMS by MEANS of SMALL-ANGLE SCATTERING DATA**
V. E. Kunitsyn*, Moscow State University

LOCAL BACKPROPAGATION AND TIME DOMAIN INVERSE SCATTERING USING PULSED BEAMS

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Backpropagation and imaging of scattering data is usually performed via Green's functions or plane wave integrals. For ultrawide bandwidth interrogation fields, it is desirable to process the data directly in space-time where the field are well localized. Here, the processing kernels are the time-dependent Green's functions and transient plane-wave, respectively. The latter, can be expressed as a Radon transform of the space-time data (also termed slant stack). In this paper we present an alternative backpropagation scheme, wherein the backpropagation kernels are pulsed beams (PB), i.e. wavepacket with compact support in space-time. The holographic (image) field is thereby expresses as a phase-space superposition of PB backpropagators that emanate from all points in the measurement plane and in all directions. The amplitude of each PB backpropagator is locally matched to the space-time data via what has previously been termed the local Radon transform. This transform resolves the local spectral characteristics of the data, namely the local distribution of arrival times and directions. The image field therefore consists only of the relevant PB backpropagators, i.e., those which correspond to the local characteristics of the data. All other spectral PBs are weakly excited by the local Radon transform of the data and therefore do not contribute to the image field. Neglecting these contributions a priori render the backpropagation scheme more efficient. Furthermore, since PB have compact support, each backpropagator contributes to the image only near its propagation axis. In the conventional backpropagation approaches, on the other hand, all spectral components contribute everywhere and the image is generated only after numerical destructive interference of the non-relevant backpropagated data. In this paper we present the formulation of the phase-space backpropagation scheme for typical time-dependent scattering experiments. We then demonstrate how the Local Radon transform extracts the relevant space-time data and how the image is generated by the local backpropagators.

ELECTROMAGNETIC PROFILE RECONSTRUCTION USING THE RICCATI EQUATION APPROACH

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The Riccati differential equation for reflection coefficients in one-dimensional inhomogeneous media is applied to the electromagnetic inverse scattering problem. Two types of the Riccati equation in literature, Schelkunoff's and Redheffer's, are derived and distinguished. Based on inverting Redheffer's Riccati equation, both linear and non-linear inversion formulae are proposed. These renormalized perturbation formulae reconstruct the dielectric profile from the reflection coefficient at the surface of the medium. Existing inversion formulae (including the Born approximation) which were obtained from the Green's function approach and the Gel'fand-Levitan-Marchenko (GLM) theory are now derived from the Riccati equation. Four inversion schemes based on inverting the Riccati equation, linearized Redheffer's Riccati equation, linearized Schelkunoff's Riccati equation, non-linear Redheffer's Riccati equation and non-linear Schelkunoff's Riccati equation approaches, are used to invert several dielectric profiles. Comparison and summary of these methods are given. All these methods give higher order inversion results than the first-order Born approximation. The inversion is performed on band-limited reflection coefficients in frequency domain. An inverse Liouville transform is introduced to rigorously recover the geometric lengths from the stretched coordinates in the inversion procedure.

AN INVERSE ELECTROMAGNETIC INDUCTION PROBLEM

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Antenna pattern synthesis is now considered a mature subject. But, attention, for the most part, deals with the far field or radiation zone where the element patterns have a simple form. An interesting situation arises if we are dealing with lossy media where significant distances are small compared with the free space wavelength. Such an application occurs in geophysical sub-surface probing where the accessible source region is on or above the aerth's surface. Then the relevant distances into the conductor are coparable with the electrical skin depth. In such cases, conventional far field approximations become invalid. Similar situations arise in hyperthermia where an applicator antenna array is located near a human limb or torso. Here we consider an idealized half-space model where the source consists of annular currents located on the surface. The objective is to synthesize these currents given the desired form of the sub-surface field which we call the target function.

The general analytical procedure is to derive a forward solution for the sub-surface electric field which is a spectral integral of the surface current density. A Fourier Bessel inversion can be done exactly provided the problem is not ill posed. In other words there is a restriction on the class of sub-surface target functions that can be chosen. For time harmonic fields and for a Gaussian spatial variation of the sub-surface field, we show the procedure is viable. Furthermore, we can carry out a confirming forward calculation by representing the source as a concentric array of filamental current loops lying on or just above the upper surface of the conducting half-space. The method has also been extended to the time domain wherein we may also specify the desired temporal variation of the sub-surface field.

MULTI-FREQUENCY INVERSE SCATTERING OF MULTIPLE CONDUCTING CYLINDERS

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Images in inverse scattering problems are often contaminated by multiple scattering effects. These effects commonly present themselves as multiple-scattering ghosts. The distortions are more pronounced in approximate solutions, but exist even in rigorous methods whereby exact equations for inverse scattering are solved by numerical methods. Therefore, the forward model should account for multiple scattering in order to reduce these effects.

This paper presents a novel technique for inverse scattering of 2-D multiple conducting cylinders with E_z incident fields. In the forward model, the scattering volume is discretized on a regular grid resulting in small subscatterers. The novelty stems from the definition of binary shape functions applied to the discrete subscatterer locations to represent the larger scatterers. Here, the multiple scattering boundary conditions are enforced on each subscatterer by the T-matrix method (W.C. Chew et al, *IEEE Trans. Microwave Theory Tech.*, April 1992). The resulting matrix equation can be solved for the harmonic mode amplitudes of each subscatterer. Then, in the inverse problem, the conducting scatterers are approximated by analog shape functions. A linearized optimization is performed on the measured far-fields to iteratively solve for the analog shape functions. Multi-frequency super-resolution can be achieved with this method, while minimizing multiple-scattering ghosts.

INVERSION OF 3-D CONDUCTIVITY VARIATIONS VIA A NONLINEAR APPROXIMATION TO THE SCATTERED ELECTROMAGNETIC FIELDS

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Inversion of conductivity structures by Born or Rytov approximation procedures is attractive mainly because the estimation problem is rendered linear. This is a desirable feature since, for a finite set of measurements, the inversion problem is highly under-determined when conductivity variations are arbitrarily distributed in all three directions. Unfortunately, these linearized approaches to the inversion problem are severely penalized in their range of practical application since they are limited to small conductivity contrasts. Furthermore, both Born and Rytov approximations are unable to account for variations in the internal electric field due to static effects or to significant depolarization of the background electric field interior to the scatterers. An iterative Born inversion may require a large number of iterations to properly account for these two field distortions and therefore render the estimation problem extremely time consuming, if not prohibitive.

In searching for fast solutions to the inversion of 3-D conductivity variations energized by dipolar sources, we have employed a nonlinear approximation to the scattered fields. This approximation provides an estimate for the internal electric field which accounts for much of the full multiple scattering. Although this approximation is nonlinear in conductivity, it is much faster to compute than the full forward problem, and is almost as computationally efficient as the Born approximation. In its simplest form, the inversion approach is performed in two steps: first, linear estimation is applied to obtain a functional of the conductivity distribution. Second, a pointwise inversion is employed to invert, in a nonlinear fashion, the local values of conductivity from the previously inverted functional. In more complicated situations, the inversion may be carried out by a fast nonlinear optimization algorithm.

The proposed inversion procedure is demonstrated for the case of a hypothetical subsurface EM imaging experiment.

NEARFIELD MICROWAVE IMAGING OF BURIED MOISTURE: DIFFRACTION EFFECTS

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This paper describes radio wave imaging of buried moisture for infrastructure inspection. The method is to measure reflectance with moving antennas above ground. The paper presents measurements for wet soil samples buried in dry soil at depths down to 24 inches. Although these depths would be modest for geology, they are useful for inspection. Moreover, these depths are an order of magnitude larger than in our earlier work, which imaged dielectric objects. At the shallow depths of a few inches, the reflectance distribution resembles an objects shape so edge detection techniques generate recognizeable images. For greater depths, comparable to a wavelength in the soil, this paper shows diffraction effects for wet soil samples with transverse dimensions comparable to the wavelength.

The paper presents experiments made, with antennas that scanned an area, at frequencies between 196 MHz and 708 MHz. Complex valued reflectance was measured, and one dimensional gradients were calculated for samples of wet soil buried in dry soil. Antenna height above the air-soil interface was a parameter; it affects results significantly. However, the main result was the dependence of attenuation on burial depth. Attenuation was much greater than predicted by plane wave theory for reasonable values of loss tangents. The attenuation is described with reasonable accuracy by means of Fresnel diffraction.

A THREE DIMENSIONAL FEM/BEM FORMULATION FOR ELECTROMAGNETIC PROBLEMS

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Abstract

A method is presented for analyzing the scattering from an arbitrarily inhomogeneous, three dimensional material body. The finite element method is used in the region containing the inhomogeneity to solve for the electric vector and magnetic scalar potentials. Potentials were chosen because of their continuity across material boundaries. The potentials are coupled to the tangential electric and magnetic fields at the surface of the finite element domain. The solution of the finite element matrix involves the establishment of an admittance matrix relationship between the surface electric and magnetic fields. A surface method of moments solves for the surface fields due to an incident plane wave based on this admittance matrix. Both the scattered and internal fields are available.

This formulation has been implemented for two dimensional geometries to verify its validity. Numerical results for several test cases are presented to illustrate the solution.

SOLUTIONS OF INVERSE SCATTERING PROBLEMS BY MEANS OF SMALL-ANGLE SCATTERING DATA

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The reconstruction of a complex object internal structure is possible under the condition that the sounding wavelength much less compared with object typical details. If this condition is valid, we shall have the small-angle scattering of sounding waves. So the reconstruction of the object internal structure by means of small-angle forward scattering data is interesting in many applications. We derive the approximate integral equation analogous to Lippman - Shwinger equation for small-angle scattering

$$U(\mathbf{r}) = 1 + \int F(\mathbf{r},\mathbf{r}';\mathbf{r}_0)\, U(\mathbf{r}')q(\mathbf{r}',\omega)\, d^3\mathbf{r}',$$

where $U=E/E_0$ is the normalized field; E_0 is the field of the point sounding sourse in vacuum; $q(\mathbf{r},\omega)$ is the complex scattering potential depending on the sounding frequency ω; F is the equation kernel which depends on the sourse coordunates $\mathbf{r}_0$. The asymptotic ISP solution is given with the help of data about the complex amplitude of scattering. The projection of the product Q of the potential q and the normalized field U (Q=qU) is proportional to the complex scattering amplitude Fourier-transformation with respect to the transverse coordinate. The iteration ISP solution is suggested.

We find out the scattered field asymptotic representation and give the comparison with the well-known approximate solutions: the Born approximation, the Rytov approximation, the geometrical optics method, the Fock - Schwinger method etc. The iteration procedure using asymptotic representations is developed either for the direct problem and for the ISP. The application of asymptotic expansions allows us to fasten solutions in both cases. The asymptotically-exact solutions are obtained under the condition that the sounding wavelength tends to zero ($\lambda \to 0$). It is shown that in many important practical cases the projection Q is directly connected with the potential q projection for the strong scattering case.

The results of the ISP solution numerical modeling are given with the different approximations. In conclusion we show the examples for the reconstructions of weak-scattering and strong-scattering developing ionospheric inhomogeneities with the help of the satellite radioprobing experimental data.

Thursday PM URSI-B Session RP08

Room: Columbus C/D *Time*: 1320-1600

EM Scattering - Integral Equation Solution Methods

Chairs: Chalmers M. Butler, Clemson University; Arthur D. Yaghjian, Department of the Air Force

1320 **ELECTROMAGNETIC SCATTERING and RADIATION by ARBITRARY APERTURES in a CONDUCTING BODY**
Qinglun Chen*, Bull HN Information System, Inc.; Shian U. Hwu, Lockheed Engineering and Sciences Co.

1340 **A NEW THREE-DIMENSIONAL INTEGRAL EQUATION for MODELING THIN FERRITE COATINGS on CONDUCTORS**
John L. Volakis, S. Bindiganavale*, The University of Michigan

1400 **THE "INSIDE OUT" INTEGRAL EQUATION FORMULATION for MULTI-REGION SCATTERERS**
Paul M. Goggans*, Allen W. Glisson, Ahmed A. Kishk, Bo-Syung Yang, University of Mississippi

1420 **ELECTROMAGNETIC BACKSCATTERING by a FINITE LENGTH RECTANGULAR TROUGH in a GROUND PLANE USING a PHYSICAL BASIS FORMULATION**
H. Shamansky*, A. Dominek, N. Wang, The Ohio State University

1440 **SCATTERING by CHIRAL CYLINDER: a VOLUME FORMULATION USING SOLENOIDAL BASIS FUNCTIONS**
L. Mendes*, Universidade Estadual de Campinas/FEE; Ercument Arvas, Syracuse University

1500 **Break**

1520 **IMPROVED COMPUTATIONAL EFFICIENCY VIA NEAR-FIELD LOCALIZATION**
R. J. Pogorzelski*, General Research Corporation

1540 **LOW FREQUENCY ELECTROMAGNETIC SCATTERING from NON CONVEX BODIES**
D. Gintides, K. Kiriaki, National Technical University of Athens; R. E. Kleinman*, University of Delaware

ELECTROMAGNETIC SCATTERING AND RADIATION BY ARBITRARY APERTURES IN A CONDUCTING BODY

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Lockheed Engineering and Science Company
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This paper introduces a numerical scheme for the analysis and computation of electromagnetic radiation and scattering by arbitrary apertures in a three dimensional conducting body which may be filled with a homogeneous material having complex relative permittivity and permeability parameters. The aperture coupling problem is formulated in terms of coupling electric and magnetic field integral equations for the equivalent magnetic currents representing electric field in the aperture and electrical currents induced on the conducting surface on which the apertures are closed by conductors. The integral equations is numerically solved by method of moments and two kinds of basis functions, triangle and polygon basis functions, which are approximately spatially orthogonal to each other, are used to model the magnetic and electric currents, respectively.

Since this method employs the same basis functions and testing procedure as a method for electromagnetic modeling of 3-d piecewise homogenous material bodies does, which has been developed(Q. Chen, D.R. Wilton, 1990 IEEE AP-S International Symposium), all admittance and impedance submatrices used by that method are applied to this numerical approach after the submatrices are developed in generalized forms to be suitable to both electric and magnetic field computation. This approach also provides well-conditioned matrix equations due to use of two kinds of basis function and considerable generality in treating problems involving piecewise homogeneous material inside the aperture-perforated conducting body or multiple conducting bodies with apertures. Comparison with other available solution for the amplitude of transmitted electric field and normalized echo area of a conducting box with a square aperture validates this method.

A NEW THREE-DIMENSIONAL INTEGRAL EQUATION FOR MODELING THIN FERRITE COATINGS ON CONDUCTORS

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Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, Michigan 48109-2122

Thin dielectric coatings are often encountered on airborne vehicles and it is thus of interest to consider an efficient formulation for their numerical modeling. Standard boundary integral methods are not appropriate for modeling thin coatings because of accuracy issues and traditional volume formulations require six unknowns plus two on the conductor.

In this paper we consider the implementation of the new integral equation [Volakis, *IEEE Trans. on Microwave Theory and Techn.*, March 1992]

$$\begin{aligned}\mathbf{E}^i(r) &= \mathbf{E}(\mathbf{r}) - \iiint_{V_d} [\nabla G_0(\mathbf{r},\mathbf{r}') \times \bar{\mathbf{I}}] \\ &\quad \cdot \left\{ \frac{\mu_r - 1}{\mu_r} \nabla' \times \mathbf{E}(\mathbf{r}') + \nabla' \times [(\epsilon_r - 1)\mathbf{E}(\mathbf{r}')] \right\} dv'\end{aligned}$$

in which $\mathbf{E}^i$ denotes the excitation field, $\mathbf{E}$ is the unknown total field within the coating's volume V_d having relative dielectric constants (ϵ_r, μ_r), possibly non-uniform, $\bar{\mathbf{I}}$ in the unit dyad and G_0 stands for the free space Green's function. This integral equation is implemented using edge-based hexahedral elements with divergenceless linear basis functions. By a priori enforcing the boundary condition on the metallic surface (bottom of coating) it is shown that only three unknowns per volume cell are required for the discretization of this integral equation. This should be compared to the eight unknowns required with the traditional exact volume formulation. Details of the discretization are presented along with results for a dielectrically coated plate.

THE "INSIDE OUT" INTEGRAL EQUATION FORMULATION FOR MULTI-REGION SCATTERERS

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The usual surface integral equation formulation for scatterers composed of one or more dielectric regions proceeds by using the equivalence principle to divide the original scattering problem into an exterior equivalent situation and into interior equivalent situations for each dielectric region comprising the scatterer. Integral equations which express the boundary conditions in the equivalent situations are then written for each of the equivalent regions. These surface integral equations are in terms of equivalent electric and magnetic currents on the boundary surfaces of each equivalent situation. Because of the continuity of the electric and magnetic field in the original scattering problem, the same electric and magnetic currents appear in the integral equations of any regions with a shared boundary. The coupled integral equations for all of the equivalent situations can be solved simultaneously for the electric and magnetic currents on all of the boundary surfaces of the scatterer. The scattered fields are then determined using the equivalent currents in the exterior equivalent situation.

A numerical solution to the integral equation formulation described above can be achieved by use of the method of moments (MM). Because each equation in the moment matrix must include the current on every zone, many of the moment matrix elements are zero. This fact suggests that a more efficient formulation may exist for solving the multi-region scattering problem.

Here, we present an alternate formulation for solving the multi-region scattering problem. In this formulation only completely filled matrices are solved. For most scatterers this results in a significant reduction in the number of operations required to achieve a MM solution.

In the present formulation, in each interior region the integral equations are rewritten so that the equivalent electric and magnetic currents appear on opposite sides of the equal sign. The inverse of the operator on the electric current is applied to both sides of the equation to yield an expression which gives the electric current at each point on the interior region's boundary surface in terms of the magnetic current over the entire boundary surface of the interior region. The expressions for each of the interior regions can be combined and manipulated to yield an expression which gives the electric current at each point on the exterior region boundary in terms of the magnetic current over the entire boundary of the exterior region. Substituting this expression into the integral equations of the exterior equivalent situation gives an integral equation in terms of exterior boundary magnetic current alone. This equation can be solved via the MM. The exterior boundary electric current and the scattered fields can then be calculated.

In this paper we discuss potential problems related the the inverse operator in the interior regions (internal resonances) and present numerical examples which demonstrate the validity of the method at the internal resonance frequencies.

Electromagnetic Backscattering by a Finite Length Rectangular Trough in a Ground Plane Using a Physical Basis Formulation.

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The electromagnetic backscatter from a rectangular trough in a ground plane has received considerable attention of late, for a number of reasons. Perhaps the most important is the need to quantize and categorize the scattering from structures which contain gaps or cracks in an otherwise undisturbed surface. Such gaps and cracks can be considered an aperture in a ground plane, and if that aperture exists as part of a cavity, then the trough model can be used to predict the radar cross section (RCS). It is well known that the RCS on such structures can be dominated by the traveling wave scattering in the trough.

This paper focuses on plane wave illumination of a finite length rectangular trough present in a infinite ground plane, and uses physical insight gained from (H.T. Shamansky & A.K. Dominek, APS Transactions, AP-36, 1455-1463, Oct. 1988) to postulate the nature of the currents and thus the RCS of such a geometry. By applying such insight, the number of basis functions required can be decoupled from the physical dimensions of the trough, thus allowing electrically long troughs to be considered.

Following the technique presented by (J.H. Richmond, APS Transactions, AP-33, 64-68, Jan. 1985), the currents in the trough aperture can be approximated by one or more pairs of traveling waves traversing the length of the trough, and a forced wave following the phase of the incident plane wave. Using an exact dyadic aperture integral equation, these simple physical basis functions are employed in a Galerkin solution, and the resulting small system of equations can then be readily solved using traditional methods. The predicted RCS values are compared against a measurement to demonstrate the accuracy of this physical basis technique.

SCATTERING BY A CHIRAL CYLINDER: A VOLUME FORMULATION USING SOLENOIDAL BASIS FUNCTIONS

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In this work we use a volume formulation to analyze the problem of scattering of TE and TM plane waves by a chiral cylinder of arbitrary cross section. We use the equivalence principle to obtain, from Maxwell's equations, an integral equation that relates the equivalent volume polarization current in the chiral cylinder to the incident field. Then, we apply the Method of Moments to transform the integral equation into a system of algebraic equations that can be solved numerically.

To apply the Method of Moments, we expand the equivalent currents in terms of volume basis functions. We decompose the equivalent current into its axial and transverse components, i.e., its components respectively parallel and transverse to the axis of the cylinder. We expand the axial component in terms of pulse basis functions and the transverse component in terms of a set of solenoidal basis functions. We have obtained results showing the effectiveness of the formulation.

The use of basis functions which are not solenoidal to expand the equivalent current leads to problems for high value of the dielectric constant. We have shown (L. Mendes and E. Arvas, IEEE Trans. on Magnetics, to be published) that the use of solenoidal basis functions to analyze the scattering of TE plane waves by dielectric cylinders gives good results for cylinders of high dielectric constant. Here we extend that work to analyze the problem of scattering of TE and TM waves by a chiral cylinder. Up to now, we don't know of anyone else that have used solenoidal basis functions to study the problem of scattering by penetrable cylinders. The formulation is applied to problems of scattering by circular and square cylinders.

IMPROVED COMPUTATIONAL EFFICIENCY VIA NEAR-FIELD LOCALIZATION

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In selecting basis functions appropriate to moment method solution of the integral equations of modern electromagnetics, a recent consideration is the "local nature" of certain possible choices. That is, in the interest of reducing the number of significant elements in the impedance matrix, one selects basis functions which correspond to electric fields which are, in some sense, of minimal support on the surface of the structure in question. Efforts in this direction were recently reported by Canning. [F. X. Canning, IEEE AP-S Mag., 32, 18-30, Oct. 1990]. In this work, the bases produce directional beams of radiation intersecting the surface of the structure. This results in the desired reduced coupling. The use of these same functions for testing further reduces the coupling and yields a sparse impedance matrix. These considerations, however, are based upon a "far field" conceptualization of the fields radiated by the sources.

The present work concerns the use of a "near-field localization" concept leading to a more effective method of achieving the desired local fields on the boundary of the structure under consideration. By choosing sources so as to radiate a focussed field, one can achieve a very high degree of localization of the electric field on the boundary and thus greatly reduce the corresponding coupling elements in the impedance matrix. (The number of these which can be neglected of course depends upon the tolerable error level.) Serendipitously, the research also produced functions which are very much like the familiar (sin x)/x functions arising in the sampling theorem and leading to the so-called Nyquist sampling rate. [G. Herrmann, IEEE Trans. AP-38, 134-137, Jan. 1990.] As a result, the present representation fortuitously achieves a reduced sampling requirement on the field representation. A two dimensional example revealed that this corresponds to a 6:1 reduction in the required number of unknowns and a consequent reduction by 36:1 in the number of impedance matrix elements exclusive of sparseness considerations. Moreover, approximately two thirds of these matrix elements were negligible so that an overall reduction of 100:1 in the number of required matrix elements was realized.

In light of the above preliminary investigation, this approach, when applied to fully general three dimensional problems, promises to provide significant improvement in the computational efficiency of the calculations.

LOW FREQUENCY ELECTROMAGNETIC SCATTERING FROM NON CONVEX BODIES

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In the present paper we find the leading term the low frequency expansion of the scattered far field when a plane wave is incident upon a member of a class of rotationally symmetric nonconvex perfectly conducting scatterers. The class of scatterers consists of inverse prolate and oblate cyclides, figures obtained by subjecting prolate and oblate spheroids to a Kelvin transformation. This class includes a variety of shapes varying from peanuts to blood platelets.

The scattered field is represented in terms of electric and magnetic polarizability tensors, the elements of which are known to be representable as functionals of solutions of elementary exterior Dirichlet and Neumann problems for Laplace's equation. These boundary value problems for the complicated shape are transformed, via the Kelvin transformation, to interior Dirichet and Robin problems for the inverted surface which is taken to be a spheroid. These problems are solved explicitly in spheroidal coordinates and the corresponding solutions of the exterior problems are obtained via the Kelvin transformation.

Using this approach explicit expressions for the polarizability tensor elements are found. The scattered far field is then easily obtained for plane wave incidence from any direction.

These results consist of analytical expressions for the far field scattered by shapes which themselves are not level surfaces of any separable coordinate system. By combining the Kelvin transformation with low frequency approximations, the method of separation of variables (which is used in the solution of the interior problems for the inverted surface) is extended to obtain results for nonseparable shapes.

Thursday PM AP-S, URSI-B Session RP09

Room: Columbus E/F *Time*: 1320-1620

Multiple Scattering

Organizers: W. Ross Stone, Stoneware Limited; David G. Falconer, SRI International
Chairs: W. Ross Stone, Stoneware Limited; David G. Falconer, SRI International

1320 **ENHANCED RADAR CROSS SECTIONS due to MULTIPLE SCATTERING in TURBULENCE**
Edward J. Fremouw, Northwest Research Assoc.; Akira Ishimaru*, University of Washington

1340 **MULTIPLE SCATTERING from RANDOM DISTRIBUTIONS of INDIVIDUAL ROUGH SURFACE SCATTERERS**
Ezekiel Bahar*, M. El-Shenawee, University of Nebraska

1400 **IDENTIFICATION of MULTIPLE SCATTER in IMAGES**
John Stach*, SRI International

1420 **DOUBLE SCATTERING in MICROWAVE IMAGING**
David G. Falconer*, Ron Ueberschaer, SRI International

1440 **DOUBLE-SCATTER TRACKS in 1D and 2D IMAGES**
Ron Ueberschaer*, SRI International

1500 **Break**

1520 **EFFECT of MULTIPLE SCATTERING on RESOLUTION in INVERSION USING the BORN ITERATIVE METHOD**
M. Moghaddam*, Jet Propulsion Laboratory; W. C. Chew, University of Illinois, Urbana-Champaign

1540 **MICROWAVE IMAGING of MULTIPLE METALLIC CYLINDERS USING SHAPE FUNCTIONS**
W. C. Chew, Gregory P. Otto*, University of Illinois, Urbana-Champaign

1600 **INVERSE SCATTERING SOLUTION for INHOMOGENEOUS DIELECTRIC BODIES**
N. Joachimowicz*, Ch. Pichot, CNRS-ESE

ENHANCED RADAR CROSS SECTIONS DUE TO MULTIPLE SCATTERING IN TURBULENCE

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Enhanced backscattering and imaging in turbulence has been observed theoretically and experimentally in recent years. This paper presents a theoretical study of the altered radar cross sections and the scintillation index on monostatic and bistatic paths.

We develop an expression for the intensity scintillation index on a two-way (radar) path in terms of the one-way index and the correlation between scintillations produced on the uplink and downlink. The expression is appropriate for monostatic (fully correlated) and bistatic (totally or partially uncorrelated, or anticorrelated) paths whose links are statistically similar and obey Nakagami-*m* statistics. A companion expression for the mean apparent radar cross section (RCS) in the presence of scintillation describes enhancement on monostatic paths and energy-conserving depletion of mean apparent RCS on small-angle bistatic paths. The companion expression, which does not depend upon Nakagami-*m* statistics nor require statistical similarity, is consistent with more detailed calculations by previous authors. Special cases of both expressions are consistent with recent monostatic measurements by Knepp and Houpis.

Enhancement occurs due to the correlation between the uplink and downlink propagations. If the uplink and downlink amplitudes are assumed to be Nakagami-*m* variables, the apparent radar cross sections are enhanced by a factor ranging from 1 to 2 (Rayleigh) to 3. The square of the two-way scintillation index for the monostatic path varies from 0 to 5 (Rayleigh) to 10.7. The enhanced energy on the monostatic path is accompanied by a depletion in the mean apparent RCS at small bistatic angles in the presence of scintillation conserving the total energy. The related phenomena of enhanced imaging, lensless imaging, and backscatter from planetary satellites are also discussed, as well as some of the historical development of enhancement phenomena in turbulence.

IDENTIFICATION OF MULTIPLE SCATTER IN IMAGES

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Conventional imaging methods are based on models of weakly interacting scattering elements. For targets with strong interactions, these imaging methods create artifacts that may be difficult to interpret. There are methods that include these interactions in the imaging model. However, these methods require more computations and target information than conventional methods to produce an image.

An alternative approach is to compute a series of conventional images that are used to identify the location and delay (interaction distance) of regions in the original image that represent multiple scattering. In a typical imaging application, a reference delay is chosen so that all of the direct scattering from the target is focused. In anechoic chambers, this is accomplished by a reference target, usually a sphere, that is measured before the target of interest. In an image formed using the reference delay, direct scattering is focused and scattering that arises from interactions is blurred and displaced, i.e., artifact. However, if the original data are shifted by the time delay over which an interaction takes place, the *interaction* will be focused and direct scattering will be blurred and displaced in the image. Therefore, a region can be identified as resulting from an interaction if its' corresponding peak is formed in a time-shifted image. The spatial location of the peak represents the center of the interaction and the time shift represents the interaction distance. The center and circle corresponding the location and interaction distance respectively can then be overlaid onto the original image to provide insight into the sources of the interaction.

This concept will be presented by posing the imaging solution as a Hough transform of range-azimuth monostatic data. Examples of the method applied to monostatic two-dimensional images using FFTs will be presented. Extensions of this method to higher dimensional and bistatic images will also be addressed.

Double Scattering in Microwave Imaging

David G. Falconer, Ph.D.
Ronald M. Ueberschaer, B.S.
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Microwave imaging usually entails an optical picture of the scattering activity, *e.g.*, Mensa's scattering centers [D. Mensa, *High-Resolution Radar Imaging* (Artech House, 1984)], Jaggard's extended Born approximation [D. Jaggard, "Electromagnetic Imaging Techniques for Dielectric Objects," *Abstracts of the 1987 XXXIInd General Assembly of the URSI*, Tel Aviv (August, 1987)], or Crispen, *et al.* 2n X H^{inc} currents [J. Crispen, J. Goodrich, and K. Siegel, "A Theoretical Method for the Calculation of the Radar Cross Section of Aircraft and Missiles," University of Michigan Radiation Laboratory Final Report, Contract AF 19(604)-1949 (July, 1959)]. In developing optical pictures, it is generally assumed that single scattering dominates multiple scattering. In practice, double scattering is often an important—even the dominant—scattering mechanism [D. Falconer and R. Ueberschaer, "Double-Scattering Effects in Radar Scattering and Imaging," *1991 Large Range Users Group (LRUG) Conference,"* Lancaster, CA (May, 1991)]. The corner reflector is the classic double scatterer, but other re-entrant bodies produce significant double scattering as well. When double scattering is strong, the microwave image will suffer artifacts, such as fictitious off-body scattering centers.

We have invoked an optical picture for the scattering process and the Born approximation to the scattering integral to identify, estimate, and correct for double scattering in microwave images. For simplicity, our model uses a scalar picture for the scattering activity. We base our formulas on the assumption that the target's scattering centers are essentially isotropic in character and largely independent of the illumination conditions, *i.e.*, incidence angles and polarization states. We also assume that the double-scattering amplitudes are weaker than the single-scattering ones, but still strong enough to impact the microwave image.

We have applied our double-scattering model to analytical problems, numerical simulations, and laboratory measurements. Our analytical work started with a scattering body consisting of two isotropic point scatterers. We used this target to illustrate both off-body scattering centers and aspect-dependent imagery. Our numerical simulation considered a scattering body consisting of a pair of coplanar wires. We used the Numerical Electromagnetics Code (NEC) to model the scattering patterns produced by these wires and to assess the effectiveness of our double-scattering integrals in accounting for double-scattering effects. Finally, our laboratory work measured the scattering pattern produced by a linear array of five ping-pong balls between 1 and 18 GHz. Using these measurements, we have estimated both the single- and double-scattering amplitudes associated with this array.

DOUBLE-SCATTER TRACKS IN 1D AND 2D IMAGES

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ABSTRACT

This presentation illustrates double-scatter phenomena by examining the types of tracks which result from forming ISAR images of targets with strong multiple scattering. One-dimensional images are illustrated first, for which the tracks consist of varying range vs angle. Two-dimensional images are then illustrated, via video animation, for which the tracks consist of varying range and cross-range vs angle.

Range-azimuth tracks for direct scatterers are sinusoids centered about the zero-range axis. In this presentation, it is shown that double-scatter tracks are also sinusoids, but that they are offset downrange by half the distance between their scattering sources. The size of the sinusoidal variation is shown to depend on the range to the interaction centroid.

2D image tracks are simplified by introducing a relatively unusual target-based coordinate system. Normally, 2D images are displayed with the downrange axis fixed vertically on the page. As the aspect angle changes, the target effectively rotates by the negative of the aspect angle. This gives the viewer a fixed-radar perspective—the radar is always at the bottom of the page, pointing up toward the rotating target. An alternative imaging method gives the viewer a fixed-target perspective—the target remains stationary while the radar revolves around it.

By using this target-based coordinate system, the tracking of 2D image peaks is simplified. Direct scatterers remain stationary. Double-scatter tracks are circles in the image plane. The two sources of each double-scatter circle lie on that circle, diametrically opposed.

Measured and simulated examples of 1D and 2D tracks for direct and double scatterers are given in this presentation.

EFFECT OF MULTIPLE SCATTERING ON RESOLUTION IN INVERSION USING THE BORN ITERATIVE METHOD

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In the Born iterative method (BIM) of inverse scattering, the problem is formulated as a volume integral equation, and the unknown is found by performing Born-type iterations and using a regularized optimization process. The integral is linearized at each iteration, however, the final solution is that of the nonlinear inverse scattering problem. This is evidenced by the results of reconstructions of scatterers with contrasts as high as 30 times that of what could be inverted with linear algorithms.

It was found previously [Moghaddam and Chew, *IEEE Trans. Geosci. Remote Sensing*, vol. 30, no. 1, pp.147-156, 1992] that using BIM, a super-resolution of 0.1λ can be obtained for an E_z-polarized problem, where λ is the smallest wavelength in the spectrum of fields when time-domain data are used (or the operating wavelength in case of the single-frequency solution [Wang and Chew, *Int. J. Imaging Systems Tech.*, vol. 1. pp. 100-108, 1989]). Here, it will be shown that the ability to account for multiple scattering is the reason behind the high resolution in BIM. Examples will be shown comparing the results of a linear algorithm and BIM for resolution of two objects separated by 0.1λ: in the linear solution, the objects are not resolved and the contrasts not recovered; in the BIM solution, the two objects are resolved increasingly well as more iterations are performed. An analysis will also be carried out to prove that the evanescent spectrum does not contribute significantly to the scattered fields measured by the receivers, and hence is not responsible for the enhanced resolution. This will further confirm the role of multiple scattering and the subsequent mode conversions in obtaining high resolution.

INVERSE SCATTERING SOLUTION FOR INHOMOGENEOUS BODIES

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This paper deals with a Newton type iterative method for solving a non-linear ill-posed inverse electromagnetic scattering problem: the quantitative reconstruction of complex permittivity distribution of inhomogeneous 2D or 3D objects from scattered near field data.
Recently, an increasing interest has been devoted to the determination of the complex permittivity from moment method solutions of the integral equations. At present, they appear to be among the most promising approaches for Microwave Imaging. Nevertheless the stability of such approaches is very sensitive to the observation point locations and measurement accuracy (due to ill-conditioning matrix which has to be inverted). This involves, in general, the use of a regularization procedure. That why the use of an iterative procedure is important: effects of ill-conditioning can be significantly reduced by enforcing the convergence with a priori information (object external shape, upper and lower bounds of complex permittivity, presence of different media, etc...). The domain of validity of this method is directly related to the signal to noise ratio. The method is illustrated with various numerical simulations of practical interest performed on dissipative inhomogeneous dielectric objects (biological phantoms, human arm,...) in view of biomedical applications of microwave imaging. The influence of noise has been also studied in order to test the robustness of the algorithm and reconstructions using real experimental data have been made.

Thursday PM URSI-B Session RP10

Room: Columbus G *Time*: 1320-1700

Chiral, Bianisotropic and Complex Media and Their Applications II

Organizers: Nader Engheta, University of Pennsylvania; A. Priou, DGA, Ministry of Defense
Chairs: Nader Engheta, University of Pennsylvania; A. Priou, DGA, Ministry of Defense

1320 **BACKSCATTER from RADIALLY STRATIFIED CHIRAL OBJECTS**
Dwight L. Jaggard*, John C. Liu, University of Pennsylvania

1340 **MUELLER MATRICES for CURVED CHIRAL SCATTERERS**
John C. Liu*, Dwight L. Jaggard, University of Pennsylvania

1400 **WAVE REFLECTION and TRANSMISSION from LAYERED GENERAL BIISOTROPIC STRUCTURES**
Sergei A. Tretyakov*, St. Petersburgs State Technical Univ.; Markku Oksanen, Ismo V. Lindell, Helsinki University of Technology

1420 **HIGHER ORDER IMPEDANCE BOUNDARY CONDITIONS for CHIRAL COATINGS**
Daniel J. Hoppe*, Y. Rahmat-Samii, University of California, Los Angeles

1440 **EM SCATTERING by a CHIRO-DIELECTRIC BODY of ARBITRARY SHAPE in the PRESENCE of an IMPEDANCE WEDGE**
R. G. Rojas*, Michael F. Otero, The Ohio State University

1500 **Break**

1520 **PROCESSING and MICROWAVE CHARACTERIZATION of CHIRAL COMPOSITES CONTAINING FERROELECTRIC CERAMIC INCLUSIONS**
F. Guerin*, Pennsylvania State University; V. K. Varadan, Vasundara V. Varadan, The Pennnsylvania State University

1540 **STRONG COUPLING BETWEEN CHIRAL RECTANGULAR WAVEGUIDES**
K.- S. Chan, P. L. E. Uslenghi*, University of Illinois at Chicago

1600 **REFLECTION and TRANSMISSION of GUIDED ELECTROMAGNETIC WAVES at an AIR-CHIRAL INTERFACE in a PARALLEL-PLATE WAVEGUIDE**
Frederic Mariotte*, Nader Engheta, University of Pennsylvania

1620 **EIGENVALUE EQUATIONS for GENERAL BI-ISOTROPIC (NONRECIPROCAL CHIRAL) WAVEGUIDES**
Paivi Koivisto, Helsinki University of Technology; Sergei A. Tretyakov*, St. Petersburgs State Technical Univ.; Markku Oksanen, Helsinki University of Technology

1640 **SKEW INCIDENCE SCATTERING from a CIRCULAR CHIRAL CYLINDER**
Asoke K. Bhattacharyya*, New Mexico State University; Akhlesh Lakhtakia, Pennsylvania State University; J. Takada, Naohisa Goto, Tokyo Institute of Technology

BACKSCATTER FROM RADIALLY STRATIFIED CHIRAL OBJECTS

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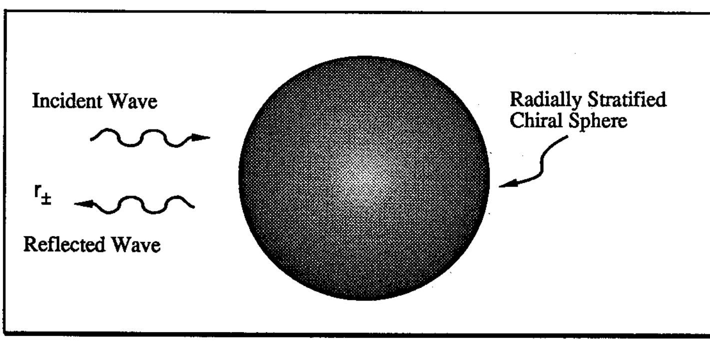
There is considerable current research interest in electromagnetic chirality and scattering. Electromagnetic chirality is evidenced by the coupling of electric and magnetic waves within a chiral medium through the constitutive relations. This coupling is embodied in the chirality admittance ξ_c whose magnitude indicates the strength of chirality and whose sign indicates the handedness of the medium.

It has been shown that the chiral Riccati equation for planar layers and its associated jump condition is a useful and practical technique for determining the exact reflection from continuously stratified, planar chiral surfaces [D. L. Jaggard, X. Sun, and J. C. Liu, "On the Chiral Riccati Equation", to appear in *Microwave and Optical Technology Letters*, (March 1992) and D. L. Jaggard and X. Sun, "Theory of Chiral Multilayers," to appear in *J. Opt. Soc. Am.* (Spring 1992)]. Here we generalize this technique to spherical geometry.

The problem of scattering from homogeneously layered chiral spheres and cylinders has been previously examined [D. L. Jaggard and J. C. Liu, "Chiral Layers on Curved Surfaces," chapter to appear in PIERS book, *Wave Interactions in Chiral and Complex Media*, N. Engheta, ed. (1992)]. Continuing and generalizing this work, we develop a spherical chiral Riccati equation and jump condition for backscatter from a radially stratified chiral sphere, as indicated in the figure below. As with its planar counterpart, the spherical Riccati equation transforms the boundary value backscatter problem to an initial value problem. This formulation is reminiscent of the planar case. Here two reflection coefficients, $r_{\pm}$, appear and are decoupled for the eigenmodes.



Problem Geometry: Backscatter from a radially stratified chiral sphere

MUELLER MATRICES FOR CURVED CHIRAL SCATTERERS

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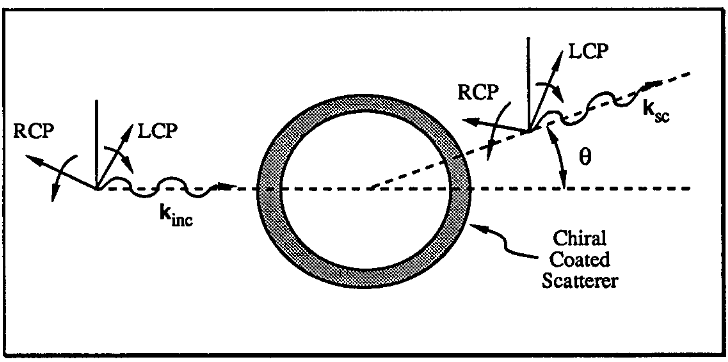
Coatings placed on conducting targets can significantly alter their electromagnetic scattering characteristics. The use of chiral† coatings [D. L. Jaggard, X. Sun, and J. C. Liu, "Spherical Chiroshield™," *Electronics Letters* (27), 77-78 (1991)] in modifying backscatter from canonical geometries has lead to the present interest in the angular scattering properties of these coatings. Mueller matrices, which relate the Stokes parameters of the incident and scattered waves, contain all of the relevant information concerning the scattering characteristics of these targets.

We examine the Mueller matrices for angular scattering from two canonical chiral scatterers: a chiral coated conducting sphere and cylinder as shown below in cross section. Of interest is the cross-coupling effect of the electric and magnetic fields due to chirality, which leads to distinct scattering properties evident in the Mueller matrices. The sensitivity of specific elements of the Mueller matrix to chirality and curvature and their interplay are examined.



Problem Geometry Cross Section: Scattering from a chiral object as a function of scattering angle θ and polarization using circular bases functions.

† Chiral materials are represented by the constitutive relations: $\mathbf{D} = \varepsilon\mathbf{E} + i\xi_c\mathbf{B}$ and $\mathbf{H} = \mathbf{B}/\mu + i\xi_c\mathbf{E}$, where **D**, **E**, **B**, and **H** are the usual time-harmonic electromagnetic field vectors. In addition to the usual permittivity and permeability μ and ε, the chirality admittance ξ_c is introduced to indicate the handedness of the material.

WAVE REFLECTION AND TRANSMISSION FROM LAYERED GENERAL BIISOTROPIC STRUCTURES

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The vector circuit theory, shown to be a superior method for analysing reflection and transmission properties of reciprocal chiral multilayer structures, is in this report extended to more general biisotropic (nonreciprocal chiral) layeres. The theory is shown to be similar to that for reciprocal chiral layers and enables one to study in a very systematic way plane wave reflection and transmission for arbitrary polarization and at obliques angles of incident wave.

The theory is applied for single and multilayer general biisotropic structures and for nonreciprocal Tellegen material layers situated either in air or as coatings next to the metal surface. The results of reflected and transmitted fields reveal that biisotropic layers possess much better antireflection and polarization shield properties than the reciprocal chiral layers. It will be shown, for example, how the nonreciprocal parameter will effect on the reflection properties as the angle of incidence changes, and what is the effect of the chirality on the results. Their combined effect will be studied as well. If the layer is used as a coating, the absolute value of the cross polarized reflected field will be same for indicent TE and TM polarized waves, provided that either chirality or nonreciprocity parameter is zero. If both parameters are nonzero, the absolute values of the cross polarized fields will still remain the same, but the phase will be different and the coating behaves nonreciprocally. Ideal mode coupling properties of a nonreciprocal biisotropic layer will be shown. More than 30-40 dB mode coupling for a wide frequency band can be achieved. The results are almost independent on the coating losses.

Studies on biisotropic single or multilayer structures in air will shown that chirality will have a major contribution to the transmission field level at small angles of incidence. As the angle increases, the nonreciprocity parameter will play a more significant role. For a true biisotropic slab having both chiral and nonreciprocal characteristics, the transmitted field is only slightly dependent on the angle of incidence. This can be understood in a way that chirality and nonreciprocity will partly compensate each other's effects. For this slab mode coupling between incident TE and TM modes in the transmitted field will be different, also.

It should be stressed that for the normal angle of incidence and for biisotropic coatings, formulas for the reflection coefficients can be given in analytical forms. This will simplify the analysis for obtaining optimum material parameter choices for particular requirements for the coatings.

HIGHER ORDER IMPEDANCE BOUNDARY CONDITIONS FOR CHIRAL COATINGS

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In many cases, the problem of electromagnetic scattering by dielectric-coated conducting bodies may be simplified through the use of higher-order impedance boundary conditions, [Hoppe and Rahmat-Samii, 1992 URSI National Radio Science Meeting, Volakis and Syed, JEWA 1990 pg 1157-1180]. The higher-order impedance boundary conditions, (HOIBC), reduce the number of unknowns required in the scattering problem, and simplify the resulting numerical solution. A similar simplification of the problem of scattering by chiral-coated bodies is possible if the appropriate higher-order impedance boundary conditions can be determined. One method of obtaining these boundary conditions for planar structures has been discussed previously, [Rojas, 1991 North American Radio Science Meeting Digest, pg. 358]. In this paper, an alternative method for obtaining higher-order impedance boundary conditions for chiral coatings is presented. The method is applicable to planar or curved multi-layer chiral coatings.

As a first step, approximate boundary conditions which are appropriate for use on surfaces with negligible curvature are derived. By examining the exact solution for plane wave scattering at a planar chiral-coated conductor, an exact boundary condition, involving only the tangential components of the electric and magnetic fields is derived. This exact spectral boundary condition is then approximated using ratios of polynomials in the transform variables, and expressed in the spatial domain using elementary Fourier transform relationships. In this way, a pair of differential equations which relate the spatial derivatives of the tangential electric and magnetic field components on the chiral to free space boundary is obtained directly. These differential equations may then be used to model the behavior of the chiral coating in scattering problems, provided the curvature of the scattering body is negligible. The detailed behavior of the field inside the chiral coating need not be computed. Thus, scattering from chiral coated bodies can be computed without the use of the Green's function for the chiral material.

When only one of the two principle radii of curvature is much larger than the wavelength of operation, higher-order impedance boundary conditions may be derived in a similar manner. In this case, the canonical problem of plane wave scattering by a conducting cylinder with a chiral coating is considered. As expected, the curvature is found to modify the coefficients which appear in the differential equations relating the tangential electric and magnetic field components.

The accuracy of the second order boundary conditions for planar and curved chiral coatings will be considered for several coating parameters. Numerical methods for determining the coefficients which appear in the higher-order impedance boundary conditions will also be discussed.

EM SCATTERING BY A CHIRO-DIELECTRIC BODY OF ARBITRARY SHAPE IN THE PRESENCE OF AN IMPEDANCE WEDGE

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The scattering of a plane wave by a two-dimensional chiro-dielectric body of arbitrary shape in the presence of a wedge whose faces satisfy the Leontovich (or impedance) boundary conditions is considered here. Note that the two faces of the wedge can have different impedance values and the chiro-dielectric body can be attached or be away from the wedge tip. The incidence field is assumed to have no z-dependence, where the z-axis coincides with the axis of the wedge. Thus, it is a two-dimensional problem which means that it is sufficient to calculate the E_z and H_z fields. Note that for a achiral body, the TM_z and TE_z fields would be decoupled; however, the presence of the chiral body will couple the TM_z and TE_z fields. Therefore, it is important to obtain an integral equation with as few unknowns as possible. The integral equation is developed by a repeated application of the two-dimensional divergence theorem and Green's second identity to the Helmholtz wave equation. The resulting integral equation can be expressed in terms of a combination of line and surface integrals. The Green's function used in this integral equation corresponds to the radiation by a line (electric or magnetic) source in the presence of the impedance wedge. This implies that the integrals are restricted to the chiro-dielectric scatterer because the Green's function satisfies the Leontovich boundary conditions over the wedge faces. In general, the integral equation cannot be solved in closed form. Here, it is discretize and solved by the well known Moment Method technique where the integral equation is transformed into a system of linear simultaneous equations. To maximize the efficiency of this numerical scheme, it is very important to obtain an expression for the Green's function which is numerically efficient. A brief review will be given of the main steps in the development of this Green's function. Finally, several examples will be shown with some comments on the application of the present problem in the design of scatterers loaded with material bodies.

PROCESSING AND MICROWAVE CHARACTERIZATION OF CHIRAL COMPOSITES CONTAINING FERROELECTRIC CERAMIC INCLUSIONS

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In the past few years, numerous theoretical articles have been written on chiral media. It has been shown that these materials could be successfully used as microwave absorbers (V. K. Varadan et al, J. Wave-Mater. Inter. 2, 71-81, 1987). However, so far only a few experimental results, concerning chiral polymers as well as chiral composites made of metallic springs embedded in a polymer matrix, have been reported (Guire et al, IEEE– EMC 32, 300-303, 1990; Maher et al, Radio Science 26, 1327–1334, 1991). Composites comprising ferroelectric ceramic inclusions are interesting for several reasons. The use of ceramic inclusions allows the fabrication of high temperature electromagnetic composites. By varying the composition of the ceramic, its properties change significantly and therefore the effective properties of the composite can be easily adjusted. Finally, this is a first step towards producing active electromagnetic composites, whose performance can be tuned by the application of an external field.

Chiral ferroelectric ceramic inclusions consisting of barium strontium titanate helices are prepared by coating graphite filaments with a slurry and winding the resulting fiber on a graphite rod. After heating and sintering, graphite-free, dense ceramic springs are obtained. Polymer matrix composites and high temperature composites (15.2 cm x 15.2 cm in cross-section) are fabricated by dispersing the springs in an epoxy resin and a cement, respectively. The samples are characterized from 6 to 40 GHz in a free space microwave measurement system comprising of two focused horn lens antennas, mode transitions, a network analyzer and a computer. This set-up can be used in conjunction with a furnace in order to perform high temperature measurements.

For the first time, results obtained for electromagnetic chiral materials with ferroelectric ceramic inclusions will be described. The effective properties of these composites, in particular, the permittivity, permeability and chirality parameter, will be presented. The measured values of the reflection and transmission coefficients, as well as reflection reduction will be reported. Finally, the influence of different parameters such as inclusion concentration and temperature will be discussed.

STRONG COUPLING BETWEEN CHIRAL RECTANGULAR WAVEGUIDES

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The coupling between rectangular dielectric waveguides embedded in a dielectric substrate of lower refractive index has been studied by Marcatili (Bell Sys. Tech. J., September 1969, p. 2071-2102) in the weak-coupling approximation of Miller (Bell Sys. Tech. J., May 1954, pp. 661-719). On the basis of Marcatili's approximation, it is possible to describe the power transfer between the two guides by means of a first-order nonlinear differential equation, which yields Miller's approximation when the nonlinear term is neglected. The solution of this nonlinear equation, which describes strong coupling between the guides, has been given by Uslenghi and Kazkaz (Digest of URSI Meeting, Amherst, MA, October 1976, p. 150).

The rectangular waveguide made of chiral material and embedded in a dielectric substrate has been studied recently by Chan and Uslenghi (Proceedings of PIER Symposium, Cambridge, MA, July 1991, p. 338), who extended Marcatili's treatment to the case of a chiral guiding region. The same authors (Digest of North American Radio Science Meeting, London, Ontario, June 1991, p. 362) also developed a theory for the chiral rectangular directional coupler in the Miller approximation.

In the present work, the theory of the chiral rectangular directional coupler is extended to the case of an arbitrary distance between the two chirowaveguides. It is shown that power transfer occurs back and forth between the guides. Design criteria are developed which yield the coupling length as a function of the percentage of power transfer. The formulation reduces to that of Uslenghi and Kazkaz (1976) for the case of zero chiral admittance, and to that of Chan and Uslenghi (1991) for the case of a large distance between the two chirowaveguides.

REFLECTION AND TRANSMISSION OF GUIDED ELECTROMAGNETIC WAVES AT AN AIR-CHIRAL INTERFACE IN A PARALLEL-PLATE WAVEGUIDE

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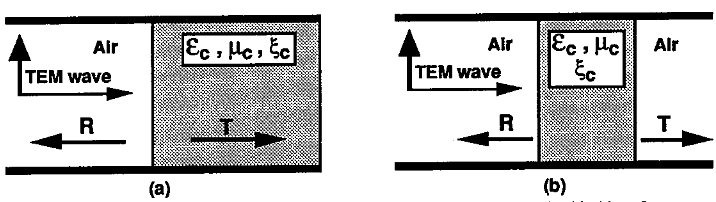
Isotropic chiral materials for time-harmonic fields exp(-iωt) can be characterized by the constitutive relations $\mathbf{D} = \varepsilon_c \mathbf{E} + i\xi_c \mathbf{B}$ and $\mathbf{H} = \mathbf{B}/\mu_c + i\xi_c \mathbf{E}$, where ε_c and μ_c represent the usual permittivity and permeability and ξ_c the chirality admittance which is a measure of the handedness of the medium. Such materials are circular birefringent, thus they possess two bulk eigenmodes of propagation, a right circularly polarized (RCP) and a left circularly polarized (LCP) plane wave with two differing wave numbers. A new class of waveguides, named *chirowaveguides*, which exhibit some novel and interesting properties due to electromagnetic chirality was introduced recently [N. Engheta and P. Pelet, *Optics Letters Vol. 14*, No. 11, 1989]. These guided-wave structures consist of cylindrical waveguides containing chiral materials and can have potential applications in integrated-optical devices, electronic communication systems and measurement techniques.

In this talk, we address another problem associated with *chirowaveguides*, namely the problem of reflection and transmission of guided waves at an air-chiral interface and at a chiral slab in a parallel-plate waveguide shown below. The motivation behind this study is the potential application of this problem in the design of novel measurement techniques for determining material parameters of chiral composites. We first present the results of our analysis on reflection and transmission of guided electromagnetic waves at an achiral-chiral interface in a parallel-plate waveguide. It is found that in order to satisfy the boundary conditions at the achiral-chiral interface, the reflected and transmitted waves need to be hybrid. The role of chirality of the medium on the reflected and transmitted wave is discussed and physical insights into these results are provided. Furthermore, we discuss the problem of guided electromagnetic wave propagation through a chiral slab placed in a parallel-plate waveguide. Reflection and transmission of guided modes in this geometry are analyzed and the effects of slab's chirality on related quantities such as reflection and transmission coefficients and polarization are presented. Potential applications of these analyses in material characterizations, electromagnetic shielding and design of devices and components are also addressed.



Reflection and transmission of guided electromagnetic waves (a) at an air-chiral interface and (b) at a chiral slab in a parallel-plate waveguide

* Visiting scientist from French Atomic Energy Commission CEA-CESTA, Le Barp, France (Frédéric Mariotte is supported by French Ministry of Defense DGA/DRET No 911458)

EIGENVALUE EQUATIONS FOR GENERAL BI-ISOTROPIC (NONRECIPROCAL CHIRAL) WAVEGUIDES

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There has been recently an extensive research on wave propagation in waveguides filled with reciprocal chiral material, so called chirowaveguides. General bi-isotropic media are described by linear constitutive relations that couple electric and magnetic fields by four scalar parameters

$$\mathbf{D} = \epsilon\mathbf{E} + (\chi - j\kappa)\sqrt{\epsilon_0\mu_0}\mathbf{H}$$

$$\mathbf{B} = (\chi + j\kappa)\sqrt{\epsilon_0\mu_0}\mathbf{E} + \mu\mathbf{H},$$

where ϵ is permittivity, μ permeability, κ chirality parameter and χ is the Tellegen parameter. Because of the fourth parameter χ general bi-isotropic medium offers a still more flexible tool in designing new microwave devices, compared to chiral composites.

In this paper eigenvalue equations for guided modes in general bi-isotropic waveguides have been derived. The analysis utilizes field decomposition techniques in order to simplify wave equations in bi-isotropic medium. Using characteristic electric and magnetic field ratios subject to particular waveguide surface impedances, corresponding eigenvalue equations are derived first for arbitrary waveguide cross sections and then applied for a special circular cross section. The eigenvalue equations are given for different isotropic and anisotropic impedance boundaries, ideally conducting and for open waveguides, all in closed forms. In all cases, the waveguide filling material can be either bi-isotropic or reciprocal chiral.

In particular, it has been established that the eigenvalue equation of a general waveguide with an ideally conducting wall has the same form as for a nonreciprocal chiral filling, with a modified refractive index of the medium. This means that the bi-isotropic waveguide with the ideally conducting wall is reciprocal in terms of the propagation factor and acts as a chiral one. For a circular waveguide, the situation is exactly the same as for the chiral reciprocal guide: when one changes the sign of the propagation factor *and* the sign of the Bessel function index, the equation is preserved. It should be stressed that this fact does *not* mean that the bi-isotropic waveguides never exhibit nonreciprocity, since other boundary conditions on the wall dictate different dependence on the nonreciprocity parameter. Then, even for the circular guide, the field patterns do not have to be reciprocal.

Calculated curves show how nonreciprocity (χ) together with chirality (κ) of the media effects on the propagation constant and attenuation in circular bi-isotropic waveguides with lossy boundaries. Special cases are compared with the earlier results available from the literature.

SKEW INCIDENCE SCATTERING FROM A CIRCULAR CHIRAL CYLINDER

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In the last few years there has been a great deal of activity towards the understanding of wave interaction with chiral materials[Lakhtakia et al - Time-Harmonic Electromagnetic Fields In Chiral Media', Springer-Verlag, 1989] and their practical use as components and devices. It appears to the authors that only the normal incidence case has been considered for scattering by circular chiral cylinders apart from a forthcoming paper[P.L.E. Uslenghi; Special issue on Chirality and Applications, Jour. EM Waves and Applications]. The motivation of the present research is to extend the scattering problem of the chiral cylinder to the general case of skew incidence and to examine the role of chirality in controlling the scattering characteristics and its possible practical applications.

The key conclusions of this preliminary study are (1) there could be a significant difference between the copolarized radar cross sections with TE and TM excitations (2) There is a cross-polarized contribution in case of chiral cylinder even for normal incidence unlike in an achiral case (3) Using chirality it is possible to more effectively control the co- and cross-polarization scattering characteristics of the cylinder and (4) the chiral cylinder may act as a polarization transformer with proper choice of parameters including chirality. Details of the results will be discussed during the presentation.

Thursday PM URSI-B Session RP11

Room: Columbus H *Time*: 1320-1700

Time-Domain Simulation and Modeling

Chairs: Stan J. Kubina, Concordia University; L. J. Bahrmasel, McDonnell Douglas Research Labs

1320 **FIRST-PRINCIPLES SUPERCOMPUTING SIMULATION of CROSSTALK in HIGH-SPEED DIGITAL INTERCONNECTS**
Melinda Piket-May*, Allen Taflove, Northwestern University

1340 **TLM SYNTHESIS of CONDUCTING SCATTERERS by ALTERNATE FORWARD and INVERSE TIME STEPPING**
Michel Forest, Wolfgang J. R. Hoefer*, University of Ottawa

1400 **NUMERICAL SIMULATION of SHORT PULSE EXCITATION of a PARABOLIC REFLECTOR**
Carey M. Rappaport*, Northeastern University

1420 **TRANSIENT ANALYSIS of INFINITE MAGNETIZED FERRITE USING the FINITE-DIFFERENCE TIME-DOMAIN METHOD**
F. Hunsberger*, Raymond Luebbers, Karl S. Kunz, The Pennnsylvania State University

1440 **INVESTIGATION of NUMERICAL DISPERSION and IMPROVEMENT TECHNIQUES in FDTD METHOD**
Jianqing He*, Sedki Riad, Aicha Elshabini-Riad, Virginia Polytechnic Inst. & State Univ.

1500 **Break**

1520 **THE STABILITY and ACCURACY of TIME-DOMAIN COMPUTATIONAL METHODS**
Richard C. Booton, Jr.*, University of Colorado at Boulder

1540 **USING DIGITAL SIGNAL PROCESSING TECHNIQUES with the FD-TD METHOD**
Zheqiang Bi*, John Litva, Ke-Li Wu, Chen Wu, McMaster University

1600 **IMPROVED BOUNDARY CONDITION for TREATING CONDUCTORS in FINITE-VOLUME TIME-DOMAIN METHOD**
A. H. Mohammadian*, V. Shankar, W. F. Hall, Rockwell International Science Center

1620 **A COMPARATIVE STUDY of THREE ABSORBING BOUNDARY CONDITIONS for the 21/2D SCATTERING PROBLEMS**
B. Stupfel*, R. Le Martet, CEA, Centre d'Etudes de Limeil-Valenton; R. Mittra, University of Illinois, Urbana-Champaign

1640 **INFINITE ORDER ON-SURFACE-RADIATION-CONDITION for SCATTERING by TWO DIMENSIONAL ARBITRARY SHAPED BODIES**
Jeff L. Barnes*

FIRST-PRINCIPLES SUPERCOMPUTING SIMULATION OF CROSSTALK IN HIGH-SPEED DIGITAL INTERCONNECTS

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In the past, digital logic designers have not seriously considered the electromagnetic details of their systems. Clock speeds were low enough and logic levels high enough that the electromagnetic problems were negligible. But as voltage levels drop well below one volt and clock speeds increase to 100 MHz and above, the electromagnetic issues must be addressed.

Attempts have been made to model signal propagation, ground current flow, and crosstalk in high-speed digital interconnects using finite elements, SPICE, and a variety of other analysis programs and modeling packages. These programs are limited in their ability to provide full-vector information of the electromagnetic fields, show detailed coupling between adjacent lines, or provide details of the current flow on the ground planes. We are applying the 3-D finite-difference time-domain (FD-TD) solver for Maxwell's equations to study these problems. FD-TD provides the full-vector information required for a detailed analysis of coupling and ground current problems. This is especially useful in observing high speed transient behavior.

We are examining two cases where a detailed study of electromagnetic behavior provides a better understanding of the system. Case 1 involves reflection effects of a transmission line matched load in the picosecond regime. Signal propagation and ground currents are studied. Case 2 involves modeling a circuit board connector module. First, a single multi-layered board is studied. Details of strong cross-coupling between adjacent pins when one pin is excited are shown. Next we model signal propagation through four multi-layer boards and three multi-pin connectors and look at the signal propagation and crosstalk occurring between adjacent pins.

For each case, the device geometry is incorporated into into an FD-TD cartesian grid. We can predict each system's response to a wide variety of electromagnetic excitations by simulating signals of various widths. We can observe the field patterns anywhere in the device at any point during the time evolution of the signal. The Cray Multi Purpose Graphics System (MPGS) visualization software is used to create color video displays that track in time the digital signal pulses and the resulting ground current distribution.

We are currently working on a Cray Y-MP/8 with 128 MWords of storage. In our largest model to date (the four multi-layer board/three multi-pin connector module of Case 2), we employ a uniform spatial resolution of 0.004 inches, the thickness of an *individual layer* of the board. This involves the tracking of 56-million vector field unknowns in time and requires 117 MWords of storage. This is most likely the largest and most complex digital circuit board assembly modeled by any means to date.

TLM Synthesis of Conducting Scatterers by Alternate Forward and Inverse Time Stepping

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In a recent paper (Sorrentino, So and Hoefer, 21st EuMC Dig.,pp. 1273-1277, Stuttgart, 9 - 12 Sept. 1991) the basic principles of TLM synthesis through inverse time stepping have been described. It has been shown that the topology of a conducting scatterer can be reconstructed by injecting the *particular* part of its impulse response (obtained as the difference between the *total* and the *homogeneous* TLM solutions) back into the empty computational space in reverse time sequence. Obviously, the results of a previous forward analysis are required to perform this reconstruction. However, in a synthesis problem the topology of the scatterer is normaly not known, and no analysis can thus be performed. What is given most of the time is its frequency domain response over a *limited* operating range, usually too narrow to yield a sufficiently detailed time response through inverse Fourier transform. The designer must therefore generate this missing information somehow.

In this paper it is shown how the missing high-frequency information can be obtained by the forward analysis of an *approximate* scatterer (first guess) and subsequently combined with given low-frequency specifications. The new frequency response is then inverse Fourier transformed and injected backwards in time into the computational domain, yielding an *improved* geometry, which is then analyzed again, and the process is repeated until the synthesis converges to a topology which yields the desired low-frequency response.

Numerical experiments involving two-dimensional single scatterers have demonstrated that the convergence of this numerical forward-backward time domain procedure is extremely fast, yielding stable results after typically two or three cycles only. This approach is thus considerably more efficient than repeated analysis combined with an optimization strategy. During the presentation of this paper, typical examples will be shown, and the design procedure will be demonstrated by means of the results obtained at each step of the cycle.

NUMERICAL SIMULATION OF SHORT PULSE EXCITATION OF A PARABOLIC REFLECTOR

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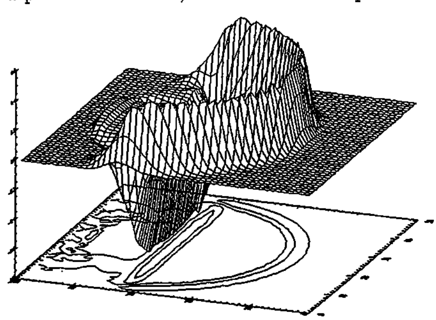
This paper addresses the problem of extremely short-time pulse excitation of a parabolic reflector antenna. When a pulse is short compared to the time required for it to traverse the reflector, only a fraction of the reflector is illuminated at any given time. This partial reflector illumination is the cause of recent speculation concerning its affect on the antenna radiation pattern. It has been stated [Hansen, R. L., *IEE Proc., H*, 6, 557-559, 12/87] that the leading and trailing edges of a short pulse have different antenna patterns, leading to a differential transient radiation characteristic.

Previously, ray methods have been used to simulate the reflection characteristics of parabolas. However, because the illuminating pulse is so short, standard frequency domain methods of analysis are impractical. Instead, the Finite Difference Time Domain (FDTD) method can be used to analyze the wave propagation and reflection of the reflector surface.

The FDTD analysis indicates that the commonly perceived assumptions of differential transient reflection appear to be inaccurate. Field distributions have been simulated for a deep parabola in both transmit and receive modes for Gaussian pulses. The parabolic reflector has insignificantly small characteristic transient behavior besides that of a simple aperture.

The figure shows a transmitted cylindrical wave with Gaussian amplitude dependence, centered at the parabola focus, and its reflection off a parabolic cylinder at left. The reflected wave is a planar wavefront, with minimal amplitude variation.

Although it must be cautioned that using numerical methods to prove theoretical assertions is dangerous, it is the transient behavior that is of concern, and only by employing a procedure which emphasizes the different temporal aspects of the field can this problem be effectively analyzed.



TRANSIENT ANALYSIS OF INFINITE MAGNETIZED FERRITE
USING THE FINITE-DIFFERENCE TIME-DOMAIN METHOD

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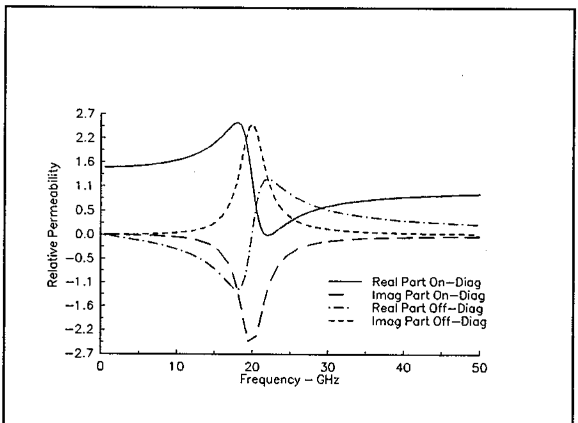
When certain ferrites are subjected to a static magnetic field, they become strongly anisotropic and the permeability of the ferrite must be represented by a tensor, rather than scalar, quantity. As a consequence, the ferrite is gyrotropic, possessing a polarization dependent wavenumber. Among the phenomena which can be shown for magnetized ferrites is Faraday rotation, which occurs when a linearly-polarized wave undergoes rotation as it traverses the ferrite parallel to the direction of the biasing magnetic field.

The presence of this anisotropy alone increases the complexity of any FDTD algorithm, since the magnetic field update equations for at least two of the rectangular components become coupled. In addition, for wideband analyses, the frequency-dependence of the permeability tensor must be incorporated at the same time. A typical dispersive permeability is shown below. During this presentation, it will be explained how the corresponding time domain magnetic susceptibilities can be efficiently handled to allow the FDTD algorithm to treat this class of gyrotropic media. Finally, results will be shown for a simple wave/ferrite simulation.



INVESTIGATION OF NUMERICAL DISPERSION AND IMPROVEMENT TECHNIQUES IN FDTD METHOD

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Blacksburg, VA 24061-0111

The finite difference time domain (FDTD) method, introduced by K.S. Yee in 1966, has been used recently by many researchers to achieve approximate solution of time dependent Maxwell's curl equations. A Gaussian pulse is usually used as an input excition in applying the FDTD method due to its smoothness in time and its Gaussian spectrum distribution after Fourier transform. Literature survey indicates that numerical dispersion introduces significant errors, forming a deep dip at the tail of the Gaussian pulse and therefore causing a deterioration of the simulation waveform.

Mathematical theory can prove that the ratio of the time step Δt to the spatial discretization increment Δh is required to satisfy the stability condition $\Delta t/\Delta h \leq k\lambda$, where λ is a constant determined by the propagation velocity and the dimensions of simulation domain, and k is a parameter ranging between $1 \geq k > 0$. For k selected closer to unity, an improved accuracy can be achieved on the expense of stability. Therefore, a k value less than 1/5 is often selected in practice in order to ensure good stability.

In this paper, numerical computations of simulated results indicate that numerical dispersion occurs when k is selected to be away from unity. This research studies are conducted on a coaxial line and a microstrip line. A new technique is implemented to improve the dispersion while the stability condition is satisfied at the same time. The technique consists of updating the input boundary value and all other boundary values using a large time step. A fraction of the large time step is used in the computation of the finite difference approximation and the computation in all interior points is iterated as many times as the reciprocal of that fraction (for example that fraction can assume a value equals to 1/5 or 1/10 or others. This new technique is applied to simulate an open-end on the microstrip line. The simulation results indicate a significant improvement of the numerical dispersion. In addition, the order to compute the interior points is designed in a way that most recently updated values are used to calculate new values in order to further improve the simulation accuracy.

THE STABILITY AND ACCURACY OF TIME-DOMAIN COMPUTATIONAL METHODS

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Time domain solutions of Maxwell's equations and the wave equation are used both to determine time-dependent phenomena such as pulse response and through Fourier transforms to determine resonant frequencies. The classical method in electromagnetics is the finite-difference time-domain (FDTD), but other methods are available. The customary finite-element method uses spatial-nodal expansions but a finite-difference approximation for time-derivatives. Several new time-domain algorithms have been described recently by Booton and Chang and others which utilize the finite-element method with edge-element expansions. Also, a modified FDTD method, which has a different stability limit, recently has been described.

The FDTD method has a well-known maximum size for the time step as a multiple of the spatial interval, and accuracy results have been reported in the last few years. The maximum size for the time step for finite-element algorithms can be expressed in terms of the largest eigenvalue of the computational matrix, but this approach is of no practical value if the eigenvalues are not known. Stability and accuracy results for several of the recently derived algorithms are described in this talk. Stability limits are derived by using the well-known discrete Fourier-transform method utilized by von Neumann with FDTD, modified to handle boundary conditions. The accuracy with which resonant frequencies can be calculated follows from the same equations used to derive the stability limits.

The various methods have different maximum time steps and accuracies. A method of comparing methods based upon maximum time step size (minimum run time if other factors are constant) for equal accuracy is discussed, and this comparison is applied to the methods considered above.

USING DIGITAL SIGNAL PROCESSING TECHNIQUES WITH THE FD-TD METHOD

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The FD-TD method has proven to be a very powerful technique for many electromagnetic problems because of a number of highly desirable features. Firstly, it can be applied to structures exhibiting complex geometries which may prove to be too difficult for other analytical or numerical methods. Secondly, only one computation is required to get the frequency domain results over a large frequency spectrum. Thirdly, it can be easily applied to inhomogeneous, anisotropic and frequency dependent material problems. The main disadvantage of the method is its requirement of large computer memory space and long computation time for three dimensional problems. Overcoming these difficulties depends on two factors: the development of computers and the improvement on the method itself. **The purpose of this presentation is to systematically demonstrate that the efficiency and capability of the FD-TD method can be improved greatly in several aspects by using the extensive techniques developed in the Digital Signal Processing field.** These aspects are:

1. It will be shown that time domain signal obtained using the FD-TD algorithm is much over sampled. The data which must be stored for later processing can be greatly compressed without degrading the accuracy of the analysis.

2. It will be demonstrated that by incorporating the spectrum estimation techniques with FD-TD, when undertaking dielectric resonator and microstrip component analyses, the efficiency of the method can be improved by one order of magnitude. In addition, a new excitation source for the FD-TD method will be investigated, also based on the parameter estimation techniques. This source is found to offer a number of advantages.

3. It will be shown that digital filter theory can be used to develop a new dispersive boundary condition (DBC) for the FD-TD method. Based on this DBC, several other DBCs can be unified and developed.

4. Recently, several authors have investigated the analysis of frequency dependent material by using the FD-TD method. Some of these authors use a convolution integration equation in their modelling, while the others use a differential equation. In this presentation, we use the system concept to unify these two models.

All of the above developments can also be applied to other time domain methods, such as the Transmission Line Matrix method.

IMPROVED BOUNDARY CONDITION FOR TREATING CONDUCTORS IN FINITE-VOLUME TIME-DOMAIN METHOD

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The finite-volume time-domain (FVTD) method, originally developed for the hierarchy of fluid dynamics equations, was adapted by these authors over four years ago to solve Maxwell's equations. Since then a lot of progress has been made both in improving the algorithm and developing a sophisticated and comprehensive computer code to solve three dimensional realistic problems in electromagnetic scattering and RCS prediction, impedance and mutual coupling computation in complex antenna and array problems, and electromagnetic pulse computations. While the similarities between the electromagnetic and fluid dynamic problems have been exploited to the fullest extent, innovative modifications from time to time have become necessary in order to deal with peculiarities unique to electromagnetic problems. Some of these innovations such as treating frequency-dependent materials and impedance boundary condition were reported in the past. This presentation discusses an improvement to the algorithm for treating conductors which better represents rapid field variation along the conducting surface.

In the framework of FVTD, based on the (numerical) knowledge of the tangential electric and magnetic fields on the surfaces of the cells that form the computational domain, average values of the field components in those cells are computed. This is merely the numerical implementation of the well-known Riemann integral. However, for those cells that neighbor a conducting surface, evaluation of the tangential magnetic field is not a trivial task. The approach that we initially used was to apply the jump condition across the characteristic in the cells neighboring a conductor. This resulted in approximate values for the tangential components of the magnetic field on the conductor. (The corresponding tangential electric fields are of course exactly known, since they are zero.) Subsequently, we demonstrated that the approximation used was adequate in many problems. As the resolution increases, the approximate value of the fields becomes more and more accurate. This obviously increases the cost of the numerical computation. Recently, we revisited this issue and came up with a more accurate representation of the tangential magnetic field on the conductor. In this approach that will be discussed in more detail during the talk, the unknown quantities are expanded in terms of the eigenvalues of the Maxwell's equations with two unknown coefficients. These coefficients are solved for, based on the fact that tangential electric fields are known to be zero on perfect conductors. Once these two coefficients are computed, the tangential magnetic fields are immediately obtained.

With this improvement used in the code, we found that generally same level of accuracy can be achieved with fewer grid points used on the conductors. Particularly, in scattering problems where surface waves become important, this new boundary condition has produced very accurate results. Some of the results that will be presented are RCS of a long circular rod, a delta wing, a rectangular plate, two closely spaced spheres, and several other cases that have recently been compiled.

A COMPARATIVE STUDY OF THREE ABSORBING BOUNDARY CONDITIONS FOR THE 21/2D SCATTERING PROBLEMS.

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R. Mittra
Electromagnetic Communication Laboratory
University of Illinois, Urbana, Illinois 61801

In this paper, we investigate the numerical efficiencies of three different types of Absorbing Boundary Conditions (ABCs) for mesh truncation, applied in conjunction with the finite element technique. To test these boundary conditions, we consider the problem of computing the Radar Cross Section (RCS) of inhomogeneously-coated or imperfectly conducting cylinders whose cross-sections can be arbitrary. To evaluate the accuracy of the different boundary conditions, we compare the FEM results, derived by using the different ABCs, with those obtained by using a numerically rigorous formulation that combines the finite element method applied in the interior of the computational domain with an integral equation formulation for the boundary (see P. Bonnemason, R. Le Martret, B. Stupfel, Oblique Incidence Scattering by Large, Coated Cylinders of Arbitrary Cross-Section, 1992).

The first ABC considered is ABCR, a multiple plane-wave type of condition which is associated with a rectangular boundary. The ABCR is derived from the boundary condition described in a recent paper (J. F. Lee and R. Mittra, URSI Symposium, London, Ontario, 1991) for the time-domain analysis of arbitrary scatterers using the FDTD algorithm.

The second boundary condition investigated is associated with a circular boundary. Both the second- and third-order Bayliss-Turkel type of boundary conditions, that are derived from the Wilcox's expansion, are tested. The RCS is calculated either directly from the values of the electromagnetic field computed on the boundary, or after modifying these values by substracting the undesired reflected waves generated by the approximate boundary condition used for mesh truncation. It is shown that the latter procedure, which is relatively easy to implement provided the boundary is strictly circular, yields accurate results for the RCS, even when this boundary is situated reasonably close to the scatterer.

The last ABC investigated is designed to work for an arbitrarily shaped boundary. It is locally cylindrical in nature, of third order (Bayliss-Turkel), and was also derived from the Wilcox's expansion. Not unexpectedly, it is found to be equivalent to the ABCR on portions of the boundary where the radius of curvature is infinite.

The numerical results presented in this paper provide some useful insights into the question of suitability of a particular kind of ABC for a given scatterer geometry, when the underlying objective is to minimize the size of the domain to be meshed without an undue sacrifice of the numerical accuracy.

INFINITE ORDER ON-SURFACE-RADIATION-CONDITION FOR SCATTERING BY TWO DIMENSIONAL ARBITRARY SHAPED BODIES

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Recently Kriegsmann,Taflove and Umashankar reported on a technique termed the " On Surface Radiation Condition". In their approach, an approximate, two dimensional, one way differential equation whose solution yields waves propagating away from a scatterer (but which does not admit as solutions waves propagating into a scatterer) is applied directly on the surface of the scatterer itself. This one way equation is in essence a radiation condition generalized to the near field. An application of the boundary condition for the scatterer, together with this radiation condition, yields an expression for the induced surface source density.

The "On Surface Radiation Condition" B2 operator was introduced with excellent results for normal wave illumination, but its accuracy degrades at grazing incidence. An operator of higher order would theoretically solve this problem; however, such an operator has not been introduced and would require higher order numerical derivatives involving a larger number of sample points.

In this paper a modified B-infinity operator is presented. Improved accuracy compared to B2 is obtained with this method for various geometries and angles of wave incidence on perfectly conducting objects having arbitrary edges and corners.

Numerical results will be presented for various shaped bodies, including a blade ogive, which will be compared to B2 and the method of moments. Data will include normal and grazing wave incidence for TM and TE illumination for both currents and radar cross section. A study will also be presented, on the accuracy, as a function of frequency.

Thursday PM1 URSI-B D Session RP12

Room: Columbus I/J *Time*: 1320-1500

Millimeter and Submillimeter Wave Passive Devices

Organizers: M. Salazar-Palma, Universidad Politecnica de Madrid; Roberto Sorrentino, Universita degli Studi di Perugia

Chairs: M. Salazar-Palma, Universidad Politecnica de Madrid; Roberto Sorrentino, Universita degli Studi di Perugia

1320 **THE COPLANAR WAVEGUIDE AS TRANSMISSION LINE for MM-WAVE INTEGRATED CIRCUITS: PROPAGATION CHARACTERISTICS and MODELLING APPROACHES**
Wolfgang Heinrich*, Institut fur Hochfrequenztechnik

1340 **NOVEL LOW-LOSS MONOLITHIC TRANSMISSION LINES for SUB-MILLIMETER WAVE APPLICATIONS**
Linda P. Katehi*, The University of Michigan

1400 **COMPARISON of JUNCTIONS in BOTH DIELECTRIC GUIDES and METALLIC GUIDES ABOVE 75GHZ**
R. J. Collier*, M. F. D'Souza, University of Kent at Canterbury

1420 **ELECTROMAGNETIC SIMULATION of PACKAGE RESONANCES for MMICS**
Cheok H. Thng, David C. Chang*, Richard C. Booton, Jr., University of Colorado at Boulder

1440 **DIELECTRIC RESONATOR WHISPERING GALLERY MODES APPLICATION to MILLIMETER WAVELENGTH DEVICES**
D. Cros*, P. Guillon, IRCOM-UA CNRS

THE COPLANAR WAVEGUIDE AS TRANSMISSION LINE FOR MM-WAVE INTEGRATED CIRCUITS: PROPAGATION CHARACTERISTICS AND MODELLING APPROACHES

Wolfgang Heinrich

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Abstract:

An increasing number of monolithic microwave integrated circuits (MMIC's) for the mm-wave frequency range is based on the coplanar concept, i.e. the CPW is used as the standard transmission-line element. This enables one to scale down the cross-sectional dimensions. As a consequence, both low dispersion at mm-wave frequencies and higher packaging density can be achieved.

The total width of such CPW structures ranges about several ten microns. Such low characteristic dimensions provide quasi-TEM behaviour up to 100 GHz and more. On the other hand, however, the miniaturized cross sections give rise to special effects that could be neglected for the microstrip lines employed so far.

First, the metallization thickness t has to be accounted for. Typical values of t $(0.5 \ldots 3\mu)$ are comparable to the slot widths and thus the conductors can no longer assumed to be infinitely thin.

Second, conductor loss becomes an important parameter. The skin depth and the cross-sectional dimensions both range in the same order of magnitude. One can conclude already from this simple statement that the fields inside the conductors will contribute significantly to the propagation characteristics. One finds that they do not only influence the line attenuation but also contribute to the line inductance. Also, in contrast to the microstrip configuration, the outer inductance of the CPW depends on frequency at the lower end of the frequency band. As a result, the CPW phase constant exhibits dispersion in this range.

Accurate modelling approaches, therefore, require inclusion of finite metallization thickness as well as finite metal conductivity. One may achieve this employing rigorous full-wave approaches (e.g. mode-matching method). The numerical expenses, however, are rather high and do not allow application in practical design tools.

Hence a simplified model has been developed. Under the assumption of quasi-TEM conditions the CPW is described by the equivalent line inductance L, capacitance C, and resistance R, with R and L being a function of frequency. The values of R, L, and C are obtained by mathematical expressions that are lengthy but of closed form. Accuracy has been checked by comparison to a full-wave mode-matching approach. The resulting maximum errors are of the order of 3% in effective dielectric constant and characteristic impedance and 15% for the attenuation constant, respectively. Thus, the model is well suited for implementation in CAD packages and for mm-wave circuit design.

Novel Low-loss Monolithic Transmission Lines for Sub-millimeter Wave Applications

by
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Abstract

Technology based on the sub-millimeter wave range offers narrow-beam, high-resolution antennas which are essential for intelligent computer control guidance, command systems for space applications, and sensors operating in an optically opaque environment. There are two typical approaches for the design of low-loss transmission lines. The first approach attempts an extension of the millimeter-wave monolithic technology to higher frequencies. In this manner, planar conductors are used extensively for the guidance of the waves but with important structural modifications in their supporting dielectric material in order to avoid excessive loss of power in the form of radiation. This approach has resulted in the successful development of low-loss planar and non-planar lines but is limited to the lower end of the sub-mm-wave spectrum (up tp 500 GHz) due to ohmic losses and fabrication tolerances. The second approach extends optical techniques to lower frequencies and has resulted in low-loss, quasi-planar lines made exclusively of intrinsic semiconducting materials combined in an appropriate way. Due to the present status of the fabrication processes, this second approach is limited to the higher end of the sub-mm-wave spectrum. However, as technology advances, the range of validity of this approach will be extended to lower frequencies.

Since the sub-mm-wave region is rather unexploited, the development of the above referenced lines is still in its infancy. However, a detailed presentation of the available information on their electrical properties will be given. Furthermore, these lines will be compared to more conventional monolithic lines, such as microstrip and coplanar waveguides, in terms of performance, fabrication feasibility and availability. There are three types of novel monolithic waveguides which have shown promise for use in the submillimeter frequency range: monolithic dielectric guides, microshield lines, and lens-supported coplanar waveguides. The advantages as well as disadvantages associated with the use of these guides will be discussed extensively.

Comparison of Junctions in both Dielectric Guides and Metallic Guides above 75 GHz

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Abstract

One of the limitations in microwave impedance measurements at frequencies above 75 GHz is the performance of waveguide flange connections. This involves not only the repeatability of a pair of flange connectors, but also the interconnectability to other flange connectors. In the N.P.L. Report DES 95, Bannister, Griffin and Hodgetts give a theoretical background to the link between the uncertainty in $\Gamma = O$ and the dimensional tolerances of waveguides and their flanges. The purpose of this paper is to show, by using practical measurements in the range 75-100 GHz and comparing them with the theoretical measurements mentioned above, that dielectric guide connections are capable of better performance than waveguide connections. The authors have already published some results which demonstrate that dielectric guide can be used in appropriate configurations to make both six-port and multistate reflectometers of similar performance to those constructed in metallic waveguide. Since the performance of metallic waveguide connectors becomes one of the major limitations of microwave impedance measurement at frequencies above 100 GHz, then dielectric waveguide could be a viable alternative. It is worth noting that dielectric waveguides are used extensively as the only waveguide at optical frequencies, and there must therefore be a lower frequency at which their use is still preferable. This paper suggests this frequency is around 100 GHz. Finally, the paper will discuss some aspects of the design of an all dielectric multistate reflectometer. The design includes a novel broad-band programmable phase shifter. Such a dielectric guide reflectometer should have a better performance than its waveguide equivalent for microwave impedance measurements above 100 GHz.

ELECTROMAGNETIC SIMULATION OF PACKAGE RESONANCES FOR MMICs

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As monolithic microwave integrated circuit (MMIC) technology is becoming more mature, the computer-aided design issues are quickly evolving from the chip level to the module level involving complex packages. The physical phenomenon of package resonance emerges to become a primary concern for designers, because their occurrence often will render modules utilizing otherwise good MMIC chips useless. Hence determination of resonant frequencies and field distributions at these frequencies has become of great importance, because the package design may have to be modified to remove certain effects.

Realistic models of MMIC packages may involve complex metallic structures, dielectric substrates, and sometimes intentionally introduced lossy materials. A finite-element method using as cells tetrahedra and rectangular cylinders has advantages in the accurate simulation of such complex packages. Last year, we described such an approach using edge-element expansions, and earlier this year we described in two dimensions an improvement in which one field, say E, is described by edge-elements and the other is described by average values over the cell. Such a method combines some of the computational efficiency of the finite-difference method with the advantages of the edge-element method in matching geometric structures and boundary conditions.

The present talk extends the previously presented two-dimensional approach to three dimensions. The approach can be shown to be similar to the weak form of the finite-element method. One set of computational equations is derived by weighted integration of the approximation to one Maxwell curl equation, where the weighting function is a vector edge-element interpation function. The other set is derived by a differently-weighted integration of the approximation to the second curl equation.

Geometries appropriate for analysis of MMIC packages will be used for numerical computation. The resonant frequencies and field distributions at these frequencies will be presented for typical package configurations.

DIELECTRIC RESONATOR WHISPERING GALLERY MODES APPLICATION TO MILLIMETER WAVELENGTH DEVICES

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This paper discusses of planar millimeter wavelength "Whispering Gallery" dielectric resonators modes for the design of W band power combiners and oscillators. These modes of WGE types for which electric field is essentially radial and of WGH types for which magnetic field is essentially radial, are excited into thin dielectric disks, which permit to use them in planar millimeter integrated wavelength devices.

Various advantages of these resonators modes allow their utilisation in the millimeter wavelength range. Their dimensions are relatively large, their unloaded Q factor is only limited by the value of the loss tangent of the material used to realize the resonators, they offer good suppression of spurious modes, and a good level of integration. They also permit, by chosing the type of excitation to excite both travelling and stationnary waves. The analysis of these resonators by means of the three dimensional finite element method permits to predict theoretical response of any devices in particular : resonance frequencies and electromagnetic field associated with each modes, equivalent network and scattering parameters of a resonator coupled to one or two transmission lines and so to be able to simulate W band passive and active devices.

Using "Whispering Gallery" dielectric resonators modes, we have realised planar power combiners which combine two or three sources at 94 GHz. The efficiency of this device evaluated in the coupling plane is about 70%.

The other realization concerns a W band Gunn diode oscillator. The oscillator acting on a $WGE_{10,0,0}$ mode at 98 GHz, has a power level of about 6 dbm and its noise figure is better than that of a conventional metallic cavity oscillator.

Thursday PM URSI-B Session RP13

Room: Columbus K/L *Time*: 1320-1700

Gratings

Chairs: Lloyd S. Riggs, Auburn University; Ercument Arvas, Syracuse University

1320 **EM SCATTERING from a CONDUCTING GRATING with an ARBITRARY CROSS SECTION**
X. Shen*, Ercument Arvas, R. F. Harrington, Syracuse University

1340 **ANALYSIS of VERTICALLY/HORIZONTALLY STRATIFIED LOSSY GRATINGS USING the FINITE ELEMENT METHOD of LINES**
Marat Davidovitz*, University of Minnesota

1400 **DIFFRACTION ANALYSIS of PERIODICAL DIELECTRIC GRATINGS USING a TRANSMISSION MATRIX**
E. Griese*, University of Paderborn

1420 **EFFECTS of IMPERFECTIONS on PLANE WAVE SCATTERING from FINITE ARRAYS of PERFECTLY CONDUCTING STRIPS**
T.-T. Hsu*, Lawrence Carin, Polytechnic University

1440 **ANALYSIS and DESIGN of a TWO OCTAVES POLARIZATION ROTATOR for MICROWAVE FREQUENCY**
R. P. Torres*, M. F. Catedra, Universidad de Cantabria

1500 **Break**

1520 **A BROADBAND, COMPACT, LOGARITHMICALLY PERIODIC STRIP GRATING ANTENNA**
Ronald R. DeLyser, David C. Chang*, E. F. Kuester, University of Colorado at Boulder

1540 **THIN FILM FILTER and LASER USING SECOND ORDER BRAGG INTERACTION**
Masoud Kasraian*, University of Wisconsin-Madison

1600 **A FREQUENCY DEPENDENT EDGE MODE CURRENT DENSITY APPROXIMATION for TM SCATTERING from a CONDUCTING STRIP GRATING**
Frank B. Gross, William J. Brown*, FAMU/FSU College of Engineering

1620 **ON the USE of CONFORMAL MAPPING to IMPROVE a FREQUENCY DEPENDENT EDGE MODE CURRENT DENSITY for TM SCATTERING from a CONDUCTING STRIP GRATING**
Frank B. Gross*, FAMU/FSU College of Engineering

1640 **RIGOROUS ANALYSIS of SCATTERING from THIN SCREENS and GRATINGS**
Vladimir Veremey*, A. Pojedinchuk, Yu. Tuchkin, Ukrainian Academy of Sciences

EM SCATTERING FROM A CONDUCTING GRATING WITH AN ARBITRARY CROSS SECTION

X. Shen*, E. Arvas, R. F. Harrington
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Determination of electromagnetic scattering from a conducting grating has attracted much attention in last decade because of its important role in modern technology. Most previous work dealt with scattering from a conducting strip grating. We here consider the electromagnetic scattering from a conducting cylinder grating. The grating is composed of an infinite number of identical perfectly conducting cylinders of infinite extent along the z axis and arbitrary cross section in the x-y plane. The cylinders are d meters apart from each other along the x axis. The grating is illuminated by a linearly polarized TM (or TE) plane wave at an incident angle ϕ^i.

Floquet's theorem and the method of moments are applied to obtain a set of linear equations. Each element of the moment matrix contains an infinite summation which is slowly convergent. In order to accelerate the convergence of the summations, a method is employed which combines Shanks' transformation and Poisson's transformation. A complete power analysis has been carried out and the parameters of the generalized network have been obtained.

Both TM and TE excitations are considered. The reflection and transmission coefficients, and the reflected and transmitted power, are computed for various types of gratings. The computational results obtained for an infinite number of cylinders are compared with the moment solution for a finite number of conducting cylinders of the same type. We observe that the greater the number of cylinders, the closer the results obtained.

Analysis of Vertically/Horizontally Stratified Lossy Gratings Using the Finite Element Method of Lines

Marat Davidovitz
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The Finite Element Method of Lines is applied to investigate plane wave scattering from two-dimensional periodic structures defined by vertical and/or horizontal boundaries. The theory covers gratings containing lossy dielectric materials of arbitrary (within computational accuracy) conductivity, and as such also applies to highly conductive structures. The Method of Lines approach used to obtain the numerical algorithm entailes a finite element discretization of the problem along one Cartesian direction, yielding a system of coupled Ordinary Differential Equations in the remaining coordinate. This system is solved analytically after the unknowns are uncoupled. Among the advantages of this method is the fact that it gives rise to significantly smaller numbers of unknowns than the fully-discrete finite element or hybrid finite/boundary element solutions. Consequently, when applicable, it affords greater computational efficiency.

To validate the solution, several examples were considered for which previously derived results were available. Among them is the problem of E- and H-plane scattering from periodic, thick-walled arrays of waveguides. Comparison of preliminary numerical results with data computed by other means indicates very good agreement. Additional results will be derived for several problems of interest, including

- scattering from a lossy-dielectric half-space with periodic vertical stratifications;
- reflection from thick, multiply tuned strip gratings;
- transmission and reflection from periodic arrays of cavity backed slots.

Numerical characteristics of the employed algorithm will be assessed.

ANALYSIS AND DESIGN OF A TWO OCTAVES POLARIZATION ROTATOR FOR MICROWAVE FREQUENCY

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A polarization rotator is a passive device able to rotate a predeterminate direction of linear polarization to another fixed one. It usually consists on five or six parallel wire grids having everyone a slightly different azimuth from the previous grating (N. Amitay, A. Saleh. IEEE AP-31, No.1, Jan. 1983). The technical advantages of the dielectric-backed strip grid makes this last structure more convenient than the wire grid. Several surfaces of strip grid will be cascaded to perform a multilayered rotator structure.

A 45 degrees polarization rotator has been designed. A two octaves frequency band has been achieved (4.5 to 18 GHz.) with only three strip grid each one of them rotated respect to the previous one. Over this band the transmission loss is less than 0.5 dB, the circular polarization ratio is less than 2.0 dB, and the major axis of the polarization ellipse forms 45°± 3° respect to the linear polarization direction of the incident plane wave.

The analysis method is an original scheme based upon Conjugate Gradient-Fast Fourier Transform Method (CG-FFT) to analyze periodic structures (M.F. Cátedra, R.P.Torres. PIER 4, Chapter 9, Elsevier 1990), and the Generalized Scattering Matrix (GSM) method to study their connection. The cascade connection used in this work takes advantage on the fact that the adjacent dielectrics to the metallic structure are taking into account by the CG-FFT method. A comparison between numerical and measured data shows very good agreement.

A BROADBAND, COMPACT, LOGARITHMICALLY PERIODIC STRIP GRATING ANTENNA

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University of Colorado at Boulder, Boulder, CO 80309-0425

The bandwidth of a microstrip patch antenna is considered to be its single most limiting characteristic. It is known that rectangular patches of slightly different sizes will resonate at slightly different frequencies. When these patches are placed in close proximity, the resonance frequencies will couple and give a wider bandwidth than either of the single elements taken separately. The major problems associated with multiresonator antenna configurations are that they require comparatively large areas and because of this, have variations in radiation pattern over the bandwidth of the antenna.

This paper describes an antenna consisting of a configuration of a number of rectangular patches each located in close proximity to one another and to the feed line. The antenna is compact and has a power bandwidth 6 times that of a single solid element of the same size. Because the antenna is made of closely spaced, narrow elements, the currents are essentially in one direction, subsequently, cross polarization characteristics are expected to be good.

The antenna elements are mounted on the top of the top layer of dielectric material which has a dielectric constant of 2.2. The elements are scaled such that the individual lengths and widths are reduced by a small percentage as one proceeds from the largest to the smallest element. The gaps between the radiating elements are maintained constant at a few tenths of a millimeter.

The feed line is between the two dielectric layers, the lower of which has a dielectric constant of 2.2. It is expected that the optimum bandwidth is yet to be achieved and that one of the relevant factors for a wider bandwidth is the number of elements chosen. This is verified by the design, building and testing of two antennas, one with 10 elements, the other with 12 elements.

Electromagnetic coupling to all elements is necessary in order that each element be excited by the primary source of energy. This is accomplished in this design by use of a double layer structure with the feed on the lower layer and the antenna on the upper layer. Variations of this design could be made by using a single layer with the feed line at the edge of the antenna so that all elements of the antenna are in close proximity to the feed line.

A 10 element design gives a calculated power bandwidth of 17.80% at a center frequency of 4.26 GHz. The measured power bandwidth is 19.80% at a center frequency of 4.19 GHz. A 12 element antenna with overall dimensions the same as the 10 element antenna (0.5 x 1.0 guide wavelengths) gives a calculated power bandwidth of 19.44% at a center frequency of 4.31 GHz. The measured power bandwidth is 22.04% at a center frequency of 4.22 GHz.

THIN FILM FILTER AND LASER USING SECOND ORDER BRAGG INTERACTION

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The characteristics of the second order Bragg interaction are investigated for the transverse electric (TE) mode of a corrugated active dielectric film waveguide sandwiched between two different passive dielectrics. Four canonical equations that are valid for a distributed coupler with two guided waves in the dielectric film waveguide and two free waves (incident and radiated) in the cover and the substrate (see Fig. 1) are derived systematically. General relations among the coupling coefficients are deduced. The coupling coefficients are shown to satisfy all the requirements imposed by symmetry, reciprocity in the sense of phase conjugation, and power conservation. From the solution of the canonical equations, the characteristics of both passive and active devices are investigated. For the passive devices, performances of the frequency-selective filter, output coupler, and input coupler are examined by determining the various design parameters such as the operating frequency range, the coupling efficiency, and the radiation efficiency. For the active devices, the characteristic parameters of distributed feedback (DFB) lasers, such as the frequency of oscillation, the growth rate, and the gain threshold are studied. Multi-parameter optimizations are carried out to determine the design parameters that lead to the optimum performance of these devices. The optimization procedures are based on slight alteration of the corrugated section (i.e., the period and the amplitude of the corrugation) and introduction of a phase adjustment region in the grating structures.

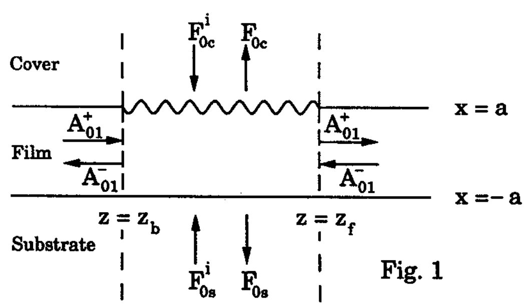

Fig. 1

A FREQUENCY DEPENDENT EDGE MODE CURRENT DENSITY APPROXIMATION FOR TM SCATTERING FROM A CONDUCTING STRIP GRATING

Frank B. Gross and William J. Brown*
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Typically conducting strip gratings have been analyzed with the moment method augmented by an edge mode term. This edge mode term is frequency independent and helps the convergence of the moment method by modelling the strip edge singularities. This behavior was observed by Meixner. The traditional edge mode functional form can be shown to be identical to the single strip charge density. It can also be derived by the radiation integral for a single strip using a low frequency approximation for the Hankel function.

In this presentation, a frequency dependent edge mode current density approximation for TM scattering from a conducting strip grating is derived by substituting the classic edge mode function with an unknown frequency dependent function into the radiation integral. The kernel of the radiation integral is the periodic Green's function. By satisfying the conducting boundary condition where, $E^i = -E^s$, one can easily derive the unknown function to yield a frequency dependent current density. This new current density is the product of the traditional edge mode term and a frequency dependent function which is inversely proportional to a series of Bessel functions. The new current density exhibits the expected nulls as a function of frequency and exactly matches the moment method for low frequencies. At high frequencies the mutual coupling between the strips is not accounted for and the accuracy of the solution breaks down. This new solution can serve to give better insight into strip grating behavior and also can be used to augment moment method calculations.

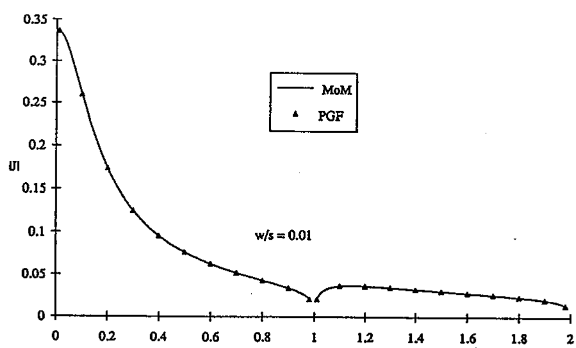

Fig. (1). Current density at y=0 for w/s = 0.01

ON THE USE OF CONFORMAL MAPPING TO IMPROVE A FREQUENCY DEPENDENT EDGE MODE CURRENT DENSITY FOR TM SCATTERING FROM A CONDUCTING STRIP GRATING

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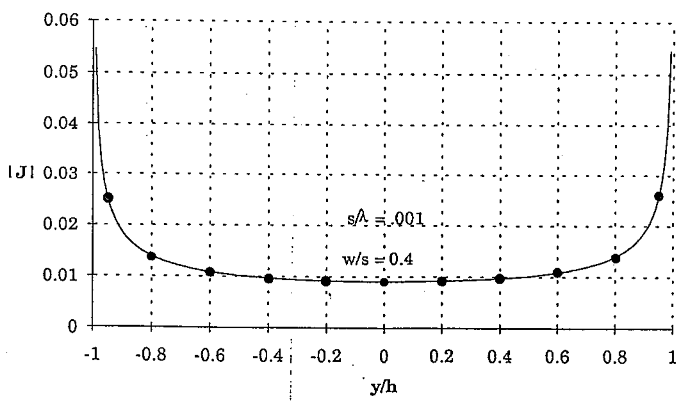
Frequently conducting strip gratings have been analyzed assuming an edge mode term describing the current density behavior. This edge mode term demonstrates singularities at the edges and is valid for very narrow strips in a grating with large periodicity. When the strip width becomes a reasonable fraction of the period, then the classic edge mode term breaks down and fails to correctly model the current distribution. In a previous paper, authors Gross and Brown derived a frequency dependent edge mode current density using the classic edge mode function. This new current density was derived by use of the radiation integral and the periodic Green's function. It was shown that the frequency dependent current density was valid for strip width to grating period ratios of < .2. This small strip width dependence is principally attributed to using the classic edge mode function for this derivation. The traditional edge mode functional form can be shown to be identical to the single strip charge density. It can also be derived by the radiation integral for a single strip using a low frequency approximation for the Hankel function.

In this presentation, a new edge mode function is derived by the use of conformal mapping for the TM mode in a conducting periodic strip grating. One cell of the grating is modelled with magnetic boundaries in the gaps. The charge density is derived and it's functional form accounts for the coupling between the strips. The current density is shown to have the exact same variation across the strips as does the charge density. This new edge mode current density reduces to the classical edge mode function for narrow strips but now also accounts for all strip widths. When the strip width is equal to the grating period, the grating becomes an infinite ground plane. The new current density even accounts for this case by automatically eliminating the edge singularities and yielding the physical optics current density.



RIGOROUS ANALYSIS OF SCATTERING FROM THIN SCREENS AND GRATINGS

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In recent years a variety of numerical methods have sprang up. Simplicity of direct numerical methods accounts for their wide application in the study of complicated scatterers and waveguide structures of different kinds. But all these methods as a rule result in ill-conditioned matrices; That is the condition numbers of these matrices rapidly increase with the matrix size. So far these methods cannot guarantee the solution of problems with any arbitrary fixed accuracy.

There exist mathematically correct methods which reduce the initial boundary value problems to the infinite systems of linear algebraic equations of the second kind in l_2

$$[I + C] x = b, \quad x,b \in l_2 \qquad (1)$$

where C - is compact operator in l_2.
A wide range of diffraction wave problems on canonical obstacles and gratings have been solved in recent years. The present paper offer a review of the methods suggested for studying single canonical scatterers (circular cylinder with infinite longitudinal slot, flat strip, spherical cap, strip grating, circular strip, thin circular disk and others), diffraction gratings, open resonators with circular cylindrical mirrors, antennae with circular cylindrical or spherical reflectors and open waveguides.

In the spotlight of the paper is the rigorous method of solving the two-dimensional diffraction wave problems on screens with arbitrary cross-sections, on diffraction gratings and on wavy surfaces with an arbitrary profile. The initial boundary value problems are reduced to the integral or integral-differential equations of the first kind which, in its turn, is reduced to some specific dual series equations (DSE) involving trigonometrical functions. The proposed method of solving DSE of the first kind reduces them to equation (1).

The electromagnetic scattering properties of open resonators with/without an inhomogeneity, antenna with spherical reflectors, multireflector antennae are discussed.

Thursday PM2 URSI-B Session RP14

Room: Grand D *Time*: 1520-1700

Virtual Rays

Organizers: Pyotr Ya. Ufimtsev, N. G. Alexopoulos, University of California, Los Angeles
Chairs: Giorgio Franceschetti, IRECE; Pyotr Ya. Ufimtsev, University of California, Los Angeles

1520 **THE METHOD of VIRTUAL RAYS in SCATTERING THEORY**
N. G. Alexopoulos*, University of California, Los Angeles

1540 **VIRTUAL RAYS - the HALF-PLANE**
Giorgio Franceschetti, Adriana Brancaccio*, IRECE; N. G. Alexopoulos, University of California, Los Angeles

1600 **VIRTUAL RAYS - SURFACE RAY EXCITATION**
N. G. Alexopoulos, University of California, Los Angeles; Giorgio Franceschetti*, IRECE; Pyotr Ya. Ufimtsev, University of California, Los Angeles

1620 **SCATTERING from COATED and IMPEDANCE WEDGES USING the METHOD of VIRTUAL RAYS**
David R. Jackson*, University of Houston; N. G. Alexopoulos, University of California, Los Angeles

1640 **VIRTUAL RAYS and a CONE DIFFRACTION PROBLEM**
Pyotr Ya. Ufimtsev, N. G. Alexopoulos*, University of California, Los Angeles

THE METHOD OF VIRTUAL RAYS IN SCATTERING THEORY

Nicolaos G. Alexopoulos, Electrical Engineering Department, University of California, Los Angeles, CA 90024-1594

The method of virtual rays is a new asymptotic technique apparently first introduced by Yu. I. Orlov ("Dissertation for the Scientific Degree of Candidate of Technical Sciences, Moscow Energy Institute Press, 1969). In subsequent efforts it was developed by L.A. Vainshtein for application to plasma diagnostics (L.A. Vainshtein, E.S. Birger, N.B. Konyukhova, E.L. Kosarev and G.P. Prudkovskii, "Shortwave plasma diagnostics", Sov.J. Plasma Phys., Vol.2, No.4, pp. 362-369, July-August 1976 and L.A. Vainshtein and E.A. Tishchenchenko, "Wave-tracing and shortwave diagnostics of a cylindrical plasma", Sov.Phys.Tech.Phys., Vol.21., No.11, pp. 1338-1343, November 1976) and to study the diffraction of electromagnetic waves from a wedge (L.A. Vainshtein and P.Ya. Ufimtsev, "Virtual rays in the problem of diffraction from a wedge", Radiotechnika i Electronika, Vol.2, No.4, pp. 625-633, 1982).

In recognizing the difficiencies of GTD and PTD to deal with impedance and/or absorber coated scatterers, this author proposed the introduction of the method of virtual rays in 1988 to solve such diffraction problems. This resulted in a report (D.R. Jackson and N.G. Alexopoulos, "Scattering by the Method of Virtual Rays, PRD Inc., December 1989) and it eventually led to the organization of this special session.

Virtual rays in general do not obey the usual principle of geometrical optics along the path of propagation from the source to the observer. Virtual rays may propagate in free space obeying geometrical optics, they may suddenly change direction or they may be trapped to propagate without attenuation along the boundary of a contour (for a two dimensional problem) or a surface (three dimensional geometry) before "shedding" off and assume a path obeying geometrical optics again.

A variety of general examples will be given in this presentation to establish the method as a novel technique which may be used to yield diffraction coefficients from objects with a realistic surface impedance or absorber coating. The papers which follow this presentation will deal with canonical diffraction problems wherein the validity of the method and its accuracy will be discussed.

VIRTUAL RAYS - THE HALF-PLANE

Giorgio Franceschetti*, IRECE, Via Diocleziano, 328-80124, Napoli, Italy, University of California, Los Angeles, CA 90024, Adriana Brancaccio, IRECE, Via Diocleziano, 328-80124, Napoli, Italy, N.G. Alexopoulos, University of California, Los Angeles, 90024

We apply the virtual ray (VR) theory [L.A. Vainshtein, P. Ya. Ufimtsev, "Virtual Rays in the Problem of Diffraction from a Wedge", Radiotechnika i Electronika, Vol.2, No.4, pp. 625-633, 1982] to compute the scattering by a half-plane whose boundary conditions are specified in terms of wave number dependent (i.e. physically realizable) surface impedances. The full ray solution is composed of four terms, each one containing an infinite series of round rays centered at the half-plane edge. The solution can be cast in such a way so as to exhibit usual direct, reflected and edge scattered cylindrical rays each consistent within its pertinent geometrical region of existence. In this analysis, possible excitation of surface rays is ignored.

The round rays contribution given in terms of an infinite series can be transformed into an infinite product. These two representations are useful in as much as they may lead to a closed form for the rays contribution. This is the case when the (normalized) upper and lower surface impedances are purely reactive and either complex conjugate i.e. $iX_1 = -iX_2$ or inverse complex conjugate $iX_1 = \frac{-1}{iX_2}$. This allows to recover known solutions for comparison purposes from one side and to generate new solutions for the other.

A full comparision of the VR theory is presented vs Maliuzhinets' solution [G.D. Maliuzhinets, "Excitation, Reflection and Emission of Surface Waves from a Wedge Given Face Impedances", Sov. Phys. Dokl., Vol.3, pp. 752-755, 1958] which, however, requires wave-number independent surface impedances. Accordingly, we first refer to the latter case and compare consistency between the two theories. Then, we relax the surface impedance limitiation and exhibit the difference introduced in the ray pattern by use of physically realizable surface impedances.

VIRTUAL RAYS - SURFACE RAY EXCITATION

Nicolaos G. Alexopoulos, University of California, Los Angeles, CA 90024, Giorgio Franceschetti*, IRECE, Via Diocleziano, 328-80124, Napoli, Italy, University of California, Los Angeles, CA 90024, Pyotr Ya. Ufimtsev, University of California, Los Angeles, CA 90024

It is well known that surface wave excitation upon surface impedance objects is possible when the incident wave exhibits spectral components in the pole region of the surface reflection coefficient. If a plane wave representation is used for the incident field, surface wave excitation is obtained when the integration path in the spectral domain is deformed and crosses reflection coefficient poles.

We consider excitation of surface rays where virtual rays representation is used for the incident field. Two approaches are explored: a heuristic one, with reference to the half-plane case; and a rigorous one, applied to the infinite plane.

Let us consider a plane wave impinging on the upper face of the impedance half-plane. Virtual ray theory allows to compute the field incident (i.e. before hitting) upon the lower face of the half-plane. Expressions of the field at this real angle of incidence can be continued analytically and evaluated at the complex resonant angle of the reflection coefficient, thus providing (but for a normalization constant) a possible surface ray. Assessment of the ray existence requires comparison with the canonical problem of the impedance infinite plane, which provides conditions of existence and appropriate normalization constants. We derived the surface ray excitation coefficient by using the above sketched technique and compared it with known Maliuzhinets' results [G.D. Maliuzhinets, "Excitation, Reflection and Emission of Surface Waves from a Wedge with Given Face Impedances", Sov. Phys. Dokl., Vol.3, pp. 752-755, 1958].

A basic study of this surface ray excitation requires a thorough examination of the virtual ray solution when the ray path is extended in the complex domain. This is done with reference to the simplest problem of an infinite plane whose boundary condition is given in terms of a surface reactance. A full discussion about surface ray excitation is provided.

SCATTERING FORM COATED AND IMPEDANCE WEDGES USING THE METHOD OF VIRTUAL RAYS

D.R. Jackson*, Department of Electrical Engineering, University of Houston, Houston, TX 77204-4793, Nicolaos G. Alexopoulos, University of California, Los Angeles, CA 90024-1594

The method of virtual rays is a novel technique for solving diffraction problems by superimposing the contributions of "virtual ray" fields. It is shown in [L.A. Vainshtein and P.Ya. Ufimtsev "Virtual Rays in the Problem of Diffraction from a Wedge", Radiotechnika i Electronika, Vol.2, No.4, pp. 625-633, 1982] that the free-space Green's function for a line source in the scalar wave equation (corresponding to either a TM or TE field radiated by an electric or magnetic line current) can be expressed in terms of virtual rays. These virtual rays are rays which propagate from the source along straight-line paths until reaching the point of tangency with a circle of arbitrary radius, at which point the rays are "captured" and propagate without attenuation along the boundary of the circle before "shedding" off and propagating along a straight-line path toward the observation point. By expressing the incident field of a line source in terms of this set of virtual rays, it is straight-forward to solve the problem of diffraction from a perfectly absorbing wedge [L.A. Vainshtein and P.Ya. Ufimtsev "Virtual Rays in the Problem of Diffraction from a Wedge", Radiotechnika i Electronika, Vol.2, No.4, pp. 625-633, 1982]. The absorbing wedge solution may also be extended to the case of an impedance wedge [L.A. Vainshtein and P.Ya. Ufimtsev "Virtual Rays in the Prolem of Diffraction from a Wedge", Radiotechnika i Electronika, Vol.2, No.4, pp. 625-633, 1982].

The method of virtual rays, discussed in [L.A. Vainshtein and P.Ya. Ufimtsev "Virtual Rays in the Problem of Diffraction from a Wedge", Radiotechnika i Electronika, Vol.2, No.4, pp. 625-633, 1982] for the solution of diffraction by a perfectly absorbing or impedance wedge is first reviewed, and then extended to solve the problem of diffraction by a wedge coated with one or more layers. The virtual ray solution reduces analytically to the known closed-form asymptotic solution for scattering from a PEC wedge as a limiting case, and numerical results demonstrate good agreement with published results for an impedance wedge. Results will be presented for a PEC wedge which is coated with material layers, to show the effects of dielectric or magnetic layers, which may be lossless or lossy. The method will then be extended to the case of a truncated (finite size) coated wedge.

VIRTUAL RAYS AND A CONE DIFFRACTION PROBLEM

P. Ya. Ufimtsev*, University of California, Los Angeles, CA 90024-1594, N.G. Alexopoulos, University of California, Los Angeles, 90024-1594

An axisymmetrical case of a cone excitation by a plane wave is considered. A key problem is a representation of an incident plane wave through virtual waves. A three-dimensional set of virtual rays is introduced to describe a plane wave. Each family of such rays is connected with a spherical surface. Rays come to this surface along tangents and leave it along other tangents. At exit points on a virtual sphere they undergo a sharp bend and move toward an observation point. A field brought to the observation point is described by a double integral. One of the integrals is taken over a horizon line and the second one over a variable radius of a virtual sphere. An asymptotic evaluation of the double integral gives exactly the given plane wave.

To investigate diffraction of a plane wave on a cone we put centers of virtual sphere at a cone tip. Now all virtual rays excited by a plane wave can reach a cone in two ways: they can meet a cone by being on a virtual sphere and they can leave a sphere and go to a cone. In the first case virtual rays undergo multiple reflection from a cone and only then travel to an observation point.

At present only the scalar problem of primary reflected virtual rays is considered. A formal solution is constructed and directions of subsequent investigation are discussed.

Friday AM URSI-B Session FA07

Room: Columbus A *Time*: 0820-1200

Theoretical Electromagnetics I

Chairs: Jin A. Kong, Massachusetts Institute of Technology; Y. T. Lo, University of Illinois, Urbana-Champaign

0820 **CONDUCTIVE PROBLEMS in SCATTERING with MAXWELL'S EQUATIONS**
T. S. Angell*, R. E. Kleinman, University of Delaware; A. Kirsch, University of Erlangen and Nurenberg

0840 **APPLICATIONS of FOURIER TRANSFORM PATH INTEGRAL METHOD to SCATTERING from TWO-DIMENSIONAL DIELECTRIC BODIES**
Zuoguo Wu*, Chenhong Huang, R. D. Nevels, Texas A&M University

0900 **THIN FILM BOUNDARY CONDITIONS**
Shyh-Kang Jeng*, National Taiwan University

0920 **CLOSED-FORM SOLUTIONS to SOMMERFELD INTEGRALS in MICROSTRIP PROBLEMS**
David C. Chang, University of Colorado at Boulder; Ahmad Hoorfar*, Villanova University

0940 **EFFICIENT ANALYTICAL-NUMERICAL ANALYSIS of SHORT PULSE PLANE WAVE SCATTERING from MULTILAYERED PERFECTLY CONDUCTING STRIPS**
Lawrence Carin, E. Cago Ribas*, L. B. Felsen, Polytechnic University

1000 **Break**

1020 **PROPAGATION of ELECTROMAGNETIC PULSES EXCITED by an ELECTRICAL DIPOLE in CONDUCTING MEDIA**
J. Song, K. M. Chen*, Michigan State University

1040 **THE TRANSIENT ELECTROMAGNETIC FIELD GENERATED by a PULSED ELECTRIC POINT SOURCE ABOVE an IMPERFECTLY CONDUCTING HALF-SPACE**
B. J. Kooij*, Delft University of Technology

1100 **FUNCTIONALS for VARIATIONAL PRINCIPLES in ELECTROMAGNETICS**
W. A. Davis*, C. F. Bunting, Virginia Polytechnic Inst. & State Univ.

1120 **TIME DOMAIN SCATTERING from FINITE PEC CYLINDER with ONE END OPEN and ONE END CLOSED: PO and GTD SOLUTION**
Barton Kahler*, Asoke K. Bhattacharyya, New Mexico State University

1140 **A NOVEL MIXED METHOD BASED on the COUPLING BETWEEN INTEGRAL EQUATION and FDTD METHOD for APPLICATIONS on EMC PROBLEMS**
Alain Reineix*, Universite de Limoges; F. Torres, University of Limoges; Bernard Jecko, IRCOM URA CNRS No 365, Equipe "EM"

Conductive Problems in Scattering with Maxwell's Equations

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Newark, DE 19716

A. Kirsch
Institute of Applied Mathematics
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D–8520 Erlangen, Germany

Both in problems of electromagnetic scattering from an object coated with a thin layer of high conductivity as well as in the study of electromagnetic induction in the earth (magnetotellurics), boundary conditions of resistive and conductive type have been found useful in describing the total field outside the scattering object.

In the time–harmonic case, in which the exterior and interior wave numbers are different, these resistive and conductive conditions lead to generalizations of the classical transmission problem. Specifically, if Ω is a bounded domain in $I\!R^3$, we consider the time–harmonic Maxwell equations

$$\operatorname{curl}\mathbf{E} = ik(\mathbf{x})\mathbf{H}\,, \operatorname{curl}\mathbf{H} = -ik(\mathbf{x})\mathbf{E}\,, \quad \text{in} \quad I\!R^3\backslash\partial\Omega$$

with

$$k(\mathbf{x}) = \begin{cases} k_1\,, & \mathbf{x}\in\Omega \\ k_2\,, & \mathbf{x}\in I\!R^3\backslash\overline{\Omega}\,, \end{cases}$$

subject to conductive conditions

$$\mathbf{n}\times\mathbf{E}\big|_+ - \mathbf{n}\times\mathbf{E}\big|_- = 0 \quad \text{on} \quad \partial\Omega\,,$$

and

$$\mathbf{n}\times[\mathbf{n}\times(k_2\mathbf{H}\big|_+ - k_1\mathbf{H}\big|_-)] = \mu_0\tau\omega\,\mathbf{n}\times\mathbf{E} \quad \text{on} \quad \partial\Omega\,,$$

and with an appropriate radiation condition.

While these generalized transmission conditions have been used at least since the mid 1970's, it was not until recently that any systematic attempt was made to show that these problems are well–posed in the sense of proving the existence and uniqueness of solutions as well as their continuous dependence on the data.

We report here on recent work in which boundary integral equation methods are used to show that these generalized transmission conditions lead to mathematically well posed scattering problems. In addition to proving existence, uniqueness and continuous dependence, we present a reciprocity principle and use this result to show that the class of all far field patterns corresponding to incident plane waves of any direction and any amplitude is dense in the space of all L^2–tangential fields on the unit sphere provided certain pairs of wave numbers (k_1, k_2) are avoided.

APPLICATIONS OF FOURIER TRANSFORM PATH INTEGRAL METHOD TO SCATTERING FROM TWO-DIMENSIONAL DIELECTRIC BODIES

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The path integral is a method that has recently been adapted for applications in electromagnetic scattering. Originally developed in quantum mechanics, the path integral has been shown to be a comprehensive method which can determine the scattered field to a distance of several wavelengths from an object. A new Fourier transform method which takes advantage of well developed fast Fourier transform software has recently been created to evaluate the path integral. The Fourier transform path integral (FTPI) method does not require a smoothly varying permittivity profile in the scattering region. However with the FTPI method unless the reciprocity theorem is used the position of the source and the observation points are limited to a region in the vicinity of the source determined by the computer memory size.

Here we will be presenting a comparison between the fields computed with the path integral Green's functions and other analytical and numerical methods when a source is placed in the presence of various dielectric objects. These will include the dielectric half space and cylinder cases. It will be shown that the path integral results agree favorably in all cases.

In obtaining the path integral Green's functions the entire two-dimensional space is confined to 50 wavelengths by 50 wavelengths and the Fourier transform array size is 400 by 400, which allows an object surface resolution of approximately one-eighth wavelength. Computation time is about 500 CPU on a CRAY Y-MP2 supercomputer. It will be shown that aliasing due to the FFT algorithm reduces the region of accuracy by approximately 50%.

Thin Film Boundary Conditions

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In the past many studies and applications are related to the scattering of an object with thin film structures. The moment method solution of a surface integral equation derived in an ordinary way for such a structure is not accurate, because the matrix elements related to both sides of this thin film are approximately equal, and the matrix becomes singular. The impedance boundary condition method, on the other hand, is only applicable to coated PEC objects, and when applicable, it is not accurate when the object has edges and sharp curvatures.

This presentation will propose a set of boundary conditions for a thin film structure (the thickness approaches to zero). It will show that the resistive card is a special case of this theory. When applied to the scattering of a PEC object with thin magnetic coatings, this theory results in a surface integral equation equivalent to that derived in an earlier paper (X. Min, W. Sun, W. Gesang, and K. M. Chen, IEEE Trans. Antennas Propagat., vol. 39, pp. 448-454, 1991). The integral equation by this theory involves only unknowns on one surface, instead of two by ordinary approach, and thus is more efficient. Some applications of this theory, including the transmission of waves through a thin composite material slab, and scattering from 2D PEC and dielectric cylinders with thin coatings will be demonstrated. The reason that the thin magnetic coating is superior than the electrically lossy material in reduction of RCS for a PEC body will also be given by simple circuit models. The discussions will include the validity regions of these boundary conditions and the comparison of results with those obtained by modal series solution (when available) and by the impedance boundary conditions.

CLOSED-FORM SOLUTIONS TO SOMMERFELD INTEGRALS IN MICROSTRIP PROBLEMS

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In the mixed potential formulation of the integral equation for solving the current distribution on a monolithic microwave integrated circuit, one often has to numerically compute the Sommerfeld integrals of electric and magnetic type since they appear as the kernels of the integral equation. These integrals often are first evaluated numerically for a range of distances and frequencies, stored and thenb interpolated as part of the solution process using spatial-domain techniques. As a result, an analytic expression for integrals with acceptable accuracy for distances that are small compared with free-space wavelength can considerably speed up the computation time required for the multi-frequency simulation of a MMIC circuit.

Other than for computational reasons, our interest in examining the electric and magnetic field responses as represented by these integrals is also motivated by a curious behavior numerically observed earlier by Mosig and Gardiol, and later by us: A large dip in the magnitude of the Sommerfeld integral of electric type occurred when $k_0 r$ is around 0.2 where r is the distance between a source and an observation point, and k_0 is the wave number in free-space. This phenomenon was explained as the transition from a pure static field to one more influenced by the TE surface-wave of the ground dielectric slab. For a MMIC circuit, the GaAs substrate typically has a thickness of 100 microns and a relative permittivity of 13. A quick calculation shows that both the distance and the substrate thickness are still very small compared with wavelength; consequently, one does not expect the surface-wave field to show up so strongly.

By invoking in this work a small thickness approximation, we are able to first able to extract the contribution from the point source and its partial images, and then evaluate the remaining integral analytically in terms of Bessel and Struve functions. We are able to show that this residue term behaves like

$$-a \ln \varepsilon_r \text{ as } \vec{r} \rightarrow 0$$

where

$$a = (1 - \varepsilon_r^{-1}) k_0 h$$

and ε_r is the relative permittivity and h is the substrate thickness. Furthermore, this term is not at all due to the surface-wave pole in the Sommerfeld integral. It produces a phase reversal effect so that the magnitude of the response can indeed become exceedingly small. Detailed comparisons between the analytical solution and the numerical results will be given in the presentation.

Efficient Analytical-Numerical Analysis of Short Pulse Plane Wave Scattering From Multilayered Perfectly Conducting Strips

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Plane wave scattering from multilayered strips has important applications in several areas of electromagnetics (optics, microwaves, etc.). With recent interest in short pulse electromagnetics, it is important to investigate scattering from such structures under short pulse plane wave illumination. For the purposes of this paper, a short duration pulse is defined as one with significant energies at wavelengths both much larger and much smaller than the strip width. Analysis of short pulse scattering from such strip arrays is therefore challenging since purely numerical or analytical techniques either fail or are inefficient over a significant portion of the pulse bandwidth.

In this work a hybrid analytical-numerical approach is used to efficiently analyze short pulse plane wave electromagnetic scattering from a larger but finite number of multilayered, perfectly conducting, infinitesimally thin strips residing in free space. The problem is analyzed in the frequency domain, with the time domain results found via the Fast Fourier Transform. As will be demonstrated, under short pulse conditions, thousands of frequency domain data points are required to accurately compute the scattered time domain waveform. Therefore, special considerations will be addressed such that such an analysis is practical computationally.

The problem is formulated at each frequency in the (spatial) spectral domain and is solved numerically using a Galerkin moment method procedure. The highly oscillatory reaction integrals for expansion and testing functions associated with different strips are evaluated asymptotically when appropriate. A uniform spectral domain asymptotic procedure is used, and is found accurate even when the strips are separated by a fraction of a wavelength. The asymptotic analysis of the reaction integrals will be described in detail, and it will be demonstrated that such a technique results in a significant reduction in computational time when compared with standard numerical integration techniques.

Once the analysis technique has been demonstrated, it will be used to study short pulse scattering from multilayered strip arrangements. Of particular interest will be how frequency selective surfaces perform under short pulse illumination.

PROPAGATION OF ELECTROMAGNETIC PULSES EXCITED BY AN ELECTRIC DIPOLE IN CONDUCTING MEDIA

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It is well known that a sinusoidal EM wave suffers a strong attenuation of exponential decay nature when it propagates in a conducting medium. However, an EM pulse excited by an antenna in a conducting medium may not attenuate that rapidly and may propagate over a moderate distance from the antenna because it contains a wide band of low frequency components.

We were able to find the exact solution of transient EM fields excited by an electric dipole antenna with an impulse antenna current in a conducting medium. Thus, by convolution, the propagation of EM pulses excited by the antenna with currents of arbitrary waveforms can be evaluated. We have found the optimum waveform for the antenna current which can generate an EM pulse with a maximum intensity at a particular distance from the antenna. We have found that the EM fields of an EM pulse excited by an antenna in a conducting medium can be divided into two parts: The first part is an impulse wave which propagates with the speed of light $(1/\sqrt{\mu_0 \varepsilon})$ and decays exponentially. The second part of EM fields builds up gradually and propagates slowly. More importantly, this second part of the EM fields attenuates as an inverse power of distance (between the third and the fifth inverse power of distance depending on the waveform of the antenna excitation current), which is a much slower rate than the exponential decay. This wave behaves somewhat like a "diffusion wave" in nature.

Numerical results based on FFT algorithm and branch cut integration scheme are compared with the exact solution.

THE TRANSIENT ELECTROMAGNETIC FIELD GENERATED BY A PULSED ELECTRIC POINT SOURCE ABOVE AN IMPERFECTLY CONDUCTING HALF-SPACE

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Previous work of Kooij [Radio Science, Vol. 25, Number 4, pp. 349 – 356, 1990] has been extended to further investigate the more general configuration of the transient electromagnetic field that is excited by an electric pulsed point source above an imperfectly conducting half-space. A new method is applied in order to obtain exact closed-form space time expressions for the electromagnetic field components. The method is based on Laplace integral representations of the reflection and transmission coefficients, which are of a form suitable for the application of the Cagniard-de Hoop method for obtaining the space-time domain couterparts of the field components. The method can be applied even in the case we have contrast in both the permeability and the permittivity. It is shown that a headwave occurs when the wave speed of the imperfectly conducting half-space exceeds the wave speed of the non-conducting half-space. Closed-form expressions are derived for large horizontal and large vertical offset approximations in the modified Cagniard method which lead to considerable reduction in computing time for the space-time electromagnetic field components compared with the full three dimensional version of the modified Cagniard method. Numerical results of the exact closed-form expressions of the field components in the space-time domain are presented for different values of the permittivity, permeability and conductivity as well as numerical results for the field components obtained by using the large vertical and large horizontal offset approximations in the modified Cagniard method.

FUNCTIONALS for VARIATIONAL PRINCIPLES in ELECTROMAGNETICS

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The problem of determining an appropriate functional for solution of electromagnetics problems using variational methods has long been a challenge. This paper considers an approach to determining appropriate functionals based on energy and power considerations in the time domain. The transient form is then transformed to the sinusoidal steady-state to determine the needed functional forms. From the formalism, the standard functionals for both electrostatic and magnetostatic problems will be developed as well as the classic linear operator form of functional typical of energy minimization. If the expansion functions are chosen to be formed as finite elements, these functionals give rise to the classic finite-element method.

The application of the concepts to time-varying dynamic fields is found to be more difficult. In general, the linear operator is generally found to not be self-adjoint when taken in an inner-product form. However, some insight may be obtained by consideration of the fundamental energy and power constraints obtained from the development mentioned above. It is found that an additional constraint must be imposed on the system as compared to the simpler linear operator form. This constraint corresponds to a conservation of power and enforcing this constraint becomes a matter of concern. A simple method for applying what is hope to be this constraint leads one to use the method of weighted residuals. The emphasis is on the aspect of hope since the method of weighted residuals is not based on variational principles. In fact, one must choose between using the original expansion functions for weights or the conjugate. It will be shown that the incorrect choice of conjugation or not may indeed lead to an incorrect answer.

To further consider the choices suggested, propagation in a closed waveguide will be considered. We will indeed find incorrect solutions depending on the approach taken to the functional form and its ultimate enforcement.

TIME DOMAIN SCATTERING FROM FINITE PEC CYLINDER WITH ONE END OPEN AND ONE END CLOSED: PO AND GTD SOLUTION

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Time domain(TD) scattering from various radar targets have been of interest for quite sometime. Recently, there has been a renewed interest with the availability and use of wide band radars. It appears to the authors that on time domain scattering problems much more work has been done using numerical methods rather than analytical. In this work, analytical expressions for time-domain scattered fields from a PEC cylinder with one end open and one end closed have been obtained using time-domain physical optics(TDPO) and time-domain geometrical theory of diffraction (TDGTD). The TDGTD coefficient [Ref: T.W. Veruttipong- 'Time-Domain Version of the Uniform GTD', IEEE Trans. Antennas and Propagat., Vol. AP-38, No.11, Nov 1990, pp.1757-1764] for a PEC straight wedge has been used to obtain the TD scattered fields from the cylinder. The time domain scattered fields were obtained for different combinations of parameters, namely, the bandwidth of the incident wave, cylinder dimensions, aspect angle and both TE and TM polarizations. The cases of incidence where the energy predominantly penetrates the open end are not included in this presentation. The effect of different radar and target parameters on the characteristics of the TD response of the structure are discussed. Also included is a comparison of TDPO and TDGTD results. Some closed end scattering results of the cylinder have been compared with Dominek's recent investigations[A.K. Dominek- 'Transient Scattering Analysis For a Circular Disk',IEEE Trans. Vol. AP-39, No.6, June 1991, pp. 815-819] on disk scattering. The contribution from double diffracted rays(DDR) around the broadside was estimated and it was found that for a cylinder of diameter 4" and length 60 inches, the DDR is about 14.5 dB weaker than single diffracted ray (SDR) for broaside and the DDR further weakens away from broadside. For the closed end, the DDR is about 52.5 down with respect to SDR at normal incidence and further weakens away from the normal.

A NOVEL MIXED METHOD BASED ON THE COUPLING BETWEEN INTEGRAL EQUATION AND FDTD METHOD FOR APPLICATIONS ON EMC PROBLEMS

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In order to reproduce electromagnetic phenomena, it's often necessary to realize an experimentation and to build simulators : a typical case is the NEMP problem. As a result, we have to concept simulators which are able to reproduce the real field that would arrive on a structure. Generally, the simulator is only able to take into account one or two polarization of the incident field, this is a factor of limitation of experimental investigations. To overcome this limitation, a theoretical procedure should be developed by modeling theoretically the experimentation. Two reason can be invoqued : first, to find the experimental results, and in a second time, to extend it to many cases of polarization.

A classical example of such a simulator is an antenna which produce field on a system.

Numerically, the challenge is to give a sufficiently accurate model for representing the emittor (antenna), the system (a car, a plane...) and the coupling between them. The idea is to develop a mixed method that couples two theoretical time-domain methods, the Integral Equation and the Finite-Difference Time-Domain, and to take the advantage of each one.

Generally, the system is complex and can be decomposed into volumic and surfacic cells, the FDTD is a good candidat for representing it.

The antenna can often be represented by thin wires, using the Integral Equation method. It's generally YAGI, log-periodic or biconical antennas.

The coupling between the system and the antennas is made by a radiation integral on the E field and another on the H field. An optimization of these integrals, which has the drawback to be time consuming, must be made each time limit conditions are to be applied on the system (at every discretization points of the structure).

The main advantage of such a method comes from the fact that it is not necessary to model a 3D domain that surrounds the antenna and the structure, because such a modelization could mean a very large grid, particularly when the distance between the antenna and the structure is important (to be in far field zone). Here, we only have to make a grid surrounding the structure. An other advantage comes from the characteristics of time-domain methods : after only one run, results on a large bandwidth are available. The method has been applied to study the coupling between a car and a log-periodic antenna on a large bandwidth [200 MHz, 1 GHz].

Friday AM URSI-B Session FA08

Room: Columbus C/D *Time*: 0820-1200

High Frequency Diffraction

Chairs: John L. Volakis, The University of Michigan; R. Tiberio, University of Florence

0820 **APPLICATION of MALIUZHINETS METHOD to DIFFRACTION PROBLEMS INVOLVING GENERALIZED IMPEDANCE BOUNDARY CONDITIONS**
H. C. Ly*, R. G. Rojas, Prabhakar H. Pathak, The Ohio State University

0840 **SCATTERING by a DIELECTRIC COATED CONDUCTING WEDGE. ASYMPTOTIC and HYBRID TECHNIQUES.**
V. Gerard, MOTHESIM; D. Lesselier, CNRS - ESE; F. Molinet*, MOTHESIM; W. Tabbara, E.S.E./C.N.R.S.

0900 **A SPECTRAL INCREMENTAL DIFFRACTION COEFFICIENT**
R. Tiberio*, S. Maci, University of Florence

0920 **MULTIPLE WEDGE DIFFRACTION**
Giuliano Manara*, University of Pisa; S. Maci, Giuseppe Pelosi, R. Tiberio, University of Florence

0940 **WAVEFRONT and RESONANCE ANALYSIS of SCATTERING by an IMPEDANCE STRIP**
Joseph D. Kotulski*, Sandia National Laboratories

1000 **Break**

1020 **DIFFRACTION by a TERMINATED PARALLEL-PLATE WAVEGUIDE CAVITY with PARTIAL MATERIAL LOADING**
Kazuya Kobayashi*, Shoichi Koshikawa, Akiko Sawai, Shigeki Tsuboi, Chuo University

1040 **USING PHYSICAL OPTICS for HIGH FREQUENCY ANALYSIS of the PLANE WAVE SCATTERING by an ELLIPTIC CONE**
M. Martinez, A. Martin*, R. Villar, Consejo Superior de Invest. Cientificas

1100 **AN ASYMPTOTIC ANALYSIS of the NEAR FIELD EM SCATTERING from a SMOOTH CONVEX BODY**
Mimi Hsu*, C. W. Chuang, Prabhakar H. Pathak, Ri-Chee Chou, The Ohio State University

1120 **BEAM RADIATION from SMOOTH CONCAVE-TO-CONVEX BOUNDARY**
T. Ishihara*, K. Goto, K. Kitamura, National Defense Academy

1140 **A COMPARISON of RAY TRACING METHODS for the ANALYSIS of HIGH FREQUENCY SCATTERING by ARBITRARILY SHAPED CAVITIES**
Antonio Garcia-Pino*, F. Obelleiro, J. L. Rodriguez, A. M. Arias, Universidad de Vigo

APPLICATION OF MALIUZHINETS METHOD TO DIFFRACTION PROBLEMS INVOLVING GENERALIZED IMPEDANCE BOUNDARY CONDITIONS

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The generalized impedance boundary conditions (GIBCs), which involve field derivatives of higher order than the first, have frequently been used by many authors to model thin material slabs in electromagnetic scattering problems. The application of GIBCs provides more accurate models for non-metallic surfaces than the traditional Leontovich boundary conditions. However, difficulties arise when GIBCs are used because they yield solutions which are neither unique nor reciprocal even after the edge condition is applied. In most solutions involving GIBCs found in the literature, with the exception of [Rojas, et al., Radio Science, 26, pp. 641-660, 1991], the reciprocity condition had to be imposed explicitly so that the solutions are reciprocal. After enforcing reciprocity, some authors fail to address the issue of uniqueness, while others claim additional constraints are required yet fail to specify those constraints in a rigorous way. In this paper, Maliuzhinets method is used to solve two diffraction problems which are modeled by GIBCs of second order, and unique solutions are obtained after the determination of an additional junction condition following Leppington's approach (F.G. Leppington, Proc. Roy. Soc. A386, 443-460, 1983). The first problem considered is the diffraction by the junction of a two-part thin material coated perfectly conducting ground plane; the second problem is the diffraction by a thin material coated perfectly conducting half-plane where the coatings on the top and bottom faces are different. In both problems, the incident field is assumed to be a normally incident plane wave. To ensure a unique solution for each problem, it is required to impose an additional condition, sometimes referred to as a contact condition, which can be determined if the field in the proximity of the junction is modeled by an approximate quasi-static solution. In other words, the contact condition is the additional condition obtained by matching the quasi-static solution with the Maliuzhinets spectral function which is expanded in the region where the quasi-static solution is valid. The final solutions thus obtained are complete and automatically satisfy reciprocity without having to enforce reciprocity a priori. To verify the accuracy of our solutions, some numerical results presented in this paper are compared with results computed from an independent moment method solution.

SCATTERING BY A DIELECTRIC-COATED CONDUCTING WEDGE. ASYMPTOTIC AND HYBRID TECHNIQUES.

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Scattering by perfectly conducting structures of simple shapes which are coated by dielectric or magnetic layers is the focus of many investigations, first, because of the academic value of the problem, second, since complicated objects whose properties, e.g., RCS, are attracting a wide interest can be made up of such simple parts. The problem here is the plane wave scattering by a metallic wedge coated by a dielectric plane layer which is not necessarily thin with respect to the wavelength of the incident wave and whose electric properties are arbitrary. We are interested both in the near field and in the far field. For the sake of simplicity, only the case of a normal incidence TE- or TM-polarized wave is considered, and each face of the wedge is assumed to be covered by the same linear isotropic lossless material.

There exists a rather involved canonical approach [*A. Michaeli, Electron. Let., 24, 1291-1292, 1531, 1988*] where the author extends to the coated wedge an asymptotic solution developed earlier by Maliuzhinets in the case of a constant face impedance. It is based on a plane wave spectral expansion of the fields and one of its main assets lies in the fact that it accounts for the exact variations of the impedance of the metallic-backed coating vs. the incidence angle of each spectral plane wave. The solution is the sum of the incident field, of the field reflected by the coating, of an edge-diffracted field (that cancels out on the wedge itself when we limit the asymptotic expansion to the first-order) and of fields due to surface waves whose contribution is important only inside and near the coating. In the first part of the exposé, we summarize how this procedure performs (we did not know of any complete numerical investigation before) from the analysis of a number of test cases with respect to the various parameters of the modeling (angle of the wedge, thickness and electric parameters of the coating, incidence and polarization of the illumination) and attention to usual questions (reciprocity, symmetry, ...), and comparisons with others, e.g., [*J. Bernard, Wave Motion, 9, 543-561, 1987*].

The second part of the exposé is devoted to a hybrid technique of calculation combining a Method of Moments with the above asymptotic approach in order to rigorously treat the field near the edge and use time-saving but accurate approximations at some distance from it. Hybrid techniques are able to handle a variety of cases which, as ours, may be difficult to solve either asymptotically (leading to a poor description of the field near the edge) or by MoM (due to modeling the wedge by domains of finite extent). The case of the perfectly conducting wedge is well-known [*W. D. Burnside et al., IEEE Trans. Antennas Propagat., AP-23, 551-558, 1975*] and the much more involved coated wedge is worth investigating along close lines. To do so, we introduce a polygonal "junction" zone whose one summit is at the edge and which covers a limited part (a wavelength long or so) of the coating on each face. Exact boundary integral equations satisfied by the unknown scattered field (total field minus incident and reflected field if any) result from enforcing the Green's theorem inside and outside the junction. The coefficients of pulse-basis expansions of the unknown on the junction boundaries near the edge and the excitation coefficients of the surface waves that are the main contributors to the field farther from the edge are then calculated by point-matching on the various boundaries. Numerical simulations with emphasis on the influence of tuning parameters (junction length, number of basis functions, location of matching points, ...) and on comparisons with the asymptotic approach, allow us to show the pros and cons of the hybrid method and to discuss possible improvements in the fields' modeling and in the method itself via iterative schemes.

A SPECTRAL INCREMENTAL DIFFRACTION COEFFICIENT

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As is quite well known, two leading theories have been widely used to describe the scattering phenomenon by a complex object at high-frequencies; namely, the Geometrical Theory of Diffraction (GTD) and the Physical Theory of Diffraction (PTD). Although the Uniform GTD has removed the singularities that occurr in the original GTD formulation at the shadow boundaries of the GO field, still there are serious difficulties in applying this ray method close and at caustic directions. The PTD, in principle, is not affected by these above imparements; however, as a counterpart it requires a significant numerical effort. In order to alleviate such a limitation, Incremental Length Diffraction Coefficients (ILDC) (know also as Equivalent Edge Currents (MEC) or Edge Waves (EW)) have been formulated to asymptotically describe fringe current contributions, which occur whenever an edge discontinuity introduces a relevant distorsion of the PO currents. It has been found that different results are obtained depending on the direction which may be chosen to integrate the non uniform currents predicted by PTD. Correspondingly, different singularities may or may not occur. Although they are subtracted out when a fringe contribution evaluation is performed, some questions may arise about their physical significance. Also, it can be shown that different applications of the equivalence principle to the same canonical problem of a perfectly conducting wedge, may lead to different formulations of the ILDC. This appens even if the same (more or less promising) criterium is adopted to chose the direction of integration. In particular in a ray fixed coordinate system, quite different off-diagonal (cross-polar) components may be obtained, as well as different modifications occur in the diagonal (co-polar) components of the ILDC. In any case, they do not satisfy reciprocity.

In this paper, these somewhat puzzeling circumstances are examined and discussed. Also, a different formulation is suggested, which may avoid such difficulties; at the same time, it may provide a useful tool to extend the applicability of the UTD.

MULTIPLE WEDGE DIFFRACTION

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In analyzing the scattering from complex structures, compact, uniform high-frequency expressions for the description of multiple wedge diffraction may be important. In particular, a simple, successive application of the Uniform Geometrical Theory of Diffraction (UTD) coefficients for single wedge diffraction may lead to invalid results when the edge of a wedge is illuminated by transition region fields. This happens when the source, two or more diffracting wedges and/or the observation point lie on a straight line or are slightly displaced from this alignement. It should be noted that this is just the situation where the multiple diffraction significantly contributes to the scattering phenomenon. Among a variety of practical applications, such a uniform solution may be for instance, particularly useful in treating the scattering from two staggered parallel, thick screens and in predicting the propagation path loss in the presence of both hilly terrain and man made environments.

Although the double diffraction phenomenon has been treated extensively, a uniform solution for multiple diffracted field contributions is not yet available. In this paper a suitable asymptotic expression for multiple wedge diffraction is presented, which can be applied to uniformly describe up to four interactions of an incident plane wave with the edges of a multi-wedged structure, when also the observation point is in the far zone. To this end, an extended ray method is applied. In particular, when considering three cascaded diffracting edges, first the field singly diffracted by the first edge is interpreted as a spectrum of inhomogeneous plane waves. Next, each component of the spectrum is doubly diffracted by the following edge. Thus, a double integral formulation for the triply diffracted field is then obtained, which can be asymptotically evaluated to yield a uniform solution in the UTD format. A special care is required in the evaluation of the double integral in order to obtain the pertinent distance parameter, taking also into account that one of the involved pole singularities depends on both the variables of integration. Both standard and modified Fresnel integral functions occur in the final expressions.

In the case of four diffracting edges, a triple spectral integral formulation is obtained which need to be reduced to known transition functions. To this end, by conveniently rearranging the singularities in the integrand, it is found that one integration can be performed without involving any singularity so that the asymptotic problem is reduced to a double integral evaluation.

Several numerical results are presented to show that the complete ray solution is uniform and to demonstrate its accuracy.

WAVEFRONT AND RESONANCE ANALYSIS OF SCATTERING BY AN IMPEDANCE STRIP

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An impedance strip is a two–dimensional flat strip with an impedance boundary condition on the upper and lower surfaces. Previous investigations of the impedance strip have identified the complex pole positions using two different methods. One method was based on ray techniques and consisted of ray tracking on the strip surface combined with a ray closure condition. This ray closure condition implies that multiple rays combine in phase after multiple circumnavigations and yield the resonances. The impedance strip solution differs from a perfectly conducting strip by the appearance of surface waves and the Maliuzhinet's function in the diffraction coefficient. The other method utilized the electric field integral equation which was discretized using the moment method. This is a low–frequency solution. The zeroes of the determinant of the impedance matrix then yield the resonances. The resonances using these two techniques compared well, and this demonstrates the connection between rays and resonances. The present study considers the time response of the impedance strip. Two techniques will be used to calculate the transient response of this scatterer. One technique is based on the Singularity Expansion Method(SEM) which is a resonance description. The time response is found by inversion of the Laplace integral closed in the left–half plane to give a contour that encloses the singularities which results in a residue series.

Alternatively, the scattered fields can be described as spectral integrals(in the frequency domain). These integrals are constructed in the context of ESRM(extended spectral ray method) and account for the multiple edge interactions which may occur. Due to the impedance condition on the scatterer, additional surface–wave contributions may exist. Because of the high–frequency nature of representation this solution is a wavefront expansion. The time response can then be found by inversion of the spectral integrals. The results from these two techniques will be compared and discussed. The effect of different impedances on the upper and lower faces will be considered as well as the inclusion of the surface wave.

DIFFRACTION BY A TERMINATED PARALLEL–PLATE WAVEGUIDE CAVITY WITH PARTIAL MATERIAL LOADING

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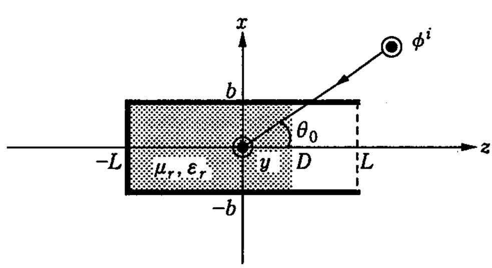
Analysis of the scattering and diffraction by open–ended waveguide cavities has been of great interest recently in radar cross section (RCS) reduction and electromagnetic penetration/coupling studies. As an example of simple two–dimensional cavity structures, we have previously considered a finite parallel–plate waveguide cavity with a planar termination, and analyzed the plane wave diffraction rigorously using the Wiener–Hopf technique (K. Kobayashi and A. Sawai, *J. Electromagnetic Waves & Applics.*, to be published, 1992). The results have been recently generalized to treat the case of a cavity with a thick planar termination (S. Koshikawa and K. Kobayashi, to be presented at *National Electromagnetic Theory Meeting, IEE Japan,* May 21–22, 1992). Other generalization to the material–loaded case has also been discussed, in which the whole region inside the cavity is filled with dielectric/ferrite media (K. Kobayashi, *IEEE–APS International Symposium Digest*, 1054–1057, 1991 ; S. Koshikawa and K. Kobayashi, *ibid.*, 1058–1061, 1991).

In the present contribution, as a generalization to the material–loaded case treated in our previous papers, we shall rigorously analyze the plane wave diffraction by a terminated parallel–plate waveguide cavity with partial material loading as shown in the figure using the Wiener–Hopf technique, where ϕ^i is the incident field. The surface of the cavity is infinitely thin, perfectly conducting and uniform in the y–direction, and the medium inside the cavity for $-L < z \leqq D$ is characterized by the relative permittivity ε_r and the relative permeability μ_r. The problem reduces to the one treated in the previous papers by letting $D \rightarrow L$. The exact solution is obtained and an approximate solution useful for numerical computations is then derived. Both E and H polarizations will be considered, and the scattering characteristics will be discussed via numerical examples of the RCS.



USING PHYSICAL OPTICS FOR HIGH FREQUENCY ANALYSIS OF THE PLANE WAVE SCATTERING BY AN ELLIPTIC CONE

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As it is well known, the physical optics (PO) method is applicable when the wavelength of the incident radiation is small with respect to the characteristic dimension of the body. In the past, this method has been largely used for calculating radar cross section of bodies of revolution (K.M. Siegel et al., J. Appl. Phys., Mar, 1955). Siegel studied the plane wave scattering of circular cones for axial incidence. Scattering near axial incidence has been treated in a recent paper (K.D. Trott, P.H. Pathak, F.A. Molinet, IEEE Trans. Ant. Prop. Aug. 1990). They obtain tip diffracted fields and the results are very accurate in comparison with a rigorous asymptotic solution for the narrow angle cone.

In this paper we analyze the plane wave scattering by a perfectly conducting elliptic cone using the physical optics approximation. For axial incidence, using spheroconal coordinates (S. Blume, G. Kahl. Optik, 70 no. 4, 1985), analytical expressions are derived for the monostatic radar cross section and the bistatic one in symmetry planes, solving the physical optics integral by known methods. In order to obtain uniform expressions in bistatic situations and non axial backscattering, an asymptotic evaluation of the PO integral is presented that includes the tip contribution for the semi-infinite cone and the tip and base contributions for the finite one. In addition near field calculations are considered. The near field results for the tip on axial incidence can be used to calculate the tip-base interaction. Results can be compared with the ones of the circular cone.

AN ASYMPTOTIC ANALYSIS OF THE NEAR FIELD EM SCATTERING FROM A SMOOTH CONVEX BODY

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The development of a modified asymptotic high frequency solution to the problem of near field scattering from a perfectly conducting convex body illuminated by a near field source is presented. The results will allow us to treat the problem of an arbitrarily-located source and observation point. Presently, asymptotic solutions exist for the following limiting positions of a source and an observer: source and observer on the surface of a convex body and source and/or observer not too close to the body. The first case is referred to as the mutual coupling case (P.H. Pathak and N.N. Wang, IEEE Trans. on Antennas and Propagation, p. 911-922, 1981). If the source is assumed to be far from the conducting body, the problem is referred to as a scattering type (P.H. Pathak, W.D. Burnside, and R.J. Marhefka, IEEE Trans. on Antennas and Propagation, p. 631-642, 1980). On the other hand, if the source is on the surface of the body and the observer is in the far field of the source, the problem is a radiation type (P.H. Pathak, N.N. Wang, W.D. Burnside, and R.G. Kouyoumjian, IEEE Trans. on Antennas and Propagation, p. 609-622, 1981). These new results will allow us to essentially bridge the gap between the three limiting cases indicated above.

These new results are developed by formulating the solutions for the near field scattering from the canonical circular cylinder and sphere geometries and then generalizing the results to treat the case of an arbitary convex surface via the uniform theory of diffraction (UTD) concepts. The canonical solutions are first expressed in terms of generalized spectral integrals. Both the source and observer are assumed to be close to the surface of the canonical body; consequently, all terms involving the heights of the source and observer above the surface can be expanded in a power series about the radius of the body. Next, appropriate asymptotic approximations are used in place of the special functions (Hankel functions). The form of these approximations varies depending on which region the source or observer is in. Finally, using various asymptotic techniques appropriate to the form of the resulting integral, we obtained expressions which are valid for near field scattering due to a near field source.

These new equations will be shown to numerically yield a smooth transition from the fields that they predict to the fields predicted by the three limiting cases discussed above.

BEAM RADIATION FROM SMOOTH CONCAVE-TO-CONVEX BOUNDARY

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When the source is located near or on the concave boundary, waves with many reflections are confined near the surface, with consequent piling up of caustics in that vicinity. These waves with many reflections cannot be treated as the conventional geometrical rays since they interfere with each other during the propagation process. The high order reflected waves or the interference waves, instead, must be treated collectively, either in terms of a selected number of whispering gallery modes that are guided along the surface or in parabolic equation (PE) form. The phenomena of the field behavior for convex shapes such as geometrically reflected fields and creeping wave diffracted fields in illuminated and shadow regions, as well as transition fields near shadow boundaries are well understood.

When the curvature of the boundary changes smoothly from concave to convex through the inflection point,there exists, unfortunately, no canonical prototype configuration that yields a tractable rigorous solution, from which the inflection point transition can be inferred. Therefore,it is necessary to rely on direct asymptotic method.

In this work we consider a beam-like wave and a creeping wave over a concave-to-convex boundary radiated by whispering gallery modes which are incident on an inflection point of the boundary from the concave side.

Numerical comparisons reveal the validity and utility of the various alternative field representations. Included are PE method, Fresnel-Kirchhoff diffraction formula, modified adiabatic whispering gallery mode technique and Kirchhoff (current) approximation.

A COMPARISON OF RAY TRACING METHODS FOR THE ANALYSIS OF HIGH FREQUENCY SCATTERING BY ARBITRARILY SHAPED CAVITIES

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Different methods have been used for the analysis of High Frequency Scattering of Cavities [P.H. Pathak, R.J.Burkholder. "Modal,ray, and Beam Techniques for analyzing the EM Scattering by Open-Ended Waveguide Cavities". IEEE Tap. May 1989, vol .37, no. 5] [H.Ling,S.W.Lee,R.C.Chou. "High-Frequency RCS of Open Cavities with Rectangular and Circular Cross Sections". IEEE Tap. May 1989, Vol. 37, no. 5]. This paper presents a comparison of different ways to implement ray methods which combine G.O. models for the propagation of the rays inside the cavity and aperture integration to obtain the scattered fields.

Wideband and multiple polarization analysis is made by independently taking into account the phase changes due to path length and those due to caustics in the field associated with each ray.

We have compared different models of the tubes of flux defined by rays:
a) Rays are grouped in triads. Linear distributions of phase and amplitude are used for the triangular domains determined by the rays on the exit aperture.
b) A cross-sectional area for the tube is associated with each ray along the ray propagation. Once the ray abandons the cavity, a rectangular cross sectional area is considered, and then, aperture integration is carried out using a quadratic phase model according to the two principal curvatures of the phase-fronts of the axial ray.

The number of rays necessary for the algorithms can be optimized by an adaptative ray tracing which concentrates greater density of rays only where cross sectional area becomes excessively large.

We have used parametric Bezier patches to model the arbitrarily shaped surfaces numerically. Special difficulties arises from that parametric description in the ray tracing process, specifically in the determination of reflection points.

In order to obtain such points, some iterative algorithms are used, which can be accelerated by adequate election of the initial points. This election can be achieved by tracing the whole bundle of rays between consecutive reflections.

Friday AM URSI-B Session FA11

Room: Columbus H *Time*: 0820-1200

Advances in Numerical EM Analysis I

Chairs: Tapan K. Sarkar, Syracuse University; D. H. Schaubert, University of Massachusetts at Amherst

0820 **APPLICATION of CONJUGATE GRADIENT-FFT METHOD to MICROSTRIP ANTENNAS by USING DISCRETE IMAGE TECHNIQUE**
Yuan Zhuang*, Ke-Li Wu, John Litva, McMaster University

0840 **CG-FHT-FFT METHOD for the ANALYSIS of RADIATION from a LOOP ANTENNA in an INHOMOGENEOUS MEDIUM with ROTATIONAL SYMMETRY**
Q. H. Liu*, Schlumberger-Doll; W. C. Chew, University of Illinois, Urbana-Champaign

0900 **COMPUTATION of ELECTROMAGNETIC SCATTERING from 2D and 3D OBJECTS - a CLASS of FFT-BASED METHODS**
T. V. Tran*, A. McCowen, University College of Swansea

0920 **ANALYSIS of MICROWAVE MULTILAYER CIRCUIT USING CONVENTIONAL and PULSED SPECTRAL DOMAIN TECHNIQUE**
Leopoldine Kaliouby*, Y. Delisle, Renato G. Bosisio, Ecole Polytechnique de Montreal

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J. E. Roy*, The University of Manitoba; G. A. Morin, Department of National Defence; L. Shafai, The University of Manitoba

1000 **Break**

1020 **NUMERICAL MODELS for PRACTICAL FEEDS and TERMINATING LOADS in PRINTED CIRCUITS**
A. B. Kouki*, A. Khebir, Renato G. Bosisio, F. M. Ghannouchi, Ecole Polytechnique de Montreal

1040 **AN EFFICIENT COMPUTATION of the EFFECTIVE LENGTH of an OPEN-CIRCUITED HOLLOW CYLINDRICAL DIPOLE**
Robert T. Johnk*, Motohisa Kanda, NIST

1100 **COUPLED SPHERICAL-WAVE APPROACH to SCATTERING from DIELECTRIC OBJECTS**
Al J. Gasiewski*, M. Bliesener, Georgia Institute of Technology

1120 **CALCULATION of a SURFACE CURRENT DENSITY on a THREE-DIMENSIONAL CONDUCTING BODY**
Hiroyoshi Ikuno*, M. Gondoh, Masahiko Nishimoto, Kumamoto University

1140 **DISTRIBUTED MEMORY TANGENTIAL FINITE ELEMENTS for INHOMOGENEOUS SCATTERERS in FREE SPACE**
J. W. Parker*, R. D. Ferraro, P. C. Liewer, Jet Propulsion Laboratory

Application of Conjugate Gradient-FFT Method to Microstrip Antennas by Using Discrete Image Technique

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In this paper, the conjugate gradient FFT (CG-FFT) method is combined with discrete image technique to analyze microstrip antennas and arrays. The major advantage of the combination is that it merges the merits of the both techniques and extend the application of CG-FFT to the analysis of microstrip antenna problems without the difficulty of calculating Sommerfeld-type integral.

By using CG-FFT method in solving the integral equation associated with microstrip antennas problem, the large computer storage and long CPU time, which are required if Moment Method(MM) is applied, are reduced significantly. Since the computer storage requirement is $O(N)$ and CPU time requirement is $O(4N+log_2N)$ for CG-FFT method in opposite to $O(N^2)$ and $O(N^3)$ for MM respectively. These factors makes CG-FFT method very suitable for large structure analysis, such as microstrip antenna arrays. However, in the application of CG-FFT method to the analysis of microstrip antennas, the Sommerfeld-type Green function is involved, which is very cumbersome in computation and very hard to get the closed form of its fourier transform.

We extend the application of CG-FFT to microstrip antenna problems effectively by combining the CG-FFT with the full-wave discrete-image technique, one of the recently developed algorithms for efficient calculation of the Sommerfeld-type Green's function, . The important feature of full-wave discrete image technique, which makes it very suitable to be combined with CG-FFT method, is that once the discrete images are found for a given substrate and frequency, the complex Sommerfeld-type integral function becomes a summation of a number of exponential functions (usually four or five is enough). These exponential functions have the closed form of the Fourier transform, so that the CG-FFT method can be implemented on the integral equation without any difficulty. By the combination, One can convert a spectral domain problem into a spatial domain problem without losing any full-wave information. Therefore, microstrip antennas with large dimension, such as arrays, can be analyzed much more effectively with the combination of the techniques. The computer time required for generating the discrete image is negligible compared to the time required for the implementation of CG-FFT. And for a given substrate(one layer or multilayer), only one set of images has to be found for each frequency, regardless of the antenna configurations. In this paper, various types of microstrip antennas and arrays are investigated by the approach given above. The results show that the CG-FFT with full-wave discrete-image technique is a very effective and efficient approach for the analysis of microstrip antennas and arrays. The detail of our study will be presented in the conference.

CG-FHT-FFT METHOD FOR THE ANALYSIS OF RADIATION FROM A LOOP ANTENNA IN AN INHOMOGENEOUS MEDIUM WITH ROTATIONAL SYMMETRY

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In this paper, we propose a CG-FHT-FFT method (the conjugate gradient method combined with the fast Hankel transform and fast Fourier transform) for the efficient solution of the radiation from a loop antenna in an inhomogeneous medium with rotational symmetry. We assume that the loop antenna is located concentrically with the axisymmetric inhomogeneous medium, even though the algorithm presented here can be extended to other cases where the source is located anywhere in space. For the study of radar cross section, the source can be replaced by an incident plane wave.

For a concentric loop antenna in an inhomogeneous medium with rotational symmetry, we will show that the scattered field from the inhomogeneous medium can be written in terms of the Hankel transform in ρ and Fourier transform in z of the unknown induced current $J(\rho, z)$. We obtain an integral equation for $J(\rho, z)$ as

$$\frac{1}{k^2 - k_b^2} J(\rho, z) - \mathcal{H}^{-1}\mathcal{F}^{-1}\left\{\frac{1}{(k_\rho^2 + k_z^2 - k_b^2)}\mathcal{H}\mathcal{F}\left[J(\rho, z)\right]\right\} = E_\phi^{\mathrm{inc}}(\rho, z), \qquad (1)$$

where $\mathcal{H}$ stands for the Hankel transform in ρ, and $\mathcal{F}$ stands for the Fourier transform in z. Instead of using the conventional method of moment, we propose a new method based on the conjugate gradient (CG) method combined with fast Hankel transform (FHT) and fast Fourier transform (FFT) to solve the integral equation (1) iteratively (hence, the name CG-FHT-FFT method). In each iteration of the conjugate gradient method, fast Hankel transform and fast Fourier transform are used to reduce the computation complexity to $N \log_2 N$ (where $N = N_\rho N_z$ is the total number of unknowns). Another advantage of this method over the method of moment is that only vectors of dimension N are stored. Therefore, the CG-FHT-FFT method is advantageous over the method of moment in terms of both computation time and storage requirement.

We have implemented the CG-FHT-FFT method to solve problems related to electromagnetic well logging. Numerical examples will be shown to illustrate the efficiency of the CG-FHT-FFT method and to compare with the available results obtained by other numerical methods.

COMPUTATION OF ELECTROMAGNETIC SCATTERING FROM 2D AND 3D OBJECTS - A CLASS OF FFT-BASED METHODS

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The matrix interpretation of the spectral iteration technique (MSIT) has recently been demonstrated to perform well for both 2D and 3D dielectric scatterers in the resonant region, (A.McCowen & T.V. Tran, IEE Proc, Pt H, Vol 138, 219-224, 1991). The defining equation is the volume form of the Electric Field Integral Equation (EFIE) with discertisations being performed by pulse basis functions and Dirac delta-function point matching. The discretised forms are then solved by Van den Berg's Conjugate Contrast Source Truncation (CCST) technique, (P.M. Van den Berg, IEEE Trans AP 32, 1063-71, 1984).

The MSIT and conjugate gradient FFT method (CGFFT) can be looked at as belonging to a family of methods that use the FFT to perform the required convolutions. This is made possible by the unified scheme of Van den Berg, who showed that the well-known and often called Conjugate Gradient Method can be derived by an appropriate choice of variational basis function, whereas the SIT-inspired selection gives rise to the MSIT.

Tests have been performed on a wide range of 2D and 3D dielectric scatterers from which the number of iterations and CPU time required for each method is compared between the two methods which have identical storage requirements.

During the course of this investigation a 'third choice' of variational basis function has emerged. Tests performed on the same scatterers have shown that the 'third choice' has the potential of significantly reducing the CPU time, with no additional storage. In 2D and 3D the 'third choice' shows an improvement in CPU time of typically 50% against the MSIT and CGFFT. The additional advantage here is that the 'third choice', unlike the MSIT, also solves for inhomogenous dielectric scatterers.

This paper will discuss the 3 choices of variational basis function to yield the MSIT, CGFFT and 'Third choice' schemes and give details of the performance of the different schemes against a range of 2D and 3D dielectric scatterers in the resonance region.

ANALYSIS OF MICROWAVE MULTILAYER CIRCUIT USING CONVENTIONAL AND PULSED SPECTRAL DOMAIN TECHNIQUE

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Spectral domain technique can be used for the analysis of microwave integrated circuit. The principle of the method consists in taking the Fourier transform of the boundary conditions and solving using Galerkin optimization technique.

For quasi-static analysis, one major problem with the spectral domain technique is the choice of basis functions to describe the charge distribution on the conductor. Usually, these functions are chosen on an intuitive basis, and thus constitutes by definition an approximation of the exact charge distribution.

One approach to solve this problem is to use pulsed spectral domain technique. In this method, the charge distribution is represented as a series of pulse functions; thus, by choosing Δx sufficiently small, one can represent with good precision the value of the charge distribution.

As an example of application, the design of a directional coupler with septums shows the following results:

- the value of the even impedance is more precise by 1.5% for values of s/(10.h) = (L-a)/h = 5 and decreases monotically for decreasing values of s/(10.h) = (L-a)/h, to attain 8.5% for values of s/(10.h) = (L-a)/h = 1.
- the value of the odd impedance is more precise by ~ 1.5% for values of s/(10.h) = 5 for all values of (L-a)/h and increases monotically for decreasing values of s/(10.h) to attain 9.5% for values of s/(10.h) = 1.

Performance of a Simple Circular Polarization Selective Surface

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This paper presents a parametric analysis of a simple Circular Polarization Selective Surface (CPSS) performed with the program NEC-2 (Numerical Electromagnetic Code). The operation of the unit cell and of an octogonal array made of 37 identical cells are shown in incidence angle, frequency and cell size.

An ideal Left hand Circular Polarization Selective Surface (L-CPSS) is a surface that would reflect completely an impinging Left Hand Circular Polarized (LHCP) wave and yet, would be completely transparent to an impinging Right Hand Circular Polarized (RHCP) wave. Such a surface would be sure to find many applications, the most obvious one being that of a circular polarizer. Another application, which is the one that we target, is the Cassegrain reflector antenna in which the hyperboloidal subreflector is replaced by a flat CPSS in order to minimize the aperture blockage and so reduce the sidelobe level of the antenna. A flat CPSS is well suited for this application since the large physical surface area is, in principle, transparent to the desired polarization. The flat geometry permits however a much easier fabrication process. As the incidence angle varies from point to point on the subreflector surface, the effect of the incidence angle on the performance of the CPSS becomes of paramount importance. In this paper, we investigate the performance of the CPSS with respect to incidence angle as well as frequency and cell size.

NUMERICAL MODELS FOR PRACTICAL FEEDS AND TERMINATING LOADS IN PRINTED CIRCUITS

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With the continuing progress in the field of numerical modeling and simulation of microwave printed circuits and devices, there is an increasing need for more accurate models of practical feeding and terminating arrangements. Coaxial probe-type feeding (See Figure 1.a) is one of the commonly used methods for feeding microstrip-type circuits. The other two common feeding mechanisms are the bond wire attachment (See Figure 1.b) which is frequently used in miniature circuits and the end-attachment scheme used to feed printed circuit components with relatively large dimensions. In all of these arrangements, an good numerical model should satisfy the continuity equation in the transition region. Although a rigorous analysis should treat the currents carried by the feeding elements as unknown, using some determined values for these quantities does not introduce any significant error.

One of the most common configurations used in terminating microstrip circuits is the "matched load" arrangement. This is usually implemented by matching the impedance of the terminating device with that of the microstrip line. Since the concept of impedance is not well defined for microstrip lines, a numerical model based on it is difficult to obtain. This difficulty and possible remedies to it will be discussed. In particular, the extension of the microstrip lines with segments that have some surface impedance will be examined as an alternative termination model.

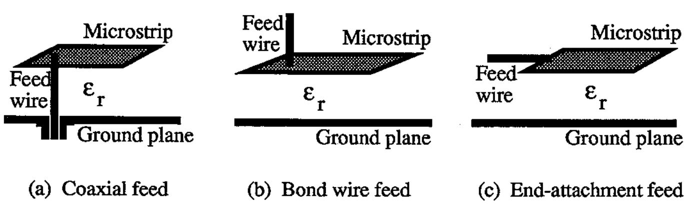

Figure 1. Different microstrip feeding arrangements.

AN EFFICIENT COMPUTATION OF THE EFFECTIVE LENGTH OF AN OPEN-CIRCUITED HOLLOW CYLINDRICAL DIPOLE

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The Fields Interference and Metrology Group at the National Institute of Standards and Technology (NIST) has been engaged in the generation and measurement of standard fields for many years. One type of measurement that is performed at NIST is the determination of field strength using sets of standard tuned dipoles. Because of detection and instrumentation requirements, each of the tuned dipoles has a symmetrically displaced gap which must be accounted for in the effective length computation.

In order to study the gap effects on the effective length of a dipole, the scattering problem of a plane wave incident on the broadside of an open-circuited dipole of length L with a gap of width G is solved. A solution of this problem was presented earlier (R. T. Johnk and M. Kanda, Proc. URSI Symp., Jan. 7-10, 1992) by solving an electric-field integral equation (EFIE) using a Galerkin moment method procedure to obtain the antenna current distribution and, thereby, the antenna electric field. The effective length was then found by evaluating a line integral of the electric field along an appropriate contour. One of the limitations of the earlier approach is that a thin-wire approximation is used in the formulation of the EFIE. This approximation works well when the gap width is much greater than the dipole radius, but in the case of a narrow gap the use of a thin-wire approximation is questionable.

In order to obtain results that are valid for gaps of arbitrary size, the dipole current density is modelled as two cylindrical shells with open ends, separated by the gap width G. Exact free-space Green's functions are employed in solution of the EFIE and in the subsequent evaluations of the electric field and the effective length. This procedure is tantamount to solving the scattering problem of a plane wave incident on a hollow cylindrical dipole. As was the case previously, the choice of the appropriate path for the electric field line integral in the effective length evaluation is critical in order to avoid convergence problems.

Coupled Spherical-Wave Approach to Scattering from Dielectric Objects

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A coupled-spherical-wave (CSW) numerical solution for the T−matrix coefficients of an arbitrarily-shaped dielectric object is described. The CSW solution follows the coupled-plane-wave (CPW) approach for scattering from periodic surfaces as described by Moharam and Gaylord (J. Opt. Soc. Am., 72, 1385-1392, 1982).

In the CPW approach, the periodic region is divided into thin slabs and the fields within each slab are expanded in a series of Floquet harmonics. Each harmonic has an amplitude that varies with surface depth; the degree of variation is set by the amount of coupling caused by the dielectric structure within the slab. Eigenanalysis and subsequent application of boundary conditions at the slab boundaries provides yield an exact numerical field solution. This technique has been successfully used to predict the scattering characteristics of optical gratings and absorbing microwave calibration targets.

For dielectric objects of finite extent, the CSW approach proceeds in an analogous fashion. The region between the minimum and maximum spheres is divided into thin shells and the fields within each shell are expressed in a series of vector spherical harmonics. Each harmonic has an amplitude that varies with radius; the degree of variation is set by the amount of coupling caused by the dielectric structure within the shell. Again, eigenanalysis and subsequent application of boundary conditions yield a matrix equation for the harmonic amplitude coefficients; this can solved numerically for either the T−matrix coefficients or the spherical harmonic amplitudes.

An analogous technique can be formulated for dielectric extrusions using coupled cylindrical waves (CCW). The numerical implementation and limitations of the three coupled wave approaches will be discussed.

CALCULATION OF A SURFACE CURRENT DENSITY ON A THREE-DIMENSIONAL CONDUCTING BODY

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The Yasuura method that belongs to the generalized multipole expansion method has dual algorithms [K.Yasuura, Progress in Radio Science 1966-1969, URSI, **3**, 257-270, 1971] ; one is an algorithm for calculating a scattered field and the other is an algorithm for calculating a total tangential magnetic field on the surface of scatterer from which we can compute a surface current density. We have applied them to two-dimensional scattering problems [H.Ikuno and K.Yasuura, IEEE Trans., **AP-21**, 657-662, 1973 ; K.Yasuura and Y.Okuno, ibid., **AP-33**, 1369-1378, 1985] and obtained several interesting results [H.Ikuno and K.Yasuura, Radio Sci., **13**, 937-946, 1978]. Recently, we successfully applied the Yasuura method to the three-dimensional scattering problem and found some new aspects about this problem [H.Ikuno and M.Nishimoto, Trans.IEICE, **J72-C-1**, 689-696, 1989 ; H.Ikuno, M.Gondoh and M.Nishimoto, ibid., **E-74**, 2855-2863, 1991].

The purpose of this paper is to show an algorithm for calculating a total tangential magnetic field on the surface of scatterer. An approximate total tangential magnetic field on the surface of scatterer can be represented by a linear combinations of the cross product of the unit normal vector on the surface and the complex conjugate of the vector spherical wave functions and can be matched with a total tangential magnetic field in the least squares sense. Minimizing the difference of the boundary value and using the reaction formula [V.H.Rumsey, Phys. Rev., **94**, 1483-1491, 1954], we have a simultaneous linear equation about expansion coefficients. Solving this equation, we have an approximate total tangential magnetic field on the surface. The cross product of the unit normal vector and the approximate total tangential magnetic field results in the surface current density on the surface of the scatterer. On the other hand, we have another algorithm for calculating the surface current density on a sufficiently smooth surface. We expand a scattered electric field into a linear combinations of the vector spherical wave functions and determine expansion coefficients by matching the boundary condition in the mean squares sense [H.Ikuno and M.Nishimoto, Trans. IEICE, **J72-C-1**, 689-696, 1989]. Using this scattered electric field, we may calculate a total tangential magnetic field on the surface of the scatterer, although its convergence rate is very slow. Now we discuss a numerical algorithm for the calculation method of the total tangential magnetic field on the surface directly. To do so, we replace the surface integral about the square of the absolute value of the difference of the tangential magnetic field on the surface with a discrete double sum with respect to sampling points which are determined according to the Gauss-Legendre quadrature formula by considering the property of the associated Legendre function [C.E.Froberg, Introduction to numerical analysis, Addison-Wesley, 205-213, 1972]. A number of sampling points is set to twice as large as the largest mode number in the approximate multipole expansions. Then, it is numerically show that a calculated surface current density converges to a limiting value as the mode number increases and the convergence rate of this solution is faster than that of the solution calculated from the scattered field mentioned above. The current density on the body of revolution has an essentially different feature from that on the cylindrical body.

DISTRIBUTED MEMORY TANGENTIAL FINITE ELEMENTS FOR INHOMOGENEOUS SCATTERERS IN FREE SPACE

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The finite element technique for solving electromagnetics problems based directly on the underlying vector differential equation holds out the promise of computing scattering from arbitrary geometries and combinations of materials. However, useful solutions in three dimensions have been limited by available memory and numerical difficulties called vector parasites. A validated finite element code is presented which addresses both these problems. The memory limitations are eased by writing the code for distributed memory computers with explicit message passing communication. The program currently runs on the JPL/Caltech Mark IIIfp hypercube (0.25 Gbytes of core) and is targeted for Intel iPSC/860-based machines, such as the Touchstone Delta at Caltech with about 8 Gbytes. Such capacities allow solution to 3-D problems with diameters of several wavelengths. The numerical vector parasite problem is overcome by using tangential finite elements.

The distributed memory tangential element code performs the following steps. A partition file (from a domain decomposition program) directs each processor to retain a small portion of the mesh file elements and nodes. From this local element and node data, a unique local tangential degree-of-freedom number is assigned to each edge (or edge-node combination) of the mesh, and a message list is compiled based on shared edges. Basis-function overlap integrals for each element are computed independently in each processor and summed into a local stiffness matrix. Either an iterative or direct solver is invoked, which solves the distributed-memory stiffness matrix using explicit inter-processor message passing. The tangential-vector solution is interpolated to 3-component vectors at each node, which are written to disk. Post-processing allows near-field extraction on curves and planes, and calculation of the bistatic RCS.

Whitney edge-tangential elements are found to result in robust convergence of simple iterative matrix solvers, in particular the diagonally preconditioned bi-conjugate gradient method. Tests to date indicate the higher-order tangential elements of Lee (J.F. Lee, Int. J. Numer. Methods, 3, 235-246) result in more accurate solutions for a given number of unknowns, but require direct matrix solution for reliable calculations; such solvers require much more memory. An additional drawback of the Whitney element is its lack of surface-divergence support, requiring a more distant wave-absorbing boundary. Numerical RCS and near-field solutions are presented from conducting spheres and cubes, and dielectric spheres. RCS values typically are within 1/2 dB of solutions found by alternative techniques.

Friday AM1 URSI-E, NEM Session FA12

Room: Columbus I/J *Time*: 0820-1000

Hybrid CW Simulators

Chair: Cinzia Zuffada, Kaman Sciences Corporation

0820 **TOPOLOGY for TRANSMITTING LOW-LEVEL SIGNALS from GROUND LEVEL to ANTENNA EXCITATION POSITION in HYBRID EMP SIMULATORS**
Carl E. Baum*, William D. Prather, Phillips Laboratory; Donald P. McLemore, Kaman Sciences Corporation

0840 **ELECTROMAGNETIC MODELING of LARGE LOOPS with CONCEALED DRIVE for REMOTE GAP FEED**
Cinzia Zuffada*, Kaman Sciences Corporation; Carl E. Baum, William D. Prather, Phillips Laboratory

0900 **TEST RESULTS for the PHILLIPS LABORATORY HIGH FREQUENCY CW SIMULATOR**
Tyrone Tran*, William D. Prather, Phillips Laboratory; Donald P. McLemore, Joe Martinez, Cinzia Zuffada, Kaman Sciences Corporation

0920 **AN EXPONENTIALLY TAPERED TRANSMISSION LINE ANTENNA**
N. H. Younan*, B. L. Cox, C. D. Taylor, Mississippi State University; William D. Prather, Phillips Laboratory

0940 **HIGH FREQUENCY ANALYSIS of the ELLIPTICUS ANTENNA**
N. H. Younan*, B. L. Cox, C. D. Taylor, Mississippi State University; William D. Prather, Phillips Laboratory

TOPOLOGY FOR TRANSMITTING LOW-LEVEL SIGNALS FROM GROUND LEVEL TO ANTENNA EXCITATION POSITION IN HYBRID EMP SIMULATORS

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In a typical hybrid EMP simulator there is a multi MV pulser above the ground, inserted in the resistively loaded wire-cage antenna. Suppose now one wishes to use a CW source over some broad band of frequencies in place of the high voltage pulser. This can be done by replacing the pulser with a CW source in the same (large, say a few meters in diameter) wire-cage antenna. Recognizing that for CW transfer functions one needs only low-level fields, and that efficiency in the sense of kV/m per MV in the pulser is not a problem, one can modify the design of the antenna. In particular the antenna could be a resistively loaded single wire with an equivalent diameter in the cm range.

Suppose one were to have the source on the ground and transmit the signal via a high-quality coax cable up to the old source location, perhaps with some matching network there to drive the antenna. Such a cable is a very large electromagnetic scatterer and, except under special symmetry conditions, will strongly perturb the fields produced in the test volume. The test volume needs to be far from this cable to avoid interaction with the test object. What is needed is a special kind of "wormhole" to make the cable effectively disappear for external scattering purposes. This can be approximately accomplished by alternating electric (conductor) and magnetic (choke) boundary conditions with suitably small spacing. Topologically the low-level source (CW or pulse) is fed from the earth surface up to the antenna feed position via a high quality coaxial cable. With the chokes suppressing the external cable-shield currents the source is moved to one of the connections of the hybrid antenna to the earth, while the loaded cable is moved to closely follow the path of hybrid antenna. Then transferring the resistors in the hybrid antenna to load the chokes (in parallel) it is observed that the loaded cable and the hybrid antenna can be one and the same.

There are limitations in the practical realization of this technique. The choke impedance has to be large compared to the loading R for frequencies of interest. At high frequencies the cable needs to be of sufficiently low loss for the length needed. Furthermore, there should be a sufficiently small spacing between chokes so that there are not significant resonances on the cable shield exterior.

ELECTROMAGNETIC MODELLING OF LARGE LOOPS WITH CONCEALED DRIVE FOR REMOTE GAP FEED

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Abstract

A new concept for a broadband low level hybrid EMP simulator has been investigated. It consists simply of a thin half loop of arbitrary shape, made of low loss coaxial cable, erected above the ground. Its original feature is in the feed: the signal is transmitted inside the cable from the RF source located on the ground to a remote point high above the ground where the cable outer conductor is cut open and an actual gap source is created. The current flows along the external surface of the conductor and through the ground, giving rise to EM fields. To give these fields the desired features of a plane wave at low frequency, proper resistive loading is achieved by placing RF chokes along the cable. Because the coupling is inductive the loading is effective on the external flow of current only, and does not interfere with the drive signal traveling inside the coaxial cable. A simple analytical model to calculate the fields produced by this antenna was developed, based on an asymptotic antenna theory for thin loops, which assumes that the ground is perfectly conducting. The load, although localized, is modeled as a frequency dependent impedance uniformly distributed along the antenna. Comparisons are presented between the calculations obtained from our simple, efficient code and experimental results, as well as calculations obtained with the NEC under consistent assumptions. The satisfactory agreement of the calculations from our model with NEC's and with experimental results indicate that we have developed a viable, efficient tool for field predictions of thin loops of arbitrary shape.

TEST RESULTS FOR THE PHILLIPS LABORATORY HIGH FREQUENCY CW SIMULATOR

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The Phillips Laboratory's low level CW illuminator which is described in two other papers*, was field mapped during the summer of 1991 in two basic configurations. One configuration was a notional twin catenary, the apex of the antenna being supported 20 meters in the air by ropes connected to telephone poles separated by 65 meters. The other configuration was a more elliptical shape with additional dielectric ropes supporting the antenna at regular distances to achieve the more elliptical geometry.

For the Twin Catenary configuration, the coaxial cables in each arm were connected to a fiber glass panel (approximately 1 meter x 1 meter) at the center and each of the arms was connected to a grounding rod at the earth-connected end. An resistive and inductive loading was used on the coaxial cable to control the impedance of the antenna as a function of frequency using 110 lower frequency torroids (material # 77-maganese/zinc) and 110 higher frequency torroids (material #43-nickel/zinc). To eliminate the need for a matching balun between the coaxial feed and the the antenna at the gap, a 50 ohm resistor was placed in parallel with the antenna. The Elliptical antenna was similarly configured with respect to ground connections and torroid loading.

Electric and Magnetic fields produced by these antennas were measured from 100 kHz to 200 MHz with a HP 3577 network analyzer and from 75 MHz to 1 GHz with an HP 8753C network analyzer within the working volume. The results illustrate relatively constant fields produced by these antennas over this frequency range in the working volume, which recommends its use as a CW simulator. This antenna was also used to measure both internal and external cable currents on a mobile communications system. Results from this test will also be presented.

*Baum, C., "Topology for Transmitting Low-Level Signals from Ground Level to Antenna Excitation Position in Hybrid EMP Simulators"

*Zuffada, C., Baum,.C. and Prather, W., "Electromagnetic Modeling of Large Loops with Concealed Drive for Remote Gap Feed"

AN EXPONENTIALLY TAPERED TRANSMISSION LINE ANTENNA

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ABSTRACT

For EMP applications, the illumination of large system structures should be uniform to be representative. However, radiative illumination tends to be highly nonuniform at frequencies where the test object characteristic dimension exceeds several wavelengths. Accordingly, an exponentially tapered transmission line antenna is designed to operate over the frequency range of 500 KHz to 1 GHz. This antenna has radiator characteristics at high frequencies and serves as a matching section at low frequencies.

The high frequency analysis is accomplished by using numerical techniques. Since transmission line theory does not account for radiation, the NEC-2 computer code is used to model only a portion of the exponentially tapered transmission line structure where electrically short straight wires segments are used to model the structure. Accordingly, a Thevenin model is used to replace that section of the structure. The Thevenin voltage and impedance are obtained via transmission line theory.

The evaluation of the design of the exponentially tapered antenna is obtained in terms of the input impedance and the radiation pattern of the antenna over the desired frequency range. For an open circuit termination, transmission line theory yields an input impedance that is purely imaginary. However, the numerical solution yields, in addition, a resistive component that is proportional to the radiated power for a constant input current. This is expected since the numerical solution includes radiation effects. Although the input impedance exhibits resonant peaks, the variation with frequency is appreciably smoothed. Also, as the frequency increases, the corresponding pattern calculations indicate that the transition section becomes an effective radiator.

HIGH FREQUENCY ANALYSIS OF THE ELLIPTICUS ANTENNA

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ABSTRACT

Present EMP test facilities, in general, do not provide the required high frequency illumination. Accordingly, a low level CW facility that incorporates the Ellipticus antenna is used to provide a horizontally polarized electric field to illuminate test objects. The original design specifications for the Ellipticus are provided such that it operates over the frequency range of 10 KHz to 100 MHz. Upgrading the Ellipticus to cover frequencies up to 1 GHz is accomplished by using a transition section from the driver to the antenna. The transition section is needed for impedance matching and for driving efficiently the Ellipticus antenna.

Due to the wide operating frequency range, a numerical rather than an analytical analysis of the Ellipticus illuminator is required. Accordingly, a procedure that incorporates the use of the NEC-2 computer code is used to examine the electromagnetic fields that can be developed in the working volume of the Ellipticus antenna. A parametric study is performed to ascertain the performance of the antenna for frequencies up to 1 GHz.

In the NEC modeling of the Ellipticus illuminator at high frequencies, i.e., 200 MHz and up, the entire transition section is replaced by its Thevenin model due to the large structure to be analyzed and to the limitations of the wire spacing in the NEC code. For frequencies below 200 MHz, the transition section is modeled with straight wires up until the wire spacing approaches 4 or 5 wire radii. Thevenin model is then used for the remaining length of the transition section.

The NEC results obtained from modeling the Ellipticus illuminator over a lossy ground plane indicate that the amplitude of the current decreases rapidly with distance from the driving point at high frequencies. Moreover, field uniformity is achieved within the working volume of the Ellipticus antenna.

Friday AM URSI-B Session FA13

Room: Columbus K/L *Time*: 0820-1120

Applications of High Frequency Methods

Chairs: Robert T. Brown, Lockheed Advanced Development Co.; F. Molinet, MOTHESIM

0820 **SIMPLE APPROACH to MULTIPLE INTERACTIONS in PHYSICAL OPTICS SCATTERING**
Robert T. Brown*, L. A. Takacs, Lockheed Advanced Development Co.

0840 **RCS COMPUTATION of 3D COATED RADAR TARGETS at HIGH FREQUENCY**
S. Vermersch*, CEA - CESTA Service Informatique

0900 **OPTIMAL CONTROL APPLIED to R.C.S**
M. Mandallena*, CEA - CESTA Service Informatique

0920 **RCS of STEALTH AIRCRAFT: PREDICTION and OPTIMIZATION by GRAPHICAL PROCESSING TECHNIQUES**
Juan M. Rius*, Merce Vall-llossera, Angel Cardama, L. Jofre, ETSE Telecomunicacio - UPC

0940 **COMPUTING OPEN-ENDED WAVEGUIDE SCATTERING VIA ITERATED PHYSICAL OPTICS**
L. A. Takacs*, Robert T. Brown, Lockheed Advanced Development Co.

1000 **Break**

1020 **CROSS SECTION CALCULATIONS and MEASUREMENTS of CONDUCTING TEST TARGET TOWLINES**
E. D. Evans*, MIT Lincoln Laboratory

1040 **RADAR CROSS SECTION COMPUTATIONS of COMPLICATED TARGETS by the APPLICATION of the PANEL METHOD**
Zhou Jianjiang*, Shu Yongze, Nanjing Aeronautical Institute

1100 **ELECTROMAGNETIC SIMILARITY for the COATED TARGETS**
Xuegang Zeng*, Geyi Wen, Chengli Ruan, Univ. of Elect. Science & Tech. of China

A Simple Approach to Multiple Interactions in Physical Optics Scattering

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The most widely used computational method for predicting the scattering of electromagnetic radiation from electrically large targets of arbitrary shape is that of physical optics (PO) combined with the physical theory of diffraction (PTD). Currently available PO techniques do not include the effects of multiple scattering, although there have been studies of physical optics scattering from concave bodies constructed of electrically large flat plates. This is the approach used for example by Atkins and Shin (*J. Electromagnetic Waves and Applications* vol. 2, pp. 687-712, 1988), and Balanis and Griesser (in *Radar Cross Sections of Complex Objects*, W. Ross Stone, ed., New York: IEEE Press, 1989, pp. 260-274). Other PO-based approaches combine PO with geometrical optics raytracing (Cleveland) or beamtracing (Lam), described in *Data Book of High-frequency RCS*, S. W. Lee and R. J. Marhefka, eds., Urbana: Electromagnetics Code Consortium, 1989.

This paper describes an extension of the methods of physical optics to bodies in which multiple interactions between portions of the target are included. The method uses the standard tangent-plane approximation of physical optics, with the surface divided into planar triangular facets. Multiple interactions are handled by nested bistatic PO integrals, and each bistatic interaction is assumed to form an approximate plane wave for the secondary illumination. There are two significant differences between the approach outlined here and the bistatic PO methods mentioned above. One is in the treatment of the phase of the bistatic field, which is assumed linear rather than quadratic. The other is in the inverse r_{ij} factor, which is assumed constant over each surface element. With these two approximations the bistatic integral that is required reduces to the usual far-field bistatic PO formulation for a planar facet, greatly reducing computational complexity. Another advantage is that the method is immediately applicable to arbitrary shapes, since the surface has to be tessellated whether curved or not. The method has been found to give very satisfactory results provided that the surface elements are not much larger than a wavelength. For a dihedral corner reflector 5.6λ on a side, an element size of 1.4λ gives results in very good agreement with moment method calculations.

RCS COMPUTATION OF 3D COATED RADAR TARGETS AT HIGH FREQUENCY

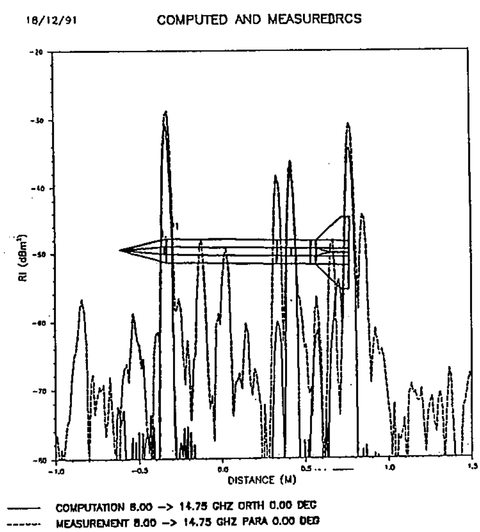
VERMERSCH - C.E.A. / C.E.S.T.A. - BP N°2 - 33114 LE BARP FRANCE

The Physical Theory of Diffraction (P.T.D.) is very well suited to RCS computation of complex objects, because it is free from divergence problems at caustics ans shadow boundary and gives always bounded results, regard less of incidence. We have extended the range of applicability of the PTD to coated bodies. To this end, we use an approximate solution for the diffraction by a wedge at oblique incidence. We deduce from this solution fringe wave equivalent currents that have the same properties as those of classical PTD.

Moreover, we have included double reflection and reflection diffraction effects to be able to compute the RCS of objects with reentrant corners. To do this, we have added to the PTD surface field, the field due to the reflection of thė incident wave on other parts of the target.

In order to validate this approach, we have compared the results with those obtained with a MoM method, on axysimetric objects, and with experimental measurements.

The figure compares the computed (plain line) and measured (dashed line) impulse responses on a missile mock up. The agreement is good for the main contributors. Low level peaks are due to the residual noise of the anechoic chamber.



TRASER

OPTIMAL CONTROL APPLIED TO R.C.S.

M. MANDALLENA - C.E.A. / C.E.S.T.A. - BP N°2 33114 LE BARP FRANCE

We minimize the RCS of coated 2D bodies by using an optimal control method. The shape of the body is specified. The control variable is the impedance Z on the surface. Z is chosen in a set of admissible impedance: U_{adm}. The cost function J to be minimize, is the square of the RCS norm : $J = |RCS|^2 = J(Z, g(Z))$,where g represents the surface's currents, which are solution of the Maxwell equation by a variational integral formulation :

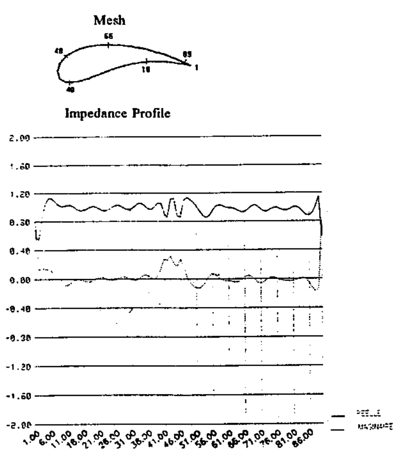
$$a(Z ; g , \varphi) = F(Z, \varphi) \quad \forall \varphi \in V .$$

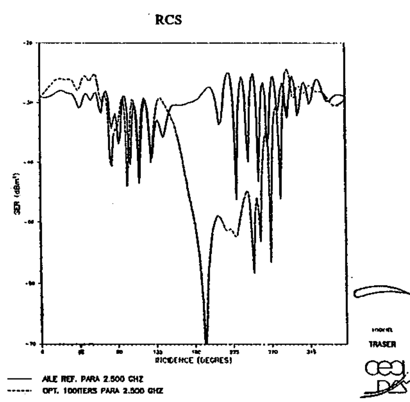
The problem is to find $Z_{opt} \in U_{adm}$ so that $J(Z_{opt}, g(Z_{opt})) = \inf_{Z \in U_{adm}} J(Z, g(Z))$

We deal with time harmonic fields, thus the quantities $a(Z ; g , \varphi)$ and $F(Z ; \varphi)$ are complex numbers. So we introduce the Lagrangian, which must be a real number :

$$L(Z , g , q) = J(Z, g) - a(Z ; g , q) + F(Z ; q) - \overline{a(Z ; g , q)} + \overline{F(Z ; q)} \quad .$$

We obtain the optimality system by deriving L with respect to the control Z and the state variable g, and solve our minimization problem by a steepest descent method. The figure compares RCS for constant (plain line) and optimized (dashed line) impedance for an airfoil The optimization is made for incidence angles between 180 and 270 degrees. We see from the figure that the optimization method allows signification reduction of the RCS in a wide range of angle of incidence.





RCS OF STEALTH AIRCRAFT: PREDICTION AND OPTIMIZATION BY GRAPHICAL PROCESSING TECHNIQUES

Juan M. Rius*, Mercè Vall-llossera, Angel Cardama, Lluis Jofre

Introduction

A new and original approach to compute RCS in real-time has been presented by J.M.Rius et al. in the preceding IEEE-APS Symposia: Dallas'90 and London'91. Real-time computation is achieved through graphical processing of an image of the target present at the workstation screen, using the hardware capabilities of a 3-D graphics accelerator. First-order reflections are obtained by rendering of the target with a local illumination algorithm, and multiple scattering with a global illumination one.

The I-DEAS computer aided design package for geometric modeling of solids has been used for modeling target geometry. The target is described as a collection of parametric surfaces, defined with two-dimensional NURBS (non-uniform rational B-splines).

The following high-frequency scattering phenomena are considered by the real-time graphical processing approach: Reflection at perfectly conducting surfaces by physical optics approximation, reflection at coated surfaces by physical optics and IBC approximations, diffraction at edges by method of equivalent currents using PTD diffraction coefficients, and multiple reflections between surfaces by radiosity global illumination method.

Graphical processing has the following advantages over the classical facets and wedges model approach: Hardware graphics accelerator removes hidden surfaces and edges so that they do not contribute to surface or line integrals, real-time computation (from 0.2 sec. to 10 sec.) is independent of target electrical size, the target can be modelled by parametric NURB surfaces, requiring less mass storage memory that the faceting approach and, finally, real-time RCS prediction software can be integrated with CAD geometric modeling package, thus providing an efficient tool for interactive modeling, design and analysis of aircraft with RCS specifications.

High-frequency RCS prediction by graphical processing techniques has been fully validated for simple objects and non-stealth radar targets.

RCS of F-117 Stealth Aircraft

In this communication, RCS prediction for Lockheed F-117 stealth aircraft will be presented, compared with RCS measurements of a scale model performed at our compact range facility. A perfectly conducting (PEC) surface will be assumed for both the numerical and scale models, so that the results will not correspond to the RCS of the real F-117, which has radar absorbent loading.

Although the results of graphical processing using the physical theory of diffraction (PTD) are very good for non-stealth radar targets, we expect that it will fail for the F-117 stealth aircraft. The reason is very simple: PTD, like GTD, is valid only for observation on the Keller cone. In the case of monostatic RCS prediction, the observation lies on the Keller cone only when the incidence direction is perpendicular to the edge. This means that there must be a specular reflection point on the edge, which is not expected on any stealth aircraft. In particular, all the edges on the F-117 are straight lines that may be oblique to the direction of incidence.

For that reason, Mitzner's Incremental Length Diffraction Coefficients (ILDC) will be implemented in the graphical processing algorithm, and the results will be compared with those of PTD. A better agreement with scale model measurements is expected.

We will also present results for the problem of RCS minimization of PEC shapes using constrained non-linear optimization techniques together with the real-time graphical processing algorithm for RCS prediction.

Computing Open-ended Waveguide Scattering via Iterated Physical Optics

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The high-frequency EM scattering from 3-dimensional open-ended waveguides of arbitrary shape is computed using a modification of the usual Physical Optics (PO) procedure. The Iterated Physical Optics (IPO) method is related to the Shooting and Bouncing Rays (SBR) method in precisely the same way that Phyical Optics is related to Geometrical Optics (GO). The IPO method is only approximate and reduces to the SBR in the short-wavelength limit.

At finite wavelengths however, the IPO carries additional information about the fields internal to the guide. Unlike any technique which uses GO rays to propagate fields inside the guide, the IPO method implicitly contains the partial effects of internal ray caustics, inflection scattering, and any diffraction due to electrical or physical discontinuities. While the Generalized Ray Expansion (GRE) method does include the significant initial diffraction caused by the aperture itself, it fails to account for any subsequent diffractions inside the guide.

In the IPO formulation, the usual far-field PO expressions for the bistatic scattered fields are written so that the scattered fields form secondary plane wave sources for the subsequent re-illumination of adjacent surfaces. In order to simplify the integration, a constant-phase approximation is made. This permits a surface-current sampling rate possibly as coarse as ≈ 16 samples per square wavelength. In practice, 20 or more are found to be adequate. The constant-phase approximation also causes the computation time to be proportional only to n_B, the number of bounces, rather than to a quantity raised to the power n_B. Results from various calculations will be presented.

Cross Section Calculations and Measurements of Conducting Test Target Towlines

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The detection performance of a radar system can be measured by towing unpowered airborne targets of known cross section through the radar's coverage region. Such targets are usually towed with a steel cable attached to a conventional Learjet-size aircraft. To ensure that the towline does not interfere with the return from the test target, it is important to understand the towline's scattering characteristics. This paper presents calculated and measured cross section results for a typical towline shape and orientation.

Figure 1 shows the geometry of a typical radar test with a towed target. In the figure, a towing aircraft pulls a test target directly towards a ground-based surveillance or tracking radar. The aircraft, towline, and test target are usually at a low elevation angle and a large distance from the radar. The towline adopts a profile that is essentially linear and horizontal near the towing aircraft and has a gradual curvature near the target end. Test target towlines may have a length up to 8 nmi and a diameter near 50 mils. The lines are usually constructed with conducting materials because they are stronger, cheaper, and more reliable than nonconducting materials such as nylon or kevlar.

In this paper we derive expressions for the cross section of conducting towlines. We consider the case where the range extent of the illuminating radar pulses are much smaller than the towline length. This complicates the derivation because the entire towline length is not uniformly illuminated. We first consider the cross section of the curved end of the line and then derive general expressions for the longer straight section. For both cases we give measured cross section results.

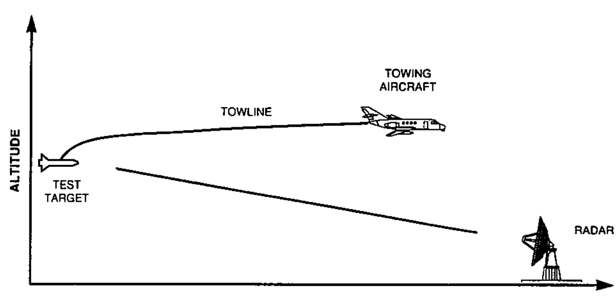

Figure 1: Typical configuration of towed target tests.

RADAR CROSS SECTION COMPUTATIONS OF COMPLICATED TARGETS BY THE APPLICATION OF THE PANEL METHOD

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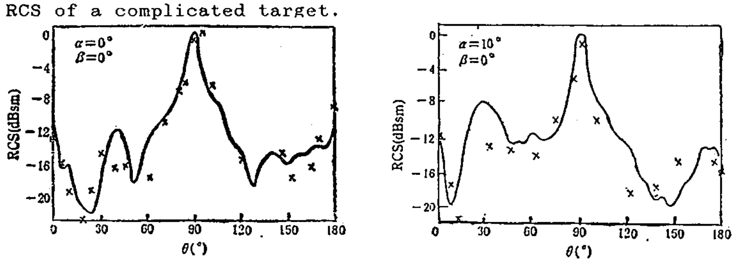
Abstract The present paper deals with the panel method for the radar cross section (RCS) computations of complicated targets based on the work by D. Klement et al.(D. Klement, J. Preissner & V. Stein, IEEE Trans. on AP, 2, 228-237, 1988). With this method, the surface of a complicated target consisting of convex,concave, cavities and edges is broken up into panels with the deviation between a panel and the corresponding true surface not exceeding a value of $\lambda/16$.The Stratton-Chu vectorical integration of three dimensional curved surface may be converted into the sum of the vectorical integration of two dimensional flat plate on each panel,thus obtaining an analytical expression of the Stratton-Chu integration for a metal target. In the same way, a curved edge of the target may be replaced by straight edges, and an analytical expression of the vectorical line integration concerning the curved edge--the line integration resulting from the equivalent current (EC) method and the physical theory of diffraction (PTD) --can also be obtained. The field distribution on a cavity aperture, which is taken as a panel, is determined by analyzing the transmission characteristics of electromagnetic wave inside the cavity, and the scattering field of the cavity may be calculated according to the equivalent electric current and magenetic current on the panel. By the method, the RCS of classic scatters, for example, a cone and a cylinder, are computed with the result of good agreement of the computations with experimental data. Then the RCS of an aircraft model, including the inlet and nozzle, at various attitudes is calculated with the result of good agreement of computations with experimental data also (see Fig.1), except for the computational data around 30 degree. The errors around 30 degree arise from the application of a rectangular straight waveguide to simulating the ellipsoidal and S-shaped inlet. The examples show that the panel method is convenient in use, fast in operation and precise in calculating RCS of a complicated target.



(a) (b)

Fig.1. The RCS of an aircraft model. (a) HH polarization, monostation. (b) VV polarization, monostation.
——— computation x x x x experiment

ELECTROMAGNETIC SIMILARITY FOR THE COATED TARGETS

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Abstract: Electromagnetic scale models are of value in the design and testing of electromagnetic systems that are on a scale too large or too small for routine laboratory investigation. For example, the Radar Cross Section (RCS) of large targets can be evaluated in the laboratory using reduced size scale models (scaled-down models) operated at frequencies higher than those used for the actual targets. Scaled-down measurements of RCS depend on principle of similitude, which allows a relationship to be established between model and full-scale behavior (Proc. IRE, Vol. 36, 1364-1370, Nov. , 1948 and AD A167467, 1986). However, practical difficulties with scaling properties of realistic materials now exist that, for most scattering measurements, discourage all but simple geometric scaling, especially for the targets coated with lossy materials. Geometric scaling is a partial form of scaling, where the scaled target has the same dimensions in scaled wavelengths as the actual target has in actual wavelengths, but material properties are ignored.

In terms of an asymptotic high frequency estimation of monostatic far field RCS of the rectangular flat plate coated with lossy material, which is derived here from a UTD formula of the impedance wedge, the electromagnetic similarity for the coated targets is studied in this paper, while the lossy material used in scaled-down model cannot satisfy the physical similitude conditions. Some results are obtained as below:

- It is theoretically possible to construct an exact scaled-down model to simulate a given full-scale electromagnetic system by choosing a suitable scale factor p and materials satisfying the similitude conditions. However, in practice, there are many difficulties in preparing scaled-down models satisfying the similitude conditions, especially for the targets coated with lossy materials.
- If the lossy materials used in scaled-down models cannot satisfy the similitude conditions, it is impossible to find a simple relationship between RCS and RCS′. Even for a simple situation, the coated rectangular flat plate, the multiple factor p_n^2 is a function of the incident angle θ_0.
- Although there are many problems in preparing the models themselves and in making measurements, scale models provide important means of qualitatively determing the scattering performance of targets for which no other method is practical.

Friday AM URSI-K Session FA14

Room: Columbus B *Time*: 0820-1200

Electromagnetics in Biology and Medicine

Chairs: James C. Lin, University of Illinois at Chicago; Charles Polk, University of Rhode Island

0820 **BIOLOGICAL EFFECTS in ANIMALS EXPOSED to EXTREMELY LOW FREQUENCY (ELF) ELECTRIC and MAGNETIC FIELDS**
Larry E. Anderson*, Pacific Northwest Labs

0850 **BIOLOGICAL EFFECTS of WEAK LOW FREQUENCY ELECTRIC and MAGNETIC FIELDS: the SEARCH for PHYSICALLY PLAUSIBLE MECHANISMS**
Charles Polk*, University of Rhode Island

0920 **A MODEL for POSSIBLE EFFECTS of ELECTROMAGNETIC FIELDS on the OCCURRENCE of CANCER**
Lothar O. Hoeft*, BDM International, Inc.

0940 **ALTERED PROTEIN SYNTHESIS in a CELL-FREE SYSTEM EXPOSED to a SINUSOIDAL ELECTROMAGNETIC FIELD**
E. M. Goodman, Univiserty of Wisconsin-Parkside; B. Greenebaum*, J. Sustachek, University of Wisconsin-Parkside; M. T. Marron, Office of Naval Research

1000 **NEW COILS for MAGNETIC NERVE STIMULATION**
Karu P. Esselle*, Health and Welfare Canada; Maria A. Stuchly, University of Victoria

1020 **PRACTICAL ANTENNA COMPOSED of COAXIAL SLOTS for INTERSTITIAL MICROWAVE HYPERTHERMIA**
Koichi Ito*, Katsumi Furuya, Haruo Kasai, Chiba University

1040 **ABSORBED POWER DISTRIBUTION PREDICTIONS for SUPERFICIAL ELECTROMAGNETIC HYPERTHERMIA**
V. Sathiaseelan*, B. B. Mittal, Northwestern Memorial Hospital; C. Reuter, Melinda Piket-May, Allen Taflove, Northwestern University

1100 **NUMERICAL CONVERGENCE PROPERTIES of 2-D FD-TD MODELS of the SIGMA-60 HYPERTHERMIA APPLICATOR**
C. Reuter*, Melinda Piket-May, Allen Taflove, Northwestern University; V. Sathiaseelan, B. B. Mittal, Northwestern Memorial Hospital

1120 **TEMPERATURE RECONSTRUCTION in CYLINDRICAL STRUCTURES by MULTIFREQUENCY RADIOMETRY: THEORY and EXPERIMENT**
F. Bardati*, V. J. Brown, P. Tognolatti, University of Rome "Tor Vergata"

1140 **INTERACTION BETWEEN PERSON and HANDHELD TELEPHONE at 900 and 1800 MHZ**
J. Bach Andersen*, J. Toftgaard, S. N. Hornsleth, Aalborg University

BIOLOGICAL EFFECTS IN ANIMALS EXPOSED TO EXTREMELY LOW FREQUENCY (ELF) ELECTRIC AND MAGNETIC FIELDS

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PO Box 999, Richland, Washington 99352 USA

There is now convincing evidence from a large number of laboratories that exposure to extremely low frequency (ELF) electric and magnetic fields produces biological responses in animals. Many of the observed effects appear to be directly or indirectly associated with the neural or neuroendocrine systems. Such effects include increased neuronal excitability, chemical and hormonal changes in the nervous system, altered behavioral responses related to sensing the presence of the field, and changes in endogenous biological rhythms. Many additional indices of general physiological status appear relatively unaffected by exposure, although effects have occasionally been described in bone growth and fracture repair, reproduction and development, and immune system function. Two major challenges exist for ongoing research 1) knowledge about the mechanisms underlying observed bioeffects is still incomplete, and 2) although no animal studies clearly demonstrate deleterious effects of ELF fields, several are suggestive of potential health impacts. The need to define basic mechanisms and investigate health consequences of ELF exposure has been enhanced because of emerging information on possible field associations with cancer and immune system impairment.

Studies have been conducted at Battelle, Pacific Northwest Laboratory, to examine ELF electromagnetic fields for possible biological effects in animals. Three areas of investigation will be reported 1) studies on the nervous system, including behavior and neuroendocrine functions, 2) experiments on cancer development in animals, and 3) measurements of currents and electric fields induced in animal models by exposure to external magnetic fields.

In behavioral experiments, rats have been shown to be responsive to ELF electric field exposure. Further experimental data indicate that short term memory may be affected in albino rats exposed to combined ELF and static magnetic fields. Neuroendocrine studies have been conducted to demonstrate an apparent stress-related response in rats exposed to 60-Hz electric fields. Nighttime pineal melatonin has been shown to be significantly depressed in animals exposed to either electric or magnetic fields. A number of animal tumor models are currently under investigation to examine possible relationships between ELF exposure and carcinogenesis. Finally, theoretical and experimental measurements have been performed which form the basis for animal and human exposure comparisons. Work sponsored by U.S. Department of Energy/Office of Energy Management under Contract #DE-AC06-76RLO 1830.

BIOLOGICAL EFFECTS OF WEAK LOW FREQUENCY ELECTRIC AND MAGNETIC FIELDS: THE SEARCH FOR PHYSICALLY PLAUSIBLE MECHANISMS.

Charles Polk, Department of Electrical Engineering, University of Rhode Island, Kingston, RI 02881

The electrical properties of biological materials and the principal, relevant characteristics of low frequency (LF) electric and magnetic fields will be reviewed. As a consequence of boundary conditions, low frequency electric fields that are applied through air are reduced by many orders of magnitude upon penetration into living tissue. Modes of action of spatially uniform and non-uniform electric fields upon charges, dipoles and polarizable matter are, depending upon the specific environment, conduction current or electrophoresis, polarization and dielectrophoresis. Simple application of Ohm's law to biological fluids will frequently not be possible since diffusion currents may become important. However conservation of charge will always be obeyed.

A simplified model of a biological cell will be described and the possible effects of applying to it a low frequency electric field will be considered, taking into account reasonably realistic properties of the cell membrane, the "electrical double layer" and "counterion polarization." Signal-to-noise considerations will then be introduced. The nature of thermal and 1/f noise will be discussed and it will be shown under what conditions LF fields can possibly affect receptor molecules in cell membranes or influence inter-cell ion traffic. Necessary field amplitudes will be compared with amplitudes that have been shown to produce measurable effects in several *in vitro* experiments.

At number of recent experiments, as well as some epidemiological studies suggest that LF magnetic fields of low intensity (<100 μT) are more effective in producing biological effects than low intensity electric fields ($<10^{-3}$V/m in tissue). It is first shown why the paths of electric currents induced into tissue or cell cultures by time varying magnetic fields differ substantially from the paths of currents that are caused by an externally applied electric field. Conditions under which such magnetically induced currents can be more effective biologically are then illustrated. For example, when multiple cells are connected by gap junctions, magnetically induced LF currents can flow through the cytoplasm of cells - a situation which cannot be achieved by the application of a LF electric field. Nevertheless, some reports of LF magnetic fields (B) involve such low intensities (<1 μT) that the possibility of direct magnetic field effects must be considered. Rotation of anisotropic diamagnetic and paramagnetic particles, which are known to be present in some biological systems, requires relatively large values of B. Lorentz (v x B) forces on moving charges are very small when B<100 μT unless velocities are higher than is possible within biological fluids. "Cyclotron resonance", which requires simultaneously present DC and AC magnetic fields, cannot affect particle motion in that environment, although the cyclotron frequency of many biologically important ions lies below 100 Hz in the presence of the geomagnetic field. However several quantum mechanical effects at the molecular level cannot be entirely excluded as candidates for field - biosystem interactions. They are the influence of magnetic fields on free radical chemical reactions, nuclear magnetic resonance and Lednev's "parametric resonance" of Ca ions in Ca-binding proteins.

A MODEL FOR POSSIBLE EFFECTS OF ELECTROMAGNETIC FIELDS ON THE OCCURRENCE OF CANCER

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Concern is growing, both inside and outside the electromagnetics community, that there is a possible relationship between exposure to electromagnetic fields and the occurrence of various cancers. To date, most of the evidence is epidemiological. Attempts to find a mechanism have generally been unsuccessful. To a large extent, this is because the electromagnetic fields of concern (particularly fields at power line frequencies) do not have enough energy to damage cell in the same manner as nuclear radiation and certain chemicals. In addition, the occurrence of cancer does not seem to be directly related to field strength or exposure. Some evidence even suggests that field strengths above a certain level have no effect. This is quite different from most other carcinogens which are generally lethal at extremely high doses.

A new model has been developed that has a mechanism by which electromagnetic fields could produce cancer. The essence of this model is that exposure to electromagnetic fields produces a physiological stress that increases the rate of cell division and therefore increases the rate of occurrence of natural or spontaneous cancers. The postulate is that electromagnetic fields are mutagens, not a carcinogens. A similar model has been proposed for explaining how natural and artificial pesticides cause cancer.

The literature contains a considerable number of references to experiments where electromagnetic fields have increased the rate of cell division, although the mechanism for this effect does not seem to be established. This model recognizes that the human body produces a significant number (maybe 15 to 25) of defective cells a day. Most of these do not survive. Very occasionally, one survives and is able to reproduce. The off-spring of this cell have defective genes, but their primary function is not significantly disrupted. These type of cells have been found in people who eventually suffer from colon-rectal cancer. When enough of the DNA is removed, enzymes that suppress tumor growth are no longer produced or other mechanisms are activated for the uncontrolled growth of tumor cells.

Experiments suggest that electromagnetic fields affect the production of chemicals, that, in turn affect the rate of cell division. The time history of the production of these chemicals suggests that the body adapts to the presence of these fields with a rather long time constant. Thus, the most harmful exposure times are of the order of hours. This should comfort the people working in EMP where the duration times are in microseconds. It is not very comforting to people who use electric blankets.

This model predicts that the rate of cancer occurrence due to magnetic fields should be related to how much electromagnetic fields can change the cell division rate. This is probably in the range of tens of percent to a few factors of two. Thus it would never be a lethal effect in the sense that nuclear radiation and some chemicals are.

Finally, electromagnetic fields may be only one of many different kinds of stress that can increase the cell division rate and therefore can affect the occurrence of various cancers.

ALTERED PROTEIN SYNTHESIS IN A CELL-FREE SYSTEM EXPOSED TO A SINUSOIDAL ELECTROMAGNETIC FIELD

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Most of the theories addressing the mechanism of interaction between electromagnetic fields and biological systems invoke the plasma membrane as the primary site of interaction and transduction between the environment and the cytoplasm (Blank, M.,and Findl, E. 1987). We have been examining weak fields interactions using a cell-free transcription/translation system. This approach allows a rigorous test of the hypothesis that an intact plasma membrane is a primary and necessary site of EMF interaction. We prepared S-30 extracts of *Escherichia coli* by breaking the bacteria in a French pressure cell (Aminco Instrument Co.) and centrifuging the lysate at 30,000 x g. The supernatant was combined with plasmids containing the alpha and beta subunits of DNA dependent RNA polymerase and exposed to a sinusoidal 72 Hz, 1.5 mT peak magnetic field. The transcription/translation system was exposed to the field for periods ranging from 10 minutes to an hour. The data show that exposures as short as 10 minutes significantly enhanced the incorporation of (^{35}S) methionine into protein. We are currently using this system to determine if the enhanced synthesis of protein is a result of altered transcription or translation. The data obtained to date indicate that an intact plasma membrane is not required to induce an bioeffect from EMF exposure.

NEW COILS FOR MAGNETIC NERVE STIMULATION

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Since mid-1980s magnetic stimulation of neurons has gained rapid acceptance as a diagnostic and research tool in neurology (L.A. Geddes, *J. Clin. Neurophysiol.* 8, 3-9, 1991). Various medical conditions associated with abnormal conduction in motor pathways can be diagnosed by stimulating an appropriate neuron and measuring the conduction velocity by recording motor action potentials. Neural stimulation occurs when an externally applied stimulus has a sufficient amplitude and duration to cause current to flow through a cellular (neural) membrane and change its potential above a threshold value. In case of magnetic stimulation the stimulus is produced by a pulse of magnetic field from an external coil.

The spatial derivative of the induced electric-field component along the neuron, also referred to as the activating function, plays an important role in magnetic stimulation of long, straight neurons; the situation is more complex in case of short neurons with dendrites. Apparently both the electric field component and its spatial derivative are important.

We have derived in a previous paper analytical expressions for the induced electric field and its spatial derivatives in a semi-infinite tissue half-space produced by a very short element of current-carrying coil (K.P. Esselle & M.A. Stuchly, *IEEE Trans. Biomed. Eng.*, in press). In this presentation we further extend this method and develop closed-form expressions for coils consisting of linear segments of wire parallel or perpendicular to the air-tissue interface. Methods are developed to calculate the inductance of such coils. The coil size is optimized to obtain the strongest stimulus at a given depth. Three promising coil configurations: quadruple square coil (QS), quadruple triangular coil (QT) and three-dimensional (3D) coil are described, analyzed and compared. Performance of these coils is evaluated by considering the following criteria: the strength of the peak stimulus for a given voltage, the rate at which the peak stimulus decreases with depth, the peak hyperpolarization level as a fraction of the peak depolarization level, and the size of the stimulation region (spot).

The QT coil appears to offer advantages over other shapes for stimulation of shallow nerves. For deep nerves spaced QS and 3D coils are preferred.

PRACTICAL ANTENNA COMPOSED OF COAXIAL SLOTS FOR INTERSTITIAL MICROWAVE HYPERTHERMIA

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Hyperthermia is a cancer treatment to heat tumors up to therapeutic temperatures (42 °C to 45 °C) without overheating the surrounding normal tissue. Microwave interstitial hyperthermia is considered to be an effective technique to heat deep-seated or large-volumed tumors.

The authors et al. have proposed a practical interstitial antenna made of a thin semirigid coaxial cable. Several small slots, which will radiate microwave energy into the tumor, are cut at short intervals on the outer conductor of the cable. The antenna is loaded into a thin plastic catheter and then inserted into the tumor to be treated. Typical antennas used at 430 MHz have 8 to 12 coaxial slots at intervals of 5 mm along the cable of 0.86 mm outer diameter.

An SAR (specific absorption rate) distribution along an antenna is one of the most important characteristics to evaluate such an interstitial microwave antenna. A heating pattern produced by the antenna can be derived from the SAR distribution. To demonstrate the validity of the coaxial-slot antenna, SAR distributions around various antennas were measured in 0.4 % saline solution. From the experiments, wide SAR distributions were observed along the antenna as expected. In addition, a considerable SAR was obtained around the antenna tip. This "hot tip" is desirable for the interstitial antenna. The SAR distribution along the antenna can be controlled by adjusting the slot parameters.

An antenna array will be formed to treat large-volumed tumors. As an example, a seven-element array was inserted into an agar phantom which is almost equivalent to muscle tissue. Six antennas were on the apexes of a hexagon and the last at its center. The antenna spacing was chosen to be 3 cm. After 3-minute heating, the size of the heating region within 1 °C degradation from the peak temperature was found to be more than 7 cm. The heating volume will be easily expanded by using more antennas.

The coaxial-slot antenna has been found to be practical and useful through some animal experiments. Clinical trial is planned in the near future. On the other hand, the antenna has been analyzed theoretically as a boundary value problem to know its basic characteristics and to establish the design procedure for the antenna.

ABSORBED POWER DISTRIBUTION PREDICTIONS FOR SUPERFICIAL ELECTROMAGNETIC HYPERTHERMIA

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Electromagnetic techniques are extensively used at present in the clinical application of hyperthermia for superficially located tumors. Electromagnetic hyperthermia has been demonstrated to be a safe and useful adjuvant to ionizing radiation in the treatment of malignant tumors. However, at present applicators and systems for delivering the optimum treatment prescribed by the physicians are far from being available. Also the performance of the applicators currently used in the clinic have not been investigated extensively in realistic clinical set up. Experimental investigation of the optimum applicator set up and a coupling configuration for a given treatment can be very time consuming and may not be practically achievable. Alternatively computer modeling can provide a reasonable solution to this difficult problem.

In this paper, we present the results of finite-difference time-domain (FD-TD) computational models of realistic clinical applicators for superficial hyperthermia. FD-TD is the only numerical modeling approach currently available to calculate specific absorption rate (SAR) patterns in complex 3-D heterogeneous biological objects. It is accurate and has a small computer burden relative to frequency-domain integral equation and finite-element techniques. Following extensive validation of the code, 2-D and 3-D absorbed power distributions have been calculated for a number of realistic tissue geometries excited by a waveguide-type applicator with different coupling configurations. A model of the human thigh reconstructed from computed tomography scans and a model of a planar phantom were used in these studies.

Some interesting results have been observed. Consider the water bolus that is routinely used in the clinic to provide energy coupling and surface (skin) temperature control. With the bolus in place, we find that inhomogeneous tissue structures significantly modify the SAR patterns compared to those computed in planar and homogeneous structures. For example, with the water bolus, a hot spot is observed in the inhomogeneous thigh case near the top edge of the applicator. This hot spot is not present in the case of the homogeneous thigh. Deepening and broadening of the SAR pattern is also observed with the bolus in place. Further, for the inhomogeneous case, a number of smaller hot spots and cold spots arise due to tissue inhomogeneities.

Our results indicate that the SAR patterns measured in planar phantoms may not give an accurate picture of the SAR patterns in clinical situations where patient tissue shape and inhomogeneity arise. This will be demonstrated via a comparison of 2-D and 3-D results. We will conclude with a discussion of the clinical significance of these findings.

NUMERICAL CONVERGENCE PROPERTIES OF 2-D FD-TD MODELS OF THE SIGMA-60 HYPERTHERMIA APPLICATOR

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Currently electromagnetic (EM) energy is used clinically to provide therapeutic heating of malignant tumors. An example of a commercially available EM hyperthermia unit is the BSD-2000 which has four amplifiers each driving a pair of dipole antennas radiating in the frequency range of 60 to 120 MHz. The eight dipole antennas are equally spaced around a 60-cm diameter plastic annulus and are phased to provide constructive interference of the energy deep inside the body of a patient centered in the annulus. Energy is coupled from the antennas to the patient via a water bolus filling the space between the plastic annulus and the patient.

As a first step to provide patient-specific treatment planning, we have developed 2-D finite-difference time-domain (FD-TD) models of this system for the case of an elliptical phantom embedded in the circular water bolus. Initial results were encouraging and showed a close correlation between FD-TD computed E^2 field values and experimental measurements. However, further investigations revealed the water bolus/phantom to be an extremely high-Q structure. The high conductivity of the phantom does not quickly damp out the applied fields as initially expected. Apparently, energy is repeatedly reflected from media interfaces causing the model to slowly progress towards the sinusoidal steady-state.

In fact, to reach the sinusoidal steady state, the FD-TD code required computation of 150 or more sinusoidal cycles of the exciting fields. The convergence properties of the 2-D FD-TD code were investigated with respect to 1) space resolution, 2) air gap between the modeled geometry and the grid radiation boundary, and 3) number of sinusoidal cycles that are time stepped. It was concluded that both (1) and (2) affect the rate of convergence of the model to steady state. Generally a larger air gap between the modeled geometry and the grid radiation boundary shortens the time required to attain steady state. However, a condition is reached when adding additional air gap has no improved effect on convergence. Furthermore, insufficient air gap will result in an unstable model.

With respect to (3), we have observed a curious "mode flipping" in our computations. Two distinct electromagnetic field patterns within the bolus/phantom structure alternated every 40 sinusoidal cycles of computation.

We are attempting full 3-D models of the Sigma-60 to determine if these phenomena persist. These phenomena have not been reported before, and could affect the accuracy of future clinical applications of the modeling process.

TEMPERATURE RECONSTRUCTION IN CYLINDRICAL STRUCTURES BY MULTIFREQUENCY RADIOMETRY: THEORY AND EXPERIMENT

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The temperature distribution within a lossy body may be imaged by externally measuring the electromagnetic microwave radiation emitted naturally by the body itself. A thermal image may be formed in a completely passive non-invasive manner if measurements are made at a number of different frequencies. The technique is of promising interest clinically for the monitoring of temperature during hyperthermia treatment of cancer. In the microwave frequency range emission of radiation from the subcutaneous tissues, which, at these frequencies, is directly proportional to the temperature of the tissues, may be received at the skin surface by an antenna. Since this emission is also dependent on frequency, the information carried by measurements at different frequencies may be used to reconstruct the temperature distribution in the tissue.

To ascertain the capability of multifrequency microwave radiometry for imaging an inhomogeneous temperature distribution inside a cylindrical region of the human body such as a neck, a limb or a thigh, equivalent cylindrical phantoms have been constructed. Experiments have been made with the use of a four-channel radiometer (1.1, 2.5, 4.5, 5.5 GHz). The thermal structure was a small cylinder at temperature T + dT embedded off-axis in an outer cylindrical region at uniform temperature T, for various distances of the cylinders axes. Both cylinders were filled by a liquid having the dielectric properties of a muscle, and their temperature was externally controlled by thermostats. The data were generated by rotating the antennas around the phantom on a plane normal to the axis.

The temperature retrieval from radiometric data has been modelled as the solution of a Fredholm integral equation of the first kind . This inverse problem has been shown (F. Bardati et al., Inverse Problems 3, 347-369, 1987) to be severely ill-conditioned, therefore only a small number of independent pieces of information can be extracted from radiometric noisy data. As a consequence the spatial resolution of temperature retrieval is usually poor. The use of a suitably defined space of temperature functions can improve the retrievals. In this paper the temperature space has been assumed to be the space of continuous functions which satisfy a steady-state heat transfer equation together with a Dirichlet condition on the boundary of the observed region. Results show an improvement in the retrievals with respect to reconstructions obtained by other techniques.

Interaction between Person and Handheld Telephone at 900 and 1800 MHz

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The FDTD-method has been applied to the situation of a person holding a portable telephone. The telephone is modelled by a metallic box and a quarter-wave monopole, and the person is modelled by a spherical head and a hand surrounding the box. The modelling is based on cubic cells and the material parameters correspond to muscle tissue, the antenna assumed to be perfectly conducting. The frequencies of interest, 900 and 1800 MHz, are related to the forthcoming European mobile and cordless telephone systems, GSM and DECT. The applied signal is a modulated pulse in the time domain of a width corresponding to the bandwidths of interest. Antenna characteristics such as impedance, gain, cross-polarization and efficiency are computed and compared with experiments with good agreement. The experimentrs are carried out in an anechoic chamber with real persons. The reaction back on the antenna gives a decrease in resonance frequency of about 10 percent. The results clearly show the rapid decay of the fields inside the head, the shadowing by the head and the near-field diffraction around the head. At the higher frequency the shadowing is larger. A considerable cross-polarization takes place with deep minima in the radiation pattern. The absorption in the head is about 50% of the total power, the absorption in the hand being minimal. When a person moves around in a natural manner, deep nulls may occur due to the interaction between the antenna and head.

Friday AM2 AP-S, URSI-B Session FA15

Room: Columbus E/F *Time*: 1020-1200

Advances in Radiation Boundary Conditions

Organizers: Kenneth K. Mei, University of California at Berkeley; Allen Taflove, Northwestern University

Chairs: Kenneth K. Mei, University of California at Berkeley; Allen Taflove, Northwestern University

1020 **ABSORBING BOUNDARY CONDITION for 3D FINITE ELEMENT MODELS with MAGNETIC VECTOR and TIME-INTEGRATED SCALAR POTENTIALS**
John R. Brauer*, The MacNeal-Schwendler Corporation; Jin-Fa Lee, Worcester Polytechnic Institute; R. Mittra, University of Illinois, Urbana-Champaign

1040 **THE MEASURED EQUATION of INVARIANCE a NEW CONCEPT in FIELD COMPUTATION**
Kenneth K. Mei*, R. Pous, Z. Chen, Y. W. Liu, University of California at Berkeley
[1040-1140]

1140 **DISCUSSION**

Measured Equation of Invariance
A New Concept in Field Computation

by **K. K. MEI, R. POUS, Z. CHEN,** and **Y. LIU**

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Abstract

In recent years, there has been a surge of effort in solving field problems by finite difference and finite element methods. The advantage of using those methods over the popular method of moment is their ability to solve problem which are locally inhomogeneous as convenient as they solve homogeneous problems. The additional advantage of having sparse matrices, however, is off set by the need to have the mesh covering large volumes, so that the absorbing conditions can be applied at the expanded mesh boundaries. It is not surprising that there have been several attempts to terminate the mesh boundaries close to the object boundary. The first attempt is represented by Kriegman et al.'s on surface radiation condition, which brings the high order absorbing boundary conditions on to the object surface [1]. The most recent effort is by Ramahi et al. [2], which uses multipoles to calculate the radiation condition near the scatterer surface. The results associated with the above close to boundary radiation conditions are mixed. They seem to offer good results if the object is close to be circular but in general the errors are unpredictable. And, furthermore, they are not expected to work on concave bodies.

In this paper, we shall approach the problem from a different perspective. Instead of radiation conditions, we shall try to arrive at a finite difference type equation, i.e., same sparsity, at a mesh boundary, which satisfies both the conditions of near fields and far fields. This is indeed a topic of great challenge to an electromagnetic scientist.

In this paper, we shall first explore different methods of arriving at the finite difference equations. In doing so, we realize that the conventional finite difference equation is actually a general equation of invariance. Other methods may lead to equations of limited invariance. By controlling the conditions on invariance, we may arrive at the desired equations at the mesh boundaries, which can accomodate both the near field conditions and the far field conditions.

There are several ways the amount of invariance can be measured. And, these measured equations lead to robust solutions. The comparisons of surface current densities on scatterers using this new method and those using method of moment on a varieties of geometries including concave objects show that the new method is in general better than the method of moment and uses only a small fraction of time and memories required by the method of moment.

The measured equation of Invariance is very general in that it can be applied to antenna scattering and microwave component problems. It can reduce many important computations to PC level.

[1] G. A. Kriegman, A. Taflove, and K. R. Umashankar, "A New Formulation of Electromagnetic Wave Scattering Using an on Surface Radiation Condition Approach," *IEEE Trans. on Antennas and Propagation*, vol. AP-35, no. 2, pp. 152-161, February 1987.

[2] D. M. Ramahi, A. Khebir, and R. Mittra, "Numerically Derived Absorbing Boundary Condition for the solution of Open Region Scattering Problem," *IEEE Trans. on Antennas and Propagation*, vol. AP-39, no. 3, pp. 350-354, March 1991.

Friday AM2 URSI-E, NEM Session FA16

Room: Columbus I/J *Time*: 1020-1220

EMP and HPM Simulation

Chair: C. D. Taylor, Mississippi State University

1020 **NEW GENERATION of BROADBAND GIGAHERTZ FIELD SIMULATORS**
Andrew S. Podgorski*, National Research Council of Canada

1040 **CW FIELD MAPPING of the SWISS EMP SIMULATOR MEMPS for PREDICTION of PULSE DATA**
Bruno Brandli*, E. Dorr, B. Reusser, Markus Nyffeler, NC Laboratory; Frederick M. Tesche, Electromagnetics Consultant

1100 **PREDICTION of the E and H FIELDS PRODUCED by the SWISS MOBILE EMP SIMULATOR (MEMPS)**
Frederick M. Tesche*, Electromagnetics Consultant; Bruno Brandli, Markus Nyffeler, NC Laboratory

1120 **100 MHZ - 4 GHZ NEAR-FIELD FACILITY for COUPLING CROSS-SECTION MEASUREMENTS**
J. C. Bolomey*, Ecole Superieure d'Electricite; G. Cottard, Satimo; D. Serafin, Centre d'Etudes de Gramat

1140 **MEASURED VARIATION of RF FIELD AMPLITUDES INSIDE ENCLOSURES**
Paul Tsitsopoulos, William Slauson*, Llewellyn Jones, Raytheon Company

1200 **FACILITIES for RADIO FREQUENCY SUSCEPTIBILITY TESTING**
Jeffrey E. Casper*, SRI International

NEW GENERATION OF BROADBAND GIGAHERTZ FIELD SIMULATORS

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Over the years, the Electromagnetic Field Protection Community has developed many methods for the measurement of radiated susceptibility and radiated emission. The widely used measuring methods rely on facilities that were developed over the last 50 years. These facilities constitute a tremendous asset that cannot be replaced with just another concept. For that reason it was the intention of the author to enhance the existing facilities, by proposing unifying modifications that will broadband the measuring capability of currently existing facilities.

The development of the Broadband Gigahertz Field (BGF) Simulator is based on a hybrid concept, as it consists of a parallel line simulator and a broadband horn antenna. The parallel line simulator provides a uniform TEM field under the septum at frequencies extending from DC to about 300 MHz. At frequencies below 300 MHz the resistors at the end of the septum provide for the termination. At frequencies higher than 300 MHz, most of the field in the testing area is supplied by the broadband horn. The electromagnetic field is very well focused into a narrow 20% cone of radiation that is terminated with a wall covered by absorbing material. However, if the energy leakage is not a problem the absorbing wall can be removed and the septum can be terminated to the ground. The BGF Facility concept assures that all of the currently used facilities, except for Reverberation Chambers and TEM cells, can be modified into a BGF Facility. Modification performed on an Open Area Facility will reduce the noise level by 20 dB and will lower the environmental radiation impact by the same amount. The proposed modification will result in better electromagnetic field confinement, which in turn will be beneficial to a Weather Protected Open Area Facility. Because of better field confinement in the simulator, the metallic building can be used as a weather protector. For that reason, the EMP and EMC testing of an aircraft can be done in existing hangars without being concerned that noticeable degradation in electromagnetic field uniformity exists.

The greatest advantage of the use of BGF simulator can be observed when the BGF simulator is incorporated into an Anechoic Chamber. Such a design provides for a field uniformity of ±4 dB, which is considerably better than the ±6 dB field uniformity obtained for a BGF simulator used in an Open Area Test Facility. The use of the BGF simulator in Shielded Rooms and Anechoic Chambers also assures low background noise level and low emission level. The use of the BGF simulator with an Anechoic Chamber will permit simulation of both horizontal and vertical polarities.To summarize, the BGF simulator is the only field simulator that provides broadband simulation for both vertical and horizontal polarizations.

CW FIELD MAPPING OF THE SWISS EMP SIMULATOR MEMPS FOR PREDICTION OFPULSE DATA

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The fields in the working volume of an EMP simulator are usually described by field-map data. Several problems, however, make an accurate description of these fields difficult. Pulse-to-pulse variations of the pulser output must be taken into account by measuring the field for each shot at a suitable reference point. In addition, the pulse shape depends, to some extent, on the operating voltage of the pulser and other pulser settings. A more accurate way of determining the working volume field on a shot-by-shot basis is to use the measured reference fields, and calculate the field components at a desired location in the working volume with the help of field transfer functions.

As the Swiss MEMPS simulator can be modified to operate in a CW mode, a CW field-mapping was conducted to directly measure the field transfer functions from the reference point to selected points in the working volume. Using these CW transfer functions, the working volume transient fields were calculated, based on the measured transient fields at the reference location. A comparison of these results with measured transient fields at the same locations shows a fairly good agreement.

The measured CW transfer functions are also used to analyze some properties of the simulator and its environment, such as structural symmetry, waveform reflections, antenna resonances, etc. To conclude, it may be stated that these CW measurements yield a good description of the pulsed simulator fields, including the effects arising from the simulator surroundings.

PREDICTION OF THE E AND H FIELDS PRODUCED BY THE SWISS MOBILE EMP SIMULATOR (MEMPS)

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It is often necessary to test critical systems for hardness against electromagnetic (EM) field threats such as an electromagnetic pulse (EMP). To this end, a number of full-scale, threat-level simulators have been developed to permit system-level testing. Typically, these simulators produce an EM field within a specified "working volume" of the simulator. Of key importance in the simulator design and its use is the accurate knowledge of the EM fields within this volume. These fields are usually measured before a test, in an activity referred to as a "field mapping." This can be a time consuming and expensive proposition.

An alternative to a detailed field mapping procedure is to measure the field at one or several reference points. These limited measurements are then to calculate the fields at other locations within the working volume using a suitable calculational model. In this manner, the details of the pulser source waveform, such as amplitude and rise-time are taken into account in determining the simulator fields.

This paper discusses the application of this concept to the Swiss Mobile EMP Simulator (MEMPS). A simple transmission line analysis procedure for determining the electromagnetic fields radiated by the simulator is described. The currents flowing on the simulator structure are first obtained. This takes into account both the resistive loading along the simulator and the dispersive nature of the lossy earth under the simulator. Once this current distribution is determined, the fields at an arbitrary location are determined by integrating the fields produced by an electric current element located over a lossy air-earth interface. As will be shown in the paper, results from this calculation compare favorably with both measurements and other results using a different modeling approach.

Using this modeling approach, a technique to accurately calculate the transient field at an arbitrary location within the simulator is described. This requires a knowledge of the primary **E** and **H** field components at a reference point near the simulator, or equivalently, a knowledge of the incident E or H field at this point. Results of this limited study indicate that it is possible to predict the simulator fields at other points, based on the reference fields and the calculational model.

100 MHz - 4 GHz NEAR-FIELD FACILITY FOR COUPLING CROSS-SECTION MEASUREMENTS

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Understanding coupling mechanisms and determining coupling cross-sections (CCS) are of prime importance in view of hardening processes. Most of time, CCS are determined directly from a convenient illumination of the test object, in a simulator or in free-space. As well known, a reciprocal approach consists of considering the test object as a transmitting antenna. Indeed, it can be shown that the CCS of an object in a given direction is proportional to its radiation pattern in the same direction. As it is usual in antenna practice, far-field (FF) patterns can be derived from near-field (NF) measurements by means of NF to FF transformations. Two advantages of this indirect approach with respect to the direct one are 1) to avoid plane wave illumination over a broad frequency band, and 2) to provide increased flexibility to simulate arbitrary polarization state and incidence angle. For these reasons, a NF facility has been designed for microwave CCS measurements, in a broad frequency band extending from 100 MHz to 4 GHz. The spherical geometry has been selected to accomodate poorly directive radiating objects. In the upper part of the frequency band, from 1 GHz to 4 GHz, NF measurements are performed by means of a semi-circular array of 128 dual-polarized probes. Such an array allows to drastically speed up the probing process. The radius of the array is equal to 2 meters. Each probe consists of two orthogonal short dipoles loaded by a PIN diode, modulated at a low frequency rate according to the modulated scattering technique (J.Ch.Bolomey et al., IEEE Trans. AP-36, 804-814, 1988). Rapid NF data are obtained while the test object is continuously rotated. After only one revolution, the whole NF distribution on a sphere has been measured, from which FF patterns can be derived in arbitrary cuts. The lower part of the frequency band, from 100 MHz to 1 GHz, is covered by classical single-probe scanning technique. In that case, the probe is mechanically moved along a semi-circular arc. This NF spherical arrangement is located in an anechoïc chamber, the external dimensions of which are 10 m X10 m X 8 m. This paper describes the performances and the capabilities of this NF facility, and presents some preliminary results obtained with generic objects of simple shapes.

MEASURED VARIATION OF RF FIELD AMPLITUDES INSIDE ENCLOSURES

Paul Tsitsopoulos, William Slauson*, Llewellyn Jones
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The penetrating RF field levels in different locations within enclosures can vary by an order of magnitude or more. The internal structures impose complex resonant behavior on the leakage, causing order of magnitude changes within small frequency ranges. These variations along with those for orientation will cause great variations in the induction in any exposed interconnects within the enclosure. Consequently, estimates of RF induction for HPM evaluations must include a large error bar to account for field variations. An experiment showed these large variations.

Two relatively generic enclosures, a rectangular "box" and a sphere, were tested for RF penetration from 0.85 to 12.4 GHz. They had seams, apertures, and attached cables. The sphere had a covered port as the main point of entry and was relatively empty inside. The box had seams around the connectors as the main points of entry and had many metallic partitions inside. Both were tested in several orientations to the RF source and in two basic conditions, normal and "sealed" with copper tape. B-dot probes were used to measure the magnetic fields. All measurements were made relative to the incident fields; i.e., shielding effectiveness (SE) was measured.

The results showed that both resonances and location can change the internal fields by an order of magnitude. Even the relatively empty sphere showed very fine resonant structures in the SE spectrum. The resonances were greatly reduced by placing some RF absorbing material inside. The cover on the port was ineffective in maintaining SE in lower spectral regions. The box showed an order of magnitude change in field with probe location. The orientation of the box or sphere caused at least half an order of magnitude of change in field. Sealing each with copper tape proved effective only with the main points of entry. These results illustrate the large variations in internal fields caused by location, resonances, enclosure orientation, and condition of points of entry. RF field levels can vary by 2.5 orders of magnitude just due to location, orientation and resonances.

FACILITIES FOR RADIO FREQUENCY SUSCEPTIBILITY TESTING

Jeffrey E. Casper, SRI International, Menlo Park, California

This talk will review the various types of facilities that can be used to evaluate the radio frequency (RF) susceptibility of electronic equipment. The advantages and limitations of each type of facility will be discussed. The facilities considered include:

- Anechoic chambers
- Reverberation chambers
- TEM cells and tapered TEM cells
- Open area test sites
- Stripline test facilities
- Direct drive facilities
- Special RF facilities.

The parameters of interest for these facilities include the usable frequency range, the capability for continuous wave (CW) and/or pulse exposure, and the ability to provide free-field illumination.

Anechoic chambers and open area test sites simulate free space propagation, can illuminate large test objects, and can be used for either CW or pulsed operation within certain practical limits. Reverberation chambers (also known as mode-stirred chambered) allow the simultaneous testing of frequencies, angles of illumination, and polarizations, but the system response is not relatable to the source specifics. Its value is in the identification of frequencies of concern, for which additional testing would be warranted. Tapered TEM cells provide a well-controlled, uniform RF environment and are useful for small test objects. Stripline and direct drive test facilities provide high field strengths and input powers from limited energy sources. Their usefulness is in maintenance and surveillance efforts.

A brief description of the design and capabilities of the SRI Microwave Exposure for Damage and Upset Susceptibility Assessment (MEDUSA) facility will also be provided.

Friday PM AP-S, URSI-B Session FP06

Room: Grand F *Time*: 1320-1700

Antenna RCS

Organizers: John L. Volakis, The University of Michigan; N. G. Alexopoulos, University of California, Los Angeles

Chairs: John L. Volakis, The University of Michigan; N. G. Alexopoulos, University of California, Los Angeles

1320 **RADAR CROSS SECTION ANALYSIS and CONTROL of MICROSTRIP PATCH ANTENNAS**
John L. Volakis*, A. Alexanian, J. M. Jin, The University of Michigan; C. Long Yu, Pacific Missile Test Center

1340 **SCATTERING and RADIATION PROPERTIES of VARACTOR-TUNED MICROSTRIP ANTENNAS**
James T. Aberle*, M. Chu, C. R. Birtcher, Arizona State University

1400 **RADIATION and SCATTERING from PLANAR MICROSTRIP STRUCTURES of ARBITRARY SHAPE**
K. A. Michalski*, C.-I. G. Hsu, M.-H. Ho, Texas A&M University; D. Zheng, Integrated Engineering Software, Inc.

1420 **ULTRA-WIDEBAND SCATTERING from RESONANT STRUCTURES USING OPTOELECTRONICALLY SWITCHED ANTENNAS**
Kamil Agi*, Lawrence Carin, Polytechnic University

1440 **STEADY-STATE SCATTERING from MICROSTRIP DIPOLE and PATCH ANTENNAS EVALUATED by the SINGULARITY EXPANSION METHOD**
George W. Hanson*, University of Wisconsin-Milwaukee

1500 **RCS of CONDUCTING/DIELECTRIC STRUCTURES OVER a FINITE/INFINITE LAYERS of a DIELECTRIC MEDIUM**
Sadasiva M. Rao, Auburn University; Tapan K. Sarkar*, Syracuse University

1520 **MULTIFUNCTIONAL ANTENNAS with LOW RCS**
Hung-Yu Yang*, Jesse A. Castaneda, Phraxos Research and Development Inc.; N. G. Alexopoulos, University of California, Los Angeles

1540 **SCATTERING from a FINITE MICROSTRIP ARRAY with a MULTIPLE-LAYER RADOME**
Adrian S. King*, Sandia National Laboratories; David R. Jackson, University of Houston

1600 **RCS of PRINTED DIPOLE ANTENNA ARRAYS with a DIELECTRIC COVER**
Gary D. Hancock*, New Mexico State University; Adrian S. King, Sandia National Laboratories

1620 **RESONANT FREQUENCY & RCS of ARBITRARILY SHAPED MICROSTRIP ANTENNAS**
Manohar D. Deshpande*, Vigyan Inc.; Dave Shively, AVRADA JRPO, NASA LaRC; C. R. Cockrell, NASA LaRC

1640 **AN ITERATIVE MPIE FORMULATION for the RCS COMPUTATION of MICROSTRIP PATCHES**
S. A. Bokhari*, H. K. Smith, J. R. Mosig, F. E. Gardiol, Ecole Polytechnique Federale de Lausanne

RADIATION AND SCATTERING FROM PLANAR MICROSTRIP STRUCTURES OF ARBITRARY SHAPE

K. A. Michalski[†*], C.-I. G. Hsu[†], M.-H. Ho[†], and D. Zheng[‡]

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A space-domain approach based on the mixed-potential integral equation formulation is applied to the computation of electromagnetic fields radiated and scattered by planar microstrip structures having arbitrary or irregular shapes. The effects of the substrate—which may consist of any number of planar, possibly uniaxially anisotropic dielectric layers backed by a ground plane—are rigorously incorporated in the analysis by means of the vector and scalar potential Green's functions. The latter are expressed in terms of two scalar functions, which are the voltages on the transmission-line analogues of the layered medium, associated with the TM and TE partial fields. The current distribution induced on the conducting patch is approximated in terms of vector basis functions defined over triangular elements. Once the current expansion coefficients are computed by the method of moments, the far zone fields are easily found by the stationary phase method, and are given in terms of the Fourier transformed basis functions and the transmission line voltages evaluated at the stationary point values of the spectral variables. Computed current distributions, radiation patterns, and RCS results are presented for several microstrip patch antennas of various shapes. For patches of simple, regular shapes, the results are in agreement with measured data and with published computed results obtained by specialized techniques, which—unlike the method presented here—are not easily extendable to arbitrary shapes.

Ultra-wideband Scattering From Resonant Structures Using Optoelectronically Switched Antennas

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Farmingdale, N.Y. 11735

Planar antennas are photoconductively switched to generate and coherently detect ultra-wideband (UWB), transient radiation. This radiation has a bandwidth covering from 5 to 70 GHz. The antennas are switched photoconductively using a 76 MHz train of 5 psec duration, 527 nm wavelength optical pulses generated from a frequency doubled, pulse compressed, mode-locked Nd-YLF laser. The UWB microwave and millimeter-wave radiation generated by these antennas, is used to perform UWB transient scattering measurements from resonant targets.

The resonant behavior of a given target is manifested in the late-time response of the scattered transient signal. This has lead many researchers over the years to study transient scattering from targets both experimentally and theoretically. By using an UWB waveform, there is the potential to excite more resonances in a given target, thus enhancing resolution.

In this work prototype UWB time-domain scattering measurements will be performed using a unique table-top scattering facility. The experimental results will be compared with theory. Particular attention will be addressed to the application of accurately measuring the late-time response of targets using such a system. The scattering facility mentioned above has no conventional microwave or millimeter-wave devices (i.e. sources, waveguides, etc.), and uses a low frequency measurement technique to obtain the desired information.

RCS OF CONDUCTING/DIELECTRIC STRUCTURES OVER A FINITE/INFINITE LAYERS OF DIELECTRIC MEDIUM

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Department of Electrical Engineering
Syracuse University
Syracuse, New York

Abstract: The objective of this paper is to develop a unified methodology for the computation of bistatic and monostatic RCS of conducting/dielectric objects situated over a layered media. The analysis is quite different if the layered media is finite as opposed to an infinite dielectric layer. The surface equivalence principle along with the conventional integral equation technique is utilized to convert the physics to a mathematical entity. The integral equations are then solved utilizing the conventional method of moments. For the infinite layered structures, the Sommerfeld Green's functions are utilized to take into account the effect of the various lossless/lossy dielectric media. For finite layered media, one utilize the equivalence principle and replaces the layers by surface equivalent electric and magnetic currents. So as a part of the solution procedure one also has solve for this additional equivalent surface electric and magnetic currents. The former approach gives rise to a complex Green's function, however the number of unknowns are quite small. For the latter, one utilizes the free space Green's function however the number of unknowns becomes large. For complicated structures greater than a few wavelengths, one need to use computers with significant memory. However, this is not a problem as computers with gigebytes of memory are becoming quite common.

Once the electric/magnetic currents are known the monostatic or the bistatic RCS can easily be computed. For finite structures, this process is quite straightforward. However for infinite structures, one has to image the excitation over the layered media to obtain the correct excitation. This has been achieved in this formulation by utilizing the reciprocity principle. For the bistatic RCS computation this procedure has to be repeated again.

Numerical results will be presented to describe the application of this technique for the computation of monostatic and bistatic RCS of structures over a layered media, both of finite and infinite extent.

RCS OF PRINTED DIPOLE ANTENNA ARRAYS
WITH A
DIELECTRIC COVER

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Printed dipole antenna arrays have found wide use on low observable (LO) platforms due to their low cost and low profile properties. The design and analysis of these antenna arrays is often times complicated by the addition of a dielectric cover to protect the printed dipoles from the environment. Due to the widespread use of printed dipole antenna arrays for many government applications, the ability to predict array performance sensitivities, limitations, and tradeoffs without undue experimental effort is very important to the LO community. In this presentation, a full-wave solution for the RCS of a finite array of printed dipoles in a substrate-superstrate geometry will be discussed as well as a massively parallel computer implementation of the solution. RCS data is to be presented as a function of the printed dipole antenna array geometry and incident signal properties.

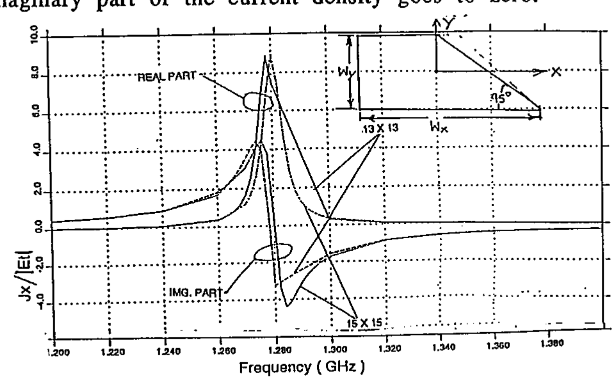
The technical approach to be presented is to solve the exact electric field integral equation utilizing the spectral domain moment method. This method is very time consuming due to the slow convergence and oscillatory nature of the function to be evaluated for the matrix fill operation. In addition, the matrix solve operation is computationally intensive for large arrays. The need for high resolution wideband RCS information further increases the amount of computations required. The use of massively parallel computing overcomes the computational intractability of the full-wave moment method solution. The moment method solution presented is based on massively parallel computers with hypercube architectures. The moment method solution to be presented utilizes toroidal wrap mapping to minimize the communication penalty associated with a large number of processors. This scheme has achieved order of magnitude speedups relative to a Cray X-MP supercomputer.

Resonant Frequency & RCS of Arbitrarily Shaped Microstrip Antennas

Manohar D. Deshpande*, Vigyan Inc., Hampton , VA.
Dave Shively, AVRADA JRPO, NASA LaRC, Hampton, VA
C. R. Cockrell, NASA LaRC, Hampton, VA.

The paper describes an application of the method of moments to determine the resonant frequency and monostatic RCS of arbitrarily shaped microstrip patches. The Electric Field Integral Equation (EFIE) in conjunction with the method of moments has been extensively used to determine radiation characteristics of microstrip antennas. However, the early work on the EFIE approach is restricted to microstrip patches of regular shapes such as rectangular, circular etc.. The present work describes extension of EFIE approach to predict RCS and resonant frequencies of arbitrarily shaped microstrip antennas.

An arbitrarily shaped patch is first assumed to be enclosed by a rectangle. By dividing the rectangle into rectangular subdomains the surface current density over the patch is then expressed in terms of subdomain basis functions and a shape function. The shape function, which is 1/0 if subdomain is inside/outside the patch, insures zero current outside the patch. The surface current density on the patch is determined by solving the EFIE. The figure below shows variation of current density at the center of the patch as a function of frequency. The resonant frequency of the patch is defined as a frequency at which imaginary part of the current density goes to zero.



Friday PM URSI-B Session FP07

Room: Columbus A *Time*: 1320-1700

Theoretical Electromagnetics II

Chairs: R. D. Nevels, Texas A&M University; Xiao-Bang Xu, Clemson University

1320 **REFLECTION and TRANSMISSION of CANONICAL ELECTROMAGNETIC PULSES at a CONDUCTIVE HALF-SPACE**
K.-D. Leuthauser*, Fraunhofer Institut fur Naturwissen.

1340 **EXTENDED RAY THEORY for ANALYZING TRANSIENT SCATTERNG from a SMOOTH DIELECTRIC CYLINDER**
Hiroyoshi Ikuno*, T. Ohmori, Masahiko Nishimoto, Kumamoto University

1400 **UNIQUENESS THEOREMS for STATIC INTEGRAL EQUATIONS USED in the CALCULATION of SCATTERING from NARROW CYLINDRICAL DENTS**
Thorkild B. Hansen*, Rome Laboratory / ERCT

1420 **THE FOURIER TRANSFORM PATH INTEGRAL METHOD**
R. D. Nevels*, Zuoguo Wu, Chenhong Huang, Texas A&M University

1440 **THEORETICAL COMPARISON of MODAL EXPANSION and INTEGRAL EQUATION METHODS for NEAR-FIELD to FAR-FIELD TRANSFORMATION**
Peter Petre*, Tapan K. Sarkar, Syracuse University

1500 **Break**

1520 **MODELING of ELECTROMAGNETIC WAVES AS FIELD VORTEXES**
Swen Alfas*, ELKRAFT Power Company Ltd

1540 **ALGEBRAIC INTEGERS and MODE DEGENERACIES in HIGHLY OVERMODED RECTANGULAR WAVEGUIDES**
P. L. Overfelt*, Naval Weapons Center

1600 **SCATTERING from BURIED INHOMOGENEOUS CYLINDERS-A HYBRID INTEGRAL EQUATION APPROACH**
Xiao-Bang Xu*, Wen Yan, Clemson University

1620 **HIGH FREQUENCY BRAGG REFLECTORS for SELECTIVE FEEDBACK in CYLINDRICAL RESONATORS**
Masoud Kasraian*, University of Wisconsin-Madison

1640 **COAXIAL-FED MODEL for MICROSTRIP PATCH ANTENNA USING the FINITE-DIFERENCE TIME-DOMAIN METHOD**
Chen Wu*, Ke-Li Wu, Zhiqiang Bi, John Litva, McMaster University

REFLECTION AND TRANSMISSION OF CANONICAL ELECTROMAGNETIC PULSES AT A CONDUCTIVE HALF-SPACE

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5350 Euskirchen, Germany

ABSTRACT

If an electromagnetic plane wave of frequency ω impinges from the vacuum (or air) on a conductive half-space, the reflected and transmitted wave can be determined by means of Fresnel coefficients which depend on frequency, angle of incidence, polarization of the wave as well as on conductivity, permittivity and permeability of the half-space.

For an electromagnetic pulse of arbitrary time dependency E(t), the corresponding problem can be solved in the frequency domain, with subsequent transformation to time domain.

The present paper especially deals with analytical expressions for reflected and transmitted electromagnetic fields if delta or unit step function pulses impinge on a conductive half-space. Their response functions are obtained by analytic continuation of the Fresnel coefficients into the whole complex ω -plane and their Fourier transform back to the time domain by means of contour integration techniques. From a mathematical point of view, the Fresnel coefficients are double-valued with a branch cut, and it is important for all considerations to remain on the 'physical' Riemann surface. Besides the branch cut no further singularities (e. g. poles) appear on this Riemann surface.

All response functions for reflection R(t) and transmission T(t) can be represented by sums of two terms. The first term originates from the path integral encircling the branch cut, the second corresponds to the incident pulse shape multiplied by the asymptotic value (i. e. ω -> ∞) of the Fresnel coefficient.

Numerical results are presented for the two states of polarization. Other representations of the response function are also given (e. g. in terms of modified Bessel functions, and series expansions), and some examples for the convolution with specific canonical waveforms (unit step funtion, exponential decay, reciprocal sum of exponentials) in time domain are presented.

EXTENDED RAY THEORY
FOR ANALYZING TRANSIENT SCATTERING
FROM A SMOOTH DIELECTRIC CYLINDER

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When we treat the transient scattering problem that an incident electromagnetic pulse is illuminated on a target, it is possible for us to reveal its scattering mechanism by using the extended ray theory (ERT) that is an extension of the ordinary ray theory and the GTD to complex coordinate space. For example, we encounter non-specular events in reflected field which can not be explained by real ray theory; these events can be expressed in terms of complex rays [H.Ikuno and L.B.Felsen, IEEE Trans. AP-36, p.1272, 1988]. On the other hand, transient scattering from a dielectric circular cylinder has been interpreted by using the ERT, although it is complicated due to the surface scattering and volume one [H.Ikuno et al., 1989 URSI, Stockholm].

In this work, we show that the scattering mechanism by an arbitrarily shaped smooth dielectric cylinder can be explained by the ERT systematically. Here we postulate that scattering processes on a smooth object can be represented in terms of reflection, refraction, and diffraction events in the ERT. Then, we can show that any scattering process can be classified into six elementary processes on electromagnetic scattering problem, as indicated in reference [Y.M.Chen, J. Math. Phys., 5, p.820, 1964]. To investigate these elementary processes, we have constructed two kinds of charts with the help of the ray tracing technique. These charts represent the relation between the observation angles versus the incidence points of GO rays or creeping rays and show the distinctive scattering angular regions described by Nussenzveig [J. Math. Phys., 10, p.125, 1969] e.g. 1-ray and 2-ray regions and so on. Then, from these charts we can easily calculate scattering centers such as reflection, refraction or diffraction points and positions of the caustics; there are not only real scattering centers but also complex ones with a selection rule [H.Ikuno et al., 1989 URSI, Stockholm]. After giving the ray path, the amplitude and phase of the ray for each elementary process can be determined by the intuitive rule of the ray theory and the GTD; the amplitude and phase can be calculated by the conservation of energy and the ray path length, and reflection, refraction, and diffraction coefficients are given by Fresnel ones [Y.M.Chen, ibid., 1964]. Thus we can evaluate the transfer function of the scattering problem with the aid of the ERT. To check the validity of the ERT solutions, reconstructed scattered waveforms from a smooth dielectric object are compared with those given by the reference solutions provided by the Yasuura method [H.Ikuno and K.Yasuura, Radio Sci., 13, p.937, 1978]. Both solutions well coincide with each other except for the ray fields in the near caustic region and near the forward directions. Therefore, the unified theory based on the ERT interprets scattering processes on two-dimensional arbitrarily shaped objects.

UNIQUENESS THEOREMS FOR STATIC INTEGRAL EQUATIONS USED IN THE CALCULATION OF SCATTERING FROM NARROW CYLINDRICAL DENTS

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It has been shown recently in (Hansen and Yaghjian, IEEE AP-S Symposium Digest, London, Ontario, Canada, 794-801, June 1991) how three-dimensional incremental length diffraction coefficients can be found directly from the corresponding two-dimensional far-fields for cylinders of arbitrary cross section using a direct substitution procedure. These incremental length diffraction coefficients can be used, for example, to determine the scattering contribution from curved ridges and channels in conductors.

It was also shown that the exact expressions for the leading terms in the low-frequency far fields diffracted by an arbitrarily shaped perfectly conducting cylindrical dent in a ground plane are completely determined by evaluating one single constant. This constant depends only on the shape of the cross section of the dent and it is found from the solution to either an electrostatic or magnetostatic problem. Once the value of the constant is determined for a certain dent, the three-dimensional incremental length diffraction coefficients for the corresponding narrow channel are immediately obtainable using the direct substitution procedure. The constant can be written as a simple integration over the dent of a magnetostatic current K_z^{0D} or an electrostatic potential F_z^{0D}. The magnetostatic current K_z^{0D} is determined by the three coupled integral equations

$$\int_D K_z^{0D}(\bar{r}')\frac{\partial}{\partial y'}G^0(\bar{r},\bar{r}')ds' = \frac{1}{2} - H_x^{0D}(\bar{r}), \quad \bar{r} \in A$$

$$⨍_D K_z^{0D}(\bar{r}')G_N^0(\bar{r},\bar{r}')ds' + 2\int_A H_x^{0D}(\bar{r}')G^0(\bar{r},\bar{r}')ds' = 0, \quad \bar{r} \in D$$

$$\int_D K_z^{0D}(\bar{r}')ds' + \int_A H_x^{0D}(\bar{r}')ds' = 0$$

while the electrostatic potential F_z^{0D} is determined by the two coupled integral equations

$$\int_D F_z^{0D}(\bar{r}')\frac{\partial}{\partial n'}G^0(\bar{r},\bar{r}')ds' = \frac{1}{2}x - F_z^{0D}(\bar{r}), \quad \bar{r} \in A$$

$$⨍_D F_z^{0D}(\bar{r}')\frac{\partial}{\partial n'}G_D^0(\bar{r},\bar{r}')ds' + 2\int_A F_z^{0D}(\bar{r}')\frac{\partial}{\partial y'}G^0(\bar{r},\bar{r}')ds' = -\frac{1}{2}F_z^{0D}(\bar{r}), \quad \bar{r} \in D$$

where D is the dent and A is its aperture. The functions G^0, G_N^0, and G_D^0 are two-dimensional static Green's functions. These static integral equations were derived from time-harmonic integral equations given in (Asvestas and Kleinman, Private communication, 1990).

In the present paper it is shown that each of the two sets of coupled static integral equations have a unique solution. It is also shown how the integral equations can be solved numerically using pulse expansion functions and point matching. A similar analysis has been carried out for the bump on an infinite ground plane. The qualitative results for the bump are the same although the integral equations and uniqueness proof are much simpler.

THE FOURIER TRANSFORM PATH INTEGRAL METHOD

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Texas A & M University
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The path integral is a single integral expression which is the Green's function for Helmholtz equation at every point in an inhomogeneous region. Research on the path integral relevant to classical electromagnetic field analysis is rare and has primarily been concerned with asymptotic diffraction theory and propagation through stochastic media. Methods for evaluating the path integral have been mostly analytical and have relied heavily on asymptotic approximations. Applications therefore have been limited primarily to wave propagation in continuously varying media with media parameters that have a smooth continuous first derivative and scattering from conducting objects for which real or complex images of the source can be constructed.

In this paper we will describe a Fourier transform path integral (FTPI) method which takes advantage of fast Fourier transform (FFT) numerical routines and which can compute the scattered field in a region which is inhomogeneous with a permittivity profile that can contain discontinuities. FTPI method advances the status of the path integral as an alternative to various other numerical methods. However there are certain numerical constraints associated with the FFT algorithm. Among these are first order limitation of the source and observation points to the region of the FFT grid points, the matrix size of the FFT grid, anomalous data around the grid periphery caused by aliasing and jaggedness of the scatterer surface produced when the FFT grid points are equally spaced. Methods for resolving each of these problems will be discussed. Comparison will be made between the path integral and moment method for transverse magnetic scattering from a perfect conducting cylinder.

Theoretical Comparison of Modal Expansion and Integral Equation Methods for Near-Field to Far-Field Transformation

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Department of Electrical Engineering
Syracuse University; Syracuse, NY 13244-1244

Near-field antenna measurements have become widely used in antenna testing since they allow for accurate measurements of antenna patterns in a controlled environment.

The earliest works based on the modal expansion method in which the fields radiated by the test antenna are expanded in terms of planar, cylindrical or spherical wave functions and the measured near-fields are used to determine the coefficients of the wave functions. The primary drawback of the modal expansion technique is that when a Fourier transform is used, the fields outside the measurement region are assumed to be zero. Consequently the far-fields are accurately determined only over a particular angular sector which is dependent on the measurement configuration.

The equivalent current approach which represents an alternate method of computing far-fields from measured near-fields has been recently explored. This method utilizes near-field data to determine equivalent electric, magnetic or both electric and magnetic current sources over a fictitious planar surface which encompasses the aperture of the antenna. These currents are used to ascertain the far-fields. Under certain approximations the currents produce the correct far-fields in all regions in front of the antenna regardless of the geometry over which the near-field measurements are made.

A theoretical comparison for the application and derivation of both modal expansion and integral equation method is presented. It is shown that one formulation can be transformed into the other one using the Fourier transform. From this point of view it can be stated that both method solves the same integral equation but for the modal expansion approach, the integral equation is solved in the spectral domain while for the integral equation method the same equation is solved for the space domain. In the numerical solution process for the first approach the approximation that the measurement field plane is truncated is assumed while for the second method the source plane is truncated. It is shown that for most of the practical antenna types the integral equation approach gives more accurate far-field estimation than the modal expansion method, particularly in the planar and cylindrical case.

Numerical results are presented using both integral equation and modal expansion approach for several antenna configurations by extrapolating the far-fields using synthetic and experimental near-field data.

ALGEBRAIC INTEGERS AND MODE DEGENERACIES IN HIGHLY OVERMODED RECTANGULAR WAVEGUIDES

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Overmoded waveguides have been used for many years as a means of reducing the ohmic losses of smaller dominant-mode waveguides at microwave frequencies and have been used also to avoid breakdown when high-power transmission applications at millimeter wavelengths are needed. The analysis of highly overmoded rectangular waveguides can be made easier by the use of some concepts in number theory. In particular, we show that the expression for the cutoff wave numbers in such a waveguide can be viewed as the norm of an algebraic field, i.e., either the field of the rationals or the complex quadratic field, $\mathbf{Q}[\sqrt{-\sigma}]$, where σ must be a positive square-free integer. We can then use the simplest algebraic integers (the rational and quadratic integers of the above fields) and $\sqrt{\sigma}$ = (a/b) (the length-to-width ratio of the waveguide) to obtain analytic formulas for the complete mode degeneracy of those guides with length-to-width ratios given by rational integers or by the square roots of rational integers. The general complex quadratic field can be divided into those fields that are Euclidean (those in which the fundamental theorem of arithmetic is true) and those that are not. In the former case, unique factorization into primes and conjugation devices exist and give procedures for finding degenerate modes. In the latter case, we must consider the products of ideals (G. H. Hardy and E. M. Wright, *Introduction to the Theory of Numbers*, Oxford, 1938) rather than the products of numbers as for Euclidean fields. We speculate that interpreting the cutoff wave number formula as the norm of an algebraic field can be extended to more complicated waveguide geometries.

SCATTERING FROM BURIED INHOMOGENEOUS CYLINDERS - A HYBRID INTEGRAL EQUATION APPROACH

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Clemson University
Clemson, SC 29634-0915

This paper presents a hybrid integral equation method for determining the scattering from inhomogeneous dielectric/ferrite cylinders buried below the planar interface seperating two semi-infinite half-spaces of different electromagnetic properties. The inhomogeneous cylinders of general cross section are of infinite extent and the excitation can be either transverse magnetic or transverse electric to the cylinder axes. The hybrid integral equations are formulated by employing both the surface equivalence principle and the volume equivalence theorem. In the formulation, attention is focused on avoiding the computation of Sommerfeld integrals which is often encountered in dealing with buried objects, and on reducing the number of unknowns. The Green's functions of all the volume integrals and part of the surface integrals in the formulated integral equations, which will be encountered in the computation of the majority of the matrix elements in the numerical solution procedure, are simply free-space Green's functions that do not contain Sommerfeld integral terms. Also, the formulated integral equations have less unknowns comparing to volume integral equation formulations.

The formulated hybrid integral equations are solved by employing a moment method numerical solution technique. Based on the knowledge of the equivalent surface current, the far-zone scattered field is computed. The equivalent currents and the far-zone field patterns are presented graphically as functions of electromagnetic properties of the two half-spaces and the buried cylinder. As a partial check, the numerical results for buried homogeneous cylinders, which can be considered as a special case of inhomogeneous cylinders, obtained by using the hybrid integral equation method are compared with those determined by employing surface integral method, a good agreement is observed.

HIGH FREQUENCY BRAGG REFLECTORS FOR SELECTIVE FEEDBACK IN CYLINDRICAL RESONATORS

Masoud Kasraian
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University of Wisconsin-Madison
Madison, Wisconsin 53706

A treatment of Bragg reflectors in the form of azimuthally symmetric periodically corrugated cylindrical waveguides is presented. Four coupled mode equations for both the transverse electric (TE) modes and the transverse magnetic (TM) modes are deduced. Selective coupling of forward and backward waves is discussed. Using the governing equations, a Bragg reflector carrying only the fundamental waveguide (TE_{11}) mode is designed. Characteristics of the designed Bragg reflector as a function of amplitude and length of the corrugated section are investigated. Effects of the parasitic modes such as the TM_{11} mode and the TE_{12} mode on the performance of the designed reflector are discussed. Two methods of optimization of this distributed reflector are presented. The optimization procedures are based on slight alteration of the corrugated section and introduction of a phase adjustment region in the corrugated structure. The characteristics of a Bragg resonator consisting of a smooth section of a cylindrical waveguide terminated by Bragg reflectors on both sides (see Fig. 1) are determined. The spectral response of the quality factor (selectivity) of the Bragg resonator is obtained using an approximation method (neglecting the contribution to the resonator Q of stored energy within the Bragg reflectors themselves) and the steady state oscillation condition.

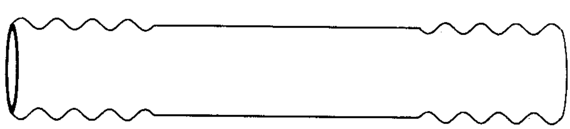

Fig. 1

COAXIAL-FED MODEL FOR MICROSTRIP PATCH ANTENNA USING THE FINITE-DIFFERENCE TIME-DOMAIN METHOD

Chen Wu, Ke-li Wu, Zhiqiang Bi and John Litva

Communications Research Laboratory,
McMaster University, Ontario, Canada, L8S 4K1

ABSTRACT

The coaxial feed is a common used structure in microstrip antenna design. There are many numerical techniques to model this structure in frequency domain. The most accurate treatment of a coaxial probe in frequency domain assumes that the portion of the inner coaxial conductor embedded in the substrate belongs to the patch. The whole structure is then excited by a frill of magnetic current existing between the inner and outer conductors of the coaxial line on the ground plane. The magnetic current is determined by the transverse electromagnetic (TEM) mode in the coaxial line. However, the discontinuity between the coaxial line region and patch region cannot be taken into account.

The Finite-Difference Time-Domain (FD-TD) method has been widely used to solve electromagnetic problems since 1966. Because Maxwell's equations are discretized directly using central difference in both space and time, the FD-TD method is more flexible than frequency method and can be applied to very complex structures, which may not be amenable to model by using frequency domain methods. On the other hand, one simulation in time domain can give very wide frequency domain information. Some investigators have used the FD-TD method to analyze microstrip problems, but for coaxial line-fed patch antenna the analysis is still based on the assumptions that deviate from practice. For example, the effect of the discontinuity between the coaxial line and patch antenna is replaced by an equivalent lump resistance. Furthermore, the characteristic impedance of the coaxial line is not reflected in the model. Obviously it is very difficult to give an accurate resistance to incorporate all the details contained in the discontinuity near the connector.

In this paper, the FD-TD method is used to model the coaxial line-fed microstrip patch antenna directly. The patch antenna can be an arbitrarily shaped and can consist of multilayerd structures. In this model the antenna is divided into two computation regions. One is the coaxial line region and another is the patch region. These two regions are carefully merged near the connector place. The advantage of using two region is that the electromagnetic field in the coaxial line can be defined by a small matrix, so that the computational space as well as CPU time expended in the coaxial line region is less than two percent of that expended in a single patch antenna region. Although the step boundary is used to approach the curve of the coaxial line, it has been found that a very good result can be obtained as long as the numerical coaxial line has 50 Ohm characteristic impedance. As the leap-frog time marching computation carries on in the time domain, all of the discontinuities will be taken into account. It can be used to study the coaxial line fed microstrip patch antenna, as well as other structures fed by coaxial line. The refined lattice model will be used in the coaxial line region to improve the model. More details will be presented in the conference.

Friday PM URSI-B Session FP08

Room: Columbus C/D *Time*: 1320-1700

Antennas and Radiation II

Chairs: Hassan A. N. Hejase, University of Kentucky; Jian-Ming Jin, The University of Michigan

1320 **THE ANTENNA K-PULSE-DEFINITIONS and ILLUSTRATIONS**
David L. Moffatt*, The Ohio State University

1340 **EFFECT of FINITE GROUND PARAMETERS on the RADIATION CHARACTERISTICS of a LINEAR ARRAY OVER a CLIFF**
S. A. Saoudy*, Memorial University of Newfoundland

1400 **RADIATION CHARACTERISTICS of a CIRCULAR LOOP ANTENNA ABOVE a FINITE CONDUCTING SCREEN**
Hassan A. N. Hejase*, Stephen D. Gedney, University of Kentucky

1420 **TIME DOMAIN STUDY of ANOMALOUS ELECTROMAGNETIC RADIATION**
George C. Giakos*, T. K. Ishii, Marquette University

1440 **SCATTERING and RADIATION ANALYSIS of THREE-DIMENSIONAL CAVITY ARRAYS VIA a HYBRID FINITE ELEMENT METHOD**
Jian-Ming Jin*, John L. Volakis, The University of Michigan; C. Long Yu, Pacific Missile Test Center

1500 **Break**

1520 **ON an EXACT CLOSED FORM LINEAR ARRAY ANTENNA SAMPLING THEOREM**
G. A. Somers*, The Ohio State University

1540 **A DUAL-FREQUENCY K/KA-BAND SMALL REFLECTOR ANTENNA for USE in MOBILE EXPERIMENTS with ADVANCED COMMUNICATIONS TECHNOLOGY SATELLITE**
V. Jamnejad*, Jet Propulsion Laboratory

1600 **MEASUREMENT and MODELING of the HF MONOPOLES and DIPOLES in IRREGULAR TERRAIN**
J. S. Young*, J. K. Breakall, D. H. Werner, Pennsylvania State University; G. H. Hagn, SRI International; D. Faust, Eyring Corporation; R. W. Adler, Naval Postgraduate School

1620 **BACKFIRE ANTENNA with MODULATED SURFACE WAVE STRUCTURE**
A. Kumar*, AK Electromagnetique Inc.

1640 **ELECTROMAGNETIC COUPLING INTO a CAVITY CONTAINING a THIN WIRE with ARBITRARY LENGTH UNDER RESONANT CONDITIONS**
Gu Zeji*, Beijing Broadcasting Istitute

The Antenna K-Pulse-Definitions and Illustrations

*D.L. Moffatt**
ElectroScience Laboratory
The Ohio State University
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Kennaugh (E.M. Kennaugh, *IEEE Trans. Antennas Propagat.*, AP-29, 2, 327-331, 1981) defined the K-pulse of a linear distributed parameter system as that waveform of finite duration which, as an excitation, produces response waveforms of finite duration at each point of the system. As noted by Kennaugh (E.M. Kennaugh, unpublished notes), the concept can be applied to a radiating antenna, in which case the appropriate generator waveform of finite duration is selected so as to produce antenna currents and radiated fields of finite duration. The internal impedance of the generator influences this waveform as well as the antenna itself. In application to the receiving antenna, an incident plane waveform of finite duration is specified which is independent of the antenna orientation. Such a waveform produces finite duration waveforms of terminal voltage and current. The terminal impedance of the antenna also influences these waveforms.

For the radiating antenna, assuming single-mode currents and voltages at the receiving terminal, Thevenin and Norton equivalent circuits are used to demonstrate the nature of the system K-pulse transform. Both the Thevenin and Norton models lead to the <u>same</u> system K-pulse. In the Thevenin model, the transform of the generator waveform is an entire function of s (complex frequency) whose zeros match the zeros of the sum of the antenna impedance and generator impedance. The response in each case is an entire function of s whose zeros match the poles of the impedance sum. Given the poles and zeros of the terminating impedance (assumed to be a ratio of polynomials) the K-pulse for any terminal impedance can be expressed in terms of the special K-pulses of an open-circuited and short-circuited antenna. K-pulse waveforms are illustrated for various thin wire antenna models.

EFFECT OF FINITE GROUND PARAMETERS ON THE RADIATION CHARACTERISTICS OF A LINEAR ARRAY OVER A CLIFF

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The Ground Wave Radar (GWR) which has been built at Cape Race, Newfoundland is being used for over the horizon target detection. It has a log periodic array dipole antenna as a transmitter with 120 degree azimuthal beam width. The receiver antenna is in the form of 40 element linear array with half wave spacing at 6.75 MHz. The receiver array has a total length of 866 meters with half power beam width of 2.5 degrees when the main lobe is directed toward the broadside direction. The array elements which are planer diamond shaped monopoles are placed on top of a 50-foot high cliff.

In this work, the linear array radiation characteristics are investigated for different schemes of the ground wire-grid. Scattering and diffraction effects due to the cliff are studied in both transmission and reception modes. For a non-straight cliff top, the linear array elements lie at different distances to the cliff edge. Accordingly, the differences in the values of received power of every array element are investigated.

Present results are obtained using the Numerical Electromagnetics Code (NEC-2) which is based on the moment method. This study considerS three types of array elements, namely quarter wavelength monopole whips, planer diamond shaped monopoles, and set of three elements Yagi-Uda monopoles directed toward the broad side direction of the linear array.

The outcome of this investigation will enhance present knowledge for choosing the proper coastal site for a ground wave radar and setting correction factors used to compensate for the difference of received power values due to different spacings among each element and the cliff edge.

RADIATION CHARACTERISTICS OF A CIRCULAR LOOP ANTENNA ABOVE A FINITE CONDUCTING SCREEN

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Lexington, KY 40506–0046

ABSTRACT

In the analysis of an antenna or scatterer above a conducting ground plane, it is a common practice to assume the ground plane to be of infinite extent. However, this assumption may significantly influence experimental measurements if the edge effects are not considered. This work is aimed at establishing a criterion into how large should a conducting screen be in order to be considered infinitely large. This information will be invaluable in EMC as well as antenna applications. In this paper, we will study the radiation characteristics of a loop element above a finite conducting screen of square shape. The current distribution of a loop antenna above a ground plane of infinite extent is first computed by solving a Pocklington integral equation in terms of the antenna current. The current distribution is expanded in terms of Fourier series and the moment method is then applied to solve for the unknown Fourier current coefficients. Once the loop current is computed, we calculate the current induced on the finite screen from the tangential magnetic field component. If the screen is assumed to be infinite in size, the radiated fields may then be obtained from the equivalent two–element loop antenna by enforcing image theory. For a finite screen, the fields can be expressed as a sum of the electric field due to the loop antenna current (determined from the infinite ground plane case with the array factor removed) and the electric field due to the surface current induced on the finite ground plane (correction term). This approach represents only a first–order approximation. The effect of the screen edge diffraction is also considered. The computer code is validated by comparing results with those obtained using a MOM patch code. Numerical results show the far–field radiation pattern as well as the loop gain as a function of the screen size.

TIME DOMAIN STUDY OF ANOMALOUS ELECTROMAGNETIC RADIATION.

*George C. Giakos+ and T. Koryu Ishii++

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++Department of Electrical and Computer Engineering, Marquette University, Milwaukee WI 53233

Recently, time-domain experimental investigations of pulse-modulated X-band microwaves revealed an anomaly in the detected power. This introduces an analogous anomaly in the transit time observation of these microwaves reported in elsewhere (G.C. Giakos, PhD Dissertation, Marquette University, August 1991).

Figs 1 and 2 display detected received power and propagation speed respectively, of pulse-modulated microwaves of 8.245 GHz, launched through an X-band rectangular waveguide. Microwave signal detection was performed on the H-plane, through a horn antenna, set initially at a distance of 71.5 cm, face to face with respect to the transmitter, and then moved on a plane parallel to the transmitter waveguide aperture. Power and propagation speed measurements were obtained, at every 2 cm, for a maximum parallel shifting distance as is shown in Figs. 1 and 2. Data are reported in two different receiver orientations. One is when the receiver horn antenna is parallel oriented to the geometrical axis of the microwave transmission. The other is the case where the receiver is aimed towards the geometrical center of the transmitter waveguide aperture.

This work is different from previously reported cases of large velocities of propagation of microwave signals with no detected power anomalies (see for example, G.C. Giakos and T.K. Ishii, IEEE Microwave and Guided Wave Letters, vol.1, No. 12, 1991). On the other hand, the anomalous observed power spectra and speed shown in Figs 1 and 2 are attributed to the coexistence of different modes of propagation.

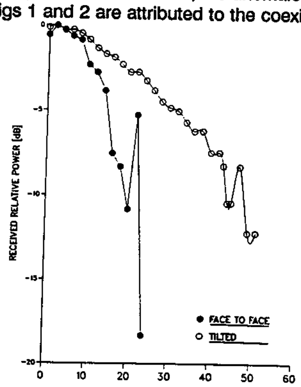

Fig. 1. Received relative power measurements detected versus parallel shifting of the receiver with a face to face distance of 71.5 cm at the operating frequency of 8.245 Ghz.

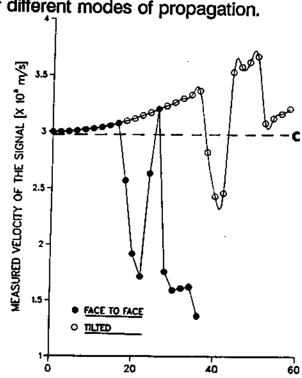

Fig. 2. Measured velocity of the pulse-modulated signals versus parallel shifting of the receiver at a frequency of 8.245 Ghz.

SCATTERING AND RADIATION ANALYSIS OF THREE-DIMENSIONAL CAVITY ARRAYS VIA A HYBRID FINITE ELEMENT METHOD

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Recently, a hybrid numerical technique was proposed for a characterization of the scattering and radiation properties of several three-dimensional cavity-backed structures including microstrip patch antennas and arrays (J.M. Jin and J.L. Volakis, *IEEE Trans. Antennas Propagat.*, vol. AP-39, pp. 1598-1604, Nov. 1991). The technique combines the finite element method with the boundary integral equation to formulate a system which is solved via the conjugate or biconjugate gradient method in conjunction with the fast Fourier transform. By virtue of the finite element method, the proposed technique is applicable to complex structures such as those involving patches, strips, probes and impedance loads. Accurate results have been obtained for scattering and radiation by cavities, slots and microstrip patch antennas which demonstrated the promise of the technique.

In practical applications, one often encounters an array of cavities or patches rather than an individual element. Though the technique can be readily applied for a numerical solution of the problem, it is nevertheless very costly when the array is large. Recent investigation shows, however, that the approximate solution based on the analysis of a corresponding infinite array using Floquet's theorem is quite accurate for medium and large size arrays and can thus be used for an efficient engineering analysis or design (J.M. Jin and J.L. Volakis, "Scattering by a finite frequency selective surface," submitted for publication). In this presentation we describe the infinite array solution and its use for computation relating to finite size arrays.

Though in principle the aforementioned hybrid finite element technique is extendable for an analysis of infinite cavity arrays, there are new issues that must be addressed. For example, the application of Floquet's theorem leads to a system which is not only non-symmetric but also dependent on the incidence or scaning angle. Obviously, for such a system an iterative method such as the conjugate gradient method is preferred over direct methods. In the presentation, we will show how the finite element method is combined with the boundary integral involving Floquet's field expansion and how the conjugate gradient method is applied to the solution of the resultant system. Numerical examples will also be presented to demonstrate the application of the technique.

ON AN EXACT CLOSED FORM LINEAR ARRAY ANTENNA SAMPLING THEOREM

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A sampling theorem has been developed for a finite linear array of equidistant identical elements with arbitrary excitations. It is shown that by sampling the field at a finite number of specified points in the far field, the exact radiation pattern over all space can be efficiently reconstructed in closed form.

In recent years there has been much work done in the area of field reconstruction based upon values of the field sampled at a sequence of field locations. The emphasis has been primarily on the application to large reflector arrays. The work presented in this paper is spatially bandlimited, as is the reflector work, and in addition is also discrete and periodic (finite) which unlike the reflector sampling theories provides an exact closed form simple sampling expression.

We are considering a linear array of equally spaced elements. The elements of the array are arbitrary providing the element pattern is known and all the element patterns (and orientations) are identical. Since there exists a Fourier series relationship between the array element domain and cosine space, and the array is spatially bounded, Shannon's Sampling Theorem is applied in cosine space. The infinite number of sampling points dictated by the sampling theorem and the array factor are periodic in cosine space. This periodicity permits a simplification by which only a finite (minimal) number of sampled points are required to exactly reproduce the array factor. A limitation in the application of this theorem is that the inter-element spacing must be greater than or equal to one half of a wavelength for the sampled field points to lie in real space (at a real angle). The latter restriction is significant and excludes an empirical application of this theory to some practical arrays.

A DUAL-FREQUENCY K/KA-BAND SMALL REFLECTOR ANTENNA FOR USE IN MOBILE EXPERIMENTS WITH ADVANCED COMMUNICATIONS TECHNOLOGY SATELLITE

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California Institute of Technology
Pasadena, Ca 91109

JPL/NASA has recently undertaken the development of a mobile terminal system to be used in experiments with the Advanced Communications Technology Satellite developed by NASA/LeRC. The ACTS satellite to be launched in 1993 is an advanced communications technology satellite with advanced on-board switching and multiple fixed and switched beams operating at Ka band (20/30 GHz). Two types of small antennas for use on the mobile vehicles on the ground are under development. One is an active planar array and the other is a small reflector antenna which will be discussed here. The AMT antenna system shall be able to acquire and track the ACTS satellite signal while maintaining a specified gain.

The reflector antenna has an elliptic aperture (6 x 15 cm) in an offset-fed configuration. A single feed horn is used which provides illumination for the reflector at both 20 and 30 GHz bands. Transmission at 30 GHz is with a linear horizontal polarization, while reception at 20 GHz uses a vertical polarization. The antenna provides an elliptic beam ($\approx 4°$ beamwidth in azimuth, $\approx 12°$ in elevation). The antenna peak gain in the transmit mode will be 22 dB while in the receive mode it will maintain a figure of merit (G/T) of better than -8 dB/K°.

The antenna platform is rotated by a flat pancake motor. Satellite Tracking in azimuth is provided by a mechanical dithering scheme. The beam is fixed in elevation but can be manually adjusted. The whole antenna system fits within an elliptic radome of 9 cm in height and 22 cm in diameter.

The reflector antenna system parameters will be addressed in detail and design figures and pattern measurement results on the feed and reflector at both frequency bands and polarizations will be presented and discussed.

MEASUREMENT AND MODELING OF HF MONOPOLES AND DIPOLES IN IRREGULAR TERRAIN

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The patterns of HF monopoles and dipoles were measured in irregular terrain using a full-scale antenna pattern measurement system. The antennas were situated on hilltops, on hillsides and near the bases of hills. The patterns exhibited perturbations, especially at the lower elevation angles compared to patterns for the same antennas over flat earth. These perturbations, which could be operationally significant for communications systems, have been successfully modeled using a Geometrical Theory of Diffraction (GTD) approach where the hills were approximated by a series of two-dimensional dielectric-coated plates. In general, the dipole patterns experienced greater perturbations than the monopole patterns for similar siting situations, and the size of the perturbations tended to increase with frequency. The effects of adjacent hills were found to be significant. Comparisons between the GTD model predictions and measured results will be presented for frequencies of 8, 15 and 27 MHz for a 16 ft whip and a half-wave horizontal dipole at 15 ft above local ground. These initial modeling results are significant in that the model has the potential for helping establish antenna siting criteria in irregular terrain.

The patterns were measured by using helicopter flyovers with trailing beacon antennas. The helicopter contained the transmit antenna which was a dipole. Three polarization options were available for the transmit antenna. Vertical polarization was obtained by hanging the dipole vertically under the helicopter. Horizontal on axis polarization was obtained by suspending the dipole antenna in a plane parallel to the ground and aligned with the flight path. Horizontal cross axis polarization was obtained by suspending the dipole antenna in a plane parallel to the ground and aligning the dipole perpendicular to the flight path. The vertical polarization was used to measure the monopole pattern, and the horizontal cross axis polarization was used to measure the dipole pattern. Patterns are obtained by data reduction software involving range correction, conversion of the helicopter position into elevation and azimuth angle, and polarization and pattern effects of the transmitter beacon antenna at the helicopter.

The results show that the GTD approach is a viable technique for modeling irregular terrain. Although not a complete solution GTD extends the valid prediction range to beyond the caustics of geometrical optics techniques.

BACKFIRE ANTENNA WITH MODULATED SURFACE WAVE STRUCTURE

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The objective of this research work is to develop a medium size high gain backfire antenna at S-band. The antenna consists of a leaky cavity resonator formed from two shaped reflectors of different diameters, spaced four to six wavelength apart, with a source (feed) placed near the small reflector. An addition small reflector is added to provide optimum performance. The main reflector diameter is in the range of five to seven wavelength. A gain of 25 dBi has been achived by optimization of reflectors and surface wave structure. The antenna size can be reduced by using a modulated corrugated surface wave structure. A critical review of the work on the cylindrical corrugated surface wave structure has been described by Kumar and Hristov (Microwave Cavity Antennas, Artech House, 1979). An antenna has been developed at AK Electromagnetique, Inc. to provide 24.5 dBi gain in the frequency range of 2.50 to 2.75 GHz.

A detailed description on design, measured results and application will be given at the conference.

ELECTROMAGNETIC COUPLING INTO A CAVITY CONTAINING A THIN WIRE WITH ARBITRARY LENGTH UNDER RESONANT CONDITIONS

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Beijing, 100024 P.R. China , Fax 0086 1 5762817

ABSTRACT: A thin wire with arbitrary length in a rectangular cavity is treated by the moment method. The wire and cavity interior are excited by electromagnetic sources exterior to the cavity which couple to the cavity interior through a slot-aperture in the cavity wall. Some important resonant behavior have been found which were previously not noted by other authors. It is pointed out that two aperture-cavity resonances and two aperture-cavity-wire resonances exist, in which the wire is attached to both ends of the wall, and that three aperture-cavity-wire resonances exist in the large region of the different length wire corresponding to the given cavity configuration. The electric currents excited on the different length wire at resonances are calculated and compared with that of the same wire in a free space. The maximum current ratio peaks at 146 when the length is 0.8 times of the wall length.

Note:
Ica: The electric current excited on the wire at resonances
Ifs: The electric current on the infinite length wire in a free space
w : Angular frequency, from w a/c, it is easy to obtain frequency f.
c : Light speed in a free space.

Cavity dimensions:
b/a=1./2.25, dl/a=0.6, d2/a=0.4
w/a=0.04, l/a=0.55, r/a=0.01
h changed from 0 to b

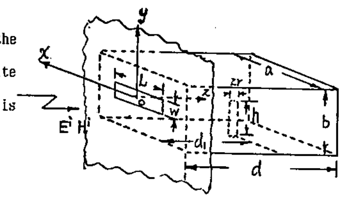

Fig.1. Geometry of a rectangular cavity with a thin wire

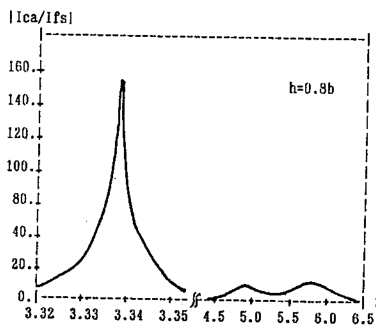

Fig.2. Ratio of the electric current on the wire at resonances to that on the infinite length wire in a free space as a function of frequencies.

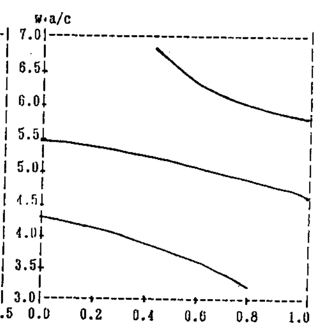

Fig.3. The resonant frequencies as a function of wire length

Friday PM AP-S, URSI-A B, NEM Session FP10

Room: Columbus G *Time*: 1320-1700

Electromagnetic Properties of Materials

Organizers: R. Mittra, University of Illinois, Urbana-Champaign; Richard G. Geyer, National Inst. of Standards & Technology

Chairs: R. Mittra, University of Illinois, Urbana-Champaign; Richard G. Geyer, National Inst. of Standards & Technology

1320 **THE DETERMINATION of DIELECTRIC PROPERTIES at NEAR MILLIMETRE WAVELENGTHS**
J. R. Birch*, National Physical Laboratory

1340 **MICROWAVE CHARACTERIZATION of HIGH-Tc SUPERCONDUCTING THIN FILMS and DEVICES**
W. G. Lyons*, D. E. Oates, MIT Lincoln Laboratory

1400 **BROADBAND MICROWAVE DIELECTRIC MEASUREMENTS with OPTOELECTRONICALLY GENERATED PICOSECOND TRANSIENT RADIATION**
G. Arjavalingam*, IBM Research Division

1420 **MICROWAVE TECHNIQUES for MEASUREMENT of RADAR ABSORBING MATERIALS-- a REVIEW**
Genevieve Maze-Merceur*, J. L. Bonnefoy, J. Garat, CEA-CESTA; R. Mittra, University of Illinois, Urbana-Champaign

1440 **MICROWAVE CHARACTERIZATION of FERRITES**
Richard G. Geyer*, James Baker-Jarvis, National Inst. of Standards & Technology

1500 **Break**

1520 **THEORY of MEASUREMENT of the CONSTITUTIVE PARAMETERS of CERTAIN MAGNETOELECTRIC MEDIA**
T.-T. Kao, P. L. E. Uslenghi*, University of Illinois at Chicago

1540 **ESTABLISHMENT of EMPIRICAL MODELS for LOW-LOSS DIELECTRICS**
K. Fidanboylu*, H. Geramifar, Ioannis M. Besieris, Sedki Riad, Virginia Polytechnic Inst. & State Univ.

1600 **MEASUREMENT of ELECTROMAGNETIC PROPERTIES of ABSORBING MATERIALS in the AEROSPACE INDUSTRY: ISSUES and (SOME) ANSWERS**
D. A. Luippold*, K. M. Mitzner, D. S. Hunzeker, W. Hant, F. J. Murray, Northrop Corporation; S. S. Locus, Electromagnetic Engineering Co.

1620 **MEASUREMENT of MICROWAVE DIELECTRICS: EXPERIENCE, NEEDS and IDEAS**
G. R. Traut*, Rogers Corporation

1640 **A QUASI-CLASSICAL, LINEAR KINETIC THEORY for a FERRIMAGNETIC MEDIUM-LINEAR MAGNETIZATION**
Robert A. Schill, Jr.*, University of Illinois at Chicago; John M. Tischer, Motorola, Communications Sector

THE DETERMINATION OF DIELECTRIC PROPERTIES AT NEAR MILLIMETRE WAVELENGTHS

J. R. Birch

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National Physical Laboratory
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Abstract

There are several important scientific and technological reasons why accurate knowledge of the optical or dielectric constants of solids are required in the near millimetre wavelength region of the electromagnetic spectrum between about 1 cm and 0.3 mm. First, interests in radar, telecommunications, remote sensing and surveillance applications will create their own design requirements for quantitative knowledge of the frequency variation of these constants. Second, the general increase in the use and application of near millimetre wave techniques in areas of potentially important developments such as fusion plasma diagnostics and biological studies points to a requirement for standard reference materials. These would be specimens of known dielectric properties for use in the calibration of spectrometers in order to assess levels of measurement error. Third, the detailed origins of many loss mechanisms at near millimetre wavelengths are poorly understood. Accurate knowledge of the frequency dependence of the real and imaginary parts of the complex permittivity would permit a detailed evaluation of various models of such loss processes. This improved understanding of the microscopic charge transport dynamics of materials should point to advances in areas of technological and industrial interest.

The presentation will review those methods which are presently being used for dielectric measurements on solids at near millimetre wavelengths over a range of temperatures from 4.2 to values in excess of 1500 K. The methods will include both resonant and non-resonant techniques, and monochromatic and broad band ones. There will be some discussion of the results of a recent intercomparison exercise in which a number of such techniques were used in a study of the dielectric properties of a group of specimens.

MICROWAVE CHARACTERIZATION OF HIGH-T_c SUPERCONDUCTING THIN FILMS AND DEVICES

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Lexington, MA 02173-9108

Development of high-transition-temperature (T_c) superconducting thin-film microwave components has progressed dramatically over the past five years following the discovery of $YBa_2Cu_3O_{7-x}$ (YBCO) in 1987. This material is a member of a new class of superconductors with transition temperatures higher than the boiling point of liquid nitrogen. Although other superconducting materials with higher transition temperatures have been produced since 1987, most efforts toward device fabrication have focused on YBCO because of the comparative ease with which single-phase material can be grown. A very successful microwave application for high-T_c materials has been planar passive components such as resonators and filters which take advantage of the low loss of superconductors.

The high-frequency surface resistance R_S of high-T_c thin films is typically determined by measuring loss (or quality factor Q) in a resonator and then accounting for the current distribution in the film so that an equivalent surface resistance for a semi-infinite-thick slab can be calculated. A stripline resonator has been the characterization tool of choice at Lincoln Laboratory, although other resonators and cavity techniques can also be used. The best R_S values obtained in this work for YBCO at a frequency of 1.5 GHz are $2.6 \times 10^{-6}\ \Omega$ at 4 K and $8.3 \times 10^{-6}\ \Omega$ at 77 K. The surface resistance depends on power, not only because of the nature and quality of the superconducting film, but because the design of the device will affect current distribution. In particular, current crowding at the edge of transmission lines produces a nonlinearly increasing R_S with increasing power, and this, in turn, leads to the generation of harmonics, intermodulation products, and reduction of the Q. In linear device applications, power levels must be selected to avoid such nonlinear effects. Noise generated by nonlinearities and other mechanisms is also an important consideration. This talk will summarize the current state of reported R_S measurements.

Many passive high-T_c microwave components have been demonstrated thus far, including narrowband filters for frequency multiplexers, chirp filters for real-time multigigahertz spectrum analysis, delay lines for analog memory storage, resonators for oscillator stabilization, and superconductive feed networks for microstrip antenna-patch arrays. An overview of the results obtained at Lincoln Laboratory for each of these components will be presented. Performance of each component must be carefully characterized for loss, accuracy, power-handling capability, intermodulation, and noise because of the impact on the corresponding microwave subsystem performance.

High-T_c superconducting components will have a substantial impact on microwave systems. Depending on the frequency of operation, superconductors provide many orders of magnitude lower loss than equivalent metallic components. For many types of devices and systems, this lower loss enables system performance that would otherwise be unattainable. Integration of high-T_c passive components into microwave receiver subsystems for actual field demonstrations is now beginning, and convincing applications are promised within this decade.

Broadband Microwave Dielectric Measurements with Optoelectronically Generated Picosecond Transient Radiation

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The recently developed coherent microwave transient spectroscopy (COMITS) technique will be described and its application to the characterization of the complex dielectric properties of materials, in the 15 - 140 GHz frequency range, will be presented (G. Arjavalingam et al., Trans. MTT, Vol. 38, p 615, 1990). The COMITS technique is based on freely propagating electromagnetic pulses radiated and received by broadband antennas which are integrated with high-speed optoelectronic devices. Ultrashort optical pulses are used to generate the picosecond-duration electrical pulses which drive the antennas and also to photoconductively sample the received waveforms. No traditional microwave sources or detectors are used in the experiment. The spectrum of the transient radiation has components extending up to 150 GHz and vanishes towards zero frequency. Since the measured time-dependent waveform is proportional to the received field, phase information is preserved. In order to characterize a given material two waveforms are recorded with two different sample thicknesses. The time-domain data are Fourier transformed and the corresponding spectra are divided to eliminate the effect of the sample surfaces and to extract the net contribution due to the bulk. The real part of the dielectric constant is calculated from the net phase delay, and the loss coefficient from the reduction in amplitude. Consequently, the complex dielectric constant of the material is determined over the wide available bandwidth, in a single experiment.

The COMITS experimental set-up has been used to characterize low-loss materials such as Teflon, and materials of interest to the digital electronics industry such as Polyimide and ceramics. Recently, it has been extended to characterize the properties of thin polymer films and also to explore the dispersion properties of novel photonic-band structure (PBS) samples. The radiation is highly polarized facilitating the characterization of anisotropic material properties. These include crystals such as Sapphire and Quartz, and anisotropic conductors such as some conducting polymers.

In addition to the transmission experiments, we have also developed a reflection-COMITS configuration to characterize lossy materials such as doped semiconductors. The same set-up has been used to study the scattering of pulses by three-dimensional objects.

MICROWAVE TECHNIQUES FOR MEASUREMENT OF RADAR ABSORBING MATERIALS -- A REVIEW

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The characterization of radar absorbing materials is of great interest in a number of microwave and millimeter-wave applications. Examples include reduction of clutter due to multipath reflections from buildings and structures; minimization of radiations pattern perturbations due to coupling between antennas and their environment; and stealth applications for RCS reduction of radar targets. The synthesis of absorbing screens typically leads to requirements for specific material properties, i.e., complex permittivities and permeabilities, for the various layers. It is essential to be able to measure the properties of the materials in the frequency range of interest with good accuracy to ensure that the synthesized screen would indeed perform as designed. It is also necessary to be able to do this for various ranges of temperature. The characterization of the complex permittivity and permeability, ε and μ, is carried out in different environments, e.g., in transmission lines and waveguides, in resonant cavities, or in free space, depending upon whether the material is thick or thin, homogeneous or inhomogeneous, and isotropic or anisotropic. Whatever the approach, it is essential that the method of measurement be efficient enough to handle a large variety of manufactured samples from which the final selection of the materials is to be made.

In this paper, we begin by describing the transmission line approach, used in conjunction with a network analyzer, to measure the complex values of ε and μ of homogeneous as well as heterogeneous, but isotropic and thick samples. For biaxial samples, we present a method that uses a guided-wave structure with a preferential axis, such as a coaxial line or a waveguide of rectangular cross-section. Next we turn to the problem of measuring the permeability of anisotropic thin films by using a loop, the extraction of μ from the knowledge of the flux variation, and the validation of these results by comparison with theoretical values of μ vs. frequency that can be computed from the static measurements (VSM). This is followed by a discussion of the single frequency measurement techniques, based on cavity resonance perturbation approach, for accurate characterization of small samples.

Finally, we turn to the free space techniques that are useful for the measurement of anisotropic and heterogeneous materials. Typically, free-space mesurements are carried out in anechoic chambers, involve both the reflection and transmission measurements, and yield information on absorption and surface impedance characteristics of the sample. This information is useful for designing the shape as well as the coating of complex targets with a view to reducing their RCS.

In situ measurements for validating such low-observable designs are also described in the paper.

MICROWAVE CHARACTERIZATION OF FERRITES

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Abstract

With continued advances in microwave and millimeter-wave theory and computer technology, computer-aided design plays an important role in the development of ferrite devices. In order to utilize these advances, it is necessary to have accurate broadband spectral characteristics of ferrite materials. This presentation is limited to magnetic spectra of polycrystalline ferrites for several reasons. First, satisfactory ferrite monocrystals are difficult to grow and produce. Second, the perfection and regularity of monocrystals make it difficult to observe important resonance phenomena due to domain walls and the influences of internal demagnetizing fields on relaxation behavior due to domain rotations. Finally, major microwave applications of ferrites still involve sintered polycrystalline materials. Ferrite electromagnetic properties may be anisotropic and nonlinear. In the presence of an externally applied dc-bias field or in the case of a significant internal anisotropy field, the behavior will be non-reciprocal, and the permeability must be described as a tensor rather than scalar. The emphases in this investigation are on the techniques by which accurate, constant- temperature complex permeability and permittivity measurements can be made, as well as on the construction of physical models which spectrally characterize ferrite permeability variation. Magnetic loss mechanisms due to classical hysteresis, domain-wall motions, and gyromagnetic resonance are examined, and differential uncertainty analyses which treat sources of measurement error are performed.

THEORY OF MEASUREMENT OF THE CONSTITUTIVE PARAMETERS OF CERTAIN MAGNETOELECTRIC MEDIA

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We consider linear magnetoelectric (or bianisotropic) materials with constitutive relations in the frequency domain:

$$(1)\quad \underline{D} = \varepsilon_0 \bar{\varepsilon}\, \underline{E} + c_0^{-1} \bar{\xi}\, \underline{H}\ , \qquad \underline{B} = \mu_0 \bar{\mu}\, \underline{H} - c_0^{-1} \bar{\eta}\, \underline{E}\ ,$$

where $\bar{\varepsilon}$, $\bar{\mu}$, $\bar{\xi}$ and $\bar{\eta}$ are dimensionless tensors represented by 3 x 3 matrices in the rectangular (x, y, z) coordinate system:

$$(2)\quad \bar{\varepsilon} = \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix},\ \bar{\mu} = \begin{pmatrix} \mu_1 & 0 & 0 \\ 0 & \mu_2 & 0 \\ 0 & 0 & \mu_3 \end{pmatrix},\ \bar{\xi} = \begin{pmatrix} 0 & \xi_4 & 0 \\ \xi_5 & 0 & \xi_6 \\ 0 & \xi_7 & 0 \end{pmatrix},\ \bar{\eta} = \begin{pmatrix} 0 & \eta_4 & 0 \\ \eta_5 & 0 & \eta_6 \\ 0 & \eta_7 & 0 \end{pmatrix}.$$

Several interesting materials have constitutive relations which are particular cases of (1,2). The case $\xi_6 = \xi_7 = \eta_6 = \eta_7 = 0$ has been previously studied: the measurement of constitutive parameters has been discussed (P.L.E. Uslenghi, Proc. ICEAA'91, pp. 149-151, Turin, Italy, Sept. 1991) and the propagation in slab waveguides examined (J.D. Ali and P.L.E. Uslenghi, Nat. Radio Science Meeting, Boulder, CO, Jan. 1992). Propagation in slab waveguides for the more general case (1,2) will be presented (URSI Intnl. Symp. on Electromagnetic Theory, Sidney, Australia, Aug. 1992).

The determination of the consitutive parameters (2) is considered when a slab of material with planar boundaries at $z = 0$ and $z = d$ is available. If the slab is sufficiently large, free-space measurements may be possible; hence, we study the case of a linearly polarized plane wave incident on such a slab, and extract as much information as possible on the constitutive parameters from the measurements of amplitude and phase of the reflection and transmission coefficients.

When the sample cannot be made sufficiently large, other types of measurements must be conducted. Firstly, we examine what information can be extracted by measuring reflection and transmission coefficients for a sample inserted in a rectangular waveguide. Secondly, we consider measurements in a stripline configuration.

A general conclusion is that no single experimental setup can provide all the information needed to solve this inverse problem. Hence, several measurements utilizing different experimental setups must be conducted on the same material.

ESTABLISHMENT OF EMPIRICAL MODELS FOR LOW-LOSS DIELECTRICS

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An overview of existing empirical dielectric models, as well as trends for establishing new ones, is presented. The ultimate goal is to develop models that provide physical representations for low-loss dielectrics that are applicable over a wide frequency spectrum. The commonly used Debye model for the complex dielectric permittivity has been shown to be valid only for some liquid dielectrics. The dielectric behavior of more general materials, especially solids, departs from the Debye representation drastically. In order to obtain more accurate representations for a general group of materials, several researchers, such as Cole-Cole, Davidson-Cole, Havriliak-Negami, Nakamura-Ishida, Jonscher, Fuoss-Kirkwood and Hill, have attempted to obtain empirical models by modifying the basic Debye representation.

Later on, Shin-Yeung have shown that the Debye model as well as the empirical models developed by the above researchers satisfy a non-linear differential equation having the following property:

$$Q(Q(F)) = k\, Q(F)$$

where, Q is the non-linear differential operator, k is a proportionality constant, and F is the susceptibility spectral shape function. The solution to this non-linear differential equation provides a guide for developing new empirical models that might be applicable for certain class of materials.

In order to investigate the spectral behavior of these models, several computer simulations have been performed. By using the Debye model as a reference, the empirical models available in the literature have been compared with each other. This comparison have revealed very useful information about the limitations of each model. As a result of these simulations and experimental data, in this paper, we discuss the validity of the existing empirical models for low loss dielectrics, especially for Polymer type materials.

MEASUREMENT OF ELECTROMAGNETIC PROPERTIES OF ABSORBING MATERIALS IN THE AEROSPACE INDUSTRY: ISSUES AND (SOME) ANSWERS

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An overview is given of electromagnetic measurements problems that arise in connection with the use of Radar Absorbing Material (RAM) in aerospace design and production. Some of the most successful and most promising measurement techniques are discussed. These include resonant stripline, waveguide, free space insertion loss, impedance measurement in a capacitive fixture, and Q-spoiling of a cavity. In many cases, a customary measurement procedure has had to be modified to take into account the special properties of the material under test, the necessity for data over frequency ranges where neither quasistatic nor high frequency techniques are convenient, and/or the special demands of a reliable quality assurance system for routinely checking bulk quantities of material. Accuracy and precision requirements vary from a few percent to stringent. The availability of modern network analyzers with supplementary custom software has greatly simplified the development and implementation of these materials characterization procedures.

One case history shows how a requirement to measure resistive sheet material at very high frequency (VHF) through a dielectric coating was satisfied by developing a network analyzer probe that couples capacitively to the sheet. This device exhibits some of the properties that are important to a practical industrial application: portability, robustness, ability to measure continuously along a run of material, and sensitivity to local material variations and defects.

MEASUREMENT OF MICROWAVE DIELECTRICS: EXPERIENCE, NEEDS AND IDEAS

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Abstract

For several decades foil clad laminates based on PTFE-based composites for microwave and mm-wave applications have seen extensive use where printed circuit technology has been exploited for producing microwave components and systems. The formats used include stripline, microstrip, coplanar waveguide, finline with variations on these. The most critical characteristic for success of almost any design is complex permittivity at the frequency of the application.

This characteristic must be monitored and controlled by supplier and user. We have lacked convenient standardized definitive methods with traceable reference specimens. The ASTM D3380 (IPC 2.5.5.5) stripline resonator method with its numerous limitations is in use along with some less convenient microstrip methods. A variety of possible methods see less use.

New compositions, many not based on PTFE, are finding their place. Some do not lend themselves to present measurement methods.

The permittivity of dielectric substrates cannot simply be considered independently of other parameters. Its relationship to temperature, frequency, electric field orientation needs to be understood. Its variability and the precision with which it can be determined are important.

Measurement methods are needed to satisfy several important goals in areas of convenience, specimen cost, relevance to the application, repeatability, traceability, cost and complexity of instrumentation. Some measurement methods are proposed but they need to be better understood and developed into standards.

A QUASI-CLASSICAL, LINEAR KINETIC THEORY FOR A FERRIMAGNETIC MEDIUM - LINEAR MAGNETIZATION

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An enormous amount of theoretical and experimental works in the area of magnetic mediums exist. The classical phenomenological approach is widely used by engineers. Quantum mechanics provides a more rigorous structure in the study of magnetic mediums. Such a description is very difficult if not nearly impossible to apply in practice. There are a variety of effects which can not be accounted for using a classical description. A classical kinetic theory modeling the effects of magnetic mediums does not exist and for good reason. In statistical mechanics, the phase space approach violates the Hiesenberg uncertainty principle since each phase point designates the exact state of the particle, magnetic ion. Even so, the correspondence principle stipulates under suitable limits that both classical and quantum theory must agree.

A self consistent, quasi-classical, linear kinetic theory adopting a six dimensional angular momentum/configuration phase space, is used to develop the linear magnetization for a finite, anisotropic, magnetic medium biased with a large, uniform, magnetostatic field. Only the classical dipole and quantum mechanical exchange interactions are incorporated into the theory. With suitable approximations, the equilibrium and linear magnetizations agree with existing theories. The ferrimagnetic medium is composed of two interpenetrating magnetic ion sublattices. The exchange interaction gives rise to transverse wave oscillations due to boundary effects. With exchange interaction, Maxwell's equations are of differential/integral form. The kinetic model and simple characterizations of the magnetization will be presented.

Friday PM URSI-B Session FP11

Room: Columbus H *Time*: 1320-1620

Advances in Numerical EM Analysis II

Chairs: Anthony Martin, Clemson University; L. N. Medgyesi-Mitschang, McDonnell Douglas Research Laboratories

1320 **ELECTROSTATIC IMAGE THEORY for the DIELECTRIC SPHERE with an INTERNAL SOURCE**
Johan C-E. Sten*, Ismo V. Lindell, Helsinki University of Technology

1340 **AZIMUTHAL PROPAGATION CONSTANTS of WAVES GUIDED ALONG a CYLINDRICAL SUBSTRATE- SUPERSTRATE GEOMETRY**
K. Naishadham*, Wright State University; L. B. Felsen, Polytechnic University

1400 **ON the EFFICIENT EVALUATION of SINGULAR and INFINITE INTEGRALS**
Surendra Singh*, Ritu Singh, The University of Tulsa

1420 **RESONANT FREQUENCIES of DIELECTRIC OBJECTS by the SURFACE WAVE PHASE MATCHING METHOD**
Douglas Taylor*, Naval Research Laboratory; Herbert Uberall, The Catholic University of America

1440 **ON the THEORY of ORTHOGONAL TRANSMISSION LINE WIRES**
Jeffrey L. Young*, University of Idaho

1500 **Break**

1520 **ON USING DEL-SQUARED PLUS BOUNDARY CONSTRAINTS INSTEAD of CURL-CURL for VECTOR SCATTERING PROBLEMS**
J. W. Parker*, R. D. Ferraro, P. C. Liewer, Jet Propulsion Laboratory

1540 **THE NON-HUYGENS PRINCIPLES of the SCATTERED FIELD'S APPEARANCE in the DIFFRACTION PROBLEMS**
V. F. Apelt'cin*, Faculty V. M. K. of Moscow University

1600 **THEORY for RADIATION of TIME-HARMONIC ELEMENTARY CURRENT in MAGNETIZED ELECTRON PLASMA HALF-SPACE**
Dajun Cheng*, Weigan Lin, Liangjin Xue, Univ. of Elect. Science & Tech. of China

ELECTROSTATIC IMAGE THEORY FOR THE DIELECTRIC SPHERE WITH AN INTERNAL SOURCE

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The well-known electrostatic image theory for a point charge in front of a conducting sphere, originally discovered by Lord Kelvin some time before 1850 [Maxwell, J.C., *Treatise on Electricity and Magnetism*] has by one of the authors been generalized to the dielectric sphere with sources located outside the sphere [I.V. Lindell, "Electrostatic image theory for the dielectric sphere", *Radio Sci.* Jan-Feb. 1991]. Subsequently the theory was also extended to the problem of a magnetic sphere, a more general bi-isotropic sphere and a multilayer sphere. As an application, the interaction of two dielectric spheres in a homogeneous electric field has been examined. The present paper treats the image problem for a point source located inside the dielectric sphere, thus completing the theory. The point charge is located at the distance d from the center of the sphere with radius a.

The approach is to compare the expressions for the electrostatic potential, written in terms of series of spherical harmonics, with the expression for the assumed image line charge. The image charge function can be solved analytically by applying the Mellin integral transformation on the integral equation for the charge function. For the two problems, the field outside and inside the sphere there are two different image charge functions. In both cases they turn out to be combinations of simple point charge and line charge functions. The line charge obeys a simple power law with an integrable singularity at the center of the sphere. Depending on whether the field is calculated outside or inside the sphere, the corresponding image charge distribution is located at the opposite side of the surface of the sphere. For field calculation outside the sphere the image line charge function extends from the center of the sphere to the charge point. The transmitted field outside the sphere can be calculated through an image line charge, extending from the Kelvin point a^2/d outside the sphere to infinity. The special limiting cases are examined and image functions for differently oriented static dipole sources inside the sphere are developed.

The present problem has been straightforwardly reformulated to cover DC current problems with general values for the conductivities of the sphere and the surrounding medium. The theory can be applied for example to problems of electrocardiography.

AZIMUTHAL PROPAGATION CONSTANTS OF WAVES GUIDED ALONG A CYLINDRICAL SUBSTRATE – SUPERSTRATE GEOMETRY

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Wave propagation along the outermost surface of thin dielectric layers deposited on a perfectly conducting circular cylinder serves as a canonical problem for the analysis of conformal antenna arrays mounted on more generally curved bodies. In this paper, we examine the effects of curvature and of the electrical parameters of the layers on the modal dispersion of waves guided tangentially along the outer (superstrate) layer of a two–layer geometry, the inner layer being referred to as the substrate. To chart the propagation characteristics of the dipole–excited layer–guided modes relevant to the three–dimensional Green's function for this geometry, it is necessary to solve the radial eigenvalue problem for the complex azimuthal propagation constants $\nu_p(\beta)$, p = 1,2, ... , which also identify pole locations in the ν–dependent spectral integrand of the Green's function. Here, β is the spectral variable along the axial direction and the Green's function is synthesized as a double spectral integral over ν and β. The pole locations are obtained numerically by solving the characteristic (dispersion) equation for several values of β using Davidenko's method, and are parametrized in terms of layer radius, dielectric constant and thickness. They are classified as leaky, creeping or trapped, depending on the magnitude of the ratio of azimuthal to radial wavenumbers relative to unity (L.B. Felsen, J.M. Ho and I.T. Lu, J. Acoust. Soc. Am., 87, 543–569, 1990).

Although an infinite number of modes are supported by the substrate - superstrate cylindrical geometry, only a few low–attenuation modes occur, which are potentially significant in the analysis of radiation by elements deposited on the layers. The number of such modes to be retained in the analysis depends on layer thickness and source–observer distance on the surface. It is shown that thin or low dielectric constant layers support highly attenuated creeping wave modes, while thick or high dielectric constant layers support well–trapped modes, characterized by low attenuation. Leaky wave modes occur for electrically small cylinder radii, but appear to be well–damped. The dispersion relation, and hence the propagation constants, are shown to reduce correctly to the corresponding results for the planar geometry in the limit where the superstrate outer radius approaches infinity.

ON THE EFFICIENT EVALUATION OF SINGULAR AND INFINITE INTEGRALS

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In recent years, a considerable amount of work has been carried out for the efficient evaluation of finite range singular and infinite integrals. The evaluation of such integrals is needed in a variety of problems in computational electromagnetics. The most notable among these being integrals encountered in the Sommerfeld halfspace problem. Such integrals often pose difficulty in their efficient computation as the integrands may exhibit singular and oscillatory behaviour. The methods suggested include the use of fast Fourier transform, chirp z-transform and the accelerated quadrature sequence technique employing Wynn's ϵ-algorithm. However, the techniques suggested so far for efficient evaluation of these integrals apply for only a limited range of parameters.

In this work, we present general purpose techniques which are applicable to a variety of infinite integrals, oscillatory and singular in nature. The procedure involving integration between the successive zeros of the integrand to convert an infinite integral to an infinite summation, is extended to handle singularities in the range of integration. This is accomplished by using the well-known tanh transformation of Schwartz. The transformation effectively moves the singular points of the integrand to infinity. Following this, a low-order quadrature rule such as the trapezoidal rule can then be effectively used. The transformation is simple to implement and has proved to be very effective for a wide class of integrals. The simplicity and numerical stability of the tanh rule allows an easy extension to double integrals with singularities. Numerical examples showing the effectiveness of this method are presented. The work is expected to be applicable in moment method solution of printed circuit antenna problems where Sommerfeld type integrals are encountered.

RESONANT FREQUENCIES OF DIELECTRIC OBJECTS BY THE SURFACE WAVE PHASE MATCHING METHOD

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Dielectric objects display a rich resonance spectrum that has been the subject of inquiry by many researchers, both theoretical and experimental. A mathematical model for complex electromagnetic resonances based on phased matched circumferentially propagating surface waves has provided a physical basis for further work with penetrable dielectric objects with non-canonical geometries. The lowest order (m=0) resonant frequencies of a dielectric cylinder with hemispherical endcaps are predicted using a phase matched surface wave method. The resonance condition is expressed mathematically as,

$$\int \frac{ds}{\lambda(s)} = \frac{1}{2\pi} \int k(s)ds = n + \frac{n'}{4}$$

where a surface wave traverses a path which is *n* wavelengths plus $\frac{n'}{4}$ advance for each time a caustic is encountered. The surface wave propagation constant, k(s), and wavelength, λ(s) vary along the path s, and depend on the surface curvature and dielectric properties of the object. The propagation constants of the surface waves are not known exactly and are approximated with values computed from equivalent spherical and cylindrical canonical geometries.

ON THE THEORY OF ORTHOGONAL TRANSMISSION LINE WIRES

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In a previous article (Young, J.L. and J.R. Wait, IEEE AP, vol. 39, 1991), the canonical problem of two crossing wires over a homogeneous half plane was rigorously addressed. The unknown spectral currents were shown to be solutions to a set of coupled Fredholm integral equations of the second kind. For example, $I_x(\lambda) + I_x^w(\lambda) + I_x^s(\lambda) = 0$ where,

$$I_x^w(\lambda) = \int_{-\infty}^{\infty} I_y(\beta) G_y(\lambda, \beta) d\beta$$

Here, I_x and I_y are the induced currents and I_x^s is the applied current. If the conductivity of the half space approaches infinity, then the problem is reduced to two crossing transmission lines which share a common ground plane. This is the point of departure for this work.

On the spectral plane, the kernel G_y has a set of poles on the real axis (i.e. the TEM mode response), an infinite number of poles along the imaginary axis (i.e. evanescent modes) and a logarithmic branch-cut. These singularities form the complete spectrum for the induced spatial currents. The real axis pole is rendered removable by the following singularity extraction technique:

$$I_x^w(\lambda) = \int_{-\infty}^{\infty} I_y(\beta)[G_y(\lambda, \beta) - G_y^{TEM}(\lambda, \beta)] d\beta + \int_{-\infty}^{\infty} I_y(\beta) G_y^{TEM}(\lambda, \beta) d\beta$$

where G_y^{TEM} is the limiting form of G_y near the real axis singularity. The difference kernel contains only a logarithmic singularity along the integration path, which is integrable; the second term is the weighted TEM response. After additional manipulations, the integral equations are cast into a form which is then numerically approximated.

The iterative method of successive approximations is applied to decouple the integral equations. The first term in the series is evaluated in closed-form and is given in terms of the Exponential Integral; the remaining terms are evaluated numerically. Due to the weak electromagnetic coupling between wires, the series converges to an acceptable accuracy after two terms; for all practical purposes, the third term is shown to be inconsequential. A numerical example is presented to demonstrate the theory.

ON USING DEL-SQUARED PLUS BOUNDARY CONSTRAINTS INSTEAD OF CURL-CURL FOR VECTOR SCATTERING PROBLEMS

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An operator-based technique for avoiding vector parasite errors with node-based finite elements has been advocated (K. D. Paulsen & D. R. Lynch, IEEE MTT 39, 395-404). Their method replaces the curl-curl operator with a del-squared operator in the second-order vector differential equation for the electric field. In addition, an extra boundary condition on the normal field component is imposed at material interfaces.

We numerically examine the technique for 2-d vector solution of a wave scattered from a 2-d dielectric cylinder in free space, with the computational domain truncated by an absorbing boundary condition at twice the cylinder radius. In order to implement the extra boundary condition at conductors and dielectrics, we interpret the degrees of freedom at the interface to be the tangential **E** component and the normal **D** component. This interpretation is enforced by a coordinate rotation and scaling of both **E** and the test vector field **T** in the element assembly phase of the computation. The absorbing boundary condition is related to the second-order Bayliss-Turkel condition for scalar scattered field, relating the field curl to the tangential field and the tangential second derivative of the tangential field component. We find empirically that no additional conditions at this boundary are required. When using the del-squared operator, vector parasites are dramatically eliminated for a dielectric 2.56 cylinder, at incident frequencies ranging from ka=0.3 to ka=3, where a is the radius of the cylinder; in contrast, large errors result from the curl-curl operator. Numerical tests with a magnetic field wave incident on a conducting cylinder without the extra boundary condition enforced at the conductor show large errors, demonstrating the necessity of normal-field condition enforcement. Comparisons to the analytic solution and the bistatic RCS show that solutions with acceptable accuracy are obtained with the del-squared operator plus the extra boundary condition. We conjecture that this technique will be successful with 3-D node-based finite elements as well.

ON THE NON-HUYGENS PRINCIPLES OF THE SCATTERED FIELD'S APPEARANCE IN THE DIFFRACTION PROBLEMS.

V.F. Apelt'cin
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The Huygens - Poincare principle of scattered field's forming in the wave's diffraction problems for the finite bodies supposes the bodie's surface being a support of the scattered field's sources (currents) and absence of the field in the interior of a perfect conductor (H.Honl, A.W.Maue, K. Westpfahl, Theorie der Bengungen, Springer- verlag, Berlin, 1961). From the mathematical point of view it corresponds to the Fredholm integral equation methods due to the potential theory (D.Kolton, R.Kress, Integral equation methods in scattering theory, New-York, 1983) Nevertheless there exists another model of the scattered field's forming which corresponds to the image method's generalization when the scattered field is synthesized by the sources distributed in the interior of the bodie's geometric boundary.

It's demonstrated that an analytic continuation of the solutions of external two-dimension wave's diffraction problems due to the Dirichlet or Neumann's boundary value conditions into the domain's interior with a smooth closed boundary leads to the appearance not only of point source's singularities in the points of an external source's images (as for the most simple boundary value problems in the semi-plane, semi-space or strip) but also of some singular linear set corresponding to the system of cuts on a Riemann surface due to the analytic function induced by the domain's boundary. The Riemann surface has a finite-sheet structure if the domain's boundary is algebraic (may be described by polynomial). Solutions of the initial boundary value problems may be expressed by means of the fundamental solutions of the Helmholtz equation on the Riemann surface mentioned above. According to the Sommerfeld's branched solutions method these fundamental solutions may be constructed by means of the solutions of Dirichlet and Neumann's boundary value problems for the singular set which is a simple connected starlike system of the linear segments.

THEORY FOR RADIATION OF TIME-HARMONIC ELEMENTARY CURRENT IN MAGNETIZED ELECTRON PLASMA HALF-SPACE

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Recently, we introduced coupled image principle to describe the fact that right- and left-circular polarized eigenmodes couple mutually to determine the amplitude and phase of the image source for the radiation of time-harmonic elementary current in chiral half-space, bounded by an ideal electric wall (Microwave Opt. Technol. Lett., 4, 391-394, 1991). And it has long been known that there exist two characteristic waves both in chiral materials and in gyrotropic media. Due to this similarity between chiral materials and gyrotropic media, we can't help asking: is coupled image principle appropriate for gyrotropic half-space?

In this paper, the radiation emitted by a time-harmonic elementary current in the half-space, filled with magnetized electron plasma and bounded by an ideal electric plane, is investigated using the same method as we have employed for chiral half-space. Two cases have been considered: (1) vertical magnetization case and (2) parallel magnetization case. For both cases, radiated field expressions are rigorously given in terms of two-dimensional integrals in the Fourier-transform spectral domain. It is found that: conventional image principle holds for the vertical magnetization case; while for parallel magnetization case, coupled image principle seems to be valid.

In addition, for the parallel magnetization case where coupled image principle can be applied, explicit expressions for the coupled terms are presented for time-harmonic elementary currents placed both vertically and in parallel . It may be seen that the coupled term depends both on the oriented direction of the elementary current and on the parameters of the magnetized electron plasma.

Friday PM1 URSI-E, NEM Session FP12

Room: Columbus I/J *Time*: 1320-1500

Guided Wave EMP Simulators

Chair: Frederick M. Tesche, Electromagnetics Consultant

1320 **DESIGN, CONSTRUCTION and CHARACTERIZATION of DREMPS**
M. Burton*, S. Kashyap, J. S. Seregelyi, P. Sevat, Defence Research Establishment Ottawa

1340 **A THREAT-LEVEL EMP SIMULATOR for SHIPS (EMPSIS)**
W. Pont*, J. J. A. Klaasen, TNO Physics and Electronics Laboratory

1400 **PRELIMINARY TEST RESULTS from INSIEME BOUNDED WAVE EMP SIMULATOR in ITALY**
P. Papucci, CRESAM; L. Bolla, AEITALIA; F. Pandozy, FACE; C. Noya, U. Sinibaldi, C. Cacciatore, ELMER; B. Augsburger*, K. Salisbury, Y. G. Chen, R. White, Maxwell Laboratories Inc.; D. Giri, PROTECH

1420 **CALCULATION of the RADIATED ELECTROMAGNETIC FIELDS from PARALLEL-PLATE EMP SIMULATOR**
Frederick M. Tesche*, Electromagnetics Consultant; Charles T.C. Mo, Logicon/RDA; William Shoup, Field Command, Defense Nuclear Agency

1440 **TIME DOMAIN INCIDENT-FIELD EXTRAPOLATION**
J. J. A. Klaasen*, TNO Physics and Electronics Laboratory

Design, Construction and Characterization of DREMPS

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This paper describes the design, construction and preliminary characterization of the Canadian Defence Research EMP Simulator (DREMPS). Figure 1 shows an artist's view of the bounded wave simulator. It is made from two sets of parallel wires to minimize ice and wind loading. The simulator is designed to produce a threat level EMP field of 50 kV/m within a working volume of 10m x 20m x 30m. This volume is large enough to accommodate a helicopter, tank or communication van. The facility has been designed with a helicopter pad to allow EMP assessment of heavy transportable equipment. Electromagnetic fields inside and around the simulator have been computed and an environmental assessment of the simulator regarding health, safety and interference has been done.

Preliminary measurements of both electric and magnetic fields inside and outside the simulator and time domain reflection (TDR) measurements have been made. As a result of these measurements, changes were made to the load end taper and the resistive load in order to minimize the reflections.

Details of the design, construction, and preliminary electromagnetic field and reflection measurements will be presented.

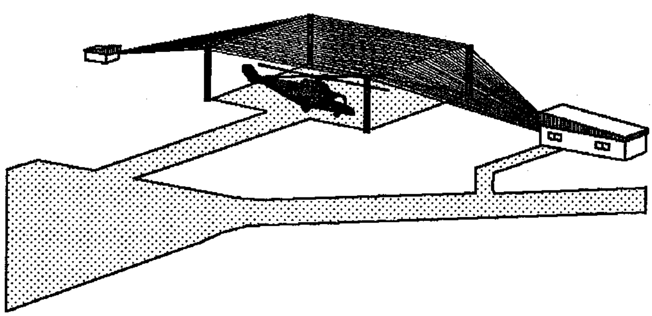

Figure 1. Artist's View of the DREMPS

A THREAT-LEVEL EMP SIMULATOR FOR SHIPS (EMPSIS)

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NEMP assessments on large ships have been carried out with the low-level simulator EMIS-3 in the Netherlands, for many years. Since 1982, the possibility of a full-threat level simulator for naval vessels has been discussed within a cooperation project between the United Kingdom, Norway and the Netherlands. A feasibility study was initiated by the navies of the mentioned countries in 1989. This study resulted in a small-scale experiment (simulator height 10m) with a parallel-plate simulator over sea water and at threat level, in Norway in 1990. The experiments showed that sea water can be used as part of the waveguide structure of the simulator.

In 1991 TNO-FEL got the task to draft the pulser specifications and to make a preliminary design for the transmission line of the simulator. The simulator, that was baptized as EMPSIS (ElectroMagnetic Pulse SImulator for Ships), must be able to test vessels up to 200m length and 46m height at threat level for both the old and the new exo-atmospheric-NEMP requirements.

Data for the design was gathered from the following experiments performed by TNO-FEL:

- Measurements in a 6m-high parallel-plate simulator connected to a 10kV/0.9ns pulse generator (1989),
- Measurements in a 10m-high parallel-plate simulator over sea water in Norway (1990, with participation of UK and Norway),
- Measurements in 10m-high parallel-plate and conical-plate simulators connected to a 10kV/0.9ns pulse generator (1991).

In this paper is referred to the results of these experiments. The expected rise time, pulse distortion, and the homogeneity of the generated field in the EMPSIS simulator will be highlighted. Some expectations are given about a fast-pulse generator and its ability to drive a transmission line with a rather low impedance.

PRELIMINARY TEST RESULTS FROM INSIEME BOUNDED WAVE EMP SIMULATOR IN ITALY

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F. Pandozy, FACE, Rome, Italy
C. Noya, U. Sinibaldi, C. Cacciatore, ELMER, Pomezia, Italy
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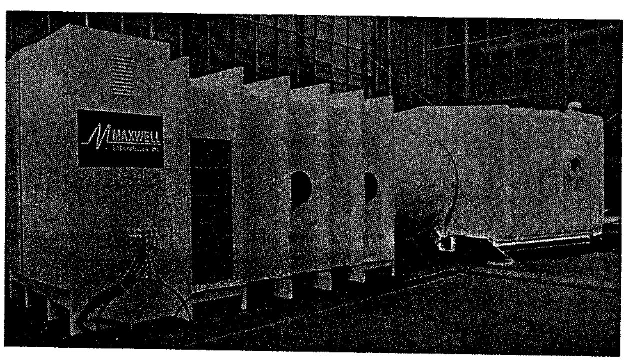
R. White,
D. Giri, PROTECH, Berkeley, CA. USA

Impianto Nazionale per la Simulazione di Impulsi Electro-Magnetici Esoatmosferici is a conical transmission type EMP simulator which was designed and built for CRESAM, near Pisa in Italy. In this paper we will present the preliminary test results for INSIEME which was conducted into a resistive load. This simulator has a 100 Ω TEM mode characteristic impedance which is excited by a 1.3 MV, < 5 nanosecond risetime pulse generator. Some aspects of the engineering design will be discussed such as the pulse power configuration and the coaxial to parallel plate transition. The expected Electromagnetic performance will be compared with the experimental test results.

The INSIEME EMP simulator has been tested with the customers presence (CRESAM, ELMER) at the MAXWELL facility in San Diego, California. The tests were conducted into a resistive dummy load with a nominal resistance of 100 Ω. The dummy load consists of four 400 Ω water resistors which are connected in parallel to a mock-up antenna extenstion. Using a mock-up antenna transition and connecting the dummy load resistors in a horizontal fashion provides the clear time (25 ns) necessary for conducting the Electromagnetic mesurements. The test series demonstrated the pulse power characteristcs such as Marx generator voltage, peaking capacitor voltage, and FWHM. The Electromagnetic field data was measured to determine the pulse risetime and field amplitude. INSIEME will be tested into the CRESAM antenna during the summer of 1992.



CALCULATION OF THE RADIATED ELECTROMAGNETIC FIELDS FROM A PARALLEL-PLATE EMP SIMULATOR

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Recent concerns about the environmental and biological effects of radiated electromagnetic (EM) fields have lead to an increased awareness desire to predict and control such fields at locations far from their source. For system-level electromagnetic pulse (EMP) testing, large-scale bounded-wave simulators have been constructed for the purpose of illuminating systems by a fast-rising, large-amplitude transient E-field. Although the behavior of the E and H fields in the working volume of most such simulators is very well understood, little attention has been paid to the field levels outside the simulator at distances of several kilometers. The behavior of the fields at these distances depend not only on the details of the simulator structure and its pulser source, but also on the nature of the lossy ground terrain over which the fields propagate.

One example of such a concern is the E and H field environment produced by the Advanced Research EMP Simulator (ARES). Under the auspices of the Defense Nuclear Agency (DNA), this paper investigates an approximate model and presents its estimated EM fields on the ground and in the air at locations away from the simulator. These estimates compare favorably with preliminary peak field measurements on the ground. Further measurements in the air are currently being planned.

The model calculates the radiated fields from the simulator by first determining its current. This is done by modeling the parallel-plate ARES simulator as a two-conductor transmission line structure, and using TEM transmission line theory. Then the expressions developed by Norton for the fields of elementary vertical and horizontal electric dipoles over the lossy earth can be used as a Green's function to determine the E and H fields at distant points. As this formulation is in the frequency domain, numerical fast Fourier transform (FFT) methods are used to obtain the transient responses. This paper describes the details of the analysis and compares calculated fields on the ground with measured data. Accuracies on the order of 30% are noted in many of the data comparisons. In addition, fields at observation locations in the air away from the earth, including peak field contours, have been calculated, and the relative importance of the Norton surface wave in the overall solution is delineated.

TIME-DOMAIN INCIDENT-FIELD EXTRAPOLATION

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Most NEMP simulators do not reproduce the expected NEMP threat. They fail to reproduce both the waveform and the peak field strength of the perceived threat level. This is especially true for radiating and hybrid simulators, which produce a waveform that is significantly different from the waveform of the perceived threat. To compensate for these shortcomings, the measured responses in NEMP assessments have to be corrected (extrapolated) to calculate the response that would be expected from a NEMP.

In this presentation, what is known as incident-field extrapolation will be addressed. This type of extrapolation not only corrects for the difference in waveform, but also tries to correct the different spatial behaviour of the incident field of the simulator compared with the criterion environment. An extrapolation function that is an average over the space of interest, i.e., the simulator test volume, is therefore constructed.

The incident-field extrapolation method that will be presented performs the extrapolation directly in the time domain (see also J.J.A. Klaasen, *Defence Research Establishment Ottawa (DREO) report no. 1076*, May 1991). This method is based on a time-domain extrapolation function which is obtained from the Singularity Expansion Method representation of the measured incident field of the NEMP simulator.

Once the time-domain extrapolation function has been determined, the responses recorded during an assessment can be extrapolated simply by convolving them with the time-domain extrapolation function.

It is found that to obtain useful extrapolated responses, the **incident-field** measurement needs to be made minimum phase; otherwise unbounded results can be obtained.

Results obtained with this technique are presented, using experimental data.

Friday PM URSI-A B Session FP13

Room: Columbus K/L *Time*: 1320-1600

Time Domain Techniques

Chairs: Sadasiva M. Rao, Auburn University; Edmund K. Miller, Los Alamos National Laboratory

1320 **TRANSIENT SCATTERING from TWO-DIMENSIONAL DIELECTRIC CYLINDERS of ARBITRARY SHAPE**
Douglas A. Vechinski*, Sadasiva M. Rao, Auburn University

1340 **TRANSIENT SCATTERING from DIELECTRIC BODIES of ARBITRARY SHAPE**
Sadasiva M. Rao*, Douglas A. Vechinski, Auburn University

1400 **INVESTIGATION of the EARLY-TIME BEHAVIOR of RADAR TARGETS EXCITED in the RESONANCE REGION**
J. Ross*, E. J. Rothwell, K. M. Chen, Dennis P. Nyquist, John Nathan, Michigan State University

1420 **NATURAL RESONANCE EXTRACTION with PHYSICAL CONSTRAINTS**
P. Ilvarasan*, E. J. Rothwell, K. M. Chen, Dennis P. Nyquist, Michigan State University

1440 **SURFACE CURRENTS INDUCED by SHORT PULSES**
R. K. Ritt*, Illinois State University

1500 **Break**

1520 **PULSED BEAM DIFFRACTION by a PERFECTLY CONDUCTING WEDGE**
Reuven Iancunescu, Tel-Aviv University; Ehud Heyman*, A. J. Devaney Assoc., Inc.

1540 **ELECTRIC FIELD on the AXIS of a CYLINDRICAL TUBE with a TRUNCATED CONICAL CAP**
Chalmers M. Butler*, Zhiqiang Qui, Clemson University; J. Patrick Donohoe, C. D. Taylor, Mississippi State University; Erik K. Reed, KEMET Electronics Corp.; Glenn L. Brown, REAP; W. LaVaughn Hales, U. S. Army MICOM

TRANSIENT SCATTERING FROM TWO-DIMENSIONAL DIELECTRIC CYLINDERS OF ARBITRARY SHAPE

Douglas A. Vechinski* and Sadasiva M. Rao, 200 Broun Hall, Department of Electrical Engineering, Auburn University, Auburn, AL 36849,

In this work we present a solution technique to determine the transient scattering by two-dimensional homogeneous dielectric cylinders of arbitrary cross section located in another homogeneous medium of infinite extent. The cylinder is assumed to be illuminated by an electromagnetic pulse of finite duration. There exists a number of applications for such a problem: broad-band response of dielectric or material targets, target identification, and scattering from biological media to name a few.

The marching-on-in-time technique suffers from late-time oscillations which is common to all the time-stepping algorithms. Tijhuis (*Electromagnetic Inverse Profiling: Theory and Numerical Implementation.* VNU Science Press, 1987) attempted to control these oscillations and developed a modified version by introducing a relaxation parameter. This relaxation parameter is iteratively modified to reduce or eliminate the late-time oscillations. Using this technique, he not only solved the conducting cylinders problem (both TE and TM cases using the magnetic field integral equation), but also attempted for the first time the dielectric cylinder problem using the volume integral equation approach.

In this work we develop an alternate formulation for the dielectric cylinder problem based on the surface equivalence principle. In this formulation, we define a pair of equivalent currents on the surface of the cylinder, and by enforcing the continuity of the tangential components of the electric and magnetic fields, a pair of integral equations are derived. These equations are later solved by employing the method of moments and the marching-on-in-time algorithm. The late-time oscillations are eliminated by a simple stabilization procedure which involves a negligible amount of extra computation. Numerical results are presented for two cross sections *viz.* a circle and a square, and compared with inverse discrete Fourier transform (IDFT) techniques. In each case, good agreement is obtained with the IDFT solution.

TRANSIENT SCATTERING FROM DIELECTRIC BODIES OF ARBITRARY SHAPE

Sadasiva M. Rao* and Douglas A. Vechinski, 200 Broun Hall, Department of Electrical Engineering, Auburn University, Auburn, AL 36849,

In recent times the transient analysis of electromagnetic scattering has received a great deal of attention. With the advent of faster computers and an increase of memory space, many scattering problems of complex objects are being performed directly in the time domain. In this work, a solution procedure is presented to obtain the transient scattering from arbitrarily shaped, homogeneous dielectric, three-dimensional objects located in another homogeneous medium of infinite extent directly in the time-domain using the marching-on-in-time method. The scatterer is assumed to be illuminated by an electromagnetic pulse of finite duration. A number of applications exist for such a problem: broad-band response of dielectric or material targets, target identification, and scattering from biological media.

The body is modeled by a set of triangular patches which have the ability to conform to any geometrical surface boundary. Also, the patch density may be increased in areas where more resolution is required. We develop an alternate formulation for the dielectric body problem based on the surface equivalence principle. In this formulation, we define a pair of equivalent currents on the surface of the cylinder, and by enforcing the continuity of the tangential components of the electric and magnetic fields, a pair of integral equations are derived. These equations are later solved by employing the method of moments and the marching-on-in-time algorithm. The late-time oscillations are eliminated by a simple stabilization procedure which involves a negligible amount of extra computation. Numerical results for surface current density and far-scattered fields are given for various structures and compared with other methods.

INVESTIGATION OF THE EARLY-TIME BEHAVIOR OF RADAR TARGETS EXCITED IN THE RESONANCE REGION

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D. P. Nyquist and John Nathan
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East Lansing, MI 48824

It is known that the pulse response of a radar target is dominated by a number of distinct specular reflections from scattering centers when the excitation is within the realm of physical optics. If the excitation waveform has frequency content primarily within the resonance region, the response is composed of an early-time period during which the excitation field is traversing the target followed by a late-time period which is a pure natural resonance series.

The late-time portion of the target response has received much attention recently for use in radar target discrimination. Its physical composition is to give a global view of the target; the natural frequencies are aspect independent and are functions of the complete target geometry. The early-time period of a target response is more complicated. As the waveform passes across the scattering centers, specular reflections occur as in physical optics scattering, representing the local behavior of discontinuities on the target. In addition to these, the early-time scattered field is composed of the resonances of smaller substructures and the building resonances of the overall structure. It is important to understand these physical phenomena if the early-time period is to be used for target discrimination.

This paper investigates the importance of various components of the early-time scattered field response for excitations in the resonance region (pulse widths approximately 20%-50% of maximal target transit time). An association will be made between the physical structure of the target and the features observed in the early-time scattered field response. Both the theoretical responses of canonical targets and the measured responses of realistic aircraft models are considered.

NATURAL RESONANCE EXTRACTION WITH PHYSICAL CONSTRAINTS

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Michigan State University
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Radar target discrimination based on natural resonances requires an accurate and efficient means of extracting natural frequencies from measured data. The E-pulse technique provides an automated scheme for mode extraction, but, like Prony's method, to which it is related, does not restrict the poles to the left half-plane. Mode extraction using experimental data often produces extraneous frequencies resulting from attempts to fit natural modes to localized aberrations. These frequencies often have positive damping coefficients and are thus non-physical. A new scheme has been developed based on the E-pulse technique with constraints applied to the amplitudes of the E-pulse basis functions, restricting the poles of the extracted modes to the left half-plane.

In this version of the E-pulse scheme, the late-time norm of the convolution of the target response with the E-pulse is minimized with constraints placed on the amplitudes of the E-pulse. The natural resonance frequencies are then taken as the zeroes of the E-pulse spectrum. If the E-pulse basis functions are chosen to be rectangular pulses, this leads to a polynomial equation with the basis function amplitudes as the coefficients. Since a real polynomial has all the roots inside the unit disk when the coefficients of the polynomial satisfy the necessary conditions given by the Jury-Marden theorem, these conditions are taken as the constraints used in minimizing the norm of the convolution. Finally, the optimal E-pulse duration is chosen as that producing the minimum squared error between the original waveform and the waveform reconstructed using the extracted natural resonances.

Examples using the theoretical responses of thin wires with additive noise and measured responses of various radar target models are considered. Initial results have demonstrated that the new scheme produces better results than the unconstrained E-pulse technique in the presence of random noise due to the elimination of non-physical modes.

SURFACE CURRENTS INDUCED BY SHORT PULSES

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Illinois State University, Normal, IL, 61761

We have previously shown that the surface current on a perfectly conducting scatterer, induced by an impulse current source, with compact support, can be represented in the form:

$$\mathbf{J}(t) = \frac{(t - t_0)}{\pi} \int_{\Omega}^{\infty} \omega[\mathbf{J}_-(\mathbf{E}_0, \omega) - \mathbf{J}_+(\mathbf{E}_0, \omega)]\, d\omega + o(\Omega^{-1}) + O(\Omega^2(t - t_0)^2)$$

in which t_0 is the time at which the free space field arrives at the scatterer, $\mathbf{E}_0$ is the free space field at time t_0. $\mathbf{J}_\pm(\mathbf{E}_0, \omega)$ is the monochromatic current induced by the field $\mathbf{E}_0 \exp(\pm i\omega t)$, and the asymptotic error estimates are in the energy norm.

In the present paper, we consider the applications of this result to the calculation of currents induced by short pulse current sources, on scatterers for which the geometric optics current is known. For such sources, the impulse response is computed by inserting the geometric optics approximation for $\mathbf{J}_\pm(\mathbf{E}_0, \omega)$ into the integral. For such scatterers there is generally a characteristic length, δ, such that the $o(\Omega^{-1})$ term in the representation can be ignored if $\delta\Omega >> c$, c being the propagation velocity. Then the $O(\Omega^2(t - t_0)^2)$ term can be ignored if $(t - t_0)\, c << \delta$. Because the short pulse response is computed by convolution of the short pulse wave form with the impulse response, one expects that the approximation just described will be accurate, provided that the pulse width is much less than the characteristic dimension δ. This recipe provides an improvement on the physical optics response, computed by the well known method of Kennaugh and Moffett.

We perform the calculation for ellipsoidal scatterers, in which the problem has axial symmetry, and compare the result to the physical optics calculation, for several idealized short pulse wave forms.

PULSED BEAM DIFFRACTION BY A PERFECTLY CONDUCTING WEDGE

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Pulsed beams (PB) are short pulse wave fields that are directed in space like well collimated beams and propagate along ray trajectories. Because they are well localized in space-time, these wavepackets may be useful in various applications involving high resolution interrogation of targets or of the propagation environment. The PBs also form a new set of basis functions for spectral expansion of time-dependent fields, as an alternative to the conventional plane-wave or the Green's function representations. Since the PBs can be tracked locally in inhomogeneous media and though interactions with boundaries, these basis functions are convenient for computational algorithms of pulsed fields propagation and scattering in large complicated environments. Finally the PBs can be used as basis functions for local space-time processing and imaging of ultrawide bandwidth scattering data.

An important part in the development of the theories mentioned above is the derivation of solutions for PB propagation and scattering. Exact solutions for certain canonical configurations can be obtained via the complex source technique. Because of the local nature of these fields, it is then possible to extract scattering models that apply for non canonical configurations. In this paper we present an *exact*, simple to calculate, closed form solution for the benchmark problem of PB diffraction by a perfectly conducting wedge. Different scattering phenomena are monitored as function of the characteristics of the incident wavepacket, namely its pulselength, its beamwidth and collimation, its direction and its transverse displacement from the wedge's vertex. We also derive approximate uniform local model that explains the physics of the scattering process explicitly in terms of these local characteristics. It is shown that when the incident PB hits near the vertex of the wedge it generates a toroidal wavepacket that propagate essentially along Keller's cone. The solution describes uniformly how the excitation of this diffraction phenomenon weaken and how the diffraction cone is distorted as the distance of the incident PB from the vertex increases. The results extend the uniform geometrical theory of diffractions to pulsed beam fields that are compact in space-time.

ELECTRIC FIELD ON THE AXIS OF A CYLINDRICAL TUBE WITH A TRUNCATED CONICAL CAP

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An ultra wideband pulse is considered incident on a conducting cylindrical tube that is closed at one end and linearly tapered to a circular aperture at the other. The surface current density on the modified cylindrical tube and the axially-directed electric field on its axis are determined. Both time-domain and frequency-domain interaction characteristics are studied. A system of integral equations is derived for components of the frequency-domain surface current density. The circumferential variations of the components are expressed in terms of Fourier series and tangential variations on the surface normal to the circumferential direction are determined from numerical solutions of integral equations for the Fourier coefficients of the current components. The influence on convergence of the use of alternate schemes for expanding the current coefficients, including one which is forced to satisfy the appropriate edge condition, is studied. From these solutions, frequency-domain data are obtained for the current on the tube surface and for the axially-directed electric field on the tube axis. It is demonstrated that this electric field component on the tube axis can be computed from knowledge of only the zero-order Fourier coefficient of surface current even under conditions for which the total current is rich in modes. The time-domain results are obtained from the frequency-domain data by means of Fourier transform techniques. Two distinct excitation pulse types are considered: a Gaussian pulse with significant spectral energy content up to 4 GHz and a pulse which is similar in shape to a single cycle of a 100 MHz sinusoid and whose spectral energy is negligible above 2 GHz. Several resonances of the tube are encompassed within the spectra of both excitations. Current density and electric field are computed for several angles of incidence of the exciting pulses. The solution method described above is applied to a thin, straight cylindrical tube for which a marching-in-time solution of a time-domain integral equation has been developed. Data obtained by the two methods applied to the tube are found to be in very close agreement, which lends a degree of confidence to the analysis of the modified cylindrical tube structure of interest.

Friday PM1 URSI-A K Session FP14

Room: Columbus B *Time*: 1320-1500

Measurements for Biomedical Applications

Chair: J. Bach Andersen, Aalborg University

1320 **A NEW TECHNIQUE for MEASUREMENT of DIELECTRIC CONSTANT of LIQUIDS with LARGE VISCOSITY**
Bin Song*, Junmei Fu, Xi'an Jiaotong University

1340 **SAR PATTERNS from NON-IDEAL INTERSTITIAL MICROWAVE DIPOLE-ARRAYS**
K. L. Clibbon*, A. McCowen, University College of Swansea

1400 **ELECTRICAL IMPEDANCE IMAGING of INHOMOGENEOUS MEDIA**
Valdis V. Liepa*, K. Reeves, C. Thomas, The University of Michigan

1420 **IMAGING for OBJECTS BURIED in a HOMOGENEOUS DIELECTRIC BACKGROUND**
Hsueh-Jyh Li*, Gen-Tay Huang, National Taiwan University

1440 **FREQUENCY RESPONSE of HUMAN BLOOD to PULSATING ELECTROMAGNETIC FIELDS**
P. Kokoschinegg, M. Kokoschinegg, Inst. f. Biophysik und Strahlenforschung; N. Pekaric-Nadj*, University of Novi Sad

A NEW TECHNIQUE FOR MEASUREMENT OF DIELECTRIC CONSTANT OF LIQUIDS WITH LARGE VISCOSITY

Bin Song , Junmei Fu
(Dept. of Information & Control Engineering,
Xi'an Jiaotong University, Xi'an, Shaanxi, P.R.China)

The main purpose of our study is to develop a method for the dielectric constant measurement of liquids. Some liquids and especially the biological liquids, e.g., blood, have large viscosity which gives to their free surface a nonplanar geometry. This geometry does not allow to measure the dielectric properties with methods applied to solid bodies. If we put the liquids in a closed cylindrical glass tube , the free surface problem may be overcome. So we can design a new sensor, where the full glass tube is placed in the middle of a rectangular waveguide and the reflection and the transmission coefficients may be measured by an experimental set-up. These coefficients are related to the dielectric constant of the liquid, where the relation can be found by our theoretical approach.

In this paper the scattering of a plane electromagnetic wave by a cylindrical post placed in a rectangular waveguide is presented. In addition, an useful experimental set-up has been designed in our laboratory, and with it we measure the reflection or the transmission coefficients or both , then by the help of our theoretical model we can define the permittivity r. One of the essential advantage of our experimental method is that it can be used to measure the dielectric constant of liquids with any value of viscosity. On the other hand , in some cases, e.g., biological liquids, we have very few quantity of the liquid and it is impossible to use any other methods for measure the dielectric constant, however, this measurement can be completed easily with our approach because only glass tube with small inner diameter is employed.

Many experiments have been accomplished, and we have obtained a large number of data. From the obtained results, it can be found that our approach is an effective way for the dielectric constant measurement of liquids.

SAR PATTERNS FROM NON-IDEAL INTERSTITIAL MICROWAVE DIPOLE-ARRAYS

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University College of Swansea, Wales, U.K.

The use of interstitial microwave antenna-array hyperthermia (IMAAH) systems in cancer therapy has been under investigation by several groups (notably: Thayer School of Engineering, Dartmouth College). The arrays generally considered in the literature comprise a uniform arrangement of linear dielectric-coated dipoles. To maximise the heating within the array where the tumour will be sited, the array is usually fed coherently so that the electric fields add in-phase. In practice the positioning of the dipoles is ofter determined by radiological considerations resulting in a non-uniform arrangement in which the dipoles may be off-alignment and skewed. The non-ideal positioning of the dipoles upsets the phasing of the electric field patterns within the array and degrades the SAR distribution.

Within the Computational Electromagnetics Group at Swansea, a software package has been developed with the capability of calculating the SAR distributions from an arbitrary non-ideal array of non-symmetric dipoles embedded in a uniform biological medium. In addition the code has been coupled to a CGM-FFT electromagnetic solver so that SAR distributions can be determined when the IMAAH system is embedded in a heterogeneous biological medium. This paper will discuss the development of this work and also present initial results demonstrating the degradation of SAR resulting from a non-ideal antenna configuration.

Electrical Impedance Imaging of Inhomogeneous Media

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Apparatus is described that has been designed and built to generate data to test and verify numerical imaging algorithms. The medium is a cylindrical tank with 12 equally spaced electrodes placed around the perimeter and, as such, creates a two-dimensional geometry. Using relays and digital meters interfaced with a computer, a voltage source can be applied to any pair of electrodes and voltages measured between any electrodes desired. The source current is also measured. The tank is 10.5 in. in diameter and 24 in. in height and is made of acrylic (plexiglass) materials. For the tests it is filled with distilled water containing about 3 percent tap water to provide conduction to give about 1kohms resistance between the electrodes.

With only water in the tank, the medium is said to be homogeneous. To provide an inhomogeneous medium, metal (conducting boundaries) and plastic strips (insulating boundaries), as well as cylindrical shapes, are placed in the tank. The data measured under various loading conditions are then provided to University of Delaware, Department of Mathematical Science, where algorithms that they have developed are applied to determine the "unknown" shape and material of the loading. The extracted images will be presented and compared with the actual geometries used. The specific algorithms that were used in extraction of images will also be discussed.

FREQUENCY RESPONSE OF HUMAN BLOOD TO PULSATING ELECTROMAGNETIC FIELDS

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The low frequency pulsating electromagnetic fields (PEMF) have been shown lately to produce many useful biological effects. Although many facts have been known for about 20 years, the complete mechanism of the fields influence is still not clear. It is evident that this mechanism must be very complex. This work is aimed to point out one of the aspects. According to our researches we found that in vitro PEMF stimulation dramatically changes the physical structure of water. We were able to observe it by monitoring the pattern of dried water drops under microscope (magnification 100 - 1000 times). The influence was more observable and more pronounced when more minerals and diluted substances were present. This gave us the idea that, as human organisms consist mainly of water, blood and body liquids should exhibit the same changes after PEMF stimulation. In order to prove this a group of volunteers were stimulated with PEMF once a day for 30 minutes, every second day to a different frequency. A suitable applicator generated magnetic field component of a peak value of 1 mT in a backbone region of the patient. The pulses were 15, 24, 30 and 72 pps. The venous blood was taken before, immediately after the stimulation and 3 hours lafter the stimulation. Blood serum remedy drops were prepared and dried. The results were observed by microscope for each case. We found different cristallisation patterns that were linked to the repetition rate of the pulses. The difference remained present for at least 3 hours after the stimulation. If we recall that for each person the bood serum remedy crystallisation pattern is different and expresses the situation in the whole organism, it is evident from our researches that PEMF changes the information content in blood. Although we are not able to do any quantification at the moment it seems possible to define a new approach to judge the PEMF influence on a patient by a simple blood serum remedy test.

Friday PM2 AP-S, URSI-B Session FP15

Room: Grand A *Time*: 1520-1700

Neural Network Techniques

Chairs: J. Schindler, Rome Laboratory; R. S. Zich, Politecnico di Torino

1520 **SCATTERING SIGNAL EXTRACTING USING SYSTEM MODELLING METHOD BASED on a BACK PROPAGATION NEURAL NETWORK**
Liang-jie Zhang*, Weng-bing Wang, Xi'an Jiaotong University

1540 **APPLICATION of NEURAL NETWORK to the TRANSIENT SYSTEM CORRECTING for IMPROVED TARGET DETECTION**
Liang-jie Zhang*, Weng-bing Wang, Xi'an Jiaotong University

1600 **ADAPTIVE DIRECT RECEIVING SIGNAL CANCELLING USING NEURAL NETWORKS**
Liang-jie Zhang*, Weng-bing Wang, Xi'an Jiaotong University

1620 **ELIMINATION of DIRECT WAVES in TIME-DOMAIN MEASUREMENTS of ELECTROMAGNETIC SCATTERING by ADAPTIVE ARTIFICIAL NEURAL NETWORK**
Bin Song*, Gong Long, Junmei Fu, Xi'an Jiaotong University

1640 **ANN for REAL-TIME IDENTIFICATION of RADAR OBJECTIVES**
Bin Song*, Gong Long, Junmei Fu, Xi'an Jiaotong University

SCATTERING SIGNAL EXTRACTING USING SYSTEM MODELLING METHOD BASED ON A BACK-PROPAGATION NEURAL NETWORK

Zhang Liang-Jie Wang Wen-Bin
Department of Information & Control Engineering
XI'AN JIAOTONG UNIVERSITY
XI'AN 710049 SHAANXI , P.R.CHINA

ABSTRACT

In practical transient subsurface radar system(TSRS), there is a problem that the direct receiving signal y(n) can not be directly obtained because when the aided antenna will not be allowed for convenient , the object is always present . Moreover , the excitation of the transmitting antenna is also varying slightly although its signal can be obtained . Thus , when the excitation signal x(n) is given , in order to extract the real time scattering signal, a problem how to obtain the direct receiving signal appears.

It is well known that the system modelling method is the only choiced way in order to solve the above problem . In the past, in order to model the TSRS , that is, to obtain the DRS when the x(n) is given , we often make use of deconvolution to find the impulse response of the TSRS . Unfortunately , the traditional deconvolution method often result in instability .

In this paper , we describe a neural network called Back-Propagation net and its use in learning the impulse response function of the the TSRS necessary for this system modelling . Neural network modelling was selected because of their ability to adapt to the environment through training , which allows them to avoid many of the problems associated with traditional system modelling method . Generally speaking , the neural network is of great benefit when the nature of the nonlinearity is unknown or is difficult to characterize .

Simulations are described which use experiment data as inputs and desired outputs of the neural networks during the training process . The excitation signal x(n) are used as the inputs of the neural network , and the DRS y(n) are used as outputs respectively here . The neural network "learns" to solve this problem by being trained on many training sets of pairs {x(n), y(n)} . The size and nature of the training set will be discussed briefly within this paper .

Results are shown of the TSRS modelling . Examples with new experiment data of the excitation signal and testing (nontraining) results are also shown . The results show considerable promising . When the testing sample x0(n) is used as input of the trained neural network , the result of the DRS's least square error estimated value is obtained . i.e., the DRS was subtracted from the received signal including the DRS and the scattering signal , leaving the object scattering signal . The high performance of this neural network modelling is shown in the scattering signal extracting processing .

APPLICATION OF NEURAL NETWORK TO THE TRANSIENT SYSTEM CORRECTING FOR IMPROVED TARGET DETECTION

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XI'AN JIAOTONG UNIVERSITY
XI'AN, SHAANXI, P. R. CHINA

ABSTRACT

The quest for the highest resolution in radar target detection has been the primary motivation for recent developments in transient scattering measurement . In this paper, we consider the design of a inverse transient measurement system modelling from combinated measurement data by using a neural network called Back-Propagation net. First, we discuss the background of the problem and then the design of the system corrector .

The transient scattering measurement system was developed primarily to determine the transient response characteristics of scale models subjected to various electromagnetic excitations. The system consists of major subsystem as follows: pulser generator, transmitting antennas, cable, receiving antenna, digitizers, and microcomputer. When the receiving antenna is placed a radial distance from the source antenna and no object is present, the antenna measures the free field response called direct receiving signal(DRS). When a test object is present, the receiving antenna measures the combinated signals including the DRS and the scattering signal of the test object. Unfortunately the DRS and the combinated signal cannot be measured simultaneously, because the field is disturbed by the presence of the object. This practice bring up the problem of an output sequence generated by an input sequence different from the measured one because of environmental electromagnetic noise. Moreover, the amplitude of DRS is much larger than that of scattering signal, and the early time signal associated with the antenna coupling excites a response which extends into the range window in which the target is to be observed. This and measurement distortions distort the portion of the waveform caused by scattering from the target and makes it difficult to detect, identify. The purpose of this paper is to compensate for the distortions for compressing the DRS by designing a system corrector using a neural network.

Here, a computing architecture for adaptive inverse system modelling based on computational features of nonlinear neural network is introduced. These features are massively parallel and distributed structures for signal processing, with the potential for ever-improving performance through dynamical learning. In this paper, we describe a neural network called Back-Propagation net and its use in learning the inverse impulse response function of the transient scattering measurement system.

In this work, we train a neural network model to identify inverse dynamics of an unknown transient measurement system, and then apply it as a system corrector, as is shown in fig. 1, where the output signal(DRS) of the corrector(neural network), y(t), should match the desired response, Xd(t), a delay of the excitation signal X(t). The neural network model here performs a specific form of adaptive inverse system modelling, with the adaptable parameters being the strength of synaptic connections to the neurons.

After training the neural network, we input a received signal(i. e. combinated signal comprise DRS and scattering signal) to the system corrector(i. e. neural network). This output result shows that the input of the distortion of the receiving signal may be reduced, and the direct receiving signal is compressed. Obviously, this method can improve greatly the ability and performance of target detection. Moreover, the advantage of this technique is greater speed and tolerance.

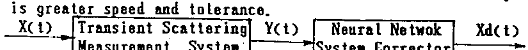

Fig. 1. Block diagram of System Corrector Using Neural Network

Adaptive Direct Receiving Signal Cancelling Using Neural Networks

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XI'AN 710079

[ABSTRACT]

In time-domain scattering measurement system (TDSMS) , the is a main unrequired signal called direct receiving signal(DRS) will seriously interfere the required target scattering signals(TSS) because that the amplitude of DRS is much larger than that of the TSS. So the problem of cancelling DRS has been becoming a very key technique in our TDSMS . In other words, the problem of interest is the efficient extraction of TSS buried in high noise environment.

Recently, ANN(Artificial Neural Network) has attracted the attention of scientists and engineers in many fields based on its many computational features such as massively parallel and distributed structures for signal processing, and gives a new way to solve many problems. So, In this work, we make use of a layered neural network models trained according to the Back-propagation learning algorithm to perform a specific form of adaptive filtering ,which will take a role in the DRS cancelling.

In this paper, the first option is in choosing the problem defined specifically so that a selection of inputs and outputs to ANN may be made. Next, the internal design choice must be made----including the topology and size of the network. Finally, the selection of training data presented from the TDSMS to the ANN influences whether or not the network "learns" a particular task. In other words to say that, this paper describes the adapation model architecture and application performance in our DRS cancelling field.

One of the problems using neural network is that the training time is a function of the size of the training set and the number of weights to be learned . During the training time, a DRS sample which is correlated with the original corrupting signal DRS is used as input to a single hidden layer neural network . At the same time , a received signal sample involving the TSS and DRS is used as the desired output to the neural network .

The neural network filters the DRS y(t), which is correlated with the original corrupting signal DRS y0(t), and subtracts the result from the primary input s(t)+y0(t). The obtained TSS s(t) for target identification is promising and shows better and more robust performance than traditional signal processing approach because of the parallel nature of the computation taking place . This examples illustrate the nature and breadth of potential ANN applications in the field of the measurement signal processing.

Friday PM2 URSI-E Session FP18

Room: Columbus I/J *Time*: 1500-1720

Noise Suppression, Characterization and Interference

Chairs: Masashi Hayakawa, The University of Electro-Communications; R. L. Gardner, Phillips Laboratory, USAF

1500 **VIABILITY ASSESSMENT for RELIABLE LONG-WAVE COMMUNICATION LINKS**
T. S. Cory, Engineerng Consultant; T. R. Holzheimer*, E-Systems Inc.

1520 **SUPPRESSION of RECTENNA HARMONIC RADIATION by a FREQUENCY SELECTIVE SURFACE**
James O. McSpadden*, Kai Chang, Texas A&M University

1540 **DIRECTION-FINDING of TWEEK ATMOSPHERICS and THEIR PROPAGATION**
Masashi Hayakawa*, The University of Electro-Communications; K. Ohta, Chubu University

1600 **OVERALL PERFORMANCE of DIVERSITY and LEVEL DISTRIBUTION in COASTAL-DESERT MICROWAVE LOS LINKS SUFFERING from SEVERE FADING CONDITIONS**
Said E. El-Khamy*, Alexandria University; Samir A. Matbouly, Saudi TELECOM

1620 **ON the MINIMIZATIONS of SKY-WAVE INTERFERENCE in GROUND-WAVE RADARS**
S. A. Saoudy*, F. Hartery, Memorial University of Newfoundland

1640 **EMI SUPPRESSION and NOISE REDUCTION in RADIO TRANSCIEVERS by the USE of IMPEDANCE MISMATCH METHODS**
Masood Ghadaksaz*, GTE Laboratories

1700 **INTERFERENCE from CONTACT POWER LINES of ELECTRIFIED RAILWAY with UNDERGROUND TRANSMISSION SYSTEM**
Han Fang*, Northern Jiaotong University

VIABILITY ASSESSMENT FOR RELIABLE LONG-WAVE COMMUNICATION LINKS

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ABSTRACT

The continuous ELF through VLF frequency spectrum in the range of 0.1 to 30 kHz was revisited for the purpose of assessing statistical communication link performance possibilities at long range, nominally 9000 kilometers, to two widely geographically separated receive locations from a variety of transmit locations. The analysis model assumed a deterministic MSK-modulated skywave signal of median value in the presence of atmospheric noise. C.C.I.R Report 322-2 and LNP noise models were considered. A C.C.I.R. based noise model was modified to use NBS Monograph 23 APD's, and the noise power was linearly extrapolated downward in frequency from 10 kHz. The receive locations were inland, in low-latitude regions likely to be influenced by climatic storm centers. The signal model used the incoherent sum of wavehops, per Bremer. These incoherent computations versus frequency ignore the difficult-to-predict coherent waveguide cutoff effects which to first order apply to both signal and noise. The link analyses suggest an optimum frequency for communications for fixed ERP; between 7 and 10 kHz for inland ground receive sites, and at 20 kHz or above for semester paths to near-coastal or ship-borne receivers (confirming the U.S. Navy choice of frequency for VLF broadcast stations). Based on analyses with frequencies and ERP's commensurate with existing Navy broadcast stations, a 50-baud signalling rate is expected to be available at either receive location 90% of the time during 50% of the hours for error rates of less than 10^-3 if selected transmit sites are used. A single transmit site cannot be used for both receive locations because each path must be predominantly over sea water. Alternatively, similar error rate performance at half the baud rate (25 Hz) would be expected from selected Omega radionavigation stations running only about a tenth of the ERP of the broadcast stations, if the Omega stations were presumed to transmit near the low frequency end of the radionavigation band (approximately 10 kHz) with no received interference from other like transmit stations being experienced. This surprising result shows the expected impact of operating near the optimum frequency. The overall result from the above analyses is that reliable long-wave communications can be accomplished with the use of existing transmit stations.

SUPPRESSION OF RECTENNA HARMONIC RADIATION BY A FREQUENCY SELECTIVE SURFACE

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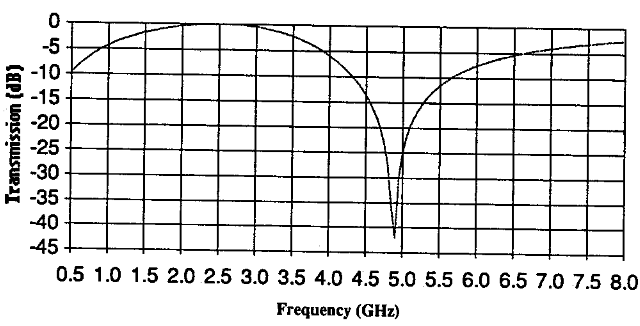
Frequency selective surfaces (FSS) have been used for a number of applications including reflector antenna systems and dielectric radome designs. A new application of an FSS is to reject the harmonics produced by a rectenna. A rectenna is a receiving antenna that converts a microwave beam into useful DC power. Harmonics of significant power levels are produced by a diode that converts the RF to DC power. This harmonic power is then radiated into free space which may cause potential problems. If the rectenna were placed aboard a satellite, the harmonic radiation could interfere with communication signals. It is desirable to suppress these harmonics by use of an FSS.

A gridded square FSS has been developed to act as a band stop filter. The theoretical frequency response is shown in the figure below. A transmitting frequency of 2.45 GHz is normally incident on 4 foot square rectenna array with the FSS located in front of the array. The FSS is designed to pass the 2.45 GHz signal and reject the 4.9 GHz second harmonic. The insertion loss at the fundamental frequency is designed to be less than .1 dB. The transmission of the second harmonic is designed to be less than -30 dB. The third harmonic power level is small compared to the second harmonic but will still encounter a transmission of less than -3 dB. To prevent the harmonics from leaking at the edges between the FSS and rectenna, reflectors are added at the four sides to enclose the structure. An equivalent circuit model of the gridded square FSS is used for the design (C.K. Lee & R.J. Langley, IEE Proc., Vol. 132, Pt. H, No. 6, 395-399, Oct. 1985). Theoretical and experimental results with and without the rectenna will be presented. The effect of placing the FSS in the near-field of the rectenna will also be examined.

Gridded Square Frequency Selective Surface
Transmission - 2.45 GHz Rejection - 4.9 GHz



DIRECTION-FINDING OF TWEEK ATMOSPHERICS AND THEIR PROPAGATION

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and

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The field-analysis direction finding developed for magnetospheric VLF waves (whistlers and VLF emissions) has been applied, for the first time, to tweek atmospherics. This direction finding system is based on the simultaneous measurement of three field components (two horizontal magnetic, Bx, By and a vertical electric, Ez) over a wide frequency range, which yields the arrival direction (incident and azimuthal angles) and the wave polarization. The following experimental results are found for tweek atmospherics. (1) For the 0-th order mode at the frequency below the cutoff frequency of the 1st-order mode (≅1.7kHz), the wave is nearly vertically linearly polarized. (2) The incident angle (measured from the zenith) of the 1st-order mode exhibits a decrease toward 0° (vertical incidence) with the decrease of wave frequency toward the cutoff frequency, (3) The polarization of the 1st-order mode wave is exactly left-handed circular when the frequency is very close to its cutoff frequency from above, and when the frequency departs from the cutoff, the polarization becomes more linear, but left-handed elliptical. These experimental results are interpreted in terms of the Earth-ionosphere waveguide propagation, and we suggest that these experimental results would indicate some important information on the anisotropy of the ionosphere etc.

OVERALL PERFORMANCE OF DIVERSITY AND LEVEL DISTRIBUTIONS IN COASTAL-DESERT MICROWAVE LOS LINKS SUFFERING FROM SEVERE FADING CONDITIONS

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ABSTRACT

Anomalous propagation conditions that cause fading in microwave line-of-sight (LOS) links are highly pronounced in coastal-desert areas. This is due to the high probability of occurrence of temperature inversions and high variations in humidity. Space diversity techniques are often used in such links to reduce the effect of fading on the operational unavailabilities. Most of the operating analog links use the simple switching combining technique. In this paper, measurements on an experimental link located on the eastern coast of the red sea (described by El-Khamy and Matbouly,MELECON'87, Rome, Italy, Mar. 87) are used to investigate the overall performance of such simple diversity techniques in combating severe fading effects. Also, the overall distribution functions and the propagation parameters that characterize such strong fading areas are extracted from the measured data. Emphasis has been placed on the sunrise period when most of the severe fading conditions were monitored. A special chart that helps in evaluating the usefulness of the used diversity system has been developed. The results show that the used space diversity system is not efficient in combating the severe fading effects and thus more sophisticated diversity systems and combining techniques are most suitable for such links. Examples of the overall scattering diagrams and distribution function are shown in Fig.1 and Fig.2 respectively.

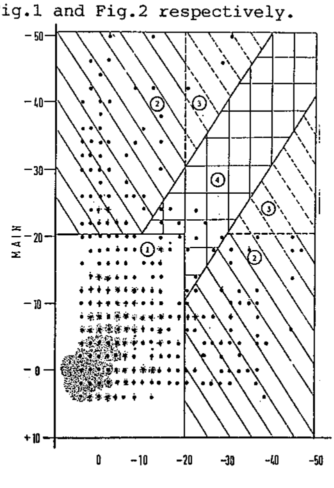

Fig.1 Overall Scattering diagram.

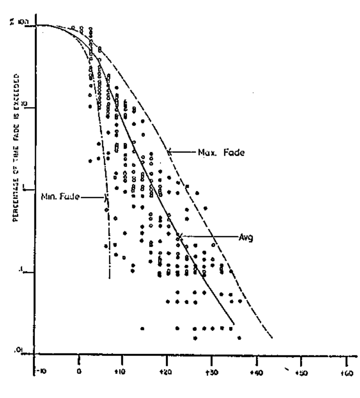

Fig.2 Overall distribution function.

INTERFERENCE FROM CONTACT POWER LINES OF ELECTRIFIED RAILWAY WITH UNDERGROUND TRANSMISSION SYSTEM

HAN Fang, Member, IEEE
EMC Research Section, Northern Jiaotong Univ., Beijing, 100044, CHINA

INTRODUCTION

The interference from contact power lines of electrified railway with nearby underground transmission system such as communication cables and metal pipes, has aroused more and more attention. In short, the current feeding the electric locomotive will flow back to the supply terminal in two path, one is absorbing lines (including rail itself), the other is the earth. All the currents in contact power lines, in absorbing lines, and in the earth could excite on and couple with underground transmission systems, leading to unwanted interference. There are a few publications discussing the approach to calculate the coupling and estimate the interference (Y. G. Gao, Railway J., 4, 1981; W. Machczynski, IEE Proc. 129, 279–288, 1982). However, for underground coupling problems with earth conductive effect and loss effect being taken into account, these approach is invalid because the transmission line method could not be simply applied. Moreover, both inductive coupling and resistive coupling should be taken into account.

Considering these factors, a more general approach to analyse and calculate the coupling of the contact power lines and their return currents with underground conductors of both infinite and finite length is presented on the basis of equivalent transmission line equations forwarded previously by the author (F. Han, J. Electr. Tech. 1. 12–17, 1989). By this approach, distributions of the currents and potentials induced along two underground conductors of infinite length by unit current can be determined respectively by

$$\begin{aligned} I_n^0(x) &= I_n^p(x) + I_n^r(x) \\ V_n^0(x) &= V_n^p(x) + V_n^r(x) \end{aligned} \qquad n = 1,2 \qquad (1)$$

where, superscript p and r represents the coupling from contact power line and return path, respectively.

EMI SUPPRESSION AND NOISE REDUCTION IN RADIO TRANSCEIVERS BY THE USE OF IMPEDANCE MISMATCH METHODS

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ABSTRACT

One of the most active areas of research in the field of electromagnetic interference (EMI) is interference suppression. In today's congested radio spectrum EMI is a frequent occurrence. In cellular and land mobile radio communications networks the increasing proliferation of mobile (vehicular, portable, base station) radios has created a serious problem of electromagnetic compatibility (EMC). In tactical communications and particularly in combat network environment radio transceivers are commonly subject to colocation and other forms of friendly and hostile electromagnetic interference. The interference problems such as spurious signals, harmonic and subharmonic emissions, intermodulation products, and broadband noise are generated by transmitting radios. The interference signals arriving at the victim receiving antenna together with the lack of adequate receiver channel selectivity and the nonlinear effects within the receiver front-end can cause desensitization of the victim receiver or its complete jamming. The characteristics of the interference signal such as magnitude, frequency, and bandwidth can exhibit a wide range of values. In addition, time and frequency of occurrence of interference signals particularly those generated by transmitting hopping radios are unpredictable. Present techniques to combat EMI such as frequency relocation, filtering, relocation of equipment, antenna nulling, interference cancelers,..etc. are inadequate and their effectiveness is limited to only certain types of interference. Furthermore while some of these techniques require costly and elaborate complex signal processing, others are not always operationally or mechanically feasible particularly for mobile and portable communications sets. As a result it is generally desired to develop a technique for suppression of electromagnetic interference independent of its characteristics, mechnisms, time, and frequency of occurrence such that it can be implemented in any radio communications set. This paper describes a universal method for interference suppression in communications receivers. The proposed method is based on the simultaneous absorption of RF interference energy in a resistive load in one direction, and in the opposite direction reflection of the desired received signal towards a directional network for detection and further signal processing.

ON THE MINIMIZATION OF SKY-WAVE INTERFERENCE IN GROUND-WAVE RADARS

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Ground Wave Radars (GWR) are used for offshore over the horizon surveillance of icebergs, ships and low flying objects. A prototype monostatic radar system has been built at Cape Race, Newfoundland, Canada. At an operating frequency of 7 MHz, a reduction of the radar's intended range of 400-450 km to about 235 km can be attributed to external noise and self-generated sky-wave interference.

Direct ionospheric reflections from the F layer introduce a shadow to mask the portion of the radar range from 235 to 450 Km. Predominantly this relates to high angle radiation from the transmitting antenna which is in the form of a Log Periodic Array (LPA) dipole antenna. The commercially available transmitting antenna was designed for long range communication where the reduction of vertical radiation was not fully studied.

In this work, the radiation characteristics of the log periodic array antenna will be studied using the Numerical Electromagnetics Code (NEC-2) which employs the moment method. Possible modifications in the design of the LPA are investigated in an effort to minimize vertical radiation from the antenna. The modifications take into account the effects which the Guy wires supporting the 120-foot antenna tower and the feedline arrangements have on the radiation pattern.

The modifications of the LPA include changing the antenna elements inclination angles with respect to the vertical direction. As for the steel guy wires, one can either replace them by non-conducting support wires or introduce insulators along their length every one eighth of the wavelength of the highest operational frequency.

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NOTES

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1993 IEEE - APS International Symposium and URSI Radio Science Meeting

The University of Michigan
Ann Arbor, Michigan, USA
June 27 - July 2, 1993

The 1993 IEEE AP-S International Symposium sponsored by the IEEE Antennas and Propagation Society and the URSI Radio Science Meeting sponsored by USNC Commissions A, B, D, E , F and K of the International Union of Radio Science will be held at the University of Michigan Main Campus, Ann Arbor, Michigan, June 27 to July 2, 1993. The technical sessions will cover the five-day period June 28 to July 2, 1993, and will be coordinated among the two symposia to provide a comprehensive, well balanced program.

- General information about the 1993 joint IEEE AP-S Symposium and Radio Science Meeting may be obtained from Professor John L. Volakis, 1301 Beal Avenue, Ann Arbor, MI 48109-2122.
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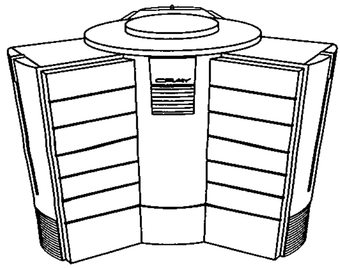

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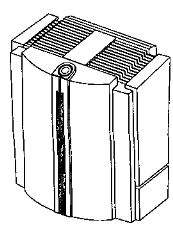

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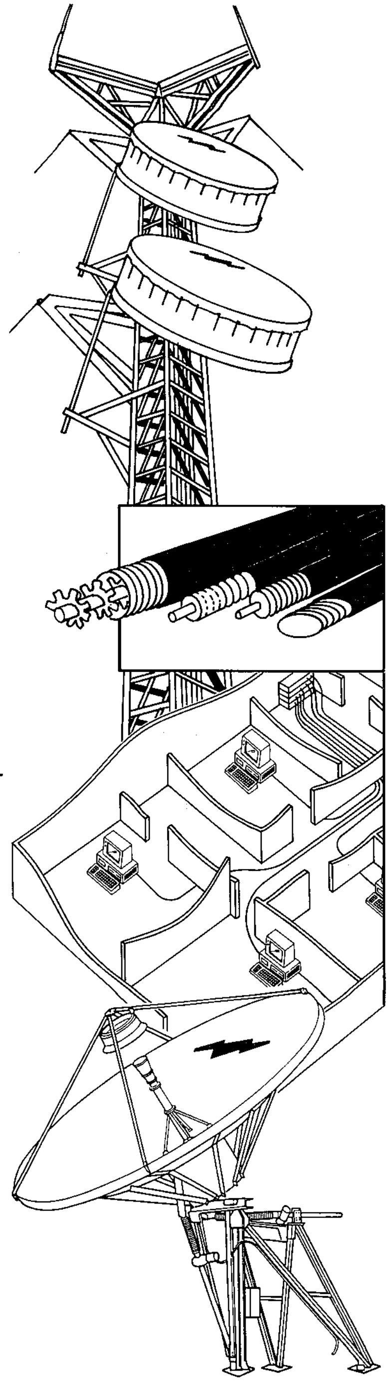

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