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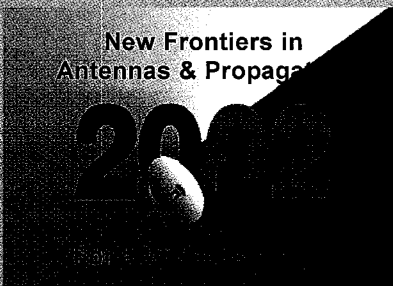

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USNC/URSI
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New Frontiers in Antennas & Propagation
2002
for a Wireless World

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Chairman's Welcome

Welcome to Texas!

On behalf of the Steering Committee, I offer you the warmest of welcomes to San Antonio, Texas, and the 2002 IEEE AP-S and USNC/URSI Symposium. The conference theme, "New Frontiers in Antennas and Propagation for a Wireless World," reflects the historically forward-looking attitude of the people of Texas and a creative viewpoint that has been a hallmark of this conference. This year the conference is being hosted by a Steering Committee representing several universities and Texas industries. Our widely dispersed group is doing our part to support the wireless technology industry, which will undoubtedly be improved by your participation in this year's conference.

Our technical program, Chaired by Krys Michalski and Co Chaired by Don Wilton, will include AP-S and commissions A, B, D, F, and K of USNC/URSI. The technical program consists of 129 sessions and half-sessions. Among these are 19 special sessions that will explore new frontier topics such as 'Computational Challenges', biomedical applications, and applications of new materials in the design of antennas and waveguides. Several workshops and short courses, held on Sunday June 16th and Friday, June 21st, will allow you the opportunity to explore these subjects in more depth, as well as the chance to study leading edge advances in antennas and propagation from some of the top people in our field. Also, please stop by to see our industry representative booths presenting hardware and software products for antenna design and measurement.

The conference committee expresses our special thanks to this years sponsors; to Raytheon for our conference 'tote' bags, to Southwest Research Institute for subsidizing Tuesday nights Fiesta Noche del Rio put on by the San Antonio Kiwanis Club who will donate half of the proceeds to a local children's home, to NSF for Student Paper Contest travel grants, and to Schlumberger for subsidizing the spouses program.

The steering committee and I look forward to seeing you and hope that you will have a fun and memorable experience as well as a scientifically productive week in San Antonio.

Robert Nevels, *Chair, 2002 Joint Symposia*
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for the paper "A Maximum Likelihood Beamspace Processor for Improved Search and Track," July 2001

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for the paper "A 5-Frequency Millimeter Wave Antenna for a Spaceborne Limb Sounding Instrument," May 2001

R. W. P. King Award

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for the paper "Calculating the Mutual Coupling between Apertures on a Convex Circular Cylinder Using a Hybrid UTD-MoM Method," co-authored with Lars Josefsson, April 2001

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Fast and Efficient Numerical Methods

Co-Chairs: ***Y. Leviatan, Technion, Israel***
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A Fast Numerical Method for Electromagnetic Scattering from Inhomogeneous Objects in Layered Medium

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Abstract

Electromagnetic scattering from buried inhomogeneous objects in planarly layered media is an important research area in remote sensing. It finds applications in subsurface sensing such as oil exploration, utility pipes detection, land mine detection and medical imaging.

In this work, an iterative method, the stabilized biconjugate gradient (BiCGSTAB) method, combined with the fast Fourier transform (FFT) for solving large-scale electromagnetic scattering from inhomogeneous objects in layered media is developed for 3-D volume electric field integral equation (EFIE) formulation.

The unknown in the EFIE is chosen to be the electric flux density. Simple and uniform basis and testing functions–the "roof-top" function, which is piece-wise linear in one direction and piece-wise constant in the other two directions, is chosen for the following two reasons. First, such a basis function can represent the electric flux density correctly; the normal component is continuous across cell boundaries and thus is expanded by a linear function. Secondly, one of the second order derivative in the EFIE will be shifted to the testing functions. The other derivative is taken care of by expanding also the magnetic vector potential in terms of basis functions. As a result, the discrete EFIE has no derivative for the dyadic Green's function and the convergence rate is significantly improved by this discretization process.

The discrete EFIE is solved by the efficient stabilized biconjugate conjugate gradient (BiCGSTAB) linear solver combined with the fast Fourier transform (FFT) to calculate the discrete convolution and correlation kernels. The computational cost is $O(KN \log N)$ for the BCGS-FFT method compared to $O(N^3)$ for MOM, where K is the number of iteration and N is the number of unknowns. With this BCGS-FFT, we can solve large-scale problems with millions of unknowns on a single CPU workstation.

Parallel Processing Schemes for Multiple Dielectric Targets in MLFMA

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Two parallel processing methods have been developed for calculating electromagnetic scattering from multiple dielectric targets in the Multi-Level Fast Multipole Algorithm (MLFMA). One method calculates each target separately on a single processor. Data from the individual calculations are then passed between processors to iteratively update the overall solution. The computations and updates are performed until the overall solution converges. Another scheme treats the ensemble of targets as a whole. This scheme divides the work among the different processors based on the number of edges in the overall geometric model and passes the necessary data between processors.

The main difference between the two methods is that the first method calculates the scattered fields of each target separately and uses the individual solutions to iteratively solve the overall problem, while the second method solves for the scattered fields of the entire target ensemble in one calculation. An iterative matrix solver is used as a part of the solution process. The total number of iterations needed for the matrix solver is the number of iterations used in the solution of the matrix solver times the number of times the matrix solver is run. When the first method is used, the matrix solver is run multiple times to obtain the overall solution, but only once for the second method. However, the matrix that must be solved for the second method is larger than the first by a factor of the square of the number of targets. It therefore requires more iterations to solve once.

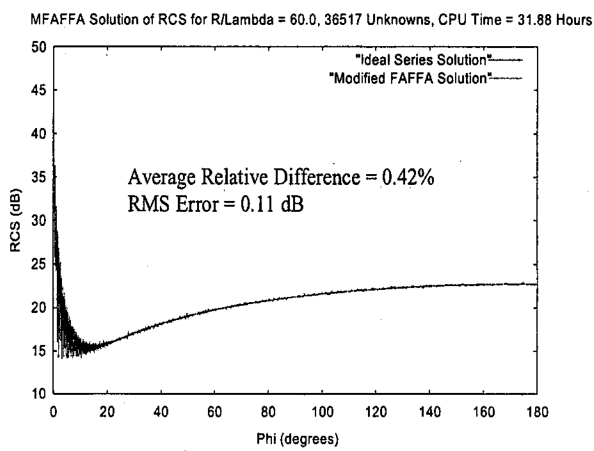
An overview of the two parallel processing schemes will first be given. The advantages and disadvantages of each method will then be compared. The memory requirements, computation times, and total number of iterations for solution convergence will be analyzed for both parallel-processing schemes. The analyses will be performed over an increasing number of processors and for a range of target geometries and target sizes. This inquiry will be used to determine the characteristics and utility of each method. It will also demonstrate under which conditions it is advisable to use the first method and which conditions it is advisable to use the second method.

A More Accurate Fast Far Field Approximation for Calculating Electromagnetic Scattering From Infinite Conducting Cylinders

John Michael Hall, Lockheed Martin Space Operations, Hampton, Va.
Manohar D. Deshpande, NASA Langley Research Center, Hampton, Va.

The Fast Far Field Approximation (FAFFA) has long been explored as a promising method for accelerating the computation of electromagnetic scattering from electrically large objects of arbitrary shape. Using this method, a conventional dense matrix-vector product requiring N^2 operations reduces to $N^{1.5}$ operations with a memory requirement of N, where N is the number of unknowns [Chew and Lu, ACES Conference Digest, 1995]. However, such acceleration can be acquired only at the expense of some accuracy. The FAFFA is without question the fastest of all the Fast Multipole Methods, but it also suffers from a substantially higher error than the others [Volakis, et. al., IEEE Press, 1998]. A method that could significantly reduce this error without incurring additional computational penalties or increasing memory requirements would be very attractive.

A technique will be presented by which the calculation of scattering from infinitely long, perfectly conducting cylinders can be appreciably accelerated without incurring significant loss of accuracy using a Modified Fast Far-Field Approximation. This modification significantly reduces error without incurring additional computational penalties or increasing memory requirements, yielding results superior to those given by the conventional FAFFA in a similar time interval. The figure below shows bistatic scattering from an infinite conducting cylinder of R/Lambda = 60, illustrating the outstanding agreement of the MFAFFA solution with the analytic series solution. The MFAFFA formulation will derived, results will be compared with uncorrected results obtained using the conventional FAFFA, and the implications discussed.



Domain Decomposition and Polar Grid Interpolation Algorithms for Fast Iterative Solution of Scattering Problems

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Rigorous analysis of scattering by arbitrary shaped bodies is often effected via numerical solution of pertinent integral equations. For simplicity, we consider a two-dimensional scattering by an open perfectly conducting surface analyzed via the Electric Field Integral Equation (EFIE). The number of field and current sampling points on the surface is proportional to its electrical dimensions, i.e. of $O(N)$, where $N = kR$, R being the radius of the smallest circle circumscribing the scatterer and k - the wavenumber. Due to $O(N^3)$ computational complexity of conventional direct solvers, iterative approach becomes a necessity for analysis of electrically large problems. Solving EFIE, each iteration requires evaluation of the electric field due to a given surface current. Straightforward evaluation of the field at $O(N)$ points by surface integration involving summation of $O(N)$ terms amounts to $O(N^2)$ operations. This high computational burden underlines the need for using fast field evaluation techniques.

In this paper, we present a novel scheme that facilitates numerically efficient evaluation of the field produced by a given current distribution. The algorithm is based on the observation that locally the field radiated by a finite size source is an essentially bandlimited function of the angle and radial distance multiplied by a common phase factor. The pertinent angular bandwidth is proportional to the linear dimensions of the source, while the local bandwidth with respect to the radial distance decreases rapidly with distance from the source region. Therefore, the radiated field can be sampled on a non-uniform polar grid with radial density decreasing with the distance away from the source. Consequently, the radiated field on the surface can be interpolated from its samples at a number of polar grid points proportional to the source region dimensions. With this in mind, we decompose the scatterer surface into subdomains and compute the field for each of them separately. The field of each subdomain is directly evaluated at a small number of polar grid points and subsequently interpolated, thus providing computational savings. The phase common to all source points in a given subdomain is removed from the field prior to interpolation. Following the interpolation, we restore the phase and aggregate these partial fields into the total field due to all subdomains combined. The two-level domain decomposition algorithm reduces the computational cost of evaluating the field (a single iteration) from $O(N^2)$ to $O(N^{3/2})$. A multilevel algorithm is obtained upon starting from small subdomains, for which the field is computed directly over a very coarse grid, and repeating the interpolation and aggregation steps for progressively finer grids, while doubling the subdomain sizes. The multilevel algorithm attains an asymptotic complexity of $O(N \log N)$.

Multi-Level Fast Multipole Algorithm (MLFMA) of Volume Electric Integral Equations for Electromagnetic Scattering from Dielectric Scatterers above or Embedded in a Half-Space Interface

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The multi-level fast multipole algorithm (MLFMA) is considered for electromagnetic scattering from dielectric targets totally above or embedded in a half-space interface environment. We have developed and implemented the method of moment (MOM) solutions of volume electric integral equations (VEFIE) for this purpose. The three-dimensional (3D) tetrahedral volume model is used to mesh and model the scatterer. The 3D vector basis function, which is defined in two neighbored tetrahedral volume elements, is used to represent the electric field and equivalent electric current inside the scatterer. The nearby terms of the impedance matrix of MOM in the MLFMA framework are evaluated by using complex image techniques (CIT) for the half space Green's function. The far interactions (non-nearby terms) are calculated via rapid MLFMA scheme, where an approximation to the dyadic Green's function is employed. In this approximation, the dyadic Green's function in half space is expressed in terms of a direct-radiation term plus the reflected term from the interface. The reflected term is characterized by the polarization-dependent Fresnel reflection coefficient. The VEFIE model can be applied for both homogeneous and inhomogeneous scatterers, and the rapid method can be used for both lossless and lossy half-space environments. Several examples are presented to validate the code through comparison with the MOM solution of surface integral equation model and time domain finite difference (FDTD) method.

In this presentation, the volume electric integral equation (VEFIE) modeling is firstly used in the solution of electromagnetic scattering problems in half-space environment, and the MLFMA solution of VEFIE in half-space environment is firstly developed and implemented. It represents a combination and extension of the MLFMA of VEFIE in free space and of our previous MLFMA solution of surface-model electric-field, magnetic-field and combined-field integral equations in a half-space environment.

New MLFMA Formulation for Closed PEC Targets in the Vicinity of a Half Space

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Integral-equation formulations have been used for several decades in the analysis of scattering from targets. In this context researchers have developed electric-field integral equations, magnetic-field integral equations, and combined-field integral equations (EFIE, MFIE and CFIE, respectively). More recently researchers have sought to understand the limitations in the underlying continuous integral equations that manifest poor conditioning in the subsequent discrete (matrix) equation. In this context it has been recognized that the hyper-singular characteristics of the EFIE are responsible for much of the poor conditioning, particularly when the basis-function sample rate is high relative to wavelength. If T is used to represent the EFIE operator, it has been recognized that improved matrix conditioning is realized when employing the modified underlying operator T^2 (i.e. the EFIE matrix equation is based on T^2 rather than T). In this paper we discuss techniques by which T^2 can be discretized, yielding a matrix equation.

In this paper, we focus on the new formulation in the context of a multi-level fast multipole algorithm (MLFMA) formulation. Discretization of T^2 is implemented based on an intermediate space, used to implement the right operator in $T^2=TT$. By choosing this intermediate space appropriately, the right operator is implemented in a form very similar to the original MLFMA. The left operator T in $T^2=TT$, representative of transitioning from the intermediate space to the testing-function space, is here evaluated approximately by only accounting for near interactions. This is shown to yield both computational efficiency and highly accurate results.

Having modified the EFIE, we use it in the context of a CFIE formulation employed for closed PEC targets. In particular, recall that the CFIE is designed to eliminate the resonances present in isolated EFIE and MFIE formulations (these present when the EFIE and MFIE are not combined). The modified EFIE (M-EFIE) operator T^2 is characterized by both EFIE and MFIE resonances, and therefore a direct combination of the M-EFIE and MFIE does not eliminate internal MFIE resonances. We therefore modified form of T^2 that eliminates MFIE resonances while still retaining improved numerical conditioning, with this employed in the subsequent CFIE.

This new CFIE employing modified EFIE formulation is implemented in CFIE MLFMA analysis for closed PEC targets. Several example results are presented, in which comparisons are made to traditional MLFMA formulations.

Multigrid Analysis of Scattering by Large Quasi-Planar Structures

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Wave scattering by infinite periodic structures has been extensively treated by many researchers since the pioneering work of Lord Rayleigh. On the other hand, scattering by finite quasi-planar periodic and non-periodic geometries received relatively meager attention in terms of numerically rigorous analysis. Examples of such structures comprise rough surfaces, Fresnel lenses and planar reflector antennas as well as realistic finite frequency selective surfaces and antenna arrays. Scattering by quasi-planar structures can be formulated in the integral equation form, which is conventionally discretized using the Method of Moments (MoM). The direct solution of the MoM matrix equations for electrically large bodies is impractical due to $O(N^3)$ complexity of direct solvers. Recently, a number of fast direct and iterative algorithms for the solution of the problem have been proposed (see E. Michielssen, A. Boag, W. C. Chew, *IEE Proc.-Microw. Antennas Propag.* **143**, 277-283, 1996).

In this paper, we propose an alternative iterative solution based on the general multilevel approach for fast evaluation of integral transforms with oscillatory kernels, that was first presented in (A. Brandt, *J. Comp. Phys.*, 1991) and adapted for problems of scattering from planar structures in (O. Livne, A. Brandt, and A. Boag, *Microwave Opt. Tech. Lett.*, March 20, 2002). This approach avoids the fixed discretization inherent to the MoM and allows for local refinements of the solutions leading to higher order accuracy. We consider a two dimensional scattering by a large but finite array of perfectly conducting quasi-planar strips in the (x,y) plane. The problem is that of solving the two dimensional electric field integral equation, where the strips are very narrow in the y-direction. Utilizing the asymptotic smoothness of the Hankel kernel in the y-direction, we replace its continuous values by an interpolation from its values on a very coarse grid in that direction, up to a desirably small error. Thus, it is possible to replace the original integral by a sum of a few one dimensional integrals along the x-direction, whose kernels can be shown to be oscillatory in the sense of (A. Brandt, *J. Comp. Phys.*, 1991). As a result, they can be evaluated fast with the multilevel algorithm of (O. Livne, A. Brandt, and A. Boag, *Microwave Opt. Tech. Lett.*, March 20, 2002.). This implies that the original field evaluation can be carried out in linear complexity. The multilevel integral evaluation can be adapted to the efficient solution of the integral equation for the current, again in linear complexity.

Simulation of large printed antennas with the synthetic-function, discretization-diversity approach

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In previus works, the authors addressed the issue of the EFIE-MoM complexity reduction in the analysis of large and complex printed antennas. One of such proposed approaches is the Synthetic Function Compression (SFX) technique [L. Matekovits, G. Vecchi, G. Dassano, M. Orefice, APS2001, 568 - 571, and references therein]; it is based on the decomposition of the antenna domain into sub-domains (of arbitrary shape) -termed "blocks"- on the (numerical) generation of entire-domain basis functions on the blocks -termed Synthetic Functions (SF), and their subsequent use to represent the global solution. The SFX approach reduces the MoM matrix memory occupation, and considerably reduces the time needed to solve the linear system, without affecting the solution accuracy.

The present communication deals with an approach to further enhance the SFX efficiency by reducing the filling time of the MoM-SF matrix.

The technique is based on the fact that a fine discretization is needed to account strong, near-field interactions, and hence, to generate the SF. On the other hand, weaker, far-field interactions are insensitive to the current details of the SF; therefore, a coarser grid would suffice to this aim. The proposed scheme is a two-grid one (extendable to multi-grid), profiting of the fact that finer grids are obtained in typical meshers by "h-refinement" of coarser grids, so that both a coarser and (the derived) finer grid are available. The SF are generated on the fine grid, which is also used to compute the self- and near-couplings of SF; when computing the farther SF interactions, the SF are projected back onto the coarser grid, and these "coarser SF" are then used to compute their couplings. Note that the method allows for two (or more) grids without affecting the MoM matrix, since the latter is computed in the SF basis. The method can be applied to existing MoM codes, with minimal code modifications.

The method is applied to reference data and shows definite numerical advantages.

FMM Computation of the Bistatic RCS of Stealth and Nonstealth Targets

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In many civilian and almost all military applications, an accurate knowledge of the radar cross section (RCS) of the involved targets is highly desirable. The RCS information is used for numerous purposes, ranging from the design of novel stealth vehicles with reduced radar signatures to the decision of what kind of electronic counter measures (ECM) to engage against a certain threat.

In this paper, bistatic radar cross section (BRCS) values of stealth and nonstealth airborne targets are predicted by performing both numerical simulations and scaled-model measurements. In order to achieve the solution of large-scale electromagnetic problems in the numerical simulation environment, the fast multipole method (FMM) is implemented and used to solve the electric-field integral equation of the scattering problem. The FMM has produced remarkably accurate results, in addition to its efficiency.

The efficiency of the FMM is due to its reduced computational complexity and memory requirement, which are both $O(N^{1.5})$ for a single-level implementation of the FMM. We will address several other points that lead to an efficient implementation of the FMM, such as the choices of the preconditioner and the initial guesses required for the iterative solver.

The BRCS values of stealth and nonstealth airborne targets are computed for several different illumination angles. In addition to comparing results obtained for various illumination angles, we will also compare the BRCS results of a stealth target and a nonstealth target for the same illumination conditions.

RCS prediction can be achieved through numerical calculations or scaled-model measurements. In this paper, the use of both of these techniques to predict the RCS of a stealth airborne target is reported, and the validation of the numerical results has been achieved by comparing to measured RCS values of the same stealth target obtained by scaled-model measurements. Comparison of the measured and computed BRCS values has resulted in a surprising agreement, which serves to validate both of the prediction techniques.

Special Session

Influence of the Triangular Surface Patches Bases 20 Years Later

Organizer(s): *L. W. Pearson, Clemson University, USA*

Co-Chairs: *L. W. Pearson, Clemson University, USA*
D. R. Wilton, University of Houston, USA

A PROLOGUE TO THE TRIANGULAR SURFACE PATCH BASIS FUNCTION

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In this presentation, numerous of the thought processes leading to the development of the triangular patch basis function will be described. In addition to discussions of the technical development of the basis function, its history will be related too. As one contemplates this basis function, the *triangular surface patch* (TSP), as it is labeled, one might readily conclude that its construction, and its properties resulting therefrom, are intuitively appealing or even obvious. This is almost certainly the conclusion that would be reached by a neophyte who studies the triangular basis function today as its features are laid out in detail in light of the properties of the mixed potential integral equation – field represented in terms of both the vector and scalar potentials. But the inch by inch progress en route to the synthesis of the triangular basis function, which began with experience acquired from investigations of the simple pulse basis function for solving one-dimensional electrostatic integral equations and extended to studies of the roof-top basis function for the rectangular plate integral equation, came at a very slow pace over several years. It is this step by step process of acquiring an understanding of the key features of numerical techniques for solving simple integral equations that will be described in the presentation. Not only will the gratifying successes be discussed but also revealed will be some of the fruitless paths taken down blind allies.

In the context of lessons learned that revealed the properties desired in a general basis function, e.g., the TSP ultimately, effective and efficient ways will be described for solving simple integral equations often associated with electrostatic problems, two-dimensional conducting cylinders and strips, infinite slots in conducting surfaces, straight and curved wires, and flat and bent plates. But the focus will be on the reasons for the choices of the basis and testing functions and on the consequences of these choices, as well as on the selection of the integral equation to be used to solve a given problem. After a brief discussion of what was learned from solving simple electrostatic integral equations, the lessons learned from investigations of methods for solving the TM-excited strip and cylinder problems, the TE-excited strip and cylinder plus the curved wire problems, and ultimately the flat plate problem are outlined sequentially.

With a collection of properties in hand that should be possessed by an effective basis function, the construction of the TSP so that it exhibits these properties is outlined.

Numerical Methods for Antenna Arrays

Co-Chairs: *M. D. Deshpande, NASA Langley Research Center, USA*
P. H. Pathak, Ohio State University, USA

Comparison of Array Design Methods for Strongly-Coupled Large Array Using a Network Description of Array Antennas

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http://antenna.ece.vt.edu

The performance of array antenna system is typically considered to be limited by the effect of mutual coupling between the elements that varies with frequency and scan direction. The same mutual coupling effect can be utilized in a strongly coupled array to increase the impedance bandwidth. The coupling to the neighboring elements effectively increases the size of antenna and lowers the operating frequency from that of a single element.

Traditionally, array antennas are designed in the bottom up fashion where the antenna elements are designed first in an isolated environment for the optimum element input impedance and radiation pattern. Once the elements are designed, their geometrical locations in the array are determined assuming no mutual coupling among the elements. The element shape, array geometry, and array excitations are then optimized while including the mutual coupling effects.

The traditional array design method works well when the elements and their locations are chosen such that their mutual coupling effects are small. As the coupling becomes stronger, the changes in the radiation pattern and input impedance of the array elements also become large. In some cases, the designer must spend a large quantity of time optimizing the array design to reduce the mutual coupling effects.

An alternative design method for a strongly coupled uniform array is the top down method where the antenna elements and their array geometries are designed in the infinite array environment. The finite array is designed using the antenna elements and the array geometry optimized in the infinite array. This method works particularly well when the number of elements in the final array is large.

In this paper we will compare the two array design methods for the strongly coupled array antennas. Antenna elements with varied mutual coupling and array sizes will be investigated using the simulated data. The resulting N element arrays are analyzed using a N+2 port network description, where the additional 2 ports represent the radiation patterns in two polarizations. The mutual coupling effects on the radiation pattern, gain, input impedance, bandwidth, and scan capabilities will be discussed in terms of network descriptions.

A Hybrid Cavity/MoM Analysis for a Finite Array of Microstrip Antennas

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Infinite-array analysis is often used to simulate practical finite arrays of microstrip antennas. However this analysis does not account for the truncation effects of the finite array, which may be significant, depending on the size of the array and the level of the mutual coupling. Furthermore, infinite-array analysis cannot be used to calculate the input mismatch of a practical finite array at a scan blindness angle, since infinite-array analysis predicts a complete mismatch. For these reasons, finite arrays of microstrip antennas have been studied extensively in the past using finite-array analysis. Perhaps the most common finite-array analysis technique is the Method of Moments (MoM) in the spectral domain. This method is very useful, although there are some limitations that make the method difficult to apply in certain circumstances. For example, the formulation becomes difficult to apply when dealing with geometries for which the Fourier transform of full-domain basis functions is not readily available. Also, the formulation becomes more complicated when the patch cavity contains vertical shorting walls (e.g., a quarter-wave shorted patch) due to the presence of both horizontal and vertical currents on the structure. Shorting pins within the cavity also require vertical currents, and complicate the analysis even further by requiring attachment modes, at least if the feed inductance is to be modeled accurately. Spatial-domain MoM solutions overcome these limitations, but often at the expense of numerical efficiency.

In this presentation, a new hybrid cavity/MoM analysis is proposed for microstrip antennas, which combines the advantages of both the cavity model and the spectral-domain method. The cavity model accounts for feed inductance, easily allows for vertical currents inside the cavity, and is used to calculate the equivalent magnetic currents at the edges of the patches in the absence of mutual coupling. The spectral-domain method is used to accurately account for the effects of mutual coupling by defining mutual coupling coefficients that are based on the edge magnetic currents. Two types of coefficients are introduced. One is a feed-edge mutual coupling coefficient and the other is an edge-edge mutual coupling coefficient. By using these coefficients, a simple matrix formulation can be derived that accounts for all mutual coupling in the finite array. In this presentation, finite arrays of circular microstrip antennas and "Reduced Surface Wave" (RSW) antennas will be used for illustration, although the method is general and can be used for other canonical patch shapes.

Optimized Design of 8X8 Broad Band Printed Circuit Board Dipole Phased Array using HFSS

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Abstract—The design of an 8 x 8 broadband printed circuit board dipole standing over a finite ground plane is presented. The design is made by using HFSS. Since the advent of printed circuit technology, a low-cost and lightweight approach of the phased array is to use dipole elements printed on periodic dielectric substrates protruding over a finite ground plane. By this technology, the dipoles are etched into the ground screen side of a printed circuit board and capacitivively coupled to a loop feed formed by the printed microstrip line. The elements are compatible with monolithic fabrication techniques.

Due to the complicated geometry of the problem, it is difficult to analyze the dielectric loading effect on the active impedance and radiation pattern using expansions of ordinary space modes, such as transverse electric (TE) and transverse magnetic (TM) modes. Actually, the nature modes that exist in the periodic dielectric structure are hybrid modes. In this presentation, we will report the detailed procedure how to use HFSS to design a broadband periodic PCB dipole phased array. We will first introduce optimization of the isolated dipole design. Then, we will present the active impedances and radiation patterns for different scant angles over the PCS frequency band in the array environment, which are simulated by unit cell technique built in HFSS. Our simulation shows that the blindness effect for large scan angles is not observed even in the dielectric substrates are present. We attribute the absence of the blindness to the surface wave caused by the presence of the dielectric substrates is not strong enough. The results have been successfully applied in design of broadband printed dipole phased arrays with large scan angles.

FDTD Model of the Foursquare Antenna in a 3x3 and Infinite Array

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The Foursquare antenna was developed at Virginia Tech for use in a broadband array. Measurement of the single foursquare element shows that it has broad E- and H-plane patterns and a broad impedance bandwidth. When used as an array element the Foursquare antenna is strongly coupled to neighboring elements. This coupling effectively increases the size of the antenna and lowers the operating frequency from that of a single element. The active element pattern and fully active pattern of a 3x3 Foursquare array were modeled, using the in-house FDTD code FACT, to determine the effects of strong mutual coupling. This paper reports results of the FACT simulation on an infinite Foursquare array. The simulation determines if the Foursquare maintains the desirable pattern and impedance characteristics in a fully active infinite array.

The FDTD model of the 3x3 Finite array shows a distorted active element pattern. However, the fully active array has a well-formed array pattern. The directivity of the fully active array as predicted by the half-power beamwidths and the directivity calculated based on the array area, A, compare well, giving confidence in the FDTD model. The patterns will be shown for frequencies from 2.0-4.0 GHz.

The FDTD model of 3x3 array was scanned using a uniform time delay between elements. The time delay was calculated using simple array theory, which assumes negligible mutual coupling. The mutual coupling between elements caused the array to fall short of the predicted beam-pointing angle predicted from simple array theory. The scanned beam pattern will be shown for frequencies from 2.0-4.0 GHz for desired beam pointing angles of 30°, 40° and 50°.

The FDTD model of the infinite array was used to optimize the spacing between elements and the height above the ground plane for maximum impedance bandwidth. The optimum geometry had a height, h=0.06 λ and spacing between elements of d=0.2 λ to 0.4 λ for frequencies from 2.6 to 4.7 GHz. The VSWR<2 bandwidth was found to be 58%. The frequency of operation shifted from 6.0 GHz for the single Foursquare element to 3.7 GHz for the Foursquare element in an array.

The FDTD models of the Foursquare element show that the strong mutual coupling between can increase the bandwidth and shifts the frequency of operation of the antenna.

A Fast Hybrid DFT-MoM for the Analysis of Large Finite Periodic Antenna Arrays on Grounded Substrates

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A method based on a hybrid DFT-MoM is developed to efficiently predict the element input impedances of and the radiation from large finite periodic planar arrays of printed dipoles on grounded substrates of infinite extent. Basically, an electric field integral equation is formulated to solve the unknown currents on the dipole array consisting of $N \times M$ elements with a known excitation, and the unknowns are represented by a Discrete Fourier Transform (DFT) macro basis set over the whole array to describe the global array current distribution; the actual current on each element is described by a micro basis set. The number of DFT components strictly required are $N \times M$; however, these are reduced to $O(N+M)$ via arguments based on the new Uniform Geometrical Theory of Diffraction (UTD) for uniform planar finite arrays. The unknowns are then solved using a Galerkin based Method of Moments (MoM). Such a substantial reduction in the number of unknowns in this hybrid DFT-MoM makes the analysis of large finite arrays efficient and tractable. Conventional brute force MoM requires the solution of the $O(N \times M)$ unknowns making such an approach very cumbersome, time consuming, and even intractable as the finite array dimensions become large. The present method is an extension of a hybrid DFT-MoM (H-T. Chou et al., A Hybrid DFT-MoM for the Fast Analysis of Large Rectangular Phased Arrays, 2001 IEEE AP-S Intl. Symp., Boston, Mass., USA) for a large planar array of dipoles in air in which a least square point matching based MoM was utilized. The present approach, as noted above, utilizes a Galerkin based MoM which is found to be far more robust since the previous MoM becomes somewhat sensitive to a choice of matching points. Note that the grounded substrates can support surface waves; this constitutes an added complexity not present in the previous work. Also, the mutual coupling between the elements, which forms the MoM operator matrix, is calculated very fast in the present work because the grounded substrate Green's function is evaluated asymptotically in closed form and the latter is valid for source and field point separations as small as half a free space wavelength; for even smaller separations, the Green's function must be calculated numerically from the usual Sommerfeld type integral representation. Furthermore, the DFT basis set offers another important advantage in that the fields radiated both in the near and far zone of the finite array, by each of the DFT components, can be evaluated in essentially closed form via the UTD ray technique for arrays. The latter provides physical insight into the array radiation mechanisms, and it is also efficient as compared to the conventional element by element field summation technique since only $O(N+M)$ terms are necessary in the present method instead of $N \times M$ radiation calculations required in the conventional approach. Several numerical results will be indicated to demonstrate the robustness, accuracy and efficiency of the present hybrid DFT-MoM analysis of large finite planar arrays of printed dipoles. The present approach can be directly extended to multilayered grounded substrate/superstrate configurations, and to include slots or other types of antenna array elements.

On the Application of Numerical Synthesis Techniques to Moderately Wide-Band and Multi-Frequency Array Configurations

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The anticipated increased data rates in future wireless communication systems will require wider, or several, operating frequency bands. Since antennas are important components in such systems there will be renewed interest in antenna array configurations that are able to provide a performance that is retained over wider frequency bands. Most array synthesis work, both for uniformly spaced and non-uniformly spaced arrays, has been done for single frequency situations.

Classical closed-form synthesis methods are not suitable for other than single frequency synthesis. However, it is possible to adapt existing array synthesis techniques that are based on numerical approaches to the synthesis of multi-frequency and moderately wideband array configurations, where performance requirements must be achieved at more than just a single frequency. These numerical synthesis methods, either explicitly or otherwise, require users to select some sort of objective function whose extremisation they believe will lead to the best solution of the synthesis problem they have in mind. The adaptation consists in properly selecting these so as to ensure that they simultaneously fully represent the array synthesis goals and constraints over the additional operating frequencies. This paper is concerned with the examination of the effectiveness of the above-mentioned extentions, and will compare the success of several existing synthesis techniques (so extended) when applied to moderately wideband and multi-frequency problems.

Numerical techniques have already been applied to pattern synthesis at a number of frequencies simultaneously (eg. P.C.Strickland, *IEEE Trans.*, AP-40, 463-465, 1992) with constraints on the overall pattern shape. However, such studies are few, and of purposefully limited scope. We are here interested in the application of recently developed numerical approaches that are able to optimise specific performance indices (eg. directivity) subject to sidelobe level constraints and possibly even excitation constraints, rather than accepting some pattern performance simply because it remains relatively invariant at several frequencies. The arrays of interest are those with uniform inter-element spacing, as well as non-uniformly spaced configurations proposed for wider bandwidth operation (eg. Y.Yamada, et al., *IEEE AP-S Int. Symp. Digest*, 644-647, 2000).

Parameter Optimization Using the Divided Rectangles Global Algorithm with Kriging Interpolation Surrogate Modeling

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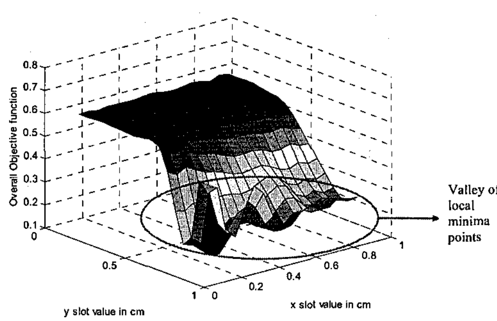
Most of the work done so far in optimization for electromagnetic applications has focused on evolutionary optimization schemes like Genetic Algorithms (GA). The primary focus of this paper is to present a comparison of gradient based optimization algorithms like SQP against that of derivative-free, deterministic, global optimization algorithms like DIRECT (Divided Rectangles).

Unlike GAs, DIRECT is a derivative-free global optimization scheme which can be tuned for both local and global properties. It begins at the center of the design space (the starting point) and divides the design space into smaller rectangles. The algorithm iteratively continues this process of selecting and subdividing those rectangles that have the highest likelihood of producing an objective function lower than the current lowest value. This is based primarily on the Lipschitzian optimization theory. It is this process of subdividing the rectangles that the algorithm achieves both global and local properties. Unlike GA which is a global scheme, DIRECT is a deterministic process and needs to be run only once. A disadvantage of this scheme is that it only terminates after a certain number of iterations have been achieved.

The above optimization scheme is then applied to a surrogate model, created by making use of the Kriging non-linear interpolation function to curve fit the data obtained from finite element boundary integral (FE-BI) simulation results. The spatial correlation kriging function R(w,x) = $\prod_{j=1}^{n} R_j(w_j - x_j)$ and $R(w_j, x_j) = e^{-\theta |w_j - x_j|^2}$ for each jth variable is employed here. As an example, the above optimization is applied to a unit cell slot array FSS with the dimensions of the slot used as variables. The overall objective/ cost function is written as a weighted summation of the reflection coefficients at several frequency points using the following form: F = $\sum_{i=1}^{N} w_i |\Gamma_{in,i}|^2 + \sum_{j=1}^{M} w_j |\Gamma_{in,j} - 1|^2$, i denoting the reflection coefficients in the pass band of the slot array FSS, j denoting the reflection coefficients outside the pass band.

Mapping the overall cost function with kriging and FE-BI shows a highly wrinkled surface with many local minima causing SQP to converge at the valley of local minima (right). Graphs will be presented comparing DIRECT with kriging surrogate modeling to : (1) using linear exact line search SQP with kriging surrogate modeling and (2) using Armijo inexact line search CFSQP with direct integration to the FE-BI simulator.



Characterizations of Reflectarrays: A Generalized Analysis Methodology

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A reflectarray incorporates a key feature of reflector antennas whereby a feed illuminates its main reflector's array elements to produce a collimating beam. This mechanism eliminates the feed-network as required in phased-array antennas. To maximize antenna gain, a phase correcting mechanism is applied to the array elements of the reflectarray. Phase correction can be achieved in a number of ways among which are stub tuning the elements [R. D. Javor, et. al., IEEE Trans. Ant. Prop., 43, 932-939, 1995], employing variable size patch elements (single [D. M. Pozar, et. al., IEEE Trans. Ant. Prop., 45, 287-296, 1997], multi-layering [J. S. Encinar, IEEE Trans. Ant. Prop., 49, 1403-1410, 2001]), and by introducing a variable rotational angles for each element in circular polarized antennas [J. Huang, R. J. Pogorzelski, IEEE Trans. Ant. Prop., 46, 650-656, 1998], and etc.

Once the phase correction is applied, antenna radiation characteristics are often computed based on an array modeling of the reflectarray geometry. In this study, we attempt to illustrate a unified method in analyzing antenna radiation characteristics of reflectarrays based on a modification of a multi-reflector code that has been proven in a wide range of applications in reflector analysis.

In many efficient multi-reflector codes, a great deal of machinery is often incorporated to accurately model and analyze the performance of a multi-reflector geometry [D. W. Duan, Y. Rahmat-Samii, IEEE Trans. Ant. Prop., 41, 1164-1167, 1993]. Consequently, our goal in this paper is to demonstrate how one can employ these existing machineries in conjunction with reflectarray antennas to analyze a more generalized reflectarrays topologies. These reflectarrays can be composed of either single or dual-reflector geometries with a host of array feed configurations which can be modeled and incorporated into the geometrical model. This code takes advantage of the already existing erected local coordinate system on each one of the reflector components (i.e. feed, sub-reflector, and the main-reflector) to compute the composite antenna radiation pattern. Consequently, a variety of reflector geometries such as Cassegrain or Gregorian can be modeled with a reflectarray serving as the main reflector.

A feed can either directly illuminate the reflectarray or indirectly through a subreflector from which a set of excitation coefficients are determined at the center of each reflectarray patch elements. The field excitation from the subreflector is evaluated using either the Physical Optics (PO/PTD) radiation integral or the Geometrical Optics (GO/GTD) construction. A transformation matrix modifies the field excitation on each patch based on the phase correcting mechanism chosen for a given particular design. Radiation from each array element can then modeled using representative element patterns from which a composite antenna pattern is obtained.

We will demonstrate the above capabilities through a series of computation for single and dual reflector antennas incorporating reflectarray as the main reflector. Results will be compared with some of the existing measured data for large reflectarray geometries operating at X or Ka bands.

Equivalent network analysis of phased arrays integrated with patch based FSS structures

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Latest trends in the applications for array antennas involve the requirement of broadband, frequency selectivity, multi-band and multi-polarization characteristics and, especially for military purposes, low Radar Cross Section (RCS). Some of these requirements can be fulfilled integrating directly in the antenna design polarizing grids, dielectric radomes and in general frequency selective surfaces (FSS). However at the present state of the art these latter are usually designed as stand alone elements and then fitted with the array antenna in a second phase. In this conditions the full control of the performances of the overall structure is not a straightforward matter.

In order to tackle these geometries, the Antenna group in TNO has recently developed a dedicated tool. This latter (G.Gerini and L.Zappelli, 2001 AP-S Digest, 3, 816-819) allows one to easily analyze structures that involve tuning elements as well as filtering structures inside the waveguides of a conformal or planar phased array. Moreover it consents to analyze frequency selective screens and radomes in front of the array.

The code is based on the Multi-mode Equivalent Network formulation (MEN) which obtains the multi-mode impedance matrix of the whole periodic cell as a cascade of the multi-mode impedance matrices. These matrices can be associated to each of waveguides or to the transitions between two adjacent waveguides. It should be noted that these waveguides can also be phase shift waveguides (dielectric radomes).

The basic idea that renders extremely efficient this network representation consists in separating the modes excited at each discontinuity in accessible and localized modes. The accessible modes are lower order modes responsible for the energy exchange while the localized modes are higher order modes, which contribute to the stored energy. Therefore the modes that actually propagate in each line are the accessible ones plus some of the non-propagating ones, while the localized modes are all the remaining non-propagating modes. On this basis, each line can be represented by an impedance matrix with as many input and output terminals as the number of accessible modes that propagates in the line (multi-mode impedance matrix). The multi-mode impedance matrix of the transition between two lines is then calculated by solving the Integral Equation that characterizes the fields and the currents at the transition. A Frequency Extraction technique is used in order to accelerate the numerical solution of the Integral Equation. Such a formulation has already been successfully applied to the analysis of multi-layer conformal or planar structures containing slot FSS (thick slotted metal screens).

In this paper the formulation is extended to the study of structures, containing patch based FSS. The formalism of the integral equation is maintained the same as in (G.Gerini, G.Lastoria and M.Guglielmi, 1988 IEEE MTT-S Digest, 1747-1750) with the difference that now the integral equation is solved applying the Method of Moments with sub-domain basis functions. This renders the code extremely versatile and capable of tackling fairly complicated structures. Numerical results that validate the code will be presented during the oral presentation

Analysis of Finite Arrays of Printed Dipoles on Electrically Large Cylinders

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The analysis of conformal arrays of printed antennas is of interest for their applications ranging from satellite and wireless communications (mobile phone base stations, space division multiple access (SDMA) applications, etc) to military systems (radio guidance of missiles) due to their scanning, beamforming and beamsteering capabilities, which are difficult to obtain with fixed planar arrays. Although these applications have stringent aerodynamic constraints that require the use of array elements that conform to their supporting surface, most of the developed efficient methods are for the analysis of printed finite and infinite arrays of planar geometries.

In this paper, various arrays consisting of finite number of printed dipoles on electrically large dielectric coated circular cylinders are investigated using an efficient and accurate hybrid method based on the combination of method of moments (MoM) with an appropriate spatial domain cylindrical Green's function. This method is basically an "element by element" approach in which the mutual coupling between dipoles through space wave as well as the surface wave is incorporated. Although this calculation can seem to be extremely time consuming for large arrays, its efficiency comes directly from the computation of the Green's function. Three type of spatial domain cylindrical Green's function representations are used interchangeably, based on their computational efficiency and regions where they remain highly accurate. These representations are (*a*) a steepest descent path (SDP) representation, which is valid everywhere except along the paraxial region and electrically small separations between the source and observation points, (*b*) an asymptotic-based, spatial domain representation which is valid along the paraxial region and complements the SDP representation, and (*c*) an efficient integral representation of the of the planar microstrip dyadic Green's function for the evaluation of self-terms.

An electric field integral equation (EFIE), whose kernel is the aforementioned Green's function, is formed by enforcing the boundary condition that the total $E_u(u = \hat{\phi}$ or $\hat{z}$ depending on the orientation of the dipoles) field must vanish on the dipole surfaces. This EFIE is then solved using a Galerkin's MoM solution. The dipoles are assumed to be center-fed with infinitesimal generators where the terminating resistance of the dipoles can be included to the solution for the "source-free" case. Various sized arrays will be considered and results will be given in the form of active reflection coefficient magnitudes, active element patterns, etc.

Special Session

Conformal Antennas I

Organizer(s): *R. G. Rojas, Ohio State University, USA*
V. B. Erturk, Bilkent University, Turkey

Co-Chairs: *R. G. Rojas, Ohio State University, USA*
V. B. Erturk, Bilkent University, Turkey

ON MAXIMUM AVAILABLE DIRECTIVITY OF CONFORMAL ARRAYS

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There is presently a lot of interest in conformal antennas, mainly for their good scanning characteristics. For optimum design, it is of interest to know the maximum available gain for a given structure and radiating element, the optimum amplitude and phase distribution, which generates this maximum directivity.

We have previously presented (N. Herscovici, Z. Sipus, P-S. Kildal, S. Raffaelli, 2nd European workshop on conformal antennas, The Hague, Netherlands, April 2001) a numerical approach to determine the maximum directivity of a conformal array. After this presentation there have been comments to us that the maximum gain of conformal antennas already had been considered analytically (A. Hessel, J-C Sureau, IEEE Trans. Antennas Propagat., 1971, pp. 122-124), and that their results were more general than ours. In the present paper we will explain the difference between the two approaches, and we will show by numerical computation that our approach is simpler and actually gives higher directivity than the previous approach.

The **maximum realized gain** (i.e. gain including mismatch losses) of a given array in a specified direction was by Hessel and Sureau found to be equal to the sum of the individual element gain functions in the direction of interest. The disadvantage of using this approach is that we need to determine the element gain function of each of the elements in the array in the presence of the other elements, when each of these are terminated in a load with the same impedance as the transmission line connecting to it. These element gain functions are very laborious and time costly to determine, independent of whether we do it by measurements or computations. Furthermore, the approach is valid for a given antenna, and it will normally be possible to improve the realized gain by matching each of the antenna elements in the active situation, in which case an iterative procedure must be applied. The maximum **available** realized gain will be the realized gain when all elements are ideally matched, and this is clearly larger than that obtained by Hessel and Sureau's approach.

We use numerical optimization of the excitations of the array to obtain the radiation pattern with the **maximum directivity**. As an example, we consider an array of cylindrical microstrip patches, but the analysis approach can be easily applied to other types of antenna elements. The optimization procedure gives as a result the optimum element current distribution along the array. This distribution does not correspond to the optimum source voltage distribution, because the active impedance of each element will be different. We will demonstrate numerical results showing that our optimum current distribution of the array elements give higher **directivity** than the "optimum" source voltage distribution from Hessel and Sureau. In addition, we calculate the optimum source voltage distribution from our optimum element current distribution, and we show that this is significantly different from that of Hessel and Sureau. Thus, our approach is a way of determining the maximum available directivity of a conformal array, i.e., an upper limit of the realized gain, whereas Hessel and Sureau's approach gives the maximum realized gain of a given antenna if we are allowed to change the excitations of each element but not the impedance match. The latter can normally be improved by matching the elements of the array better in the active situation. In order to determine the maximum directivity by our method, the isolated element pattern of the array is needed, i.e. the element pattern when the other elements are removed. This is (normally) the same for all elements. Our approach to determine the maximum directivity is thereby much simpler as we do not need to determine the mutual coupling matrix.

The numerical analysis has been performed by computer programs for antennas on multilayer circular cylinders based on the G1DMULT algorithm.

The Polarization Problem in Singly and Doubly Curved Conformal Array Antennas.

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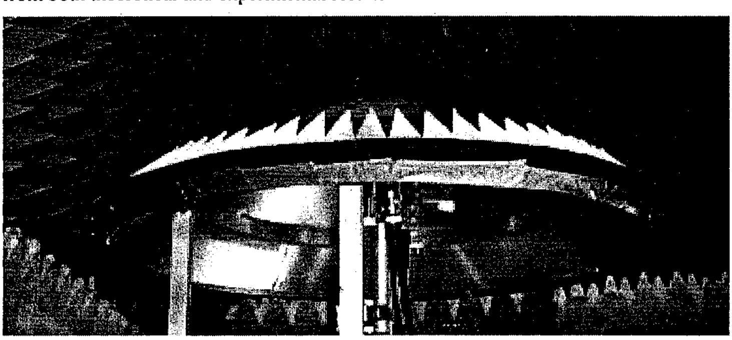
In array antennas the active element patterns determine the radiated far field polarization. In planar arrays an element factor common to all elements is typically introduced. This is not possible in conformal arrays, since the elements point in different directions.
When including a polarization requirement in the synthesis several additional issues must be dealt with, viz.:

- what cross polar level is accepted
- what is meant by "cross polar", i.e. what are the reference polarization states
- what are the means for polarization control
- how are mutual coupling effects accounted for

Even a cylindrical array of elementary dipoles could exhibit substantial cross-polar levels in the far field simply depending on the choice of polarization basis. We will present some examples of cross polarization calculations for scanned beams from cylindrical arrays with various types of radiating elements.

Circular polarization is sometimes proposed as a solution to the polarization problem. However, many applications require linear polarization, which means that radiators with polarization control are necessary. This implies typically two-port elements fed by a variable power divider.

The figure below shows a doubly curved conformal test array antenna with two-port circular waveguide elements. This configuration offers wide angle beam steering. There are, however, also several challenging problem areas associated with this structure besides polarization control, e.g. shape optimization, choice of active region, pattern synthesis, mutual coupling compensation etceteras. We will present isolated and active mutual coupling data for this array. The role of polarization is illustrated from both theoretical and experimental results.



Efficient Analysis of Conformal Antennas on a Large Dielectric Coated Cylinder

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The analysis and design of conformal antennas is becoming more important as various commercial and military applications for this class of devices become prominent. Although a variety of methods have been proposed, most of them tend to be applicable for electrically small structures.

In this paper we review a method that is based on the combination of the Method of Moments (MoM) with a highly efficient spatial domain Green's function for an electrically large dielectric covered PEC cylinder. The antennas can be printed antennas (dipoles, microstrip patches) mounted on the dielectric layer or waveguide-fed aperture antennas on the PEC cylinder covered by a dielectric layer. Note that an important property of the Green's function is that it becomes more efficient as the separation between the source and observation points increases and as the radius of the cylinder becomes larger. This implies that this method is applicable for large arrays mounted on large cylinders.

Two types of solutions are presented in this paper. The first one is the input impedance and mutual coupling between antennas. Although the mutual coupling between antennas is an "element by element" approach and may appear time consuming for large arrays, it is actually an efficient approach due to the fast computation of the Green's function. An electric field integral equation (EFIE), whose kernel is the aforementioned Green's function, is formed by enforcing the appropriate boundary conditions. This EFIE is then solved using a Galerkin's MoM solution.

The second type of solution presented here is concerned with the fields radiated by electric and magnetic dipoles mounted on an electrically large dielectric coated PEC cylinder. The fields are valid for large cylinders away from the paraxial region and make it possible to calculate the radiation pattern from waveguide fed apertures located on the metallic surface as well as printed antennas mounted on the dielectric layer. The uniform solutions presented here are valid along the transition region between the lit and shadow regions. They also correctly reduce to the deep lit and deep shadow results. Note that solutions for the radiated fields valid along the paraxial region are currently being developed.

High–Frequency Radiation Pattern Analysis for Antennas Conformal to Convex Platform Surfaces

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While the radiation characteristics of antennas designed for platform–surface–conformal mounting can, for an antenna in isolation, be readily analyzed via rigorous computational electromagnetics (CEM) techniques such as the Method of Moments (MoM) or the finite–element method (FEM), full inclusion of platform effects via these methods can become computationally prohibitive as the frequency increases. Such computational difficulties invite consideration of hybridizing these rigorous CEM techniques with high–frequency asymptotic techniques such as the Physical Theory of Diffraction (PTD) or the Uniform Geometrical Theory of Diffraction (UTD). The limitations of such a hybrid approach may largely be identified with the limitations in terms of accuracy and scope of the asymptotic techniques themselves. Accuracy limitations that derive from the approximate nature of asymptotic theories are unavoidable, but are perhaps less consequential than accuracy limitations usually associated with numerical implementation of these theories. Of principle interest to us is the fact that implementation of the UTD, which is required to compute the radiation pattern in the shadow region of a convex body, has, until recently (Hussar *et al, IEEE Antenn. Prop. Mag*, April 2000), involved constructing an approximate representation of the antenna environment in terms of simple canonical shapes. In terms of scope, while dielectric and magnetic materials play an increasingly important role in platform design, UTD techniques that account for the effects of convex surfaces have been largely limited to environments consisting of perfect conductors.

In this paper we will describe efforts to perform high–frequency conformal–antenna radiation–pattern analyses that are faithful to both the antenna's internal and platform–environmental geometries and that can also account for environmental dielectric/magnetic materials. Hybridization of finite–element methods with recently developed techniques that permit implementation of the UTD on facetized CAD platform surfaces results in an approach in which realistic CAD geometrical representations are employed on both the antenna and platform levels. Numerical radiation patterns obtained for several antenna/platform combinations via this hybrid scheme will be exhibited and discussed.

A UTD–type solution useful in radiation–pattern analysis for a conformal antenna embedded in a uniform material layer covering a smooth convex conducting surface is currently available in terms of generalized Fock–type integrals (Munk and Pathak,*IEEE Ant. Prop. Soc. Int. Symp.*, July 1996). The applicability of this solution in the far shadow region is limited by Fock–integral definitions that are specific to the source–point surface geometry and do not incorporate the expected sensitivity of the solution to the intermediary geometry along a surface–geodesic segment of a ray path (Syed and Volakis,*Radio Sci.*, Oct. 1991). A recently obtained residue–series solution for the near–surface fields (Hussar and Smith–Rowland,*J. Elec. Waves Appl.*, Feb. 2002) exhibits the required sensitivity. Here we will extend this result to provide a far–zone solution for a radiating source embedded in a material layer above a convex conductor.

Effect of Curvature on Conformal Antenna Radiating Characteristics

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As the demand for more sophisticated avionics has grown, so has the demand for RF antennas to support these functions. Significant portions of the surface of any commercial or non-commercial aircraft are dedicated to antennas, with many antennas competing for the locations that provide the maximum field of view and minimum electromagnetic interference. Traditionally, antennas designers developed and manufactured antennas for a specific function, then sold them to airframe maintainers to "bolt on" or "bolt in" to aircraft structure. Mechanical / structural considerations often imposed size and placement constraints on the antenna resulting in a compromise in performance.

Recently, structural, material and antenna designers have begun to pool collective talents to develop technologies applicable to conformal antennas. Using this approach, traditional aperture antenna installations are replaced with a variety of structurally integrated antenna imbedded in the outer mold line of the host platform. The use of structurally integrated antenna technology allows antennas of much larger size to be placed in locations heretofore unusable.

In this presentation, we will describe current advancements in conformal antenna structures. This presentation will focus on the effects of curvature on the antenna radiating characteristics. Results will be shown and discussed.

Radiation from Current Distributions Placed on a Dielectric Coated Elliptic Cylinder

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Radiation and scattering from cylindrical objects have been largely investigated as such structures can be used to model many real situations. Recently, the need of reliable tools to develop conformal antennas has revitalized this interesting field of research. The analysis of conformal radiators is usually carried out by solving the electric field integral equation with the method of moments(Habashy, T.M., Ali, S. M., Kong, J. A., 'Input Impedance and radiation pattern of cylindrical-rectangular and wraparound microstrip antennas', IEEE Trans. Antennas Propag., 1990, AP-38, pp.722-730). This technique has been proved to be very effective but it is conditioned to the knowledge of the appropriate Green's function. The Green's function, in a cylindrical coordinate system, is obtained in the spectral domain through the expansion, with a proper set of eigenfunctions, of the field radiated of elementary dipoles in the presence of the cylindrical object. A limitation to the method stems from the fact that complete sets of eigenfunctions are available only for a few coordinate systems and that they are very often difficult to treat. For this reason only circular cylindrical patch antennas have been fully investigated. The elliptic cylinder can be seen as a generalization of the circular case and it can be used to model surfaces with a variable radius of curvature. Printed structures conformal to elliptical surfaces have been already treated with an approximate model but no attempts have been done to develop a full wave procedure (Amendola, G.,'Analysis of the rectangular patch antenna printed on elliptic-cylindrical substrates',IEE Proc.-Microw. Antennas Propag., Vol 147, pp.187-194, 2000). The difficulties encountered to determine the dyadic Green's function in this particular case lie in the characteristics of the set of eigenfunctions to be used, namely radial and angular Mathieu functions. Firstly, Mathieu functions depend on the wave number which assumes different values in layers which have different dielectric constants. As a result, orthogonality between angular functions cannot be invoked when boundary conditions at the separation between two layers are imposed. Furthermore, no recurrence relations are available for such class of functions and the techniques used to speed up the computation of Sommerfeld integrals adopted for the circular case cannot be applied. In this work the study of the dyadic Green's function for the dielectric coated conducting elliptic cylinder is presented. The difficulties encountered in the developments will be discussed. Results relevant to the radiation of known current distributions placed on the interface between two layers will be presented and discussed.

Green's Function and Function-Theoretic Techniques

Co-Chairs: *A. Ishimaru, University of Washington, USA*
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On the Eigenvalues of Pyramidal Horn Antennas

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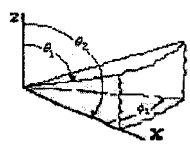
One of the most common techniques for analysis of the radiation characteristics of pyramidal horn antennas is the aperture field method which can be obtained from the fields in the pyramidal waveguide at the aperture plane. Harrington formulated this problem [see "Time Varying Electromagnetic Fields", McGraw-Hill, 1961, chapter 6, equations 6-65 to 6-68 and 6-75 to 6-77 and Fig. 6-7 (e) -(f)] as a sectoral section of the space ($0 \le \phi \le \phi_1$) exterior to two conducting cones ($\theta_1 \le \theta \le \theta_2$), which is valid for two flat walls in the E-plane and two conical walls in the H-plane. This resulted in very complicated eigenvalue equations in terms of the Legendre functions and their derivatives for the TM modes (equation 6-66) and TE modes (equation 6-68) whose roots υ vs mode number m (or $\omega_h = p\pi/\phi_1, p = 1,2,3,...$ as in Harrington's formulation for the pyramidal horn in equation 6-76) were not presented. An approximate numerical solution was later derived by Narasimhan [IEEE Trans. On AP, vol. AP-21, no. 1, Jan 1973] who replaced the Legendre function $P_\upsilon^m(\cos\theta)$ by $J_m(q\theta)$ where $q=[\upsilon(\upsilon+1)]^{0.5}$ leading to the final result for the eigenvalues as $\upsilon = -0.5 + [0.25 + (p_{mn}/\alpha_o)^2]^{0.5}$ where p_{mn} is set by the boundary conditions and mode number while $\alpha_o = (\theta_2 - \theta_1)/2$.



The first purpose of this paper is to present a simplified formulation of the problem by using an interior instead of Harrington's exterior formulation. Thus, instead of satisfying the E-plane boundary conditions at $\theta = \theta_1$ first (resulting in Harrington's equations 6-65 and 6-67 for the TM and TE modes, respectively) and then at $\theta = \theta_2$ next (resulting in Harrington's equations 6-66 and 6-68 for the TM and TE modes, respectively), we satisfy both conditions simultaneously by measuring θ off the horn axis since $\cos\theta$ is the same at $\theta = \pm\ (\alpha_o)$. The resulting eigenvalue equation is $P_\upsilon^{\omega}(\cos\theta) = 0$ or $dP_w^{\omega}(\cos\theta)/d\theta = 0$ at $\theta = \pm(\alpha_o)$ for the TM or TE modes, respectively. Since ω_h is already known, the eigenvalue υ is obtained by following the procedure already published by Hamid for the eigenvalues of a conical horn [IEEE Trans. On AP, vol. AP-16, pp. 520-528, Sept. 1968]. The resulting eigenvalues for the dominant TM and TE modes are presented and compared with those of Narasimhan. The second purpose of this paper is to simplify the formulation further by considering pyramidal horns with four flat walls as the case in practice. Here the horn is viewed as the intersection of two wedge waveguides at 90° to each other where the two wedge edges intersect at the horn apex. The resulting eigenvalues are $\omega_e = s\pi/\alpha_o$ and ω_h where s=1, 2, 3,.. which agree with the classical results of Barrow and Chu [Proc. IRE, vol. 27, pp. 51-64, Jan. 1939]. These results are also compared with the values of Narasimhan for the lowest order TM and TE modes.

Magnetic Field Emission of Power Frequency of a 3-Phase Transformer Substation in Hong Kong

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The high current loading in power transformer substations produces a magnetic field emission. For new transformer station installations, the transformer will be house in a separated building. In Hong Kong, one of the world's most densely populated places, offices and residential areas are often extremely near to transformer substations, particularly in some of the older districts. This causes a concern about human safety due to the high level magnetic flux. In this paper, we have carried out a site analysis and measurement of magnetic flux in an office site located at the first floor in a building where the substation is located at the ground floor in the same building. The closest distance between the busbars and the office is only about 0.5m. The transformer is rated 11kV with a busbar loading of 2kA. The magnetic flux due to the 3-phase busbars was evaluated and a maximum magnetic flux up to 250μT was recorded in the initial measurement, which is well above the safety limit of 100μT stated in the Guideline of ICNIRP (International Commission on Non-ionizing Radiation Protection). The initial measurement of the magnetic flux is shown in Figure 1. The flux distribution of the 3 phase busbar was simulated and remedial actions were then considered. We considered two methods for reducing the magnetic flux to a safe level: Mumetal with a high permeability (μ_r=22000), which provides a high attenuation of magnetic flux; and double-layer shielding using iron (Fe) and aluminum (Al). The cost of using Mumetal is very high. Extra care of the magnetic flux saturation problem has to be taken. The double-layer shielding method was chosen to be installed in the transformer substation; detailed reasons for our choice will be presented at the conference. After these remedial actions were completed, another site measurement was carried out. The maximum magnetic flux had been reduced to 15μT, satisfying the ICNIRP's Guideline. Full results will be presented at the conference.

Special Session

Complex Media and Metamaterials I

Organizer(s): *N. Engheta, University of Pennsylvania, USA*

Co-Chairs: *N. Engheta, University of Pennsylvania, USA*
R. W. Ziolkowski, University of Arizona, USA

In search of an Ideal Absorber for Microwaves using artificial media

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Despite decades of research invested in the area of microwave absorber design, the search for an "ideal" one which is very thin, wideband, angle-independent, etc., continues to proceed unabated. We begin this paper by posing two questions: "Why is the problem so difficult?" and, "What are the fundamental limitations to designing such an absorber?" Next, we discuss three possible approaches to addressing the problem, present some representative results from numerical simulations, and draw some conclusions on the basis of these results.

It is evident that to provide a match to the free space, the impedance of absorbing layer should equal that of the free space, over the frequency and angular ranges of interest. In addition, since the absorber typically has to be designed to shield a conducting surface upon which it is placed, the layer must be sufficiently lossy to attenuate the fields reflected from its conductive backing.

Ideally, then, one would look for a material whose effective ε and μ are both complex (material with dielectric and magnetic losses) and, they satisfy the condition $(\varepsilon/\mu)^{1/2} = \eta_0$ = intrinsic impedance of free space. While there is an abundance of lossy dielectric materials available with a wide range of ε_r and $\tan\delta$, and one could tailor-make them as desired (within reason, of course), the same can not be said for the lossy magnetic materials. This is because the available range of μ_r and μ_i (real and imaginary parts of μ) are rather limited, and to find a material whose complex permeability and permittivity satisfy the impedance condition alluded to above, remains an elusive goal which is yet to be met.

This prompts us to explore the several alternate approaches to designing the absorber using artificial media, some of which are: (i) lossy magnetic material synthesized by introducing certain type of inclusions in a background medium; (ii) checkerboard type of panel with tiles that have alternating complex μ and ε properties; and, (iii) lossy periodic structures embedded in multilayer lossy dielectrics. The paper will discuss both the analysis and synthesis issues pertaining to the three approaches mentioned above, via the use of numerical techniques as well as optimization methods based on the Genetic Algorithm (GA).

Transmission Line Approach of Left-Handed (LH) Materials

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Waves with anti-parallel phase and group velocities have been known for decades in the microwave domain under the name of "backward waves" (S. Ramo, J.R. Whinery and T. Van Duzer, "Fields and waves in communication electronics", Wiley, 1994), but they have not been investigated in real circuits or materials. The recent interest for LH materials, in which new effects of backward waves have been demonstrated, has created a need for new approaches to better understand and characterize such materials. We propose here a transmission line approach of LH materials.

The simplest LH transmission line is presented as the dual of the conventional line, in which the per unit length inductance and capacitance have been swapped. In this line, left-handedness is straightforwardly understood from the propagation constant $\beta(\omega) = -1/(\omega\sqrt{LC})$, which yields the velocities $v_p = -\omega^2\sqrt{LC} < 0$ and $v_g = +\omega^2\sqrt{LC} > 0$. This line, in which the characteristic impedance is still the same as in the conventional line $Z_c = \sqrt{(L/C)}$, exhibits equivalent parameters $\varepsilon(\omega) = -1/(\omega^2 L)$ and $\mu(\omega) = -1/(\omega^2 C)$, which are shown to satisfy the entropy condition and to be associated with a negative index of refraction $n = -\sqrt{(\varepsilon_r \mu_r)}$. This form of $\varepsilon(\omega)$ is similar to that of previous works at low frequencies, but that of $\mu(\omega)$ is different from previously reported "plasma-like" expressions, which are of a resonant type and therefore associated with a very narrow bandwidth. An essential point is that LH lines can be lossless, of unlimited bandwidth and with moderate dispersion, which are all positive features not shared by the other LH structures investigated so far.

In the transmission line approach, a LH line is realized in a *discrete* form by repeating periodically (period is just a convenience, not an EM condition!) a unit cell constituted of a series capacitor and a shunt inductor. The resulting ladder-type circuit is fundamentally a high-pass filter, the cutoff frequency of which is the cutoff of the lumped-elements approximation. At frequencies sufficiently higher than cutoff, the circuit is perfectly equivalent to the theoretical LH line, with lossless transmission over an unlimited bandwidth, and phase unwrapping is shown to yield a ω-β diagram in perfect agreement with the analytical formula of β. In addition, *distributed* implementation of the LH line, using interdigital capacitors and spiral inductors is proposed. Also, it is shown that the series connection of a conventional right-handed (RH) line and of a LH line yields a dual-mode band-pass filter, in which the lower part of the pass-band is LH while the higher part is RH, which would lead to different line/material behaviors for the envelope and the carrier of a modulated signal, if the envelope and carrier frequencies would lie in the LH and RH regions, respectively. Finally, possible links between the transmission line approach and previous approaches of LH structures are discussed.

Novel Artificial Meta-Materials with both ε-μ Parameters: A Composite Periodic Structure of Dielectric/Split Ring Resonators

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In a sense, every material can be considered as a composite, even if the individual ingredients consist of atoms and molecules. The main objective in defining the permittivity ε and permeability μ for a medium is to present the homogeneous view of the electromagnetic properties of the structure. Therefore, it is not surprising if one replaces the atoms of the original concept with the structures in larger scale to achieve the new electromagnetic phenomena.

Meta-materials are a class of periodic structures, which its building block unit cell is a proper composition of dielectric, magnetic, and metallic materials in such a way the novel desired performances are obtained. The word "meta-materials" refers to materials beyond (i.e. the Greek word meta) the ones that could be found in nature. The main challenge in the meta-material development is to properly tailor the distribution of $\varepsilon(x,y,z)$, $\mu(x,y,z)$, and $\sigma(x,y,z)$ within each unit cell of structure to present the unique periodic composite, which exhibits the prescribed EM properties. The artificially designed meta-materials increase the range of the naturally available materials and are categorized as, (a) positive ε/positive μ, (b) negative ε/positive μ (band-gap structures), (c) negative ε/negative μ (Left-Handed (LH) materials), and (d) positive ε/negative μ (again band-gap structures) media.

To characterize and obtain the interactions of electromagnetic waves within the periodic composite meta-materials a powerful technique based on the FDTD/Prony with PBC/PML boundary conditions is applied. Taking advantage of the broadband analysis of FDTD method provides great efficiency and accuracy in obtaining the frequency performance of complex structures. The split-field approach is used to discretize the Floquet-transformed Maxwell's equations derived in the periodic structures.

The objective in this paper is to present a unique periodic meta-material structure composed of dielectric/Split Ring Resonators (SRR) to determine an artificial material with both effective permittivity and permeability characteristics. Notice that utilizing the available materials in nature one can easily obtain the dielectric materials with relatively large permittivity property; however, the atoms and molecules prove to be a rather restrictive set of elements from which to build a magnetic material. This is particularly true in the frequencies in the gigahertz range where the magnetic response of most materials is beginning to tail off. It is shown that the split ring resonators excited by the magnetic fields polarized along their axis have the potential to obtain μ materials. Proper combination of the SRR and dielectric material produces the building block unit cell of the composite structure with both permittivity and permeability parameters. The periodicity of structure is assumed to be very smaller than wavelength. It is demonstrated that in a specific frequency range with generated equally ε - μ feature, the meta-material completely transmits the electromagnetic waves. The proposed meta-material can be integrated into the novel applications in the areas of band-gap structures and antenna miniaturization.

A Periodic-Structure Negative-Refractive-Index Medium Without Resonant Elements

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Much interest has been expressed recently in a new class of periodic structures that can act as a medium that possesses an effective negative refractive index. These structures have also been characterized as metamaterials, as backward-wave materials (since the phase and group velocities point in opposite directions), as negative-refraction materials, and as double-negative materials. This class of periodic structures can properly be designated by any or all of these names (since they each describe a different aspect), but the term double-negative (DNG), introduced by Ziolkowski, seems to be the only one that is unique to this class. It indicates that the periodic structure is composed of pairs of elements, in which an array of one of the elements by itself produces an effective negative dielectric constant and an array of the other element corresponds to a negative value of permeability. A proper combination of the two arrays results in a negative product, yielding a backward-wave medium corresponding to a negative refractive index.

The structure in this class that has been analyzed and measured utilizes a resonant element (a split-ring configuration) for the effective negative permeability. This has led to the widespread perception that the array of periodic elements must contain a resonant constituent. The paper to be presented here describes an example of a double-negative array of elements that does not contain any resonant elements. It consists simply of element pairs comprised of an inductive vertical metal post (or strip), together with a simple capacitive series gap. It is surely one of many possible examples, but it has the virtue of employing very simple elements, characterizable by almost-rigorous simple analytical expressions.

In order to achieve the capacitive gap in series form, the proposed structure is placed within a parallel-plate waveguide, so that the medium is a 2D rather than a 3D one, being periodic in both directions in the horizontal plane, but confined vertically. Within the parallel-plate guide, the electric field arrangement has the form in strip line, with the electric field reversed in the upper and lower halves.

The arrays of inductive posts and capacitive gaps, when used independently, provide very wide stop bands (or photonic band gaps) that extend from zero frequency up to about $k_0 d = \pi/2$ or even $3\pi/4$, where d is the period and k_0 is the free-space wavenumber. These stop bands, for which the periodic structures are below cutoff, of course, correspond to frequency ranges for which the permittivity and permeability are each negative. The periodic structure comprised of the combined elements permits a pass band to appear somewhere within the individual stop bands, where the width of the pass band depends on the dimensions of the individual elements comprising the combination of elements. The backward-wave nature of the propagation within the pass band has been verified by observing the slope of the curve in the band-structure (or Brillouin) diagram, and independently by solving for the phase and group velocities.

The talk will present the precise structure of the elements, the analytical expressions for their equivalent circuits, and the detailed band-structure plots for the arrays of the individual constituents and for the array of the combined elements.

Backward-Wave Meta-Materials for Perfect Lenses

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Backwards-wave (BW) materials with simultaneously negative permittivity and permeability have received renewed attention as they have recently been experimentally demonstrated for the first time. In these materials, which are necessarily dispersive, phase propagation and energy flow are in opposite directions. It can be shown that at the interface of free-space and a BW material half-space the sign of the normal component of the wave vector changes. If the relative permittivity ε and permeability μ of the BW material both equal negative one, the normal component of the wave vector changes sign but retains its magnitude. The propagation in the BW material affects the wave in the opposite manner as does propagation in free-space. Thus it is possible that, for all the waves that interact with a BW slab, the phase and amplitude at a point on one side of the slab are identical to those at a particular point on the other side of the slab, i.e., the image of a source is not diffraction limited and could even be called "perfect" (J. B. Pendry, Phys. Rev. Lett. 85, 3966–3969, 2000).

In practice BW materials are composites whose effective permittivity and permeability are negative in some frequency range. The composite nature makes the precise location of the interface problematic. We present calculations based on a slab of BW material with a two-step interface where the discontinuity in permittivity and permeability are spatially offset. The transition layer introduced by this offset strongly changes the behavior of the system with respect to evanescent waves. In particular, the transition layer thickness influences the wave vector and frequency dependence of the surface modes that are supported at any interfaces between free-space and a BW material.

For a BW slab embedded in free-space, the phase compensation of the propagating waves inside the slab is independent of the propagation direction only for the special case of $\varepsilon = \mu = -1$. At a frequency where this is the case, a non-vanishing transition layer supports the existence of a surface mode (which has associated with it a fixed wave vector). For evanescent waves with their phase propagation oriented tangential to the interface and amplitude decay oriented normal to it, one finds that waves with a tangential wavelength smaller than that of the surface mode are strongly reflected. On the other hand, the transmission coefficient is nearly unity over a range of tangential wavelengths larger than that of the surface mode. Thus, the existence of the surface mode establishes a lower limit on the feature size that is resolvable with such a system.

Transmission and focusing properties of a slab of negative refractive index

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Material with negative relative permittivity and relative permeability was first discussed by Veselago in 1968, who showed that a slab of such material can focus the radiation from a point source located at a distance closer than the thickness of the layer. Recently, J.B. Pendry showed that such a slab can make a perfect lens if both relative permittivity and permeability are –1, focusing onto an area smaller than a square wavelength. The reason is that such a slab restores all spatial Fourier components including evanescent waves. Thus, at the focal plane, all Fourier components contribute to form a perfect image.

In this paper we conduct a study of the transmission coefficient of a slab whose relative permittivity and permeability are close to but not equal to –1. We consider a line source behind a slab of negative refractive index material and examine the field at the focal plane for p and s polarization. For a passive medium, ε_r and μ_r have negative imaginary parts, and the branch of the square root for refractive index must also be chosen to give a negative imaginary part. It is shown that the evanescent wave increases and then decreases as a function of the transverse wavenumber if μ_r and ε_r are not equal to –1, and therefore the spot size at the focal plane is finite. As μ_r and ε_r approach –1, the spot size becomes smaller. It is also noted that the propagation constant in the medium is in the third quadrant (negative real part and negative imaginary part) in contrast to the propagation constant in free space, which is in the fourth quadrant. Since negative refraction materials are artificial (D.R. Smith et al., *Phys. Rev. Lett.*, **84**, 4184-87, 2000) methods of designing for a given μ_r and ε_r are very much under development. Any expectation that μ_r and ε_r could both be within a fraction of a percent of –1 is probably optimistic.

Image Resolution Limitations of a Negative Refractive Index Slab

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Recently, Pendry has proposed that a planar slab of material, for which the real parts of both the electric permittivity (ε) and the magnetic permeability (μ) have the values of -1 (i.e., refractive index n=-1 and impedance z=+1), can bring not only the propagating field components associated with a nearby source to a focus, but can also amplify and refocus the nonpropagating near-field components (J. B. Pendry, *Phys. Rev. Lett.*, **85**, 3966, 2000). These near-fields provide subwavelength information on the source that is lost in traditional imaging configurations; the negative index slab can thus produce an image that has a narrower width than that predicted by the diffraction limit associated with traditional optics. In principle, the negative index slab can perfectly reproduce the fields associated with an arbitrary localized electromagnetic source, and has been referred to as a "Perfect Lens."

Pendry's analysis of the Perfect Lens, though compelling, was restricted to certain idealized conditions that cannot easily be met in practice. We have explored the sensitivity of the subwavelength focus associated with the Perfect Lens to variations in permittivity, permeability, losses, and spatial periodic modulation of the material parameters. We find that small deviations in these parameters from the optimal condition severely degrade the subwavelength focus, and can introduce image-distorting artifacts related to the excitation of surface plasmon modes on the surfaces of the slab.

We conclude that subwavelength resolution is achievable with available technology, but only by implementation of a critical set of design parameters. For example, to achieve an image of an S-polarized source one-tenth of a wavelength ($\lambda/10$) in dimension using a slab that has a width of $\lambda/10$, the deviation in the relative permeability μ from -1 can be no more than ~0.2%. While the limitations are severe, the may be surmountable by carefully engineered metamaterials operating at rf or microwave frequencies.

RESONANCE CONE FORMATION, REFLECTION, REFRACTION AND FOCUSING IN A PLANAR, ANISOTROPIC METAMATERIAL

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The metamaterial under study is a square-celled, planar, wire-grid network that is series-loaded with capacitors in one direction and inductors in the orthogonal direction (or equivalently loaded with distributed elements). This two-dimensional metamaterial can be free-standing or positioned over a ground plane, excited by a source that can be embedded in the grid or wire-connected to it. It is analogous to a sheet of uniaxial plasma with permittivities of opposite signs in two orthogonal, in-plane directions. In the anisotropic plasma context, resonance cones are well known as conical high-field regions that extend outward from any localized source and are sharply defined, especially in the near field. The relevant plasma literature is extensive, beginning with the 1960 papers by Herwig Kogelnik and the apparent first use of the "resonance cone" term by R.K. Fisher and R.W. Gould in 1969.

In the present case of the novel wire-grid anisotropic metamaterial, we report computational and experimental results, mostly with a square grid over a ground plane and parallel to it, fed at one corner with respect to the ground plane. The cone angle scans with frequency, and, with peak frequencies detected at the mid-points of the grid sides, an end-to-end frequency ratio of 2:1 was achieved experimentally, with a grid of only 4 cells by 4 cells. The experimental model used has a center frequency of 1.4 GHz and employs commercial chip capacitors and inductors to create a compact array that is small enough to be entirely hidden under a 1-cent coin. A larger computational model of 24 cells by 24 cells displays resonance cones that show little or no near-field beam spreading with increasing distance from the source. Further, when a cone "beam" encounters an edge with insufficient resistive absorption, specular reflection of the beam is clearly observed.

Changing the reactive loads in the grid creates a different planar metamaterial, for example the "transpose" material generated by interchanging the inductors and capacitors. At the interface between the material and its transpose, consider the possibility of resonance cone refraction. The resulting computational model displays very clear resonance-cone backward refraction accompanied by point-source focusing, effects reminiscent of the backward refraction and focusing of plane waves at the interface between "left-handed" and "right-handed", isotropic, three-dimensional metamaterials (V.G. Veselago, *Sov. Phys. Uspekhi*, **10**(4), 509, 1968; J.B. Pendry, *Phys. Rev. Lett.*, **85**(18), 3966, 2000; R.A. Shelby, D.R. Smith, S. Schultz, *Science*, **292**, 77, 2001). For the novel planar material, potential microwave applications include a passive spectrum analyzer or an antenna multiplexer.

ENGINEERING METAMATERIALS TO ACHIEVE PHASE COMPENSATORS

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In the past few years, there has been a renewed interest in using subwavelength structures to develop materials that mimic known material responses or that qualitatively have new response functions that do not occur in nature. These metamaterials are often generated by artificially fabricated, extrinsic, low dimensional inhomogeneities in some background substrate. Metamaterials have been designed and fabricated that produce negative indices of refraction. Such metamaterials have numerous practical applications. Several will be considered in this presentation.

Phase compensation in one dimension can be achieved readily with double negative (DNG) metamaterials, i.e., those with negative permittivity and permeability and, consequently, a negative index of refraction. A DNG metamaterial allows the possibility to have a slab that exhibits complete transmission with a negative phase shift. Complete phase reversal metamaterials are thus possible. Examples of DNG metamaterial designs will be presented that produce a complete phase reversal. More complicated 1D electromagnetic band gap (EBG) structures consisting of a stack of alternating thin regular medium layers and DBG medium layers have also been designed that achieve such a complete phase reversal. Examples of these EBG metamaterial designs will be presented. The application of these phase compensating metamaterials to source and sensor technologies will be discussed.

Phase compensation in two dimensions can also be achieved readily with DNG metamaterials. In particular, concave as well as convex dispersions surfaces arise when DNG metamaterials are considered. Paraxial focusing within such DNG metamaterials has been demonstrated in [R. W. Ziolkowski and E. Heyman, Phys Rev. E, 64, 056625, 1-15, 2001]. This requires the associated dispersion surface to have local concave regions in addition to the usual convex regions. The concave regions produce rays that focus rather than diverge. Local modifications of the shape of the dispersion surface are thus possible to achieve desirable wave front designs. As an example, cascaded slabs of alternating convex and concave dispersion surface materials produces a metamaterial stack that delays the spread of a wavefront. As will be discussed, such a wavefront-compensated stack may have useful applications in local energy transmission.

Omega Medium as a Metamaterial with Negative Permittivity and Permeability

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In 1967, Veselago theoretically studied the problem of time-harmonic monochromatic plane wave propagation in a material whose permittivity and permeability he assumed to be simultaneously negative at the frequency of interest, and he showed that such a material could possess interesting electromagnetic features such as anomalous refraction. [V. G. Veselago, "The electrodynamics of substances with simultaneously negative values of epsilon and mue," *Soviet Physics Uspekhi*, vol. 10, no. 4, pp. 509-514, 1968. (*Usp. Fiz. Nauk*, vol. 92, pp. 517-526, 1967)]. Recently, Shelby, Smith, Schultz and their group constructed such a composite medium for the microwave regime, and experimentally showed the presence of anomalous refraction in this medium [R. A. Shelby et al., "Experimental verification of a negative index of refraction", *Science*, vol. 292, no. 5514, pp. 77-79, 6 April 2001.] These complex materials have gained considerable attention nowadays.

In 1992, Saadoun and Engheta theoretically introduced the idea of "omega" medium as a particulate medium conceptually made of many small inclusions in the shape of Greek letter Ω embedded in a host medium, and in 1994 in their theoretical work on analysis of wave propagation in "omega" media (both "local" and "nonlocal" omega media) they studied the modelling of effective permittivity, effective permeability and effective (omega) coupling coefficient in such media using the circuit-model approach for the omega inclusions. [M. M. I. Saadoun and N. Engheta, "Theoretical study of electromagnetic properties of non-local omega media" chapter 15 in *Progress in Electromagnetic Research (PIER) Monograph series*, vol. 9, A. Priou, (Guest Editor), 1994, pp. 351-397]. Although not of interest at the time, their circuit-model analysis had also revealed the possibility of having negative permittivity and permeability in omega media for certain range of frequencies. In light of the recent interest in metamaterials with negative permittivity and permeability, we have been motivated to extend Saadoun and Engheta's analysis by studying electromagnetic wave interaction with the omega inclusions using full-wave modelling with numerical method-of-moment technique, to evaluate frequency dependence of electric and magnetic polarizability tensors for omega inclusions, and to obtain effective permittivity and effective permeability of bulk omega media using combined numerical and analytical techniques, with the goal of exploring situations when the omega media may possess negative permittivity and permeability at certain band of frequencies. Our theoretical analysis thus far has shown that, under certain conditions, omega media may indeed behave as a metamaterial with negative permittivity and permeability at some frequency band. In this talk, we will present our results; discuss how certain modifications to the geometry of omega inclusion can affect the material parameters, and will provide physical insights into the results.

Electromagnetic Absorption in Biological Bodies

Co-Chairs: *C. Furse, Utah State University, USA*
F. Barnes, University of Colorado, USA

Rigorous Analysis of EM Absorption in High Resolution Anatomical Models Using FDTD

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Introduction

Current safety standards are based on the dosimetric knowledge obtained in the late seventies using greatly simplified human and animal models. In the meantime, technology has greatly advanced, providing spatial resolutions enhanced by a factor of 10^6 and more. Improved data and knowledge are therefore necessary, especially since safety standards are currently being revised. In parallel numerical techniques are more and more becoming an alternative to experimental evaluation of absorption within biological tissue. An IEEE standard for numerical dosimetry was evaluated by the working group SCC 34. This standard is meant to take all situations into account arising from compliance testing of mobile phones.

Objective

Assessment of the ratio of spatial peak and whole-body average SAR as a function of polarization and frequency for rodents as well as for humans using the highest spatial resolutions currently available, whereby spatial peak values were to be determined for averaged tissue masses of 0.01, 0.1 and 1g weight in animals and 1 and 10g in human models. In addition, similar assessments for selected organs were also to be obtained. The SAR was to be evaluated according to the new standard, implemented into the post-processing unit of the simulation platform SEMCAD.

Methods

The animal models were generated using a newly developed technique based on Microtom slices. Microtom slices provide color pictures with a resolution up to 0.05x0.05x0.05mm and are very well suited for further segmentation. MRI based scans used up to now deliver grey scale digital images and are limited with respect to resolution due to physical constraints (a resolution of 0.25x0.25x1mm is achievable). More than 30 different tissue types were discriminated. Based on the data from the Visible Human Project a numerical whole body phantom was generated. The separation between the slices is 2mm for the whole body. The SAR distributions were calculated using the simulation platform SEMCAD. SEMCAD is based on the FDTD method and optimized for applications in numerical dosimetry as well as for antennas embedded in complex environments. It contains various local refinement schemes that enable the generation of non-homogeneous grids containing nested subgrid regions. Numerical phantoms can be imported into the simulation environment and positioned grid independently within the computational domain. A voxel viewer enables verification of the anatomical correctness of the numerical models. Further, the SAR distribution as well as other field quantities can be displayed within and on the surface of single parts of the bodies.

Results

Two models of a pregnant OF1 mouse were generated with an axial resolution of 0.74 and 0.37mm. Analogously, two models of a pregnant Sprague Dawley rat with an axial resolution of 0.6 and 0.3mm were generated. The whole body human model was generated with an axial resolution of 2mm. SAR distributions were calculated at the mobile telecommunication frequencies 900MHz and 1.8GHz for E, H and k polarization with respect to the model axis. The ratio between spatial peak SAR and whole body SAR is given as a function of frequency, polarization and resolution. Organ specific SAR values are compared with respect to different resolutions. The standard for numericaly evaluating the specific absorption rate was compared to measurements using phantoms for compliance testing and the corresponding numerical models.

Effects of Inaccurate Electric Constants of the Biological Tissue-Equivalent Phantom on the Local Averaged SARs at 900 MHz and 2.0 GHz

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The local 1 g or 10 g averaged SAR has been used for the primary dosimetric parameter of electromagnetic waves exposure in the standards (1 g: Supplement C to OET bulletin 65, FCC guidelines, 2001), (10 g: CENELEC prEN50361, 2001). The SAR is generally estimated from numerical simulation and experimental evaluation. In the experimental evaluation, the biological tissue-equivalent phantom is usually used to realize the human tissue in most of the cases (Y. Okano, et al., *IEEE Trans. MTT*, no. 11, pp. 2094-2103, 2000).

However, it is difficult to realize perfect agreement of electric constants (relative permittivity, conductivity) between the phantom and the human tissue because of various factors; e.g., fabrication error, evaporation as times go by, etc. In the measurement, differences of electric constants between the two cause an error on the estimated SAR. Hence, it is necessary to understand the effects of inaccurate electric constants of the phantom on the local averaged SARs in order to realize the precision evaluation.

In this paper, we investigate the effects of inaccurate electric constants of the brain-equivalent phantom on the local averaged SARs when the electric constants are changed from criteria to ±20.0 % at 900 MHz and 2.0 GHz. From this study, we have made it clear that the error of the local averaged SARs is almost proportional to the inaccuracy of the electric constants at both frequencies. In addition, it has been confirmed that the effect of the inaccurate electric constants on the local 1 g average SAR is larger than that on the local 10 g average SAR at each frequency. We have also confirmed that the maximum variation in the local averaged SARs at 900 MHz (1 g: 15.9 %, 10 g: 12.2 %), which is caused by the inaccuracy of electric constants, is larger than that at 2.0 GHz (1 g: 15.4 %, 10 g: 8.5 %).

Radiation Characteristics of Loop Antennas for Wrist Cellular Phone Affected by Human Body

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The trend of miniaturization for the cellular phone will lead to the watch-type wristphone carried at the wrist position of a human body. In order to comply the conformal requirement of the antenna for the wrist radiophone, in stead of the typical dipole-type antenna for the hand-held radiophone, the loop-type antenna is a suitable choice. The rectangular loop antenna used for the wristphone may have different position and orientation with respect to the wrist. The loop antenna embedded in the watch belt can also encircle the wrist. Compared with the dipole-type antenna for the handset close to the head, a loop antenna mounted on the wrist position will have stronger and more complicated EM interaction with the human body. The communication performance of the wrist radiophone is expected to be much more influenced by the human body.

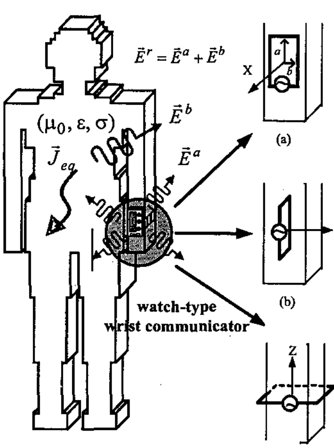
In this paper, numerical simulation of a full-scale human body model on radition characteristics of loop antennas at the wrist position is presented. The loop antenna with a superquadric curve is used to model the rectangular loop antenna with rounded corners. The loop antenna may have different position and orientation relative to the wrist. The coupled integral equation (CIE's) and the method of moments (MoM) are employed for numerical simulation. Numerical results of detail antenna radiation characteristics in free space and mounted on the wrist of the body at 900 MHz and 1800 are presented and discussed. The developed numerical simulation scheme is useful for the antenna/RF design and the link budget consideration of for wrist radiophone or other personal wireless communication applications.

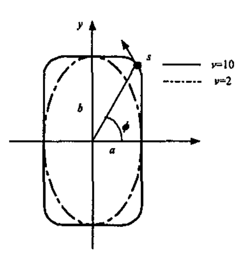
(A) ***900 MHz Operating Frequency***

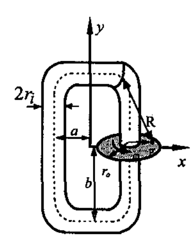
The body absorption efficiency of the x-oriented loop is the smallest ($\eta_{b\Omega} = 7\%$), which means the radiated power absorbed by the body is highest. The average power gain of the x-, y-, and z- loop is about –17.33, -11.32, and –13.86 dB for the E_θ field (vertical pol.) and –15.21, -14.67, and –5.44 dB for the E_ϕ field (horizontal pol.).

(B) ***1800 MHz Operating Frequency***

The average power gain of the x-, y-, and z-oriented loop antenna worn on the wrist is about –16.47, -0.73, and –21.53 dB for the E_θ component and –1.1, -16.3, and –3.62 dB for the E_ϕ component. Compared with 900 MHz case, the loop antennas at 1800 MHz have much higher E_θ or E_ϕ average power gain. This means the wristphone equipped with a loop antenna may have better communication performance at 1800 MHz than at 900 MHz band.







Special Session

Computational Challenges in Electromagnetics

Organizer(s): *R. Mittra, Pennsylvania State University, USA*
T. Cwik, Jet Propulsion Laboratory, USA

Co-Chairs: *T. Cwik, Jet Propulsion Laboratory, USA*
R. Mittra, Pennsylvania State University, USA

Computational Electromagnetic Challenges for the Radar Signature Prediction of Ground Combat Vehicles

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Much of the research in the Army science and technology community is focused on the Chief of Staff's initiatives on Future Combat Systems (FCS). The FCS family of vehicles will not rely on conventional armor for survivability; significant signature reduction measures will be required to achieve first tier survivability on the modern battlefield. The radar signature is an integral part of the system survivability specifications and guidelines where the frequencies of concern now extend into the millimeter wave (MMW) spectrum. Existing sources have translated into threats throughout this spectrum extending up to *W*-band. Exploiting existing computational electromagnetic (CEM) tools at MMW frequencies in high performance computing (HPC) environments currently requires extensive amounts of computation time and resources to impact the design concept of ground vehicles. Radar signatures are often controlled through a combination of vehicle shaping and material treatments so that RCS calculations for industry concept vehicles will be essential in the development process.

Advances in numerical algorithms, hardware/software environments, and efficient visualization of the CEM model and results must be exploited to provide a rapid radar signature prediction capability of concept vehicle designs. To this end, the U.S. Army Research Laboratory (ARL) often uses asymptotic techniques such as the shooting and bouncing ray (SBR) method (J. Baldauf et al., *IEEE Trans. Ant. and Prop.*, Vol.39, no. 9, pp. 1345–51, 1991), as implemented in the Xpatch commercial software. This hybrid geometrical and physical optics approach, including first-order edge diffraction, is used on HPC platforms, with simple parallelization to calculate the radar cross section (RCS) for triangular facet representations of combat vehicles. We have found Xpatch to be accurate and efficient at *X*-band frequencies when using high-fidelity facet models of tank-like vehicles (i.e., ~800,000 facets). We present an Xpatch simulation for such vehicles as tested on the ARL outdoor radar range that is appropriate at *X*-band but requires further validation at higher frequencies. Accurate signature prediction of stealthy vehicles employing advanced materials and operating in complex clutter environments is required at frequencies up to *W*-band. Conventional CEM approaches to this problem quickly overwhelm existing HPC resources, and asymptotic methods can have reduced accuracy for low-RCS targets where traveling wave and surface discontinuity effects can become important (E. F. Knott et al., *Radar Cross Section*, chap. 5 – 6). We describe Phase I Small Business Innovative Research Projects that potentially will allow practical simulations of modern ground combat vehicles throughout the MMW spectrum.

Some Challenging Problems in Computational Electromagnetics

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Through there exist a very wide spectrum of challenging Computational Electromagnetic problems in search of solutions, we will select two representative ones that task the capabilities of even the most sophisticated CEM codes available today, including those utilizing the FMM and MLFMA methods.

The first one of these is a large, finite array, operating in close proximity of an FSS radome with which it interacts.

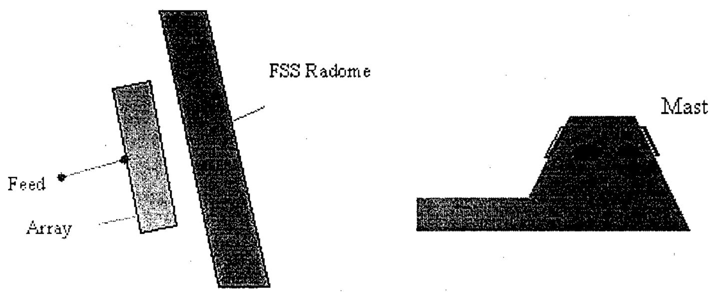

Fig. 1(a) Array Antenna with FSS radome; (b) Multiple Apertures sharing a mast

The second configuration is a platform with shared apertures—which may be of the type shown in Fig. 1a—and the problem is to predict the coupling level and EMI effects between those apertures.

The above problems are difficult for a number of reasons: (i) the periods of the FSS and the array (Fig. 1a) are non-commensurate; hence, the strategy of deriving the solution to the problem by using a perturbation approach based on the analysis of infinite, doubly-periodic structures fails for this case; (ii) both the apertures and the platform (Fig. 1b) are typically very large compared to the wavelength; hence, their geometries are not conducive to treatment with ray optical methods and are also beyond the tractability range of numerically rigorous techniques.

Challenges in the Hybridization of Time Domain Methods

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Numerical techniques for the prediction of electromagnetic fields scattered by complex objects, directly operating in time domain (TD), have recently received considerable attention. The availability of computer codes based on such techniques is of remarkable importance from a practical point of view, especially when the interest is often extended to wide frequency bands. However, according to the specific technique employed, stability issues might become of major concern. It is worth mentioning the TD formulation of the well-known method of moments (MoM), which proves computationally efficient. If an explicit scheme is used, this algorithm suffers from a definite tendency to instability, that is, the calculated induced current and field distributions typically exhibit spurious fluctuations of growing amplitude and eventually diverge. Similar problems arise when different time domain techniques are hybridized, although each method is fully stable. We mention, for instance, the hybrid FEM/FDTD technique which results to be very flexible in handling complex problems with arbitrary geometries, but tends to exhibit instabilities.

Many of the remedies classically utilized rely on averaging techniques in order to filter out the late time oscillations. However, this operation does not solve completely the problem, being the achievement of a stable numerical procedure strongly dependent on how the original problem is discretized, both in space (size and shape of the discretization) and time (time step and shape of basis functions). A different approach should be employed, as for instance the use of higher order basis functions both in space and in the time domain. Alternatively, one can resort to an implicit scheme.

This paper is aimed to discuss the stability issues related to some hybrid techniques with particular reference to the discretization stage, *i.e.*, the conversion of the time domain equations to a discrete space-time model. In particular, numerical aspects of stability for different techniques will be analyzed with reference to the memory and runtime additional requirements.

Coping with Challenges in Computational Electromagnetics by Utilizing Hybrid Techniques

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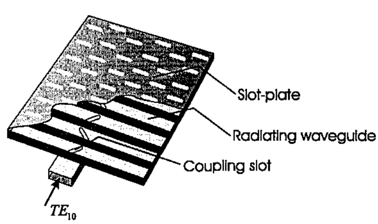
Invited Paper

THE DESIGN of modern waveguide components and aperture antennas requires adequate CAD tools, which are based on rigorous electromagnetic (EM) methods to achieve the necessary accuracy. The challenge is that the applied EM methods have to be sufficiently fast to allow the direct optimization of components to meet given specifications within reasonable CPU time.

Well proven EM methods used typically so far for the CAD of waveguide components and antennas are the finite element (FE), method-of- moments (MoM), finite-difference (FD), and mode-matching (MM) techniques. Since any method has its advantages and disadvantages depending on the structures under investigation, a very efficient way to improve the CAD performance is utilizing the hybridization of methods, where the advantages of different techniques are combined: Efficiency of the MM with the flexibility of the FE, MoM, FD methods.

This paper presents, first, line-integral formulations of coupling integrals and a comparison of the node and edge element approach for the hybrid MM/FE technique. Second, the advantageous applicability of a MM/transFE method is demonstrated for waveguide components which contain planar sub-structures of arbitrarily shaped boundary contour. Third, a hybrid MM/FE/MoM technique is described for aperture antennas taking arbitrarily shaped apertures and full-wave external and internal coupling effects rigorously into account by combining the corresponding generalized scattering matrices (GSMs). Fourth, it is shown that coax fed ridged waveguide/ combline filters and diplexers can be modeled in an efficient way directly by an extended MM/FE method. The coax feeds include capacitive, direct post connected and slope type couplings.

Several CAD and optimization examples will demonstrate the flexibility and efficiency of the CAD tool using the hybrid MM/FE/transFE/MoM/FD technique. The accuracy of the hybrid method is verified by measurements.



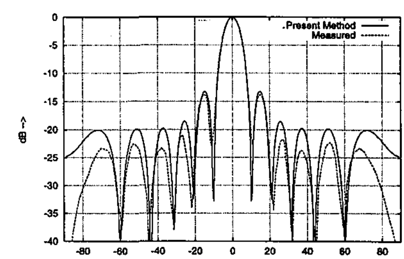


Fig.: Computed E-plane pattern of a waveguide slot array (9.75 GHz), compared with measurements [H.Y.Yee].

Challenges in the Numerical Analysis of Fractal-Shaped Antennas

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Fractal technology offers an efficient solution which allows antennas to be reduced in size. Moreover, antennas based on fractal-shapes are interesting due to their multiband capacity. Several work has been done since the first practical example of an antenna inspired on a fractal geometry was described in (C.Puente, Fractal and Multifractal antennas, Invention Patent ES 2112163). Fractals are actually a mathematical abstraction which includes an infinite number of elements. Instead, some other structures such as the so called multilevel (C.Puente, J.Romeu, C.Borja, J.Anguera, J.Soler, Multilevel Antennae, Invention Patent WO0122528) and space-filling geometries (C.Puente, E.Rozan and J.Anguera, Space-filling Miniature Antennas, Invention Patent WO0154225) could be used to approach ideal fractal shapes. An example of both, a multiband multilevel and a miniature space-filling antenna is depicted in Fig. 1.

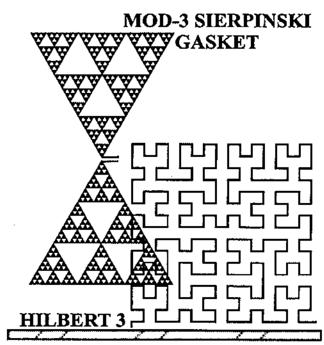

Fig 1 Three-iteration Hilbert monopole and three-iteration Mod-3 Sierpinski dipole antenna.

The problem in the numerical analysis of fractal-shaped antennas is two folded. Firstly, in addition to the denser required meshing in the analysis of conventional electrically small antennas, miniature space-filling antenna geometries feature a high number of small segments, which dramatically increases the number of knowns. Secondly, multiband fractal-shaped antenna geometries, include a high number of small polygons which are connected through narrow junctions, which implies a considerable increase in the number of elements in the mesh. Moreover, due to the multiband capacity of these antennas, they have to be analyzed with impedance bandwidth ratios on the order of 1:50 and hence a big number of frequency points has to be considered in the analysis.

The challenges in the simulation of fractal-shaped antennas will be discussed together with some efficient solutions which take into account the nature of these particular geometries.

Electromagnetic Performance Characterization in Complex Environments

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The continuous expansion of the wireless industry has led to the creation of a growing number of products that communicate with one another. This provides opportunities and challenges for antenna and electromagnetic design engineers. In order to design and characterize the performance of electromagnetic devices, including intentional and unintentional radiators, a high degree of fidelity is required of electromagnetic simulation tools. Although many of the available simulation tools are quite capable of providing good simulation results for antennas and passive circuits, they can be inadequate when it becomes necessary to analyze the electromagnetic system in a complex environment. Common limitations of simulation tools are directly related to the overall computational requirements that arise from the geometry which in turn are related to the fidelity of the model. A significant amount of the simulation effort is allocated to creating a sufficient representation of the physical geometry without creating a model that simply requires too many unknowns, which can lead to an intractable memory requirement, or an impractical run time. This paper will present several examples illustrating computationally challenging problems, where a feature common to each is the complex environment in which the electromagnetic characterization takes place.

A first example is the analysis of a cellular phone antenna in the presence of fully populated circuit boards and the appropriate housing. In general, the fine features of the phone geometry lead to meshing issues in differential based methods. Subgridding has been used with various degrees of success. However, it is a tedious process creating and revising models with fine features. When the user of the product is also included in the simulation model, the number of unknowns and overall size of the problem grow tremendously. Another example involves the analysis of antennas and circuitry on curved or rolled flex. A tractable representation of the unknowns on rolled flex presents a challenge. A third example involves an inventory tracking system with the objective of computing the propagation characteristics between two antennas where one antenna is in the cab of a truck and the other is in the trailer. Each antenna is in a locally complex environment requiring high fidelity modeling. A final example is an automotive application where the goal is to identify and eliminate the unintentional sources of radiation formed by loops in the traces of lead frame circuitry. The troublesome resonant structures interfere with the vehicle's FM radio. In this problem, fine features are on the order of 0.1mm while the cables from the IC package to the detector block are on the order of 2m, a ratio of 20,000:1.

BASE STATION ANTENNA MODELLING FOR DOSIMETRIC ANALYSIS IN THE VICINITY OF THE TRANSMITTER

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Thousands of base station antennas (BSA) have been installed to support the development of mobile telephony. The arrival of the third generation should increase this number. Worldwide a public concern about the Electromagnetic Field induced by these BSA have growth. In 1999, the European council output recommendations based on the International Committee on Non Ionizing Radio Protection (ICNIRP) guidelines . These recommendations define limits in term of basic restrictions and reference levels to protect general public and workers from electromagnetic field hazards.
Presently there is, in the vicinity of these antennas, a need for estimation and visualization of electromagnetic fields. The analysis of the field radiated by antenna has been studied for a long time. In the far field the antenna gain allows a rapid, simple and accurate method to estimate the field strength, but in the vicinity of the antenna, for instance few tenth meters around it, such simple approach does not exist. The far field gain is still not valid and full wave analysis is often requested. Therefore we developed a method able to estimate in the vicinity of the antenna the field in a rapid, simple and accurate way.
This method takes advantage that base station antenna are composed of often composed of array of dipoles or patch antennas with back reflector and horizontal separators that reduce the coupling between the elements and in particular, between any element and the image of the adjacent element. Consequently, the radiated near field of the entire antenna should be considered as the superposition of the fields radiated by one unit cell of the antenna array, shifted in space. Moreover, the far field gain of the sub-antennas may be used to estimate the near field of the entire antenna. The key point for accurate results is the input power distribution., the amplitude and phase of the input power of each sub-antennas depend on the parameters such as electric tilt and side lobe limitation. Since these information are often not known we performs an optimization, based on genetic algorithm, of the power distribution according to the measured BS far field vertical diagram.
This antenna model is valid in the far field of the antenna but also in the near field. Since the sub-antenna far field is close to the antenna, the gain of the sub-antenna is in valid in the near field of the antenna.. Because of possible reflection, the environment should have an influence on the field strength. To take into account this possible scattering, the estimation of the field in the vicinity of the antenna is carried out using the image theory. Using a 3D software, the vicinity of the antenna is model; buildings, roofs, walls and ceilings are localized and visualized. Using this 3D model, the software localized the images of each sub-antenna related to these reflectors. Using all this secondary sources, the total field is computed by summation of all the contributions. This approach allows the determination of compliance boundaries as well as the estimation of the field strength in the vicinity of the antenna.

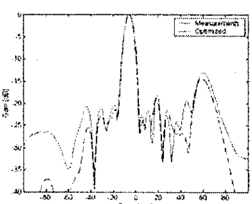

Figure A: Simulation versus Measurement

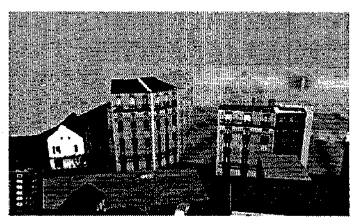

Figure B: Visualization of the Result

EM Modeling and Inversion Challenges in Oilfield Exploration

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The primary goal of oilfield exploration is to identify and quantify hydrocarbons and to estimate their producibility. Various measurement techniques are employed to achieve this objective. These techniques among others include, resistivity, acoustic, nuclear, magnetic resonance, fluid sampling, coring, and imaging. In this paper we discuss some of the electromagnetic challenges in designing sensors for resistivity and magnetic resonance tools. We also present difficulties in inverting measurement data for the formation parameters.

In a typical resistivity sensor, there are several transmitters and receivers inside a borehole, operating at frequencies ranging from a few Hz to a few MHz. By measuring voltage across receiver coils, one can deduce properties of the formation. The main difficulty in modeling the sensor is the fact that the geometry involves many small-scale as well as large-scale electromechanical features. The medium, the earth formation, surrounding the sensors is inhomogeneous, anisotropic, and arbitrarily layered. Furthermore, the conductivity contrast may be several orders of magnitude. Finite element and finite difference methods are often used to solve for electromagnetic fields in the formation. The degrees of freedom may run into millions. To the best of our knowledge, there is no EM modeling software that can effectively handle sensor geometry as well as the complex formation.

The nuclear magnetic resonance (NMR) sensors, on the other hand, involve solving static magnetic field as well as the RF field. The difficulties in designing the RF antenna are similar to those with resistivity sensors. The design of the magnet is complicated by the presence of ferrites and steel materials, which make the model nonlinear. It requires many executions of the forward nonlinear magnetostatic model to arrive at a satisfactory magnet design. We will outline a method to accelerate the design process of an NMR magnet.

Three-dimensional data inversion is a challenging area in oilfield exploration. Inverse problems associated with many geophysical measurements are often nonunique and multimodal. Consequently, the gradient-type optimization methods to obtain model parameters become ineffective since the accuracy and the convergence of these methods depend highly on initial position and search direction in the parameter space. Evolutionary-type of methods - genetic algorithm, differential evolution, for example – have been recently applied to such problems. We will briefly discuss some issues concerning inversion of geophysical data.

Computational Challenges at the Extreme
Millimeter-Waves, Infrared and Beyond

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NASA has a set of requirements for active and passive remote sensing, observational astronomy, and telecommunications that extend into the millimeter-wave, infrared and optical portions of the electromagnetic spectrum. The systems may include focal-plane devices for infrared sensing of planetary surfaces or atmospheres, millimeter-wave antennas for earth observing spectrometry, large deployable optic elements for detection of planets about stars or deep-space optical communication. The systems use components that have been traditionally designed using asymptotic based methods such as geometric optics or scalar diffraction but are being pushed to sizes and tolerances that require full-wave solutions of Maxwell s equations for accurate design models. The performance of the system can also be a critical factor in the design, requiring high-fidelity models to understand issues such as signal-to-noise or tolerances.

Computational issues involved in the above systems include a) material modeling; for example sensor devices involve semiconductor materials with losses dependent on wavelength at infrared wavelengths. b) geometry modeling; devices involve layers and metal-dielectric interfaces; optical elements can be non-traditional shapes or include gratings and coatings; c) large-scale computation; at these short wavelengths the components are electrically very large, and may require volumetric calculations; and d) interdependence with structural and thermal models; impacts of thermal loads that cause structural deformations need to be coupled to the electromagnetic models. The classes of techniques used for modeling these systems range from the general volumetric methods such as finite difference time domain methods or finite element methods to more specific techniques such as physical optics or beam methods.

This talk will highlight some of the applications, modeling methods and challenges in simulation and design for systems operating at the short wavelengths described.

Scattering I

Co-Chairs: *P. L. E. Uslenghi, University of Illinois at Chicago, USA*
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Geometrical and Physical Theory of Scattering, Forward or Backward Theorem of Scattering

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Abstract

The total scattering cross-section (T.S.C.) of a perfectly conducting body will be investigated, first, by the geometrical theory of scattering and, then, by the physical theory. Both yield the same answer, being twice the projected area of the body.

According to Born and Wolf (Principle of Optics, Pergamon Press, pp. 650-658, 1965) the excitation power or the extinction power of a scattering body obeys the forward scattering theorem. Our study shows that it is governed by a backward scattering theorem. Our observation is also supported by the classical theory of receiving antenna based on the reciprocity theorem, the derivation of the backward scattering theorem will be shown briefly in this paper. We apply Hulst's theory of scattering (Physica, XV, No. 8-9, pp. 740-746, 1949) to a receiving antenna. By making use of the effective height function of the induced current on the receiving antenna it is possible to demonstrate convincingly that the backward scattered field together with the incident field are responsible to produce the excitation power. There is a commonly accepted notion that the scattering area of an obstacle according to the geometrical theory of scattering is equal to the project area of the body. We will show that based on the classical geometrical theory of diffraction the total scattering cross-section is equal twice the project area, the same as the one obtained by applying the physical theory of scattering.

Scattering of a Plane Wave by a Perfectly Conducting Cube

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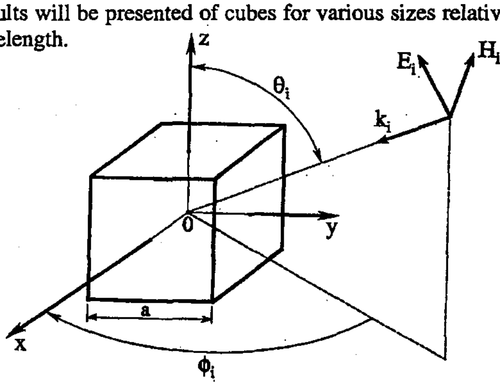
Almost a century ago Mie obtained the solution for the scattering of a plane electromagnetic wave by a sphere (*Ann. Physik*, 25, p. 377, 1908). He made use of potential functions leading directly to the spherical multipole fields $M(r, \theta, \phi)$ and $N(r, \theta, \phi)$ scattered by the sphere.

In this paper we also use multipole fields to represent the field scattered from a perfectly conducting cube as shown in the diagram below where a plane wave is incident on the cube of a metres^3 from the (θ_i, ϕ_i) direction. In the case of a sphere where the total tangential electric field must vanish on its surface, multipole fields can be used and their orthogonality leads to simple closed form solutions (Stratton, *Electromagnetic Theory*, p. 563, 1941) for the scattered field amplitudes. In order to match the total fields on the six sides of the cube, in this paper we transform the scattered multipole fields $M(r, \theta, \phi)$ and $N(r, \theta, \phi)$ into rectangular (x, y, z) coordinates. The fields are given in terms of a finite series of plane wave functions. This is the spherical analog of the representation of circular cylindrical waveguide modes in terms of a finite plane wave function series (R.H. MacPhie and Ke-Li Wu, *IEEE Trans. MTT*, 47, p. 232, 1999).

In the case of the cube the outgoing Hankel-type multipole fields with origin 0 are transformed into Bessel-type multipole fields near each side of the cube which in turn are transformed into rectangular plane wave-type fields. Then Galerkin's method in rectangular coordinates is used on each of the six sides of the cube to obtain a set of linear equations for the amplitudes of the multipole fields scattered by the cube.

Numerical results will be presented of cubes for various sizes relative to the incident field's wavelength.



THE ISOREFRACTIVE WEDGE REVISITED

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The diffraction of electromagnetic waves by a penetrable wedge is still an unsolved problem. An exact solution has been obtained only for the isorefractive wedge, either by employing a Kontorovich-Lebedev transform in the frequency domain (Knockaert et al., *IEEE Trans. AP*, 45, 1374-1381, 1997), or by using a Green function approach in the time domain (Scharstein and Davis, *IEEE Trans. AP*, 46, 1148-1158, 1998). An alternative solution in the frequency domain has been obtained recently by applying a Wiener-Hopf technique (Daniele and Uslenghi, *Electromagnetics*, submitted, 2001).

In this work, we re-examine the isorefractive wedge by utilizing the separation of variables method in the two angular regions inside and outside the wedge. This method was used by Macdonald (*Electric Waves*, Cambridge, 1902) to study scattering by a PEC wedge. It is applicable to two-dimensional problems in which the primary field is either a plane wave propagating in a direction perpendicular to the edge of the wedge, or a line source parallel to the edge. The field components in each of the two angular sectors are expressed as infinite series of eigenfunctions, each term consisting of the product of a Bessel function, a trigonometric function, and an unknown expansion coefficient. The boundary conditions at the two surfaces of the wedge lead to a one-to-one mode matching between the fields inside and outside the wedge. The expansion coefficients must satisfy a set of homogeneous algebraic equations, thus leading to a transcendental equation for the order of the Bessel functions. This equation and its solutions have been derived and discussed by Uslenghi (*Proc. Asia-Pacific Microwave Conf.*, Hong Kong, P.R.C., Dec.1997; *Proc. ICEAA'01*, Torino, Italy, Sept. 2001).

A complete solution of the isorefractive wedge problem in the Macdonald approach still requires the determination of the expansion coefficients, and this goal cannot be achieved by a simple extension of the procedure used for the PEC wedge. We solve the problem by introducing an analytic function with poles at the order of the Bessel functions, and whose corresponding residues are the expansion coefficients. This function is constructed via a function-theoretic method based on the knowledge of the expansion coefficients for the incident field. The previously known results for a PEC wedge of arbitrary angle and for a right-angle isorefractive wedge follow as particular cases.

Synthesis of Multilayer Aperiodic Scattering Structures

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Specific diffracting structures can be designed for many applications, such as wavelength division multiplexing and demultiplexing, mode converters and filters, and power combiners and dividers. Most diffractive elements are designed using periodic concepts. We take another approach to achieve irregular, aperiodic diffractive structures that are designed for a specific field transformation. The scattering elements can be conductors or dielectrics which are varied in shape, size and position during a synthesis procedure. Wafer-based optical structures with dimension of a few wavelengths on a side can potentially be fabricated using electron beam lithography and etching. We are initially considering the scatterers as perfect conductors in free space. In two-dimensions, the shape and location of these scatterers are synthesized to achieve a particular field transformation. While there are aperiodic elements such as the binary Fresnel zone plate that focus a plane wave at least approximately, we are considering more general elements that could be employed in wavelength division multiplexing and mode control applications.

We synthesize irregular multi-layer scattering structures using a multi-resolution iterative procedure. The forward problem is solved using a two-dimensional finite element method (FEM) with a radiation boundary condition imposed (B. Lichtenberg et al., Electromagnetics, 16, 359-384, 1996). The multi-resolution code is written using Matlab. Our experience indicates the importance of iterating using coarse and then fine steps in the geometry. The choice of initial guess in this process is important. During the iteration, a cost function defining the desired scattered field as a function of position is minimized by adjusting the conducting scatterers in a multi-layer arrangement. We present the multi-resolution algorithm, example numerical designs for field transformation with practical applications, and plans for fabrication and testing.

Time Domain Incremental Theory of Diffraction: Range of validity and Comparison Between Predictions and Measurements

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The incremental theory of diffraction (ITD) developed in ([1] R. Tiberio et al., *IEEE Trans. Antennas Propagat.* **42**(5), 600-612,1994; [2] **43**(1), 87-97, 1995; [3] **44**(5), 593-599, 1996) refined in ([4] R. Tiberio et al., *Proc. URSI Inl. Symp. on Electromagnetic Theory*, Thessaloniki, Greece, May 1998, pp. 175-177) provides a unified description of high-frequency scattering phenomena than can be applied to a large variety of configurations. The ITD provides some advantages with respect to standard ray-tracing techniques based upon the Uniform Theory of Diffraction because it overcomes caustic singularities of ray-techniques and extends the field prediction outside the diffraction cone. This is accomplished by considering elementary contributions that are integrated along the edges of the scatterer. Recently, a time domain (TD) version of the ITD was shown in ([5] F. Capolino and R. Tiberio, *Proc. Int. Conf. on Electromagnetics in Advanced Applications*, Turin, Italy, Sept. 10-14, 2001, pp.395-398). In this TD approach, the transient scattered field is constructed by superposition of sequentially delayed spherical pulses distributed along the edge of the scatterer, where each pulse is turned-on by the incident field at the same location. Here, the range of validity of the TD-ITD will be discussed, by comparison against measurements, showing that the TD-ITD extends the prediction of the field to time instants moderately behind the wavefront. Two simple geometries, metallic disk and rectangular plate, will be considered using the formulation of the ITD given in [4], [5], and measurements will be conducted to make comparisons with the theoretical predictions. The experimental setup for the measurements is described in the following. The scatterer is located between the transmitter and receiver horn antennas operating in the frequency range from 18GHz to 26GHz. One of the two antennas is moved, at small increments, to measure the field scattered by the obstacle at various observation points. In this way measurements will be available for the shadow zone, the lit zone and the transition zone between the two. The measurements are taken in the frequency domain, and automatically transformed into the TD by windowed Fourier transform to eliminate late responses arising from unwanted scattering mechanisms. The TD measured data will be used as a reference solution to check the accuracy and range of validity of the TD version of the ITD [5], providing physical insight into the TD diffraction mechanism by curved objects.

Heuristic Incremental Field Contributions at the Edge of a Non Perfectly Conducting Half Plane

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Local, incremental field contributions to be distributed and then integrated along specific lines on the actual object, may provide effective tools to overcome those difficulties that occur in applying ray methods close and at caustics. Also they may be usefully applied to augment the Physical Optics estimate of the scattered field. A field based, quite general systematic procedure was developed for defining such incremental field contributions, within a unitary, self-consistent framework, which is referred to as Incremental Theory of Diffraction (ITD). According to a well-established high-frequency background, the incremental fields are deduced from local canonical configurations. Among them, the canonical problem of a non perfectly conducting half plane is of importance for a variety of practical applications. First, by establishing a Fourier transform pair between a spectral integral representation and a spatial integral convolution, the solution for the infinite uniform local canonical configuration is represented as a spatial integral along the edge of the half plane. Next, the integrand of the spatial integral representation is directly used to define the desired incremental field contribution. By resorting to this systematic procedure, explicit ITD formulations have been obtained for perfectly conducting (p.c.) cylindrical canonical configurations. Recently, it has been shown that the same ITD procedure may also be applied to the case of a half plane with impedance boundary conditions (b.c.). Indeed, it has been found (Bucci and Franceschetti,1976; Senior and Volakis,1995) that for an impedance half-plane, convenient combinations of the spectrum functions of the longitudinal (z) components of the fields can be obtained, that exhibit uncoupled b.c.. These potential functions allow to directly derive the expressions of the various field components. Due to this specific property, the 3D solution for such potential functions may be obtained by spectral synthesis of the 2D solution of the same canonical problem. Consequently, this Fourier spectral synthesis representation quite naturally leads to the desired spatial integral convolution representation. Its integrand is then used to define the ITD incremental field contribution. This rigorous procedure yields a formulation that is rather involved. In any case, its applicability is limited to those practical examples that involve non penetrable screens with a coating for which a surface impedance model is adequate.

Recently, simple heuristic high-frequency expressions of a UTD dyadic diffraction coefficient for thin dielectric screens have been presented, which provide a uniform description of the field across the shadow boundaries, explicitly satisfy reciprocity and exhibit dominant contributions that at the first order satisfy the b.c. at the faces of the screen. These expression can also be specified to describe the diffraction at the edge of grounded dielectric screens. Furthermore, the same expression can be easily adapted to treat impedance b.c.. In this latter case, numerical comparisons with the rigorous Maliuzhinets solution have shown that this heuristic formulation is quite accurate for most practical purposes. In this paper, simple approximate incremental diffraction coefficients for thin dielectric screens are presented. As has been done for extending the UTD, the incremental coefficients are derived, in the framework of ITD, by heuristically modifying the formulation for defining incremental field contributions at the edge of a p.e.c. half-plane. The final incremental dyadic expression exhibits reciprocity, and recovers the known ITD dyadic expression for both p.e.c and p.m.c b.c.. It is worth pointing out that the relevant high-frequency expression have been obtained by applying a specific asymptotic analysis which yields closed form expressions that are applicable at any incidence and observation aspects. For the sake of providing a significant validation, these expressions have also been specified for impedance b.c.. Numerical comparisons with results obtained by a rigorous, Maliuzhinets method based solution, are found very encouraging.

DIFFRACTED FIELD BY A NONPLANAR JUNCTION OF A PEC HALF-PLANE AND AN ANISOTROPIC DIELECTRIC SHEET: UAPO EXPRESSION

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Abstract.

The high-frequency description of the electromagnetic scattering by junctions formed by materials with equal or different electromagnetic properties is of interest in a large class of applications. Unfortunately, the derivation of rigorous diffraction coefficients for edges in such structures is usually difficult, and sometime impossible. Moreover, the numerical efficiency is strongly reduced when the solution requires the calculus of special integral functions. Therefore, the derivation of approximate diffraction coefficients, which are efficient and easy to handle, becomes very appealing. In this context, a Uniform Asymptotic Physical Optics (UAPO) approach has been recently proposed in (Gennarelli, Pelosi, Pochini and Riccio, *J. Electromagnetic Waves Appl.*, **13**, 963-980, 1999). Every time it has been applied, the corresponding solutions are resulted to be simple to implement in an efficient computer code and accurate when compared with those available in literature.

Aim of this work is to derive the UAPO diffraction coefficients for a nonplanar junction formed by a pec half-plane and an anisotropic dielectric thin layer. This last is homogeneous and isotropic with respect to the directions parallel and orthogonal to the planar surface, and is described by the second-order boundary conditions introduced in (Idemen, *Electron. Lett.*, **24**, 663-665, 1988). According to the UAPO approach, for each semi-infinite structure, the first step consists in the derivation of a PO approximation for the surface currents induced by an arbitrarily polarized plane wave obliquely incident with respect to the edge. Then, a uniform asymptotic evaluation of the corresponding radiation integral provides the edge diffracted field able to compensate the Geometrical Optics (GO) field discontinuities at the shadow boundaries. Note that the solution is expressed in terms of the standard transition function relevant to the Uniform Theory of Diffraction (UTD).

Synthesis of different methods to characterize RCS of antennas

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The knowledge of antenna Radar Cross Section (RCS) is more and more necessary for military platforms, particularly for obtaining the maximum of stealthy. It is well known that the use of high gain antennas on military platforms (aircraft, ship, ...) increases their RCS levels. RCS computation is generally more complex for antennas than for passive targets, but it is now an indispensable step for military vehicle designers.

Depending on the authors (*R.B. Green, "Relationships between antennas as scatterers and radiators", IEEE TAP, vol. 14, n°1, pp. 17-21, january 1966; Collin & Zucker, "The receiving antenna, Antenna theory", part 1, McGraw-Hill, New-York, 1969; R.C. Hansen, "Scattering from conjugate-matched antennas", Proceedings of the IEEE, vol. 77, issue 5, pp. 659-662, may 1989; G. Salin, L. Beaulieu, "Rayonnement et rétrodiffusion d'éléments imprimés sur structures conformes", Séminaires Antennes Actives MMIC, 3ème édition, 23-26juin 1997, Saint-Raphaël, France*), there are different formulations for deriving the scattered field created by an antenna of arbitrary load when it is illuminated by a plane wave. However, these authors have shown that the RCS of an antenna can usually be expressed by the sum of two terms :

- a structural term which is principally due to the wave diffraction on the antenna structure (patches, ground plane, edge effects...).
- an antenna term which is principally due to the radiation properties of the antenna. This term depends on the antenna terminal load Z_L and/or the feed circuit.

The purpose of this communication is to homogenize these different expressions in only one formulation of the scattered field $E_s(Z_L)$. This new formulation as written below, is a function of any two independent terms that can be obtained easily, such as for example short circuit and open-circuit scattered fields.

$$\vec{E}_s(Z_L) = \frac{\vec{E}_s^{sc} Z_a + \vec{E}_s^{oc} Z_L}{Z_a + Z_L} \qquad \text{or} \qquad \vec{E}_s(Z_L) = \frac{V_{oc}\vec{E}_s^{sc} + Z_L I_{sc}\vec{E}_s^{oc}}{V_{oc} + Z_L I_{sc}}$$

where,

- $\vec{E}_s^{oc}$ and $\vec{E}_s^{sc}$ are the scattered fields when the antenna is respectively open or short circuited.
- Z_L represents the antenna load.
- Z_a is the antenna input impedance : $Z_a = \dfrac{V^{co}}{I^{cc}}$.
- V_{oc} represents the antenna voltage when it is open circuited.
- I_{sc} is the antenna current when it is short circuited.

These parameters are available thanks to computation or measurement.

In this paper, we will recall the steps leading to this new formulation. RCS calculations of a simple printed antenna and of an array are then presented. The final expression is then validated by comparison with RCS results obtained from measurements and MoM calculations.

Analytical method to compute metallic photonic band-gap RCS

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Photonic Band-Gap (PBG) materials are periodic arrangements of metallic and/or dielectric elements. Their capabilities are very attractive for most of microwave and optical applications like filtering, passive and/or active antenna substrates, ... Several applications have been shown and there are no doubts about their potentials. We are in our side interested in their applications in Radar Cross Section (RCS). In this case, a great number of numerical tools have been developed to analyze this kind of material. However, to design them quickly and efficiently with the required accuracy, we have had to develop our own software. This paper proposes an explicit formulation to compute the RCS of 2D Metallic PBG (MPBG) materials. The MPBG under investigation are composed of perfectly conducting vertical thin cylinders (or wires), located along the z-axis. The structure is illuminated by a TM plane wave. Each cylinder is supposed very thin in comparison with the wavelength.

The simple formulation proposed here to describe MPBG RCS has been developed by extending a method published in *(S. He, C.R. Simovski & M. Popov, "An explicit and efficient method for obtaining the radiation characteristics of wire antennas in metallic photonic band-gap structures", MOTL, vol. 26, No. 2, July 2000)*. In our case the MPBG is excited by a plane wave and not by the near field of a dipole inside the structure as in the previous paper. Our formulation is also based on some results of the following references: *(R.F. Harrington, " Time harmonic electromagnetic fields", McGraw-Hill, New-York, 1961) (J.R. Mentzer : "Scattering and diffraction of radio waves", Pergamon Press, 1955)*. First, we define the cylinder scattering problem for a cylinder whose length is supposed infinite. The different cylinders of the MPBG structure are periodically spaced in an array. For each wire, other wires behave like a source of current. So, the current on a wire is induced by the incident plane wave and also by the fields created by the surrounding wires. All the interactions between the wires are established and, finally, a linear equation system as $A \cdot I = b$ can be easily solve to give the current distribution on each thin wire supposed infinitely long.

Next, the current distribution is integrated along the length of each wire to compute the far field scattered by the 2D MPBG composed of finite length wires. The MPBG is now considered like an array of linear sources of current. So, the total scattered field is obtained summing the scattered field created by each finite length wire.

Finally, the MPBG RCS can be deduced with the classical formula :

$$\sigma = \lim_{R \to \infty} 4\pi R^2 |\mathbf{E_s}|^2$$

where :
R is the distance between the MBPG and the radar receiver,
$\mathbf{E}_s$ is the scattered electric field at the receiver,
the magnitude of the incident field on the metallic PBG is normalized to one.

The detailed method, its advantages and drawbacks will be evaluated. Results will be compared with those of numerical methods (FDTD, MoM) for different kinds of MPBG.

Diffraction by a Rectangular Groove with Resistive Walls

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The analysis of electromagnetic wave scattering from rectangular grooves has received much attention recently in connection with the prediction and reduction of the radar cross-section of a target. There have been a number of investigations on the scattering by grooves of various shapes based on high frequency (ray-based) and low frequency (numerical) techniques as well as a hybrid ray.

In this study, electromagnetic plane wave scattering from a rectangular groove having resistive vertical walls with material loading is analyzed for E polarization by using the Fourier transform technique. This diffracting structure belongs to the class of the modified Wiener-Hopf geometry of the third kind, and therefore it can be treated formally through the Wiener-Hopf technique. The Wiener-Hopf technique is one of the powerful rigorous approaches for analyzing wave scattering and diffraction problems associated with canonical geometries. The advantages of the Wiener-Hopf technique over the other methods are that it is rigorous in the sense that the edge condition is explicitly incorporated in the analysis, and that it provides accurate and reliable results over broad frequency range.

The basic procedure adopted in this work is to take the Fourier transform of the reduced wave equation and apply the boundary conditions in the transform domain. This leads to a modified Wiener-Hopf equation (MWHE) of the third kind, which can be reduced to a pair of simultaneous Fredholm integral equations of the second kind. The approximate solution of this MWHE involves two sets of infinite number of unknown constants satisfying two infinite systems of linear algebraic equations. Numerical solutions of these systems are obtained for various values of the resistance and the sizes of the groove from which the effects of these parameters on the diffraction phenomenon are studied. The scattered field is evaluated by taking the inverse Fourier transform and applying the saddle point method. Numerical results showing the effects of the dielectric loading on diffracted field are also presented.

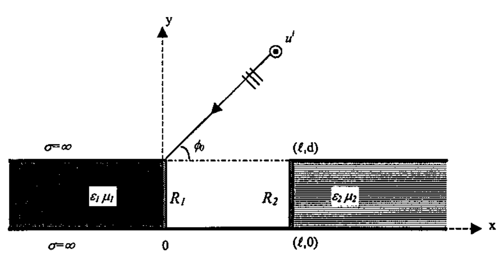

Fig.1. Geometry of problem.

Special Session

Conformal Antennas II

Organizer(s): *R. G. Rojas, Ohio State University, USA*
V. B. Erturk, Bilkent University, Turkey

Co-Chairs: *R. G. Rojas, Ohio State University, USA*
V. B. Erturk, Bilkent University, Turkey

1:15 Opening Remarks

22.1 1:20 Modeling Cavity-Backed Apertures Conformal to Prolate Spheroids using the Finite Element-Boundary Integral Technique ....AP
C. Macon, L. Kempel, Michigan State Univeristy, S. Schneider, Air Force Research Laboratory, USA

22.2 1:40 Mutual Coupling Between Microstrip Antennas on an Elliptic Cylinder ....AP
C.-W. Wu, L. Kempel, E. Rothwell, Michigan State University, USA

22.3 2:00 Efficient Analysis of Conformal Phased Arrays using a Subdomain Method Combining Integral Equations and FEM 76
P. Caudrillier, ONERA-DEMR and Universite Paul Sabatier, A. Barka, ONERA-DEMR, O. Pascal, P. Combes, Universite Paul Sabatier, France

22.4 2:20 An Hybrid UTD-DCIM-MOM Approach for the Analysis of the Radiation with a Large Conformal Microstrip Patch Array 77
F. Molinet, S. Tort, L. Beaulieu, MOTHESIM, France, H. Buscher, Buscher Associates, USA

22.5 2:40 Analysis of a Circumferential Slot Antenna on a Sectoral Cylindrical Cavity Excited by a Probe using Method of Moments...AP
N. Pasri, C. Phongcharoenpanich, M. Krairiksh, King Mongkut's Institute of Technology Ladkrabang

Efficient analysis of conformal phased arrays using a subdomain method combining Integral Equations and FEM.

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Abstract

In this paper we will describe several improvements on a mutidomain multimethod methodology devoted to the analysis of conformal phased arrays. The accuracy and efficiency of this technique will be demonstrated by comparison of our simulated results with commercial softwares.

1 Summary

The electromagnetic radiation of passive and active antennas has been widely investigated in the literature with both asymptotic and exact tools. ONERA has developed a multidomain and multimethod scheme (called FACTOPO) based on generalized scattering matrix computations of 3-D sub domains. The global geometry is split into several sub domains separated by a set of fictitious surfaces. Several expansion functions such as "Rao-Wilton-Glisson" divergence conforming basis functions, "spectral" numerical basis functions and "Deltagaps" basis functions can be used on these fictitious surfaces. For each sub domain (even the exterior 3-D volume), the generalized scattering matrix S is computed with different methods such as the 3-D FEM or the electric field integral equation (EFIE). Then, the different objects are connected together by solving a network equation. In the context of parametric investigations, the scattering matrices of the modified domains have to be re-evaluated, the other ones are simply re-used in the connection step. The FACTOPO scheme has been intensively used at ONERA for Radar Cross Section applications and also in a context of Electromagnetic Compatibility. It has been demonstrated that this strategy reduces significantly the computation time compared to traditional hybrid methods for which a geometric or electromagnetic modification requires a new computation of the complete target. Furthermore, the condensed operators are totally independent allowing code and data protection during a multi-industrial aircraft project.

The subdomain scheme applied to phased arrays consists to attribute a 3D volume at each source of the phased array. The exterior radiation domain of this antenna is also represented by a volume possessing N fictitious surfaces linking it to the N volumes representing the radiating sources. In this way the antenna may be graphically represented by a graph made up of (N+1) volumes and N interfaces. The scattering matrix of the radiation volume is computed with the EFIE and the sources volumes with FEM or EFIE. It can be noticed that the global array shape can be arbitrary designed which leads us to analyse in the same way classical plane arrays as well as conformal ones. The beam forming step is easily processed by tuning the amplitude and the phase of each current feeding the N internal volumes. For each needed scan angle, the graph equation is solved providing the antenna patterns, gains and input impedance. Furthermore, if a slight modification of the primary source geometry is required, the new radiation pattern can be fastly computed. This point makes our method very suitable for sophisticated multisource antenna design.

The accuracy and efficiency of this technique will be demonstrated by comparison with ANSOFT HFSS simulation results. In order to get reasonable CPU times, we consider an antenna of limited volume. Therefore little horns are used as elementary sources and their apertures are placed on the faces of a metallic box. We exhibit results taking into account the effects of mutual coupling between sources and diffraction by the box which allows us to get even the back radiation. Finally, we show that a slight modification of the horns' geometry or excitation leads to reasonable simulation time to achieve the new radiation patterns.

An Hybrid UTD-DCIM-MoM Approach for the Analysis of the Radiation from a Large Conformal Microstrip Patch Array

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An hybrid method, which combines the UTD ray technique and the Discrete Complex Image Method (DCIM) with the Numerical MoM approach has been developed to provide a relatively efficient analysis of the EM radiation from an electrically large conformal patch array.

The UTD algorithm is applied to the calculation of the mutual coupling between two different patches. It is based on a local circular cylindrical approximation of the surface and on an asymptotic evaluation of the exact dyadic Green's function for a substrate on a circular cylinder. Special asymptotic solutions are used in the paraxial region. Olver and Debye asymptotic approximations of the Hankel functions are used elsewhere (V.S.Ertürk and G.R.Rojas, IEEE ANP, Oct. 2000, pp. 1507-1516). The calculation of the special functions entering in the solution have been optimized. In the Olver region, the Fock-type integrals are calculated by localizing the poles of the integrand using Davidenko's method and applying the residue theorem.

For the calculation of the self-coupling of a patch a planar approximation of the substrate is used. The corresponding dyadic Green's function involves Sommerfeld integrals which are calculated by using the DCIM. The decomposition in exponentials is performed with the Matrix of Pencil Method (T.H. Sarkar and O. Pereira, IEEE Ant Prop. Magazine, Feb. 1995, pp. 48-55). This computation has to be performed only once since it does not depend on the position of the observation point. The DCIM algorithm has been optimized by a tabulation procedure and is very fast. The CPU time needed for calculating the self-coupling terms is only 1.5 the time necessary for the same calculation for a patch in free space.

The integral equation formulation for the unknown currents on the array elements expressed with both dyadic Green's functions is solved within the MoM frame work.

The combination of UTD with DCIM is new. It avoids the search for asymptotic solutions valid very close to the source point.

Numerical examples giving the currents on a patch, the radiation characteristics of a patch, the radiation pattern of an array of patches and the element input impedance will be presented.

Partial Differential Equation Methods: FDTD and FEM

Co-Chairs: *J.-F. Lee, Ohio State University, USA*
H. A. Kalhor, State University of New York New Paltz, USA

The Concurrent Complementary Operators Method applied to the Finite Difference Frequency Domain (FDFD) Simulation of Scattering Problems

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The procedure by which the computational domain in a finite volume method is truncated plays a major role in affecting not just the accuracy of the simulation, but also its efficiency. In earlier work, the Concurrent Complementary Operators Method (C-COM) has been shown to be a very effective mesh truncation technique when used in the Finite Difference Time Domain (FDTD) simulation of open-region problems [Ramahi, Proc. IEEE Antennas and Propagation Society International Symposium, 2000]. When applied to time-harmonic numerical simulation methods, such as the Finite Elements (FE) or the Finite Difference Frequency Domain (FDTD) methods, the C-COM requires simple, but careful manipulation of the system matrix. Recently, the C-COM has been successfully applied to the FDFD solution of the problem of radiation by a current source. In this work, we extend the application of the C-COM technique to the problem of scattering by conducting and dielectric cylindrical object in two-dimensional spaces. More specifically, the development is demonstrated for the problem of plane wave scattering from a perfect electric conductor and dielectric cylinders of rectangular cross section. In this application, we employ a very efficient sparse matrix solver, thus reducing the memory requirements and also leading to shorter run time. We show that the C-COM can effectively annihilate surface waves that are extremely difficult to treat using other previously developed mesh-truncation techniques. Results will be presented where comparison is made to the Method of Moments solution.

Fast frequency sweep of a wide-band bowtie antenna modeled using a 3D tangentially continuous vector FEM and solved with MGAWE model order reduction

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For wide-band fast frequency sweeps of electromagnetically radiating structures, a computationally efficient method is required to achieve a tractable simulation in a (relatively) short period of time. To this end, it is necessary to have: a versatile modeling methodology, a robust frequency sweeping simulator, and a linear system of equations preconditioner and solver that does not require many iterations to converge. Recently, research in these areas have produced methods that, when combined, can accomplish this task.

It is well known that the finite element method (FEM) is capable of modeling complex, three-dimensional geometries. Much research has gone into the development of vector basis functions for FEM, starting with the classic paper [Nedelec, *Numer. Math.*, 35, 315-341, 1980] and then including such works as [Bossavit and Verite, *IEEE Trans. Magn.*, 18, 431-435, 1982], [Cendes, *IEEE Trans. Magn.*, 27, 3953-3966, 1991], [Graglia, et. al., *IEEE Trans. Ant. Prop.*, 45, 329-342, 1997], [Anderson and Volakis, *IEEE Microw. Guided Wave Lett.*, 8, 127-129, 1998], and [Webb, *IEEE Trans. Ant. Prop.*, 47, 1244-1253, 1999]. In this work, the basis functions, multilevel preconditioner, and corresponding conjugate gradient solver described in [Sun, et. al., *SIAM J. Sci. Comput.*, 23, 1053-1076, 2001] are used to rapidly converge to the solution of the linear system of equations.

To effect the fast frequency sweep portion of the simulation, a model order reduction (MORe) technique is employed. In this work, the automated version of the multipoint Galerkin asymptotic waveform evaluation (MGAWE) process [Slone, et. al., *IEEE Trans. Magn.*, 38, Mar. 2002] is used. In MGAWE, a desired bandwidth is specified for the simulation, and then the original, large FEM model is reduced to a small system of equations (called a reduced order model, or ROM). The ROM still exhibits the same frequency response in the specified bandwidth as the original FEM model. In addition, the automated MGAWE process is also very versatile; the authors have used it in several fast frequency sweep simulations including: finding the S parameters of microwave devices, computing the field scattered from a target, and computing the field radiated from an antenna.

For example, a wide-band bowtie antenna is simulated from 500MHz to 5GHz. The original FEM model contains 884670 unknowns. After applying MGAWE, the ROM has 65 unknowns. The time required to create the ROM is equivalent to 18 frequency point simulations of the original FEM model. The utility of the ROM is twofold. First, the ROM can be used to find the poles in the complex plane in the specified bandwidth. Second, after the ROM is created it can be solved for as many frequency points as desired. Solving the 65×65 ROM is inexpensive; therefore MGAWE is more computationally efficient than solving the original FEM model at as many points as necessary to obtain the shape of the frequency response curve. Finally, the accuracy of the ROM is impeccable; it's solution is indistinguishable from the original FEM solution throughout the entire specified bandwidth.

FDTD Modeling of Millimeter-Wave Photonic Bandgap Structures for Potential Use as Ultrahigh-Speed Bandpass Wireless Interconnects

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Since their inception, electronic computers have been constructed using metallic interconnects to transfer baseband data streams (logic ones and zeros) between processors. However, much above the present clock rates of about 2 GHz, problems with signal integrity, cross-coupling, and radiation may render this type of interconnect impractical. Since clock rates approaching microwave frequencies of 20 GHz are projected by 2010, attention is being drawn toward alternative technologies, including wireless interconnects, that have relatively favorable signal transmission characteristics. One possibility in this category is to use bandpass wireless interconnects wherein the baseband digital bit stream modulates a millimeter-wave carrier. Such an approach could take advantage of the waveguiding physics provided by dielectric channels and photonic bandgap (PBG) structures. This paradigm shift in digital data transmission technology would actually invert present unfavorable trends associated with metallic interconnects. That is, bandpass wireless interconnects involving ever-faster digital bit streams modulating ever higher-frequency RF carriers would allow progressively more effective data transmission using ever-smaller waveguides.

This paper is an engineering study of two-dimensional PBG waveguiding structures to implement such bandpass wireless interconnects. Using the finite-difference time-domain (FDTD) method, we study optimization of the transmission bandwidths for several candidate PBG arrays of silicon rods and slabs in air for the E_z-polarization case. These include square, isosceles-triangle, and equilateral-triangle arrangements of rods, as well as a periodic array of planar slabs functioning as a distributed Bragg reflector (DBR). We conclude that waveguides bounded by planar DBR structures provide the best transmission bandwidth, up to about 40% of the center frequency. This exceeds the bandwidth calculated for waveguides formed by optimized equilateral-triangle PBG's by about 12:1. Over the entire bandwidth of the DBR waveguide, the variation of the transmission magnitude is only ± 0.3 dB, and the corresponding phase shift is linear to within $\pm 2.4° / \text{GHz}$. Combined with the advent of THz-class silicon transistors, these characteristics of planar DBR waveguides indicate the potential for dielectrically confined wireless transmission of bit streams running into the hundreds of gigabits/sec.

A Finite-Difference Time-Domain Method for the Analysis of Reverberating Chambers with Electronic Mode Stirring

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INTRODUCTION- Reverberating chambers have found extensive use in performing high frequency measurements such as electromagnetic interference susceptibility testing and shielding effectiveness of cables and connectors. The main goal of using such cavities is to create a statically uniform field that eliminates the need to rotate the test object. A uniform EM field achieved by means of exciting a large number of cavity modes close to each other in terms of their modal frequencies. However, a simple enclosure by itself is unable to satisfy the uniformity requirement of the internal field. In order to provide field uniformity at all test points, in all directions, and different locations of the radiating source, mode stirring must be performed. Stirring can be accomplished either mechanically or electronically. Mechanical stirring requires the rotation of metallic paddles at a very slow rate and its analysis is very complicated [Wu and Chang, IEEE Trans. Electromagn. Compat., May 1989]. The idea of the electronic mode stirring lies on the fact that if the source has a non-zero and rather large bandwidth, then a large number of cavity modes are excited which in turn results in a uniform random field via mode mixing. Hill [IEEE Trans. Electromagn. Compat., Nov. 1994] has developed a technique for the analysis of the electronic mode stirring reverberating chambers further eliminating the need for the rotating vanes which simplified the analysis greatly. His approach is based on a modal analysis applicable to only two dimensional cavities, and is approximate.

FORMULATION- We propose an accurate and general finite-difference time-method (FDTD) of the analysis for the electronic mode stirring reverberating chambers. Electronic mode stirring is achieved by means of exciting a dipole antenna inside the chamber by a white Gaussian noise source. The noise source is modeled as a superposition of discrete impulses. The analysis of a dipole antenna driven by a discrete impulse and a Gaussian noise source is presented in free space first. The results are validated by comparing with the corresponding results obtained by the method of moments (MOM). The analysis of a two dimensional electronic mode stirring reverberating chamber is presented next and the results are validated by comparing them with those obtained by Hill. Finally, the direct application of the proposed method to the analysis of the three dimensional enclosures is discussed.

Higher Order Curl Conforming Vector Finite Elements for Analyzing Wave Guiding Structures

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The analysis of two-dimensional wave guiding structures is of significant importance in microwave engineering. It provides impedance information of the transmission lines, the modal configuration of energy propagation, and it is becoming more popular that the two-dimensional eigen analysis is an integral part of studying real life three-dimensional electromagnetic problems.

Efforts have been carried out by many authors [E. Schwig and W. B. Bridges, *IEEE Trans. Microwave Theory Tech.*, 32, 531-541, 1984], [T. Q. Ho and B. Beker, *IEEE Trans. Microwave Theory Tech.*, 39, 1021-1025, 1991], [J. F. Lee, *IEEE Trans. Microwave Theory Tech.*, 42, 1025-1031, 1994] previously using various frequency domain and time domain numerical electromagnetic techniques. Among them, the finite element method (FEM) is the most suitable and versatile in handling arbitrary material properties and geometric shapes.

In this paper, we extend the FEM into higher order bases in a hierarchical way. In doing so, the approach naturally adopts into one of the most powerful FEM technologies: *hp* mesh refinements using small-sized elements for regions containing singularities and higher order basis functions in regions where the fields are smooth.

Furthermore, the conventional edge elements, the lowest order curl conforming FEM, will suffer low frequency instability. Namely, when the operating frequency becomes very small, the solution process may break down and fail to provide any meaningful solutions. Also this difficulty will surface in performing adaptive mesh refinement, particularly the *h* version adaptive process, where element size can vary several orders of magnitude over a single problem domain. Thus in a FEM mesh where extremely small elements, compared to wavelength, are employed, bad condition number matrices will usually be resulted. It then becomes increasingly difficult to solve such matrices and will contaminate any good "error" estimation in adaptive process. To remedy this difficulty, a tree-cotree splitting of the edge elements is proposed and implemented. Details of the hierarchical higher order curl conforming elements and tree-cotree splitting will be discussed in the presentation.

A Pseudospectral Frequency-Domain Algorithm for Computational Electromagnetics

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In the frequency domain, conventional methods in computational electromagnetics include the finite-element method (FEM) for partial differential equations, and the method of moment (MoM) for integral equations. Recently, intensive research has been pursued to accelerate these methods and to improve the order of accuracy of numerical solvers of partial differential and integral equations. Examples of such fast algorithms include the higher-order finite-element method, fast multipole method (FMM), CG-FFT type methods and adaptive integral method.

In this work, we develop a pseudospectral method in the frequency domain to increase the order of accuracy in numerical solution of partial differential equations. First, the computational domain is subdivided into subdomains conformal to the problem geometry, so that each subdomain contains only one homogeneous medium or a smoothly varying inhomogeneous medium. This subdivision guarantees that the electromagnetic fields within each subdomain will be continuous functions. Then, this method uses high-order Jacobi-type polynomials to represent unknown fields within each subdomain. Chebyshev points are chosen as the collocation points within each subdomain, thus providing a spectral accuracy of the solution. By using this representation, the partial differential equations can be converted into a matrix equation, which is then solved iteratively.

Because of the high-order basis functions used within subdomains, this pseudospectral frequency-domain (PSFD) method has the following attractive advantages compared with other conventional methods: (1) The number of unknowns is greatly reduced as the method has a spectral accuracy. Usually only π unknowns per wavelength are required. (2) The condition of the resultant matrix is greatly improved from the FEM matrix. Thus an iterative procedure will generally give a fast convergence. (3) The subdomain division provides this method with the flexibility similar to the FEM. Numerical examples will be demonstrated for multidimensional electromagnetic problems and for nonlinear electro-mechanically coupled systems.

A New Global Modeling Approach of Active Microwave Devices Using Wavelet-Based Adaptive Grids

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Abstract Global modeling is a tremendous task that involves advanced numerical techniques and different algorithms; as a result, it is computationally expensive [*S. El-Ghazaly and T. Itoh, IEEE MTT-S Int. Sym. Dig., 151-154, 1997*]. Therefore, there is an urgent need to present a new approach to reduce the simulation time while maintaining the same degree of accuracy. One approach is to try to adaptively refine grids in locations where the unknown variables vary rapidly. Such technique is called multiresolution time domain (MRTD) and a very attractive way to implement it is to use Wavelets.

MRTD approach has been successfully applied to FDTD simulations of passive structures [*M. Werthen and I Wolff, IEEE Microwave and Guided Wave Letters, 6, 438-440, 1996*]. However, for the active devices that are characterized by a set of highly coupled and nonlinear differential equations, applying the same approach would become quite time consuming [*J. Keiser, Ph.D. Thesis, University of Colorado, Boulder, 1995*].

Several different approaches for solving PDE's using Wavelets have been considered and it has been noticed by several authors that nonlinear operators such as multiplication are too computationally expensive when done directly in a Wavelet basis. One of the approaches for solving PDE's is the interpolating Wavelets technique presented in [*M. Holmstron, Technical Report No. 189/1996, Uppsala University, Sweden.*]. Interpolating Wavelets have been successfully applied to the simple drift diffusion active device model [*S. Goasguen and S. M. El-Ghazaly, IEEE MTT-S Int. Sym. Dig., .375-378, 2000*]. The simple drift diffusion model, despite it is a good approximation for long-gate devices; it leads to inaccurate estimations of device internal distributions and microwave characteristics for sub-micrometer gate devices [*Y.K. Feng and A. Hints, IEEE Trans. Electron Devices, 35, 1419-1431, 1988.*]. Thus, a new approach for applying Wavelets to the full hydrodynamic model of active devices is needed.

In this research, a novel large-signal time-domain simulation approach for full-hydrodynamic physical modeling of semiconductor devices using Wavelet-based adaptive grids is presented. The non-uniform grids of the main variables are conceived at a given time by applying biorthogonal Wavelet transforms to the current variable solutions followed by thresholding. A general criterion is mathematically defined for grid updating of each variable within the simulation. This criterion allows grid updating only when needed. In addition, few rules have been defined to take care of the fact that boundary conditions as well as discritization have to be handled differently for each new grid. Grids of the main variables are combined into one non-uniform grid whenever a new variable grid is conceived. The proposed technique is validated by simulating a submicrometer MESFET. The results of the proposed technique are compared to the results of a regular grid case showing more than 60% simulation time reduction while maintaining the same degree of accuracy. Since global modeling requires solving the hydrodynamic model in conjunction with Maxwell's equations, this would be a first step heading for applying Wavelets to global modeling of active microwave devices aiming to reduce the simulation time.

An iterative FEM with fast multipole updates for scattering from a large 3D cavity-backed aperture

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An iterative FEM for a large body problem is proposed and applied to scattering by a long 3D crack or cavity-backed aperture. At first, the Dirichlet condition has been selected as a boundary condition used by an iterative FEM. However, this choice has been found to be not suitable for characterizing the scattering by an object such as a cavity or a scatterer with a resonant size since the Dirichlet boundary condition causes internal resonance to occur and this internal resonance corrupts a true solution unfortunately. To alleviate this problem, the iterative FEM in conjunction with a radiation-type boundary condition has been suggested and successfully applied to analyzing a 3D cavity-backed aperture(J. Park, J. Lee, H. Chae, and S. Nam, *IEEE Trans. Microwave Theory Tech.*, 2001, **44**, (12), pp. 2145-2151). In the above paper, it is shown that the iterative FEM has good properties that the system matrix preserves its sparsity which the typical FEM generates, and it does not change during iterations. Besides, a matrix for updating a residual field quantity on the artificial boundary is also invariant during iterations, so that it is computed only once at the first iteration. However, this method would fail if it is applied to scattering by an electrically large aperture since a matrix for updating the residual is represented by an integral equation with Green's function, and thus it is a full matrix. Therefore, in order to extend the iterative FEM to a large body problem, in this paper, a fast multipole method is applied to the field updating by an integral equation so that the increasing rate of computation time and memory requirements for updating procedure may decrease. Also, the almost optimal distance for the convergence of this method between the boundary where meshes are terminated and the aperture surface is determined through the numerical experiments. Since this determined value of the distance is found relatively small, the excessive increase of unknowns does not occur as the size of a scattering aperture. Hence, a sparse system matrix makes the FEM procedure efficient enough, and the fast multipole updates enables the computational time and memory requirements to be reduced to the lower order than $O(N_a^2)$, where N_a is the number of unknowns on the boundary. To verify the proposed method, scattering by a long crack is analyzed as a simple example. The result is compared with the typical FEBIM and shows an efficiency and a good agreement.

Propagation Characteristics and Techniques for Wireless Communications

Co-Chairs: *W. J. Vogel, University of Texas, USA*
A. R. Webster, University of Western Ontario, Canada

Microwave Fading Characteristics on a 51km Tropospheric Link.

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Observations on the signal characteristics on a 51 km microwave link in Ontario have been conducted over a number of consecutive fading seasons. The system used operated at a frequency of 16.65GHz and utilized a 16-element vertical array at the receiving end that allowed the resolving of individual ray components in a multipath situation. The amplitude and angle-of-arrival of these components is the primary output from the system, with a dynamic range of 65dB for the former and a resolution of ~ 0.1 degree for the latter, and sampling was continuous at one second intervals.

Previous presentations of the results have concentrated on the cumulative fading distribution and its relation to the underlying propagation conditions. It has been suggested that two basic conditions account for much of the fading structure, namely defocusing due to a ground based layer and atmospheric multipath due to an elevated layer and that there are significant differences in the statistics for the two. In this presentation we concentrate on the fading rate and the fade duration associated with these conditions, both of which would be expected to influence significantly the performance of such links using digital radio systems. Results are presented for the five consecutive fading seasons (1992-96) for the months of May to September, the period over which significant nocturnal fading was observed.

Generally, the fading associated with ground-based layers is more severe and occurs earlier in the night than that associated with elevated layers. While generally consistent from year-to-year, some variation is apparent in both the distribution and the severity.

Determination of TOA for Subscriber Geolocation Application

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Several methods have been proposed for geolocation of mobile subscriber. Among them including the Time of Arrival (TOA) method, the Direction of Arrival (DOA) method, the Time Difference of Arrival (TDOA) method and hybrids of them. The TOA is usually determined by the time bin of the first peak or the largest peak of the measured delay profile. However, in the environment with the line of sight being blocked and/or with strong reflections from other places, the largest peak may not come from the direct path. One simple algorithm to determine the TOA of the direct path is to determine a threshold (a value of several dB below the greatest peak in the delay profile) and find the TOA of the first peak that crosses the threshold. In this paper we will use simulation data and measurement data to determine the optimum threshold value.

Several different propagation models for W-CDMA environment have been proposed. Three different environment models, the typical urban model, the rural model and the hilly terrain model will be used in the simulations. For each model, each multipath has a fixed time delay and a mean relative power and each path suffers a Rayleigh fading. For each environment model, we conduct 10000 simulations with independent Rayleigh fading. For each simulation we use different thresholds and determine the path that first crosses the threshold. We then calculate the mean distance errors for each different threshold.

We also use a wideband vector channel sounder to measure delay profiles in the campus of the National Taiwan University. The base station is placed on the 13th floor of a building. We divide the measurement environments into 3 categories, with LOS, without LOS, and mobiles in indoors. The carrier frequency is 2.44GHz and the bandwidth is 120MHz. Therefore, a range resolution of 2.5m can be obtained. From the delay profile measured at each mobile position, we also use different threshold values to determine the first path across the threshold and calculate the distance error determined by the threshold. Both the simulation results and the measured results will be presented.

The Statistical Analysis of the Radio Frequency Noise Measured on a Hill Beside a City in Taiwan

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Abstract

The effect of noise on electromagnetic systems mainly depends on the number of cars, motorcycles, factories, and human activities. Mountainous terrain, great population density and much more motorcycles than cars make the noise environment in Taiwan different from that in other countries. In the UHF band, a broad ignition noise maximum is found in the interval 300 to 700MHz (*Edward N. Skomal, Man-Made Radio Noise, New York: Van Nostrand Reinhold Co., 1978. p29-p30*). Owing to a weaker shielding effect, the noise a motorcycle produces is roughly 10 dB stronger than a car. Automotive ignition noise is usually directed to vertical polarization (*Bernhard Keiser, Principles of electromagnetic compatibility, Dedham, Mass.: Artech House, c1979*). In this paper, we discover that the maximum of the noise figure is about 390 MHz in vertical and horizontal polarization and the noise figure for vertical polarization is stronger. Therefore, it can be proved that the noise sources mainly arise from ignition in the city. This paper describes the characteristics of noise statistics and the method of measuring urban radio frequency noise environment. It is analyzed by the means of CDF (Cumulative Distribution Function), APD (Amplitude Probability Distribution), NAD (Noise Amplitude Distribution), PDD (Pulse Duration Distribution), PSD (Pulse Spacing Distribution) and ACR (Average Crossing Rate). We choose a hill beside a city as the urban radio frequency noise environment for the following reasons: the noise margin in an urban area is smaller than a suburban and rural area; variation in noise margin could result in the degradation of a broadcasting system; the coverage of the measurement on a hill is larger than that of the measurement in a city; it costs less than the airborne measurement. The obtained results show the time dependent variation of the statistical character of the noise and design constraints for a broadcasting system. Thus, to improve the quality of broadcasting, we suggest that propagation of horizontal polarization is the best choice for the quality of an analog and digital transmission system.

AN EFFICIENT NUMERICAL ANALYSIS FOR LINKS OF SATELLITES IN DIGITAL COMMUNICATION SYSTEMS

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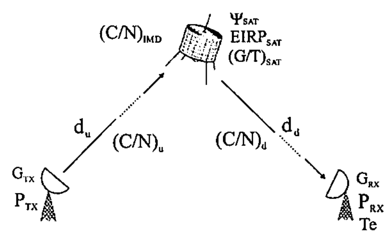
Nowadays, the actual marketing of communication systems using link of satellites takes into account some structural schemes for the essential calculations. Normally, this can not offer the possibility to do the registration of both satellites and the corresponding components which are involved in the project of the system. In this paper, we present a new alternative approach for the calculations of *links* which works in parallel of an enough set of data. This numerical tool can concentrate all essential parameters and characteristics of the satellites and components, independently of their particular companies and partnerships. By glancing of this way this innovative approach provide to all the designers involved in the projects of networks using satellites an interesting alternative tool. Many different configurations can permit the visualization of the *links,* but in all of them we need to attend an excellent cost-benefit relations. In order to optimize it, sometimes is very important to experiment different ways in the analytical analysis. Our main purpose in this paper is to use an appropriate numerical program, so that the routines can be processed with high speed. The designer can use a complete set of parameter of antennas, High Power Amplifier waveguides (*HPA*), Low Noise Block (*LNB*), Low Noise Amplifier (*LNA*), satellites and all the other essential components.

The Project of a link in systems of satellites involves some special characteristics and data. Bellow, we present a basic block diagram of the communication system.



To determine the distance of the *uplink* (d_u), and *downlink* (d_d), and the corresponding attenuation due to the rain, we must to have the geographic positions of each ground and orbital stations. These are fundamental factors in the analysis of the global attenuation due to the free space and the rain. With the transmission rates and the modulation-codification techniques, we can determine the ideal performance for the link with the respective carrier/noise ratio [$(C/N)_T$]. If we done particular analysis in both uplink and downlink, we can reach the desired performance of the satellite with respect to the intermodulation. Below, we present only the fundamental equations to determine all the parameters of the ground station :

$$\left(\frac{C}{N}\right)_T = \left[\left(\frac{C}{N}\right)_U^{-1} + \left(\frac{C}{N}\right)_D^{-1} + \left(\frac{C}{N}\right)_{IMD}^{-1} + \left(\frac{C}{N}\right)_I^{-1}\right] \; ; \; \left(\frac{C}{N}\right)_U = PTX + GTX - \Sigma A + \left(\frac{G}{T}\right) - 10\log KB \; ;$$

$$\left(\frac{C}{N}\right)_D = (EIRPSAT - BO) - \Sigma A + \left(\frac{G}{T}\right)_{SAT} - 10\log KB \; ; \; BO = f\left\{\left(\frac{C}{N}\right)_{IMD}\right\} \; ; \; BO = \psi_{SAT} - \psi_{NOM}$$

where : $(C/N)_T$ = Total carrier to noise ratio, $(C/N)_U$ = Up-link carrier to noise ratio, $(C/N)_D$ = Down-link carrier to noise ratio, $(C/N)_{IMD}$ = Intermodulation carrier to noise ratio, $(C/N)_I$ = Interference carrier to noise ratio, BO = Amplifier back off, ψ_{SAT} = Maximum satellite power density, ψ_{NOM} = Nominal satellite power density.

In this paper, we take into account another important factor present in the implementation of the link, which is the multiple access technique. With all the data of the satellite and by trying to reach the desired performance, we can determine the power transmission set by the *HPA*, the antennas gain, the temperature noises of the ground station and many others parameters involved in the project of the communication system.

Analysis and Measurement of High Speed Circuits

Co-Chairs: *L.-W. Li, National University of Singapore, Singapore*
Z. Pantic-Tanner, University of Texas San Antonio, USA

Global Modeling Approach of Active Microwave Devices Using Genetic Algorithms

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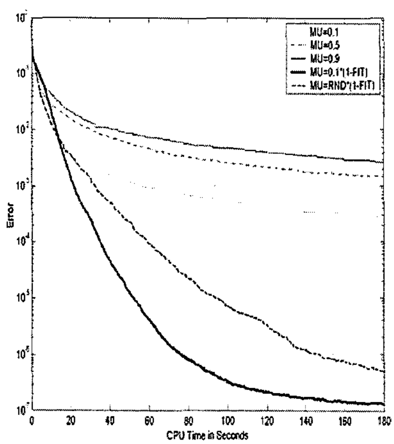
Abstract Global modeling is a tremendous task that involves advanced numerical techniques and different algorithms; as a result, it is computationally expensive [*S. El-Ghazaly and T. Itoh, IEEE MTT-S Int. Sym. Dig., 151-154, 1997*]. Thus, there is an urgent need to develop and present new simulation approaches that are robust, efficient, and fast. On the other hand, Genetic Algorithms (GA's) are numerical optimization techniques inspired by both natural selection and natural genetics. The method is a general one, capable of being applied to an extremely wide range of problems. GA's have proven themselves for solving many large and complex problems.

In this research, a novel large-signal physical modeling of active microwave devices using an adaptive real coded genetic algorithm is presented. The proposed algorithm solves Poisson's equation in a two-dimensional quasi-static full hydrodynamic large-signal physical model using a real coded Genetic Algorithm (GA). The proposed technique is validated by simulating a submicrometer MESFET. The physical insight of the problem and being able to develop an accurate mathematical model were the keys to conceiving the new algorithm. The proposed algorithm is compared to different algorithms showing excellent accuracy as well as a reasonable speed of convergence. In addition, the effect of various GA parameters on the algorithm behavior is studied. This is a first step toward applying Genetic Algorithms to Maxwell's equations in conjunction with the full hydrodynamic model for global modeling of active microwave devices aiming to develop a robust, efficient, and fast simulator. Sample results are presented below.



Fig, 1. Error vs. CPU Time for Different Values of MU (The Mutation Factor).

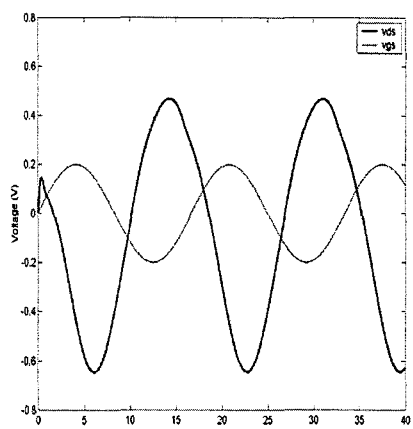


Fig. 2. Large Signal Results Obtained Using a Poisson Solver Employing the Proposed Genetic Algorithm.

Cavity Resonance Analysis and Mitigation Based on S-parameter Simulation using FDTD

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An electromagnetic radiation source, such as the heat sink of a high-speed microprocessor, when placed in an enclosure or chassis, leads to cavity resonance that can have severe impact on other electronic components housed within the same enclosure. The cavity resonance can also potentially affect the external radiation caused by ventilation or cable apertures in the body of the enclosure. Therefore, reducing the enclosure resonance is a critical step in the overall improvement of the electromagnetic compatibility potential of enclosures.

In this work, we focus on new techniques to reduce cavity resonance in structures commonly used to house high-speed electronic components. These structures are typically highly resonant. By varying the internal topology and by using novel material, the resonance of these cavities can be mitigated. However, experimenting with prototypes can be highly costly and, more critically, time consuming. Therefore, we have developed a numerical procedure using the powerful Finite Difference Time Domain (FDTD) method to predict the resonance frequencies of geometrically complex enclosures and cavities. The numerical procedure simulates the incoming and outgoing waves of the feed and the receive ports used in S parameter measurements of the physical structure. To validate our numerical procedure, a stainless steel box was constructed measuring 20 cm x 29 cmn x 39 cm. The resonant frequencies for this structure were obtained through the S parameter measurements using a victor network analyzer. The box was modeled using FDTD. The numerical procedure was able to accurately predict the resonant frequencies that were obtained from measurements. In addition to the experimental and validation results, we will present simulation results of boxes having complex internal topology, as well as cavities lined with lossy material placed at carefully selected locations. It is hoped that this study will lead to a cost-effective methodical procedure for reducing cavity resonance.

The Effect of Edge Treatment on the Excitation of Undesired Resonance Modes in Printed Circuit Boards by Broadband Digital Logic Signals

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Abstract

The non-sinusoidal signals associated with high speed logic circuitry launch radially propagating waves between printed circuit board (PCB) ground and power planes that propagate towards the edges of the PCB. The broadband spectrum of these waves in turn excite multiple radiation modes in the PCB, significantly increasing the levels of undesired radiated emissions. To suppress these radiation modes, outer layers of solid copper ground planes are added to the PCB stackup. These planes are then shorted together along the edges by a series of closely spaced vias to simulate a complete Faraday cage shield (see Figure 1). In many cases, the entire periphery of the PCB cannot be shielded, for example near card-edge connectors. The percentage of the perimeter that is shorted impacts the resonant frequencies of the radiating modes.

A series of planar PCB structures were built and measured in the frequency and time domains using a vector network analyzer and time domain reflectometer (see Figure 2). The measurement data was compared with FDTD simulations where the top and bottom sides of the PCB were modeled by electric field walls, and the edges modeled by either electric walls or magnetic walls, depending on whether the edge was shorted or left open. As can be seen from Figure 3, the resonant frequencies between measurements and simulations agree quite closely.

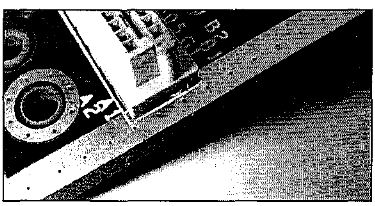

Figure 1: Via Stitching

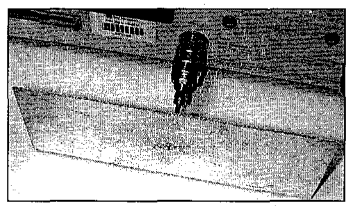

Figure 2: S11 Test Configuration

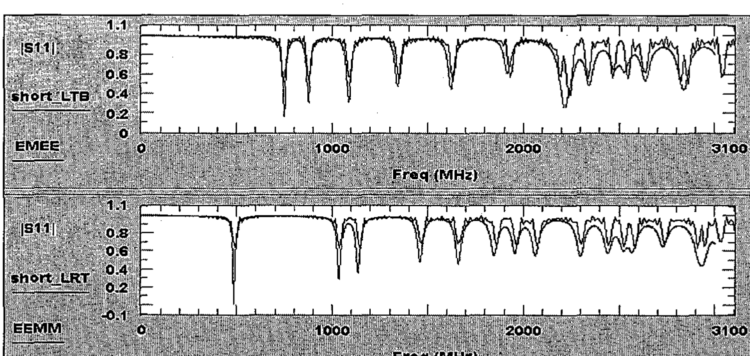

Figure 3: |S11| Measurement/Simulation Results

Experimental investigation of the global characteristics of on-chip symmetric center-tapped transformers

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ABSTRACT: Monolithic spiral transformers can find many practical applications in both monolithic radio frequency and microwave integrated circuits (RFICs and MMICs)[1, 2], such as oscilators, mixers, as well as power amplifiers. For instance, in a low-noise amplifier (LNA's) the transformer is used to provide an inductive feedback path for improving the linearity and stability of circuits. More recently, some researchers have carried on both experimental and theoretical work on modeling and characterization of on-chip transformers mainly used for RFIC design. Similar to on-chip spiral inductors, spiral transformers can be also designed in various nonsymmetrical or symmetrical patterns to meet different requirements. On the other hand, since the characterization of transformer is more complicated than that of single spiral inductor, there still exists much work to be done on accurately evaluating as well as improving the performances of on-chip transformers.

In this paper, six square and circular central-tapped on-chip transformers are fabricated, and these transformers have different turn numbers but each in a perfect symmetrical structure. The metal track width and spacing of these transformers are designed to be $W = 10\ \mu m$ and $S = 1.5\ \mu m$, respectively. In order to evaluate their perfomances the S-parameters at up to 10 GHz and 20 GHz are measured, respectively. A lumped circuit model for these symmetric transformers is developed for describing the global characteristics of transformers, and all the lumped device parameters corresponding to different turn numbers of both square and circular structures are extracted accurately and compared with one another, and an excellent agreement is achieved betweeen our measurement and simularison.

Experimental Characterizing On-Chip Inductor-Capacitor Oscillators

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ABSTRACT: Detailed experimental investigations are carried out to show the global characteristics of on-chip serial inductor-capacitior oscilallators (*L-Cs*) on silicon substrate (Fig.1). Based on the proposed equivalent circuit model together with the measured *S*--parameters using de-embedding technique, single inductor, single capacitor as well as two sets of serial *L-Cs* all examined and compared with one another, and excellent agreement are is achieved between the measured and simulated *S*-parameters. It is demonstrated that at lower operating frequency the first resonant frequency f_{res} of serial *L-Cs* can be easily determined using $f_{res}=(2\pi\sqrt{LC})^{-1}$, while at heigher operating frequency the parasitic parameter effects of both substrate and metal strip on f_{res} of *L-Cs* must be taken into account.

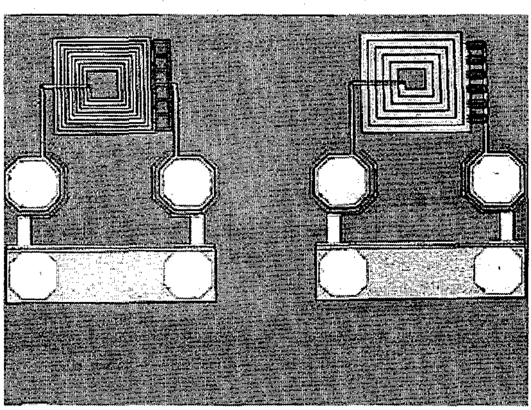

Fig. 1. Top views of on-chip serial *L-Cs*.

Advanced Sensing Measurement Techniques

Co-Chairs: *W. A. Davis, Virginia Polytechnic Institute and State University, USA*

C. Nguyen, Texas A&M University, USA

Characterization of Dielectric Substrate Material Using Fork Resonators

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The high frequency dielectric characterization of materials can be performed using stripline resonator techniques. The materials of interest are used as substrates on which stripline resonators with specified lengths are fabricated. Measuring the resonant frequency and the Q factor of a resonator, one is able to determine the real and imaginary parts of the complex dielectric constant of the substrate material. The stripline resonator technique is particularly useful because microwave integrated circuits are commonly constructed using striplines on dielectric substrates. Thus, this technique allows measurement of the dielectric properties of materials as they are used in actual substrate forms. Here, a new microstrip resonator with fork shape feeders for coupling energy in and out of the resonator is proposed for high frequency dielectric characterization of materials. The performance of this resonator is compared with that of a stripline resonator with overlap feeders.

The stripline resonators require multilayer structures and the coupling from the input feeder to the resonant segment and from the resonant segment to the output feeder can be adjusted by controlling the amount of overlap between the feeder segment and the stripline resonator. As the thickness of the substrate become very small, manufacturing these resonators become more difficult and less accurate. In this paper a microstrip fork resonator is introduced to enhance the coupling efficiency and allow for single layer characterization with no adhesive material or multi layer requirements. Measurements of several dielectric materials are performed using the proposed microstrip fork resonator. From these measurements, resonant frequencies and Q factors are directly obtained. Then, a numerical simulation is performed to determine the effective resonant length. The real and imaginary parts of the dielectric constant for the substrate material are calculated using the measured data and the relationships that model a microtrip resonator based on quasi-TEM approximations. Results for the real and imaginary parts of tested materials are presented for a frequency range of 0.5-4.0 GHz.

The satisfactory results obtained from the fork resonator measurements and the easier manufacturing process of these resonators enhance the motivation for using the fork resonator technique in future high frequency characterization of materials.

In Situ Analysis System for Diagnosis of Aging Aircraft Wiring

By Cynthia Furse, You Chung Chung, Jeremy Pruitt, Glen Mabey , Derek Bates, Santi Basava, Chris Griffin, Mark Schmidt, Krishna Konda, Nagendra Grandhi, Rory Buchanan, Eric Cannon, Suketu Naik, Sumeeth Nagaraj, Sachin Chandra, Clark Landeen, Paul Smith, Deekshit Dosibhatla, Jake Gunther, Chet Lo, Ravi B. Gopal, Alyssa Magelby

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Abstract

Aging wiring and the dangers, inconveniences, and maintenance problems it causes have been identified as an area of critical national concern by numerous industry segments. These concerns include aircraft and space vehicles, nuclear power systems, housing and consumer products, trains, buses, and automobiles, large industrial machinery and control systems. Since electrical wiring is the central nervous system of virtually any large and complex device, when these wires fail there can be fires and critical malfunctions. The wiring systems are generally so imbedded and "built in" that they cannot be easily inspected, upgraded, or replaced. Many systems are being used far beyond their original expected lifespan, still with the original decades-old wiring intact.

In situ inspection offers a new and potentially dramatic shift in maintenance options for aging wiring systems. By retrofitting existing wiring systems and building electronics into new systems, the miles of wiring in a complex system can be tested at the press of a button. Faults can be located (to within a few centimeters) before they cause failures.

This paper describes the testing and analysis of real aircraft cables with a wide range of configurations, impedances, and properties. A combination of frequency domain reflectometry (FDR) and a simple impedance measuring circuit are utilized, and their tradeoffs are evaluated. The FDR is used in applications where accuracy on the order of centimeters is required, and the impedance measuring circuit (which provides accuracy on the order of a foot) is used for wires that are lossy or longer than 400 inches. Both of these methods can be packaged into a configuration that is small enough to be imbedded directly in the aircraft wiring. The system has been tested and evaluated both in simulation, and in benchtop prototypes. Power handling, wireless communication links between the sensor units, and computational issues are addressed.

Several different signal processing methods and evaluation algorithms have been combined and compared for accuracy, evaluation of very long and very short cables, and detection of anomalies (frays, bad solder joints or crimps, etc.) that are less extreme than open or short circuits.

A KA-BAND DISTANCE-MEASUREMENT SENSOR

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ABSTRACT

Microwave sensors have been used for accurate, non-contact measurements of distance in various applications – for example, level measurements in chemical storage tanks. Most microwave distance-measurement sensors operate below 24 GHz, particularly at 5.8 and 10 GHz. Millimeter-wave sensors offer smaller size, lighter weight, finer resolution, better accuracy, and are thus attractive for industrial applications.

We report on the development of a new, compact millimeter-wave distance-measurement sensor prototype. The sensor is based on step-frequency radar (SFR). SFR was first proposed in 1972 as a time-domain reflectometer (L. A. Robinson, W B. Weir, and L. Young, *IEEE MTT Trans.*, 20, 855-857, 1972). Basically, SFR transmits sequences of sinusoidal signals of different frequencies toward a target and processes the return signals. In each sequence, the frequency is shifted in discrete values – each value is held constant for a period of time and then changed to a next higher value. The received signals at these step frequencies, reflected from the target, are down-converted into in-phase (I) and quadrature-phase (Q) signals in base band. These I and Q signals are sampled and combined to form an array of complex signals, which are transformed into a time-domain waveform using inverse Fourier transform. This waveform is then processed to reveal the distance to target.

The developed SFR operates in Ka-band (26.5-40 GHz) and is realized using microwave integrated circuits (MICs) and microwave monolithic integrated circuits (MMICs). Experimental results show that the sensor is capable of measuring distance with less than 0.2 inch of absolute error and a low transmitted power of only −20 ± 3 dBm.

Comparison of Wheeler Cap Efficiency Measurement Method Using Various Types of Enclosing Structures

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Gain and efficiency measurements of small antennas are often difficult to perform because at such small size, antenna measurements are easily influenced by the environment, such as instruments that are used to make measurement. A few methods of measurement tend to isolate the antenna from the environment in order to have accurate measurement. One of them is the Wheeler cap method, which measures the radiation resistance R_R and loss resistance R_L in order to compute the efficiency given by the following definition:

$$Eff = \frac{R_R}{R_R + R_L} \tag{1}$$

Wheeler suggests using a conducting sphere to enclose the antenna to measure the impedances. This assumes that the conducting sphere causes no changes in the current distribution on the antenna. If this assumption is correct, the real part of the input impedance with the sphere in place is R_L. Thus by making two impedance measurements, one without the sphere and one with the sphere in place, one may determine the antenna efficiency using (1).

Even though the Wheeler method is easy to perform, setting up the apparatus using an enclosing conducting box with a spherical shape is rather difficult. A cubical, rectangular, or cylindrical-shaped box is easier to make. The Virginia Tech Antenna Group (VTAG) has performed efficiency measurements on a few small antennas using the Wheeler cap method with different shapes and sizes of the enclosing box. These measured values are then compared the theoretical values computed using IE3D, Fidelity, and NEC. The traditional integration pattern method was also performed to compare the efficiency using VTAG anechoic chamber.

Microwave field probe calibrations in the near field of a standard gain horn antenna

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Anechoic chambers are currently in use for a wide variety of indoor electromagnetic measurements, e.g. EMI, EMC, antenna and field probe calibrations. The generation of a known field strength in the quite zone is a requirement for performing calibrations in an anechoic chamber. This standard electromagnetic field is usually generated with a standard gain antenna. Therefore, accurate field strengths produced by a standard gain antenna in the near field are required for the application of field probe calibrations. The theory and supporting experimental measurements of near field gain of standard gain antennas have been demonstrated over limited frequency and distance ranges. Kanda and Orr (M Kanda and RD Orr, *IEEE Trans. on Antennas and propagat.*, 33-38, 1987) performed near field gain measurements to verify theoretical near field gain calibrations at 450 MHz, over a distance of 1 m to 4 m. Their paper forms the basis for the near field gain correction factors as used in the IEEE Standard for Calibration of Probes.

The calibration of microwave field probes is performed in the region closer than 1 m from the aperture of the horn antenna generating the reference field as this significantly reduces the transmit power required to generate the reference field. In this paper the near field gain of a standard gain horn antenna at 2.45 GHz are investigated at distances closer than 1 m from the aperture of the horn antenna. Using a Narda 8700 series field probe measured and predicted field strengths will be presented at distances 0.25 m to 1 m from the aperture, distances typically used for probe calibrations. The theoretical field strengths are predicted based on edge-wave diffraction theory. The study revealed agreement within the uncertainty of the probe being used.

Comparing the data with that from Kanda and Orr good agreement exists for larger distances. However, for distances closer to the antenna aperture there is a significant difference between the measured (and predicted) gain curves and the approximate gain curves derived by Kanda and Orr and currently used by the IEEE Standard for Calibration of Probes.

Special Session

Complex Media and Metamaterials II

Organizer(s): *N. Engheta, University of Pennsylvania, USA*

Co-Chairs: *N. Engheta, University of Pennsylvania, USA*
R. W. Ziolkowski, University of Arizona, USA

Chiral and Anisotropic Fibrous Materials For Gossamer Sailcraft

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The computation of electromagnetic force and torque for fibrous microwave and solar gossamer sailcraft has been a topic of our recent research efforts (*AIAA Gossamer Spacecraft Forum*, AIAA Paper No. 2001-1615, Seattle, WA, Apr. 16-19, 2001 and *IEEE Antennas Propagat. Soc. Int. Symp. Dig.*, Boston, MA, pp. 326-329, 2001). These ultra-lightweight spacecraft are formed from a specialized network of carbon fibers with variable conductivity. Carbon fiber has a number of obvious advantages over conventional materials (such as Mylar and Kapton) including complete UV resistance, high temperature stability and no static cling (which is important in deployment).

Another advantage of carbon fiber is the potential to form the microstructure of the sail using chiral, anisotropic or other geometrical features. This capability could provide additional methods for the stabilization and control of sailcraft. With chirality present in the microstructure, for example, the sail could be spun using specialized electromagnetic illumination.

As a specific illustration, the 2-D periodic sail of Fig. 1 is normally illuminated by a uniform plane wave impinging in the $-z$ direction (t_x=7.2 mm, t_y=radius=pitch=3 mm, fiber radius=5 μm, E^{inc}=3 kV/m, f=10 GHz). The time-average torque in the z direction $<T_z>$ is shown in Fig. 2 for right- and left-handed circularly polarized illumination as the fiber conductivity σ is varied. Not only does $<T_z>$ differ in sign for the two polarizations, but it also differs in magnitude which indicates that extraction of angular momentum from incoherent sources might be feasible using chiral features in ultra-lightweight microwave and solar sailcraft.

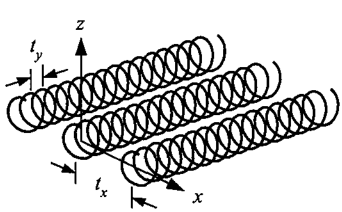

Figure 1 Geometry of chiral sail.

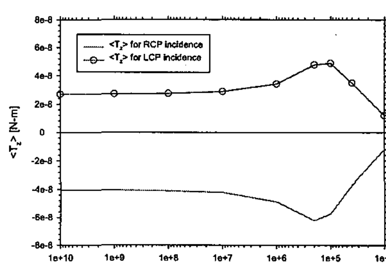

Figure 2 Time-average torque on sail.

Modeling Left-Handed Metamaterials with the EIGER MoM Code

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Composite materials that exhibit negative index of refraction, or "left-handed" materials, are of interest for their unique scattering and focusing properties. Such materials have been constructed by combining conducting strips to obtain negative permittivity ϵ and split-ring resonators for negative permeability μ in a periodic array. The negative index of refraction has been demonstrated in laboratory measurements. These structures have been modeled by finite difference techniques and the effective material parameters derived from averages of field quantities (Smith, et al., Appl. Phys. Lett., Vol. 77, No. 14).

In this paper we present results of modeling such metamaterials with the EIGER method of moments program with periodic Green's function. The square form of SRRs used by Shelby et al. (Appl. Phys. Lett., Vol. 78, No. 4) were modeled with continuous strips. A commonly used method of determining material parameters experimentally makes use of the fields reflected and transmitted by a slab. This method fails when the transmitted field is not available, as in a stop band of the material. With the EIGER program, an infinite slab of the material 12 cells deep was modeled and the near field due to an incident plane wave was computed along a path through the slab. The Generalized Pencil of Functions algorithm was applied to the field in the slab to determine the propagation constant. The reflected field was then used to solve for the effective μ and ϵ of the material. The permittivity and permeability were fit to Debye and Lorentz material models, respectively. By extrapolating from these ideal material models, scaled dimensions were determined for a structure that would yield nearly $\mu = -\mu_0$ and $\epsilon = -\epsilon_0$ to minimize reflection over a narrow band.

Results from the EIGER solution utilizing the periodic Green's function demonstrate left-handed propagation in the medium of strips and SRRs. Analysis of the near fields appears to provide accurate results for the effective permittivity and permeability of the metamaterial. Modeling permits easy modification of the structure parameters to allow tuning and optimization of the material response and could permit design of more effective structures.

This work was performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

Generalized Models of Tunable Meta-Materials Using Statistical Electromagnetics and Coupled Electromagnetic-Circuit Simulation

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In the past, there has been extensive research on EM propagation and scattering through material and conducting periodic structures, especially gratings, photonic band-gap materials, and frequency-selective surfaces. An analysis approach based on quasi-static formulations has been proven to be relatively simple and flexible enough to deal with a variety of "meta-materials" including chiral versions (Lindell et. al. 1994).

In this work we adopt a quasi-static formulation and effective media theory in order to predict the macroscopic behavior of random ensembles of electrically small structures with built-in tunable lumped circuits. This provides a way to study the behavior of "meta-materials" comprised of simple or complex shapes that include controlled impedances. In particular, we will analyze the material properties of "meta-materials" comprising of a host material with embedded rings and split-rings. It has been shown that meta-materials with split ring resonators demonstrate negative permeability in the microwave range.

In the presented approach, a rigorous coupled surface-integral formulation and circuit solver is used to simulate the behavior of electrically small inclusions attached to lumped circuits in the presence of incident fields. In particular, the equivalent electromagnetic moments are computed from the induced electric current densities. The coupled solution mechanism enables S-parameter-free interfacing between lumped elements and electromagnetic structures and allows for the design of tuning circuits comprised of passive circuit components.

The electromagnetic moments and interaction between the circuits and the structures can be studied in both the frequency and time domains. The electric and magnetic moments of the coupled electromagnetic-circuit system is then used in a generalized Lorentz formula (Jandhyala et. al. 2001) in order to obtain equivalent macroscopic material parameters for a composite material comprising of random aperiodic distributions of such electrically small particles. The proposed method holds promise in aiding in the frequency tuning of meta-materials through altering the behavior of lumped circuits within each or specific particles comprising the material.

Complex Spectrum of 3D Open Chiral Waveguides

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The analysis of 3D open dielectric waveguides is a research topic which has been treated in the literature for quite a long time. Most of the analyses have been focused in isotropic or anisotropic structures using semi-analytical or numerical techniques and concentrate on deriving field distributions and real surface wave propagation constants, when assuming ideal lossless materials.

An exception is the work of Peng and Oliner (A. A. Oliner, S.–T. Peng, T.–H. Hsu, and A. Sanchez, IEEE Trans. Microwave Theory Tech., MTT-29, 855-869, 1981) and few other researchers: a formulation has been used which takes into account the TE–TM mode coupling in the lateral walls of the inner region which maybe the reason for lateral leakage. Therefore, surface plus leaky waves are taken into account and a formulation adequate for finding the complete complex discrete spectrum of 3D open dielectric waveguides has been derived.

In the present work, the authors generalize this formulation for the case where the 3D open waveguide includes chiral materials. Research on chiral waveguides has been active in the past few years but mostly concentrating on metallic waveguides filled with a chiral media (H. Cory, J. Electromagn. Waves Appl., 9, 805-929, 1995). The work on open chiral structures has been focused on 2D planar structures (C. R. Paiva and A. M. Barbosa, Electromagn., 11, 209-221, 1991), including also periodic (X. Wu and D. L. Jaggard, IEEE trans. Microwave Theory Tech., 45, 639-647, 1997) or planar structures with step discontinuities (A. L. Topa, C. R. Paiva, and A. M. Barbosa, Int. J. Electron. Commun. (AEÜ), 55, 281-291, 2001).

The present analysis generalizes the work of Peng and Oliner to consider the case of 3D open chiral waveguides. The transverse resonance method is used and the work by the present authors on the chiral step discontinuity is used to derive an equivalent reflection matrix for the lateral walls. Due to the chirality of the media the propagating modes are hybrid. To simplify the analysis the continuous radiation modes are neglected and, therefore, the electromagnetic field is represented in each region only in terms of discrete modes.

The analysis reveals that, under certain conditions, the longitudinal surface modes leak into the outer region turning into leaky modes. Results for the real and imaginary parts of the propagation constants are presented as a function of the chiral and the geometrical parameters for a few structures like a chiral ridge waveguide.

Scattering-Matrix Analysis of Linear Periodic Arrays with Resonant Elements

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A spherical-wave source scattering-matrix description of acoustic radiators, along with reciprocity and power conservation, are applied to analyze infinite and finite linear periodic arrays that support traveling waves. We first prove that for a general linear periodic array of small radiators the traveling wave must be a slow wave with a propagation constant β greater than the propagation constant k of the media in which the array is located. For an infinite array of small isotropic radiators, the scattering-matrix analysis leads to a simple closed-form expression for the propagation constant of the traveling wave in terms of the normalized separation distance kd and the phase ψ_e of the effective scattering coefficient of the array elements. These two parameters also prove to be the only critical variables in the $N \times N$ matrix equation for the N radiation coefficients that is derived for a finite array of N elements. Resonances in the curves of total power radiated versus kd for a finite array excited with one feed element demonstrate the existence of the traveling wave predicted for the corresponding infinite array. These computed power curves, as well as directivity patterns, illustrate that the finite array becomes a more efficient endfire radiator as the value of β approaches the value of k. We also confirm that the maximum attainable endfire directivity of a finite array with a single feed element is a monotonically increasing function of the phase velocity of the traveling wave, and this function is practically independent of the parameters of the array used to obtain this phase velocity.

As the phase ψ_e of the effective scattering coefficient of the array elements varies from 0 to π, the scattered fields of each element go from being in-phase to out-of-phase with the fields impinging upon that element. The $kd - \beta d$ diagram exhibits this fact by predicting that at any given value of $d < \lambda/2$ a traveling wave exists if ψ_e is small enough, and does not exist if ψ_e is close enough to π. In applying the scattering-matrix analysis to a finite linear array of penetrable resonant acoustic spheres, one finds that both low-pass and band-pass filters can be obtained by merely changing the speed of propagation and density of the material of the acoustic spheres so as to produce a ψ_e that varies appropriately with frequency.

MICROWAVE CONFORMAL COMPONENTS WITH BIANISOTROPIC MEDIA

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In the last few years, the need for compactness and weight reduction has grown very much in space and radio-sensor system applications. This is due, besides, to the integration of microwave circuits and components on satellites or plane and terrestrial vehicles, which require very high performances in terms of speed and drag reduction.
In order to match these requirements, both transmissive and radiating components have often to be mounted on non-planar surfaces with complex geometry (e.g. wings of aircrafts, satellite arms, etc.).
On the other hand, the recent investigation on complex non-conventional media (i.e. chiral, ferrites, anisotropic, bianisotropic materials) leads to discover new properties of such materials, when applied to planar transmissive or radiative components (e.g. electronic frequency shifting, radiation pattern control, radar cross section reduction, bandwidth enhancement, directivity improvement, etc.).
Due to the aforementioned reasons, it is very promising to investigate the behaviour of complex materials when applied to components, which can be geometrically described by coordinate surfaces in complex non-Cartesian reference systems.
The analysis of such complex structures is not trivial, in particular when developed for general inhomogeneous bianisotropic substrates.
In the isotropic case Helmholtz equation, which relates electric or magnetic field components, can be easily decoupled in the Cartesian reference system and in several other non-Cartesian ones, employing the Borgnis's potentials. When the medium becomes more complex, this theory is no more effective and electromagnetic field solution is harder. This contribution presents an extension of this theory, applicable to any linear material, in order to derive the whole electromagnetic field inside and outside the conformal structure.
Starting from the generalized transmission-line equations (F. Bilotti, L. Vegni, A. Alù, "Generalized Transmission Line and Helmholtz Equations for the Analysis of Integrated Conformal Circuits and Antennas," Proc. ICEAA 01, 259-262, Torino, Italy, 2001), which relate transverse electromagnetic field components in a general orthogonal curvilinear reference system and for a generic linear material, it is possible to derive an extension of the spectral field Fourier expansion, valid for non-Cartesian reference systems. This theory can be applied to the analysis of guiding and radiating microwave components in order to solve for the whole electromagnetic field inside and outside the structure.

EFFECT OF COMPLEX MATERIAL COVER ON MICROSTRIP PATCH ANTENNAS

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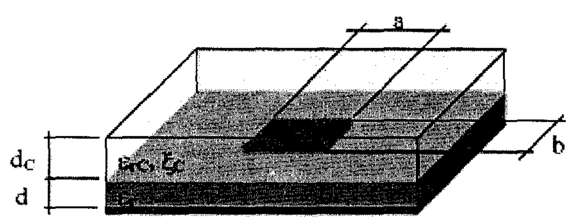
Complex materials, such as chiral and bianisotropic ones, have been recently considered in the design of microstrip antennas. Their well-known advantages in this field, such as increased bandwidth, efficiency and directivity, make them an important resource for designers. Moreover, in the case of biisotropic materials, i.e. chiral ones, these improvements are accompanied by a decrease of the resonant frequency (i.e. D.M. Pozar, "Microstrip Antennas and Arrays on Chiral Substrates," IEEE Trans. Antennas Propagat., 40, 10, 1260-1263, 1992). This effect can be straightforwardly employed to reduce antenna dimensions for a fixed working frequency.
On the other hand, covering a radiating structure with a dielectric slab increases antenna effective permittivity, with a consequent decrease of the resonant frequency and, thus, of the antenna dimensions. Therefore, analyzing the conjunct effects of cover slabs and complex material application could reveal precious information in order to control the resonant frequency of patch antennas by means of two independent design parameters (cover thickness and chirality) leading, thus, to more compact antennas for a fixed working frequency.
In this contribution, such an analysis is performed investigating the effects of covering a microwave patch antenna with a complex dielectric slab. This study is developed applying a new technique, based on the Method of Lines (MoL) approach, recently presented by the authors (F. Bilotti, L. Vegni, A. Alù, "U-Patch Antenna Loaded on Complex Substrates for Multi-Frequency Operation," Microw. Opt. Techn. Lett., 1, 32, 3-5, 2002). Such a formulation allows to study inhomogeneous planar multilayered structures loaded by any linear material. Presented results will refer to the effect of chiral and bianisotropic covers on the resonant frequency of a patch antenna, whose schematic representation is given in the figure. Design charts are eventually presented to simply analyze the separate effects of cover thickness and dielectric complexity.



Schematic representation of a planar patch antenna mounted on a conventional substrate (i.e. isotropic substrate) covered by a complex slab.

Artificial bi-anisotropic electromagnetic crystals

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Electromagnetic and photonic band gap structures attract a lot of attention in view of many potential applications. Usually, these artificial media are formed as periodical arrangements of dielectric or conducting inclusions (or voids in an isotropic matrix). The cell geometry is normally quite simple (spheres, circular cylinders, etc.) In this presentation, we will introduce a new concept of bi-anisotropic (or magnetoelectric) electromagnetic crystals. In these structures, like in quasi-homogeneous bi-anisotropic media, electric and magnetic fields are coupled through the medium response. In other words, electric fields cause both electric and magnetic polarizations, and also magnetic fields both magnetize and electrically polarize the medium. Obviously, more complicated properties of the material allow more possibilities in the design of microwave or optical devices.

Magnetoelectric coupling in media can be due to nonreciprocal properties of inclusions or due to complicated geometrical structure of the medium. In this work we explore the second possibility and study periodical media with long spiral inclusions. In particular, we present an analytical model of a two-dimensional lattice from infinitely long parallel perfectly conducting helices. The theory is suitable for the case when the wavelength is large compared to the spiral step and diameter. The structure under consideration can possess high opportunities for the dispersion properties control and can be used for prospective frequency and polarization filtering the microwave signals.

In our theory we consider the propagation of waves with arbitrary angles with respect to the spiral axis and restrict by the case of square or rectangular lattice. Each helix is modelled as a line of an electric and magnetic current referred to the spiral axis. The analytical theory recently developed for two-dimensional arrays of such spirals (for microwave applications) has been used in our model. This theory gives two simple expressions for the electric and magnetic currents induced in a spiral by local electromagnetic fields. The electric line current does not produce any axial magnetic field component and vice versa. However, spirals possess bi-anisotropic properties, meaning that electric fields excite magnetic currents in spirals, and magnetic fields excite electric currents. The developed analytical approach allows derivation of a scalar dispersion equation, which is naturally more complex than in the case of a lattice of straight conducting wires, however it is not very involved and can be easily and explicitly analysed.

Some numerical examples will be discussed in the presentation, which demonstrate possibilities to realize new polarization sensitive filters with very narrow pass bands, as well as polarization transformers.

Guiding Structures and Circuits

Co-Chairs: *F. Capolino, University of Houston, USA*
J. A. Miller, SAIC, USA

1:15 Opening Remarks

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33.2 1:40 Efficient Representation of the Mixed Potential Green's Function in a Parallel Plate Stratified Dielectric Region 119
A. Pippi, A. Polemi, S. Maci, University of Siena, Italy

33.3 2:00 Electronically Controllable Transmission Line Design for Traveling Wave Array Antenna Feed Network 120
C.-S. Shin, R. Nevels, Texas A&M University, USA

33.4 2:20 Applications of a Novel Equation for Non-Uniform Lossless Transmission Lines 121
J. Miller, SAIC, C.-S. Shin, R. Nevels, Texas A&M University, USA

33.5 2:40 Effects and Suppression of Mode Coupling Inside a T/R-Module 122
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3:00 BREAK

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33.10 4:40 Analysis of the E-Plane Metal Strip on a Dielectric Slab in Rectangular Waveguides 127
T. Pakizeh, H. Oraizi, Iran University of Science and Technology, Iran

Modeling of Mode Excitation and Discontinuities in PBG Waveguides

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The desire to achieve low-loss propagation in the millimeter-wave and optical ranges has recently motivated research into new ways of guiding electromagnetic waves. A photonic bandgap (PBG) material with a row of defects (missing elements) constitutes a waveguiding structure that provides an attractive alternative to conventional waveguides. The applicability of such materials for constructing devices such as switches, multi/demultiplexers, power dividers, couplers, etc., is also receiving increasing interest.

In this presentation we demonstrate an efficient analytic/numerical method to model mode excitation and discontinuities inside a PBG waveguide. The PBG waveguide consists of a periodic array of either metallic or dielectric posts, or holes in a dielectric slab, periodically spaced in the x-y plane. The structure is terminated at $z = 0$ and $z = h$ by metallic planes or possibly by air-dielectric interfaces (using total reflection to obtain confinement in the z direction). A row of missing posts in the x direction forms the waveguide channel (with propagation in the x direction). For generality, the PBG structure is allowed to be finite in the y direction, i.e., there is an arbitrary finite number of rows on either side of the channel. The method uses the one-dimensional (1D) periodicity properties of the waveguide along the x direction. Each layer of posts (infinite row of posts) is described using a transmission-matrix approach, and the periodic PBG material is constructed by cascading the various layers of posts. Since each layer has the same transmission matrix, and also because of the periodicity in the x direction, only one unit cell (containing a single post) needs to be numerically discretized and modeled with a full-wave numerical technique. To further improve computational efficiency, an Ewald acceleration scheme is used to improve the convergence of the periodic Green's function that is used in the unit-cell analysis. This combination of techniques provides an efficient method to construct the Brillouin dispersion diagram of the PBG waveguide, and determine the modes of propagation.

The analysis technique is then extended to treat sources or discontinuities inside the PBG waveguide. A source is modeled as a single post inside the channel, with an impressed current. Similarly, a discontinuity in the form of a metallic/dielectric post or hole inside the channel can also be modeled. The "array scanning" method is used to obtain the field from a single source (or discontinuity) post inside the PBG waveguide. First, the single-post current is replaced by a row of post currents with an arbitrary uniform inter-element phase shift, reducing the analysis to a 1D periodic one. Integration in the phase-shift variable over the Brillouin zone then recovers the current of the single post. The near-field behavior of the source or discontinuity post inside the PBG waveguide can be predicted with this technique. Furthermore, the amplitude of the modal excitations inside the PBG waveguide from the source or discontinuity can be obtained from corresponding residue contributions from the guided-wave poles in the complex wavenumber (phase-shift) plane. The method also allows for the calculation of the input impedance seen by the source post, by integrating the fields of the single post over the post current (i.e., by calculating the post self-reaction).

Numerical examples will be shown during the presentation to demonstrate the computational efficiency of the method, and also to illustrate the physical properties of mode excitation from sources or discontinuities inside the PBG waveguide, and the near-field behavior at the sources or discontinuities.

Efficient representation of the mixed potential Green's function in a parallel plate stratified dielectric region

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An efficient representation, based on a discrete spectrum of harmonics is presented for the Green's Function (GF) of a multilayered medium enclosed within a parallel plate waveguide. The formulation is based on the mixed potential integral equation (MPIE) approach [J.R.Mosig, R.C.Hall, F.E.Gardiol, Handbook of microstrip antennas, Peter Peregrinus, London], applied to meander-shaped microstrip printed into a stratified, one-side opened, rectangular waveguide. This structure realizes a leaky-wave antenna, whose solutions may be approximated by structuring the MPIE with the above GF. The mixed potential form of the Green's function is derived following the method adopted by [K.A.Michalski, J.R.Mosig, IEEE Antennas Trans. Propag., Vol.45, n.3, pp.508-519, March 1997] for the unbounded stratified media. As is well known from a background of patch antenna modeling, the MPIE method has the advantage to manage space domain quasi-static singularities of low order, thus simplifying a spatial-domain formulation of the Moment Method (MoM) solution. Consequently, it also allows an easy adaptation of already available space domain MoM algorithm structured around the free-space GF.

The formulation for deriving the GF is based on the following steps. By applying the image theorem, the metallic walls are removed and the single source inside the parallel plate waveguide is replicated yielding a collinear array of sources in an unbounded stratification. Fields and potentials in layered media of infinite lateral extent are determined in the spectral domain by a conventional transmission-line formalism, applied along the stratification axis (z). The summation of individual fields from the collinear array is next transformed via Poisson summation, into a superposition of the contributions from continuous line sources, progressively phased with Floquet wavenumbers. The outcome is a discrete spectrum of Floquet harmonics along the transverse direction (y) of the original waveguide and a continuous spectrum along the waveguide direction (x).

Each Floquet-phased spectral integral shows the usual difficulties typical of Sommerfield-type integrals, i.e. the presence of pole singularities on the integration path, and the fast oscillating and slowly decaying behavior for large argument of the exponential term. To overcome these drawbacks, and achieve an efficient and reliable solution, the integration path is first deformed onto the convenient steepest descent path (SDP), possibly capturing poles singularities. Then, a uniform asymptotic evaluation is performed, according to the Van der Waerden method. Performing the asymptotics leads to computational advantages, and provides insight into the physical mechanism. For each Floquet-phased line, the above procedure lads to space cylindrical waves, and surface and leaky plane waves, which arise from the SDP integration and residues, respectively. The surface waves (SW) and leaky waves (LW) are driven in such a direction to phase-match the Floquet wavenumber along each phased line, and, grouped in pairs, lead to discrete modes inside the original waveguide. Depending on the order of the Floquet harmonics, different behaviors are associated with the above mentioned wave contributions. Increasing this order (i.e., decreasing the phased-line wavespeed), leads to a transverse-to-line evanescent field (damped along x) for both the space wave, and the SWs. Concerning to the LW contributions, they cannot be excited except for the dominant harmonics. This aspect is particularly convenient since assures a fast convergence to the representation, for increasing distance between the source and the observer along x.

For small values of the same distance, a complementary numerical approach has been also developed, which is based on the spectral extraction of the quasi-static field.

Electronically Controllable Transmission Line Design for Traveling Wave Array Antenna Feed Network

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Abstract

A microstrip is one of the most commonly used transmission lines. The dominant propagation mode is not pure TEM, but quasi TEM if an electrically thin substrate is used. The design procedure for parameters such as characteristic impedance, effective dielectric constant, and the propagation constant is well defined in terms of w/h and ε_r. Since the propagation constant is proportional to the effective dielectric constant, if we can modulate w/h, the dielectric constant, or the area of the dielectric material, a microstrip transmission line with an electronically controlled propagation constant can be achieved.

This can be realized by modulating the conductivity of Silicon substrate. By introducing impurities into a strip of N-type silicon to produce a p^+ region in the middle and n^+ region on each side, and introducing a forward bias, the conductivity of the Silicon can be modulated. Roughly speaking, with full forward bias the silicon behaves as a metal plate. This Silicon strip modulator is attached to a dielectric substrate coated on the opposite side with copper. Depending on the structure, the operating frequency, and the carrier concentration or the resistivity in a parallel plate waveguide model for the microstrip line formed on the Si-SiO_2 system, early researchers observed three different modes; skin-effect, slow-wave, and dielectric quasi-TEM (H. Hasegawa, M. Furukawa, H. Yanai, "Properties of Microstrip Line on Si-SiO_2 System," *IEEE Trans. Microwave Theory Tech.*, 19, 869-881,1971).

In this paper we will present an eight-element aperture coupled microstrip antenna array fed by a forward biased Silicon microstrip modulator. The feed apertures of the microstrip elements are designed so that the radiation conduction, in this case a Taylor $\bar{n}$ distribution, will produce a desired beam pattern. It will be shown that by adjusting the forward bias in the silicon microstrip, the guide wavelength can be modulated, producing a progressive phase shift between array elements, thereby achieving beam scanning. It will be shown that the parameters of the microstrip system can enhance or decrease each of the modes described in the above referenced paper. Our results are compared to those obtained with an Ansoft HFSS 3D simulation of an array fed by a microstrip with a width equal to the average effective width of the biased silicon strip.

Applications of A Novel Equation for Non-Uniform Lossless Transmission Lines

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Assuming a lossless transmission line, the telegrapher's equations

$$\frac{\partial V}{\partial z} = -L\frac{\partial I}{\partial t} \quad (1a)$$

$$\frac{\partial I}{\partial z} = -C\frac{\partial V}{\partial t} \quad (1b)$$

where L and C are the distributed inductance and capacitance, can be solved simultaneously for the time domain voltage and current, V and I on the line (R.D. Nevels and J.A. Miller, IEEE Trans. Microwave Theory and Tech., 49, 721-724, 2001). A propagator is found which, when integrated against any given initial voltage and current, generates a new set of distributions that are the voltage and current after one time step. The explicit pair of equations valid for a single time step $\Delta t = t - t_o = v/\Delta z$ are as follows:

$$V(z,t) = [V(z+\Delta z,t_o) + V(z-\Delta z,t_o)]/2 + Z_o[I(z+\Delta z,t_o) - I(z-\Delta z,t_o)]/2 \quad (2a)$$

$$I(z,t) = [V(z+\Delta z,t_o) - V(z-\Delta z,t_o)]/(2Z_o) + [I(z+\Delta z,t_o) + I(z-\Delta z,t_o)]/2 \quad (2b)$$

where t and t_o are respectively the current and previous time, v is the phase velocity on the line, Δz is a spatial increment and Z_0 is the characteristic impedance of the line. This set of equations though derived for a uniform transmission line has been shown to give exceptionally accurate results for transmission line filters and for a continuously non-uniform transmission line. A non-uniform transmission line can be one in which Z_0 is a function of position z on the transmission line, but the equations in (2) are also valid when the permeability or permittivity or the transmission line is z dependent, as is realized through the velocity v.

In this presentation, results will be given for several types of inhomogeneous transmission lines with continuous inhomogenuity. In each case, excitation will be via a standard time domain Gaussian pulse. The results will be given in both time and frequency domains where comparison will be made with s-parameters (S_{11}, S_{21}) obtained using the commercial Libra® software package. Particular attention will be paid to numerical grid size versus computation error.

Effects and Suppression of Mode Coupling Inside a T/R-Module

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An essential goal of the development of a T/R-Module is a constant course of the transmission factor s21 between the output and the input signal of the T/R-module as a function of frequency. Because of coupling between the microstrip mode leading the RF, and other propagating modes in the vicinity of an amplifying circuit a feedback can occur, which causes an unexpected large variation of the transmission factor. By means of relative simple simulations, possible problems can be predicted and counter-measures can be developed.

A simplified model of a special T/R-module is considered. The housing looks like a brick. The RF path is led parallel to the axis of the brick. By means of cuts perpendicular to the axis of the brick the T/R-module can be devided into sections with cylindrical and non-cylindrical material distribution. Between 2 consecutive cylindrical sections is a non-cylindric section.

The substrate of the examined T/R-module consists of several dielectric layers. The topmost layer carries the microstrip with the RF signal and the circuit elements. Between the 1st and the 2nd layer is the ground of the microstrip. Between the other layers several lines for digital signals and one line for the power supply are located.

Each cylindrical section forms a waveguide. Therefore the electromagnetic field distribution can be well approximated by few waveguide modes, which do not exchange energy. The waveguide modes can be represented by a bundle of uncoupled transmission lines. The amount of propagating modes is at least as large as the number of seperate lines. The non-cylindrical sections can be described by S-matrices. Here an exchange of the energy of the modes occurs. The propagation properties of the modes as well as the S-matrices were calculated with a field simulator. If all the transmission lines, S-matrices and circuit elements are connected together, a network is created, of which the transmission factor can be calculated with a simple network program.

The results of the calculations with the transmission line model shows two main problems:

- Because of the kind of mounting of the amplifying circuits, a further propagating waveguide mode, similar to the parallel plate mode, exists below the circuit itself. The mode is excited at the output of the amplifying device and propagates below the circuit to the input, creating a feedback.
- The connection of an active circuit to the power supply was led parallel to the RF path for some millimetres with a slight distance. In a small frequency band the coupling of the RF-signal to a further mode increases strongly and leads also to a feedback of the amplifying device.

For both problems counter-measures were developed. The presentation will further discuss the calculation of selected S-matrix terms, which are connected to special parts of the layout. Simulation results of the transmission factor s21 will also be shown.

Efficient and Accurate Analysis of Waveguide Diplexers using Hybrid Methods and Integral Equation Techniques

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1 Introduction

Several methods have been proposed for the accurate analysis of waveguide steps and junctions (the key-building blocks of many microwave devices such as filters, power dividers, diplexers and multiplexers). These methods can be sorted into three main categories: modal methods, space/time discretization methods and hybrid methods (suitable combination of the two previous methods). In this work we present a novel hybrid method, based on modal methods and the Integral Equation technique described in (Conciauro et al., Advanced Modal Analysis, Wiley, 2000), for the efficient analysis of complex waveguide structures. This novel method has been successfully applied to the accurate analysis of an H-plane diplexer composed of inductive filters, impedance transformers and a 3-port waveguide junction. Using this novel hybrid method jointly with the well-known BI-RME method (Conciauro et al., MTT-32, No. 11, 1495-1504, 1984), we have also considered the presence of rounded corners in the cross-section of the diplexer waveguides (common mechanization effect). Very accurate results have been obtained in very low CPU times.

2 Analysis Technique

A Generalized Impedance Matrix (GIM), with asymptotic admittances in parallel to the modal ports, has been used for the accurate characterization of each single step of the diplexer. As it seems obvious, the more complex the structure to be analyzed is, the more number of modes are required to characterize all the transitions involved. Therefore, the complexity of the global linear system that must be solved at each frequency point is also increased. In order to overcome this complexity, an effective size reduction of the GIMs can be accomplished. This reduction method consists on loading the GIM ports related to weakly coupled modes. Since the number of waveguide steps is quite large for complex structures (i.e. diplexers and multiplexers), such novel reduction technique widely decreases the size of the aforementioned global linear system. Furthermore, this resulting system has a block 3-diagonal structure which can be suitably exploited in order to solve such system very efficiently (see Boria et al., MTT-Symp., vol. 3, 1567-1570, 1997).

3 Results and Conclusions

The diplexer analyzed with this novel method consists of two 6-pole inductive filters, an H-plane T-junction and impedance transformers placed at each arm of the T-junction (each transformer is based on asymmetric steps). Very accurate results have been obtained for right and rounded corners diplexers considering few interacting modes. CPU times have also revealed that the novel analysis method proposed is very efficient, and therefore it could be used for design purposes.

Resonance poles extraction : Application to Metallic Photonic Band-Gap

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Metallic Photonic Band-Gap (MPBG) are periodic classifications (1D, 2D or 3D) of metallic and\or dielectrics motives. The properties of these periodic structures depend mainly on frequency ; their applications cover a very large spectrum : from microwaves domain until optics. Their ability to filter make them very attractive for microwave applications (frequency, angular and polarization filters, reflectors, passive or active substrates for antennas). Different analytical or numerical methods allow to characterize these structures and to obtain additional informations in order to make their conception easier (for the aforesaid applications).

The technique proposed here is to associate a numerical method with a signal processing algorithm in order to extract the complex natural resonance (CNR) poles of a MPBG. The numerical method allows the resolution of the Maxwell's Equations in time or frequency domain. The characterization of CNR' is made by the Singularity Expansion Method (SEM) in frequency domain. The formalism consists in approximating the transfer function of the MPBG by the ratio of two complex polynomials. Resonance poles are then extracted from the denominator singularities.

The aim of this paper is to analyze resonance phenomena occuring in MPBG structures. Indeed, the wavelength is in the order of the geometrical MPBG period. The frequency response of MPBG structures depicts a strongly resonant behavior characterized by transmission peaks with high quality factor (figure 1.a). The SEM approach applied (figure 1.b), seems to supply a potential solution to describe the resonance MPBG behavior.

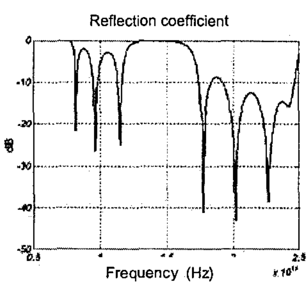

Figure 1.a Reflection coeffcient according to frequency

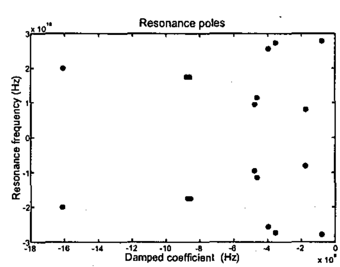

Figure 1.b Resonance poles of a MPBG in complex plane

A PROJECT OF MICROSTRIP-LINE IN PRINTED CIRCUITS AND RF CIRCUITS WITH HYBRID SUBSTRATE OF AIR-FIBERGLASS

Carlos Nazareth Motta Marins, Maurício Silveira, José Antonio Justino Ribeiro, W. N. Amaral Pereira
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The present literature show many difficulties to implement RF circuits using microstrip lines displaced as a printed circuits to operate in both UHF and SHF bands. Some of them are related with the intrinsic high loss due to the fiberglass. One way to control this problem is to adopt sophisticated substrates, like Polytetrafluoroethylene (*PTFE*) material, which have small loss tangent parameter. The high difference in the prices of both fiberglass and PTFE materials is a significant barrier for the technology solution when we have big number of devices to build in the chain of production. Nowadays, this is an essential point we need to take into account and to glance accurately on it for marketing purposes.

We have some additional problems in the design of high power devices, like TV transmitters, mobile base radio stations, and other communication systems. In such cases, the microstrip line circuits implemented must to support high level of power. In order to maintain the characteristic impedance Z_0 of the device, we need to increase the width of the lines to support the corresponding power's gone up. We can perform this demand, if we increase the thickness of the substrate. Some idea of this technological implementation we can have in Fig. 1, where it appears some parameters of the device. At the figure, Z_0 is the characteristic impedance of the transmission line, ε_{eff} is the effective dielectric constant, h is thickness of the substrate, and t is thickness of the layer of the printed circuit. (Radmanesh, Prentice-Hall, 2001)

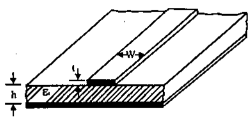

Fig. 1. Classical microstrip line.

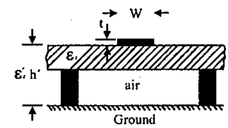

Fig. 2. Microstrip line with modified dielectric substrate.

$$\frac{W'}{h}=\frac{W}{h}+\frac{1.25t}{\pi h}\left[1+\ell n\left(\frac{2h}{t}\right)\right] \qquad \frac{W}{h}\geq\frac{1}{2\pi} \qquad (1)$$

$$\frac{W'}{h}=\frac{W}{h}+\frac{1.25t}{\pi h}\left[1+\ell n\left(\frac{4\pi W}{t}\right)\right] \qquad \frac{W}{h}<\frac{1}{2\pi} \qquad (2)$$

$$Z_0=\frac{120\pi}{\sqrt{\varepsilon_{eff}}}\left\{\frac{W'}{h}+1.393+0.667\,\ell n\left(\frac{W'}{h}+1.444\right)\right\}^{-1} \qquad (3)$$

If the implementation of the circuit is made using fiberglass, we perform low cost and low performance too, while if we adopt the choice of PTFE material we will have high cost and high performance. The cost-benefit relation can be optimized if we create a mix substrate composed by fiberglass and air. This technological implementation is depicted in Fig. 2. To show the efficacy of this technical approach we plot graphics, which present the development of the theoretic Wilkinson combiner that can offer 3 dB of loss. In the first graphic, we obtain the results with the divisor implemented by using a substrate of PTFE. In the second one, it is possible to analyze the case when the system is built with a fiberglass material. Fig. 3 depicts the results when we implement the mixed structure. The output response of the Wilkinson device combiner using a PTFE plate, offers 3.028 dB of attenuation at the central frequency, while the output response using a Fiberglass plate offers 3.28 dB attenuation at the same frequency. We can observe a performance very close to the PTFE material (the first graphical analysis), although in this last case we have a very small cost.

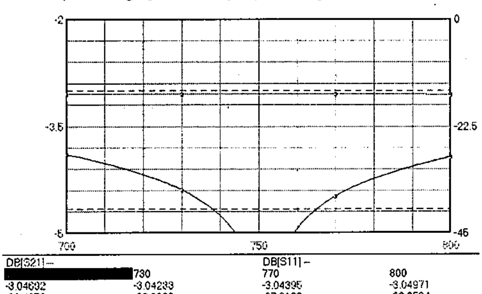

Fig. 3. Output frequency response of Wilkinson combiner using mixed fiberglass-air dielectric with 3.08 dB attenuation at 750 MHz.

ELECTROMAGNETIC CHARACTERISTICS OF DOUBLY-PERIODIC MAGNETODIELECTRIC LAYER BOUNDED BY TWO UNIFORM MEDIA

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The problem of electromagnetic wave propagation in a doubly-periodic magnetodielectric layer bounded by two uniform infinite media is solved by new method based on the rigorous volume integro-differential equations of electromagnetics (V.V.Yachin and N.V.Ryazantseva, Microwave and optical technology letters, 23, No.3, 1263, 1999).

The Galerkin method is applied to reduce these equations to a set of second-order differential ones with constant coefficients in field functionals. The functionals contain information about geometry of the scattering structure. In the paper we also introduce the new scheme of solving differential equations for thick doubly-periodic layers to overcome usual numerical difficulties associated with the undesired exponential functions in the expressions for field components. The solution is stable for very thick layer.

This method unifies the treatment of both perpendicular (TE) and parallel TM polarization by replacing ε by μ, μ by ε, E-components by H-components, H-components by E-components. The constituents of the magnetodielectric structure can approximate the structure made from perfect metal if the conditions $|\varepsilon| \to \infty$, $\varepsilon\mu = const$ are satisfied. Applying this approach to the medium behind the doubly-periodic layer we can consider the layer as a substrate having features of a photonic crystal for microstrip structure.

Waves guided by the doubly-periodic structure a appear to be characteristic solution of the boundary-value problem in the absence of an incident wave and can be found from nontrivial solutions of this problem. A rigorous analysis of wave guidance by magnetodielectric doubly-periodic layer is presented for arbitrary azimuth orientation of the guided waves which can be found with the well-known Muller's method.

The investigations were restricted to the case of a single periodic layer. However, the analysis can be easily extended to the multilayered structures. Numerical results agree well with previously published results. To illustrate the application of this approach, quantitative results are presented for the scattering and guiding of electromagnetic waves by various magnetodielectric periodic layers.

Analysis of the E-plane Metal Strip on a Dielectric Slab in Rectangular waveguides

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Abstract - An E-plane metal strip on a dielectric slab inside a rectangular waveguide may be used as a bandpass filter (called a finline filter) in the millimeter wave band. The height of the slab is equal to the narrow side of the waveguide and dielectric is assumed homogeneous and lossless. This configuration may not be treated by the method of (Q.Zhang and T.Itoh, MTT, 35, 138-150, 1987), where the finline does not completely fill the waveguide height.

The least square boundary residual method (LSBRM) is applied for the solution of the fin line, where the waveguide is divided into four regions: the input and output dielectric slab loaded waveguide (DSLW), the middle partially filled waveguide (PFW) and the middle empty waveguide (see fig.1).

The fields inside the four waveguides are expressed as their modal expansions. The eigenvalues (or equivalently the cut-off wavelengths and propagation constants) of DSLW and PFW are determined by the solution of appropriate transcendental equiations by the method of least squares. The eigenvalues depend on the location, thickness and dielectric properties of the slab (C.Cheh Yu and T.H.Chu, MTT, 38, 1333-1338, 1990) and (Z.J.Csendes and R.Silvester, MTT, 18, 1124-1131, 1970). Then, the boundary conditions as the continuity of the tangential electric and magnetic fields on the interface between the regions are imposed to construct an error function (boundary residual) in the least mean square sense.

A weighting function balances the contribution of the electric and magnetic terms in the error function. The minimization of the error function with respect to the amplitudes of the modes, eventually leads to an equivalent circuit of the fin line discontinuity. The satisfaction of boundary conditions are demonstrated by several diagrams and the discontinuity equivalent susceptances are computed as a function of various parameters. The results compare well with those data available in the literature (K.Chang and P.J.Khan, MTT, 24, 611-615, 1976) and (M.L.Riabi , M.Ahmadpanah, H.Benzina, H.Baudrand and V.Fouad Hanna, IEE Proc. Microwave Antennas Propag., 142, 364-368, 1995).

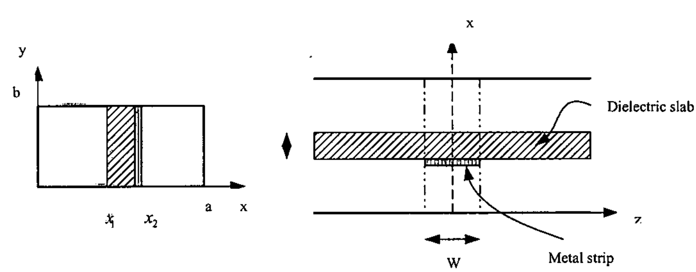


Fig.1 Geometrical configuration of E-plane metal strip on a dielectric slab in a rectangular waveguide

Special Session

Medical Applications of Electromagnetics

Organizer(s): *M. A. Stuchly, University of Victoria, Canada*
G. Lazzi, North Carolina State University, USA

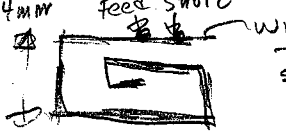
Co-Chairs: *M. A. Stuchly, University of Victoria, Canada*
G. Lazzi, North Carolina State University, USA

35.10 4:40 RF Hyperthermia: Modeling and Clinical Systems .... AP
W. Wlodarczyk, P. Wust, M. Seebass, J. Gellermann, J. Nadobny, Charite Medical School, Humboldt University, Germany

35.11 5:00 Applications of Microwave Imaging to Three-Dimensional Biological Tissues .... AP
Z. Q. Zhang, Q. Liu, Duke University, USA

Microstrip

Two shapes: Spiral and Serpentine



serpentine:

Substrate for biocompatibility
teflon 2.1 Macor 6.0 Alumina 9.6) brittle

Superstrate: Silicon and Silicon with drilled holes to get body fluid in fill

A Biocompatible Antenna for Communication with Implantable Medical Devices

Concave

Cynthia Furse*, Ruby Mohan*, Arvind Jakayar*, Sriram Kharidehal*, Brad McCleod**, Shawn Going**, Lance Griffiths*, Pichitpong Soontornpipit*, Daniel Flamm*, James Bailey*, Irwan Hadi Budiman*, Mark Hullinger**

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Abstract

Numerous medical devices are implanted in the body such as pacemakers and defibrillators, hormone and drug delivery pumps, and nerve stimulators. With the advancement and miniaturization of bio-electronics it is likely that the array of implantable medical devices will continue to expand in the years to come. Medical implants are intended to stay in the body for many years or decades, and it is often necessary to communicate with the device to download data about the health of the device or its batteries or the health of the patient, or to upload changes in settings or new procedures specified by the doctor. It is even conceivable that the patient could control the setting of his or her medical implant with the touch of a button from a wireless device or that medical data from the patient could be automatically transferred to the hospital over a wired or wireless telephone link.

The design of antennas that can communicate with implantable devices is an interesting and challenging problem. The antenna must be small, low profile and long-term biocompatible, preferably able to be mounted on existing implant hardware or to utilize part of the hardware itself. In previous work, we demonstrated the usefulness of a spiral microstrip antenna that can be mounted flush on the battery pack of a medical device. This paper describes improvements to this design and the use of biocompatible materials for the antenna for long-term implantation in the body. The antennas will be mounted in the chest or hip cavity on the titanium battery pack of the medical implant, which is approximately 1.25x1.25x0.375" in size. This box acts as the ground plane for the microstrip antenna and is in direct contact with the body. Several commercial plastics and silicones are compared for use in the antenna design, as well as an analysis of adhesives for longterm use and the use of titaniums for antenna designs. The antennas are simulated using FDTD software for a realistically implanted case. The input impedance, radiation pattern, gain, and SAR distribution are analyzed, and the antenna design is optimized using genetic algorithms. Prototyping and testing of these designs in homogeneous phantom material is presently underway.

used XFTD

Preliminary designs of the overall communication system are also given. The new medical implant frequency band of 402-405 MHz is used, and commercially available transceiver modules are evaluated for their usefulness in this design. Two types of systems are considered, one that directly transmits data from internal to the body to a receiver 10 meters away, and another that transmits data from the interior to the surface of the body, with an additional transmitter sending data to the receiver 10 meters away. The second type of system is shown to be effective with present technology, and technological advances required to make the first system functional are discussed.

C: Huynh,

Three-Dimensional Microwave Imaging via Space-Time Beamforming for Breast Cancer Detection

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Motivated by the critical need for complementary/alternative modalities to X-ray mammography for early stage breast cancer detection, we have recently proposed a method of microwave imaging via space-time (MIST) beamforming for detecting backscattered energy from small malignant breast tumors. In our MIST approach each antenna in an array sequentially transmits an ultrawideband microwave pulse into the breast and receives the backscatter. Robust space-time beamforming algorithms are applied to the recorded backscatter signals to provide a reconstructed image showing backscattered energy as a function of location. In our previous investigations we demonstrated the performance of the MIST technique by applying 2-D space-time beamformer designs to simulated backscatter data obtained from anatomically realistic FDTD breast models. In this paper, we present our preliminary experimental investigations of a 3-D beamformer design using simple breast phantoms.

For this initial testing stage the breast phantom is composed of a tank filled with a liquid simulating the dielectric properties of normal breast tissue and a small suspended synthetic tumor immersed in the liquid. A specially designed ultrawideband antenna is sequentially repositioned using a mechanical x-y scanner to virtually synthesize an antenna array placed above the breast phantom. The antenna is connected to a commercial vector network analyzer (VNA) to transmit and receive microwave energy. At each antenna location in the synthetic array, a frequency sweep is performed over a wide band of frequencies (0.05 GHz to 20 GHz). The frequency-domain backscattered signals are transformed to synthesize ultra-short time-domain pulses. After obtaining the backscattered waveforms at all antenna locations, the recorded signals are time-shifted, passed through a bank of finite-impulse filters, and summed to produce the beamformer output at a specific candidate location in the breast phantom. The beamformer output is time gated and then the energy is calculated and displayed as a function of location.

Performance of the 3-D MIST beamformer approach to detecting small malignant lesions is demonstrated by successfully imaging backscattered energy for a variety of breast phantom scenarios, such as different tumor sizes, shapes and locations, and variations in the dielectric properties of the tissue simulants. Our results suggest that microwave imaging via space-time beamforming offers the potential of detecting small breast tumors using state-of-the-art but readily available hardware and robust signal processing algorithms.

MEMS Devices and Their Application in Antenna Systems

Co-Chairs: *L. Shafai, University of Manitoba, Canada*
R. N. Simons, NASA Glenn Research Center, USA

NEW MEMS SWITCH STRUCTURES FOR ANTENNA APPLICATIONS

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MEMS devices have proven their usefulness in sensors, micromachines, and control components and now are candidates to take their place in the world of microwave applications with their reduced cost, improved performance, and miniaturized dimensions feasible for batch fabrication. MEMS components seem to take the place of off-chip components in wireless communications as well as they are used in signal routing, phase-shifting, time-delaying in phased array radar and antenna applications in microwave systems.

Over the RF MEMS components designed, switches have an important role since they are not only used as discrete components, but also used as a part of other components, such as phase-shifters. RF MEMS switches are superior to their rivals, pin diodes, in terms of performance. RF MEMS switches have lower power dissipation and loss, higher on/off impedance ratio and isolation, wider band of operation frequency.

Figure of merits in MEMS switch design are on/off capacitance ratio, actuation voltage, and switching time. Current efforts are on reducing the actuation voltage, switching time, and area of the switches. There are two ways to reduce the actuation voltage of a switch: reducing the spring constant of the structure and increasing the capacitance area, which is the source of the electrostatic force. The former increases release time of the switch significantly, while the latter increases the total area which can not be undertaken when large number of switches are considered. Therefore, there is a trade-off between actuation voltage and the switching time.

In this paper, we present two new, compact switches. The first design is shunt switch, which has a single post on the signal line of coplanar waveguide (CPW) and two cantilevers suspended over the ground planes on each side. The structure can be visualized as two single-post cantilevers whose backsides are attached to each other. This structure has the advantage of having two times the on-state capacitance at the same length; two cantilevers form two capacitances in parallel between signal line and ground planes. Also, the actuation voltage is given from the signal line, so actuating an array of these switches is easy. This is important considering phase shifter and antenna array where a number of switches must be activated with the same DC bias voltage. Another fact that makes this "T-Wing" design practicable is its small total area. This is because "T-Wing" switch uses the ground planes of CPW which are always present in large areas. "T-Wing" does not need any external actuation pads. Since its post is placed on the signal line on the CPW, its cantilever length can be extended to increase the area of actuation. Hence decreases actuation voltage, without increasing total layout area.

The second design is a cantilever type series switch which resides only on the signal line of a CPW. The post of the cantilever is on the input side. The input is physically disconnected from output when the switch is in off state. When DC bias is applied, the cantilever connected to input attracts the output signal line and collapses over the output line, so the input is connected RF-vice to the output. This switch is designed for discrete phase shifters and reconfigurable antennas. Actuation voltage is around 100V, but since DC power dissipation is zero, it is easy to supply that voltage by means of a DC-to-DC converter. This structure is designed to be used in applications that require large number of switches. The small area of the this design decreases the total layout area and its easy DC biasing from signal line makes the DC signal routing easy. The small dimensions yields a high spring constant, and hence a small switching time.

Fabrication process of the devices is started and will be followed by the measurements. The results will be presented at the conference.

X/Ku-BAND MEMS CAPACITIVE SWITCHES

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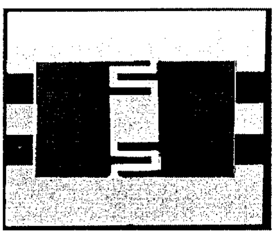
This Paper presents the design, simulation and fabrication of a single-bridge capacitive switch and a double-bridge capacitive switch of X/Ku-band with low loss and high isolation (Fig.1). The switching element consists of a thin metallic membrane, which has two states, actuated and unactuated, depending on the applied bias voltage between the metallic membrane and the bottom electrode. The switch employs serpentine folded hinge that results in a high inductance of 35pH and LC resonant frequency of 10 GHz, thereby ensures a high-isolation at X/Ku band. Figure 2 shows that the single-bridge switch achieves over 20 dB isolation at X/Ku band with an insertion loss of 0.2 ± 0.15 dB. The isolation is 37dB at 10GHz. The double-bridge switch provides an isolation of more than 50 dB at 10 GHz with an insertion loss of 0.6 dB. Besides, the spring constant of serpentine folded hinge is very small and only 3.6-volt pull-down voltage is required. The fabrication process combines bulk micromachining techniques and surface micromachining techniques. The thermal dioxide layer (buffer layer) is pattered to make it discontinuous so as to lower the attenuation loss.



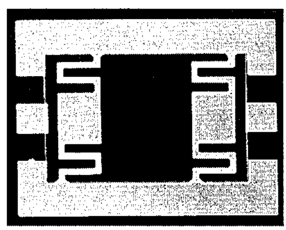
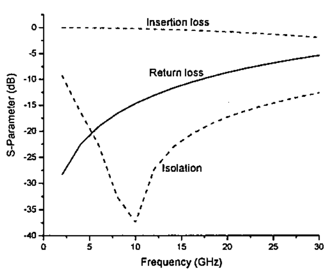
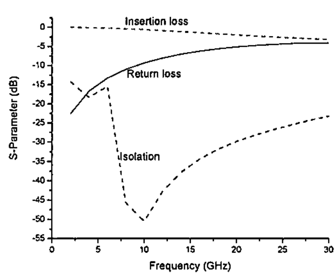


Fig.1 SEM Microphotograph of a single-bridge switch and a double-bridge switch;



(a)



(b)

Fig. 2 Simulated S-parameters of MEMS capacitive switches with (a) single bridge and (b) double bridges

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HIGH PERFORMANCE OF TUNABLE CAPACITOR USING SOI TECHNOLOGY

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Tunable capacitors, or varactors, are widely used in RF communications applications for low-noise parametric amplifiers, harmonic frequency generators, and frequency controllers such as voltage-controlled oscillators (VCO). Several figures of merit used in association with tunable capacitors include unbiased base capacitance, tuning ratio, equivalent series resistance or quality factor associated inductance or electrical self-resonance, and device linearity in response to RF power.

Recent efforts within the MEMS field [A. Dec and K. Suyama, *Electronics Letters*, 33, 922-924, 1997] have shown promising results in the realization of a MEMS-based high performance tunable capacitor. These devices were made of parallel metal plates, and the capacitance tuning functionality was achieved by adjusting physical dimensions of the device and the spacing between the parallel plates via electrostatic means. The MEMS tunable capacitors can be classified into two categories based on their tuning schemes—gap tuning and area tuning, referring to dimensional parameters that are being altered to achieve the tuning functionality. The tuning range of gap tuning capacitor, with a theoretical limit of 50%, however, requires further improvement for many RF applications. Area tuning capacitor using the interdigital comb do not have the tuning-range limitation in theory, should be a good candidate in RF applications.

The objective of the paper presented here is to develop and demonstrate a MEMS silicon-based tunable capacitor for RF communications applications. The tunable capacitor is made of single crystal silicon based on silicon-on-insulator (SOI) technology, and that has a continuous tuning range in excess of 300%. The tuning capacitance of comb structure is dependent on the length, width, and the thickness of the support beam, the thickness, the finger number, the gap, and the initial overlap distance of the comb structure, and especially on the square of applied voltage, as shown in Figures 1 and 2. Thus, a tradeoff has to be carried to optimize the whole system.

When tunable capacitor is actuated, tuning capacitance will affect both the isolation and return loss. The return loss improves as the frequency increases and at the same time, a larger tuning capacitance will contribute to a higher return loss. Thus, a coating of aluminum sputtered on after the structural release is necessary to improve the conductivity and to reduce the equivalent series resistance, and therefore improve RF performance of tunable capacitor in the fabrication of the SOI-based tunable capacitor.

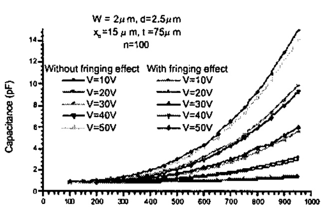

Fig. 1 Capacitance versus beam length and voltage.

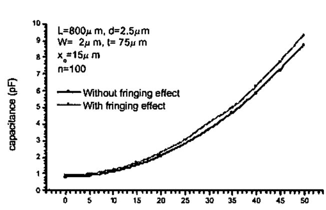

Fig. 2 Capacitance versus applied voltage.

Computational Methods for Time Domain Analysis

Co-Chairs: *B. Shanker, Iowa State University, USA*
D. S. Weile, University of Delaware, USA

Excitation of Sub-structure Resonances Using a T-pulse

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Abstract

The time domain combined electric- and magnetic-field integral equations (CFIE) provides a direct way of computing stable transient responses from structures that have an internal resonance. When applying time-domain CFIE model, almost all researchers use Gaussian pulse as incident wave. It is effectively time and band limited and is well suited to numerical computation. It has a rapid decay to a negligible value in both time and frequency domains. However. To excite a substructure resonance we need to have a narrowband pulse of strictly finite duration and not a modulated Gaussian pulse. In this paper we use a modulated T-pulse as the incident wave. A T-pulse is a transient pulse of finite duration but whose energy is concentrated in a given bandwidth. It is also orthogonal to its shifted versions and thereby minimizing inter-symbol interferences. Using optimization methods, both the non-zero-mean and zero-mean T-pulse are developed. This transient bandlimited pulses are now used for exciting and identifying sub structure resonances. We modulate a T-pulse and focus its energy in the desired bandwidth and use it to illuminate an object that has a sub-structure using time-domain combined electric-field and magnetic-field integral equation (CFIE) method.

The goal of this paper is to demonstrate that this modulated T-pulse will excite the substructure resonance without exciting the entire structure. If the entire structure is excited by a broadband pulse, the resonance from the sub-structure will be overwhelmed by the resonance from the entire structure. Hence, it is necessary to excite the entire structure with a transient narrowband pulse which will only excite the substructure resonance. Numerical results will be presented to illustrate the applicability of this methodology to illustrate that only substructure resonances have been excited.

Optimally Windowed Quasi-Planar Plane Wave Time Domain Kernels

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The recently developed plane wave time domain (PWTD) scheme (A. A. Ergin, B. Shanker, and E. Michielssen, *Journal of Computational Physics*, vol. 146, no. 1, pp. 157-180, 1998) permits the fast evaluation of transient electromagnetic fields radiated by surface-bound sources with N_s and N_t temporal and spatial degrees of freedom in $O(N_t N_s \log N_s)$ operations. This scheme has proven useful in accelerating the solution of time domain integral equations and in the construction of fast boundary kernels for finite difference time domain solvers. Like its frequency domain counterpart, viz., the fast multipole algorithm, the PWTD scheme subdivides the source support into smaller entities. It then proceeds by classically evaluating all interactions between sources that reside in each other's immediate vicinity. However, interactions between sources that are far removed from one another are accounted for through plane wave expansions that describe the source's far-field radiation pattern over a solid angle of 4π.

Because PWTD algorithms apply to arbitrarily shaped scatterers, they are suboptimal when applied to quasi-planar source distributions, viz. sources residing on surfaces whose transverse dimensions far exceed their height (rough surfaces, microstrip antennas on a finite ground plane, etc.). Indeed, it was recently demonstrated that, for quasi-planar source distributions, the cost of PWTD schemes can be reduced significantly by windowing the plane wave translation function, that is, by only retaining plane waves in a narrow cone straddling the transverse plane (E. Michielssen, A. Boag, and B. Shanker, *Proceedings of the National Radio Science Meeting*, pp. 89, Boulder, Jan. 2002). In that work, windows were constructed through entirely numerical means. Here, a scheme for constructing these windows as superpositions of doubly orthogonal concentrated polynomials (E. A. Gilbert and D. Slepian, *SIAM J. Math. Anal.*, vol.8, no.2, pp.290-319, 1977) is presented. These functions are the polynomial equivalents of prolate spheroidal wave functions and can likewise be constructed through the solution of an eigenvalue problem. Optimal windows are constructed by linearly combining highly concentrated eigenfunctions subject to the condition that the windowed interaction signals are identical to those produced by the original PWTD scheme. It is demonstrated that, while it is impossible to construct a single window function for sources with baseband temporal signatures, high quality windows can be constructed for modulated sources. Therefore, the algorithm is applied to the construction of a set of windows, each covering a given frequency band. Fields due to sources with baseband signatures are then reconstructed by representing the source signatures in a multiresolution basis.

The usefulness of the new PWTD scheme in the analysis of transient scattering from perfect electrically conducting rough surfaces will be demonstrated.

Tuesday AM AP/URSI B Session 42 Regency East 3

Special Session

Wavelets in Electromagnetics

Organizer(s): *E. Tentzeris, Georgia Institute of Technology, USA*

Co-Chairs: *E. Tentzeris, Georgia Institute of Technology, USA*
T. Sarkar, Syracuse University, USA

USE OF LINEAR PHASE FILTERS IN COMPRESSION OF IMPEDENCE MATRICES WITH WAVELETS

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ABSTRACT

In the compression of matrices by wavelets it is generally assumed that the higher the number of derivatives of the filter response is zero at the origin the better is the compression. This principle was used by Daubechies to generate the finite impulse response filters with the prescribed quadrature mirror filter property. However, the problem is that the phase response of the Daubechies filter is not linear. From a systems point of view it is known that devices with linear phase response has the least distortion and the electrical properties of such a system is always better irrespective in terms of the usual metrics used to evaluate the performance index. Hence, in this paper the thought process is suppose we take the magnitude response same as that of the Daubachies filters but replace the nonlinear phase response with a linear phase, then the question is will such a filter will be able to compress matrices better than the conventional Daubechies filters. It turns out that indeed that is the case and that better compression is achieved in general with filters that have a linear phase response than the ones without. It has been our experience that the requirement of linearity of the phase is one of the most important parameters of interest than any other criteria. Numerical results will be presented to illustrate the applicability of this technique and how it performs on compressing dense complex matrices that arise in the solution of integral equations in the method of moments context.

Review and Comparison of Absorbing Boundary Conditions for Multiresolution Time-Domain (MRTD) Schemes

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Abstract

The current drawbacks of most commercially available microwave and millimeter wave front-ends, such as the Ku-band satellite transceivers for outdoor units, are their relatively large size, heavy weight primarily caused by discrete components such as the filters, and separately located modules. Multi-layer ceramic and organic-based System-on-Package (SOP) implementations are capable of overcoming this limitation by integrating components as part of the module package that would have otherwise been acquired in discrete form. The optimization of SOP structures requires the effective modeling of complex structures that involve mechanical motion and wave propagation. Due to computational constraints, most commercial simulators utilize various approximations in order to provide fast and relatively accurate results. The drawback of these approaches is that transient and non-linear phenomena are not modeled effectively, leading to the degradation of system-level performance. Alternatively, full-wave techniques provide higher accuracy but suffer from excessive execution time requirements, thus making their efficient numerical implementation very critical. Lately, the MRTD technique has provided a mathematically correct way to implement time and space-adaptive grid, as well as to significantly decrease execution time and memory requirements. In this paper, the PML and the C-COM absorbing boundary conditions are applied to MRTD with arbitrary wavelet resolutions, and their performance is evaluated in terms of the numerical reflection coefficient and their dynamic range in frequencies. These ABC's coupled with the near-to-far field transformation and the numerical implementation of finite loss are then used for the modeling of compact packaging adaptive antennas and LTCC embedded inductors with high values of quality factor and inductance. Various conductivity profiles and number of ABC cells are investigated, and easy-to-use rules are derived for practical designs.

Parallel Implementation of Three-Dimensional Biorthogonal MRTD

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The finite-difference time-domain (FDTD) method has been widely used in many fields of computational electromagnetics, since it can easily address complex geometric features and inhomogeneous materials. Furthermore, a wideband frequency response can be obtained in just one computation. One of the main disadvantages of the conventional FDTD is that it has a poor numerical-dispersion property. That implies high spatial samplings per wavelength are required, especially for electrically large problems. To this end, biorthogonal Multi-Resolution Time Domain (MRTD) method has been demonstrated to provide a good solution to deal with the limitation of numerical dispersion. Thus larger problems can be considered with the same computer resource without sacrificing accuracy. To further harness the maximum power from presently available computer resource, the Message Passing Interface (MPI) protocol can also be employed so that much bigger problems can be accommodated. This is the main objective of this paper. We will show how the three-dimensional (3-D) biorthogonal MRTD algorithm will be parallel implemented by using just a few basic MPI commands. The division of the computational domain is implemented by creating a 3-D Cartesian topology. Implementations of the connecting surface, Huygens' surface, near-to-far-field transform, as well as the perfectly matched layer (PML) will be described in detail. Efficient communications between the neighboring processors are also presented. Numerical results have shown that the parallel 3-D biorthogonal MRTD could be an efficient, reliable, and promising method for solving electrically large scale, homogeneous, or inhomogeneous problems.

MRTD Simulation of a GPR in the Presence of a Rough Interface

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The ground-penetrating radar (GPR) response scattered from a realistic rough air-soil surface is efficiently modeled by using a three-dimensional multi-resolution time domain (MRTD) analysis. The rough ground surface is modeled as a three dimensional randomly rough surface considering, for example, with a Guassian correlation function and height distribution. We also consider fractal surfaces. The delay and amplitude characteristics of ground-induced scattered waves are analyzed to quantify the clutter variation with ground roughness. Simulations are performed for many surface realizations, with and without a target (land mine) to generate statistics for the clutter and target signal. The response of target can be enhanced and the clutter response suppressed using signal processing. Thus, the buried small, low-contrast target response can be distinguished from the rough-surface response. It has been demonstrated that MRTD achieves higher accuracy without the need for the staircase approximation of the interface between the two media, as has been employed previously by FDTD method. At the same time, the MRTD method allows significant savings in the computational resources, due to its reduced numerical dispersion.

The example results are computed for an actual ground-penetrating radar (GPR) system, with which the computed results are compared to measurements. We also discuss the complexity of detecting small low-contrast targets (*e.g.* a plastic land mine) as a function of roughness, soil and target properties.

Numerical Analysis of MEMS- Based Variable Capacitors Using The Adaptive Body Fitted Grid Generation Method with Moving Boundaries

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Abstract

The accurate design of RF MEMS switches that can be used for phase shifting or reconfigurable tuners, require the computationally effective modeling of their transient and steady-state behaviors. The use of FDTD offers the advantage of multifrequency analysis with a single run in time-domain, but suffers of loss of accuracy due to the necessity of grid-positioning of time dependent moving boundaries.

In this paper, we propose a new numerical approach to analyze MEMS devices using body fitted grid generation method with moving boundaries. This technique is based on the finite-difference time-domain (FD-TD) method with an adaptive implementation of grid generation. The key feature of this method is that the time factor is added to the conventional numerical grid generation. Employing this transformation, it is possible to apply the grid generation technique to the analysis of geometries with time-changing boundary conditions. With such a grid, the FD-TD method can be solved very easily using a time-invariant square grid (rectangular computational region) regardless of the shape and the motion of the physical region. As a benchmark, this new simulation technique is used for the analysis of a variable capacitor that consists of two moving parallel plates. The numerical results between the velocity of the plates and the capacitance are shown and the transient effect is accurately modeled. This technique can be easily generalized for the numerical simulation of RF MEMS structures (e.g.switches, capacitors) that involve motion in 1-, 2- and 3-dimensions.

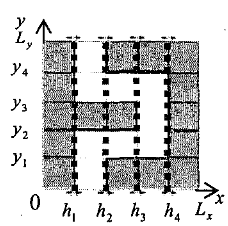

Fig1. Schematic of Capacitor

Mobile Channel Characterization: Models and Measurements

Co-Chairs: *C. Bostian, Virginia Polytechnic Institute and State University, USA*
P. S. Hall, University of Birmingham, UK

A Hybrid Technique for Physics-Based Characterization of Cosite Interference for an Ad-hoc Network of VHF Transceivers in a Multi-path Environment

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Mobile ad-hoc wireless networks are commonly used for military applications and, because of their simplicity, are also considered for a future generation of commercial wireless systems. A major drawback of ad-hoc networks is the issue of cosite interference, where in a transceiver-congested environment, leakage signals from nearby transmitters hamper the communication of each other with their distant counterparts. Depending on system specifications, cosite intereference can lead to effects that range from inter- or cross- modulation to complete densitization, that may render the whole communication link practically inactive. Since the establishment of reliable data transmission at reasonably limited bit-error rates constitutes a key-purpose for digital link design, the accurate estimation of physical layer-related factors that corrupt or block link operation, is motivated.

Despite the high interest that cosite interference problems present from both a research and an application point of view, only few efforts have been made towards their rigorous theoretical characterization. As a consequence of the close proximity of interferers and the presence of complex scatterers and antenna platforms, the straightforward calculation of interfering power levels is not possible. Therefore, some previous studies have relied on measurement-based models [Gavan and Shulman, IEEE VT-33, Nov. 94], that evidently omit the influence of system-specific parameters on communication link performance. On the other hand, time-domain methods such as FDTD and MRTD hold the promise of fully accounting not only for the effect of platforms on radiation properties of vehicular antennas, but also for the operation of front-end electronics, via a state-equation description of the latter [Kuo *et al.*, IEEE MTT-45, May 1997]. This approach has been recently adopted in [Sarris *et al.*, Proc. 2001 IEEE AP-S].

However, the computational cost of time-domain techniques grows large, when more complex operation environments are considered for cosite interference scenaria. An example of particular interest, is the case where communication between a receiver and a transmitter, under cosite interference conditions, is attempted within a forest environment at VHF frequencies. The electromagnetic phenomenology of this link has been efficiently characterized in [Sarabandi and Koh, IEEE AP-49, Feb. 2001], where a model including multiple scattering from tree trunks and the interaction of the resultant scattered field with lateral waves was presented. This paper proposes the hybrid solution of cosite interference scenaria within a forest, by modeling a multi-antenna, mobile communication system with a time-domain technique and its interaction with its forest environment by means of the Method of Moments (MoM) based approach of [Sarabandi and Koh, IEEE AP-49, Feb. 2001]. Emphasis is given on the case where multiple antennas on a platform are concurrenty on a receive-mode, while remote in-forest transmitters send data to them at the same time. Time domain waveforms extracted by Fourier transforming MoM data on a box enclosing the multi-antenna system, represent an excitation field for the FDTD/MRTD mesh. Subsequently, the operation of transceiver amplification and mixing stages is rigorously estimated. Thus, the complete characterization of cosite interference in the given system is attained.

This research has been supported by the U.S. Army CECOM through a CHSSI/HPCMO program under contract DAAD19-00-1-0173 and a DARPA FCS communication program under contract ARL-RFP S01-19.

A Millimeter-Wave Scaled Measurement System for Propagation Channel Characterization

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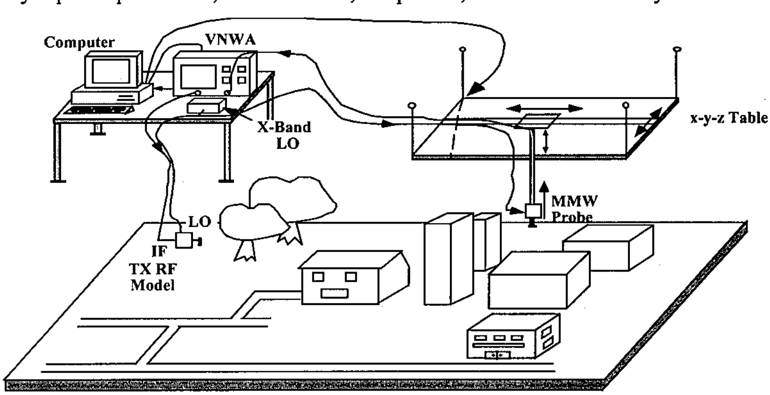
Successful implementation of novel mobile wireless networks with advanced modulation schemes and sophisticated signal processing algorithms depend heavily on the reliability of the association. Assessment of system performance under different scenarios environmental conditions is a crucial step before implementing such wireless systems. In this process the electromagnetic behavior of the propagation channel and its influence on the characteristics of the signal at the receiver must be investigated. Over the past two decades significant efforts have been devoted towards the development of simulation tools for propagation channel characterization. In general, these methods can be categorized into two groups: 1) empirical and statistical methods that are based on measurements, and 2) physics-based methods that are developed upon theoretical and numerical simulations of wave propagation for specific scenarios.

Reliable statistical models need a large set of measured data to extract the required parameters representing the channel characteristics. Also the accuracy of theoretical models need be evaluated using a complete set of signal and ground-truth data. Measurements in urban or suburban areas are both time consuming and expensive. To remedy this problem we considered developing a scale model that allows accurate measurements of well-defined channels in a laboratory environment. A millimeter wave scaled propagation measurement system (SPMS) is designed for this purpose. Confining the desired range of frequency to systems operating at UHF to L-Band (0.5-2 GHz), dimensions of the scatterers and terrain features in the scaled propagation channel can be reduced by a factor of 50-200 for the proposed SPMS that operates at around 100 GHz. The figure shows the main components of the University of Michigan W-band SPMS which includes: x-y-z probe positioner, scaled model, RF probes, and a network analyzer.



Wideband Propagation Channel Parameters Prediction for Wireless Local Loop System at Suburban Environment

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A new wideband propagation properties prediction method using Markov transition modeling for the wireless local loop systems is introduced. Our approach is to characterize multipath phenomena into different states and to describe the multipath intensity profile on each state using the modified near-far echoes model with parameters extracted from the measurement data. We obtain accurate predictions of wideband channel properties in several typical mobile user environments. A close match between simulated and measured data shows that the proposed wideband Markov transition model can be applied to predict the wideband channel parameters, such as mean delay and RMS delay spread.

In near-far echoes model, the received multipath intensity profile can be classified as one of the three components: direct path, near echoes and far echoes. The direct path contains three states: Clear, Shadowed and Blocked. The numbers of near echoes is Poisson distributed. The mean power of the near echoes is exponentially decreasing with delay τ_m. The number of far echoes is Poisson distributed, too. The delays of the far echoes are uniform distributed. We also add Rayleigh statistics in each delay tap for increasing the accuracy of modeling wideband channel parameters by more than 15%.

The Markov transition model is used to simulate the large-scale environmental changes when the mobile unit is in motion. We first separate the received impulse response into states and calculated the state transition probability matrix. For the purposes of simulation, twelve states were classified. There are one Ricean case and two shadowed cases according to the direct path power intensity and each case is further divided according to whether their multipath intensity profile has similar decay rate in the near echo region. In order to validate our proposed wideband propagation model, we compare the simulated wideband channel properties of mean delay and RMS delay spread with the measurement data in three selected measurement paths. The results are shown in Table 1. By using this proposed wideband propagation channel model with appropriate model parameters, we can predict the quality of services and performance of the wideband CDMA wireless local loop system that will soon be deployed at a research campus at Tao-Yung, Taiwan.

	P.D.F. RMS Error for Mean Excess Delay	P.D.F. RMS Error for RMS Delay
Path1	0.0786	0.0596
path2	0.0600	0.0341
Path3	0.0669	0.0367
Path1+Path2+Path3	0.0337	0.0167

Table1. RMS error of the P.D.F. between simulated and measured wideband channel parameters

Characterisation of the mobile radio channel at 2.4 GHz

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Abstract

A great amount of research effort has been devoted in the past to characterisation of the mobile radio channel. This is mainly because the time and spatial variability of the channel imposes performance limits on wireless communication systems. A thorough understanding of the channel can lead to suitable fading countermeasures such as equalization, diversity and interleaving to be designed to enhance the performance of such systems. However, most of the channel characterization conducted to date has focussed on collection of narrowband data suitable for second generation mobile systems like the Global System for Mobile Communication (GSM) with the field strength being the main parameter at frequencies below 1 GHz. While this work provided researchers with a general knowledge of the channel, the results do not provide enough detail for future wideband mobile systems designed to operate at frequencies above 2 GHz. Future systems such as IMT-2000, are likely to be deployed in microcells and picocells where the propagation is affected by the local features in the environments. In such environments, it is important to understand the dominant propagation mechanisms to improve the radio planning. This requires the channel to be sampled in greater detail than before to provide the enough information to 're-create' the propagation phenomenon via direction of arrival (DOA), direction of departure (DOD) and time of arrival (TOA) analysis.

In this paper the configuration and performance of a wideband vector network analyser is presented. For this work, the sounder has been modified to include a 100m optical fibre link to remote the transmitting antenna and two receive channel have been used to enable two channels to be sampled simultaneously thus making the system suitable for diversity measurements (figure 1). The use of the fibre optic link and the availability of a single frequency reference in the VNA increases the phase stability hence increasing the accuracy of the DOA and DOD measurements. The sounder has been used in an extensive measurement campaign to collect wideband data in both outdoor and outdoor-indoor environments at 2.4 GHz which is very close to the allocated frequency bands for IMT-2000. Sample results are then presented to highlight the variability of the channel in these two scenarios, identify dominant propagation mechanisms and demonstrate the benefits of both spatial and polarization diversity in wideband systems.

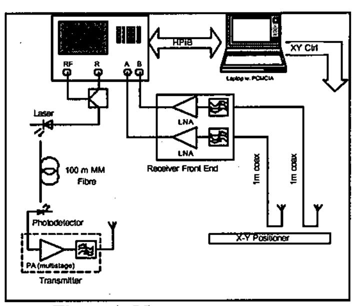

Figure 1: Measurement system

Optimization of Propagation Models based on Locally Measured Data for Mobile Communications and their Performance Comparisons with Existing Models

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Well defined propagation models are very important in the cell planning of base stations, which potentially optimizes the utilization of electromagnetic energy, minimizes the number of base stations and maximizes the overall system capacity. Many empirical propagation models including free space, Okumura-Hata, Lee and Ericsson 9999 models are widely employed in the predictions of path loss in the wireless communications due to wave propagation in complex environments.

Applications of empirical models highly depend on the similarity between the environment to be analyzed and the environment where the models are established. In realistic applications, modification on the coefficients of empirical formulations is generally required to have better performance since the terrain geometrical characteristics varies from regions. Even though most of the propagation models optimize their models in terms of global characteristics of terrain profiles such as the characteristics of dense urban, urban, suburban, rural areas and so on. However, with different regions of suburban, for example, the path loss predicted by these standard propagation models can result in large deviation of more than 10dB in various regions. It is therefore very desirable to tune the propagation models based on local characteristics of terrain geometrical profiles.

This study is a similar effort that intends to optimize the propagation models based on the locally measured characteristic data. In distinguishing from previous works that employed a single one of the standard propagation models, and adjusted the coefficients based on the globally intensive experimental measurements, the presented work integrates the propagation models mentioned above and comes out a more general form for the optimization of propagation model. This general form provides more complete considerations of propagation path loss due to various geometrical factors, and will reduce to the original standard propagation models while associated coefficients are appropriately given. Furthermore, the present study localizes the validity of the propagation model into local areas, and for different areas of interest different set of unknown coefficients is obtained independently.

The paper presents a part of series studies on the propagation models that will be established for the applications of mobile communications in the Taiwan based on measurement data. The studies divide the island into small but characterized areas, and intend to establish a database of propagation models that are modified from the integrated general form of propagation model based on the locally measured geometrical characteristics. The process is particularly suitable to be employed in a small region like Taiwan, and needs to be carried out only once for many wireless applications. The models will be employed for future improvement of cell planning for mobile communications. Primarily results of model optimization and their performance improvement in comparison with existing models will be presented in terms of coverage and interference via an integration into a cell planning tool.

Special Session

Dielectric Measurements and Sensors

Organizer(s): *O. M. Ramahi, University of Maryland, USA*
S. Trabelsi, U.S. Department of Agriculture, USA

Co-Chairs: *S. Trabelsi, U. S. Department of Agriculture, USA*
O. M. Ramahi, University of Maryland, USA

Dielectric Sensor and Automated Turn-key System for Material Evaluation

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This paper presents a review of dielectric sensor development and measurement techniques for testing and evaluation of materials in view of the current interest in various RF, microwave and millimeter wave wireless systems. Selection of materials for the design of a sensor is very critical and that depends on many operating parameters. Failure of a sensor can be catastrophic in terms of readiness, personnel, and scheduled replacement can be very expensive if the life of the sensor has not been realized especially for space and airborne applications. In addition, this review also presents the state-of-the art of automated turn-key system with a view to future applications in testing and evaluation of dielectric materials, polymer and ceramic thin and thick films, and composite absorbers, which may find applications in sensor design as well as stealth technology. Particular emphasis is placed on the fact that for tuning the desired material properties, evaluation of its composites at each level during the fabrication is important and it may required to be done in solid, liquid and powder form such that the material processing and control have to be adapted for automated measurements. This reduces the need for lengthy and expensive development by trial and error, which is particularly time-consuming for radar absorber design and FSS.

MICROWAVE DIELECTRIC METHODS FOR SENSING PHYSICAL PROPERTIES OF GRANULAR MATERIALS

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Knowledge of the physical properties of granular materials is important in many industries including food and agriculture, pharmaceutical, chemical, and mining. They are often used in quality control as well as process monitoring and control. Therefore, they need to be determined reliably and in real time to meet requirements and standards of highly automated industries. Dielectric-based sensors can provide an adequate solution for such challenges. Unlike traditional measurement methods that necessitate off-line testing of samples requiring some time, dielectric-based sensors rely on indirect determination of the desired property from measurement of the dielectric properties characterizing the electromagnetic wave/material interaction. These sensors can be used for continuous, nondestructive assessment of the physical properties of all the processed material.

The dielectric properties of granular materials such as cereal grain and seed are known to be dependent upon frequency, temperature, bulk density, moisture content and composition. Therefore, they cannot be used directly to predict one or more physical properties without compensating for or eliminating the effects of the remaining factors influencing the measured dielectric properties. In this presentation, microwave dielectric methods are developed for simultaneous and independent determination of bulk density (ρ), moisture content (M), water partial bulk density (m_w/v) and dry matter partial bulk density (m_d/v). These methods are based on a complex-plane representation of the complex permittivity for bulk density determination (S. Trabelsi et al., Meas. Sci. Technol., 12, 2192-2197, 2001), an on permittivity calibration functions for moisture sensing independent of bulk density changes (S. Trabelsi and S. O. Nelson, Meas. Sci. Technol., 9, 570-578, 1998). Some new empirical relations are given for determining partial densities. Also the foundation of a universal algorithm that remains valid across moisture sensors of different designs is presented. Finally, incentives and challenges for implementation of these methods in the design of versatile and cost-effective microwave sensors are discussed.

Dielectrometry for Radiofrequency Exposure Assessment and Sensing

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Open-probe dielectrometry, in which a flat-ended open coaxial line, with or without a ground plane, is immersed in a material whose dielectric properties are to be measured, has proven very useful in measurements of the dielectric properties of biomaterials. One advantage of this technique is that it is minimally perturbing of the sample being measured, which is very important for the measurement of *in vivo* or *in-vitro* tissue samples. The technique is also capable of good accuracy when appropriate calibration techniques are used, and can be used to make measurements of small quantities of material. For application over a wide frequency range, in our system to 26.5GHz, it is important to calibrate with materials that are similar in dielectric properties to an unknown sample. It has the capability to distinguish small differences in dielectric properties and can be used for compositional assessment of mixtures, for example alcohol/water mixtures (Jian-Zhong Bao, Mays L. Swicord, and Christopher C. Davis, J Chem. Phys. 104, 4441-4450, 1995.)

A recent important application of the technique is in the measurement of tissues in the mammalian head, which provides complex dielectric data for inclusion in exposure assessment of humans exposed to electromagnetic fields, especially those emitted by hand-held wireless phones. In addition the technique has proved valuable in the development and quality assurance of dielectric test liquids for use in "phantom" models used for wireless phone exposure assessment. In this paper various of these issues will be discussed, especially the dielectric properties of bone, and the difficulty in measuring this reliably in an *in-vivo* state, and the reproducibility of the dielectric properties of "phantom" liquids.

INTEGRATED MICROSTRIP ANTENNA ARRAY DESIGN FOR FLOWING GRAIN MOISTURE CONTENT MEASUREMENT SYSTEM

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Moisture content is an important parameter of harvested grains that affects the quality and the price. Its measurement under flowing conditions is an important task that can be accomplished with excellent accuracy at microwave frequencies. This measurement creates the need for an integrated antenna system. Microstrip array antennas can be utilized for this purpose. This paper describes a circularly polarized microstrip array antenna system where the transmitting and the receiving antennas are on the opposite walls of the measurement apparatus facing each other. The grain flows through the intervening region.

Successful design requires input impedance measurements of a microstrip antenna element radiating into or receiving signals from the flowing grains. In the design, the transmitting and receiving antennas are interchangeable. This permits measurements with both right circular and left circular polarizations resulting in more accurate results through averaging.

Frequency Selective Metamaterial Surfaces as High-Impedance Ground Planes for Sensor Applications

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Electromagnetic properties of complex "artificial" materials, nowadays known as metamaterials, have been the subject of study by various research groups over the past several decades. These composite media can be conceptualized and modeled by embedding many small inclusions within an otherwise host medium. Macroscopic electromagnetic features of such bulk particulate media depend on various parameters such as the size, geometry and composition of the inclusions, the density, alignment, and arrangement of the inclusions, and EM properties of the host medium. The ability to select and assign specific values for each of these parameters would enable a designer to "engineer" metamaterials with exciting electromagnetic properties, not readily available in natural materials, but physically realizable. There are many potential applications for metamaterials due to possibility of customizing specific electromagnetic properties for these "artificial" materials. One of our ideas is to explore how metamaterial plates can provide high-impedance electromagnetic surfaces. It is well known that if a flat structure possesses high surface impedance, the reflection coefficient for a plane wave incident on this surface will attain a value around $R \cong +1$ (as opposed to the reflection coefficient of $R \cong -1$ for a conventional highly conductive surface.) This implies that such a surface may act as a "magnetic wall" in contrast to the conventional electric wall for which $R \cong -1$. These surfaces can obviously have interesting applications for the antenna and sensor designs.

In the present study, we have been interested in exploring certain general theorems and characteristics about the features of metamaterial surfaces placed closely above conducting ground planes. Our theoretical analysis shows that when a frequency-selective surface (FSS) is placed close to, and in parallel with, a conducting ground plane, at certain band of frequency this structure may possess high surface impedance at its top surface, and as a result may act as a high-impedance ground plane (HIGP). The size and geometry of the inclusions in the FSS are among the parameters that determine the center frequency and bandwidth over which such high-impedance electromagnetic surface is achieved.

In this talk, we will present the theoretical results of our analysis, will provide physical intuitions into the findings, will discuss potential applications of such metamaterial surfaces in sensor design, and will speculate the future directions in this area.

Spread Spectrum Communication Techniques Applied to Impedance Measurement

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Abstract

Spread spectrum communication methods such as direct sequence spread spectrum (DSS) and frequency hopped spread spectrum (FHSS) have greatly enhanced the ability of modern communication systems such as IS-95 CDMA to provide high quality service for a large number of simultaneous users, even in the presence of noise and multipath interference. For DSS the input digital data signal is "spread" over a wide frequency range by multiplying it with a psuedo-noise digital data code that has a much higher bit rate than the original digital signal. This new multiplied signal is then transmitted using a digital modulation scheme such as BPSK or QPSK. For FHSS, the same high bit rate pseudo noise code is used to change the carrier frequency throughout the signal transmission time. Both of these methods utilize the entire available bandwidth for a single user, and superimposed multiple users on this same bandwidth by giving them different pseudo noise codes. This "Code Division Multiple Access" (CDMA) has less sensitivity to narrowband noise and spurious signals received from multipath interference. This method has also been demonstrated (C.-H. Liu, et al, Proc. IEEE Int. Conf. on Robotics and Automation, May 21-26, 2001) for use superimposing digital data on a DC or low frequency power supply line for "smart motors" and related power control applications where digital data control lines are physically undesirable or susceptible to noise from the high power device that is being controlled. The noise immunity of CDMA is shown to be particularly important in this application.

This paper evaluates the feasibility of using spread spectrum CDMA methods for measurement and sensing applications. When CDMA methods demodulate the signal to retrieve the original information, they correlate the known PN code of the user with the CDMA signal to retrieve the information that was meant for that particular user while in effect rejecting the data from other users. In this case the PN code is known but the data is not. If, instead, we wish to find the travel time from a transmitter to a receiver, one could analyze the length of time between correlated signals in order to determine such properties as the length of a line, or its velocity of propagation and perhaps even its bulk impedance.

DSS CDMA has been simulated for the analysis of the length of a transmission line for analysis of an aging aircraft harness. If the length has changed from the value originally measured, then it is clear that a problem has developed, and the new length of the line identifies the location of the problem. The length versus correlation time of the PN sequence is nearly linear even when significant noise, digital data, or low frequency power are added to the line under test. This new method could enable the measurement of cable integrity even for an aircraft in flight.

Application of this method to generalized impedance measurement will also be discussed.

Microstrip Antennas for Measurements of Dielectric Properties and Moisture Content in Grain

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Recent work has shown that physical properties of grain including moisture content and bulk density can be determined from measurement of their dielectric properties (Trabelsi et al., *IEEE Trans. Instrum. Meas.*, 47, 1, 127-132, 1998). Complex permittivity measurements are typically performed using laboratory-based techniques. In this work, we propose to use a transmit-receive system using printed microstrip antennas. The system consists of a box made of a dielectric material with two microstrip antennas placed on two parallel walls. The frequency region under consideration is 4-6 GHz. The primary advantages of these printed antennas are their lightweight, low cost and the fact that they can be made conformable to widely used cylindrical structure for real-time, nondestructive sensing of physical properties of flowing grain. Design of a transmission type system showed that for effective transmission measurements and maximum sensitivity the feed and receive coordinates on the microstrip antennas play a critical role. In fact, and interestingly enough, the effectiveness of these microstrip antennas for dielectric measurements is directly proportional to their inherent narrow bandwidth. In this presentation, we will present preliminary measurements for grains of different structure and composition. We will also present numerical simulation results showing the dependence of the measurement scheme on the antenna topology and feed location. The numerical simulation is intended to aid in the design of measurement and test systems that can be fine-tuned to a specific material.

Special Session

Investigations of RF Coupling and Interference I

Organizer(s): *J. L. Volakis, University of Michigan, USA*
C. M. Butler, Clemson University, USA

Co-Chairs: *J. L. Volakis, University of Michigan, USA*
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Penetration through an Aperture Backed by a Channel --Integral Equation Formulation and Solution

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Penetration of line-source illumination through a slotted screen backed by a channel of specified cross-section is investigated. The channel may be of general cross-section and it may be filled with a material different from that on the illuminated side of the screen. Specific channel shapes, e.g., rectangular, semicircular, and semielliptical, are considered but the last is emphasized so that data may be compared with those from [D. Erricolo, K. A. Greenenwald, P. L. E. Uslenghi, this digest]. Both electric and magnetic line sources parallel to the slot and channel axes are treated. Different sets of integral equations are formulated for each structure and each set is solved numerically. The field scattered by this structure and that which penetrates the slot into the channel are computed by methods based upon the integral equations and their numerical solutions. In the case of the elliptic channel, data from this work are compared with those obtained from a method based upon Mathieu function expansions. Not only are the computed numerical results compared with those obtained from the canonical solution but, also, data for a given structure and excitation obtained from one integral equation are compared with those from a different integral equation, allowing one to infer the conditions under which the various integral equation methods are most accurate. In addition, when the channel is semicircular in shape, still another integral equation is formulated and solved to enable the investigators to compare data even more extensively. When the excitation is TM to the slot axis and the source is close to the slot, the penetrated field differs very little from that found when the ground plane is of finite but large extent. However, if the slot is very narrow, the penetrated field determined as if the structure (finite-width but large ground plane) were a scatterer is very, very inaccurate.

Design of An Expert System to Detect Electromagnetic Compatibility Problems in the Automobile

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Abstract

Significant time and effort is spent detecting electromagnetic compatibility problems and ensuring electromagnetic compliance in the automobile. Methods typically rely heavily on experimental measurements after a prototype has been built – a time consuming and expensive option that prevents solution to many problems. Better, less expensive vehicles could be produced if problems could be detected analytically early in the design process.

We are developing a system-level automotive EMC expert system to be used early in the design of a vehicle. This system is being designed to help the automotive engineer with radiation and immunity problems, crosstalk, placement of modules, component grounding, and EMC testing issues. Rather than rely on sophisticated numerical models, the expert system uses simplifying assumptions and approximations and will apply the same "rules of thumb" that a human expert would apply in a similar situation. Our experience with an expert system for printed circuit boards suggests this approach works well. It allows rapid and automatic analysis of an automotive design, determination of potential problem areas, identification of critical components and structures that may be causing problems, and application of simple guidelines toward solving those problems. The system is designed to help the human EMC expert focus his efforts on a few particular areas of concern rather than on the many possible problems that could occur within the automobile and to help the majority of automotive engineers who are not EMC experts build cars that are electromagnetically sound.

The top-level expert system architecture consists of three basic stages: a) an input stage that gathers information and prepares it for analysis, b) an evaluation stage which approximates radiated and coupled noise and tests for basic design rules of thumb, and c) an output stage which feeds results back to the user, identifies problems and responsible components or structures, and suggests methods to solve those problems. The input stage includes an expert-system algorithm to identify and classify circuits within the vehicle. The evaluation stage includes algorithms to determine resistive, inductive, and capacitive coupling between harnesses, to predict radiated emissions, to predict coupling from external fields, to predict power bus coupling, to predict harness resonances, and an algorithm to apply custom design rules developed by the local EMC expert.

EXACT RADIATION FROM AN ANTENNA ON A METAL POST AT THE INTERFACE BETWEEN ISOREFRACTIVE HALF-SPACES

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A perfectly conducting metallic post of prolate or oblate spheroidal shape is located at the planar interface between two isorefractive half-spaces. The axis of symmetry of the post is perpendicular to the interface, and the interface coincides with the equatorial plane of the spheroidal post. A rotationally symmetric antenna is located on the post axis and is axially oriented, so that the boundary-value problem is rotationally symmetric.

The radiation from the antenna in the presence of the PEC post and of the planar interface is solved exactly in terms of series of prolate or oblate spheroidal wave functions (see e.g., Flammer, *Spheroidal Wave Functions*, Stanford University Press, 1957; also: Bowman et al., *Electromagnetic and Acoustic Scattering by Simple Shapes,* Hemisphere Publishing Corp., 1987, chs. 11 and 13). This exact solution is possible because the propagation constant is the same in both isorefractive media, thus allowing for the explicit, analytical determination of the expansion coefficients in the series of spheroidal eigenfunctions, by mode-to-mode matching.

Numerical results are obtained for the surface current density on the PEC post, for the fields at the interface between the isorefractive media, and for the far fields radiated in both half-spaces. Field plots are shown for several values of the ratio of the intrinsic impedances of the two media and of the dimensions of the metal post, when the primary field is that of an electric or magnetic Hertz dipole.

The analysis performed is important for three reasons. First, it yields a new canonical solution for a boundary-value problem. Second, it provides a realistic model for a metal stick (thin prolate spheroid) or a metal disk (flat oblate spheroid) at the interface between two media. Third, it may be used as a test to validate computer codes by comparing the numerical results given by the codes to those provided by the canonical solution.

Design of a Three-Dimensional TEM cell for Radiated Power Measurements

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ABSTRACT

Several types of test facilities are used today to measure the emission, immunity or electromagnetic characteristics of electronic equipments and systems. They are mainly Open Area Test Sites, (semi-)anechoic chambers, mode stirred reverberating chambers and various types of TEM cells. In all the variants of multiple plate TEM cells, the coupling planes created by each plate in the center of the test volume are parallel to each other but have different polarizations. Therefore the three-dimensional characterization can only be obtained by rotating the device under test.

In order to measure spurious electromagnetic radiation from electronic circuits in the lower frequency region we generally use a TEM cell. The problem with a TEM cell is that unless the device is properly oriented in at least three orthogonal positions inside the cell, the results for the total radiated power may not be correct. This paper starts by presenting the general concepts of a 3D-TEM cell where one does not need to orient the device to have an estimate of the total power radiated from the device under test. We then present a practical industrial design of a 3D-TEM cell where the total radiated power of an electronic equipment is measured. The presentation will cover the design of the cell using a commercially available user friendly electromagnetic simulation tool called WIPL-D and show both theoretical and experimental results to indicate the accuracy of the design tools and the correct prediction of the radiated powers. Results would also be compared to those from a GTEM cell. Finally, the repeatability and reproducibility between TEM, GTEM and 3D-TEM cells is studied and discussed.

Transient Signals in Coupled Coaxial and Cylindrical Cavities

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The characteristics of the transmission path through a complex system influence the time history of a transient signal which makes its way along this path. If a signal of specified properties enters a system at a given point, what are its properties at some other location in the system where a susceptible circuit might be located? Are these properties primarily those peculiar to the entering signal or are they influenced significantly by the "system transfer function" of the transmission path? Complex systems might be difficult to model accurately but usually one can identify features common to most: guiding mechanisms, scattering, frequency-domain resonances, attenuation and reflection, and shielding. By investigating transmission paths which incorporate, in varying degrees and combinations, the features of a typical system, one can acquire an appreciation of the range of effects that transmission paths might exert on interfering signals. In this paper we attempt to address some of the above questions about the influence of typical transmission paths on the properties of signals by investigating signal transmission through simple cascaded coaxial and cylindrical cavities whose properties can be adjusted at will. The structures considered are ordinary cascaded coaxial and cylindrical cavities in various configurations.

Apertures common to adjacent cascaded cavities are identified and frequency-domain, coupled integral equations are formulated for the electric field in these apertures. The integral equations are solved numerically and one determines field components at points in the structure from knowledge of the aperture fields. For specified input signals, the time history of field components at points in the structure are determined from frequency-domain data and the FFT. Several different cavity configurations were constructed for measurement purposes. Data collected allows one to corroborate values of quantities of interest determined from computations. Computed and measured results are presented.

Effect of Delay Skew and Transition Time Differences on the Common-Mode Component of Differential Signals

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Differential signaling is widely employed for high-speed electronic communication. Differential data transmission schemes (e.g. Fibre channel, LVDS) take advantage of the greater noise immunity and reduced radiated emissions normally associated with differential signals. Theoretically, a perfectly balanced differential data interface consisting of a differential source, a balanced conductor pair (e.g. twisted wire pair or identical co-planar traces on a printed circuit board) and a balanced receiver, will not generate common-mode currents, which are a significant source of radiated emissions. In practice however, imbalances in the transmitter, conductor pair and/or receiver generate small amounts of common-mode (even-mode) currents that tend to be the dominant source of radiated emissions and coupling to nearby circuits.

In this paper, we review two symptoms of imbalance in differential interfaces where two wires or traces are driven with an equal and opposite voltage relative to a third conductor (e.g. a ground plane or shield). The first is delay skew, which results when one half of a differential digital signal does not transition at exactly the same time as the other half. The second symptom is imbalance between the rise and fall times of the two sides of the differential signal sometimes referred to as slew-rate skew.

The results presented here demonstrate that a small amount of signal skew results in a series of common-mode voltage pulses. For a clock signal with a 50% duty cycle, delay skew creates a common-mode pulse train whose energy is primarily at the odd-harmonic frequencies. Transition time differences in the same clock signal produce a pulse train with energy primarily at the even harmonic frequencies. At higher harmonic frequencies, these pulses can have as much energy as a single-ended waveform with the same peak-to-peak amplitude.

Closed-form expressions for the common-mode current resulting from skewed trapezoidal waveforms are derived in the time and frequency domains. These expressions are used to establish guidelines for determining the maximum amount of skew that is likely to be acceptable in specific situations.

Comparison of Two Methodologies for the Analysis of Distributed Integrated Circuits with Non-linear Driver/Receiver Electronics

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The need for electromagnetic accuracy in the prediction of electrical performance signal transmission and electromagnetic interference effects in state-of-the-art high-speed integrated circuits has prompted the application of full-wave electromagnetic methodologies for the modeling of the distributed interconnect infrastructure of such circuits. The traditional modeling approach, which is found to be fairly accurate for circuits with well-balanced interconnects and for signal bandwidths in the order of a few GHz, consists of the representation of the interconnect structure as a network of sections of multi-conductor, coupled transmission lines (MTL). Through properly developed SPICE-compatible models for the MTLs, transient electrical analysis of the entire system, including the nonlinear driver/receiver circuits, is conveniently done in SPICE or related general-purpose, network analysis oriented, nonlinear circuit simulators. However, as functionality integration increases and off-chip signal switching times continue to shrink to the sub-nanosecond regime, the validity of the aforementioned modeling methodology is becoming questionable. Furthermore, recent applications of FDTD-based models of packaged microwave amplifier circuits have demonstrated that higher-order electromagnetic effects, such as the resonance behavior induced by the shielded package, need to be taken into account for accurate simulation of the amplifier response. Thus, it is clear that a more rigorous electromagnetic model for the interconnect and packaging structure is needed to replace the aforementioned transmission line-based model and enable broadband non-linear electronic system simulation with electromagnetic accuracy.

Toward this objective two methodologies are possible. The first one involves the direct modeling of the nonlinear electromagnetic problem in the time domain. While FDTD-based modeling has been applied extensively over the past several years for such modeling, the computational complexity associated with the volumetric modeling of high-density planar interconnect structures has limited its application to rather simple geometries. To overcome this complexity bottleneck, a marching-on-time (MOT) algorithm for solving a time domain electric field integral equation pertinent to the analysis of printed circuit boards with conducting surfaces/wires/junctions and (potentially inhomogeneous) finite dielectrics is constructed. In addition to the fact that only induced surface currents on conductors and polarization currents in dielectric regions need to be defined as unknowns, us of the multilevel plane wave time domain algorithm (A. A. Ergin, B. Shanker, and E. Michielssen, IEEE Antennas and Propagat. Mag., 41, 39-52, 1999), leads to a computational complexity that scales as $O(N_t\, N \log^2 N))$, where N is the number of unknowns and N_t the number of time steps. Any lumped circuits are modeled by coupling the modified nodal analysis equations that govern their behavior to the MOT system of equations for the interconnect structure. A nonlinear Newton-based solver is used at each time step to solve a nonlinear system of equations the size of which is equal to the total number of nonlinear circuit elements in the system.

The second approach consists of two steps. First, a generalized form of the partial element equivalent circuit (PEEC) method is used to solve the frequency-domain electric field integral equation formulation of the electromagnetic problem for the interconnect structure and obtain its electromagnetic response over the bandwidth of interest. The Adaptive Integral Method (AIM) is used to accelerate the numerical solution. Subsequently, a SPICE-compatible, multiport equivalent circuit representation of the admittance matrix of interconnect network is synthesized. The nonlinear circuit analysis is then performed directly in SPICE.

In addition to the discussion of the details of the aforementioned modeling and simulation approaches, the presentation focus will be on the comparison of the two approaches through their application to the analysis of representative planar interconnect geometries driven and terminated with non-linear circuits.

ANALYSIS OF CONDUCTING EMI ON RADIO-FREQUENCY INTEGRATED CIRCUITS

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Abstract This paper investigates the effect of conducting EMI on the radio frequency integrated circuits (RFIC). The emphasis is on the EMI impact on communication systems for wireless local networks (WLAN) or personal communication systems (PCS). The overall structure under investigation consists of a RF radio chip packaged on a printed circuit board, transmission line interconnects, an ISM band printed circuit antenna, and an on-board balun. The method of analysis is to use a nonlinear transient simulator based on SPICE models for active components, and EM field solutions (transmission line voltage and current and equivalent circuit parameters) for passive (linear) components. In this approach, EM modeling of passive components in integrated circuits based on the solutions of Maxwell's equation is separated from nonlinear large- and small-signal modeling. An essential step is to determine equivalent current sources to the active circuits from a full-wave electromagnetic simulation. The sources are obtained as the port currents that result when the network is under EMI with all its ports either open or short-circuited. In this work, IE3D, a commercial 3D full-wave EM simulator is used to determine the source current (input to the chip) by solving the linearized structure. In the EM simulation, the radio chip is modeled as a metal plate with arrays of pins. The resulting voltage on the pin connected to the low-noise amplifier (LNA) is the source for nonlinear transient simulator. EMI source is the noise to the circuits. Cadence, a time-domain nonlinear transient simulator and IC design tool, is used to determine signal distortion due to the non-linearity caused by the EMI at various stages of the radio including LNA and Mixer. The S/N ratio with a presumed known signal source can also be found in this procedure. This paper deals with a relatively simple example to demonstrate the use of network-based nonlinear transient simulation to analyze the impact of microwave pulses on electronic circuits and systems.

Electromagnetic Fields and Biological Tissue

Co-Chairs: *K. Ito, Chiba University, Japan*
W. Wlodarczyk, Humboldt University, Germany

Modeling fields induced in humans by 50/60 Hz magnetic fields: reliability of the results and effects of model variations

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A comparison is presented of the dosimetry of power frequency magnetic fields for anatomically realistic human models and numerical codes. The groups at the University of Victoria and the National Radiological Protection Board have calculated the induced electric fields in both their 'UVic' and 'NORMAN' models using independently developed codes. A detailed evaluation has been performed for a uniform magnetic field at 60 Hz. The rationale for the comparison stems from several factors. Numerical modeling involving realistic tissue conductivity representations of the human body has been extensively used in recent years. Such modeling allows for establishing the relationship between the external (exposure) field and the induced internal electric fields and current densities. The induced current density is often used as a benchmark for exposure levels in safety guidelines. A previous comparison of data from three laboratories indicates differences in induced field strengths that range from a few percent (3 – 5%) to nearly 100 % for some voxel maxima (Stuchly and Gandhi, *Bioelectromagnetics,* 2000). These differences can be explained by the differences in the model anatomy, resolution and tissue conductivity, as well as large errors associated with maximum values (Dawson, et al, *ACES J.* 2001). Nevertheless, the reliability of numerical modeling has been questioned by scientists not directly involved in computational electromagnetics, despite extensive verification of the methods and codes used by all groups. Measurements of the induced fields are not feasible in humans, and cumbersome, inaccurate and expensive, even in simplified models of the human body.

The numerical modeling in both laboratories uses the quasi-static approximation and the scalar potential finite difference method (SPFD). However, the actual computer codes have been developed entirely independently, and thus are quite different.

Comparisons between the data computed in two laboratories for NORMAN and UVic models, which had resolution of approximately 2 mm, indicated that for a great majority of tissues, the difference was 1% or less. Only in a few cases the difference reached 2-3 %. Differences of the order of 1-2 % are typically expected on the basis of the accuracy analysis. Additionally, effects of body size, shape and model resolution were investigated using a total of 5 models. Three independent models in addition to UVic and NORMAN included a large size male model available from Brooks Air Force (AF), two models were obtained by re-sampling other models (thus changing the voxel size). The AF model mass is 37 % greater than that of UVic model mass and 42 % greater than NORMAN. Correspondingly, the whole-body-average electric fields are 41 % and 44 % greater, while 99 percentile electric fields are 41 % and 34 % greater, respectively. This is not unreasonable, since the difference in height of the models is small (0.2 %), thus the increase in volume (mass) is mainly in the horizontal frontal dimensions of the torso. Such simple mass-based scaling does not apply even approximately to specific tissues. These results emphasize that comparisons of data need to consider all the anatomical differences in the models.

COMPUTED SCALING FACTORS FOR ELECTRIC FIELDS INDUCED IN HUMANS AND RODENTS BY 60-HZ MAGNETIC FIELDS

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Objective: Extensive data are available on electric fields induced in the human body exposed to ELF fields. Numerous biological experiments have been performed on rodents. Numerical computations permit a comparison of the electric fields induced in humans and rodents, and may assist in resolving any relationship between childhood leukemia and magnetic fields, given the lack of corroborative data from animal studies.
Method: Realistic models (Rat-M: 0.85mm, 580g; Rat-F: 0.85mm, 280g; Mouse-M: 0.34mm, 43 g; Mouse-F: 0.35mm, 20g; Man: 3.6mm, 76kg) were obtained from MRI scans. Over 30 tissues were identified and corresponding conductivity values were allocated. Numerical computations were performed for three orientations of the magnetic field with respect to the body using our scalar potential finite difference code. Aspects of two of the models are shown in Figure 1.

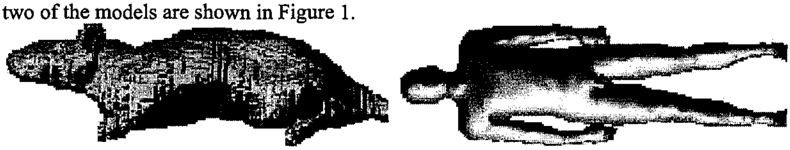

Figure 1 Skeleton of female rat model and exterior of human model.

Results: Table 1 presents actual electric field (μV/m) dosimetry for the human model ("Avg"=organ volume average; "L99"=99th percentile) for a 1-μT, 60-Hz, back-to-front magnetic source field, for selected torso organs. The rodent data are presented as percentages of the associated human data, e.g. the average electric field in the female mouse heart is 4.1% of the human value of 13.81 μV/m, or 0.5662 μV/m.

Table 1 Sample human electric field dosimetry, and rodent data as percentages.

	Human (μV/m)		MouseF/Human		MouseM/Human		RatF/Human		RatM/Human	
Tissue	Avg	L99	Avg	L99	Avg	L99	Avg	L99	Avg	L99
heart	13.81	37.90	4.1%	4.7%	6.2%	6.6%	9.4%	10.7%	14.6%	15.4%
kidneys	25.13	53.52	6.7%	6.3%	6.6%	6.8%	15.4%	14.4%	15.6%	16.1%
liver	33.83	73.25	4.5%	6.1%	4.7%	5.3%	10.2%	13.9%	10.9%	12.5%
lungs	20.84	49.23	6.2%	6.4%	6.5%	7.2%	14.2%	14.6%	15.4%	16.9%
muscle	21.23	60.39	8.1%	6.7%	9.8%	8.5%	18.5%	15.3%	23.0%	19.9%
pancreas	8.17	25.93	18.1%	14.9%	6.1%	4.3%	41.3%	34.0%	14.4%	10.0%
sp.cord	6.92	33.61	8.8%	4.3%	12.0%	5.2%	20.0%	9.9%	28.1%	12.2%
spleen	41.40	71.42	3.8%	5.7%	2.5%	3.1%	8.7%	13.0%	5.9%	7.3%
torso	25.19	87.39	6.6%	5.2%	8.4%	7.1%	15.0%	11.6%	19.9%	16.8%

Closing Remarks: The presented paper will consider implications of the scaling for three source orientations. These original organ-specific human/rodent comparisons will be shown to be in overall reasonable comparison with earlier homogeneous model studies. At the organ level, differences occur which are in agreement with modeling aspects based on voxel size and other differences between the models.

Finite-Difference Frequency Domain Analysis of Magnetic Fields of Power Lines

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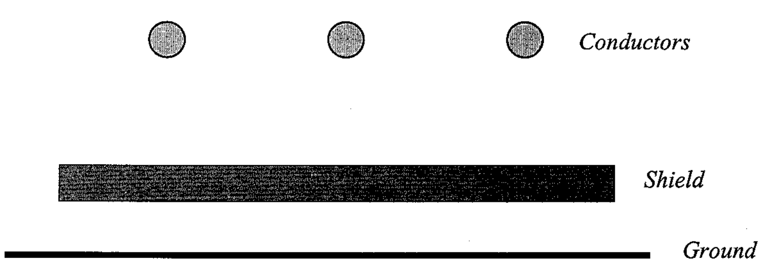
INTRODUCTION- Hazards of the power frequency magnetic fields were first reported in 1979 [Wertheimer and Leeper, Am. J. Epidemoil, June 1979]. This work that linked power frequency magnetic fields with leukemia has been both criticized and praised. Since 1979, public sensitivity to the possible adverse effects of magnetic fields on human health has prompted many more studies that still remain inconclusive. Although such adverse effects have not been established, it is reasonable to design electric power lines properly to minimize their magnetic fields. The factors that influence the strengths of magnetic fields at the ground surface are currents and line construction and dimensions. For a given block of power, the choice of a higher transmission voltage reduces the current and lowers the magnetic field but increases the electric fields and the cost. Proper operation of the transmission system and keeping the current balanced reduce the magnetic fields significantly. An unbalanced system of currents leads to zero sequence currents that flow deep inside the ground and can not neutralize the magnetic fields of the line currents. The line construction can be chosen in an optimal fashion to reduce the magnetic fields without adding much to the cost. Magnetic fields can be reduced by increasing the distance between the conductors and the ground and by making the geometrical configuration of the lines symmetrical with respect to the ground. These measures help to reduce the fields but may not be enough if magnetic fields are to be reduced to safe levels for human and electronic equipments in the immediate vicinity of the lines such as substations and switching stations. For reducing magnetic fields in such finite regions of space, various active and reactive methods may be employed.

FORMULATION- We propose to shield such finite regions by installing a flat slab of proper size, high permeability, and low conductivity material between the conductors and the ground plane as shown below. A finite-difference frequency domain technique is employed to analyze the problem to determine installations that are most effective in reducing the magnetic fields at the ground plane.



Practical Treatment System Combining Interstitial Microwave Hyperthermia and Interstitial Radiation Therapy

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In recent few decades, various types of applications of microwaves have widely been investigated and reported. In particular, minimally invasive microwave thermal therapies using thin applicators are of great interest. They are interstitial microwave hyperthermia and microwave coagulation therapy (MCT) for medical treatment of cancer, cardiac catheter ablation for ventricular arrhythmia treatment, and so on. The authors have been studying the thin coaxial antennas for interstitial microwave hyperthermia. In addition, combination of the hyperthermia and interstitial radiation therapy is effective for treatment of radiation-resistive tumor. In this study, we calculate temperature distributions around the array applicators to develop a practical treatment system combining those both therapies.

The combined treatment system is realized by using the same catheter between the interstitial hyperthermia and the interstitial radiation therapy. In this system, firstly, thin microwave antennas such as the coaxial-slot antenna with catheter heat the tumor. After heating, only the antennas are pulled out of the catheters. Then, a radiation source such as the iridium 192 is automatically inserted into the catheter by a "high dose rate afterloading system".

In order to calculate the temperature distribution around the array applicator, first, we estimate the SAR distributions around the applicator by using the FDTD method. After the FDTD calculations, we numerically analyze the bioheat transfer equation based on the resultant SAR distributions for the temperature distribution.

The temperature distribution inside the human body depends on some parameters such as input power of the antenna, heating time, blood flow rate, and so on. Therefore, in this study, we consider the relation between effective heating volume and some parameters. Moreover, we study the improvement of matching of the antennas while keeping the localized heating only around the tip of the applicator. It is considered that the results of the calculation are useful for clinical trials.

MEASURING OFEXTRA LOW MM-RANGE RADIATION FOR MEDICAL APPLICATION

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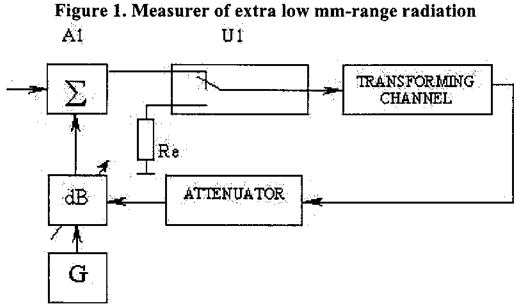
This paper reports last results of the research work on development of techniques and devices for measuring of extra low power of mm-range radiation. This radiation is widely used in medical therapy that consists in without drug correction of human physiological state.

Correction of human physiological state is carried out with non-invasive action of extra low mm-range radiation on receptor areas and acupuncture points. Individuals have certain frequencies of self-radiation. These frequencies must be used for forcing of human organism reserves. Such condition requires the procedure for selection of individual stimulating frequencies in case of using of fixed radiator in mm-range. Using of impact avalanche transit time (IMPATT) diodes do not require this one, because an organism have selective possibilities. Thus it selects only same mm-waves as individual self-radiation. At that another wavelengths do not participate in biostimulation of organism. They have not negative reaction onto normal or diseased human organism.

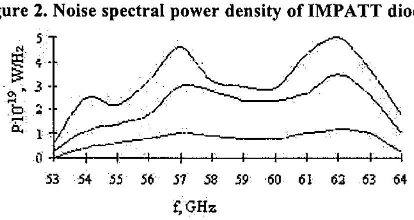
Spectral density of IMPATT diode amounts $1 \cdot 10^{-12} \ldots 1 \cdot 10^{-18}$ W/Hz at 4.8...5.7 mm wavelength range. Self-radiation of human organism amounts $1 \cdot 10^{-21} \ldots 1 \cdot 10^{-22}$ W/Hz. Measuring of this level of radiation requires the development of special techniques and devices. It has been proposed original device that scheme is shown on figure 1

Figure 1. Measurer of extra low mm-range radiation



Measured noise powers for used IMPATT diodes are shown in the figure 2. It should be noticed that noise spectral power density is different for these IMPATT diodes. This difference is not essential and all of them have the same order of noise spectral power density in 10^{-19} W/Hz.

Figure 2. Noise spectral power density of IMPATT diodes



The measurer helps researchers to get more clear understanding about physics and physiology, how low energy mm-range radiation interacts with human organism. In medical practice it could be used as diagnostic device itself and calibrating unit of therapeutic low energy mm-range device as well

Integration of Antennas in RF/Wireless Packages

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Co-Chairs: *E. Tentzeris, Georgia Institute of Technology, USA*
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Performance and Packaging Issues with Novel Reconfigurable Antennas in Laptop Computers

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High quality wireless links with fast data rates between next generation laptop computers and/or other portable communication devices will require both robust antenna designs and consideration of placement and packaging issues for all radiating components. New antenna designs for these devices may have adaptable radiation characteristics to accommodate changing electromagnetic environments as well as a vast range of operational modes to allow ad hoc communication with other portable devices. In addition, new antenna designs must also be of a modular nature to simplify integration into the intended device.

This study reports on performance and packaging issues for a generic laptop computer equipped with a novel, SMA probe-fed, reconfigurable microstrip antenna capable of thirteen operational modes spanning approximately 3.4 to 10.0 GHz. These operational modes include not only changes in resonant frequency but also radiation pattern, including broadside and omni-directional patterns. The set of antenna radiation patterns are studied to determine the performance trade-offs in gain, directionality, beamwidth, and pattern quality as a result of the interaction with, and placement around, the laptop computer's internal shielding as well as the work surface upon which the laptop resides. The effects of the conductivity of the work surface are also studied to account for differing operating environments. In conjunction with radiation performance issues, analysis of resonant frequencies with corresponding 2:1 VSWR bandwidths and input impedances of the antenna are also considered to determine the usefulness of the antenna when implemented in a modular fashion. The reconfigurable antenna is therefore situated on a laptop structure comprised of dielectric and shielding material, and the optimum position is synthesized through a parametric study of position and antenna placement utilizing the concept of electromagnetic visibility (J. T. Bernhard, *AP/URSI Int. Symp. Digest*, 2210-2213, 1997). Performance trade-offs and figures of merit are provided as a function of antenna placement, pattern quality, and frequency behavior over a selected antenna permutation range that covers the set of available operational modes.

Modeling and Surface Current Visualization of Dual Exponentially Tapered Slot Antennas with Dielectrics

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Tapered slot antennas, such as the Vivaldi antenna with an exponential inner taper, are popular broadband antenna elements. The Dual Exponentially Tapered Slot Antenna (DETSA) is similar to the Vivaldi antenna yet differs from the Vivaldi in that the outer edge of the DETSA is tapered. This outer taper allows the feeds of adjacent DETSA antennas to be isolated from one another in arrays or diversity antennas. In *Greenberg and Virga, 1999 IEEE APS Symposium* the method of moments is utilized to analyze the DETSA without dielectrics. This paper will present new research that involves the performance of DETSAs with dielectrics. The effects of using various dielectric materials on one side of the DETSA will be explored via the finite element method. Some dielectric materials used includes RT Duriod (ε_r =2.33) and alumina. This allows for the antenna performance using a range of relative dielectric constant values to be explored. The results can be used to determine how the DETSA can be efficiently integrated into RF and wireless packages.

The DETSA is an interesting antenna element because it is directional with a pattern that does not change significantly over its operating frequency band, has an excellent impedance match over a very broad frequency range, does not require tuning elements and thus bias power to achieve wide bandwidth, and it is low profile and unobtrusive. Prior research has shown that the DETSA pattern can be modified by shaping the outer taper. We will investigate how the DETSA can be made more compact by use of the dielectric. All of these are important features for high data rate wireless systems.

In this paper, the current distribution of a dielectric-backed DETSA and its Vivaldi counterpart will be presented at various frequencies. An investigation of the field pattern variation between Vivaldi and different DETSA designs as a function of frequency will be presented. Other antenna parameters such as input impedance, beamwidth, and directivity will be explored.

Porous Silicon Substrates for High Frequency Planar Circuit and Antenna Design

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Silicon has received much attention because of its potential to serve as a low cost host substrate in high-speed passive (i.e. circuit and antenna components) integrated circuit design. The combined use of the traditional integrated circuit processing methods and silicon micromachining has resulted in important design approaches that allow low loss performance in high-density environments. Thus, two new classes of high-speed design approaches have evolved. The first, packaged planar integrated circuits, enables the development of compact vertically integrated three-dimensional circuits, while the second, mechanically switched planar circuits, enables development of reconfigurable passive designs that are void of active devices for low power operation. Hence, the development of complementary microwave integrated designs in silicon to those traditionally designed in gallium arsenide (III-V semiconductor) is on the horizon as a result of active device developments in silicon germanium. Despite these remarkable advances, a number of new challenges must be addressed that arise from the industry trend to offer multi-functional features (e.g. wireless communications, computing, and sensing) onto a single chip.

From the communications perspective, complete transceiver designs requires active and passive circuits to be integrated with the antenna. But, since silicon is a high dielectric constant material, the classic integrated circuit/antenna dilemma exists and approaches to resolve the conflicting substrate thickness and dielectric constant requirements to optimize each element are needed. From the system perspective, multi-functional integration requires combining different circuit designs and technologies that are strongly coupled to the substrate resistivity. For example, the high performance RF designs printed directly onto silicon that offer low loss use high resistivity material, whereas low cost high performance computers and sensors use low resistivity material. Hence, the truly integrated solution will require use of technologically compatible methods that maximize performance and minimize cost.

Different from the research that has been investigated on the use of multi-layer methods, such as polymers, to minimize substrate losses, this research explores another semiconductor technology to modify the substrate in areas where high-speed passive circuits and antennas are to be printed. The low resistivity substrate is modified locally by chemically etching millions of nanometer size pores into the surface, namely porous silicon. The result is lower loss and lower dielectric constant than the high values in low resistivity silicon wafer. In the presentation, the fabrication will be highlighted and a variety of characterization methods will be discussed that have been investigated to determine the electrical properties of the material. Experimental results will be presented on the transmission properties and designs will be discussed that can benefit from its use in RF passive circuit and antenna design to enable multifunctional integration of planar communications, computing, and sensing elements onto a single chip.

Multiband and Broadband Printed Antennas

Co-Chairs: *J. Soler, Fractus S.A., Spain*
G. R. Kadambi, Centurion Wireless Technologies, USA

COMPACT DUAL FEED MULTIBAND PLANAR ANTENNA WITH PIFA/IFA COMBINATION

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Rapid progress of the cellular communication industry in the recent past has resulted in a need for cellular handset with multiband operation and multi system capability. With the recent advances in the cellular communication technology, there is also an enhanced emphasis for internal cellular antennas to utilize its inherent advantages. In the recent past, the multiband PIFA has been a research topic of great interest to mobile communication industry. In a multiband PIFA, the choice of either a single feed or multiple feeds is mostly dependent on the system requirements. However from the antenna design consideration, the choice of the single feed or multiple feeds has its relative merits and demerits. In a single feed multiband PIFA, the realization of the requisite bandwidth at multiple resonant frequencies will be an involved task leading to many design complexities. On the contrary, the multiband PIFA with multiple feeds has the relative advantage of diminished design complexities since the design of individual radiating elements with separate feeds is relatively easier. However, such a design recourse has to encounter the problem of mutual coupling between the individual radiating elements of a multiband PIFA. There is a great concern for multiband PIFA with multiple feed ports having its performance compromised due to mutual coupling and poor isolation of the various resonant bands. Hence in spite of the reduced design complexities, multi band PIFA with multiple feeds has not been a logical choice for practical applications mainly due to the problem of mutual coupling. In view of this, the techniques to reduce the mutual coupling between the individual radiating elements with separate feeds of a multiband PIFA are of significant importance for many system applications. This paper presents a technique of minimization of mutual coupling between the radiating elements of a multiband PIFA/planar antenna. In majority of the past research publications on dual band PIFA, the emphasis is mostly confined to the optimization of a dual feed dual band PIFA for cellular applications only. This paper proposes a technique of improving the isolation between the radiating elements of a dual feed Tri band Planar antenna for the cellular and non-cellular applications.

To accomplish the dual feed Tri band (Cellular and Non Cellular) performance of a compact planar antenna with reduced mutual coupling between its feed ports, the design presented in this paper invokes a combination of PIFA and IFA. The PIFA with its radiating element parallel to the ground plane is designed for its dual resonance in the cellular bands such as AMPS/PCS or GSM/DCS. The radiating element of IFA, which is perpendicular to the ground plane, has an operating band for the Non Cellular applications. In order to realize a Tri band design utilizing the volume of a conventional dual band PIFA only, the IFA with its separate feed is placed directly underneath the radiating edge of the PIFA. Such an arrangement results in the relative orthogonal disposition of the two radiating elements (PIFA/IFA). The orthogonal orientation of the radiating elements leads to an improved isolation between the feed ports despite no increased separation between the radiating elements. The proposed concept has been implemented in the development of dual feed (AMPS/PCS/ISM)/(GSM/DCS/ISM) band planar antennas with good gain, reasonable bandwidth and improved isolation between the feed ports. This paper presents the bandwidth, radiation and isolation characteristics of several designs of compact dual feed Tri band planar antenna for cellular and non cellular applications. Without loss of generality, the proposed concept can be extended to improve the isolation performance of dual feed dual band PIFA also.

A Single-Feed Dual Band PIFA With U-Shape And non U-Shaped Slots

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PIFAs (Planar Inverted F-Antennas) are considered as internal antennas which have the desirable features of compactness, moderate range of band-width, higher gain in principal planes for both states of polarization, are less prone for breakage, and reduced power absorption with the user as compared to external antennas. In addition to cellular applications, PIFAs have become attractive candidates in a variety of commercial applications such as Blue-tooth and mobile satellite communications. In this paper, a new single feed dual band PIFA design is proposed. This PIFA exhibits GPS (1575 MHz) and WCDMA RX (2110 – 2170 MHz) frequency bands, which is of special interest for 3G communications.

Figure 1 shows the geometry of the proposed PIFA: a wide U-shaped slot is cut at the center of the PIFA, a second slot was introduced adjacent to the U-Shaped slot, the feed and shorting pins were placed at the center of the U-shaped slot, and a shorting wall was placed at the edge of the PIFA. Figure 2 shows the VSWR plot of dual band PIFA as a result of this geometry, its VSWR < 2.5:1. The tuning of the dual band antenna was obtained by adjusting the length of the non-U shaped slot. This is due to the fact that there are currents along the edge of the U-shaped slot, so the introduction of an open slot along the edge of the U-shaped slot, produces the required frequency response characteristic. While the isolation between two bands was well controlled by the shorting wall position, the impedance matching was obtained by optimizing the position of feed and shorting pins within the U-shaped slot. The detailed design parameters and its effect on the performance of the PIFA will be presented in the meeting. When tested for free space radiation pattern, this PIFA was mixed polarized and the peak gain of the total field is > 3.0 dBi in WCDMA RX band. Although this PIFA works for GPS and WCDMA RX bands, this design concept can be extended to other frequency bands of interest.

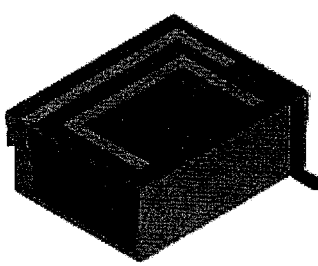

Figure 1. Geometry of the proposed PIFA design

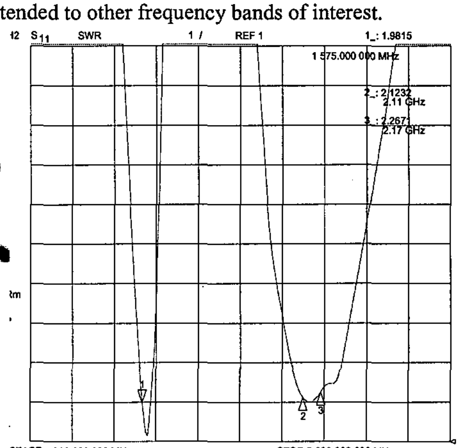

Figure 2. VSWR plot of the proposed PIFA

Novel Broadband and Multiband Solutions for Planar Monopole Antennas

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Broadband antennas represent an alternative to multiband antennas and are of special interest in those wireless communication applications that demand the integration of several services.

A wideband circular disk monopole, Fig.1, was reported in (S.Honda, M.Ito, H.Seki, Y.Jingo, A disc monopole antenna with 1:8 impedance bandwidth and omnidirectional pattern, Proceedings International Symposium Antennas Propagation ,pp.1145- 1148, Sapporo, September 1992). The antenna featured an impedance bandwidth ratio of more than 1:8 for a VSWR≤ 2. Other broadband antenna solutions based on the hexagonal and other geometries were compared to the circular antenna in (N.P.Agrawall, G.Kumar, K.P.Ray, Wide-Band Planar Monopole Antennas, IEEE Transactions on Antennas and Propagation, vol.46, no.2, pp.294-295, February 1998). Subsequently, several modifications on these structures were investigated in order to reduce the antenna size. Although the large impedance bandwidths that these type of planar monopoles exhibit, they are limited to their return loss matching levels.

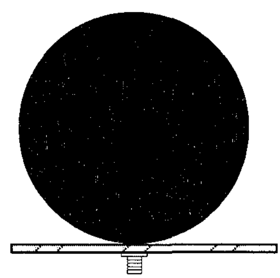

Fig 1 Wideband circular disk monopole antenna solution first reported by Honda et al.

The input return loss of the circular, elliptical and other euclidean-shaped monopole antennas can be further improved by strategically removing part of the radiating antenna surface. This novel solution permits to enhance the return loss at the lower part of the band and it represents an alternative to some of the reported wideband antenna solutions, such as those that consider a microstrip or co-planar feeding scheme. The properties of this novel solution can be understood by inspecting the surface currents over the antenna. Moreover, using the same technique; that is, filling up a hole from the antenna conducting surface, the wideband performance can be converted into a multiband response, where the return loss is also improved when compared to the conventional solid circular or elliptical solutions. The advantages of this novel proposed antenna solution are investigated and compared to other broadband techniques.

A 900/1800 MHz Dual-Band Chip Antenna

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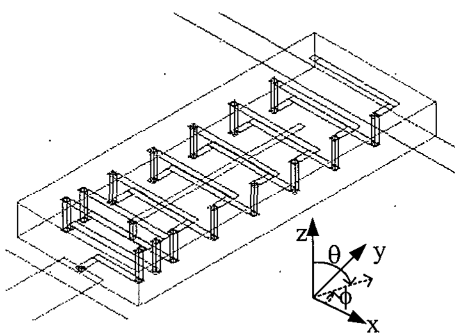
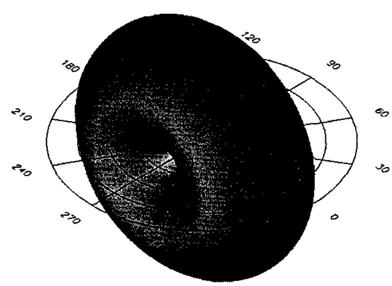
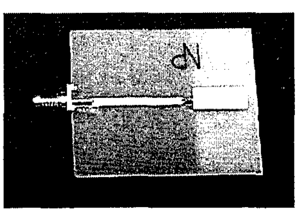
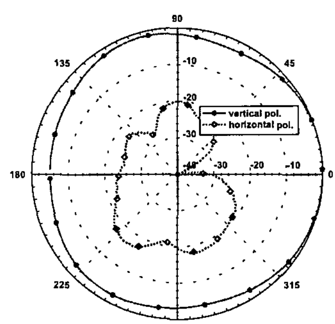
This paper presents design simulation, implementation, and measurement of a miniaturized dual band chip antenna for GSM 900/1800 handset applications. The helix-monopole type dual-band antenna is adopted to be realized in multi-layer printed LTCC structure. The High Frequency Structure Simulator (HFSS) 3-D EM simulator which based on the finite-element method (FEM) is employed for design simulation. A helix/three-monopole structure chip antenna is designed to achieve enough bandwidth at 900 and 1800 MHz bands. The realized chip antenna has an input return loss –22dB at 1.04 GHz and –21 dB at 1.9GHz. The antenna pattern is very close to the omnidirectional pattern of the dipole antenna.









Control and Measurement of Antenna Arrays

Co-Chairs: *R. J. Pogorzelski, Jet Propulsion Laboratory, USA*
O. Kilic, Army Research Laboratory, USA

Diversity combining and interference rejection performance comparison between linear and square arrays of low-profile monopole elements with omnidirectional and sector patterns: measurements and simulation

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As mobile radio systems employ higher frequencies, it is becoming possible to use compact antenna arrays at mobile and handheld terminals for diversity combining and adaptive beamforming. Diversity combining improves reliability and decreases the required margin on the downlink. Adaptive beamforming rejects interfering signals and can lead to large increases in capacity. An investigation on the performance of four element linear and square arrays for mobile (vehicular speed) and portable (pedestrian speed) terminals is reported.

We compare linear and square arrays of low-profile broadband omnidirectional monopoles and a square sectorized array of four monopole elements that are backed by corner reflectors to generate directional patterns. The elements are as described by Foltz, McLean, and Crook (*IEEE Trans AP*, 12, 1894-1896, 1998, *IEEE APS*, 3, 562-565, 1999), A square array of four half wave dipole elements was used to provide a baseline for evaluating diversity and interference rejection performance of the other arrays.

Results from extensive diversity and beamforming measurements, undertaken in urban and suburban environments for both line-of-sight (LOS) and obstructed multipath channels, were used to analyze and compare the performance of the array configurations. Diversity gain achieved from diversity combining and improvement in signal-to-interference-plus-noise-ratio (SINR) using adaptive beamforming for cumulative probabilities of 10%, 1%, and 0.1% were calculated from the measured data. Interference rejection experiments were conducted with the interfering transmitter spaced in azimuth by 0° to 180° from the direction of the desired signal transmitter.

Measurements were performed at 2.05 GHz using a four-channel version of the handheld antenna array testbed (HAAT) described by Dietrich, et al. (*IEEE Trans. AP,* 9, 1271-1281, 2001). Diversity measurements were undertaken using a single transmitter, while interference rejection experiments were performed using two mutually interfering transmitters. To investigate the performance at pedestrian speeds, controlled measurements were taken using a linear positioner, run by a stepper motor.

In a non-line-of-sight (NLOS) obstructed urban channel with maximal ratio combining the diversity gain of the arrays ranged from 11.4 to 17.8 dB. Interference rejection of 27 dB was recorded for the linear array with the interfering transmitter angle of arrival 90° from that of the desired transmitter spread as compared to 15 dB for 0° separation between transmitters. Under similar experimental conditions the sectored square array showed marginal improvement over the square array. Results of vehicular diversity combining and adaptive beamforming measurements with the arrays mounted on a ground plane suspended above the vehicle rooftop are also reported. Measurement results are compared to results of simulations using a 2-D ray tracing program that implements canonical propagation models for vector channels.

Adaptive beamforming and diversity combining measurements at 2.05 GHz using arrays of four low-profile wire elements backed with an electromagnetic band gap structure

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Compact antenna arrays are used for diversity combining and adaptive beamforming at mobile or handheld wireless terminals, with implications for system reliability, power efficiency, and most importantly, capacity. Results of investigations into the performance of low-profile four-element arrays for portable and vehicular terminals are reported. Each array element is a low-profile wire antenna mounted over a high-impedance electromagnetic band gap structure similar to the one described by Sievenpiper, et al. (*Elect. Let.*, 16, 1343-1345, 2000). Extensive diversity and beamforming measurements were undertaken in urban and suburban environments for both line-of-sight (LOS) and obstructed multipath channels.

Measurements were taken with a square four-wire sector array configuration and with a linear array configuration of single wire elements with spacing of 0.4λ to 1.0λ. A four element square array of half wave dipole elements was used to provide a baseline for evaluating the diversity and interference rejection performance. Measurements were performed at 2.05 GHz using a four-channel version of the handheld antenna array testbed (HAAT) described by Dietrich, et al. (*IEEE Trans. AP,* 9, 1271-1281, 2001). Diversity measurements were undertaken using a single transmitter, while interference rejection measurements were performed using two mutually interfering transmitters. To investigate the performance at pedestrian speeds, controlled measurements were taken using a linear positioner, run by a stepper motor. Results of vehicular diversity combining and adaptive beamforming measurements with the arrays mounted on a ground plane suspended above a vehicle rooftop are also reported.

Diversity gain, envelope correlation and power imbalance were calculated from the diversity combining measurements. Improvement in signal-to-interference-plus-noise-ratio (SINR) using a least-squares constant modulus beamforming algorithm (LS-CMA) was calculated from the interference rejection measurements for a range of cumulative probabilities of SINR. Diversity gain values of up to 16 dB were calculated for maximal ratio combining at the 99% reliability level in a non-line-of-sight (NLOS) obstructed urban channel. Substantial interference rejection was recorded, as given by improvement in SINR of 24-28 dB in urban and suburban channels for the square sector array.

A FREQUENCY TRIPLED COUPLED OSCILLATOR ARRAY

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It has been proposed and demonstrated that an array of electronic oscillators coupled to nearest neighbors can be made to mutually injection lock and oscillate as an ensemble. It has been further shown that such a locked array can provide suitable excitation for the elements of a phased array antenna and that beam steering may be effected by tuning only the perimeter oscillators. [R. A. York, IEEE Trans., MTT-41, pp.1799-1809,, Oct. 1993] [P. Liao and R. A. York, IEEE Trans., MTT-41, pp. 1810-1815, Oct. 1993] [R. Ispir, S. Nogi, M. Sanagi, and K. Fukui, IECE Trans. Electron., E80-C, 1211-1220, Sept. 1997] However, the adjacent oscillators can be no more than ninety degrees apart in phase and still maintain lock. Thus, for half wavelength radiating element spacing, the scan is limited to thirty degrees from normal to the aperture. One means of extending the scan range is to multiply the frequency of the oscillator outputs thus similarly multiplying their phases. [R. A. York and T. Itoh, IEEE Trans., MTT-46, pp. 1920-1929, Nov. 1998] Such a system employing frequency doubling from 12 GHz to 24 GHz was recently reported. [J. Shen and L. W. Pearson, Nat. Radio Sci. Mtg, Boston, MA, July 2001] Although for a half wavelength element spacing, frequency doubling is theoretically sufficient to extend the scan to endfire, in practice this is not the case and at least frequency tripling will be required to achieve full scan capability. Thus, in this paper we report on the application of frequency tripling to the S-band array previously reported. [R. J. Pogorzelski, Microwave and Guided Wave Letters, 10, pp. 478-480.] The result is an agile beam X-band transmitter with scan range corresponding to triple the interoscillator phase difference.

The oscillators in the array are Pacific Monolithics PM2503 MMICs with external varactors for tuning and buffer amplifiers which effectively isolate the output from the coupling network. The frequency triplers are Miteq MAX3M072077 separately packaged with SMA connectors. The phase distribution over the array is measured at S-band via a nine element parallel phase measurement system using mixers and ninety degree hybrids and implemented in Labview™. This system provides a graphical display of the phase distribution from which the aperture phase can be inferred.

Case Study: Intersymbol Interference of Wide Band Ka-Band Phased Array Antennas

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Abstract – In future satellite communication systems, the demand for faster access and more information is expected to increase due to the continuous growth of the Internet and direct-to-user satellite requirements. Also, in order to increase coverage and reduce latency, Low Earth Orbit (LEO) systems are being introduced for these applications. Meeting these requirements will require multibeam satellite systems having an onboard active phased array antenna system able to deliver high data rates without producing extraneous vibration and torques on orbiting spacecraft.

Phased array antennas contain a multitude of radiating elements, typically arranged in a rectangular or triangular tessellation. Beams are formed by electrically adjusting the relative phase of the radiating elements using ferrite or semiconductor devices. Phased array antennas have been developed mainly for radar applications but are being used more now for space-based communications applications due to their advantages in weight and power.

However, there are a number of potential sources of degradation in the Bit Error Rate (BER) performance of the communications link that are unique to PAA-based links. The most dominant effect of BER degradation on wideband PAA links is the modulo 2π phase shift characteristics. The fixed modulo 2π phase restriction imposed by the phase shifters, in addition to delay across the aperture, can cause Intersymbol Interference (ISI), contributing to an increased BER. The effect of ISI on the BER increases with higher data rates. For this reason, new studies are being conducted to characterize this effect.

In addition to experimentation, computer simulations are also being conducted. Many authors have modeled phased array antennas for the past 50 years. With the advent of computer programs like Matlab/Simulink we can now easily model the array radio frequencies and modulation correlations. The simulation can be custom fitted to a specific modulator/demodulator combination. The array RF simulation is well-understood and very easily implemented using Matlab.

The results of the characterization will allow for NASA and other users of high rate phased array antenna systems to design their antenna systems to mitigate these degradations. The potential mitigation techniques include modulation/demodulation techniques that are less prone to ISI, improvised match filter techniques, use of true time-delay, and synchronization techniques that are less sensitive to amplitude and phase transients.

New knowledge statement: The work presented describes the degradation on the bit error rate for phase array antennas operating at a high data rate. Future applications for phase array antennas using high data rates will require compensation techniques to mitigate this degradation. This paper bounds the problem utilizing simulation methodology.

Application of the Synthetic Function approach to arrays of aperture-coupled printed antennas

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Aperture-coupled printed arrays are widely used in communication systems. Typical applications of aperture-coupled patch antennas exploit the bandwidth enhancement, and especially the high degree of decoupling between radiators and beam forming network (BFN), that allows high polarization purities. Likewise, this technology favors dual polarization (with low cross-pol coupling), and the radiation-BFN separation is important to reduce space occupation in large and complex (e.g. dual-pol) arrays. The most commonly used slot shape is rectangular, but there are various application where for different reasons (like bandwidth enhancement, space limitation, impedance matching, etc.) non-separable apertures (e.g. bow-tie, H shaped, etc.) are involved.

In the present work we propose the extension of the Synthetic Function (SF) approach previously introduced by the same authors [L. Matekovits, G. Vecchi, G. Dassano, M. Orefice, APS2001, 568 - 571, and references therein], to the analysis of aperture coupled antenna arrays. Despite the vast research literature on the simulation of aperture-coupled patch arrays, to the best of our knowledge, this effort in increasing the efficiency is novel.

The Synthetic Function eXpansion (SFX) technique is based on 1) the decomposition of the antenna domain into sub-domains (of arbitrary shape) -termed "blocks"; 2) on the (numerical) generation of entire-domain basis functions on the blocks -termed Synthetic Functions (SF); 3) on the subsequent use of SF to represent the global solution. Few SF are required to correctly represent the current on blocks, and thus the SFX approach reduces the MoM matrix memory occupation, and considerably reduces the time needed to solve the linear system, without affecting the solution accuracy. Efficiency is still increased in arrays of identical radiators (without limitations on the amplitude/phase distribution or BFN) since in this case the SF generation is done only once for all radiating elements.

Typical results show that best efficiency is reached by including both patch and slot(s) in the "block" over which SF are generated. Since this also represents the radiating element in isolation, typical design procedure will involve optimization of the element anyway before assembly into the array, so that no practical overhead is involved in the generation of SF.

As to coding complexity, we remark that it does not require substantial modification of the core of a MoM code. Domain decomposition, generations of SF and necessary matrix handling can be effectively completed outside the core code.

Near field study of MBPG arrays

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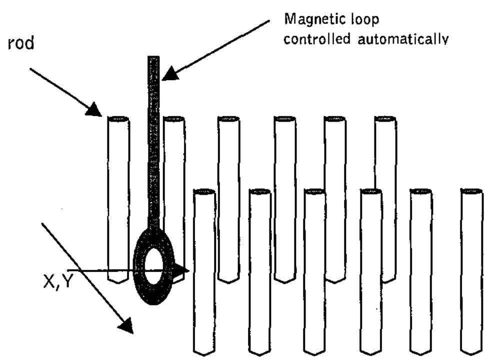
Abstract:

Photonic band-gap materials (PBG) are dielectric or metallic periodic structures that have properties analogues to semi-conductors for electron propagation. They exhibit frequency bands inside which no propagation mode exists. Several studies have been made on PBGs composed of metallic rods [M. Sigalas et al., "Metallic photonic band-gap materials", Physical Review B, Vol.52, n°16, Oct. 1995, pp.11744-11751]. Most of them considered infinite wire models and studied the nature of the band gaps and their behaviors related to the geometry of the lattices when they are excited either by a plane wave or by an antenna placed at the surface or inside the PBG.

Defect analysis is also a large field of study. Different theoretical or numerical solutions have been developed in order to understand the modes created in these cases [K. Agi et al., "An ultra-wideband photonic crystal", Ultra-Wideband, Short Pulse Electromagn. 2, edited by L. Carin and L.B. Felsen, Plenum Press, 1995, pp.341-349] but no modes have been observed experimentally inside a PBG. A near field method can be applied to perform these kind of measurements. Here a systematic study is presented where the near field is measured inside the structure (Fig. 1). The results, covering the .8-2 GHz frequency band, are compared with numerical results obtained using a time domain method [S. Collardey et al., "Metallic photonic band-gap propagation characterization", Microwave and Optical Technology Letters, vol. 28, issue 6, March 2001]. The analysis of these results will help give designers a better understanding of the overall behavior and the limits of these materials.

This understanding is actually very important for many different kinds of applications that periodic structures with defects of pseudo-periodic structures can lead to. This is in our approach the first step to the design of wideband reflectarrays.



-Fig.1-

Pattern Optimisation of Large Array Antennas by Using Only Phase Control

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Linear arrays present significant advantages such as simplicity and high-resolution but many times the fact that first side lobe level (SLL) value can not exceed the maximum of 13.46 dB is a serious limitation, which has to be overcome. Most of the published work during the last few decades describe synthesis and optimization methods for the array pattern control that accomplish this task through element position control or by using a kind of amplitude taper. In both cases, however, the simplicity of an equi-spaced and uniformly excited linear array is sacrificed.

In this work a method is presented for the easy optimization of a linear array of equally spaced elements. This method allows finding, in an optimal way, the amplitude of the excitation coefficients common to all elements and those array elements for which a π phase shift produces a pattern with improved side lobe level value. By this way, e.g. reversing the current in selected elements, a kind of amplitude taper is introduced by using only phase control, without the need for amplitude control in the elements. The array antenna, in this work, is studied using an equivalent electrical circuit. This equivalent circuit is realized using circuit elements as amplifiers and phase shifters that are specified as mathematical functions. The use of a circuit analysis and simulation program allows not only the modeling and display of antenna patterns but also their optimization. In order to find the pairs of array element with the π phase shift, the optimization tools are used which permit multiple goals with different weights. Using the presented method one can avoid the writing of complicated mathematical formulations and algorithms in order to achieve the desired results. Nevertheless, good knowledge of array theory is essential for setting achievable goals in optimization procedure and to avoid useless time-expensive tries.

A H-plane Slotted-Waveguide Array for Circular Polarization using Inclined-Slot Pairs

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Slotted waveguide antennas are quite attractive in terms of low transmission loss and high-power handling capability. Concerning a broadside beam antenna especially in the circular polarization, a H-plane cross-slotted waveguide antenna was proposed for the purpose. Although its single layer structure was advantageous in manufacturing, grating lobes are not suppressed in array configuration because the element spacing must be larger than guided-wavelength. To realize a circular-polarization broadside-beam antenna with single layer waveguide structure, a novel slot arrangement making two adjacent slots radiate in phase is required. A configuration without inner dielectric material is also preferable for low-cost manufacturing.

This paper presents a slotted-waveguide antenna-array for circular polarization using a novel slot-pair. The basic slot pair is composed of two 90° -inclined slots cut into the H-plane wall of TE_{10} rectangular waveguide. Appropriate phase and amplitude condition of the orthogonal component fields are obtained by controlling each slot length. Fig.1 shows an array configuration with the proposed slot pairs. Adjacent slot pairs are inversely placed with a one-half wavelength separation in the x-axis, therefore all the slot-pairs are excited in phase by standing wave. It does not need any dielectric materials inside the waveguide.

The proposed concept is verified numerically by using CST MW-Studio Software. Circular polarization patterns with reduced grating lobe are confirmed for array antennas.

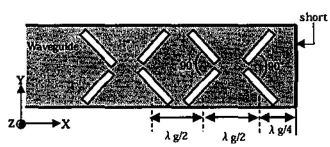

Fig.1: Array configuration

76GHz Post-Wall Waveguide-Fed Parallel Plate Slot Array with Sidelobe Suppression and 45-Degree Tilted Linear Polarization

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Sidelobe suppression and 45-degree tilted linear polarization are realized simultaneously without degrading each performance of them in a 76GHz post-wall waveguide-fed parallel plate slot array. This antenna is a candidate of mechanically-scanning planar antennas for car radars because it has light weight in large size and keeps high efficiency in a high-gain range. Sidelobe suppression is for no detection of objects except a target. 45-degree polarization is proposed since radiation with the orthogonal polarization from cars coming from the opposite direction does not affect the radar operation.

Figure 1 shows the structure. 45-degree polarization is obtained by elements consisting of one tilted slot for the radiation and two parallel slots with reflection-canceling for traveling-wave excitation in a parallel plate waveguide. Sidelobes are suppressed only in the plane parallel to the feed waveguide by a tapered aperture distribution with control of the width of the coupling windows. Aperture field perpendicular to the feed waveguide is uniform by controlling the slot length.

A model antenna is manufactured at 76.5GHz. The slot array is sized by 88mm x 58mm. Figure 2 shows the measured radiation pattern in the plane parallel to the feed waveguide at 76.5GHz. The sidelobes are suppressed below −21dB. The level of the cross polarization is −35dB at the boresight. The 3dB beamwidth is 3.0degrees x 3.7degrees. The measured peak gain is 32.8dBi at 76.5GHz. The efficiency is 45.6% for the size of the slot array. The efficiency of this antenna is almost double in comparison with that of a conventional patch array with the same size in measurements. The 1dB-down bandwidth is 0.95GHz in terms of gain.

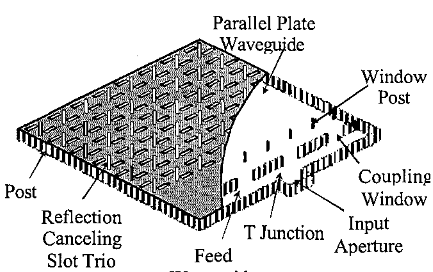

Figure 1 Post-wall waveguide fed parallel plate slot array

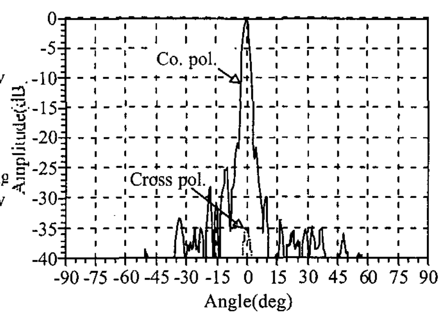

Figure 2 Radiation pattern in the plane parallel to the feed waveguide

Compensating for the effects of higher-order mode coupling in waveguide slot arrays

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Existing design procedures for waveguide slot arrays make provision for the effects of external mutual coupling and internal higher-order mode coupling between radiators. For planar arrays, other higher-order mode coupling effects are not included and should be compensated for. Waveguide branches are normally fed via inclined-slot couplers. Each coupling slot is then only $\lambda_g/4$ away from the two radiating slots which straddle it. Ignoring the effects of higher-order mode coupling may result in improper excitation of the straddling slots, thereby degrading the pattern and impedance matching of the array (R.S. Elliott, "The Design of Waveguide-Fed Slot Arrays", in *Antenna Handbook*, Y.T. Lo and S.W. Lee, Eds, Van Nostrand Rheinhold, 1988). In certain cases, sub-arraying is used to enhance the frequency performance of planar arrays. H-plane T-junctions are often used as power dividers to feed separate sub-arrays. In such feed networks, the T-junction is placed between two inclined coupling slots feeding the waveguide branches. The array geometry requires the coupling slots to be $\lambda_g/2$ apart, resulting in higher-order mode coupling between the T-junction and the coupling slots as well. This may affect the excitation of the branch lines connected to the coupling slots, and consequently also the excitation of the radiating elements of those branches.

In this paper, numerical modeling is used to investigate the severity of the effects of the higher-order mode coupling for the two mentioned cases. The aim is to compensate for these effects by changing the length, inclination angle and/or offset of the coupling slots and radiating slots, using a pre-determined database of S-parameters computed with a full-wave analysis procedure. Both theoretical and experimental results will be presented.

Tuesday PM | AP/URSI A | Session 60 | Pecan

Ultra-Wideband Radar

Co-Chairs: *S. El-Ghazaly, Arizona State University, USA*
J. D. Young, Ohio State University, USA

WIDE BAND NOISE RADAR USING DIGITAL WAVEFORM GENERATION

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A noise radar is a radar that transmits a continuous very wide band noise-like waveform. For target detection, the received signals are cross-correlated with a copy of the transmitted signal. The cross correlation at very wide bandwidth is achieved by delaying a copy of the transmit signal and mixing this delayed signal with the received signals. (We have built systems extending from 100's of MHz to several GHz.) For correlation, microwave mixers achieve the multiplication, and low pass filters achieve the integration. There need be no T/R switching. An important property of the noise radar is that the response waveform for the correlation versus time delay is in fact an impulse response of the radar target. The data produced is thus identical to that produced by an impulse radar.

In the past, we have built such radars by using a true noise waveform and a switched length or a multiple tapped transmission line to achieve the variable time delay. (Theron, Walton, Gunawan and Cai, IEEE AP, 47, 6, 1080-1084, 1999 and Theron, Walton and Gunawan), IEEE AP 46, 9, 1285-1288, 1998) In this paper, we present techniques for generating pairs of pseudo-random waveforms so that the delayed waveform is discretely generated using high-speed electronic devices. We will show an example where the waveforms are generated using a pair of linear feedback shift registers.

We will also show an object identification radar design where we store a pair of waveforms as digital values in a pair of FIFO's. One FIFO holds the transmit waveform, and the other FIFO holds the waveform to be expected to be returned from a specific target. (The second waveform is the convolution of the transmit waveform, the radar transfer function, the propagation channel, and the expected target impulse response.) The result is a very wide band cross correlation radar that acts as a matched filter for specific targets. This radar can be programmed to search for particular types of target, such as buried land mines or specific vehicle types imbedded in foliage clutter.

We will show details of the design of the two types of radars and compare experimental target tracking results.

Transient Gain Measurement of an Ultra Wideband Antenna

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Abstract:

The gain of an Ultra Wideband antenna is measured, and results are presented. The measurement technique involved scattering measurements with a set of open circuit, short circuit, and matched load antenna terminations, referenced to a standard metal cylinder scatterer. This technique extends past work (K. Lambert, et al, IEEE Trans. A & P Vol. 38, #6, June 1990) to ultra-wideband antennas. This approach not only permits use of a very well characterized reference standard, but it eliminates such error factors as cable radiation, cable phase distortion, and cable flexing noise from the data.

A gain spectrum is presented. However, there are additional antenna gain issues that are relevant for transient antennas. Assuming that the antenna is excited by a transient impulse, then an interesting and relevant concept would show the time transmission of energy. Many applications of such an antenna would wish to concentrate the maximum transmitted energy into the shortest possible time interval.

A transient energy gain parameter is introduced to characterize the coherent gain performance of an ultra wideband antenna. This new antenna performance parameter builds on past transient antenna definitions of (E. G. Farr, p 345, J. Gwynne and J. Young, p 348, 1993 URSI Radio Sceince Meeting Abstract). Data for the test antenna in this format are compared to the gain spectrum information.

Polarimetric Image Processing of an Ultra Wideband FOPEN Random Noise Radar

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The University of Nebraska-Lincoln has developed an ultra wideband (UWB) foliage penetration (FOPEN) synthetic aperture radar (SAR) system that uses band-limited random noise as its signal waveform. The random noise radar system operates over 250-500 MHz frequency range and has a transmit power of 10 W. Broadband dual-polarized log-periodic antennas are used as transmit and receive antennas for dual-polarization transmission/receiving. To obtain the phase coherence, heterodyne correlation receiver technique is used with a 70 MHz local oscillator. A fixed delay line followed by a variable delay line, consisting of a programmable microwave switch array, cables of different lengths, a programmable attenuator and a microwave amplifier, is used in the correlation receiver to obtain range profiles. This variable delay line provides constant output power with 128 delay steps having a 1-nsec time delay interval. A down range resolution of 60 cm is obtained from the 250-MHz system bandwidth.

We are currently enhancing the system by adding polarimetric image acquisition and processing capability. This is accomplished by incorporating a microwave switch in the transmit channel for automatic switching between horizontal and vertical transmit polarizations. The correlation receiver contains two polarization channels to simultaneously process the target co-polarization and cross-polarization returns. In this manner, fully polarimetric target scattering data are acquired. A 10-m high boom van is used as the operation platform for the FOPEN random noise radar system. The variable delay line provides a down range scan of 19.2 meters. Data are collected from different locations in cross-range and then processed using SAR signal processing algorithms. This results in fully polarimetric SAR images consisting of HH, VV, HV and VH polarization images. The images are further processed to reduce speckle and increase the contrast between the target and the background, and to enhance the 2-D image resolution using spatially variant apodization (SVA) filtering algorithm.

Application of an Acousto-Optic Correlation Receiver in Ultra-wide Bandwidth Random Noise Radar

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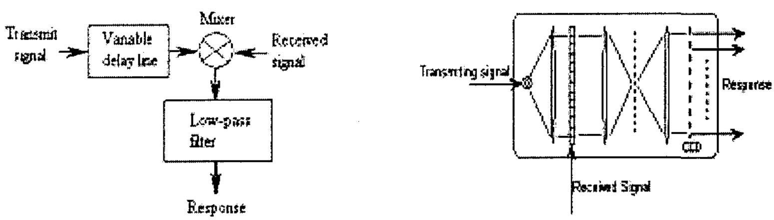
The University of Nebraska has developed a new technique that permits coherent processing of backscatter data acquired by a radar system that transmits UWB random noise waveforms and receives the returned signals using a heterodyne correlation receiver. This technique has been used in various applications, such as Doppler estimation and interferometry, buried object detection, SAR/ISAR imaging, foliage penetration imaging, and so on. In such a radar system, the correlation receiver consists of a programmable variable delay line, a mixer followed by a low-pass filter, as shown in Figure 1(a). One drawback of this type of receiver is that it sequentially processes the target returns, thus limiting the system response time and the dynamic detection range.



(a) Conventional correlation receiver. (b) Acousto-Optic correlation receiver.
Figure 1: Correlation receivers for coherent random noise radars.

In this work, a novel heterodyning Acousto-Optic (AO) correlation receiver that uses an optic correlator consisting of an AO deflector and its correlating signal processing, as shown in Figure 1(b), are developed. In this case, the operation can be viewed as a matched filtering of the optic and acoustic signals, and the real time-integration is supplied by the output photodetector array. The principal advantages of this new AO correlation receiver are its ability to generate a large range of variable delays, as well as to correlate the signals in parallel. Compared to the conventional sequential correlation receiver using a variable stepped delay line and correlator in the random noise radar system, by implementation of the AO variable delay and heterodyning correlators, the system delay is reduced due to the parallel correlation mechanism, and the number of range cells is greatly increased depending on the resolvable spot of the AO deflector.

BROADBAND TEM HORN ANTENNA FOR PULSE RADAR

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One of the current projects at the University of Liverpool is to develop a pulse radar system for obtaining the dielectric properties and thickness of the walls and ceilings of a building. Such parameters are needed to characterize the radio channel for indoor wireless communications.

One of the most critical parts of the system is the antenna, which has the most contribution to the performance of the system. The antenna should satisfy following three requirements:

1- To operate in the frequency range [300 MHz, 3 GHz], i.e. a wideband antenna.
2- To be directive and have low side lobes. This will result in more accurate measurements by decreasing the diffraction at the edges of the material under test and unwanted reflections from the surrounding objects.
3- To have a small size in order to make the system portable.

TEM horn is known to be wideband and especially appropriate for impulse radiation. In this paper, we present the design of a TEM horn that satisfies the above requirements to some extents.

The antenna consists of two parts: the TEM horn itself and a tapered balun that feeds the TEM horn. The guidance on TEM horn design is limited and there has been so far no full theoretical analysis of this structure. Thus, a trial and error optimization process, combining the analytical and numerical methods, is adopted in this work. Approximating the TEM horn as a non-uniform transmission line, the geometry of the antenna is first determined using the analytical formulation for the transmission line. The geometry is such that the minimum reflection occurs at the feed point. Then, the antenna is simulated by FDTD method and its characteristics (e.g. VSWR) are obtained accurately. Analyzing the FDTD results, the parameters of the design are modified and the process is repeated until the desired characteristics are achieved. The final design is a TEM horn having 32 cm length and loaded by a dielectric with the permittivity of 2. The dielectric loading offers two advantages: 1) reduction in the antenna size and 2) a solid support for the antenna plates.

For the most reported designs, the RF power is delivered to TEM horns directly via a coaxial connector. Because a coaxial cable is an unbalance transmission line and a TEM horn is a balance antenna, the direct connection introduces two different currents (unbalance currents) on the plates of the antenna and also induces the currents upon the outside of the cable. These result in an unpredictable skew radiation pattern together with the degradation of the VSWR. In order to mitigate these deleterious effects, a tapered balun is employed in this work. This balun has the advantages of being wideband and mechanically suitable for connecting to TEM horns over other baluns. The design of the balun is based on a near-optimum impedance profile that provides low reflection for maximum bandwidth at the balun input. Using FDTD simulation, the cross section of the balun along its length is determined such that the characteristic impedance satisfies the optimum profile. Similar to the TEM horn, the designed balun is loaded by a dielectric with $\varepsilon_r = 2$, which makes the length of the balun reduce to 18 cm.

The whole system is built and its characteristics, comprising the VSWR, E and H plane radiation patterns, are measured. The VSWR is smaller than 3 from 300 MHz up to 10 GHz, which is better than we expected.

A NOVEL LOW-COST TRANSMITTER FOR ULTRA-WIDEBAND RADAR

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ABSTRACT

Ultra-wideband (UWB) radar – operating based on nonsinusoidal signals such as impulse or monocycle-pulse – has demonstrated and received significant interest as an effective sensor for many applications such as mine detection, foliage penetration, low-probability interception, small-RCS target detection, etc. One of the most important subsystems in an UWB radar is the pulse transmitter.

We report on the development of a novel UWB, ultra-short pulse transmitter using microstrip lines, step-recovery (SRD) and Schottky diodes, MESFET, and MMIC amplifier. SRD is used to form a step function necessary for the generation of the monocycle pulse. A novel impulse-shaping network using MESFET is employed to achieve several unprecedented advantages. First, the MESFET impulse-shaping network converts the input voltage source into a current source, which drives the SRD and hence allows the generation of the monocycle pulse's half-cycle with very little distortion. Second, it facilitates a broadband matching to the transmission line. This permits the use of high pulse repetition frequency (PRF) up to the limit of the employed SRD, which, in general, is several hundred MHz. The use of this novel impulse-shaping circuitry thus makes this newly developed transmitter more suitable for a system. Additionally, a wide-band MMIC amplifier is used in the transmitter for amplification and isolation. The transmitter is realized on microstrip lines for low-cost manufacturing and produces monocycle pulses with 300-ps pulse width, about 2-Volt peak-to-peak amplitude, a pulse repetition rate of 10 MHz, small ringing level, and good balance between the positive and negative half-cycles.

The developed transmitter has been used in a short-range UWB radar for nondestructive subsurface sensing.

Radiation Characteristics of Field Radiated From and Received by Resistively Loaded Thin Half-Wave Coplanar Orthogonal Dipoles Excited by Ultra Wide Band (UWB) Signals

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Abstract

Characteristics of the radiated electric field in free space at far distance from resistively loaded thin half wave coplanar orthogonal dipoles excited by pulses are investigated. The receiving antenna consist of thin half wave resistively loaded coplanar orthogonal dipoles situated at a far distant point, not necessarily in the same plane of the transmitting coplanar dipoles. It is shown that the radiated field can become circularly polarized in the broadside direction $\theta = \varphi = 90^o$ degrees when the exciting input voltage is sinusoidal and the input to the x-axis dipole is the same as the input to the z-axis dipole but delayed by a quarter of a cycle.

The Wu-King (T.T. Wu and R.W.P. King, IEEE Trans. Antennas and Propagation, Vol. 13 pp. 369-373, 1965) loading profile is considered here. The far field of the loaded orthogonal dipoles excited by the finite number of sinusoids (N cycles) to each dipole is derived. The carrier frequency f_0 corresponds to the dipole's common length and the input to the x-axis dipole differs from that of z-axis dipole by a quarter of a cycle. That is the inputs are separated in time by $0.25/f_0$. When the input is fed directly into the dipoles and the observed direction is broadside, the time-domain field is extended in time to $(N+0.5)/f_0$ with respect to the duration of the source N/f_0. And circular polarization occurs only for the interval $(N+0.5)/f_0$.

For UWB case ($N = 1$), the radiated field's duration is 1.5 times the duration of the source and circular polarization occurs only for two-quarter period of the source (i.e. two-quarters of a cycle). This is different from that of the unloaded orthogonal dipoles case (E.L Mokole, A.K. Choudhury and S.N. Samaddar, Radio Science, Vol.33, No.2, pp. 219-229, March-April 19981). In the case of unloaded orthogonal dipoles when the dipoles and the feed network are perfectly matched and the observation direction is broadside, the time-domain field is extended to $(N+0.75)/f_0$ with respect to the duration of the source N/f_0. The circular polarization occurs for $(N+0.75)/f_0$. For the UWB case ($N = 1$), the radiated fields duration is 1.75 times the duration of the source, and the circular polarization occurs only for one-quarter of the period of the source.

Similar results are derived for voltages out of resistively loaded receiving antenna and compared with the corresponding results of the unloaded case. This paper sheds new knowledge on radiation characteristics of resistively loaded orthogonal dipoles and is an extension of earlier work by Mokole, Choudhury and Samaddar mentioned earlier.

Propagation in Inhomogeneous Media

Co-Chairs: *W. Feliciano, NASA Glenn Research Center, USA*
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KA-BAND AND V-BAND PROPAGATION EXPERIMENT IN THE TROPICS

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Abstract - Since the early years of satellite telecommunications, the evolution of systems has lead to a strong increase in satellite capacity, a decrease of boarded equipment size and a significant cost reduction. From the technical point of view, the congestion of primary allocated frequency bands resulted in the use of higher and higher bands from L, S or C bands to X and Ku bands, and in the near future up to Ka, V and EHF bands. One of the main concerns with these higher frequency bands is the influence of the atmosphere on radiowave propagation. Until now, some studies have shown that the feasibility of such links seems to be guaranteed, especially in the Ka-band. Several propagation experiments have been conducted, mainly in mid-latitude climates, with the OLYMPUS, ITALSAT, and ACTS satellites. However, it is still necessary to determine what service availability will be supplied to the user, and to predict the behaviour of these systems when affected by high fading conditions. In particular, the knowledge on propagation conditions in wet climates has to be improved.

Satellite telecommunication links in the EHF band are disturbed by tropospheric phenomena, which can degrade severely service quality. First, attenuation is caused by atmospheric gases (mainly oxygen and water vapour), by clouds (liquid water and ice particles) and by precipitation (hail, snow and particularly rain). Scintillation appears as rapid fluctuations of signal amplitude or phase caused by tropospheric turbulence in clear sky conditions or by precipitation. Depolarisation is due to non-symmetrical particles such as rain drops, snow flakes and especially ice particles.

To achieve prediction of such impairments, two kinds of models are available: statistical and deterministic ones. Statistical models, like ITU/R recommendations, use a semi-empirical approach and are quite well suited for systems studies. Deterministic models are based on a physical description of phenomena, and therefore allow a better understanding of propagation effects. Input parameters are not always available for these models, so they are more adapted to in-depth case studies.

Until now, these statistical models have been validated up to Ka band (20/30 GHz) in temperate areas, in particular with the OPEX (OLYMPUS Propagation Experiment) campaign. Currently, the ITALSAT propagation experiment studies the validity of these models in the EHF band (40/50 GHz) in European countries. The ACTS campaign was concerned with the Ka-band (20/29 GHz) in the U.S.A.

The Ka- and V- band propagation experiment in the tropics will utilize either the EHF propagation payload on the French STENTOR satellite or the United States' GBS satellite. Both of these satellites contain a Ka-band beacon and STENTOR also contains a V-band beacon. The propagation data will be collected by locating a ground terminal in Puerto Rico, which is located in a tropical rain region. The results from this experiment will be used to improve the statistical models in these higher frequency bands in wet climates.

New knowledge statement: High frequency propagation model validation will be enabled by the measured data collected in this experiment in tropical rain zones. Previous work, such as the ACTS Propagation Campaign, only contains data taken in dry to semi-tropical rain zones.

Electromagnetic fields of circular loop placed near to a planar interface

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Components of the vector electromagnetic fields of the horizontal and vertical circular loops above and under a planar interface between two mediums (air-sand, air-salt water and air-metal) were expressed as spectrum of plane waves and calculated. The spectral analysis is based on knowledge of the incident electric field (field of the isolated loop) on the planes enclosing of the loops (Glenn S. Smith, IEEE Trans. on Antennas and Propagation, 232-246, AP-32, March 1984). It was assumed that the uniform current excites in air placed loop of the radius a. Analysis was carried out for the electrically small loops provided that $k_0 a << 1$ where k_0 is wave number in air. Another parameters were varied in the ranges: operating frequency from 1.0×10^5 to $1.0\times10^6 Hz$, radius a of loops from 0.005 to $0.3m$, height H of loops above the surface from 0.4 to 0.6 m. The resulting integrals are evaluated numerically. Accuracy of the field calculation is checked by comparison of the obtained values of the incident field components with the values of components of the magnetic dipole electromagnetic field, which can be calculated analytically. It was found components of the spectral-density function. It is shown that the plane wave spectrums of electromagnetic field of horizontal and vertical isolated loops are different and consist of spectral components that represent evanescent waves in the normal direction to the surface. It was investigated properties of the reflection and transmittance coefficients in spectral domain. The results of investigation can be used in practice in all cases when are used low frequencies and circular loops of small electrical size. It can be, for example, medicine; nondestructive testing of materials and articles (Eddy current tomography); the covered mine imaging and another applications.

Thus it can be concluded that new knowledge about distribution of the vectors components of electromagnetic fields of considered circular loops placed near to the planar interface of two mediums is presented in this paper. This work can be considered as continuation of investigations of the circular loop antennas placed near to a planar interface.

Disbond Detection and Thickness Evaluation in Layered Composites Using Active Near-field Microwave Nondestructive Testing Techniques

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The use of near-field microwave and millimeter wave nondestructive testing methods, utilizing open-ended rectangular waveguide probes, has shown great potential for detecting air disbond in layered dielectric composites, which is of great interest in many industries such as aerospace, construction, and rubber production. Some examples are the shuttle heat tiles, rocket boosters and honeycomb structures. The sensitivity of the disbond detection is strongly influenced by the proper choice of parameters such as the operating frequency, standoff distance and the layered composite geometry (conductor backed or terminated by an infinite half-space of air). A recent investigation showed that disbond could be detected using active near-field microwave nondestructive testing and evaluation techniques. In this investigation, our target is to improve the detection sensitivity of the presence of disbond in layered composites and estimate its thickness. Consequently, an electromagnetic model that simulates the interaction of fields radiated by an open-ended rectangular waveguide aperture with layered structures is utilized to come up with an optimal set of parameters for disbond detection. To enhance the detection sensitivity, the standoff distance was replaced by an optimized dielectric layer with known properties. Results show drastic improvement in the measured parameters (magnitude and phase of the reflection coefficient at the waveguide aperture) indicating enhanced detection of the presence of disbond. To estimate the thickness of disbond, an empirical mixing model describing the effective dielectric properties of the media in front of the waveguide was obtained. This mixing model is found using the dielectric properties and thickness of the composite layers, the dielectric property of disbond layer as well as the measured reflection coefficient. The dielectric properties of disbond and other composite layers are fixed and only the thickness of disbond can change. Thus, using the mixing model principle, the thickness of disbond can be obtained. If the thickness of more than one disbond were of interest, the use of measurements at different frequencies can resolve the problem. The results of an experimental investigation on detecting the presence and evaluating the thickness of very thin disbond layer (0.01 mm - 0.08 mm) using an open-ended rectangular waveguide probe will also be presented.

Special Session

EM Modeling and Inversion for Geophysical Applications and Non-Destructive Testing

Organizer(s): *J. Goswami, Schlumberger Oilfield Services, USA*
T. Habashy, Schlumberger-Doll Research, USA

Co-Chairs: *J. Goswami, Schlumberger Oilfield Services, USA*
T. Habashy, Schlumberger-Doll Research, USA

An Overview of Electrical and Electromagnetic Techniques Applied to Logging While Drilling

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Logging While Drilling (LWD) is a relatively new and rapidly growing technology used in the exploration for oil and gas. Special drill collars containing sensors, electronics, power supplies and a telemetry system are located just above the drill bit. In LWD applications, electrical, electromagnetic, nuclear, acoustic and magnetic resonance measurements help determine whether a formation contains hydrocarbons, the quantities present, and whether they can be produced economically. Using real-time formation measurements, critical decisions can be made to optimize the drilling process and properly position the well in a safe and efficient manner. Because the drilling environment includes high pressures, high temperatures, great mechanical forces, severe abrasion and erosion, and high shock levels, sensors and electronics must be extremely rugged to survive.

Sedimentary rock formations can vary in resistivity by many orders of magnitude (typically 0.1 to 20,000 ohm-m), depending on the relative volume of pore space and whether the pore spaces are saturated with water or hydrocarbons. For this reason, electrical and electromagnetic measurements are the most important and ubiquitous of all LWD measurements.

Introduced in 1980, the first Logging-While-Drilling electrical measurement used two electrodes on an insulated section of drill collar to measure formation resistivity. This crude system had many deficiencies, and was surpassed in the late 1980s by electromagnetic propagation measurements. The velocity and attenuation of 2 MHz electromagnetic waves in typical sedimentary rock formations are related primarily to formation resistivity, and only weakly related to formation dielectric permittivity. A system with an axial arrangement of loop antennas on a drill collar provides a good radial depth of investigation with good axial resolution, and can operate in a conductive or insulating wellbore fluid environment. LWD electromagnetic propagation technology advanced quickly in the 1990s with multiple antenna arrays and multiple frequency operation. Considerable effort has also been devoted to modeling and interpreting these measurements in complex 3D geometries with anisotropic formations.

In the early 1990s, another LWD electrical measurement was introduced that is capable of very high spatial resolution. An electric potential is applied to the drill collar using toroidal coils, and resulting electric currents are measured in several locations on the collar. The current emitted from the drill bit provides the earliest measurement of formation resistivity. Radial currents emitted from the drill provide precise readings in thin geological beds and help determine axial and azimuthal variations in resistivity. The resulting 2D electrical images can be interpreted to yield important geological and geo-mechanical information.

Characterization of LWD Antennas Shield Effects

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The EM efficiency of Logging-while-drilling (LWD) resistivity tools is affected by the fact that tool has to be mounted on metallic drill collar, and antennas have to be covered by metallic shields. Shields not only protect the coils mechanically but also act as secondary sources and polarize the EM field.

Existing resistivity tools are designed to allow propagation of only longitudinal component of magnetic field, created by axially wound coils. Slots cut the flow of induced current in the shield, therefore make the shield EM transparent, producing axial magnetic dipole field pattern. Antennas with non-axial magnetic dipole orientation and transverse magnetic dipole (TMD) antennas are fundamental building blocks for 3-D measurements. Two new antenna concepts have been recently proposed: using shields with sloped slots and shields with transverse slots, combined with saddle or tilted coils.

Because of complexity of the geometry, characterizing interactions of EM field with metallic structure and surrounding medium is a non-trivial task. Commercial 3D time-harmonic FEM package has been used to characterize antennas with different shields. We investigated the dependence of responses on the inclination of slots, number and distribution of slots, shape of the metallic groove, conductivity and frequency.

Fig. 1 shows the distribution of magnetic field components from TMD antenna and x-directed point magnetic dipole. Results confirm that the TMD representation of such antenna is valid, for computation of field about 3 coil dimensions from the antenna.

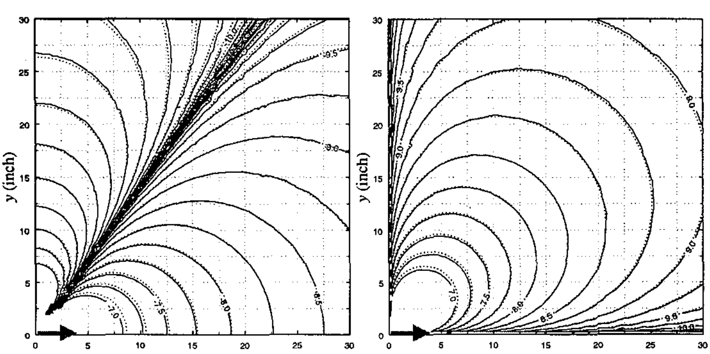

Figure 1: Field pattern of TMD sensor compared to x-directed point magnetic dipole field (dotted lines). B_x (left) and B_y (right) are shown in the plane z=0.

Approximations to EM scattering based on natural preconditioners of the Method-of-Moments' stiffness matrix: applications to the probing of subsurface rock formations.

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Tarek M. Habashy, Schlumberger-Doll Research
Sheng Fang, Baker Atlas

Volume integral equations are often used to numerically simulate electromagnetic (EM) scattering problems. Such equations provide a solution for the EM fields both inside and outside scatterers embedded within an arbitrary background medium. The method of moments (MoM) has been extensively used to solve volume integral equations. In this paper, we present a systematic study of some of the solution properties of the linear system associated with the MoM's stiffness matrix. Our work follows from the ever-pressing need to solve large-scale EM scattering problems in an efficient and accurate manner, especially in connection with geophysical inverse problems. Specifically, we construct a set of natural preconditioners of the MoM's stiffness matrix and illustrate how different adaptations of such preconditioners may yield, as special cases, partial solutions equivalent to Born (Born, 1933), Extended Born (Habashy *et al*, 1994), and Quasi-Linear approximations (Zhdanov and Fang, 1996), for instance. More efficient and more accurate partial solutions can be constructed with preconditioners that take into account both the size and spatial distribution of the pulse-basis functions (or conductivity cells), as well as the proximity of the source(s) and receivers to the scattering media.

Several examples are presented to illustrate the efficiency of simple Jacobi (diagonal) preconditioners that take into account the properties of the background (source) field. We illustrate the ability of these preconditioners to synthesize, in one single iteration, a significant component of the scattered (secondary) fields otherwise attainable only with rigorous MoM solutions. We also show that the preconditioners can be used to accelerate the solution of rigorous MoM solutions via repeated iterated schemes. The novelty of our preconditioners is that their construction is based on a physical understanding of the underlying EM scattering problem. We present examples drawn from two- and three-dimensional scattering problems arising in the subsurface probing of rock formations. Special consideration is paid to the role played by the scattering size, the probing frequency, the conductivity contrast, and the proximity of the source to the scattering medium. Our tests show that a single iteration with a Jacobi preconditioner can yield scattering solutions that favorably compare in accuracy with rigorous MoM and finite-difference solutions. However, a single iteration with a general Jacobi preconditioner may result in at least a ten-fold increase in computer efficiency compared with rigorous MoM solvers. Finally, we show examples of how MoM preconditioning methods can be used to accelerate the solution of large-scale inverse problems.

3D EM Induction Imaging for Buried Object Detection and Identification

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In this work we investigate the inverse problem of three-dimensional lossy media by using electromagnetic induction (EMI) measurements. EMI is an important technique for geophysical subsurface sensing. Applications of EMI subsurface sensing include resources exploration, environmental site characterization, detection and characterization of landmines and unexploded ordnance (UXO). In oil exploration, induction tools are also used inside a borehole to measure the conductivity distribution in rock formations.

In the past two decades tremendous efforts have been made in two- and three- dimensional inversions based on forward solvers to reconstruct the conductivity distribution. Recently we had successfully developed two-dimensional contrast source inversion (CSI) method by using EMI measurements in which we employ Polak-Ribiere procedure combined with FFT to enhance the efficiency, where forward solver is avoided during the inversion. For the two-dimensional CSI method, the CPU time is $O(N \log N)$ and memory is $O(N)$ where N is the number of unknowns. However, three-dimensional effects are often encountered where two-dimensional model does not suffice to describe the structures in such cases.

The main contribution of this work is to apply the CSI method to the three- dimensional inversion of conductivity for buried object detection and identification. The cost functional is composed of two parts in the reconstruction procedure. One is from the state equation which describes the vector scattering field. Another is from measured data which defines the measured scattering field. By using Polak-Ribiere conjugate procedure, we can minimize the total cost functional to an acceptable value to find three-dimensional complex conductivity distribution. The memory and CPU time costs are the same as two-dimensional conductivity imaging in terms of the number of unknowns.

The measured data come from the forward solution in which we use weak-form biconjugate gradient FFT method to simulate the three-dimensional electromagnetic fields. In the inversion, the initial solution is obtained through the back propagation. Since this inversion is a highly ill-posed problem, we adopt a recently proposed minimal total variation to enhance the resolution of the three-dimensional complex conductivity. Applications in landmine detection will be demonstrated.

Special Session

Novel Challenges with Electromagnetic Bandgap Surfaces I

Organizer(s): *P.-S. Kildal, Chalmers University, Sweden*
N. Engheta, University of Pennsylvania, USA

Co-Chairs: *P.-S. Kildal, Chalmers University, Sweden*
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SOFT AND HARD SURFACES BY THE PHYSICAL APPROACH, THE IDEAL PEC/ PMC STRIP MODEL, THE IMPEDANCE BOUNDARY CONDITION, AND THE ASSYMPTOTIC BOUNDARY CONDITIONS

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The concept of soft and hard surfaces in electromagnetics was defined in 1988 (P-S. Kildal, Electronic Letters, Vol. 24, No. 3, pp. 168-170, 4th February 1988) and 1991 (P-S. Kildal, IEEE Trans. Antennas Propagat, vol. 38, 10, pp. 1537-1544, Oct. 90). Since then, more than 100 papers refer to these two first papers. The concept has got renewed interest the last years in relation to work with PBG materials, so the number of references continue to increase. The concept is special in the sense that it originates as a way of thinking to solve antenna problems, at the same time as it has a solid foundation in acoustics and diffraction theory. The citations range therefore from purely theoretical papers to applications.

The purpose of the present paper is to summarize the concept in view of recent years work on electromagnetic bandgap materials. The original physical approach which is useful when designing antennas and solving practical antenna problems will be described. This makes use of the so-called **ideal soft and hard boundary conditions**. These are simple to use for physical explanations of the radiation characteristics, but unfortunately they are not very convenient to use in analytical and numerical work, as they apply to the tangential component of the field for one polarization and to the normal for the other. The last years we have instead started to use an **ideal PEC/PMC strip model** in analytical and numerical work. Such a surface of parallel and infinitely thin PEC and PMC strips defines a soft or a hard surface, depending on the orientation of the strips relative to the propagation direction of the waves. Transverse strips represent a soft and longitudinal strips a hard surface, respectively. The ideal strip model represents a simple physical image, of an anisotropic surface with electric and magnetic conductivity in one direction only, and has the advantage over the original boundary condition that it applies entirely to tangential fields. It should be noted that the two ideal surface models are not ideally equivalent.

The ideal boundary conditions and strip model are good for initial work, in order to find a possible design and check which performance is theoretically available, respectively. Thereafter, we need to consider the realization of the soft or hard surface, which may be a very difficult task. The realizations that have been considered the most are metal corrugations or metal strip-loaded grounded substrates. Transverse corrugations and strips are used for soft surfaces, and longitudinal dielectric-filled corrugations and strips for hard surfaces. Corrugations are traditionally analyzed by **impedance boundary conditions (IBC)**, but these are inconvenient and inaccurate due to their angle-of-incidence dependence. Therefore, we developed **asymptotic strip and corrugation boundary conditions** that do not suffer from the limitations of the IBC. Their main assumption is that the period of the strips or corrugations is zero. They correspond to what in classic electromagnetic theory is referred to as a uni-directional current screen, and nowadays is referred to as a homogenized boundary condition. And, they are VERY easy to implement in software and use in analytical work. The computer time is the same as when analyzing for instance a dielectric interface. The full wave analysis of a realization of a soft and hard surface will normally involve a detailed modelling of each strip or corrugation in the geometry, or alternatively expanding the solution in Floquet modes. Both these approaches are very time-consuming in numerical work.

The paper will summarize the above described approaches.

GREEN'S FUNCTIONS OF SOFT AND HARD SURFACES DERIVED BY ASYMPTOTIC BOUNDARY CONDITIONS AND HOMOGENIZATION METHOD

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The concept of soft and hard surfaces has been introduced in electromagnetic theory to help engineers in designing antennas and electromagnetic structures (P.-S. Kildal, IEEE Trans. Antennas Propagat., 1990, pp. 1537-1544). In principal, the power density along the soft or hard surface has respectively a null or a maximum. The two most common realizations are the corrugated surface and the strip-loaded grounded dielectric slab.

We have performed the rigorous analysis of open soft and hard surfaces using Floquet-mode expansion/moment method approach. If the source excites a full spectrum of plane waves, such as a dipole, the rigorous analysis is a laborious process. A simpler approach is to use approximate boundary conditions. We have used two types of approximate boundary conditions: the asymptotic boundary conditions for strips and corrugations (ASBC and ACBC, respectively), and boundary conditions obtained by the homogenization method (BCHM), i.e. by averaging the fields of the fundamental Floquet mode. ASBC and ACBC can be directly applied for analyzing curved surfaces, and in the BCHM case we have used a local planar approximation, that means we supposed that the surface where the strips are located is locally a plane surface.

The purpose of the present paper is to give derivation the Green's functions for soft and hard surfaces, and by that to analyze different realizations of soft and hard surfaces. Strips and corrugations are analyzed using approximate boundary conditions (part of the work is given in Z. Sipus, H. Merkel, P.-S. Kildal, *IEE Proceedings – part H, 1997,* pp. 321-328). Furthermore, we have modified the algorithm G1DMULT that calculates Green's functions of planar, circular cylindrical and spherical general multilayer structure. By this one can analyze general multilayer structures with strips or corrugations as one layer.

We have studied the fulfillment of the soft and hard boundary conditions in the near and far field regions. Special attention is given to the properties of surface waves that obstruct the fulfillment of these boundary conditions. The results show that the both approximate boundary conditions give good results when the period of the strips is small compared to the wavelength. However, BCHM gives more accurate results, and practically there is no difference between the moment method results and the results obtained by BCHM method if the periodicity is small enough. Numerical results are also compared to measurements showing a very good agreement.

Generalized soft-and-hard boundary conditions

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Soft-and-hard surface (SHS) is a mathematical idealization of the tuned corrugated boundary. The boundary conditions require vanishing of the electric and magnetic field components along a certain direction on the boundary. This direction can be characterized by a real vector **a** lying on the plane tangent to the boundary so that the conditions are **a.E**=0 and **a.H**=0. In the generalization discussed here we assume that the conditions be of the more general type **a.E**=0 and **b.H**=0, where both **a** and **b** may be complex vectors satisfying **n.a**=**n.b**=0, where **n** is a real vector normal to the surface. The special case **b**=**a*** was studied earlier by this author and it was shown to correspond to a so-called ideal surface for which the complex Poynting vector of any field has no normal component at the surface.

In the present more general SHS case, it is shown that there exist two eigenpolarizations for the electromagnetic field at the surface. They can be labeled as TE and TM with respect to the respective **a** and **b** vectors. Fields with these polarizations see the generalized SHS as respective perfect magnetic conductor (PMC) and perfect electric conductor (PEC) surfaces. Physical realization of such a generalized SHS can be based on this decomposition principle if we are able to construct a polarization filter separating waves with TE and TM polarization, by terminating the former by a PMC and the latter by a PEC surface. As a practical application of such a generalized SHS we can imagine a polarization transformer in terms of which any incident polarization could be changed to any other polarization for the reflected field.

UTD Coefficients for Edges in Artificially Hard and Soft Surfaces Illuminated at Oblique Incidence

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Artificially hard and soft surfaces [P.-S. Kildal, *IEEE Trans. Antennas and Propagat.*, vol. 38, pp. 1537-1544, Oct. 1990] have been widely used in microwave antenna technology as, for instance, in realizing hybrid-mode feed horns or reflector antenna struts for minimum blockage. They are usually implemented either by suitably corrugating a metallic plane and then filling the corrugations with a dielectric material or by employing grounded dielectric slabs loaded by metallic strip gratings.

The scattering properties of infinite surfaces of the above kind can be accurately analyzed by suitable numerical techniques, exploiting the periodicity of the structure. However, from an engineering point of view, a problem of remarkable importance for the simulation of actual configurations consists in accounting for the effects due to the finite extension of such surfaces. In the high-frequency region, when the dimensions of objects become much larger than the free-space wavelength, ray techniques as for instance the Uniform Geometrical Theory of Diffraction (UTD) are needed to efficiently solve the problem. In this context, homogeneous anisotropic Impedance Boundary Conditions (IBCs) can be used to account for the material properties of artificially hard and soft surfaces, being the period of the structure much smaller than the free-space wavelength. The corresponding surface impedance tensor exhibits a vanishing impedance value in the direction of corrugations or strips and a nonzero value (very high at those frequencies at which the artificial surface has been designed) in the orthogonal direction [G. Manara *et al.*, *IEEE Trans. Antennas and Propagat.*, vol. 48, pp. 790-800, May 2000].

This paper is aimed to discuss the solutions to all those canonical anisotropic impedance wedge problems that can be used in engineering applications to describe the three-dimensional scattering of arbitrarily polarized plane waves from edges in artificially hard and soft surfaces. The difficulties encountered in analytical solution procedures are due to the fact that the anisotropic IBC's holding on the wedge faces couple the components of the electric and magnetic field parallel to the edge, which are commonly used as potential functions to express all the other field components. The high-frequency expressions for the fields can be cast in the standard format of the UTD. Samples of numerical results are shown to demonstrate the effectiveness of the solutions proposed.

METAMATERIAL REALIZATIONS OF PERFECT MAGNETIC CONDUCTORS

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In the past few years, there has been a renewed interest in using subwavelength structures to develop materials that mimic known material responses or that qualitatively have new response functions that do not occur in nature. One of the more interesting potential applications is the construction of metamaterials that produce perfect magnetic conductor (PMC) responses. Numerous applications abound for such a class of metamaterials, particularly in relation to antenna design and performance.

Metamaterials are often generated by artificially fabricated, extrinsic, low dimensional inhomogeneities in some background substrate. Several metamaterial designs have been conceived and modeled with both Ansoft's High Frequency Structure Simulation (HFSS) tools (FEM based) and Finite Difference Time Domain (FDTD) simulators. They demonstrate the possibility of realizing PMC's with subwavelength inclusions in Roger's 5880 DUROID (ε_r=2.2). Theses designs will be reviewed and contrasted. Simulations of the use of these PMC metamaterials in antenna applications will be given.

An inversion approach has been developed based upon well-known techniques to extract the effective permittivity and permeability behavior from the simulated S-parameter results. This approach will also be reviewed briefly. It will be used to demonstrate that the PMC behavior occurs where the metamaterial exhibits a large negative permeability. The form of the response will be shown to be that of a Two Time Derivative Lorentz material.

Several of these PMC metamaterials have been fabricated and tested experimentally with a free space X-band measurement setup. The measurement methods will be reviewed. The results of these PMC metamaterial experiments will also be discussed. They confirm the simulation results and provide indications that these PMC metamaterials may indeed be very suitable for antenna applications.

Useful Reflection Surfaces on Bulk Electromagnetic Metamaterials

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The surface properties of materials placed nearby a radiating element strongly influence the resulting radiation pattern. In recent work, patterned surfaces and artificial materials have been introduced whose surface impedances are large over a limited bandwidth, approximating perfect magnetic conductors (PMC) (Sievenpiper *et al.*, *IEEE MTT*, **47**, 2059, 1999; Yang *et al.*, *IEEE MTT*, **47**, 1509, 1999). While patterned and frequency selective surfaces can be utilized to tune the surface impedance over a useful range, the metamaterial concept can also be applied, and may provide an alternative route to designing surfaces with desired characteristics.

An optimal reflection device would be thin (in relation to the operating wavelength) and possess a desired reflection coefficient, such as having a near unit magnitude (low loss) and a desired phase in the range of π (normal mirror/electric conductor) to zero (magnetic mirror/magnetic conductor). It is possible to implement these requirements from a theoretical bulk material using simple but realizable material response functions for the magnetic permeability μ and electric permittivity ε. The parameters of these material response functions can be optimized to obtain small penetration depths (thin device), near unit reflection coefficient magnitude and any desired reflection phase.

Electromagnetic metamaterials are structured materials whose bulk properties are derived from repeated scattering elements that can have magnetic or electric characteristics. The resulting permeability and permittivity generally are characterized by frequency-dispersive Lorentz (or "plasmonic") forms. An example of such a medium is the Left-handed metamaterial, which makes use of split ring resonators to achieve a magnetic response and thin wires to achieve an electric response (D. R. Smith *et al.*, *Phys. Rev. Lett.*, **84**, 4184, 2000). By choosing the geometrical parameters for the underlying elements, the impedance (the square root of the product of ε and μ) can be tuned over a substantial range. While the resulting material does not necessarily reject the surface modes that are problematic for antenna applications, the design procedure may offer conceptual advantages, and can be extended to address surface modes.

Anisotropic PBG Surface and its Transmission Line Model

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Recently, a novel anisotropic uniplanar microstrip PBG structure, with a ground plane comprising a periodic array of slot resonators, was proposed in (C. Caloz et. al, European Microwave Conference, vol. 2, pp. 185-187, 2001). This structure is characterized by a propagation direction and an attenuation direction (anisotropy), the existence of deep/sharp gaps in the attenuation direction, insensitivity to the line position due to effective impedance behavior (period $<< \lambda$) in both directions, extremely low stop-band radiation, and very high compactness corresponding to a surface of the order of $\lambda/2 \times \lambda/7$.

A tapered version of the structure was also investigated and shown to exhibit in addition an unprecedented gap bandwidth (C. Caloz et. al, IEEE-MTT Int'l Symp., 2002, submitted). Thanks to its low-cost and design flexibility, this tapered PBG might be used as a very efficient low-pass filter in several applications requiring high-compactness and/or super-broadband characteristics, such as for instance harmonic termination in power amplifiers.

We revisit here the anisotropic PBG structure and present a deeper and exhaustive characterization of it. In particular, a *transmission line* model is introduced, that both helps gaining a better insight into the behavior of the structure and provides the engineer with a useful design tool, avoiding lengthy full-wave simulations. In this approach, each unit cell is described by the intrinsic series inductance and shunt capacitance of the microstrip line (with values corresponding to those for the total length of the line divided by the number of slots N) in series with an ideal transformer, representing coupling from the line to the patterned ground plane; the transformer is connected to two shorted stubs modeling the slots in the ground plane on each side of the line. This unit cell is then repeated N times in a ladder configuration to model the complete structure. In the case of the tapered PBG, it suffices to adjust the lengths of the consecutive stubs so as to match the lengths of the corresponding slots. The transmission line model proposed can also be used to predict the tuning of gap harmonics obtained by shifting the line off its centered position with respect to the axis of slots.

A transmission line model is possible because the anisotropic PBG does not behave as a conventional PBG: Firstly, the gaps are due to resonances of the transverse slots and not to Bragg-like diffraction (constructive interference of the reflected wave, period $\approx \lambda/2$), that cannot be easily described by lumped elements because it is essentially an inter-cells coupling phenomenon. Secondly, in contrast to many other PBGs, the anisotropic PBG presents a 1D geometry for propagation in both orthogonal directions, which lends itself well to transmission line modeling.

A Mushroom-Like Electromagnetic Band-Gap (EBG) Structure: Band Gap Characterizations and Antenna Applications

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The electromagnetic band-gap (EBG) structures have attracted much attention recently due to their unique electromagnetic features. The EBG structures are typically realized by periodic structures such as dielectric rods, holes and metal patches. They exhibit distinguish band gap features for EM waves, resulting in various applications such as high performance microstrip antennas and low profile antennas. The purpose of this paper is to address some common concerns of EBG structures such as band gap characterizations and antenna applications by summarizing our in-depth investigations of a mushroom-like EBG structure.

EBG band gap characterizations:
The band gap features of a mushroom-like EBG structure are revealed in two ways: one is the suppression of surface waves propagation and the other is the in-phase reflection coefficient. To explore the surface waves suppression effect, the propagating fields of a dipole source with and without the EBG structure are simulated and compared using the finite difference time domain (FDTD) method. A frequency stop band for the field propagation is clearly noticed. To study the in-phase reflection property, a horizontal dipole is positioned close to the EBG structure and a band gap is defined as a frequency range inside which the dipole shows good input match. This result is compared with the plane wave reflection result. It is worthwhile to point out these band gap studies are uniquely tailored for applications.

Antenna applications of the EBG structure:
In light of its band gap features, two types of applications are discussed. First, the EBG structure is integrated with microstrip antennas and arrays on high dielectric constant substrates. Because of its surface wave suppression effect, it can significantly reduce the surface waves, resulting in high gain, low back lobe, reduced mutual coupling designs. Secondly, the in-phase reflection feature of the EBG structure makes it possible to design very low profile antennas. For an example, a curl antenna over the EBG structure is analyzed and fabricated. It demonstrates an attractive low profile as well as CP performance.

High-Impedance Metamaterial Surface using Hilbert-Curve Inclusions

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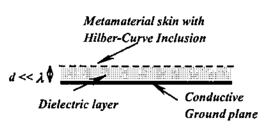
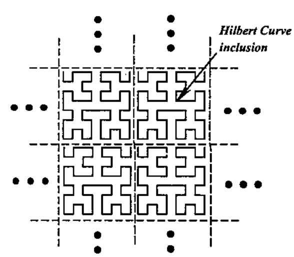
If a surface possesses very high surface impedance, the reflection coefficient for a plane wave incident on it would be $R \simeq +1$ (as opposed to the reflection coefficient $R \simeq -1$ for a usual highly conductive plane). Such a surface may effectively act as a "magnetic conductor" in contrast to the conventional electric conductor for which $R \simeq -1$. These structures can obviously offer interesting applications. For example, for a surface with $R \simeq +1$, it has been shown by Sievenpiper *et al.* that a small dipole antennas can be laid horizontally near the surface, and the image current will be in phase with the antenna current, resulting in good radiation performance [D. Sievenpiper, L. Zhang, R. F. Jimenez Broas, N. G. Alexopolous, and E. Yablonovitch, *IEEE Transactions on Microwave Theory and Techniques*, Vol. 47, No. 11, pp. 2059-2074, November 1999.] There are other interesting potential applications.

In the present study, we explore the possibility of having a metamaterial surface in which many inclusions in the shape of the "Hilbert Curve" are placed, in a 2-D periodic arrangement, on a host surface. (see Figure below.) The Hilbert curve is a member of the family of curves known in the mathematics literature as "space-filling curves". [Hans Sagan, *Space-Filling Curve*, Springer-Verlag, NY, 1994.] One of the interesting features of the Hilbert curve is the fact that as one considers higher step-orders of this curve a long "line" can be compacted into a small "surface" area. As an electromagnetic scatterer, this may provide a structure that, although small in its footprint, it can be resonant at a wavelength much longer than its footprint. Such a "compact resonator" can be quite useful in various applications, e.g., as inclusions for construction of complex media and surfaces. Here we theoretically analyze using the moment-method based numerical approach the electromagnetic wave interaction with a metamaterial surface made of 2-D periodic arrangement of "Hilbert-curve" inclusions, when this surface is closely placed above a highly conducting ground plane. At certain frequencies, the top surface of this structure attains high surface impedance, causing it to effectively behave as a magnetic wall with reflection coefficient $R \simeq +1$. We will present the results of our analysis for several stages of Hilbert curves, and will discuss certain interesting features and potential applications of such structures.



Side View



Top View

Subwavelength hole arrays at microwaves: Analytical modeling

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In this presentation, thin metal sheets periodically perforated by small round holes are theoretically analyzed. One the main motivations for this study was an optical phenomenon of "extraordinary optical transmission through subwavelength hole arrays", recently found experimentally (T.J. Kim et al., Optics Lett., vol. 24, pp. 256-258, 1999) and explained on the base of numerical studies in (L. Martin-Moreno et al., Phys. Rev. Lett., vol. 86, pp. 1114-1117, 2001). In these papers, optical transmission through metal layers periodically punched by holes has been studied and a peak of very high transmission has been found.

In this paper, we consider a microwave analogy of such systems, in form of an infinite sheet of metal with double-periodically located holes, and in form of two such parallel sheets with holes. The known analytical approaches to perforated metal layers are limited to very dense perforations (in terms of the wavelength). At higher frequencies, numerical techniques usually based on the Floquet mode expansion are used. For the goals of this study we needed an analytical estimation of the layer properties in case when the perforation period can be comparable to the wavelength, as that was the experimental situation in the cited papers. In the first part of the talk we will describe a new model, where the interaction between the holes is expressed in terms of a simple analytical function of the frequency and the geometry parameters. This theory uses our previous results for the complementary array of small disks in free space.

The results show that for the sizes used in the corresponding optical experiment, the transmission remains quite small, since there is still no resonant interaction between the holes in the array. This indicates (as was also found by Martin-Moreno et al.) that the layer thickness plays a significant role. Next, using the transmission-line analogy we consider two parallel perforated sheets at a distance close to the thickness of the experimentally studied layer. We have found that in the half-wavelength window regime the transmission through the system is very similar to that observed experimentally at the optical frequencies. From this we conclude that the main factor leading to the high transmission phenomenon in optics can be simply the half-wavelength resonance between the two metal-air interfaces. The explanation given by Martin-Moreno et al. is physically similar, although they have found that the resonance is rather due to resonant transmission through half-wavelength circular waveguide sections formed by each individual hole.

Finally we note that our results can be used in the microwave region to model perforated screens with considerably large periods as compared to the wavelength, as well as stacks of such layers.

Chiral and Complex Environments

Co-Chairs: *E. K. N. Yung, City University of Hong Kong*
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GENERALIZED FOURIER TRANSFORM FOR IRREGULAR STRATIFIED COMPLEX MEDIA

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Using the generalized Fourier Transforms presented in this paper, it is not necessary to assume the usual Raleigh hypothesis associated with rough surface scattering. Electromagnetic scattering involving two semi-infinite chiral materials with a rough interface at $y = h(x)$ is considered here in particular. The Drude-Born-Fedorov constitutive relations for chiral materials are

$$D = \varepsilon(E + \beta\nabla \times E), \quad B = \mu(H + \beta\nabla \times H). \tag{1}$$

On substituting (1) into the time harmonic form ($e^{j\omega t}$) of Maxwell's equations assuming a magnetic line source, $\mathrm{K} = K\delta(x - x')\delta(y - y')e_z$, (where e_z is the unit vector in the z-direction,) yields, after considerable manipulation, the following coupled scalar equations for the (transverse) z-components of the electric and magnetic fields:

$$\begin{aligned} \nabla^2 E_z + \frac{\gamma^4}{k^2}\left(1 + k^2\beta^2\right)E_z - 2j\omega\mu\beta\frac{\gamma^4}{k^2}H_z &= 2\beta\frac{\gamma^4}{k^2}\mathrm{K}\cdot e_z \\ \nabla^2 H_z + \frac{\gamma^4}{k^2}\left(1 + k^2\beta^2\right)H_z + 2j\omega\varepsilon\beta\frac{\gamma^4}{k^4}E_z &= j\omega\varepsilon\frac{\gamma^4}{k^4}\left(1 + k^2\beta^2\right)\mathrm{K}\cdot e_z \end{aligned} \tag{2}$$

where $k = \omega\sqrt{\varepsilon\mu}$ and $\gamma = \dfrac{k^2}{1 - k^2\beta^2}$. Note that k denotes the free space wave number.

The standard Fourier transforms of both equations (2) are found with respect to x followed by the Laplace transforms with respect to y above and below the interface. The resulting algebraic equations are solved for the Laplace-Fourier Transforms of H_z and E_z. Taking the inverse Laplace transforms and imposing the exact boundary conditions for irregular stratified media, yields the Fourier transforms of H_z and E_z. The inverse Fourier transforms are found on deforming the path of integration in the complex plane to obtain transform pairs that can be applied to problems in which the height of the interface and the media electromagnetic parameters vary along the (lateral) x-axis. The fields above and below the interface are expressed as left and right circularly polarized characteristic waves with wave numbers $\gamma_1 = \dfrac{k}{1 - k\beta}$ and $\gamma_2 = \dfrac{k}{1 + k\beta}$. Terms corresponding to the direct, reflected, refracted, lateral and surface waves are identified. The solution to problems with an electric line source can be found by using duality.

Investigation of Negative Permeability, Negative Permittivity and Backward Meta-materials in Waveguide Environment

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Recent introduction of artificial materials with simultaneously negative effective permittivity and negative effective permeability (Smith et. al., Phys. Rev. Lett. (18), 2000) have gained considerable attention. In such a 'backward' (or 'left-handed') material, direction of phase velocity (wave vector ***k***) is opposite to the direction of energy flow (Poynting vector ***P***). This unique property causes reversion of some basic electromagnetic phenomena such as Snell law and Doppler effect. Several ideas for application of new material, such as high resolution electromagnetic lens (Pendry, Phys. Rev. Lett., (18), 2000) and sub-wavelength resonator (Engheta, ICEA 2001 proc., 2001) have already been suggested.

So far, the backward materials have been studied experimentally in free-space environment (or in scattering chamber which simulates free-space propagation). Experimental investigations of waveguide filled with backward material has not been reported yet. On the other hand, a waveguide offers possibility of testing meta-material within a small, closed space, loosing requirements on size of a sample. Some of the results of on-going research on rectangular waveguide filled with backward material will be presented in this talk.

Since the electromagnetic field in dominant (TE01) mode of the rectangular waveguide can be thought of two planar waves, the previously reported artificial two-dimensional materials can be used for filling. In on-going experiments, negative permittivity is achieved using an array of parallel thin wires (Pendry, J. Phys. Cond. Matter., (12), 1998). Both the FDTD simulation and experiments show shift of the cut-off to the higher frequency (comparing with an empty waveguide), due to plasma-like behaviour of negative permittivity achieved by thin wires. Negative permeability is achieved by two-dimensional array of loaded loops (Hrabar et al, ICECOM 2001 proc., 2001) or split ring resonators (Pendry et al, IEEE Trans. MTT, (11), 1999). A waveguide with this structure exhibits very pronounced (>80 dB) stop-band associated with resonance behaviour of negative permeability. The waveguide which contains both thin wires and loaded loops exhibits a pass-band. The pass-band central frequency may be different of central frequency of the negative permeability stop-band. This shift of frequency is caused by interaction between wires and loops. The phase of S_{21} parameter has positive gradient within the pass-band, indicating negative differential group velocity associated with backward propagation. The waveguide T junction filled with prism shaped wire-loop material is simulated using FDTD method. Results verify anomalous reflection at the air-material boundary indicating reversion of Snell law.

Future research efforts will be directed toward experimental investigation of different waveguide components filled with wire-loop structures. The optimisation of the waveguide backward structure, in order to minimise interaction between elements and improve matching, will be attempted. We also envisage to experimentally confirm reversion of Doppler effect in waveguide filled with backward material.

Analysis and Design of Antennas

Co-Chairs: *W. A. Imbriale, Jet Propulsion Laboratory, USA*
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A STUDY OF SIMPLE SELF-STRUCTURING ANTENNA TEMPLATES

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Self-structuring antennas (SSAs) are adaptive antenna systems that use switches to control their electromagnetic characteristics (C. M. Coleman, E. J. Rothwell, and J. E. Ross, *IEEE AP-S Int. Symp.*, Salt Lake City, Utah, 2000). The switches connect wires and patches to create an SSA *template*. An SSA template with n switches is capable of arranging itself into 2^n discrete electrical configurations. Because of the large number of available switch configurations, evolutionary algorithms such as simulated annealing, ant colony optimization, and genetic algorithms are used to search for appropriate antenna states.

The relationship between the shape of the template, the various switch configurations, and the performance of the antenna is not well understood. Although optimal template geometries have been investigated using two-level evolutionary algorithms (C. M. Coleman, E. J. Rothwell, J. E. Ross, and L. L. Nagy, *IEEE AP-S Int. Symp.*, Boston, Massachusetts, 2001), a basic understanding of the dependence of antenna performance on the number of switches remains to be determined.

Research will be presented that concentrates on understanding SSA templates by building from simple to more complicated structures. The number of switches is first kept small enough so that exhaustive searches of the configurations are possible. Switches are then added and random samples of the possible configurations are used to characterize the templates according to input impedance and radiation pattern uniformity. Through this means, an understanding of the capabilities of SSAs and their dependence on the number of switches can be gained.

EFFECT OF SWITCH FAILURE ON THE PERFORMANCE OF A SELF-STRUCTURING ANTENNA

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Antennas are often deployed in difficult environmental conditions, where their physical degradation, alteration, or misuse results in decreased electrical performance. In many consumer applications these antennas are difficult to replace or to repair. A Self-structuring antenna (SSA) is capable of responding to changes in its physical structure or to its environment by altering its electrical shape through the opening and closing of switches on an antenna template. The template consists of conducting wires or patches interconnected by N electronic or electro-mechanical switches that are controlled by a microprocessor. When the operating conditions change, the microprocessor searches through the 2^N possible electrical configurations to find a state with acceptable antenna performance.

The successful operation of an SSA depends on the wide variation of its antenna properties, and this in turn depends on the number and position of its switches. It is anticipated that, over the lifetime of the antenna, one or more of the switches may fail or degrade in electrical performance. The template should be designed in such a way that no switch, or group of switches, is crucial to the effective operation of the SSA. That is, if certain switches fail, the performance of the SSA should degrade in a predictable way, such that it does not fall below some minimum acceptable level.

This paper investigates the effect of switch failure for a standard SSA template (C. M. Coleman, E. J. Rothwell, and J. E. Ross, *IEEE AP-S Int. Symp.*, Salt Lake City, Utah, 2000). Performance criteria such as input impedance, standing wave ratio, and antenna pattern uniformity are examined using both experimental and numerical data. Because the number of template configurations is very large for reasonable values of N, the SSA performance is analyzed statistically, by taking a sample from the total population of template configurations.

Super-Spheroidal Antenna Excited by an Annular Slot

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The slot antenna has been an actively researched over the past several years. It has attractive features such as ease of fabrication, high-power capability and lightweight nature. It is because of these features that the slot antenna is a natural choice for airborne applications. The basic structure of this kind of antenna is a small slot on a conducting plane. The shape of the cavity across which the slot is cut is critical for determining the antenna radiation characteristics. Exact analytical solutions are available only for a limited number of cavity geometries, such as spheres, spheroids, circular cylinders and elliptic cylinders.

In this research, we derive the radiation fields of a super-spheroidal antenna excited by an annular slot. The antenna consists of a conducting super-spheroid and an annular slot on its surface. The motivation for investigating this structure is that super-spheroids are aerodynamic shapes that have various applications in missile, aircraft, and spacecraft design. Furthermore, the geometry of super-spheroids can be represented by a simple parametric equation. The super-spheroidal model can be reduced to a spheroidal or a spherical antenna by appropriately choosing the parameters in the equation. Since the spheroidal and spherical structures maintain mathematical rigor, the solution to super-spheroidal model could be checked both numerically and analytically, which allow us to investigate the effects of geometry variation in a systematic manner.

The solution to the super-spheroidal antenna is obtained, which is expressed in terms of spherical vector wave function expansions. The expansion coefficients are determined by making use of surface integral equations. When the super-spheroid reduces to a sphere, the representations of the fields reduce to the same results as obtained through method of separation of variables.

Modeling of a Frequency Independent Antenna

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E. K. Miller (Santa Fe, USA)

The objective of this paper is to describe the results of numerical and experimental investigations of a planar logarithmic spiral antenna.

Frequency independent antennas are distinguished by the trait that for any frequency a region with fixed electrical dimensions can be found. This though requires infinite physical dimensions. The practical structure is truncated and has a finite feed gap. These facts limit the antenna's upper and lower frequency of operation.

The spiral antenna presented in this paper is realized on the FR4 substrate, which has a dielectric constant of 4.4. The spiral antenna by it self is a fairly simple structure. It consists of two equal arms each one being 1.5 turns and each being defined by a growth rate, an inner, and outer radii. The antenna can be connected directly to a 50 Ω coaxial cable using an wideband balun circuit, that is attached directly to the feed point of the spiral antenna.

The antenna analysis is performed using the commercial available method of moment computer program, IE3D. The result thus obtained are compared with the electromagnetic computer program based on the so-called FARS (Far-field Analysis of Radiation Sources), which was developed by E.K. Miller.

The development of FARS was motivated by the possibility on a quantitative basis to determine where and on a per-unit length or area basis, the far-field power radiated from a PEC (Perfectly Electric Conducting) object originates. Further information about FARS can be found in the open literature.

Two major topics based on the following are to be presented:

1. It is well known that dielectric loading can be advantageous in order to reduce the physical size of an antenna. This important design technique is used in order to meet the size and resonance frequency requirement in antenna design. Unfortunately, dielectric loading of the structure leads to a significant increase in the simulation time and the amount of memory used. In order to make the simulations in a reasonably amount of time the model has to be truncated. The numerical results obtained are compared with the experimental ones.

2. The average current density is located symmetrical on the two spiral arms. The highest current densities occur at the feed gap and on the edges and are independent of the frequency. A decrease in the current density as a function of distance from the feed gaps is observed. This behavior seems reasonable since the spiral antenna can be considered as a kind of a dipole antenna twisted around the feed gap. Thus, the end position of the active region may be said to rotate as the frequency is changed. For a spiral antenna, it is the shape of the radiation pattern that is independent of the frequency. However, the pattern rotates around the polar axis as the frequency is changed. This behavior was predicted using IE3D. Also, results from FARS will be presented in addition to a planned experimental verification. Results obtained for the return loss (RL), the radiation patterns as well as the current distribution on the metallic surface of the spiral are presented.

In the presentation that accompanies this abstract we will give a detailed description and analysis of the result obtained using FARS. The presentation will include examples where simulation results obtained using FARS and IE3D are compared for problems of practical interest.

Toward Real Time Compensation with a Combined DFP/AFCS System

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Over the past decade, extensive work has been performed at JPL on the use of a Deformable Flat Plate (DFP) and Array Feed Compensation System (AFCS) to correct for the gravity-induced distortions on a large reflector antenna. The DFP is placed in the beam path and deformed in order to compensate for the gravity-induced distortions as the antenna moves in elevation. Actuators controlling the plate surface are driven via a look-up table. Values in the look-up table are derived using the measured antenna distortions, ray tracing, and a structural finite element model of the DFP. The Array Feed Compensation System (AFCS) consists of a small array of horns, low noise amplifiers, down converters, and digital signal processing hardware and software for optimally combining the signals received by the horns. Each system acting alone and a combined system consisting of both the DFP and the AFCS were demonstrated on the Deep Space Network (DSN) 70-meter antenna. The combined system worked better than either one of the systems acting alone. However, even in the combined experiment, each system was operated independently in that there was no feedback from the AFCS to the DFP.

The purpose of this paper is to describe a set of experiments whose intent is to demonstrate the feasibility of real time compensation using the AFCS to update the DFP actuator positions and repoint the antenna, in order to compensate for deformations due to either gravity, wind or thermal perturbations. This is a precursor to a more complete system for compensating any time varying (not necessarily gravity dependent) deformations.

There were several parts to the experiment, carried out during recent tracks of Ka-band signals from the Cassini spacecraft. First, known subreflector displacements were applied to the antenna and the value of the displacement passed to the DFP computer. The computer then estimated and applied the actuator positions to correct for this offset. Both the "signal-to-noise ratio" (SNR) loss due to the subreflector displacement as well as the improvement with the updated actuator positions was recorded. Next, both pointing offsets and subreflector displacements were applied, and the AFCS was used to estimate the subreflector displacement and pointing offsets simultaneously, based on azimuth and elevation dependent "least-squares" models developed from previously obtained data. Third, making use of the AFCS estimates, the required antenna pointing corrections and subreflector displacements were calculated and input into the antenna system, and the correcting actuator positions computed and applied to the DFP. The SNR was measured once again, and the improvements resulting from joint AFCS-DFP compensation determined. During the next set of observations similar experiments will be performed using a closed loop system that will provide for continuous updates to correct pointing offsets and subreflector motion.

Multi-mode Feed Horn Design Tool for the NASA Advanced Technology Microwave Sounder Payload

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Abstract

Multi-mode horn radiators provide a low cost, lightweight solution for narrow band, low cross polarization and equi-beamwidth reflector illumination. These illuminations are typically required for high performance remote sensing sensors such as those used in the NASA Advanced Technology Microwave Sounder (ATMS). The primary pattern characteristics are achieved by the proper introduction of higher order (TM) modes using discontinuities along the length of the horn. Optimization of the TE/TM amplitude and phase ratios at the horn aperture is the primary goal for the analysis procedure described herein.

A design tool is described which assess the propagating electromagnetic wave modal content as a function of linear distance along the horn interior. The technique is applicable to both smooth wall and corrugated conical feed horns. The feed interior is divided into subsections, each subsection representing an equivalent cylindrical waveguide. A modal matching technique is applied at the interfaces of each discontinuity between adjacent subsections yielding the propagation characteristics across each interface. Reflection/transmission coefficient matrices are created to profile complex modal field distributions along the feed axis. This contrasts conventional S-parameter matrix outputs (e.g., A. D. Olver et al, Microwave Horns and Feeds, IEEE Press, 1994 or H. Deguchi et al, Digest of 2001 IEEE-APS Inter. Symposium) which do not afford the designer with the flexibility of evaluating modal characteristics at a discontinuity interface in the presence of other discontinuity interfaces. Feedback from this output allows rapid assessment and optimization of the discontinuity geometry (e.g. flare angle or step sizing for smooth wall horns).

The final design was benchmarked against the same design developed iteratively using TICRA/CHAMP mode matching analysis software using primary pattern performance as the figure of merit. Measured data was also compared to theory from a breadboard horn fabricated based on this design.

A STEERABLE, HIGH-GAIN, HIGH POWER MICROWAVE (HPM) ANTENNA: DESIGN, MODELING, AND SCALED EXPERIMENTS

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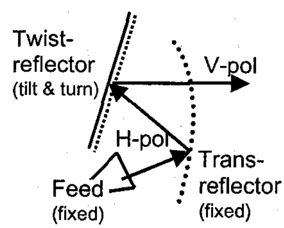
In many cases, the value of employing an antenna with a highly-directional beam depends upon how easily that beam can be scanned. This is particularly true for HPM antennas used in directed energy applications. For moderate-power single reflector dish antennas, the easiest way to steer the beam is to rotate the entire antenna, including the feed. For HPM-class (P_{pk} >100 MW) antennas operating at L-band, use of a conventional reflector makes steering difficult, since the wave-guide connecting the source to the feed must not only be large, but must also be either evacuated or pressurized to avoid breakdown. Steering the feed of an HPM reflector antenna may thus require steering the HPM source along with it, which is very cumbersome. For HPM applications, it is far better to employ an antenna that provides all the necessary steerability while the feed remains fixed. A way to accomplish that is described here.



Wide steerability (greater than a full quadrant) can be achieved by replacing the parabolic dish of a simple reflecting system with a comparably-shaped polarizing wire-grill transreflector, then redirecting the resulting beam with a polarization-rotating twistreflector. The latter rotates the wave's plane of polarization by 90° and steers the beam back through the transreflector, where it exits the antenna. This technique has long been used in certain radars and other low-to-moderate power systems ranging from X-band to mm-waves, but is new to HPM. We have explored its suitability for implementation as an HPM antenna, using moment methods and other numerical techniques to guide us in the design of an efficient configuration. Our goal is to build a highly-steerable and compact L-band HPM-capable antenna with a directivity of ~30 dBi and an aperture efficiency at least comparable to that of a conventional dish with the same gain. We have constructed a ~1/6-scale (f_0 ~8 GHz) version of a complete antenna for test purposes, along with a custom test rig to simplify the placement, orientation, and substitution of alternative feed and reflector components during experiments. Radiation patterns are measured with a near-field planar antenna measurement system, which is being used along with the test rig to characterize steerability, directivity, bandwidth, and polarization. The measured data support the predictions of our analytic and numerical models, demonstrating excellent steerability and more, as will be discussed. We are currently using the 1/6-scale test system to explore additional opportunities for optimization of the design, which will be followed by construction and testing of a full-size L-band HPM antenna.

A Numerical Solution for the Input Impedance of a Wide-Angle Biconical Shell Antenna

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The study on the input impedances of biconical antennas was first reported by Schelkunoff in 1941 (*Proc. IRE*, 1941), followed by the investigations conducted by Smith (*J. App. Phys.*, 1948) and Tai (*J. App. Phys.*, 1948 and 1949). For a biconical antenna, if the voltage between two equidistant points on the upper and lower cones is defined as the line integral of the electric intensity (E_θ) along a meridian, its input impedance can be considered as that of a conical transmission line formed by the lateral surfaces of the cones and terminated by an effective load admittance, which can be used to determine the input impedance of the antenna. Schelkunoff presented the solution of the effective load admittance for small-angle biconical antennas based on the "method of partial matching", which gives an expression of the effective load admittance in terms of a series of products of Bessel and Hankel functions, and the "e.m.f. method", which gives an expression of the effective load admittance in terms of finite terms of sine integrals, cosine integrals, trigonometrical functions, and logarithmic functions. Then, by utilizing the orthogonal properties of Legendre functions and of their derivatives, Smith obtained the exact solution of the effective load admittance that applies to the biconical antennas of any angles by matching the H_ϕ and E_θ components of the interior and exterior fields across the boundary and setting the E_θ equal to zero at the end surfaces. He proposed two approximate solutions for the effective load admittance of wide-angle biconical antennas. The first one takes into account the principal wave, one interior complementary wave, and two exterior complementary waves. The second solution neglects all the interior waves except the principal wave but includes all the exterior complementary waves. A solution based on the variational principle was presented by Tai to determine the effective load admittance using an integral equation obtained by matching the tangential electric and magnetic fields along the boundary sphere. The zeroth-order solution and the first-order solution were proposed to approximate the effective load admittance for both small- and wide-angle biconical antennas. The accuracy of the aforementioned approximate solutions is limited by the practical difficulty in covering all the terms in the infinite series and in evaluating the special functions such as the fractional-order Bessel functions. In this investigation, a numerical solution based on the *Method of Moment* is proposed to calculate the input impedance of the wide-angle biconical antenna with the given assumption of a sinusoidal current distributed on the surfaces of the cones in the radial direction due to the azimuthal symmetry of the cone geometry. A biconical shell antenna is selected to facilitate the application of the numerical method to the problem. The simulation results will be compared with the results based on the approximate solutions proposed by Smith and Tai.

ANALYSIS OF VERTICAL ELECTRIC DIPOLE ABOVE LOSSY HALF-SPACE USING DISCRETE COMPLEX IMAGE METHOD

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1.Introduction. Since Sommerfeld published his work (Sommerfeld,A. N., Ann. Physik,Vol.28, 665-739,1909)on the field of a vertical current element located on the surface of lossy half-space(in1909), radiation from sources located above lossy half-space has been thoroughly investigated. Exact approaches to this problem lead to to the solutions given by semi-infinite integrals of Bessel's functions(e.g.,Sommerfeld integrals).Their exact numerical evaluation requires the use of special integration techniques and it is time-consuming. Approximate approaches have also been proposed,valid for a limited range of half-space electrical parameters, a limited domain above soil or a limited range of frequencies. All of the exact and approximate methods dealing with the problem(except reflection-coefficient method)start either from the sommerfeld solution or from its basic idea(Popovic,B.D.,Petrovic,V.V.,IEE Proc.H,140,6,501-507,1993).

This paper presents a new approximate method to compute the closed-form Green's function of the current element, using the Discrete Complex Image Method(DCIM).

2. Outline of the method. The basic idea of the new method is to determine approximate equivalent images which produce the same space-domain Green's function as the original function in the near and far regions. Images are found to be the simplest possible sources that satisfy the following conditions: 1) The Green's function in space domain has a closed form and 2) radiation field of images and original current element must be as accurate as the exact field. The number of images, and their 'optimal' positions and amplitudes are obtained by the Generalized Pencil Of Function(GPOF) method. This paper Chooses a proper deformed integration path that play significant role in the computation of Green's function. Optimal value of deformed path parameters is obtained by extensive numerical iteration. Consequently, accurate far and near radiation fields are obtained. For vertical current element it was found that three images in the form of vertical Hertzian dipoles distributed along original dipole axis suffice for accurate evaluation of radiation fields(Cotton,G.,Kuester,E.F.,NTIA Report 2000).

ABOUT POSSIBILITY THE VECTOR'S PARABOLIC ANTENNA DP TO IMPROVE RADAR RESOLUTION

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This report presents some DP calculation results from my book *Calculation of parabolic antennas* published in Russia for various beam-scanning laws of the radiator's displacement from a parabola's focus. I will give a brief description of the two methods of DP calculations: 1) by classic Gyugens-Kirchhoff approach; 2) by the Maxwel's equations usage. The calculations were made for the regions of the main maximum and near side lobes for both symmetrical and asymmetrical antennas.

1.The Gyugens-Kirchhoff approach

The resolution of parabolic radars with various scanning patterns are defined by the width of their antenna directionality patterns (DP). Usually DPs are calculated by the field integration at the parabolic mirror's aperture, and only the real part of DP is taken in consideration. The simple formula $\theta \approx 70(\lambda/D)$, evaluates the width of such DP when a radiator is at the mirror's focus. But in a real situation, when the radiator is displaced from focus and the Gyugens-Kirchhoff approach is used for the field integration, the resulting DP becomes a complex function due to significant phase change i.e. the DP of the scanning parabolic antenna should be described by vector functions (VDPs). They have the larger maximum scanning angle than conventional "amplitude" DP, especially for the asymmetrical antenna. The examples of calculated and experimental vector DPs will be presented. The VDPs usage can vastly improve the parabolic radar resolution. This is especially important for development of large range early warning radars.

The first part presents the results for parabolic antennas with scanning angles of no more than 10 degrees. Within this range it is possible to calculate DP by the field integration at the reflector's aperture as is proved by the comparison of the calculation and the experimental results. In addition, one can get both the amplitude and the phase field components, which are amplitude and phase DP. All these allow characterizing the far-field zone by the Vector DP (VDP). It is shown that VDP, provides larger scanning angle than conventional amplitude DP.

2.The Maxwel equations usage

The Maxwel equations, for calculations two-dimensional antenna's DP by integration the currents at the mirror surface induced by the radiator inside or displaced from focus, were used. The calculations were made for the regions of the main maximum for main and parasitic polarization. The example of calculated a two-dimension DP in far field zones, will be presented.

Novel Antennas for Handsets

Co-Chairs: *Y. Chen, University of South Carolina, USA*
P. Salonen, Tampere University of Technology, Finland

U-Shaped Planar Microstrip Antenna for Dual-Frequency Mobile Telephone Communications

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In this paper, we present a novel configuration of a U-shaped, dual-frequency, single feeding port planar inverted-F microstrip antenna (PIFA), which can be potentially applied to mobile communications for telephone handsets in both the GSM and DCS 1800 systems operated at 0.9 and 1.8 *GHz*, respectively. The proposed PIFA frequency bandwidth is synthetically improved by using a slotted, partially filled dielectric substrate. Following an initial design derived from an empiric approximation and transmission line model for a standard rectangular microstrip antenna, we analyze, examine, and tune the electric performance of the antenna by means of a generalized non-uniform finite difference time domain (NU-FDTD) Maxwell's solver. For simplicity, the feeding line of the PIFA structure is approximated with a coaxial cable with rectangular cross-section and characteristic impedance of 55 Ω. We have optimized the geometrical dimensions of the antenna at both frequencies with compromising all antenna electric features including return loss, operation frequencies and frequency bandwidths, input impedance, and far-field radiation patterns. In addition to applying the generalized FDTD Maxwell's solver and developing the telephone handset PIFA structure, we also present an efficient technique in the FDTD updating procedure by using multiple computational domains in order to remove unnecessary computational space, where the total computation domain consists of a few rectangular volumes, or sub-domains, which are physically connected and their tangential fields are continuous at the interfaces between any two sub-computational domains.

Special Session

Advanced Methods for Large Scale Computational Electromagnetics I

Organizer(s): *W. C. Chew, University of Illinois, USA*
J.-M. Jin, University of Illinois, USA

Co-Chairs: *W. C. Chew, University of Illinois, USA*
J.-M. Jin, University of Illinois, USA

Fast AIM Computation of EM Fields from 3D Inhomogeneous Objects

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In this work we develop an adaptive integral method (AIM) for solving electromagnetic fields from three-dimensional inhomogeneous dielectric objects. This is a physically based fast algorithm, in which the far-field interactions are accelerated. We compute the near-field component through conventional MoM (Method of Moment). The far-field interaction is not explicitly computed; it is calculated through the auxiliary current distributions which generate a compressed matrix representation and thus operation reduction. The AIM has been applied to surface integral equation, but has never been applied to volume integral equation.

Here we utilize two sets of basis functions: The CT/LN (Constant Tangential/Linear Normal) basis function is selected to evaluate the contribution of the unknowns. The auxiliary basis function is employed to evaluate the far-field interactions, which replaces the original current distribution with an approximately equivalent set of pointlike currents. These two sets of distributions give almost identical fields at large distances. If the pointlike currents are distributed at the nodes of a regular Cartesian grid, this far-filed interactions can be computed through fast Fourier transform (FFT) algorithm.

Our main contribution here is the development of the AIM algorithm for three-dimensional inhomogeneous structures. This procedure is applicable to PEC, dielectric object or the combination of PEC and dielectric structure. The implementation of AIM costs $O(N)$ memory storage and $O(N \log N)$ complex multiplications. The flexibility of basis functions in AIM eliminate the stair-casing error in conventional FFT accelerated algorithm when curved boundaries are encountered.

MLFMA Analysis of Scattering from Multiple Targets

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We previously developed an iterative procedure to extend the MLFMA to the case of multiple targets, where each of multiple targets is analyzed in isolation via an iterative procedure, with excitation equal to the incident fields plus the scattered fields from all other targets. In that implementation, all the computations are performed on a single computer processor. The scattered fields from other targets are calculated using the target-dependent induced currents basis-function by basis-function, which means that the computation complexity for the interaction between target i and target j is $N_i \times N_j$, where N_i and N_j are the number of unknowns for the ith and jth target, respectively. When the number of targets increases and/or the number of unknowns increases, this calculation could become burdensome and time consuming.

In this work, we first developed a parallel version of the algorithm, utilizing traditional MPI (message-passing interface) implementation, in which each target is analyzed on a separate computer processor. The fields scattered from target i to target j are passed via MPI between the respective processors.

To accelerate the calculation of interactions between targets, we calculate the scattered field on a MLFMA scheme instead of basis-function by basis-function, utilizing the MLFMA formalism. In particular, the induced currents on the source target are first aggregated, then translated to the destination target, and finally distributed to its individual basis. The key issue in this method is that the MLFMA level on which the currents are aggregated and distributed is dictated by the distance between the two targets. The further apart the two targets are, the upper (coarser) the MLFMA level is, which in turn, brings considerable savings to the calculation.

With this technique, we can calculate fairly big problems using our 32 processor-computer Beowulf cluster, and results are presented for several multi-target scattering and propagation scenarios.

MLFMA-Based Quasi-Direct Matrix Inversion for Electrically Large Problems

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In the numerical analysis of electromagnetic scattering, we usually require solution of linear equations of the form $\boldsymbol{Zi}=\boldsymbol{v}$, where, $\boldsymbol{i}$ is a vector representing the unknown induced current, $\boldsymbol{v}$ is a vector representing the incident fields sampled on the target, and $\boldsymbol{Z}$ is an impedance matrix. For electrically large problems this matrix equation is generally solved iteratively, using techniques such as the multi-level fast-multipole algorithm (MLFMA). The iterative solution involves many matrix multiplications $\boldsymbol{Zi}$, with these implemented efficiently via the MLFMA.

In the work reported here we attempt a direct solution of $\boldsymbol{i}=\boldsymbol{Z}^{-1}\boldsymbol{v}$, where our goal is to compute $\boldsymbol{Z}^{-1}\boldsymbol{v}$ efficiently, rather than $\boldsymbol{Zi}$. This is effected through use of matrix identities, whereby we express $\boldsymbol{Z}^{-1}$ as a sequence of matrix multiplications involving the $\boldsymbol{Z}_{\text{near}}$ and $\boldsymbol{Z}_{\text{far}}$ employed in the conventional MLFMA. Therefore, the product $\boldsymbol{Z}^{-1}\boldsymbol{v}$ can be evaluated directly, using a series of matrix multiplications implemented much as in the conventional MLFMA. The advantage of this new formulation is that one no longer need employ an iterative solver (e.g. conjugate gradients), significantly accelerating computational efficiency.

We have implemented this approach for arbitrary, electrically large perfectly conducting targets situated in the presence of a half space, and have realized computational savings on the order of 70% vis-à-vis the already fast MLFMA. The memory requirements are as in the traditional MLFMA. In this presentation we discuss the new quasi-direct MLFMA procedure, and present several example results. The formulation is equally applicable to dielectric targets, and we expect to demonstrate results for dielectric targets as well.

Fast Evaluation of Time Domain Fields by Domain Decomposition and Non-Uniform Spherical Grid Interpolation

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We consider a three-dimensional scattering by an open perfectly conducting surface analyzed via the time domain Electric Field Integral Equation (EFIE) and Marching On in Time (MOT) computational sequence. Each MOT step requires evaluation of the electric field due to the surface currents computed at the preceding time steps. The number of field and current sampling points on the surface is proportional to its electrical dimensions, i.e. of $O(N)$, where $N=(kR)^2$, R being the radius of the smallest sphere circumscribing the scatterer and k - the wavenumber corresponding to the highest frequency present in the incident field. Straightforward evaluation of the field at $O(N)$ points by surface integration involving summation of $O(N)$ terms amounts to $O(N^2)$ operations. This high computational burden underlines the need for using fast field evaluation techniques.

In this paper, we present a novel scheme that facilitates numerically efficient evaluation of the field produced by a given current distribution. The algorithm is based on the observation that, locally, the delay compensated field radiated by a finite size source is an essentially bandlimited function of the angles and radial distance from the source region. The pertinent angular bandwidth is proportional to the linear dimensions of the source, while the local bandwidth with respect to the radial distance decreases rapidly with the distance. Therefore, the radiated field can be sampled on a non-uniform spherical grid with radial density decreasing with the distance away from the source. Consequently, the radiated field on the surface, which needs to be calculated in the EFIE can be interpolated from its samples at a number of spherical grid points proportional to the source region dimensions.

With this in mind, we decompose the scatterer surface into subdomains and compute the field for each of them separately. The field of each subdomain is directly evaluated at a small number of spherical grid points near the surface and subsequently interpolated, thus providing computational savings. The time delay common to all source points in a given subdomain is removed from the field prior to interpolation, thus rendering the field a slowly varying function of the spatial variables in the retarded time domain. Thus, the field computation and subsequent interpolation are performed at uniformly sampled retarded time points. Since the final results are needed at uniformly sampled points in the physical time domain, these points are mapped into the retarded time domain to facilitate the interpolation. Following the interpolation, we restore the delay by returning to the true time dependence and aggregate these partial fields into the total field due to all subdomains combined. The two-level domain decomposition algorithm reduces the computational cost of evaluating the field (a single time step) from $O(N^2)$ to $O(N^{3/2})$. A multilevel algorithm is obtained upon starting from small subdomains, for which the field is computed directly over a very coarse grid, and repeating the interpolation and aggregation steps for progressively finer grids, while doubling the subdomain sizes. The multilevel algorithm attains an asymptotic complexity of $O(N \log N)$.

Radar Remote Sensing Techniques and Applications

Co-Chairs: *D. E. Barrick, CODAR Ocean Sensors, USA*
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Finite Element Calculation of Normal Modes for Tidal Flow Analyses of HF Radar Data in Corpus Christi Bay and Long Island Sound

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The NMA (normal mode analysis) hydrodynamic basis functions offer a theoretically based approach to improve and extend remotely sensed HF-radar surface-current fields in bays and estuaries. The enclosing coastline represents a simple boundary condition for two scalar fields that satisfy a two-dimensional, second-order, Helmholtz partial differential equation (PDE): a stream function (Dirichlet boundary) and a velocity potential (Neumann boundary). Eigenfunction solutions to these homogeneous equations become the NMA basis functions, which are a complete orthonormal set. A subset, truncated in terms of energy content, can represent well hourly surface current maps from HF radar data. The inhomogeneous solution to this PDE, however, is appropriate and needed when inlets to the bay region are important (i.e., open boundaries). This approach is especially useful when representing harmonic tidal flows, where the source function at the inlet is obtained from HF radar data or other measurements.

We construct the appropriate NMA solutions for Corpus Christi Bay and Long Island Sound from a numerical, finite-element, FORTRAN PDE2D solver. We then express our inhomogeneous solution based on flow through the bay entrance in terms of these NMA basis functions. The results expose the dominant features of these bays in terms of the shoreline-conforming lowest-order modes according to the energy content. We examine tidal-flow spatial patterns for the two cases: Corpus Christi Bay, in which a weak diurnal constituent dominates, and Long Island Sound, where both semi- and diurnal harmonics contribute to a strong tidal response. Hourly SeaSonde HF-radar data from both of these regions have been recorded and are used for analysis and comparison. Hourly records were selected for periods of low, uniform wind stress in order to focus on the NMA representation of tidal flows. We also examine further extensions that will include tidal time-phase lags by including depth and dissipative terms in the PDE, and its resulting NMA solutions.

Least-Squares Fitting of Normal Modes Directly to HF Radar Radial Vector Current Maps in Corpus Christi Bay

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A pair of SeaSonde HF coastal radars has been recording and archiving hourly surface-current map data over Corpus Christi Bay for nearly two years. The 15 km x 25 km bay is shallow and nearly completely enclosed, except for an inlet at Aransas Pass. The dominant circulation is wind driven, with a weak tidal co-oscillatory response forced by flow through the inlet. Total vector coverage by the SeaSonde pair spans on average half of the bay surface, with gaps caused by: (i) environmental variations (noise, wave conditions, etc.); (ii) regions seen only by one radar but not the other; and (iii) zones along the baseline between the two sites where total vectors cannot be produced because both observe the same velocity component.

We test a new hypothesis: fitting NMA (normal mode analysis) hydrodynamic basis functions directly to the one-dimensional radial vector maps produced by each radar separately. Thus, a velocity field of 1-dimensional scalar components is being used to define a 2-dimensional flow pattern inherent in the coastline-conforming NMA mode functions. This is done by fitting the scalar radial SeaSonde data directly to the radar-directed components of the mode functions, and solving this over-determined linear system of equations in a least-squares sense. Derived from a finite-element solution based on the bounding bay coastline, the individual modes constituting this representation of surface circulation cover the entire bay, not just regions where total vectors from the HF radars were measured. The hypothesis of how well a single radar's scalar field can describe 2-dimensional flow is tested by withholding data from one radar, then the other, when compared with data from both used together in the fitting process. The dominant lowest-order modes are prioritized as to their importance in terms of their kinetic energy content.

Stabilizing and Extending HF-Radar Total-Vector Ocean Surface-Current Maps with Normal Mode Techniques

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Normally at least a pair of coastal HF radars operate together to produce maps of surface currents from their Doppler signals. Each radar is able to sense only a scalar component of the two-dimensional vector at the radar cell: a the radial component for backscatter or a hyperbolically directed component for bistatic geometries. Large areas are therefore seen by only one radar, beyond the reach of the other. Spatial gaps in total vector coverage often result from environmental factors. Filling in gaps, reducing vector noise, and extending coverage is a highly desirable goal. The recent application of NMA (normal mode analysis, Lipphardt et al., J. Geophys. Res., 105, 3425-3450, 2000) suggests this technique may greatly extend the coverage and improve the quality of HF radar current maps, particularly in bays and estuaries where a coastline provides a nearly closed boundary around the region.

The NMA technique is based on the incompressible nature of water. It is shown that two scalar potential functions can exactly represent the 2-dimensional velocity field over any horizontal plane like the surface. The coast becomes a Neumann boundary condition for a scalar velocity potential and a Dirichlet boundary for a scalar stream function. Eigenfuction solutions of their second-order homogeneous 2-dimensional partial differential equations are the NMA functions. Surface flows for the lowest-order modes exhibit geometry-based patterns similar to TE and TM electromagnetic modes inside of cavity resonators and waveguides. Hence, these hydrodynamic orthonormal basis functions become a natural means of representing surface currents constrained by a bay's coastal boundaries.

In this study we demonstrate their use for two simple canonical shapes whose eigenfunction solutions are well known: rectangular and circularly shaped bays. We illustrate how flow into a narrow inlet (delta-function source) sets up a pattern that can be expressed in terms of these homogeneous NMA functions. We study two methods for determining how many modes are necessary to represent this flow: (i) convergence of velocity energy as more modes are added; and (ii) the rms residual error between the finite mode sum and the true inhomogeneous solution. These in turn serve to define quality when the modes are fitted to mapped HF radar surface-current fields.

A Wavelet Atmospheric Scattering Model for Improved Turbulence Detection

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Atmospheric turbulence detection problems rely on electromagnetic models for detection of turbulent atmospheric patches. Conventional detection methods, however, often perform poorly since they do not approximate the electromagnetic scattering model of the turbulence in a compact or accurate form. Such poor approximation arises since the model used for detection does not consider the spectral contents of the electromagnetic turbulence model. We propose a method of modeling the atmospheric turbulence scattering process with a wavelet Galerkin scheme and then using a detection model that accurately represents the physical model to demonstrate improved detection performance in difficult signal to noise conditions.

It has been shown (Tatarski, V.I., *Wave Propagation in a Turbulent Medium,*McGraw-Hill, 1961) that radar reflectivity of clear air turbulence $\eta(k)$ is related to radiation wavelength λ and mean square fluctuation of the refractive index C^2_n by

$$\eta(k) \approx 0.38 C_n^2 \lambda^{-\frac{1}{3}} \tag{1}$$

With our Galerkin approximation we assume a square pulse incident plane wave to illuminate a turbulent region with scattering over three discrete center frequencies. The resulting scattering (Tentzeris et. al., Proc. IEEE Int. Symp. an Microwave Theory and Techniques, 1996, 573-576) kernel $\alpha(\nu)$ is then described in Equation 2 where the low-pass analysis wavelet function ϕ approximates each scattered wave

$$\alpha(\nu) = \int_0^{\infty} |\hat{\phi}(k_x)|^2 k_x \sin|k_x(\nu + 0.5)| dk_x \tag{2}$$

where k_x is the scattering frequency in the x dimension. Thus for each separate center frequency k_x a turbulent region should have reflected energy as a function of center frequency with $k_x^{1/3}$ from equation 1.

Next we perform our detection process with a Wiener matched filter with a wavelet-Markov detection model using a Battle Lemarie basis function. We see that the Battle Lemarie detection model approximates the turbulence spectra electromagnetic model better that the Haar as is shown in Fig. 1a/b. Thus by using a basis set that better approximate the atmospheric spectrum models' basis elements, we are able to capture the principle energy components of the turbulence better than with a poorly approximated basis set.

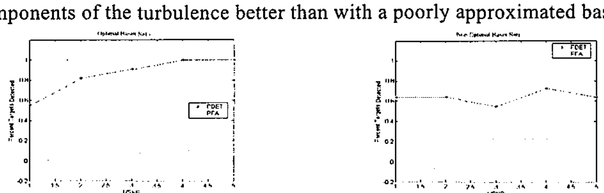

Fig. 1 Detection results with Battle Lemarie/Haar Basis

Special Session

Novel Challenges with Electromagnetic Bandgap Surfaces II

Organizer(s): *P.-S. Kildal, Chalmers University, Sweden*
N. Engheta, University of Pennsylvania, USA

Co-Chairs: *P.-S. Kildal, Chalmers University, Sweden*
N. Engheta, University of Pennsylvania, USA

Artificial quasi-magnetic surfaces: grazing wave suppression and leaky wave excitation

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Among the classes of electromagnetic bandgap structures, periodic surfaces printed in stratified dielectric media occupy an important role, as testify by the recent literature. Various configurations can be used in antenna applications, in order to realize an equivalent (artificial) magnetic surface [D. Sievenpiper *et al.*vol.47, no 11, Nov. 97, pp. 2059-2074], IEEE Trans. Microwave Theory Tech.], [Fei-Ran Yang, *et al.* vol. 47, no 11, Nov. 97, pp. 2092-2098], [N. Engheta, URSI meeting, Boston, Massachusetts, July 8-13 2001, pag. 389]. For patches or dipoles printed-over or embedded-in the artificial, stratified structure, the actual purpose is concerned with realization of compact antennas, or with suppression of surface- or grazing space-waves to reduce truncation induced diffraction lobes. Similar strategy have been devised in the past with various technological solutions [P-S. Kildal, IEEE Trans. Antennas Propagat., vol. AP-38, pp. 1537-1544, Oct. 1990], [S. Maci *et al.*, IEE Proc. H., Vol. 143, No. 4, pp. 335-340, August 1996]. From the various works in literature also emerge a different application which uses the same printed periodic surface technology, but focused on gain enhancement [H. D. Yang and D. R. Jackson, IEEE Trans. Antennas Propagat., Vol. 48, N. 4, pp. 556-564, Apr. 2000], [T. Zhao et al., AP-S Symp. Digests, , July 8-13 2001, Boston, Massachusetts, Vol. 3, pag. 248-252]. In contrast with grazing wave suppression, the basic mechanism behind the gain enhancement is the excitation of weakly attenuated leaky waves, similar as that described in the past for unbounded layered media with high dielectric contrast [D.R. Jackson *et al.*, IEEE Trans. Antennas Propagat, vol. AP-41,pp. 344-348, March 1993]. For this kind of effects, the basic concept is the realization of a parallel plate waveguide, with one perfectly electric and one quasi-magnetic (high-impedance) wall excited by a slot on the ground plane and/or a dipole in the middle of the slab.

In this talk, the concepts of surface/grazing wave suppression and leaky wave excitation mechanisms for high-impedance artificial surfaces are comparatively investigated with the help of both rigorous and simplified models, and with the objective to suggest new arrangements and technological solutions.

Advances in Electronic Beam Steering Using Electrically Tunable Impedance Surfaces

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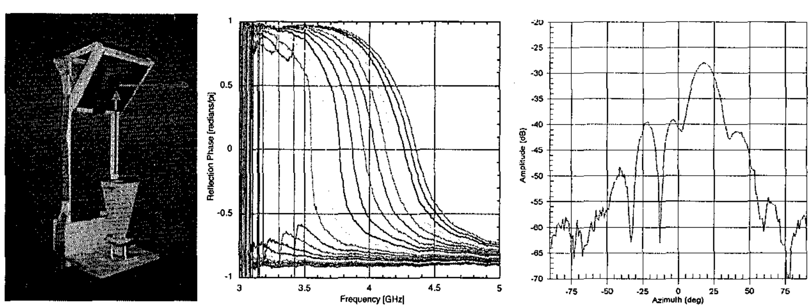
Abstract:

This paper describes advances in electronic beam steering using an electrically tunable impedance surface. The structure is based on the high impedance surface, (D. Sievenpiper, L. Zhang, R. Broas, N. Alexopolous, E. Yablonovitch, IEEE Trans. MTT 47, 2059,1999) which is a distributed network of inductive and capacitive elements. These distributed elements form a coating on a metal surface, providing it with unique electromagnetic properties, such as the ability to appear as an artificial magnetic conductor. The structure presented here consists of a printed circuit array of metal patches connected by varactor diodes, which allow the surface impedance to be tuned with an applied voltage. By varying the surface impedance as a function of position, it provides a simple method of beam steering, with potential as a low-cost alternative to conventional phased arrays. Mechanically tuned versions, consisting of arrays of movable metal plates, have also been demonstrated. In addition, prior work on grid array structures, (L. Shogren, H. Liu, X. Qin, C. Domier, N. Luhmann, IEEE Trans. MTT 42, 565, 1994) has shown the ability of tunable impedance surfaces to perform beam steering. In the present work, we show that printed circuit techniques can allow the structure to perform two-dimensional beam steering due to a unique biasing method. We also show that by optimizing the geometry, one can achieve significant improvements in bandwidth, as well as phase tunability. The structure, along with examples of the performance, are shown in the figures below, including the phase tunability, and an example of a beam steered to 20 degrees off normal. Beam steering of +/- 40 degrees has been demonstrated using this structure.



Figures: (left) Photo of the tunable impedance surface, which was about 3.5λ wide, being illuminated by a horn antenna. (center) The measured reflection phase versus frequency for various applied voltages. (right) In this example, the reflected beam is steered to 20 degrees by applying a voltage gradient.

Overview of Experimental and Numerical Work on Reducing Blockage From Cylinders

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In several antenna systems there will be increased sidelobes and reduced gain caused by scattering from mechanical structure that obstructs the electromagnetic waves. The mechanical structure consists often of one or more rods, eg. feed support struts in axisymmetric reflector antennas and the framework of space frame radomes. Scattering from rods and struts are strongly polarization dependent when the cross-section dimensions are in the order of a wavelength. The scattering is weak (desirable) when the E-field is orthogonal to the strut (TE-case), and it becomes weaker (i.e. better) when the strut cross-section is made more oblong in the direction of the wave propagation. The scattering is strong (i.e. bad) when the E-field is parallel with the strut (TM-case), and it becomes stronger (i.e. worse) as the strut cross-section becomes more oblong. When the scattering is polarization dependent like this, it can be improved for the worse polarization (and remain good for the orthogonal one) by making use of an artificially soft or hard surface, as defined in [P.-S. Kildal," Artificially soft and hard surfaces in electromagnetics," IEEE Transactions on Antennas and Propagation, vol. 38, pp. 1537-1544, 1990]. In this case the correct choice will be a hard surface, i.e. dielectric-filled corrugations or a strip-loaded dielectric coating, with the corrugations or strips running in the direction of the wave propagating passed the strut [P.-S. Kildal, A.A. Kishk, and A.Tengs, "Reduction of Forward Scattering from Cylindrical Objects using Hard Surfaces," *IEEE Transactions on Antennas and Propagation*, Vol. 44, pp. 1509-1520, 1996].

In this paper, we will present an overview of the experimental and numerical results of the design and analysis of cylindrical hard surfaces to reduce the forward scattering. Previous work was based on normal plane wave incidence. Here, the effect of the oblique plane wave incident on the struts design for both polarizations will be presented. The numerical analysis is based on the method of moments and the implementation of the asymptotic boundary conditions (ABC). The ABC simplifies the analysis of such surfaces. We will present results for struts coated with dielectric materials that make the surface hard for the TM polarization without metallic strips, then the dielectric is loaded with tilted strips to be along the direction of propagations in order to reduce the blockage for the TE polarizations.

Multi-band High Impedance Frequency Selective Surfaces

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Frequency Selective Surfaces (FSS) have been recently suggested for use in the design of electromagnetic meta-materials that behave like a Perfect Magnetic Conductor (PMC) (F. Yang, K. Ma, Y. Qian, and T. Itoh, *IEEE Trans. Microwave Theory Tech.*, **47**, 1509-1514, 1999). It has been shown previously that an FSS screen acting as a PMC can be used to improve the radiation characteristics of an antenna placed in close proximity to or in the same plane as such a surface (R. Coccioli, F. Yang, K. Ma, and T. Itoh, *IEEE Trans. Microwave Theory Tech.*, **47**, 2123-2130, 1999). However, one of the main drawbacks to date of these high-impedance surfaces has been their characteristically narrowband response.

This paper investigates various approaches to developing multi-band designs for high impedance frequency selective surfaces that could be used, for instance, to enhance the performance of multi-band antennas. One of the most promising techniques that will be discussed involves using a Genetic Algorithm (GA) approach to synthesize optimal configurations for multi-band high impedance FSS. By incorporating a GA into the development process, it is possible to modify the geometry of the FSS screen as well as the dielectric constant and thickness of any substrate or superstrate material. An example of a dual-band high impedance FSS synthesized via a GA is shown below in Figure 1:

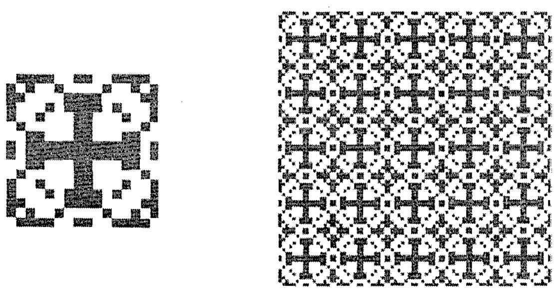

Figure 1. An Example of a Genetically Engineered Dual-band High Impedance FSS Cell and Corresponding Screen.

Hybrid finite element analysis of the effect of periodic loading at a perfectly conducting antenna reflector edge.

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The performance of antenna systems is often influenced by diffraction phenomena. Control over these diffracted fields can assume significant importance especially when compact antennas are designed. Considerable research has been devoted to the identification of suitable antenna reflector edge terminations in an attempt to minimise quiet zone ripple or field strength in the shadow zone. Hence a number of edge of configurations have been considered such as blended rolled edges, curved edges, and corrugated soft edges. Furthermore, the surface currents on the antenna reflector have been terminated gradually at the edges by tapering the conductivity of the reflector through the application of lossy materials even if in some antenna applications this is not desirable since it can adversely affect antenna noise temperature. The electromagnetic influence of some of the terminations described above cannot be easily quantified analytically. Consequently, the problem is solved by resorting to suitable numerical techniques. We present a hybrid technique which utilises a finite element/boundary element method that models the electromagnetic behaviour of a perfectly conducting, arbitrarily shaped wedge loaded near its edge. The loading is considered to be periodic along the edge, hence the formulation is able to model the effect of the presence of hard surfaces. In particular, both geometrical and material periodic variations near the edge of the wedge are analysed using a Galerkin weighted residual finite element method (FEM) employing three dimensional edge elements and periodic weighting functions. In order to find the unique field solution everywhere in this geometrically complex and infinite problem region using finite computational resources, the finite element mesh is truncated by a boundary element surface on which the field solution is expanded in terms of cylindrical Floquet harmonics. The latter are appropriately chosen by taking into consideration the field solution of the canonical wedge problem. It is assumed that the geometrical structures under investigation are illuminated by a plane wave. The proposed technique is computationally efficient and hence it can be applied not only for the analysis but also for the optimisation of reflector antenna terminations.

Non-Uniform Partially Reflective Surfaces for High Gain Planar Antennas

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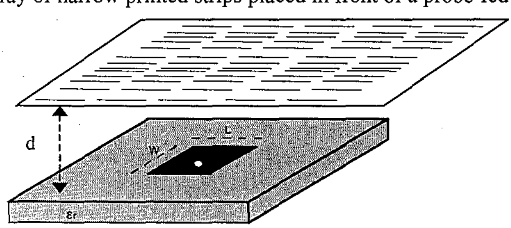
Partially reflective surfaces (PRS) have been used in antenna applications for beamforming [G. V.Trentini, "Partially reflecting sheet arrays," IRE Trans. Antennas Propag., AP-4, pp. 666-671, 1956] as well as more recently for high gain wireless applications [A. P. Feresidis and J. C. Vardaxoglou, "Double layer partially reflective surfaces for high gain planar antennas," Proceedings of ICEAA '01, pp. 243-246 , 2001]. A simple implementation of the PRS for the latter application includes a periodic array of narrow printed strips placed in front of a feeder antenna at a resonant distance of d. The strip array acts as a leaky wave surface that significantly enhances the directivity of the feeder antenna. A Floquet mode analysis of an infinite periodic PRS array shows that the separation, d, between the PRS and the feeder antenna is a function of the phase of the angle dependent complex reflection coefficient of the PRS. For the highly reflective PRS printed strip array the corresponding reflection coefficient is close to 180 degrees, resulting in a PRS-feeder element separation of about 0.5 wavelength or larger. Such an antenna system results in a high gain beam, but with no control on other parameters of the radiation pattern. In particular, the use of such a uniformly spaced PRS array may result in a relatively high side-lobe-level that may not be desirable in may high gain wireless and radar applications.

In this work we propose the use of a non-uniform PRS for better control of the antenna pattern. An example of the proposed concept when applied for gain enhancement of a microstrip patch antenna is shown in Figure below. The PRS is made of a non-uniformly spaced (aperiodic) array of narrow printed strips placed in front of a probe-fed rectangular microstrip patch antenna. The non-uniform spacing between the PRS elements can be used to control the amplitude and phase variations across the PRS plane, and, as a result, optimize the side-lobe-level for a given beamwidth. To demonstrate the feasibility of the concept we numerically model the entire structure by a mixed-potential integral equation technique, and couple the corresponding moment-method solution with a problem specific evolutionary algorithm [A. Hoorfar, "Mutation-based evolutionary algorithms for optimization of antennas in multi-layered media, Proceedings of IEEE AP-S, pp. 2876-2879, Orlando, FL, July 1999]. In the optimization scheme, a continuous parameter evolutionary algorithm is used to optimize the spacing between the PRS elements, the distance, d, and the location of the feed point on the patch antenna. Examples of the radiation characteristics of the optimized structures will be given in the presentation.



A microstrip patch antenna with a non-uniformly spaced PRS array

Microwave Band-Gaps in Array Structures. Realization and modeling

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In this paper we explore the electromagnetic properties of multi-layered materials consisting of different kinds of metal-dielectric layers with periodically distributed densely packed complex-shaped strip particles produced by planar technology (i.e. photolithography).

Resonant coupling of planar particles in neighboring layers, combined with the resonance properties of single layers lead the structure to acquire properties analogous to those of the well known photonic band gap (PBG) materials. These structures can find practical applications in high-quality polarization-selective filters : very sharp resonances due to screening the internal layers of the structure and polarization sensitivity or polarization transformation due to the inclusion shape.

The method of analysis of a single doubly-periodic array of conducting strips, based on Floquet theorem and the method of moments, is combined with a recursive algorithm suitable to calculate the reflection and transmission operators for a system of several such layers. For numerical calculation, the assumption is that the separation between layers is large enough, so that the evanescent Floquet modes between the layers can be neglected.

Numerical results for systems with inclusions of various shapes and dimensions, eventually connected to passive linear electronic loads, are presented.

A sample consisting of four layers with inclusions having the shape of the letter "C" was machined using the photolithography technique and measured. The geometry of the arrays particles was optimized so that, at resonance, the size of the unit cell remains small compared to the wavelength. For measurements, a focusing free space setup was used for the frequency band [7GHz, 54 GHz].

Some Applications of Rectangular Waveguide with Electromagnetic Crystal (EMXT) Walls

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Special waveguide with electromagnetic crystal (EMXT) walls have been fabricated and used in various microwave and millimeter wave applications. In this kind of special waveguide, EMXT structures are employed as artificial impedance surfaces that provide a desired electromagnetic boundary condition. A dual TEM waveguide implemented with all four walls covered by EMXT sidewalls can be very useful in quasi-optical amplifier applications. As shown in Figure 1, the strip sidewalls present an open circuit to the tangential E-field while the normal E-field at the top and bottom is left undisturbed, therefore, it supports both polarizations. It was estimated that up to 6 dB improvement in maximum output power could be obtained for a quasi-optical amplifier in an EMXT waveguide comparing to that in a regular metal waveguide (J.A. Higgins et al, IEEE Trans. on MTT, 47, 11, 2139-2143, 1999). We will present the experimental and simulated results of a dual TEM waveguide with EMXT sidewalls operated around 37 GHz that will be eventually used in a 37 GHz GaAs PHEMT quasi-optical grid amplifier application. Another attractive application is a waveguide phase shifter with tunable EMXT as sidewalls. The propagation constant of the waveguide with tunable EMXT sidewalls changes very fast when the resonant frequency of the EMXT is tuned. Our measurements and simulations indicate that tunable sidewall resonance can provide simple and low loss phase shifting systems.

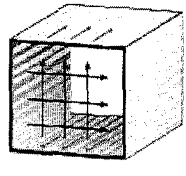

Figure 1. A dual mode TEM waveguide with all four walls covered by strip EMXT surfaces.

OVERVIEW OF RECENT WORK ON NUMERICAL ANALYSIS OF HARD CIRCULAR WAVEGUIDES AND HARD CONICAL HORN ANTENNAS

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Artificially hard walls, (P.-S. Kildal, *IEEE Trans.*, AP-38, 1537-1544, 1990), which can be realized in waveguides and horn antennas either by longitudinal corrugations filled with dielectric or by a dielectric layer loaded with longitudinal conducting strips, allow obtaining a dominant mode with uniform field distribution over the cross section. This, in turn, can potentially provide high aperture efficiency and low cross-polarization of the horn. Such features are desirable for reduction of antenna dimensions and weight, for improvement of performance of cluster feeds and limited-scan arrays, and for efficient excitation of quasi-optical grid amplifiers.

The conventional approach using a circular-cylindrical model and Kirchhoff-Huygens integration of the undisturbed modified TE_{11} mode field for analysis of the hard conical horns has demonstrated their high potential. However the predicted cross-polarization of below –30 dB has not been achieved in practice because of the excitation of standing higher order modes disturbing the required field distribution. To take such effects into account, we apply a more rigorous approach based on a step-wise representation of the conical surfaces with subsequent use of the mode-matching method in a combination with the Weinstein's method of factorization for rigorous calculation of the field scattered at open end. The necessary eigenmodes of the loaded cylindrical sections are determined by using the asymptotic boundary conditions for corrugated and strip-loaded surfaces .

The results reported before, (S. P. Skobelev and P.-S. Kildal, *ANTENN00*, 45-50, Lund, Sweden, 2000; *ICAP2001*, 2, 696-700, Manchester, UK, 2001), as well as some new ones to be presented, justify the application of the approach proposed, and show that the horn performance strongly depends on the relative length of the hard section. The best performance is achieved when the loading is laid over all the horn length. In this case, and when the horn is sufficiently long, it is possible to achieve high (above 85%) aperture efficiency and low (–30 dB and lower) cross-polarization in some frequency band, though the indicated parameters are characterized by oscillations with short period caused by the excitation of the higher order modes. Especially strong oscillations are caused by the strip-line mode resonances in the strip-loaded horn. Some approaches to elimination of such undesirable effects are also discussed.

Effects of Loading and Environment on Antennas

Co-Chairs: *S. Long, University of Houston, USA*
A. K. Bhattacharyya, Boeing Satellite Systems, USA

Radiation pattern calculations for a magnetic current mounted on a large dielectric coated PEC circular cylinder

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In this paper an asymptotic technique to calculate the radiated field from a magnetic current moment situated on the surface of a PEC circular cylinder surrounded by a thin dielectric layer is presented. The obtained solution is valid for large cylinders away from the paraxial region and makes it possible to calculate the radiation pattern and the scattering from waveguide fed apertures located on the metallic surface in an efficient manner.

Starting with the eigenfunction series representation for the fields outside the covered cylinder the slowly convergent radially propagating series representation is transferred to a rapidly convergent circumferentially propagating series representation using the Watson transform. From the resulting integral form we proceed using the Fock function representation to obtain an asymptotic solution valid within the deep shadow region all the way up to the boundary to the illuminated region.

A common technique to obtain results valid in the deep lit region is to evaluate some of the integrals using the method of stationary phase. This approach is often referred to as the geometrical optics (GO) representation and although it results in a good approximation in the deep lit region, the accuracy is reduced as the field point moves towards the transition region. Thus, this approach will not result in a uniform solution across the boundary to the shadow region. However, by modifying the shadow region solution in an appropriate manner it is shown that the modified solution is reduced to the GO solution in the deep lit region and to the shadow region solution in the transition region. Thus, a uniform solution valid over the boundary between the lit and shadow regions is obtained.

The asymptotic Green's functions contain Hankel and Bessel functions and their derivatives. From a numerical point of view it is very important how these functions are evaluated since it will affect the speed and accuracy of the entire solution. By grouping the functions as ratios whenever possible, it is shown that the resulting special functions can be evaluated in a fast and accurate manner using appropriate numerical techniques. Some examples and numerical results are given.

Effects of Magnetic Material Coating and Choke Loading on the Impedance and Radiation Pattern of a Monopole Antenna

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In some existing low frequency communications systems it is desired to overlay a much higher frequency system that uses the existing infrastructure and does not perturb the low frequency operation. To help achieve this, modifications need to be made to the low frequency antennas that will enable them to achieve the required high frequency performance, while retaining their original radiation properties. Of particular interest are monopole antennas since they are prevalent in the low frequency radiation systems of interest.

The goal of this presentation is to show the effects of various loadings on the input impedance and the radiation pattern of electrically large monopole antennas. An investigation is undertaken to determine several different ways that material coatings and inductive chokes may be applied to a monopole antenna to alter the circuit and radiation properties of the antenna. The electromagnetic software package, HFSS, is used to simulate the material coatings and choke geometries.

A wire antenna is constructed in HFSS, and a material coating is applied to the antenna. The material is magnetic, in general, and is present only over a portion of the structure. Magnetic properties of the coating material, such as the permeability and loss tangent are systematically varied, and the resulting impedance and radiation patterns are calculated. The thickness and positioning of the material coating are also adjusted, and the effects of these variations on the impedance and radiation patterns of the wire antenna are also presented.

An uncoated wire antenna loaded with an inductive choke is also investigated using HFSS. The dimensions of the choke are varied, and the effects of the choke on the impedance and radiation pattern of the monopole antenna are calculated. Effects of adjusting the position of a single choke on a wire antenna are calculated as well as that of applying several chokes. Advantages and disadvantages of using multiple chokes versus a single choke are discussed.

General conclusions of the overall effects on input impedance and radiation patterns, for both magnetic and inductive choke loading are considered. Additional applications for these radiating structures are discussed.

Theoretical Analysis and Measurement Strategy of Shielded Loads

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A cylindrical antenna's operating bandwidth may be increased by placing loading circuits at properly selected points. In a theoretical design based upon Maxwell's equations (antenna) and circuit theory (loading circuit), the use of traditional inductive loads, such as wire-wound coils, suffers due to the coupling to the coil from fields created by the antenna currents and charges. In such cases, the simplicity gained by the use of circuit theory is lost because the usual voltage-current equation fails to represent the effects of these coupled fields. Shielding a coil, however, isolates its windings from the "stray" fields, thereby ensuring the validity of computations based on the laws of circuit theory. Of course, there are other advantages realized by shielding tuning coils. The use of circuit laws to characterize load circuits, as opposed to appealing to Maxwell's equations to capture all significant effects, greatly simplifies analyses and reduces design efforts. But, on the other hand, the presence of the shield renders the characterization of a coil more complex. If the input impedance to a shielded load can be determined accurately, one may employ such loads for tuning purposes.

We describe a hybrid method for analyzing a cylindrical antenna with shielded loads inserted along the length of the radiating element. The method is a hybrid of a computational procedure for solving the loaded cylindrical antenna integral equation and of a measurement procedure for accurately characterizing the shielded load. However, direct measurement of the impedance for a typical shielded load by means of a network analyzer is not feasible due to the interface between the circuit and analyzer. That is, the circuit usually cannot be connected to the analyzer by means of a standard coax connector. A method is developed for measuring the impedance of a shielded load which fully accounts for the presence of the shield. A two-port interfacing network is designed that permits the connection of a network analyzer to one port and a shielded coil to the other. The input impedance of the load may then be determined from measurements "through" the interfacing network by means of a deembedding scheme. With data available to characterize the shielded load, one incorporates this load in the antenna integral equation and can obtain a solution which accurately accounts for the presence of loads along the antenna. Antenna input impedance data obtained from this hybrid solution method are compared with measured input impedance of an actual antenna which is loaded with a shielded coil.

The Finite-Difference Time-Domain Analysis of Top-Hat Monopole Antennas Loaded with Radially Layered Dielectric

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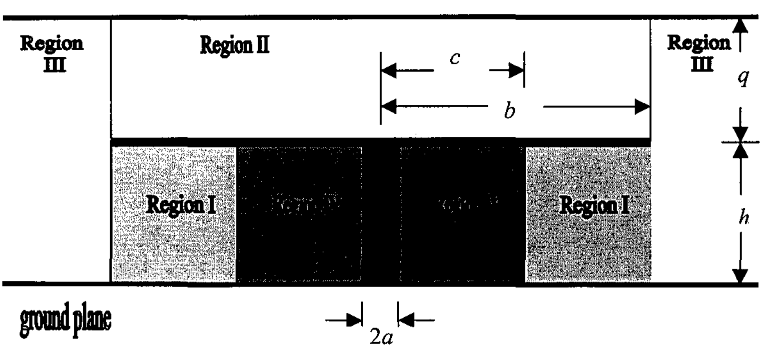
INTRODUCTION- Generating a vertically polarized, azimuthally omni-directional field is a very desirable task in the electromagnetic field practice. Such a pattern can be effectively produced by an electrically small, vertical monopole antenna radiating in the presence of conducting ground planes. The undesirable properties of these antennas however, are that they have low radiation efficiency, low radiation resistance, and are not self-resonant and require the addition of matching networks at the feeds. As a remedy, the antenna system has been top-hat loaded with dielectric and/or magnetic materials [Gangi *et al*, IEEE Trans. Antennas Propagat., Nov. 1965]. Recently, Francavilla *et al* [IEEE Trans. Antennas Propagat., Jan. 1999] have presented a mode-matching analysis of top-hat monopole antennas loaded with layered dielectrics. The electric and magnetic fields of the inhomogeneous dielectric loaded antenna are expressed in terms of series expansion. Mode matching is accomplished by setting two field expansions equal at the boundary between them and generating a system of equations. An edge condition must be enforced to obtain convergent results.

FORMULATION- In the present study, we propose a simple yet effective finite-difference time-domain technique for the analysis of the top-hat loaded monopole antenna. The problem geometry is shown below. The height of the antenna measured from ground plane is h, the top-hat radius is b, and the stem radius is a. Dielectric regions are denoted by regions I through IV. Our method can deal with any loading geometry and material, requires no condition enforcements, and does not involve the solution of a system of equations that can be computationally expensive. Numerical results of the input impedance and resonant frequencies are presented and the effect of the dielectric property of the loading material is studied. Results are validated by comparing with the corresponding measured and numerical results presented by Fracavilla *et al.*



Transient Analysis of a Horizontal Electric Dipole on a Multilayered Dielectric Medium

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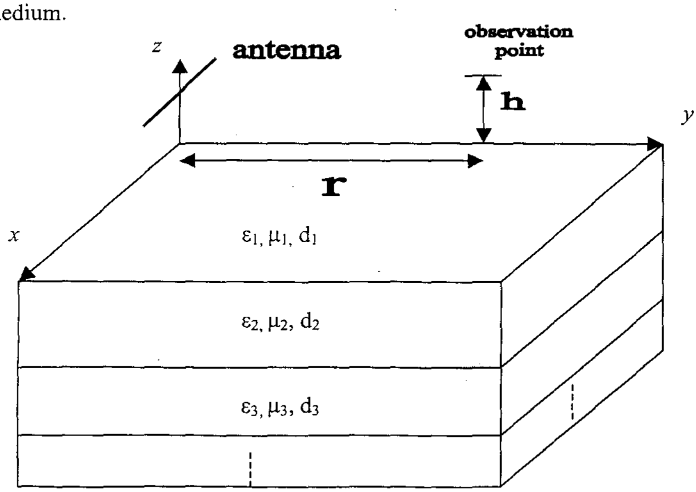
INTRODUCTION- The radiation characteristics of printed circuit antennas and the design of geo-radars are very important practical applications of the electromagnetic fields. The field distributions of such structures can be simulated by considering the radiation from an elementary dipole antenna located above a multilayered medium. The frequency domain analysis of such problem via the spatial wave-number synthesis has been previously reported [Wait, Wave Propagation Theory, Pergamon, 1981]. The transient analysis of this antenna system provides useful insight to its radiation phenomenon. Among the reported time domain analysis, Dai *et al.* [IEEE Trans. Antennas Propagat., June 1997] have presented a technique based on the *Cagniard-de-Hoop* method that first expands the frequency domain reflection coefficients for a multilayered medium into the sum of series that corresponds to the geometrical optics interpretation. The time domain solution of each term in the series is then directly obtained from the spatial wave-number synthesis expression. Numerical results are reported only for two dimensional configurations

FORMULATION- We propose a simple and effective three dimensional finite-difference time-domain technique for the transient analysis of a horizontal electric dipole antenna on a multilayered dielectric medium. The problem geometry is shown below. A short pulse voltage source is modeled to excite the antenna. The traces of the transient electric fields are obtained for various problem configurations and dielectric properties of the layered medium. The results can be used to provide a rigorous modeling for a geo-radar operating on a layered medium.



The Effect of Antenna Structure on Path Loss for Transmitters and Receivers in Close Proximity of a Lossy Earth

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The problem of an unattended sensor network is of significant interest in military applications. A system of small, low cost, low-profile sensors can provide valuable intelligence in areas where more conventional methods are not practical. These sensors have a limited amount of energy available to them and therefore efficient, low power operation is required. Also, these sensors must be omni-directional, as they are deployed in a random fashion and are of arbitrary orientation. In order to optimize a low power sensor network for maximum efficiency it is necessary to minimize path loss. Path loss is a direct effect of both the propagation channel and the antennas deployed and it is crucial that the antennas used operate in an efficient fashion.

A dipole antenna, due to its omni-directional nature, may seem a likely first choice for the unattended sensor network, however as each sensor is low-profile, and operates in close proximity to the Earth several problems arise with the dipole configuration. The transmitted field for a dipole operating in free space decays as $1/R$, where R is the distance from the dipole to the receiver position. For a dipole, of arbitrary orientation, operating above an impedance surface however, this decay is a function of the height of both the transmitter and receiver and has a direct effect on the overall path loss. Due to this height function the received fields, and therefore the current distribution across an extended dipole will not be uniform. In addition if both receiver and transmitter are very near the ground the Geometrical Optics (GO) component of the reflected fields tends to cancel with the direct field. The remaining fields are equivalent to higher order terms in the asymptotic expansion of the dipole fields and decay at a rate of $1/R^2$, thus significantly increasing the path loss of the system.

In addition to these effects the operating parameters of a dipole very near the Earth are also significantly affected. The proximity of the ground will have a direct effect on the input impedance, radiation efficiency and the current distribution of the dipoles used. With this in mind, the goal of this study is to analyze the effects of the Earth on the radiation characteristics of different antenna configurations or structures in order to find an optimum configuration that operates with high efficiency when in close proximity to the Earth, and therefore directly reduces path loss.

To perform this study a Method of Moments (MoM) numerical code, in conjunction with, and to validate an approximate solution for a dipole radiating above an impedance surface will be used. MoM is a numerical technique, which uses the Greens function for a lossy half-space, to solve for unknown currents on the antenna structures. Once these currents are known fields can be found at any observation point by application of the radiation integrals. The configurations analyzed in this study will include a monopole antenna with a finite size ground plane. Effects of the proximity of the Earth on current distribution, input impedance, radiation efficiency, and also receiver field distribution will be analyzed and provided in this study.

An Investigation of Low-Profile, Conformable, Dielectric Resonator Antennas

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Dielectric resonator antennas (DRA) have been the subject of numerous investigations over the past two decades. They have been shown to possess a number of very useful characteristics including high efficiencies, moderate directivities, and a reasonably broad bandwidths. There are, however, two disadvantages of the DRA -- its higher profile and its lack of ease of construction. These shortcomings are most likely responsible for the much smaller number of applications of this radiator into practical systems as compared to the more popular microstrip patch antenna.

An investigation is undertaken to determine the circuit and radiation properties of a low-profile version of the DRA, which might lend itself more easily to fabrication by typical printed circuit techniques. This structure could be made by etching an open "well" around the desired shaped resonator in a slab of dielectric material (such as undoped silicon which has an approximate relative permittivity of 12). Metalization of the top surface of the dielectric substrate could be used to provide the ground plane, or the whole structure might be fabricated by etching away both the upper ground plane and most of the dielectric substrate. For very high frequency applications extending into the millimeter wave range, such structures could be integrated into an existing circuit.

The goal of this work is to show the effects of the various geometrical parameters on the input impedance and the radiation pattern of such a conformal DRA. First, the electromagnetic software package, HFSS, is used to simulate various radiator structure geometries. The height, width, and shape of the well are varied with both rectangular and cylindrical DRAs of different relative permittivities and dimensions.

Secondly, a physical model of the structure is fabricated, and the radiation pattern and input impedance measured and recorded. The effects of the well height and width are investigated and compared to the more usual case of a DRA mounted directly on top of the ground plane. General conclusions of the overall effects on impedance and patterns, as well as possible applications are also included.

Active Antenna Bandwidth Control Using Reconfigurable Antenna Elements

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In recent years there has been considerable effort to develop antenna systems that have the ability to reconfigure the active radiating elements. The primary focus of reconfigurable antennas thus far has been on broadband or sub-banded apertures arrays--aperture antennas that can cover extremely wide bandwidths in smaller instantaneous bandwidth increments. Additionally, antennas have been described in the literature that use reconfigurable techniques to control radiation pattern characteristics. The proliferation of new RF switching techniques has been one of the enabling technologies for this increased interest. In particular, the functional MEMS (Micro Electro Mechanical Systems) switch is fueling much of the new interest in reconfigurable antenna development. Much work has already been performed on the integration of RF MEMS switches into microstrip patch antenna geometries.

This paper presents several methods of antenna bandwidth control using reconfigurable antennas. The antenna geometries have been initially restricted to planar structures because of the planar nature of the RF microswitches. Three fundamental antenna geometries are described which exhibit bandwidth tunable characteristics. The printed dipole, the bowtie dipole and the parasitic loaded folded dipole are examined. The bandwidth tuning methods implemented for each antenna will be presented and the limits of achievable bandwidth control are reported.

Computer simulation and design was performed using a combination of commercial codes. Both IE3D, a 2.5 dimensional moment method code, and Fidelity, a 3D finite difference time domain code were used. Results will be presented from these calculations along with measurements on prototype antennas using the Virginia Tech near-field antenna range.

Surface-Constrained, Crooked-Wire, Genetic Antenna

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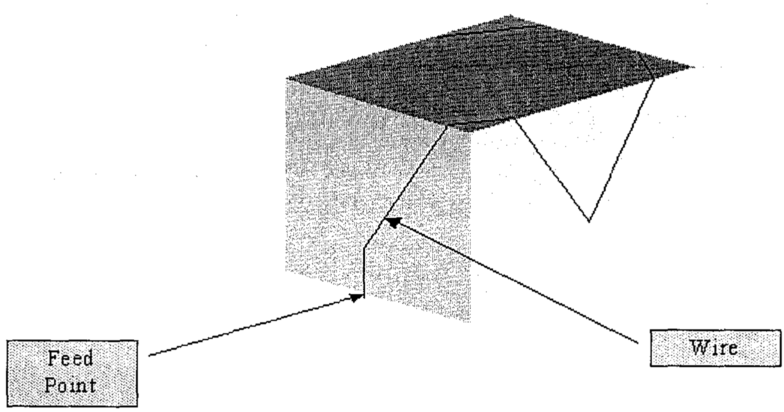
Abstract: Genetic Algorithms, in conjunction with Numerical Electromagnetics Codes (NEC), have been demonstrated as useful optimization tools in the design of wire antennas. A Crooked-Wire antenna, consisting of a segmented wire constrained within a cube-shaped volume, (presented by E.E. Altshuler and D.S. Linden) has been shown to exhibit good circular polarization performance at GPS frequencies. The Crooked-Wire concept may be expounded upon to design antennas which are constrained, not only to the volume of a cube, but to the surface as well. Such an antenna could be easy to fabricate using printed circuit board techniques.

The procedure for designing the volume-constrained crooked-wire antenna is to allow the genetic algorithm driver to pick out the (x,y,z) coordinates for the endpoints of each segment of the wire. Then, a NEC code is used to evaluate the performance of each of the candidate antenna configurations. Next, the performance is consolidated into a single fitness parameter, which is fed back into the genetic algorithm.

For the surface-constrained design, the genetic algorithm driver picks out endpoints in a two-dimensional search space. Nodes are placed at all segment intersections or cross-overs, and duplicate segments are eliminated. Parallel, overlapping segments are redistributed into non-overlapping segments. Next, the two-dimensional coordinates are mapped into the three-dimensional coordinates of the cube surface. Segments which are longer than a tenth of a wavelength are subdivided. The resultant three-dimensional design is then fed to the NEC code and evaluated, as before. (See Figure.)



The resulting designs may be optimized for many important performance parameters, such as CP with good cross-pol rejection, or good linear polarization over a wide bandwidth. Furthermore, the antennas may be easily manufactured into a physically robust product, for both cellular and vehicular applications.

Antenna platform evaluation for automotive applications

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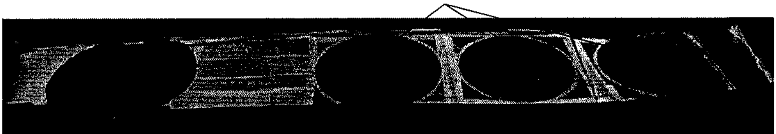
With the recent introduction of new vehicle infotainment/telematics offerings such as cellular telephone, GPS navigation and digital satellite/terrestrial radio, there is a growing need for additional antennas. However, it is well known that vehicle structures and surfaces play a significant role in the performance of these antennas. Nevertheless, antenna design is often carried out without platform considerations and moreover there are limited choices with respect to antenna placement. In spite of these constraints, some design choices are available for optimization in terms of antenna pattern/gain performance.

The goal of this paper is to integrate a suitable optimization routine within the antenna pattern simulation package and to present performance examples. Specific emphasis will be given on antennas placed on the automobile's roof and used to deliver digital radio (SDARS, DAB), mobile communications (AMPS, PCS), Global Positioning Services (GPS) and Bluetooth services. Early work in this area has showed agreement between measurements and calculations for antennas used in a specifically designed tray integrated within the automobile's structure (Fig 1.). At the conference, we will begin by showing the impact of antenna performance on positioning. We will then proceed to provide examples for optimization as well as provide a formalism for possible antenna-packaging scenarios within acceptable bounds based on the component and vehicle specifications.

Antenna positions



Antenna tray

Fig. 1 Antenna tray with three different position configurations

Microstrip Antennas Theory and Experiment

Co-Chairs: *M. Thiel, German Aerospace Center, Germany*
M. T. Chryssomalis, Democritus University of Thrace, Greece

Pattern Deformation due to Substrate Flexing

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Interest has arisen in so-called "electronic textiles" in which circuit interconnects comprising conducting polymers are formed in the weave of a fabric. Applications are likely to include antenna systems at times. The texture of a woven surface raises concern over applying antennas directly to the fabric, but one can easily envision an appliqué of a "planar" antenna system formed among plies of laminated film. Of course, the flexing of the fabric precludes the creation of a truly planar structure. This presentation reports results from a study to determine baseline data on the extent to which departure from planarity is tolerable in terms of antenna performance.

A rudimentary array of patch antennas spaced at half-wavelength intervals serves as the baseline array. A computer model has been assembled for summing the patterns of the individual elements in the presence of surface perturbation of the array plane. Perturbations in the location of a given element and in the direction of the surface normal to that element are accommodated.

The fabric modeling program FABRIX™ was used to characterize the surface contour of a square patch of fabric under the influence of an airflow. Conditions adequate to produce deformations that are a significant fraction of a wavelength were intentionally chosen so as to set an upper bound on the influence of such deformations. Pattern calculations that account for the fabric effects have been performed for the various distortion conditions, including flows at normal incidence and at oblique incidence.

Appreciable pattern distortions and main-beam breakup can be produced with deformation heights as small as 0.2 wavelengths. Numerical experiments that quantify these effects are presented and serve as a point of departure for engineering design of fabric conditions for arrays conformal to an system formed on and in an electronic textile.

On the Efficiency Measurement of Microstrip Antennas Using the Wheeler Cap Method

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The Wheeler cap method is a simple and well-known technique for measuring antenna efficiency. The method involves making only two input impedance measurements of the antenna under test, one with a conducting cap enclosing the antenna and one without. The antenna efficiency is then estimated based on either a parallel or a series RLC circuit model for the antenna. Pozar and Kaufman reported on the use of this method for measuring the efficiency of microstrip antennas (*IEEE Trans. Antennas Propagat.*, 36, 136-139, 1988). Even though it is generally believed that a microstrip antenna should be modeled as a parallel circuit, their measurement results did not support the parallel RLC model, and they concluded that the loss mechanism in the microstrip is similar to that of a series RLC circuit. In this work, we revisit the Wheeler cap method for microstrips and show that the parallel RLC model is indeed a more appropriate model to use than a series one for the microstrip. Our Wheeler cap measurement is verified by two different simulations using the commercial software ENSEMBLE: (i) simulation of the Wheeler cap method by modeling the conducting cap, and (ii) gain simulation with and without losses.

As a test, we use a standard square microstrip (patch dimension of 40.5 mm operating at 1.8 GHz) built on FR-4 substrate. A conducting rectangular cap (17cm× 17cm×8.5cm) is used to completely enclose the test microstrip. The input impedance of the antenna is measured with and without the cap. Based on the parallel RLC model, the radiation conductance G_a and the conductance due to losses G_l are extracted. The efficiency is calculated by $\eta=G_a/(G_a+G_l)$. The resonant frequency of the capped antenna is slightly shifted from the original resonance due to the cap effect. The conductance at the new resonant frequency is used to compensate for this effect. Based on the parallel RLC model, the Wheeler cap measurement shows an efficiency value of 32%. This result is checked against two different simulation results. From the simulation of the Wheeler cap method, the efficiency is found to be 39%, while the gain simulation with and without dielectric and metal losses shows an efficiency of 30%. The same methodology is applied to microstrips on other substrate materials, and the resulting efficiencies are investigated. The interior cap modes, which may prevent accurate efficiency measurements, are discussed. Furthermore, optimal shapes and dimensions of the Wheeler cap are studied.

Design Model for a Reconfigurable Single-Arm Microstrip Square Spiral Antenna

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High-speed (2-100 Mb/sec) wireless data communication – whether land- or satellite-based -- faces two challenges: (1) high error rates caused by interference and unpredictable environments, and (2) limited signal processing capability and battery life at the portable unit. Reconfigurable antenna systems can help meet these challenges. Current 'smart' systems focus on antenna functionality at base station. However, the performance gains of base station intelligence are constrained by the portable units—the weakest components of the system. Reconfigurable antennas in portable units can allow autonomous responses to local operating conditions while remaining practical and cost-effective, and may greatly improve the reliability of high-speed wireless links.

This paper addresses a square single-arm, single-turn reconfigurable microstrip spiral antenna. Depending on the placement of shorting pins to ground or shorting arms between sections of the conducting arm, this antenna can support a number of different current distributions that result in a range of far-field radiation patterns. Although several authors have analyzed spiral microstrip antennas, none has provided a comprehensive design model or considered these structures for reconfigurability.

In order to provide a practical design procedure of this microstrip spiral antenna, an equivalent circuit model is derived. Since the input admittance plot of a microstrip antenna near the resonant frequency is approximately a circle on the Smith chart, it can be represented by a simple resonant circuit (S. J. Weiss and W. K. Kahn, *IEEE Trans. on Microwave Theory and Techniques*, vol. 44, 1513-1516, 1996). The performance of the antenna is determined by the properties of the substrate, the total length of the spiral arm, the width of the arm and gaps, the length of the coupling section, and the positions of the shorting pins and arms. Influences of these parameters are reflected in the values of the circuit model. For example, increasing the spiral length increases the inductance of the circuit and decreases the resonant frequency. Plots and tables depict the effects of altering these circuit parameters on resonant frequencies and return losses, and aid in the analysis of similar designs. Using the design procedure developed with this data, new antenna designs for particular applications can be achieved.

Reduced Size, Dual Polarized Microstrip Patch Antenna for Wireless Communications

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1 Abstract

Recent years have experienced an almost explosive growth in Wireless Communications Systems Technology with rapid advances in the variety and sophistication of the wireless services being offered. The next generation of wireless systems are expected to enhance information accessibility even more providing not only basic voice and paging services, but also data intensive services such as wireless internet access, geo-positioning, database services, distributed computing and much more. In this scenario, it becomes imperative to design communication systems with enhanced capacity capable of delivering data rates in several Mbps.

Our effort addresses the issue of capacity increase by exploring novel antenna topologies that can assist in meeting such high capacity demands. This paper focuses on the development of compact microstrip antennas characterized by polarization diversity in order to increase capacity and improve quality of service. The objective was to explore strategic antenna designs for dual polarization coverage and determine the feasibility of seamlessly integrating such antenna systems on mobile nodes in a wireless system. Due to their intended application on mobile network nodes such as a portable laptop platforms, compactness was a key issue that was considered in the designs. Owing to their inherent conformal, lightweight, economical, robust and compact structure, microstrip patch antennas were selected to perform in dual polarization mode and hence increase capacity and improve multipath performance by polarization diversity.

A novel, compact, microstrip patch antenna geometry has been designed by etching a symmetric pattern of crossed slots from the surface of a probe fed patch. Reduction in patch size of up to 45% with respect to a traditional dual-polarized square patch operating at the same frequency was obtained. Linear polarizations in the $+45$ and -45 degrees with high isolation between the two ports has been observed. Further, the designed antenna exhibits a cross-polarization level of -18 dB and a broadside gain of 1.5 dBi, as opposed to a cross-polarization level of -25dB and a gain of 4 dBi for a normal sized patch at the same resonant frequency. It was also observed that wider and longer slots led to a further decrease in the resonant frequency albeit with a corresponding deterioration in gain and cross-polarization levels.

A closed-form asymptotic solution for the field radiated by a dipole on a rectangular grounded slab

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The prediction of electromagnetic diffraction in a finite grounded dielectric slab arises in several engineering applications. An important case is that of microstrip antennas printed on a finite ground plane. The diffraction effects may considerably affect the radiation pattern [J. Huang, *IEEE Trans. Antennas Propagat.*, Vol. 31, No. 4, pp. 649-653, Apr. 1983] and produce a loss of directivity, especially when surface waves (SWs) are strongly excited. The typical values of thickness and dielectric constants of the slab, suggest the effective use of a generalized Physical Optics (PO) approximation. This approximation consists of estimating the radiating currents on the finite substrate like those produced in the infinite structure. The most evident lack of the PO for grounded slab configurations is the absence of an estimate of the guided waves reflection at the open-ended interfaces. Anyway, this phenomenon is less important for low permittivities such as those used in patch antennas. The application of the PO to grounded slab structures was firstly introduced in [S. A. Bokhari, J. R. Mosig, F. E. Gardiol, *IEE Proc.-H*, Vol. 139, No. 3, pp. 278-286, Mar. 1992]. There, the calculation of the PO radiating currents was performed numerically by evaluating the relevant Sommerfeld-type integrals in each point of the structure and the far-field radiation integral was calculated by using a fast Fourier transform (FFT) technique. In [S. Maci, L. Borselli, L. Rossi, *IEEE Trans. Antennas Propagat.*, Vol .44, No. 6, pp. 863-873, Jun. 1996], the PO approach was used for the case of an electric dipole placed at the interface of a truncated semi-infinite grounded dielectric slab, for deriving an asymptotic closed-form formulation. In that work, the effects of the vertex of the structure are not accounted for. This implied discontinuities in the radiation pattern of a patch antenna printed on a rectangular grounded slab [L. Borselli, S. Maci, *JEWA*, Vol. 11, pp. 689-711, 1997]. Successively, the accuracy of the PO approach has been tested in a 2D case using a full-wave analysis [S. Maci, L. Borselli, A. Cucurachi, *IEEE Trans. Antennas Propagat.*, Vol .48, No. 1, pp. 48-57, Jan. 2000]. In this paper, the previous results are extended to include the effects of the vertices. The reference problem is that of an electric dipole printed on a doubly truncated planar substrate. By using the plane wave representation of the radiating currents, a double spectral integral is obtained. This integral is asymptotically evaluated, uniformly accounting for the presence of SW poles. The final result leads to a summation of geometrical optics (GO) contributions and ray-diffracted contributions from space waves and SWs at the edges and the vertex of the structure. The radiation from a dipole printed on a finite rectangular grounded slab is obtained by superposition of the GO field plus the contributions from each edge and vertex. Numerical results will be presented and discussed during the oral presentation, in order to show the impact of the PO assumption on the accuracy of the formulation.

A Comparison of Microstrip Patch Antenna Models in a CAD Circuit Environment

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In many cases, the efficient modelling of a rectangular microstrip patch antenna is necessary, in order to study the behaviour of a circuit as a whole, in the environment of a computer aided design (CAD) software package. Antenna parameters such as input reflection coefficient or input characteristic and resonant frequency must be predicted reasonably well, in order to have useful results of the circuit simulation. As an example, these models can be used in the area of the design of integrated active antennas.

In this work, well known approximate models are compared to each other, the basic transmission line model in its simple and more accurate form (H. Pues and Van de Capelle, IEE proc., Pt. H, 6, 1984) and the broad-band transmission line model (R. W. Dearnley and A. Barel, IEEE trans. Ant. Prop., 37, 1989). The equivalent circuits of these models are designed and their characteristics are tested both as independent circuits and as a part of a circuit of a patch oscillator design. The computed results demonstrate good agreement as regarding the resonant frequency and small differences for the input reflection coefficient, the value of which is not so well predicted. As a reference, measurement results and calculated S-parameters from the commercial software package of Antenna analysis, ENSEMBLE, from Ansoft, are used. The comparison of the results for the harmonic balance analysis of the oscillator, showed almost identical values for output power and small differences in the values of frequency. However, significant differences were obtained in the values of the second harmonic between the simpler transmission line model and the accurate and broad-band models, with the last ones be closer to the results of measurements.

Reduction by inductive loading combined with filter insertion

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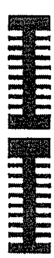
Abstract:

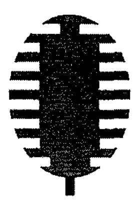
In this communication, we consider the reduction of the global size of a several types of antennas using inductive loading as well as insertion of filters.

The authors have already proposed a solution to reduce the size of a patch by a factor of two (S. Reed, L. Desclos, C. Terret and S. Toutain, "Size reduction of a patch antenna by means of inductive loads", MOTL March 2001). The principle relies on the loading of the non-radiating edges by slits (Hoefer W.J.R, "Equivalent series inductivity of a narrow transverse slit in microstrip", IEEE Trans on MTT, Vol. 25, N 10 october 1977, pp.822-824). We try then to use this technique to get more insights on its application for printed and non-printed antennas such as monopole, dipole and Planar Inverted F antennas. We characterize the typical behavior of an antenna in its classical mode and the antenna loaded. This then creates a kind of data behavioral base to establish a few sets of rules such as the ones we established previously for the patch.

For example we could say that loading a printed dipole such as in figure 1. permits to reduce its length up to 30 to 40 %. If printed, a monopole is then reduced too but has other implications if we consider it as in (L.Desclos, J.M. Floch, "Surface Mounted Components for arrays", in MOTL 20th Dec. 1998) a non printed wide band version -Fig.2-. This creates if not properly dimensioned a set of resonance's that might not be suitable for a large frequency band application. Last a PIFA loading structure is investigated. All the simulations have been performed using a moment method based software and have been verified with a set of measurements. Moreover a set of experiments are conducted with respect to combination of filters and size reduction at the same type using another technique presented by the authors (Multi-frequency printed dipole with built-in filter. R.B. Hermida, L. Desclos, Y. Mahé, S. Toutain, APS/URSI Boston 2001). A guideline on the combination limitations will be established and presented.



-Fig.1-



-Fig.2-

INCREASING THE BANDWIDTH OF A MICROSTRIP PATCH ANTENNA WITH A SUPERSTRATE

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ABSTRACT

During the last decade microstrip patches have became one of the most interesting antenna solution for many applications both in microwave and millimeter-wave bands. This huge success is due to their some well-known advantages such as low profile lightweight and low cost. Moreover they can provide a wide range of radiation pattern and polarization characteristics. However they also present some drawbacks the most important being usually narrow band. Many techniques have been proposed to increase the bandwidth of microstrip patch antennas.

A novel and very simple technique to increase the bandwidth of a microstrip patch antenna element is presented. It simply consists of adding a superstrate layer of adequate dielectric constant and thickness on top of the substrate. In that case for a specific superstrate material optimized configurations provide impedance bandwidth and gain which are both oscillatory functions of the superstrate thickness with well-defined and non-coincident maxima and minima. The maximum bandwidth can reach as much as 3 times (or even more) the bandwidth of the configuration without superstrate. However the gain can be substantially decreased. Moreover this new solution leads to a considerable increase of the antenna volume and can not be used when low profile is required.

As an application example a common square patch printed on a 62 mils RT/Duroid substrate ($\varepsilon_r = 2.20$) has been optimized for a 5 GHz frequency band. An impedance bandwidth of 3.0% (VSWR ≤ 2) and a gain of 7.1 dBi have been obtained. Adding a plexiglass superstrate ($\varepsilon_r = 2.50$) with a thickness of 10 mm has provided an impedance bandwidth of 8.3 % and a gain of 5.6 dBi. These new results have been obtained by simulation and confirmed experimentally.

Details of the optimization procedure and examples with this and other substrate and superstrate materials will be presented and discussed.

Theory and Experiment on a Tunable Equilateral Triangular Microstrip Patch Antenna

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Triangular microstrip patch is a high Q structure though the same has been studied as printed antenna by a number of researchers over a decade. The introduction of an air-gap in between the substrate and the ground plane should enhance the antenna bandwidth. An equilateral triangular patch (ETMP) antenna with a variable air-gap below the substrate, as shown in Fig.1, is investigated both theoretically and experimentally in this paper, though the tunability of a similar structure has recently been examined theoretically only (Gurel and Yazgan, IEEE MTT, 48, 334-338, Mar. 2000).

A new formulation following Guha (IEEE-AP, 49, 55-59, Jan. 2001) is proposed to calculate resonant frequencies of a tunable ETMP antenna printed on a dielectric substrate covering entire range of dielectric constant. Thus unlike the previous models, ours can be applied to the MIC design of an ETMP on semiconductor wafers. Present theory is found to predict much more accurate values compared to the earlier ones. The computed resonant frequencies for TM_{10} and TM_{11} modes are also compared with the new measurements with prototype ETMP antennas (15.5 mm side length) fabricated on RT- Duroid 5880 and performed on HP 8720C network analyzer. Excellent agreement between this theory and experiment was observed for TM_{10} mode with maximum 0.37 % relative deviation. The deviation increases up to 1.82% for TM_{11} mode of the same patch.

The enhancement of antenna bandwidth with the introduction of the air-gap was also experimentally studied and the measured data are shown in Fig. 2. The experimental curve reveals the possibility of enhancing the antenna bandwidth up to a significant value by increasing the air-gap height to a certain limit.

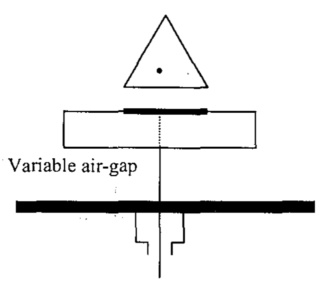

Fig.1 ETMP Antenna with an adjustable air-gap

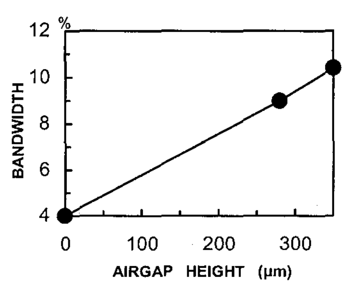

Fig. 2. Measured bandwidth (SWR<2) of an ETMP antenna with different air-gap heights.

Impedance Characteristics of an Inverted Microstrip Circular Patch Antenna

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In recent years, inverted microstrip patch has been used for various applications as active integrated antennas due to its geometrical advantages. In those design of active antennas with inverted circular microstrip, the researchers had to depend on some prior experiments with the probe-fed version of the same patch, since accurate theory to calculate the resonant frequency or input impedance was not available.

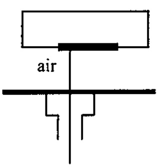

Fig.1. Coax-fed IMCPA: a cross-sectional view

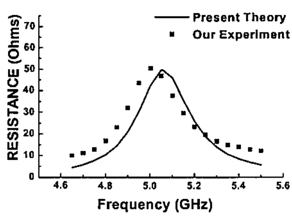

Fig.2. Input Resistance vs. Frequency

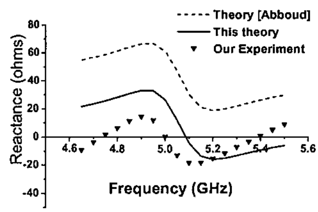

Fig. 3. Input Reactance vs. Frequency

This problem has been addressed in this paper and a new cavity model formulation has been proposed to determine accurate resonant frequency and input impedance of an inverted microstrip circular patch antenna (IMCPA). The model takes care of all the effects of the thickness and permittivity of the inverted substrate in a versatile way.

The computed results are compared with the experimental values obtained for the dominant mode of a prototype antenna of 31mm diameter fabricated on RT-Duroid 5880 and measured on HP 8720C network analyzer. The plots of the input resistance as a function of frequency are shown in Fig. 2. Very close correspondence between the theory and experiment is apparent from the figure.

In calculating the input reactance of a coax-fed antenna, we have considered the feed reactance as a combination of the probe inductance in parallel with the capacitance due to the patch and the ground plane below it while in previous models like (Abboud et.al. IEEE Trans. AP.,1882-1885,Nov.1990) only the probe inductance was considered as the feed reactance. The new concept of feed reactance adopted in this paper was proposed by Alarjani and Dahele (Elect.Lett., Vol.36,388-390, 2nd Mar. 2000). This results in close approximation with the experiments as revealed from Fig.3. A theoretical curve due to one earlier model by Abboud *et al.* is also incorporated in Fig. 3 which in comparison with our theory and experimental data indicates the accuracy of the present theory.

Special Session

Cell Phone Radiation and Interference: Issues and Solutions

Organizer(s): *D. Nghiem, University of Houston, USA*

Co-Chairs: *D. Nghiem, University of Houston, USA*
J. Wojcik, APREL Laboratories, Canada

Cell-phone Radiation Issues and Solutions

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Due to its convenience, the cellular phone has rapidly become a useful tool in people's personal lives and a necessary tool in business communications. The popularity of cell-phones is understandable; however, convenience and popularity should not get in the way of safety and efficiency. The long-term nature and complexity of biological studies to determine if radiation emissions from cell-phones are harmful means that it may be many years before we know definitely of any effects on humans due to these emissions. It is true that biological studies, at this time, are inconclusive; nevertheless it is important for the telecommunications industry and the government to inform consumers about all the facts on cell phones. A cooperative environment will foster valuable results that will benefit everyone, especially the millions of cell-phone users. In this presentation, current RF-exposure standard for cell phone (Is the current RF-exposure standard stringent enough?), and Specific Absorption Rate SAR measurement methodology (Is the current SAR measurement methodology designed for a worst-case scenario or at least truly conservative?) will be discussed. Biological studies on cell-phone effects will also be discussed. Several solutions to minimize the radiation due to cell phone, including shielding devices and hand-free set will be presented. Last but not least, practical and efficient antenna solutions that reduce the radiation generated from cell phone will also be proposed.

Biological Effects of Radiofrequency Radiation

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Increase use of wireless communication devices leads to exposure of a large human population to radiofrequency radiation (RFR). The question of possible biological and health effects of exposure has attracted a lot of attention from the general public and news media. In this presentation, research literature on effects of RFR exposure on genetics, cellular functions, morphology, and behavior of animals will be discussed. These effects could lead to temporary or permanent functional changes in an organism.

In considering the biological effects of RFR, the intensity and duration of exposure are important determinants of the responses. For repeated exposure, as in the case of the use of cellular telephones, homeostatic compensatory response can occur. On the other hand, since a relatively constant amount of body tissue is exposed, cumulative effect could occur and lead to an eventual breakdown of homeostasis and adverse health consequences. Data from existing research literature do suggest that RFR effects are cumulative over time and dependent on the duration of individual exposure episodes.

Data available also suggest a complex reaction of biological mechanisms to RFR. The response is not likely to be linear with respect to the intensity of the radiation. Other parameters of RFR exposure, such as frequency, duration, waveform, frequency- and amplitude-modulation, etc, could be important determinants of biological responses and affect the shape of the dose(intensity)-response relationship. In order to understand the possible health effects of exposure to RFR, one needs first to understand the effects of these different parameters and how they interact with each other.

Recent Progress in SAR Standards

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The global wireless community has seen several new standards related to SAR. There are two groups of standards. The first one sets limits considered as safe the other addresses methodology for assessing SAR and compliance with the set limits. Depending on the country of origin and the area of coverage, the SAR standards may have variances, which are localized and difficult to understand or decipher. Methodology standards are usually voluntary documents defining how the compliance with regulatory limits may be demonstrated. Out of all the global methodology standards there are two that are the most elaborated coming from IEEE and IEC. These standards encapsulate all of the global scientific thinking, practices, and experimentation and have more individual countries contributing towards a workable standard for evaluating wireless handsets than any other. Every standard has its merits, and should have its place where applicable. Because of the many countries, which contribute to the standards, to be sure that, one does meet requirements on a global sense understanding and working within either the IEEE or IEC standards should prove competency in evaluating wireless devices globally. Contributions towards these standards come form many diverse areas, which include academic, manufacturing, marketing, and legislative environments. By having a diverse mix of contributors towards the creation of a standard one allows a non-biased forum to work in harmony to create an acceptable working standard for all to follow. A standard helps everyone understand what is needed to prove conformity when it comes to evaluating and developing new products for the global market place. Standards work provides a forum for the sharing of information, which benefits all users of the completed standard. The work continues to harmonize standards with respect to safety limits and reliable repeatable methodologies.

Biological Effects of Low-Intensity Radiofrequency Radiation

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Wireless transmission towers for radio, TV, telecommunications, radar and many other applications emit radiofrequency radiation (RFR). Since intensity of RFR decreases with the distance from the generating source, exposure to RFR from transmission towers is usually of low intensity depending on one's proximity. However, living near a facility means the exposure will be of a long duration because a person will be exposed to radiation for many hours in the day. Thus, the relevant questions are: (1) do biological/health effects occur after exposure to low-intensity RFR?; (2) do effects accumulate over time, since the exposure is of a long duration and is usually intermittent?; (3) what precisely is low-intensity RFR and what might its biological effects be?; and (4) what does the science tell us about such exposures? These questions will be discussed in this presentation.

Briefly, biological effects do occur after a short-term exposure to low-intensity RFR. These include induction of heat-shock proteins, DNA damage, and changes in calcium efflux, immunological functions, reproduction, and cell proliferation. Furthermore, not much is known about the biological effects of long-term exposure. The effects of long-term exposure can be quite different from those of short-term exposure. Some effects can possibly cumulate over time.

The present U.S. guidelines for RFR exposure are not up-to-date. The most recent IEEE Guidelines only included research data up to 1985. In addition, effects of long-term exposure, modulation and other propagation characteristics are not considered. Therefore, the current guidelines are questionable in protecting the public from possible harmful effects of RFR exposure.

New Advanced SAR Measurement Systems

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Measuring SAR (Specific Absorption Rate) in the tissue is not a new thing, and has been around for over 20 years. All SAR measurement systems, which have been developed, have had to prove conformity with SAR standards of the day. This one factor alone has made it difficult for independent organizations to create a system for the assessment of SAR. SAR measurement systems generally consist of hardware and software, each contributing to the goal of repeatable SAR analysis and assessment. The main component for the assessment of SAR is the probe, which demodulates the RF signal emitted from the device under test. The probe is positioned within the field to determine the strength or the value of SAR. The probe is maneuvered within a phantom, which contains a homoginase liquid, which replicates a part of the human anatomy. The robot is controlled by a host system, which in turn computes the measured signals from the probe. In most systems a data acquisition system is used to sample the demodulated signal coming from the device under test. The host system will assess the measured values and provide a graphical out put for visual analysis by the operator. Positioning the device for test is also critical for the SAR measurement system, as it is imperative that the simulations are well thought. The surrounding hardware must not effect or absorb the RF field radiated form the device under test. Ambient effects should also be considered when developing a SAR measurement system. Uncertainty for the overall system must be assessed and can be extremely difficult when you take into consideration all the components, which form the SAR measurement system.

On the Uncertainty of SAR Measure

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Specific absorption rate (SAR) is of interest in wireless communications for the health consideration. Reducing the SAR in the human head is one of the challenges encountered in wireless handset designs. Accurate modeling/measuring the SAR distribution has been proved to be an effective way in providing the good direction in engineering designs. Through the numerical modeling, designers obtain not only the SAR distribution information, but also gain better physical understanding of the near-field handset radiation problem.

In most numerical modeling and experimental measurements, a fixed human head model is used, while in the reality, the human head size varies (O. P. Gandhi, G. Lazzi, and C. M. Furse, IEEE Transactions On MTT, Vol.44, pp.1884-1897, 1996). It is shown that the variation in the human head size has lead to over 10% variation in the SAR values. In addition, we have observed that the reported values of dielectric constant and conductivity loss used for head model also vary. Such uncertainties will lead to the variation of the SAR calculation.

In this work, we will investigate the SAR uncertainty through extensive numerical analysis. Specifically, we will investigate the variations of SAR as a function of human head size, relative position between handsets and human heads, and the variation of the dielectric properties of the human head model. The SAR distribution within several dielectric blocks and spheres of different sizes, different dielectric properties will also be obtained for comparison. Based on the complete data, the uncertainty of SAR measure will be discussed. The related issues will be presented.

Statement:
This work will give the complete analysis of the uncertainty of the SAR measure; it's the extension of previous work.

The Hybrid Finite Element / Method of Moments Technique for Human Exposure to Radiation from Mobile Communication Technology

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The Finite Difference Time Domain (FDTD) technique is currently the most widely used numerical method for the assessment of human exposure to electromagnetic radiation. Several important near field exposure problems exist for which the FDTD is not necessarily the best technique to employ. These include, but are not limited to: i) exposure in the near field of base station antennas, ii) exposure to electromagnetic radiation inside motor vehicles emanating from antennas in the exterior and/or interior of the vehicle, iii) exposure in the near field of personal communication devices, e.g., an antenna on a notebook. The main drawback of the FDTD when applied to these type problems is the large volume of free space between the antenna(s) and the exposed human that needs to be included in the 3D solution space. This results in high demands on CPU and memory. Furthermore, thin, curved, metallic objects are typical antenna components, which need specialized formulation extensions to the conventional FDTD.

A hybrid Finite Element Method (FEM) / Method of Moments (MoM) technique is proposed as a very efficient and elegant alternative for modeling these problems. The MoM is ideal for modeling open boundary problems which can include metallic wires and surface patches (e.g., wire antennas, helices, reflectors and the surrounding structures with electromagnetic significance such as the body of a motor vehicle). The FEM can efficiently model complex, heterogeneous, dielectric objects such as the human body with its diverse and highly heterogeneous tissue materials. With the hybrid formulation the MoM is further applied on the surface enclosure of the FEM volume, serving as an exact radiation boundary condition for the FEM and ensuring full coupling between the antenna (MoM region) and human body (FEM region).

The FEM results in a large, sparse matrix equation, consisting of millions of unknown field coefficients. The MoM leads to a relatively small, but dense matrix equation, consisting of thousands of unknown current coefficients. The hybrid FEM / MoM technique thus has unique linear algebra requirements due to the dual set of matrix equations that have to be solved. The combined solution of the FEM and MoM matrices was implemented using state of the art linear algebra technology, with an appropriate robust preconditioner and efficient sparse and dense matrix solvers. The FEM part of the solution yields the electric field values inside the body from which the energy absorption can be calculated. The MoM part yields the near field distribution *around* the antenna and human body, which is of importance for coupling and interference considerations. The MoM also yields antenna characteristics (e.g., impedances) and far field information, if the effect of the human body on the performance of the antenna is of importance.

The implementation has been verified by comparison to measurements and to conventional FDTD and MoM results, where possible. The results confirm that the hybrid FEM / MoM is an accurate and efficient technique, outperforming both the FDTD and MoM when certain important classes of near field human exposure conditions are to be evaluated.

Practical and Efficient Antenna System for Cell Phone

Dr. David Nghiem, University of Houston

Currently, cell-phone antennas sit next to the user's head. In order to make cell-phones safer and more efficient, one can simply distance the cell-phone antenna from the user's head. It is well known that positioning an antenna farther from the user's head will reduce the amount of radiation absorbed into the head and the brain. Just a few inches make a significant difference. It is important to note, however, that there is a high field concentration not only on the antenna, but also at the feed point, which is the point where the antenna connects to the electronic circuitry. Since the feed point is generally placed close to the ear, distancing the feed point or shielding it will also reduce the radiation absorption by the head. In addition, distancing the cell-phone antenna from the user's head increases the efficiency of the cell-phone antenna. Since the antenna is farther from the user's head, less power is "lost" or "wasted" by absorption into the user's head. Hence, more of the power generated by the cell-phone is available for the cell-phone system. By simply positioning the antenna farther from the user's head, the power efficiency substantially increases. A practical and efficient antenna system for cell phone will be discussed in this presentation. In addition, RF-circuit and LCD-display shielding solutions will be discussed.

Cell-phone Interference Issues and Solutions

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In this presentation, interference issues such as the emission mask requirement and its measurement methodology will be discussed. The main purpose of the emissions mask requirements for the cellular phone is to insure that the cellular phone system will not interfere with other communications systems, which is typically a far-field issue. Unless regulated by emission mask standards, the different communications systems would interfere with each other.

Far-field methodology is appropriate for the measurement of devices that will be operated sufficiently far from other devices (the necessary distance depending, of course, on the frequency and the device size). Our main concern when dealing with the issue of emissions mask, however, is the interference between objects that are close in proximity to the cellular phone. We agree that the far-field methodology is important, but we also feel that near-field methodology is equally important. The near-field method measures a few centimeters away from the electronic device, which is important when considering the possible interference between electronic devices that are in close proximity. For example, when the user holds a cellular phone close to the body, it can potentially cause interference with medical electronic devices. We are concerned about the relation between medical electronic devices and cellular phones (operating between the frequencies 824-894 MHz) because the third-harmonic frequency of the cellular phone (around 2450 MHz) is equal to the operating frequency of medical devices. Since near-field interference between medical electronic devices could have serious adverse effects, we feel that more focus should be placed on near-field measurements of the cellular phone. As shall be presented in this presentation, without performing near-field and conductive measurements we cannot accurately determine the amplitude of the third harmonic frequency, hence the possibility of interference with devices. Can cell phone interfere with a carbon monoxide alarm?

Last but not least, a Selective Harmonic Frequency Antenna SeHFA solution will be presented.

Scattering II

Co-Chairs: *R. H. MacPhie, University of Waterloo, Canada*
E. Arvas, Syracuse University, USA

Use of Genetic Algorithms for Parameterization of Scattering Data Containing Scattering Centers and Resonances

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Abstract

It is well known that scattering data from complex targets can contain both scattering center and resonance information about the target. The former comes from discontinuities in target features that are large compared to the incident wavelength, while the latter arises from scattering features on the order of the wavelength. In this paper, we address the problem of parameterizing backscattered radar data with both scattering centers and resonances. A full model is used to include both the scattering center and resonance mechanisms. The unknowns of the problem include the number of the scattering centers and the number of resonances, each scattering center's position and frequency dependent coefficient, as well as each resonance frequency, turning-on time, and damping coefficient. Our objective is to model the radar data with as few parameters as possible within the allowable error limit. Genetic algorithms are used to achieve the best solution based on these two criteria.

We study the efficiency issue by examining the behavior of the parameterization error as a function of the number of scattering centers and the number of resonances. Thereafter, the right order number can be made based on the trade-off between the parameterization error and the efficiency. While the simple GA can theoretically solve all the scattering centers and resonances simultaneously for the solution with the lowest error, in practice it suffers from the problem of prematuration, especially as the order of the problem becomes large. On the other hand, a GA-based matching pursuit algorithm works nicely regardless of the order of the problem as it extracts a single scattering center or a single resonance one at a time. But it is only a sub-optimal solution as it suffers from interference from other features. Furthermore, it is susceptible to the model mismatch error. We propose an intermediate, adaptive GA approach to better handle the parameterization problem. The adaptive GA still learns from lower-order results. But instead of fixing the extracted values as in matching pursuit, it searches in nearby regions much smaller than the entire search space for the global minimum in the higher-order problem.

The algorithm is tested with simulated data generated with the ideal data model. We also apply the algorithm to scattering data generated from numerical simulation and measurement data from complex targets. The algorithm can be applied for efficient data storage and robust feature extraction in target identification.

A Genetic-algorithm-based Extrapolation Technique for High Frequency Scattering Analysis

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Full wave solution of scattering problems at high frequencies is highly time- and memory-intensive. In this paper we propose a numerically-efficient extrapolation technique for computing the scattered field at high frequencies by using a scattering center approach employed in conjunction with the Genetic Algorithm and Prony's method.

We begin by analyzing the scatterer at lower frequencies using numerically rigorous techniques, and then construct a scattering center model from the knowledge of the scattered far fields. From the scattering physics we know that the amplitudes (weights) of the scattering centers are functions of frequency, and depend upon the geometrical nature of the scattering centers. Since most of the spectral analysis techniques restrict themselves to an exponential type of frequency behavior, it is not a simple matter to simultaneously extract the frequency factors and locations of the scattering centers using these techniques. This has prompted us to employ a combination of Prony's method and the genetic algorithm (GA) to determine the model coefficients.

To implement the above procedure, we apply a sliding frequency window to the scattered field data, and fit a damped exponential model to this data for each frequency window using Prony's method. For a sufficiently small frequency window, the locations of the scattering centers turn out to be quite accurate, even though the Prony's method assumes that the weights are frequency invariant. A statistics is then generated for the output of all the frequency windows, and the actual locations of the scattering centers are identified by separating them from numerical noise. Next, the GA is employed to determine the frequency factor as well as to fine-tune the locations of the scattering centers. The objective of the GA optimization is to minimize the difference between the data predicted by the model and the simulation. The same technique can also be generalized to two-dimensions by processing the scattered field as a function of frequency and the aspect angle. We demonstrate that the 2-D scattering can better isolate the scattering centers that may overlap in the 1-D approach.

Inverse Scattering of Dielectric Targets Embedded in a Multi-Layered Medium

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There are many applications for which one may be interested in sensing a low-loss dielectric target embedded in a lossy host medium. For example, buried plastic land mines, plastic pipes and underground tunnels generally constitute conducting voids in the presence of a lossy soil background. While such targets can in principle be detected by a radar sensor, radar suffers well-known difficulties due to soil-induced attenuation. An electromagnetic-induction (EMI) sensor, on the other hand, affords the potential for significant soil penetration. Such sensors are typically used as metal detectors, with example applications including detection of buried *conducting* land mines and unexploded ordnance. As elucidated here, such sensors can also be used to detect the *absence* of conductivity (a conducting void) in the presence of a conducting host medium. Our focus here is on generally small, shallow targets (*e.g.* plastic mines), although the computer model is quite general.

We have developed three forward models used in the inversion of such targets. Two of the models are based on the method of moments (MoM). In particular, we have developed a volumetric electric-field integral equation (EFIE), as well as a surface combined-field integral equation (CFIE). While a MoM analysis is accurate, it generally requires the inversion of a large matrix. This task is circumvented by employing the extended-Born method, this an approximate method that only requires inversion of simple 3x3 matrices. The attendant speed enhancement accrued by extended-Born, *vis-a-vis* the MoM, is critical if the model is to be utilized in the context of signal processing and/or inverse scattering.

The forward models are employed in iterative Born and distorted Born inversion of general dielectric targets embedded in an arbitrary layered medium. The basic forward and inverse framework will be discussed in detail, and results will be presented for several subsurface targets of interest. A scalable implementation of the algorithm has been developed, allowing consideration of large problems.

Numerical Study of Scattering Signatures of Subsurface UXOs Employing Novel Ultra Wideband GPR Antennas

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For countermine/unexploded ordnance (UXO) detection applications, accurate numerical models of ground penetrating radar (GPR) systems are of paramount importance to verify field measurements and generate synthetic data for the various detection/classification algorithms and (possibly) multisensor data integration. Although GPR measurements have been used to help classify and detect subsurface UXOs for a number of years, the high rate of false alarm is still a major hurdle. To reduce the false alarm, a careful numerical study of scattering signatures of target under various ground scenarios is a basic necessity.

In this study, a detailed Finite-Difference Time-Domain (FDTD) model is applied to the analysis of scattering from UXOs in the frequency range from 10 MHz to 800 MHz. A lossy earth medium is considered based on measurement results. The FDTD simulation incorporates a detailed geometric modeling of a newly developed fully polarimetric, ultra wideband (UWB) dielectric-filled Horn-Fed Bow tie (HFB) antenna.

The UWB HFB antenna is fed by a pair of coaxial cables which generates a TEM launching mode. To eliminate undesired late time ringing from the finite size of the HFB antenna, tapered resistive cards (with a properly chosen conductivity profile) are inserted at the end of the metallic arms of the antenna. The complex antenna structure, the feed system, and arbitrary positioned targets under the lossy earth medium are all incorporated in computational FDTD domain using a stair stepping approximation and a sufficiently refined grid. By scanning the HFB antenna along straight paths over the ground, synthetic scattering signatures are obtained and compared against measured data. Both simple detection/classification process involving early time linearity and ellipticity concepts, as well as SAR image generation are considered. By studying the scattering signatures of different objects and UXOs at various depths and orientation in the ground, a reference database of synthetic UWB data can be constructed to help reduce the rate of false alarms in practical measurements. Possibilities and limitations for building this reference data from the numerical analysis will be discussed in this presentation.

Efficient algorithm for evaluating electromagnetic scattering from cylinder illuminated by three–dimensional sources

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An efficient method is presented for the analysis of the electromagnetic scattering from a cylinder illuminated by three-dimensional (3D) sources. The motivation of the work arises by the need to include in the analysis of large reflector antennas the effect of the spherical wave blockage of struts of various cross-section (A. Toccafondi et al., IEEE AP–45, May 1997, pp 851–857). For this application, the scattered field from the strut illuminated by the primary field is used to correct the physical optics (PO) currents on the main reflector. Due to the large amount of calculation involved in this process, our goal is the numerical efficiency. The basic building block of the problem is the derivation of the dyadic dipole source Green's function. It is well known that the exact solution can be found from the spectral synthesis of 2D Green's function (2D-GF) (i.e. by spectral integration of the response to phased line source excitation). The fundamental steps of this procedure can be found in the Felsen and Marcuvitz book, with reference to circular cross section and perfectly conducting cylinders. The extension of this "spectral synthesis" to general cross section and boundary conditions was presented in (P-S. Kildal et al., IEEE AP–44, Aug. 1996, pp 1183–1192) and subsequently applied in a series of papers concerning antenna problems; there, the 2D-GF has been calculated numerically by solving, for each longitudinal spectral wavenumber, the 2D integral equation relevant to the transverse cross-section. The above method is rigorous and accurate, but not so fast as required for the purpose. On the other hand, a brute application of PO to the cylinder surface is not accurate enough for small radius in terms of a wavelength and it does not account creeping waves and/or shadow region diffraction effects. Recently a M. Lumholt et al. (AP–2000 Millenium Conf. on Antennas and Propagat.,9-14 April 2000, Davos, Switzerland) presented a method to reduce numerical complexity of the problem and to describe the induced currents in shadow region that leads to good results in various cases. As a good compromise of efficiency and accuracy, we have developed a method, similar to the last cited, which is presently valid for perfectly conducting cylinders. For a given source, the cylinder is subdivided along its axis in small slices, in terms of wavelengths. On each slice the incident and scattered electric field are expanded in terms of cylindrical harmonics. Then, the unknown coefficients of the scattered fields are evaluated considering an indefinite cylinder having equal cross section and by imposing appropriate boundary conditions. Moreover, on each slice only a single spectral component is considered effective and the pertinent induced current distribution is evaluated and used for calculating the 3D scattered field. It is worth nothing that, contrary to the PO approach, the constructed solution takes into account the creeping wave effects on the cylinder surface and provide a good accuracy also for struts having small cross section.

Scattering from an Arbitrarily Shaped Three-Dimensional Chiral Body

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The method of moments technique (MoM) for analyzing electromagnetic scattering from an arbitrarily shaped three-dimensional homogeneous chiral body is presented based on the combined field integral equations. The body is assumed to be illuminated by a plane wave. The surface equivalence principle is used to replace the body by equivalent electric and magnetic surface currents. These currents radiating in unbounded free space produce the correct scattered field outside. The negatives of these currents produce the correct total internal field, when radiating in an unbounded chiral medium. By enforcing the continuity of the tangential components of the total electric and magnetic fields on the surface of the body, a set of coupled integral equations is obtained for the equivalent surface currents. The surface of the body is modeled using triangular patches. The triangular rooftop vector expansion functions are used for both equivalent surface currents. The mixed potential formulation for a chiral medium is developed and used to obtain explicit expressions for the electric and magnetic fields produced by surface currents. Numerical results for bistatic radar cross sections will be presented for three chiral scatterers–a sphere, a finite circular cylinder, and a cube. Figs. 1 and 2 show the exact and MoM results for the co-polarized and cross-polarized bistatic radar cross sections of a chiral sphere of radius a with ξ_r = 0.3. The constitutive relations for a chiral medium are expressed as $\mathbf{D} = \varepsilon\,\mathbf{E} - j\xi_r\sqrt{\mu\varepsilon}\mathbf{H}$ and $\mathbf{B} = \mu\,\mathbf{H} + j\xi_r\sqrt{\mu\varepsilon}\mathbf{E}$.

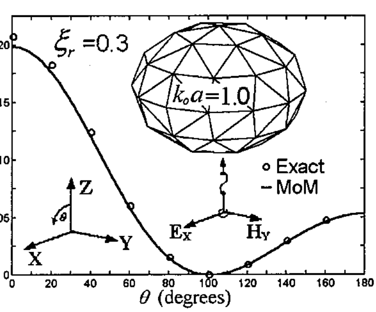

Fig. 1. $\sigma_{\theta\theta}/\lambda^2$ for a chiral sphere

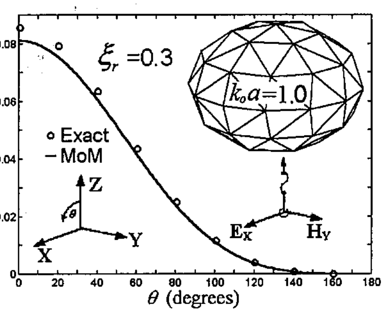

Fig. 2. $\sigma_{\phi\theta}/\lambda^2$ for a chiral sphere

Visualization of the Induced Currents on a Dielectric-Coated Cone Using the FDTD

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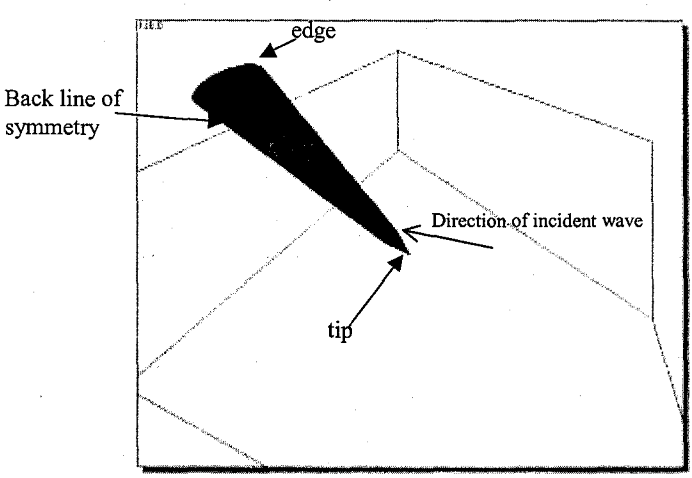
Abstract

In this paper we investigate the currents induced on the surface of a dielectric coated cone by using the finite difference time domain (FDTD) method. A short Gaussian pulse is used for the incident field and the tangential magnetic field on the outer surface of this cone is animated to show the waves traveling on its surface and to illustrate the localized diffraction mechanisms. A 2-D visualization, which shows the details in a single animation of the currents on the "developed" surface of the cone is also presented.

The results show that when the wave is incident from the direction of the tip, the fields propagate symmetrically along both sides of the cone, producing field lines whose shapes depend upon the wavefront of the incident wave. These fields add up constructively along the back line of the symmetry, and travel toward the edge. Upon reaching the edge, the fields diffract from there and then begin to creep around the circumference of the base from the lit to the shadow region. These creeping waves, which travel along both sides of the circumference of the base, meet each other at the back line of symmetry. At this point, part of the wave diffracts yet again and the rest continues on creeping to return back to the starting point. In addition, the enhanced wave along the back line of symmetry diffracts when it reaches the edge.

The paper will present animations that are helpful for understanding the scattering phenomena from objects of this type.



EM Scattering from Periodic Gratings of Lossy Rectangular Cylinders by Finite Difference Time Domain Technique

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INTRODUCTION- Due to their strong frequency dependent behavior, metallic gratings of different groove shapes find many applications in optics, electromagnetics and microwaves. Although various numerical approaches have been presented for analysis of such structures, most of these methods assume that the metal is perfect conductor. In practice, however, all the structures are made of finitely conducting materials that introduce energy losses. These conductor losses can be controlled to obtain a desirable scattering pattern. The effects of finite conductivity in gratings with triangular grove shape have been previously calculated only approximately by using a surface impedance model [Kalhor and Neureuther, J. Opt. Soc. Am., Nov. 1973]. Additionally, such lossy structures have attracted attention for their potential in reducing reflection in reflector antennas and in reduction of scattering [Hall, IEEE Trans. Antennas Propagat., Sept. 1985]. All these studies consider an idealized model. They assume the elements are infinitely long that confines the structure to a two dimensional problem. They also assume an infinite array that becomes amenable to Floquet wave expansion.

FORMULATION AND NUMERICAL SOLUTION- In the present work, our objective is to introduce a general theory to assess the effects of the simplifying assumptions that normally made. A finite number of lossy conducting rectangular cylinders of finite length are considered. An E-Polarized electromagnetic pulse is incident on the structure. A finite-difference time-domain method is employed to calculate the scattered field at selected points. The effects of element lengths, number of elements, and finite conductivity on the scattered fields are studied to assess the validity of the simplifying assumptions stated above.

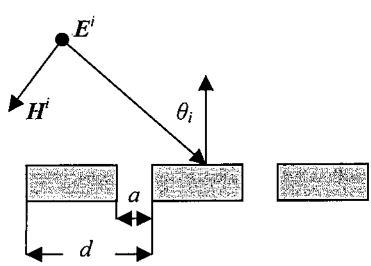

Figure 1. The Structure Arrangement

Fast Iterative Physical Optics (FIPO) Algorithms for Multiple Bounce Scattering

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High frequency scattering by arbitrary shaped bodies conventionally is analyzed using Physical Optics (PO) augmented by Physical Theory of Diffraction (PTD). Analysis of multiple bounce scattering phenomena by PO is referred as Iterative Physical Optics (IPO) and requires multiple surface integrations. For simplicity, we analyze a two-dimensional scattering from open-ended cavity type geometries dominated by multiple bounce phenomena. The number of field and current sampling points on the surface is proportional to its electrical dimensions, i.e. of $O(N)$, where $N = kR$, R being the radius of the smallest circle circumscribing the scatterer and k - the wavenumber. Each IPO iteration requires evaluation of the magnetic field due to the surface current obtained in the previous iteration. Straightforward evaluation of the field at $O(N)$ points by surface integration involving summation $O(N)$ terms amounts to $O(N^2)$ operations. This high computational burden underlines the need for using approximate or fast techniques in the IPO computations.

In this paper, we present a novel scheme that permits the numerically efficient evaluation of multiple PO integrals. The algorithm is based on the observation that the field radiated by a finite source distribution is locally an essentially bandlimited function of the angle and radial distance multiplied by common phase factor. The pertinent angular bandwidth is proportional to the linear dimensions of the source. On the other hand local bandwidth with respect to the radial distance decreases rapidly with distance from the source region. Therefore the radiated field can be sampled on a non-uniform polar grid with radial density decreasing with the distance away from the source. Consequently, the radiated field on the surface can be interpolated from its samples at a number of polar grid points proportional to the source region dimensions. With this in mind, we decompose the scatterer surfaces into subdomains and compute the field for each of them separately. The field of each subdomain is directly evaluated at a small number of polar grid points and subsequently interpolated, thus providing computational savings. The phase common to all source points in a given subdomain is removed from the field prior to interpolation. Following the interpolation, we restore the phase and aggregate these partial fields into the total field due to all subdomains combined. The aggregation step involves phase restoration and addition. The two-level domain decomposition algorithm reduces the computational cost of evaluating the field (a single iteration) from $O(N^2)$ to $O(N^{3/2})$. A multilevel algorithm is obtained upon starting from small subdomains, for which the field is computed directly over a very coarse grid, and repeating the interpolation and aggregation steps for progressively finer grids, while doubling the subdomain sizes. The multilevel algorithm attains an asymptotic complexity of $O(N \log N)$.

EXACT LINE-INTEGRAL REPRESENTATION OF THE PO FIELD SCATTERED FROM FLAT PERFECTLY CONDUCTING SURFACES ILLUMINATED BY ELEMENTARY DIPOLES

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In this paper we present a line integral representation for the PO radiation from a flat perfectly conducting surface illuminated by an arbitrary oriented elementary electric or magnetic dipole. No restriction is imposed on the position of the source and of the observation point. The main application of this result is concerned with the acceleration of the numerical PO integration for electrically large bodies.

Many different solutions has been suggested in the past literature by different authors, that express the acoustic or electromagnetic Kirchhoff aperture field in terms of line integration. Their works are excellently summarized in [Rubinowicz, *Progress in Optics,* 4, 331-377, 1965]. Their main purpose was to explain theoretically the nature of diffraction within the *boundary waves* theory. In modern key, the same concept has been recovered in [Asvestas, *IEEE Trans. Ant. Propagat.*, 9, 1155-1159, 1986] by focusing on a representation well suited for a fast numerical computation. However, his technique, based on a mathematical theorem, looses the physical interpretation provided by earlier results. Such technique, valid for aperture-radiated fields, was extended in [Johansen and Breinbjerg, *IEEE Trans. An. Propagat.*, 7, 689-696, 1995] to the PO scattering by perfectly electrically conducting flat plates, also providing a geometrical interpretation of Asvestas formulation via the divergence theorem. The final result is however constituted by a large number of different contributions, making their applicability quite cumbersome. Furthermore, in their representation the integrand experiences a singularity on the integration contour, when observing at certain aspects; despite the mathematical integrability of the function, its numerical accurate computation becomes critical close to and at these observation aspects. For both these reasons there is still a motivation for investigating on simpler and easily applicable expressions. To this purpose, we remark that the exact incremental diffraction PO contribution (i.e., the integrand of the final exact line integral representation) is *not unique;* indeed, an arbitrary irrotational field can be added to the integrand without affecting the final closed contour integration. The exact formulation used here for spherical source dipoles, takes inspiration from the procedures presented by Rubinowicz and Asvestas but is essentially different from both. From the original Rubinowicz work the present formulation preserves the elegant and physical appealing application of the equivalence theorem to a projection cone with vertex at the observation point and enveloping the scattering aperture or plate. Moreover, our line integration does not reconstruct only the diffracted field, which is discontinuous at the shadow boundaries and requires a singular integrand, but reconstructs the whole scattered field by mean of a non-singular line integrand. This is achieved by constructing, thanks to a proper modification of the Asvestas formulation, an incremental form of the Geometrical Optics contribution, which added to the PO diffracted-field incremental kernel restored the continuity of the integrand, with the consequent numerical benefits.

Special Session

Advanced Methods for Large Scale Computational Electromagnetics II

Organizer(s): *W. C. Chew, University of Illinois, USA*
J.-M. Jin, University of Illinois, USA

Co-Chairs: *W. C. Chew, University of Illinois, USA*
J.-M. Jin, University of Illinois, USA

SPARSE-MATRIX CANONICAL GRID (SMCG) METHOD FOR LARGE-SCALE ELECTROMAGNETIC SIMULATION- AN OVERVIEW

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Hong Kong SAR, China

In this paper, we will present an overview of the sparse-matrix canonical grid (SMCG) method for large-scale electromagnetic simulations. The SMCG method has been successfully applied to numerical modeling of dense-medium scattering problem, densely packed high frequency interconnects, microstrip reflectarrays, and multiple scattering among vias in electronic packaging in the frequency domain. It has also been extended to time-domain simulations. As FFTs are used, the SCMG method is particularly suitable for parallel computing. Numerical results up to several million unknowns using Beowulf-class PC clusters will be presented to demonstrate the power of the SMCG method.

The SMCG method can be applied to problems with homogeneous Green's functions, Green's functions for multi-layered medium and time domain Green's function problems. It is well-known that if the Green's function kernel in the integral equation formulation of an electromagnetic scattering problem is translationally invariant, the convolution between the kernel and the induced current can be performed by fast Fourier transforms (FFTs) leading to significant reduction both in CPU time and computer memory requirement. A typical example is the use of conjugate gradient-fast Fourier transform (CG-FFT) method for electromagnetic scattering from a square PEC plate where a uniform discretization can be adopted. Unfortunately, there are many other electromagnetic problems, which do not fall into the category that a straightforward implementation of the CG-FFT method is applicable. One example is the rough surface scattering problem for which the sparse-matrix canonical grid method was originally developed to address the problem that the Green's function depends on the separation between the source and the field points that cannot be quantized into uniform steps.

Like many fast iterative solver, the impedance matrix elements corresponding to strong interactions among nearby scatterers are computed and stored as a sparse matrix in the SMCG method. The sparse matrix-vector multiplication in the iterative solution is computed directly in the conventional manner. In contrast, the remaining portion of the matrix-vector multiplication corresponding to the weak interactiong among far-apart scatterers is computed indirectly by FFTs. To apply FFTs for the matrix-vector multiplication, we need to cast the Green's function kernel into the form that is translationally invariant. This is allowable via a Taylor series expansion of the Green's function kernel about a uniformly spaced canonical grid. In the 3-D rough surface scattering case, the canonical grid is a 2-D grid uniformly spaced in the x and y directions along the surface length for a slight rough surface. For a rougher surface, the canonical grid is a 3-D grid with the z-direction along the surface height also uniformly sampled. The indirect computation of the matrix-vector multiplication is equivalent to shifting all the sources to their nearest grid point through a block diagonal matrix premultiplication, using FFT to compute all the interactions among grid points, and finally using a block diagonal matrix postmultiplication to shift to the field point from the nearest grid point. As the far interactions dominate the matrix-vector multiplication, the memory requirement and complexity of the SMCG method scale as $O(N)$ and $O(N \log N)$, respectively.

A Parallel Framework for FFT-Accelerated Time-Marching Algorithms

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In recent years various fast Fourier transform (FFT)-based algorithms for accelerating the solution of time-domain integral equations (TDIE) have been reported. Similar to their frequency-domain counterparts (e.g., the conjugate gradient FFT and adaptive integral method), these algorithms drastically reduce the computational complexity of conventional integral equation solvers. The typical marching-on-in-time (MOT) analysis of scattering in layered, lossy, or dispersive media requires $O(N_t N_s^2)$ memory and $O(N_t^2 N_s^2)$ operations for N_t simulation time steps and N_s spatial samples. FFT-based algorithms provide acceleration by taking advantage of the space and time translational invariance of the integral kernel through the use of uniform grids that are derived from either the primary or an auxiliary mesh. These algorithms reduce the memory requirements and computational complexity of MOT solvers to $O(N_t N_c)$ and $O(N_t N_c \log(N_t N_c) \log N_t)$, respectively. Here, N_c is either N_s for uniform scatterer discretization or the number of nodes on an auxiliary projection mesh for non-uniform discretizations. The dominant cost of both types of accelerators results from the multi-level space-time FFTs (A. E. Yılmaz et. al., submitted to *IEEE Antennas Wireless Propagat. Lett.*)

Even though these FFT-accelerated TDIE solvers are faster and more memory efficient than their classical MOT counterparts, the $O(N_t N_c)$ storage requirement quickly swamps the memory resources of a single-processor computer when the scatterers grow electrically large. Here, we report on a parallel FFT-based TDIE solver that targets distributed-memory computers and uses the message-passing interface (MPI) for communication. Two approaches for distributing the requisite computations are considered: (i) a domain decomposition-based implementation, where the scatterer is partitioned into (spatial) regions with smaller sized space-time FFTs computed locally (E. Bleszynski et. al., *Radio Sci.* 31, 1225-1251, 1996), and (ii) a parallel-FFT based implementation, where the matrices and currents are slab-decomposed and FFTs are computed in parallel using the readily available fastest Fourier transform in the west (FFTW) library. Because the time histories of the unknown currents as well as the matrix entries are distributed over P processors, the memory requirement for each processor is reduced to $O(N_t N_c / P)$. In the presentation we will compare these two parallelization schemes and provide numerical results that demonstrate the resulting memory reduction and speedup for both uniformly and non-uniformly discretized scatterers.

Microwave Optical Devices and Techniques

Co-Chairs: *J. L. Young, University of Idaho, USA*
D. A. McNamara, University of Ottawa, Canada

ELECTROMAGNETIC MODELING OF ELECTRICALLY SMALL ELECTRO–OPTIC MODULATORS

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† MRC Institute, University of Idaho, Moscow, ID
‡ James F. Kelly, Pacific Northwest National Laboratories, Richland WA

To characterize and detect various chemical agents using optical spectroscopy techniques, radio frequency (i.e., 300 – 600 MHz), phase modulated, infrared laser beams are needed. The required modulation is accomplished using a non–linear optical crystal strategically placed in a high Q cavity. The crystal's index of refraction is altered by a strong electromagnetic field that is excited by a radio frequency probe (i.e., the modulating signal). As the laser beam passes through the crystal, a phase shift will occur; the amount of phase shift is directly related to the value of the index of refraction of the non–linear crystal. Unfortunately, traditional cavities associated with this application are excessively large, which is undesirable from a logistic and fabrication point of view.

By considering a split–ringed cavity configuration, Kelly and Gallagher (*Rev. Sci. Instrum.*, vol. 58, no. 4, pp. 563-566, 1987) demonstrated that cavity size reduction, with modest degradation of cavity quality factor, can be achieved. As a follow–on of that work, a complete radio frequency characterization of the split–ringed cavity is provided herein. This characterization is given in terms of electromagnetic simulation data, as obtained from a finite–difference, time–domain code, and a lumped element circuit model. The simulation data provides insight into the field structure within the cavity; the circuit model provides a simple, yet accurate set of design and analysis formulas that relate resonant frequency, voltage levels and power levels to the geometrical and material parameters of the cavity. To validate the claims made from the simulation data and circuit model, experimental data is also provided. It is concluded that the cavity under consideration can be made to resonate at low frequencies, without increasing the overall size of the cavity. The price in doing so, however, is a reduction in cavity Q and crystal voltage. For this reason, guidance is also given on how to optimize the cavity in terms of voltage, Q, power levels and voltage levels.

Integration of an Antenna with a Waveguide Photodetector for High Capacity Wireless Communication Systems

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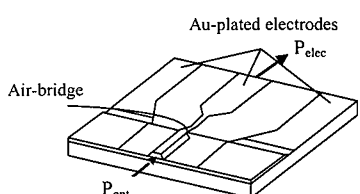
Abstract

This paper reports on the integration of an antenna with a photodetector for high capacity wireless communications. The side-illuminated waveguide photodetector (WGPD) is used to convert the RF-modulated optical power into a microwave signal, which in turn is fed to an antenna. The WGPD is a standard p-i-n device grown on a semi-insulating InP substrate and fabricated using conventional techniques. Figure 1 shows a perspective view of the used WGPD structure. The optical power is fed to the WGPD through an optical fiber that terminates at the facet of the waveguide layer of the WGPD structure. The electrodes of the coplanar waveguide (CPW) are coupled to the optical waveguide, and are used to bias the photodetector and to feed the detected RF signal to the antenna. The performance of this RF/photonic antenna as a transmitter in the frequency range 17-20 GHz is studied theoretically and experimentally. An equivalent circuit model for the WGPD is developed to estimate the photodetector impedance as a function of frequency and to assist in the impedance matching between the photodetector and the antenna. Different antenna geometries that have planar structure and easy integration with the WGPD both in monolithic or hybrid form are studied. These geometries include the CPW-fed slot and bowtie antennas.

This new RF/photonic antenna, with the appropriate space-time processing and coding, will form a "smart antenna" that is expected to be the corner stone of the high-speed and high capacity future wideband optical communication systems working in the microwave regime where both high efficiency broad bandwidth are needed. It is envisioned that a large number of such RF/Photonic antenna elements could be networked together into a star configuration, feeding in and out of a radio hub.



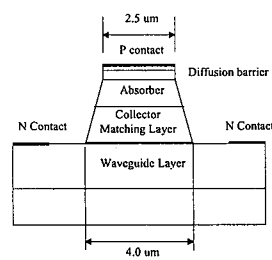


Figure 1. Perspective view of the WGPD (a) The optical power is fed to the WGPD using an optical fiber, and the CPW electrodes are extended to feed the detected microwave signal to the antenna (not shown here). (b) Cross section of the WGPD showing the important layers.

Special Session

Suppression and Control of Surface Waves in Printed-Circuit Structures

Organizer(s): *D. R. Jackson, University of Houston, USA*
G. Eleftheriades, University of Toronto, Canada

Co-Chairs: *D. R. Jackson, University of Houston, USA*
G. Eleftheriades, University of Toronto, Canada

A Reduced-Surface-Wave GPS Antenna with Low Susceptibility to Multipath Interference

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With the recent increase in high-precision Global Positioning System (GPS) applications, such as geodetic surveying, attitude determination, and differential GPS, more restrictive demands on the GPS receiver system have become necessary. In particular, the higher precision and increased reliability specifications call for a receiving antenna that is able to satisfy more stringent design requirements.

A significant contributor to amplitude and phase distortion in the received GPS signal is the interference caused by multipath reflections. Using the inherent polarization diversity between the direct GPS signal (RHCP) and reflected waves (LHEP), most current GPS systems adequately eliminate the perturbing effects of high-elevation angle multipath events. In addition, signal processing can eliminate many of the effects of late-time multipath events. However, the multipath signals that impinge on the antenna at low elevation angles, and those that are a result of ground reflections or scattering from supporting structures behind the antenna, often introduce significant error in the positional output of the GPS receiver. Attempts to reduce these effects by using "choke-ring" ground planes, coating the ground plane with resistive or absorbing materials, modifying the edges of the ground plane, and using sophisticated signal-processing techniques have proved to be only moderately successful, at best, and often introduce significant cost or weight.

In this presentation, a new GPS antenna design, based on the Reduced-Surface-Wave (RSW) microstrip antenna concept, is introduced. This GPS antenna *significantly* reduces the deleterious effects of low-angle multipath signals, and early-time multipath signals that are received due to edge diffraction at the edges of the ground plane. In addition to having the advantages common to microstrip antennas, such as being light-weight, inexpensive, low-profile, and easy to manufacture, it will be demonstrated that this new GPS antenna provides superior performance to the most commonly used GPS antennas, including choke-ring designs, and is ideal for high-precision GPS applications.

Photonic Bandgap Studies for Finite Structures

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This paper will review studies into photonic bandgap (PBG) structures used at microwave and optical frequencies. Simply speaking, photonic bandgap structures are periodic structures in which specific bands of frequencies are not propagated. There exist a number of electromagnetic problems where guided surface waves can affect the performance of guiding, radiating, or scattering devices. It has been shown that the coupling to the surface wave mode can be mitigated through use of a PBG structure. The filtering capabilities of these structures make them potentially useful in applications that require passive mitigation of surface waves or any type of transmission.

In this paper, finite-difference time-domain (FDTD) simulations will be used to model PBG structures. A variety of photonic band gap structure applications will be discussed to validate the simulation capability. The simulations will allow us to rapidly determine the frequency and time-domain characteristics of the various PBG structures.

This paper will look at the formation of waveguiding structures having PBG elements along side of a guiding channel. The finite-difference time-domain (FDTD) method will be used to simulate these waveguiding structures for a two-dimensional substrate. By varying the dimension and shape of the basic PBG element, the arrangement of these elements in the whole structure, as well as, the depth of the PBG structure surrounding the channel, the efficiency of the various guiding structures will be analyzed. A study will also be done on the frequency characteristics of the PBG elements in order to observe how these can behave as filtering devices.

Surface Wave Control for Reconfigurable Printed Antenna Applications

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With the increase in complexity of wireless communication systems and limited space availability, reconfigurable aperture antennas, which have different functionalities (i.e. instantaneous bandwidth, beam steering, and/or, switchable beamwidth) and can operate at different frequency bands while sharing a single physical aperture, become very attractive. The basic idea of reconfigurable antenna is that the antenna structure can be modified by the operation of switches in real time. Typical switches used in reconfigurable aperture are switching diodes, RF MEMS, or optical switches.

Previously, a reconfigurable antenna element consisting of a circularly polarized microstrip antenna surrounded by a metallic ring loaded with RF switches (diode switches) has been proposed and built. This antenna was implemented on a thick dielectric substrate ($\sim 0.1\lambda_d$). Antenna engineers usually avoid the use of electrically thick substrates for microstrip antennas due to the excitation of surface waves. These surface waves are considered to be a loss mechanism because the diffracted surface waves distort the main beam pattern of the antenna. However, the idea of the proposed scheme is to modify the characteristics of EM propagation inside the dielectric substrate by using a parasitic metal ring, such that the diffracted surface waves contribute positively to the main beam pattern. The element pattern can then be controlled by the operation of switches (on/off). In other words, the reconfigurable aperture has the ability to modify the RF current distribution within the aperture and hence, modify its element pattern (especially along the direction near horizon) through the use of RF switches. In this paper, a brief review of this scheme is presented. The reconfigurable scheme is designed for GPS applications to mitigate the effect of nearby jamming signals without a significant decrease in coverage.

In addition, a novel adaptive scheme consisting of a circularly polarized microstrip antenna printed on a two-layer dielectric substrate is currently being investigated. The second layer of substrate provides the designer an additional design parameter to obtain the desired antenna performance. Design procedures and detail analysis on this new scheme will be presented as well. Note that the antenna element characteristics are calculated with a 3-D finite difference time-domain computer program developed at The Ohio State University.

Hybrid Numerical Methods

Co-Chairs: *R. Kastner, Tel Aviv University, Israel*
E. Rothwell, Michigan State University, USA

Higher Order, Hybrid BEM/FEM Methods Applied to Antenna Modeling

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In this presentation, the authors address topics relevant to higher order modeling using hybrid BEM/FEM formulations. The first of these is the limitation on convergence rates imposed by geometric modeling errors in the analysis of scattering by a dielectric sphere. The second topic is the application of an Incomplete LU Threshold (ILUT) preconditioner to solve the linear system resulting from the BEM/FEM formulation. The final topic is the application of the higher order BEM/FEM formulation to antenna modeling problems.

The authors have previously presented work on the benefits of higher order modeling. To achieve these benefits, special attention is required in the integration of singular and near-singular terms arising in the surface integral equation. Several methods for handling these terms have been presented. It is also well known that achieving the high rates of convergence afforded by higher order bases may also require the employment of higher order geometry models. A number of publications have described the use of quadratic elements to model curved surfaces. The authors have shown in an EFIE formulation, applied to scattering by a PEC sphere, that quadratic order elements may be insufficient to prevent the domination of modeling errors. In fact, on a PEC sphere with radius $r = 0.58\ \lambda_0$, a quartic order geometry representation was required to obtain a convergence benefit from quadratic bases when compared to the convergence rate achieved with linear bases. Initial trials indicate that, for a dielectric sphere of the same radius, requirements on the geometry model are not as severe as for the PEC sphere. The authors will present convergence results for higher order bases as a function of the geometry model order in the hybrid BEM/FEM formulation applied to dielectric spheres.

It is well known that the system matrix resulting from the hybrid BEM/FEM formulation is ill-conditioned. For many real applications, a good preconditioner is required to obtain usable convergence from an iterative solver. The authors have examined the use of an Incomplete LU Threshold (ILUT) preconditioner to solver linear systems stemming from higher order BEM/FEM formulations in 2D scattering problems. Although the resulting preconditioner provided an excellent approximation to the system inverse, its size in terms of non-zero entries represented only a modest improvement when compared with the fill-in associated with a sparse direct solver. Furthermore, the fill-in of the preconditioner could not be substantially reduced without the occurrence of instabilities. In addition to the results for these 2D problems, the authors will present iterative solution data from the application of the ILUT preconditioner to 3D problems.

Recent publications on higher order modeling have focused on separable geometries so that numerically derived solutions could be compared with exact results. Other publications have examined convergence of the RCS solution. Recently, researchers have begun applying higher order methods to antenna models. For example, higher order bases have been applied in a surface integral formulation to analyze multilayer, microstrip antennas (Ling, F., Jin, J. -M., *Antennas, Propagation, and EM Theory, 2000.* Proceedings. ISAPE 2000). In this presentation, the authors provide results from the application of higher order, hybrid BEM/FEM formulations to antenna modeling problems. Coaxial probe feeds are modeled both with a current filament and with a coaxial waveguide interface that includes detailed modeling of the probe. The latter work extends a previously published 0^{th} order formulation (Zuffada, C., Cwik, T., and Jamnejad, V., *IEEE Trans. Antennas Propagat.*, Jan. 1997.)

EM Scattering from Arrays of Lossy Conducting Rectangular Cylinders by a Hybrid Finite-Difference Technique

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INTRODUCTION- The scattering of electromagnetic waves from array of conducting cylinders has been of great interest in areas of optics and electromagnetics because these structures exhibit strong frequency dependent behavior. A large number of rigorous, semi-rigorous, and numerical solutions have been introduced for the analysis of this problem. As examples of such works, infinite gratings of perfectly conducting strips are studied by integral equation technique [Kalhor, J. Opt. Soc. Am., Aug. 1978] and those comprised of a finite number of strips are solved by integral equation technique and physical optics approximation [Kalhor, IEEE Trans. Antennas Propagat., March 1989]. In practice, these strips have finite thickness and conductivity and are not studied much because of higher complexity of the problem [Hall, IEEE Trans. Antennas Propagat., Sept. 1985]. The objective of the present research is to solve arrays, infinite and finite, of lossy conducting cylinders by a hybrid finite-difference technique.

FORMULATION AND NUMERICAL SOLUTION- The geometry of the problem is depicted in Figure 1. An E-polarized uniform plane wave is incident at angle θ_i on an array. The array period is d, spacing between cylinders is a, and cylinder thickness is t. Above and below the cylinders, fields are expanded in terms of Floquet modes with unknown amplitudes. Finite-difference method is employed inside the lossy cylinders and in the openings between them. The necessary boundary conditions are enforced at the two interfaces to obtain equations whose solutions give wave amplitudes and fields in the groove region. Several numerical results are presented.

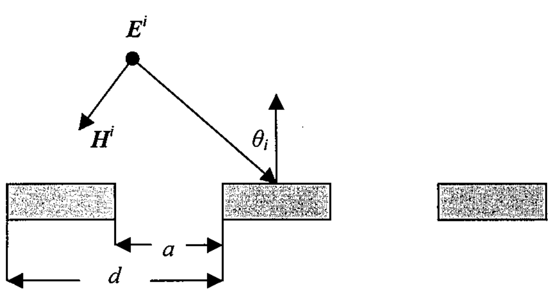

Figure 1. The Structure Arrangement

An Explicit Hybrid Boundary Integral/FDTD Algorithm

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A novel time domain Boundary Integral/FDTD algorithm for transient electromagnetic field radiation and scattering is developed. The model is based on an alternative formulation of the FDTD, the Finite Integration Technique (FIT) that makes use of the Yee space lattice in order to solve the Maxwell curl equations in integral form. The unknowns are –in contrast to the unknowns of the FDTD-method– magnetic and electric voltages across grid-edges and not fields in grid points. Due to the fact that the components of the electric and the magnetic voltages are allocated on different planes, interpolation is needed when applying the typical formulation of the equivalence principle, containing both $\vec{E}$ and $\vec{H}$ fields on the boundary. It is no advantage to apply a formulation which consist only of the electric field $\vec{E}$ and its derivative (e.g. the Kirchhoff surface integral), because the calculation of the normal derivate of $\vec{E}$ leads to the same order of accuracy than interpolating the magnetic field.

In order to overcome this problem we start with the method of moments applied to the above mentioned formulation of the equivalence principle. In order to relate the magnetic currents to electric edge voltages we define expansion functions on the edges of the grid. The method of moments leads to a set of linear equations wich allows updating the magnetic edge currents at $t=(n+\frac{3}{2})\Delta t$ as a function of the electric and magnetic currents at earlier time steps. However, the FIT does not provide a relationship between the magnetic and the electric voltages in the same plane. We therefore apply the Maxwell curl equation to an area containing the boundary between the FIT-domain and the surrounding space (fig. 1):

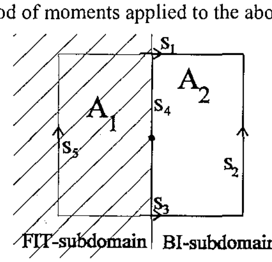

Fig. 1. Calculating the first Maxwell curl equation on a region containing the boundary of the FIT-subdomain

$$\iint\limits_{A_1 \cup A_2} \left(\frac{\partial}{\partial t}\vec{D}+\vec{J}\right) d\vec{f} = -\oint\limits_{S_1} \vec{H} d\vec{s} + \oint\limits_{S_2} \vec{H} d\vec{s} + \oint\limits_{S_3} \vec{H} d\vec{s} - \oint\limits_{S_5} \vec{H} d\vec{s}. \qquad (1)$$

If evaluated with FIT eq. (1) contains 5 known FIT-coefficients and the unknown magnetic edge voltage across S_2. A second relationship is now obtained by using Green's free space functions for evaluating eq. (1), thus relating the magnetic voltage across S_2 to the flux through A_2. Due to leap-frogging the last step results in a relationship between the edge voltage across S_2 and the electric currents at $t=(n+2)\Delta t$. If we put that relationship into the FIT equation mentioned above we can update the electric Huygens-current.

The procedure described above requires no interpolation for the application of the equivalence principle; it provides some sort of boundary condition.
We will compare the features of this global boundary condition to the features of commonly used procedures.

Analysis of Inductive FSSs Using a Hybrid Mode Matching - Finite Elements Approach with Edge Elements

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Inductive Frequency Selective Surfaces (FSSs), consisting of thick metallic screens periodically perforated with arbitrary shaped apertures, are often used as filters or polarizers in high-power microwave earth-station antennas for space applications. The objective of this paper is to present a hybrid Mode Matching (MM) – Finite Elements Method (FEM) technique to efficiently analyze inductive FSSs of the above kind. By resorting to the Floquet's theorem, the analysis of the original periodic structure is reduced to that of the elementary periodicity cell. In particular, MM is used to evaluate the Generalized Scattering Matrix (GSM) of the unit cell. To this end, each aperture in the thick screen is treated as a metallic wall waveguide, where the direction of propagation coincides with the normal to the screen. The transverse fields inside each waveguide in the basic periodicity cell are reconstructed by resorting to a specific formulation of the FEM, which makes use of Whitney's edge elements (D. Arena et al., "Analysis of waveguide discontinuities using edge elements in a hybrid mode matching/finite elements approach", *Microwave and Wireless Components Letters, IEEE*, vol.11, pp. 379 -381, Sept. 2001). More specifically, the FEM is applied in a two-dimensional domain (transverse section of the waveguide) to numerically determine both the eigenvalues and the eigenvectors, *i.e.* the mode parameters of the waveguide. This allows us to analyze apertures with arbitrary shape, avoiding also the presence of spurious solutions. The fields in the exterior half-spaces surrounding the periodic screen are then expressed as a combination of Floquet's modes. The coefficients of the Floquet's expansions are determined by imposing the boundary conditions on the metallic part of the screen and by matching the outer and the inner fields at the apertures of the basic periodicity cell. The hybrid scheme combines MM and the FEM method retaining the advantages of both techniques, *i.e.* the numerical accuracy of MM and the FEM capability to analyze inductive screens with arbitrarily shaped apertures. The latter capability is enhanced by the use of triangular sub-domains for the typical FEM unstructured mesh that conform to the most general geometries. Some numerical results will be presented at the conference to show the accuracy and effectiveness of the proposed technique.

Performance Examination of the Hybrid Discrete Fourier Transform -Moment Method Scheme in the Fast Analysis of Large Rectangular Dipole Arrays Printed on a Thin Grounded Dielectric Substrate

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Efficient but accurate analysis of electromagnetic (EM) radiation and scattering from large periodic array remains challenging due to the increasing need to employ very large arrays in the practical applications. A recent work based on a hybrid combination of discrete Fourier transform (DFT) and the conventional method of moment (MoM) approach (called DFT-MoM hereafter) was developed to treat the analysis of electrically large, rectangular planar dipole arrays located in free space. Based on the framework of MoM procedure, the DFT-MoM employs a DFT representation for the unknowns in the rigorous MoM approach. Instead of obtaining the unknowns directly from original MoM matrix equation, the DFT-MoM employs the coefficients of the DFT representation as new unknowns and solves for the DFT coefficients. The MoM unknowns are then obtained subsequently.

Several unique advantages have been demonstrated. First of all, only a few DFT terms are sufficient to accurately represent the MoM unknowns. Secondly, the criterion in selecting DFT terms is based on UTD-type decompositions of field propagation, which represents the Floquet modes, edge effects due to finite truncation and part of the corner effects. Thirdly, each DFT term represents a linearly phased impression on the entire array. The asymptotic techniques can be employed to fast evaluate the mutual impedance between basis functions of DFT terms in terms of a few ray-type contributions instead of element-by-element computation for the entire array. Furthermore, once the coefficients of DFT terms are obtained via the MoM procedure, the near and far field radiations due to each DFT term, which is again a linear phased impression, can be efficiently found via asymptotic techniques that result in the regular array factors for the far field pattern. It is noted that the asymptotic evaluation of field radiation will give rise to ray-type solutions that can be incorporated into existing ray-tracing codes to account for environmental effects when the arrays are employed in practical applications. Because only a small number of terms are required in this DFT-MoM approach, the efficiency can be readily expected.

The application of this DFT-MoM approach to treat the rectangular finite planar dipole array printed on a thin and grounded dielectric substrate is examined in this paper. It is noted that in this case the surface and leaky waves due to the presence of the grounded dielectric substrate exist, and potentially increase the computational complexity in the numerical modeling. In this DFT-MoM, which utilize full advantages of asymptotic ray-type solutions, not only the number of DFT terms required to represent the MoM unknowns remains the same, but also the computational complexity increases insignificantly since only a few additional rays due to surface and leaky waves need to be considered. The surface and leaky wave effects on the implementation of the DFT-MoM scheme will be discussed. Numerical examples will be presented to validate the accuracy and efficiency of this DFT-MoM approach.

Wednesday PM *AP/URSI F* *Session 97* *Nueces-Frio*

Propagation Predictions for Inhomogeneous Paths

Co-Chairs: *M. D. Casciato, University of Michigan, USA*
J. P. Casey, Naval Undersea Warfare Center, USA

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Random Interfaces and Propagation

Co-Chairs: *L. Carin, Duke University, USA*
M. El-Shenawee, University of Arkansas, USA

Numerical Simulation of Scattering from Three Dimensional Randomly Rough Surfaces by Using Biorthogonal Multi-Resolution Time Domain Method and MPI

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Studying the scattering features of three-dimensional randomly rough surfaces is a very important and challenging problem for detecting small buried nonmetallic objects (for example, anti-personnel land mines) in lossy or dispersive soil, since the scattered fields of those targets are comparable to the scattered fields of the randomly rough surfaces. It has been demonstrated that the moment method is a computationally expensive and time-consuming way to analyze three-dimensional problems, since the number of unknowns increase quickly with the size of the three dimensional problems. The use of the finite difference time domain (FDTD) method has gained significant popularity in this field. One of the major advantages of FDTD over the moment method is that its memory requirement is much smaller. Another advantage is that one can easily obtain the transient behavior. Besides these, FDTD can be easily employed to deal with complex-shaped, homogeneous or inhomogeneous targets. The disadvantage of FDTD is that it has poor numerical-dispersion properties, which means the fields must be over-sampled to obtain accurate results. In this paper we will introduce the biorthogonal multi-resolution time domain (MRTD) method. The numerical dispersion properties can be improved significantly by using biorthogonal wavelets as a basis. At the boundary of the rough surfaces, an average procedure is employed to deal with the non-conformal problem. The incident fields are added to the computational domain through implementation of a connecting surface. To further increase the ability of the biorthogonal MRTD, the message-passing interface (MPI) is used to parallelize the algorithm. Numerical experiments are provided, which show that the combination of the biorthogonal MRTD and the MPI may be one of the promising practical methods to simulate scattering from three-dimensional randomly rough surfaces.

Electromagnetic Wave Scattering from Multi-layered Random Rough Surfaces with Buried Dielectric Object

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Electromagnetic sensing of buried objects in the presence of a random rough interface is a crucial step for subsurface detection problems in general. Most theoreticians and experimentalists agreed that surface roughness constitutes a major source of clutter (i.e., noise) in the received electromagnetic signals. However, due to the complexity of the problem, the ground surface is often assumed to be single layered and *not* multi-layered. This is not the case in the real environment but no work has yet been published on scattering from objects buried beneath multi-layered randomly rough ground. Therefore, the objective of this work is to investigate the scattering of electromagnetic waves from a penetrable shallow object buried in 2-D multi-layered random rough surfaces. It is known that the computational complexity of the scattering problem dramatically increases for the multi-layered rough interface.

A rigorous electromagnetic model has been developed for scattering from inhomogeneous rough ground surfaces. This model is based on the classical equivalence theorem and the method of moments (MoM) that is dramatically accelerated by implementing the Steepest Descent Fast Multipole Method (SDFMM). Four different homogeneous regions are involved in this application; air, dielectric object, upper soil layer and lower soil layer. A tapered Gaussian beam is used to illuminate the multi-layered ground surface. The rough surfaces are characterized with Gaussian statistics for the height and for the autocorrelation function. Since the SDFMM was originally developed for quasi-planar structures where the whole height of the 3-D scatterer should be in the order of one free space wavelength, it is necessary to validate the SDFMM implemented for this application versus the MoM. The relative norm of the error in surface current is presented. The computer memory requirement is plotted versus the SDFMM finest block size for the multi-layered ground with the buried object. It is necessary to mention that the air-ground interface and the underground layer could be flat and/or could be random rough surfaces with different roughness parameters and lossy or lossless soil. Numerical results representing the RCS of the multi-layered ground with the buried object are shown. The effect of the physical characteristics and the surface roughness of the multi-layers are investigated. The thickness of the multi-layer ground is varied to study its influence on the buried object signature.

The results of this work could increase the efficacy of the present subsurface sensing methods by accounting for the multi-layer nature of the rough ground.

Theoretical Electromagnetics

Co-Chairs: *I. Besieris, Virginia Polytechnic Institute and State University, USA*
G. W. Hanson, University of Wisconsin-Milwaukee, USA

Natural Resonance Representation of the Transient Field Reflected by a Conductor-backed Lossy Layer

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Layered materials are often applied to conducting surfaces for the purpose of reducing the scattered field strength within specific frequency bands. Because of the band-limited nature of the reflected field, a wideband pulse can be used to interrogate the layered structure so as to characterize the materials or determine whether the materials have degraded. The E-pulse method (G.J. Stenholm, E.J. Rothwell, D.P. Nyquist, L.C. Kempel, and K.M. Chen, *IEEE AP-S Int. Symp.*, Boston, Mass., 2001) can be used to determine whether the materials properties have changed compared to baseline values determined by previous measurements. This technique is dependent on the late-time behavior of the reflected field as a natural resonance series.

In this paper we analyze the transient field reflected by a conductor-backed lossy slab and show that it may be represented as the sum of early-time and late-time components. The early-time component consists of the specular refection from the air-slab interface, which persists until the arrival of the field reflected by the conductor. The ensuing multiple reflections may be viewed as the late-time component, which can be written as a pure sum of natural resonance modes. We determine the scattered field as an inverse Laplace transform of the frequency-domain reflection coefficient, and show that the branch-cut contribution vanishes during the late-time period, allowing a pure natural resonance representation.

Results computed using the resonance formulation are verified by comparison to the direct inverse Fast Fourier Transform. The distribution of resonance frequencies in the complex plane, and the dependence on conductivity, permittivity, aspect angle, polarization, and layer thickness, is examined.

THE HYBRID BIDIRECTIONAL SPECTRAL REPRESENTATION AND ITS APPLICATION TO THE DERIVATION OF FINITE-ENERGY X-SHAPED LOCALIZED WAVES

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The possibility of exact solutions to the scalar wave equation, Maxwell's equations, as well as other types of equations (e.g., Klein-Gordon, Schroedinger, Dirac), that describe ultra-wideband, spatially localized, slowly decaying transmission of energy in space-time has been suggested by several groups in recent years. Due to the aforementioned properties, such solutions may have potential applications in different research areas, e.g., remote sensing, high resolution imaging, medical radiology, tissue characterization, impulse radar, ground penetrating radar, nondestructive evaluation, directed energy transfer and secure communications. Of these solutions, the general classes of focus wave modes (FWM)-type and X wave-type solutions, termed localized waves (LWs), can be obtained, among various methods, by means of two fundamental spectral superposition schemes: the *bidirectional* and the *boost variable representations* [I. M. Besieris, A. M. Shaarawi, and R. W. Ziolkowski, J. Math. Phys. **30**, 1254 (1989); I. M.Besieris, M. A. Abdel-Rahman, A. M. Shaarawi, and A. Chatzipetros, PIER, **19**, 1 (1998)]. In the case of the scalar wave equation in vacuum, the former uses superpositions over products of plane waves moving in opposite directions with speed c. The latter, based on the Lorentz invariance of the scalar wave equation, uses products of the superluminal boost variables involving speeds $v > c$ and c^2/v, respectively. The unidirectional nature of the superluminal boost spectral representation results in purely unidirectional X-shaped localized waves only in the idealized case that the latter contain infinite energy. Finite-energy X-shaped localized waves contain both forward and backward components. The latter must be minimized as much as possible in practical applications. This can be achieved effectively by means of a novel *hybrid spectral representation*, which is based on superpositions of products of a forward plane wave moving at a speed $v > c$ and a backward plane wave moving at the speed c. This technique has been used to construct a large class of finite-energy X-shaped localized waves, characterized by arbitrarily high frequency bands suitable for applications in the microwave and optical regime. In the limiting case $v \to c$, one recaptures well-known FWM-type localized wave solutions.

On Fractional Operators and Scattering from Impedance Wedges

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In recent years, some possible applications of fractionalization of operators and fractional calculus in certain electromagnetic problems have been studied and developed, the tools of fractional differentiation and fractional integration in various problems in EM fields and waves have been applied, and interesting results with notable features and potential applications have been obtained [see, e.g., N. Engheta, "Fractional Paradigm in Electromagnetic Theory" a chapter in *Frontiers in Electromagnetics*, D. H. Werner and R. Mittra (eds.), IEEE Press, New York, chapter 12, pp. 523-552, (2000)].

In the present study, we are exploring the potential use of fractional differintegrals in 2-D electromagnetic scattering from impenetrable impedance wedges. Starting from the Uniform Geometrical Theory of Diffraction (UTD) solution for the fields scattered from a PEC wedge with a given wedge angle under plane wave illumination, we apply the fractional differentiation/integration operator (with respect to a fixed Cartesian coordinate) on these fields. The idea is to find how the resulting fields, which satisfy Maxwell's equations thus representing actual electromagnetic fields, can be interpreted as approximation to the fields that would be scattered from a similar wedge but with specific surface impedances on its faces. The accuracy of the above approximation can be estimated through comparisons with data obtained by the application of the rigorous Maliuzhinets' solution for the scattering from the corresponding impedance wedge. The surface impedances relevant to the latter equivalent configuration are related to several parameters, including the fractional parameter of fractional operator, through a specific impedance transformation. We have already obtained some preliminary results that provide us with useful information. This technique can have interesting potential applications in simplifying analysis and treatment of electromagnetic scattering problems for impedance wedges, and may provide an alternative technique for determining the fields in such problems. In this talk, we will present the theory, mathematical methods, and the results of our numerical analysis. Physical remarks and intuitive issues will also be mentioned.

Electromagnetic Resonances of a Chiral Sphere

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Dielectric resonators have been studied extensively because of their use in filters and antennas. It is important to know the resonant frequencies and the Q factors of a resonator. The resonances of a dielectric sphere have been presented in the past. This paper studies the effect of chirality on the resonances of a chiral sphere by solving its characteristic equation. The constitutive relations for a chiral medium are expressed as $\mathbf{D} = \varepsilon\,\mathbf{E} - \mathrm{j}\xi_{\mathrm{r}}\sqrt{\mu\varepsilon}\mathbf{H}$ and $\mathbf{B} = \mu\,\mathbf{H} + \mathrm{j}\xi_{\mathrm{r}}\sqrt{\mu\varepsilon}\mathbf{E}$. The characteristic equation, which is complex and transcendental, is obtained by writing the field, inside and outside the chiral sphere, as spherical eigenfunction expansions and enforcing the continuity conditions on the surface of the sphere. The roots of the characteristic equation are numerically computed by using the search function, *fmins*, provided by *MATLAB*. The root is denoted by $k_o a\sqrt{\varepsilon_r \mu_r}$ =X+jY where a is the radius of the sphere. The resonant frequency is $f_r = \dfrac{X}{2\pi a\sqrt{\mu\varepsilon}}$, and the Q factor is $Q = \dfrac{X}{2Y}$. The field in the chiral sphere is neither TE nor TM because neither E_r nor H_r can exist without the other. In other words, the field is always a hybrid mode (HEM$_{mnr}$ mode). The HEM$_{mnr}$ mode which reduces to a TM$_{mnr}$ mode when $\xi_{\mathrm{r}} = 0$ is called a hybrid magnetic (HM$_{mnr}$ mode). The HEM$_{mnr}$ mode which reduces to a TE$_{mnr}$ mode when $\xi_{\mathrm{r}} = 0$ is called a hybrid electric (HE$_{mnr}$ mode). The expression for the resonant field contains spherical Bessel functions of order n, $\cos m\phi$ and $\sin m\phi$ but m does not appear in the characteristic equation. The subscript r is the order of the root of the characteristic equation. The roots are put in the order of their ascending real parts. Figs. 1 and 2 show X and Y of some modes as functions of ξ_{r} for $\varepsilon_{\mathrm{r}} = 4$, $\mu_{\mathrm{r}} = 1$, and n=1.

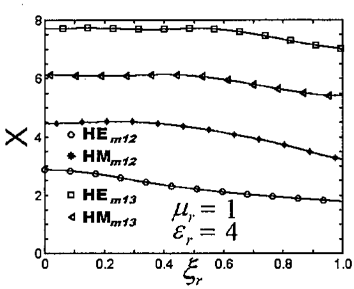

Fig. 1. X for $\varepsilon_{\mathrm{r}} = 4$, $\mu_{\mathrm{r}} = 1$, and n=1

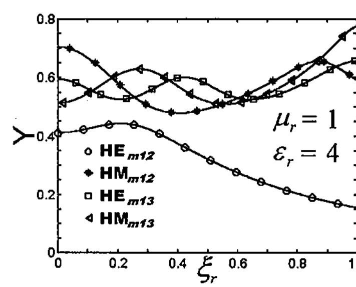

Fig. 2. Y for $\varepsilon_{\mathrm{r}} = 4$, $\mu_{\mathrm{r}} = 1$, and n=1

Rough Surface Scattering in Stratified Chiral Media with Laterally Fluctuating Electromagnetic Parameters

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Scattering of electromagnetic waves in stratified chiral media separated by rough interfaces is considered in this work. The medium parameters may also vary laterally. The constitutive relations of the complex media on both sides of the irregular interface is assumed to be given by

$$D=\varepsilon\left(E+\beta\nabla\times E\right),\qquad B=\mu\left(H+\beta\nabla\times H\right)$$

Using generalized Fourier transforms, complete local modal expansions of the electric and magnetic fields are employed. Thus the fields are expressed in terms of left and right circularly polarized waves, (associated with different branch cuts) and the surface waves (associated with poles). These complete fields expansions are substituted into Maxwells equations and exact boundary conditions are imposed. Thus the familiar Raleigh hypothesis associated with rough surface scattering is not assumed. Furthermore, term by term differentiation of the complete field expansions is avoided, since the expansions do not converge uniformly on the rough interfaces.

Maxwell's equations are converted into generalized telegraphists' equations that account for coupling between waves associated with the same branch cut as well as coupling between waves associated with different branch cuts and the surface waves. Wave coupling in general are due to the random or periodic rough interfaces and to the lateral fluctuations of the medium electromagnetic parameters. The generalized telegraphists equations can be solved numerically or iteratively for the forward and backward traveling waves (rather than upward and downward scattered waves). Both far fields and near fields are accounted for in analysis, thus subwavelength nanoscale features also can be characterized. The solutions satisfy the generalized reciprocity relationships for an isotropic media and the realizability and the duality relationships

Pseudospectral-Beam Propagation Method (PS-BPM) for Optical Waveguides

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Light propagation in optical waveguides, with longitudinally varying refractive index distributions, is widely studied using the beam propagation method (BPM). The classical BPM algorithm is easy to implement and yields accurate results due to its computational stability. The major drawbacks of the classical technique are the inability to account for reflected optical waves, high refractive index differences over small spatial displacements and polarization effects.

A number of variations of the classical technique have been developed to overcome these shortcomings. Accurate results can be obtained using the finite element-beam propagation method (FE-BPM), a BPM based on the finite element method, without any incremental computational effort. Other approaches used to treat reflected waves are finite difference time domain (FDTD) method and Bidirectional eigenmode propagation methods (BEPM).

A BPM based on a multidomain Chebyshev pseudospectral algorithm is developed in the frequency domain for two dimensional optical waveguides (medium is invariant in one transverse direction) to improve the accuracy of the classical BPM. In the proposed technique, the Chebyshev pseudospectral method is employed along the transverse direction in the computational window. In the longitudinal direction, BPM is used to compute the stationary time-harmonic light field. A well posed PML is introduced as the boundary condition to truncate nonphysical reflections from computational window edges. Physical boundary conditions are used for patching at the interfaces of different subdomains. As a consequence of using the Chebyshev pseuodspectral method, π cells are required per wavelength as compared to 10-20 cells per wavelength for FE-BPM. The total computational cost is greatly reduced while providing greater flexibility and accuracy.

For validation, PS-BPM is applied to an optical waveguide having a sinusoidally varying refractive index distribution in the longitudinal direction and the numerical results are compared with those of the present BPM techniques, specifically the classical version and FE-BPM. Advantages of this method will be demonstrated against FE-BPM.

Analytical and Numerical Aspects of Regularization Techniques for Printed Transmission Lines

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Electric field integral equations are routinely used for the analysis of conducting transmission lines in layered-media environments. The resulting first-kind integral equations having compact kernels have been solved using a variety of techniques, with the most popular methods involving expansions in Chebyshev polynomials. Pulse-function and other piecewise expansion functions have also been utilized. Due to the first-kind nature of the resulting integral equations, unless special care is taken the expansions for the unknown current density on the printed transmission lines may not be convergent, although a few terms of the expansion often provide a sufficiently accurate result. It has been observed that if too many terms are added to the expansion, accuracy may actually decrease.

In this paper we examine this phenomena, discuss its origins, and present numerical results which demonstrate the encountered problems. We then apply regularization methods which are conceptually simple, and which result in a numerically stable formulation. In particular, a logarithmic singular operator associated with the principal Green's function is extracted analytically using Neumann's expansion, and regularized by its eigenfunctions (Chebyshev polynomials). This results in a second-kind operator equation with desirable properties. In addition, matrix properties of operator compactness are studied, and the correspondence between functional and sequence spaces in microstrip problems is discussed.

Analysis of Band-Gap Characteristics of Two-Dimensional Periodic Structures Using the Source-Model Technique

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A solution based on the source-model technique is presented for the problem of electromagnetic scattering by a two-dimensional photonic bandgap crystal illuminated by a TM (transverse magnetic) plane wave. The proposed solution uses fictitious current sources of yet to be determined amplitudes to simulate the fields in each of the different dielectric regions of which the photonic bandgap crystal is composed. These amplitudes are in turn adjusted to fit the continuity conditions for the tangential components of the electric and magnetic fields at a selected set of points on the boundary between the different dielectric regions, within the unit cell of the periodic structure. The solution is applied to a structure composed of a finite number of identical layers each comprising a linear periodic array of dielectric cylinders. The calculated transmitted and reflected power densities for different frequencies and for various angles of incidence of the incident wave demonstrate the existence of a frequency bandgap. Comparison of the frequency bandgap obtained for a large number of layers to the bandgap structure obtained by solving the eigenvalue problem for the corresponding two-dimensionally infinite periodic structure shows a very good agreement. A study of the transmitted and reflected power densities as function of frequency for increasing number of layers provides a valuable insight to the relationship between the dimensions of a finite periodic structure and its frequency bandgap characteristics.

Asymptotic Green's function for a sectoral array of electric dipoles on a grounded dielectric slab

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The interest on the modeling and the analysis of finite periodic structures has received a recent impulse. The original and simplest method of prediction, based on the approximation of infinite array structure that reduces the analysis to that of the single cell of periodicity, has been now improved by formulations which account for the array truncation, while maintaining a reduced numerical effort. The rigorous integral equation analysis based on an element-by-element Method of Moment (MoM), constructed by using the single element Green's function, becomes computationally prohibitive for increasing array size. This method can be restructured, under certain assumption not excessively restrictive for practically array, into a formulation which uses the array Green's function (AGF) [A.K.Skrivervik, J.R.Mosig, IEEE Trans. Antennas Prop., Vol.45, no.9, pp.1411-1418, Sept.1997]. The AGF can be represented asymptotically in terms of Floquet wave (FW) and relevant FW-induced diffracted rays originating at the truncation. Formulating an integral equation analysis around this asymptotic AGF, leads to methods which allows a drastic compression of the Method of Moment's matrix. A series of recent papers treats this ray diffraction description for different array typologies, starting from rectangular arrays in free-space [F.Capolino, M.Albani, S.Maci, L.B.Felsen, IEEE Antennas Propagat. Trans., Vol.48, no.1, pp.67-74 and 75-85, Jan.2000; F.Capolino, S.Maci, L.B:Felsen, Radio Sci., Vol.35, no.2, pp.579-593, March-April 2000] and arrays on grounded slab [A.Polemi, A.Toccafondi, S.Maci, on Antennas Propagat. Trans.,Dec.2001]. Insertion of asymptotic AGF in the hybrid full-wave formulation was originally used for arrays in free-space; recent improvements have perfectioned the method, allowing the introduction of stratified environment, for treatment of patch phased arrays. Two similar techniques have been proposed in [O. Civi, V. B. Erturk, P.H. Pathak, P. Janpugdee and H.T. Chou, APS Symposium, Boston, July 8-13,2002] and in [A.Cucini,A.Polemi,S.Maci, ICEAA, Torino, September 10-14,2001].

In order to derive the asymptotic AGF useful for practical patch problems, one may refer to a canonical configuration composed by a sectoral array of dipoles on a grounded dielectric slab. The asymptotic treatment of the relevant AGF, which is the aim of this paper, leads to the description of complicated effects, due to the presence of the corner. In addition to the space wave mechanisms, typical for free space environment, additional surface and leaky wave excitation arises from the corner, thus leading to more elaborated transition functions. A preliminary investigation is given in [P. Janpugdee, P. Pathak, P. Nepa, O. Civi, H.T. Chou, URSI Symposium, Boston, July 8-13,2001]. In the present work, particular care has to be given to the grazing aspects of observation, i.e. at the slab-interface, since those observation aspects are the most important for applying boundary conditions in the hybrid full-wave asymptotic approach described before. At difference with [P. Janpugdee, P. Pathak, P. Nepa, O. Civi, H.T. Chou, URSI Symposium, Boston, July 8-13,2001], the asymptotics presented here is performed for grazing observation aspects, with the inclusion of higher asymptotic orders.

The final physical appealing structure of the solution is a complement to other purely numerical evaluation of the AGF integrals, which can be used inside the same full-wave method to estimate the field close (i.e. not asymptotically far) to edges and vertices of the array. This latter complementary approach is presently under development. Numerical results will be presented and discussed during the oral presentation.

Model of Electromagnetic Signal Propagation in the Two Turbulent Flows of Slightly Ionized Plasma

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The purpose of this work is a numerical investigation of the process of electromagnetic signal multiple interactions with moving turbulent inhomogeneous in the flows of slightly ionized plasma. To the analysis of this problem a method of stochastic modeling is applied (V.G. Spitsyn, IEEE AP-S International Symposium, 1, 112-115, 1998). Here is considered the propagation of waves with arbitrary frequency spectrum in the two turbulent flows with inhomogeneous profile of velocity turbulence. The task of wave propagation through the plane-parallel flows with an inhomogeneous profile of velocity is solved. In Figures 1, 2 are presented of the computation results of angular and frequency spectrums of scattering signal for case of propagation wave across the axis of flows.

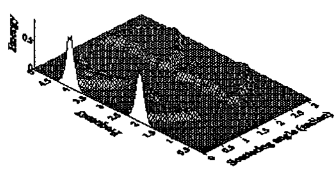

Figure 1

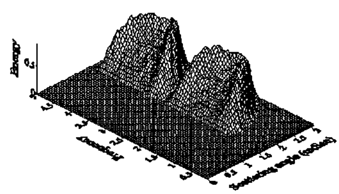

Figure 2

The indicatrix of turbulence over-radiation is supposed by isotropic type. In the horizontal plane are presented the scattering angle, calculated from the dimension of incident wave scattering, and the value of undimensional Doppler shift of frequency. By the vertical axis is calculated the energy of scattering signal, which is normalized on the maximum of energy in the every frame. In the Figure 1 is presented the results of transformation frequency spectrum of incident wave with two Gaussian components in the one flow for case of middle free wave propagation value is equal to 1 in the relative units. The size of flow along the direction of wave propagation is equal to 3. In the Figure 2 is presented the results of this signal propagation in the two flows for case of middle free wave propagation value in the first flow is equal to 0.1 in the relative units. The difference between the data in the Figure 1 and Figure 2 is explained by the increasing of back scattering energy in the result of many acts of wave interaction with turbulent inhomogeneous in the first flow.

Design, Analysis and Measurement of RF/Microwave Subsystems

Co-Chairs: *K. G. Balmain, University of Toronto, Canada*
K. Mahdjoubi, University of Rennes, France

Investigation on Multimode RF front end between 900MHz to 5 GHz.

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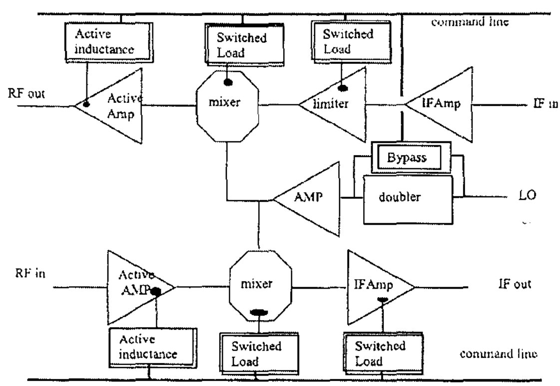
(This work was made while the author was working for NEC USA, Inc., and the patent and other intellectual property right on this work is owned by NEC USA, Inc.)

Abstract:
Recent trends in telecommunications show that the demand for small devices and multi apparatus is increasing. The services that could be offered to any customer should be as broad as possible including the support of 900 MHz Band up to 5 GHz. We investigate in the possibility to cover these frequency bands while using the same set of chips.
We report a 0.18 um BICMOS based TR chipset –Fig1- developed for multimode frequency band application. The transceiver integrates an RF amplifier, a down mixer and an IF amplifier in the down conversion path, a frequency doubler and a buffer amplifier in the LO path. All the constitutive blocks except the IF amplifier are adjustable in performances, either by switching of loads, by passing or using active inductances. The chip operates with 4-5 V and can be adjusted from 0.9 GHz to 5 GHz while dissipating 90 mW in receiving mode and 100 mW in transmitting mode. The full transceiver chip size if 4 mm x 3 mm.
We will present in this conference the results of simulation as well as results for measurements on a chip presented in the schematic represented in fig. 1. Separated results are presented for each chip like amplifier, Mixers, doubler and limiters.
Within the RF amplifier is described also an active inductance. The active inductor is using a new topology that can allow the automatic tuning of the matching of RF amplifier. Most of this show that there are some compromises. Details of the configuration will be given in the conference.



-Fig.1-

Design of Small Sized NRD Guide Ring Resonators at 60GHz

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Although it is well known that a circular ring resonator is designed by choosing the circumference to be an integral multiple of a guided wavelength, the discrepancy between the theory and the experiment has grown gradually as the radius of the NRD guide ring resonator becomes smaller.

In this paper, it has been cleared that the phenomenon is caused by two mode coupling between the operating mode and the parasitic mode generated at curved sections in the NRD guide ring resonator, and the design method has been developed based on the mode coupling theory. A technique to suppress the parasitic mode except in the ring resonator has been also introduced in the design process. Fig 1 shows the design diagram of the ring resonator at 60GHz. The dotted curves correspond to the coupled wave resonant conditions with the resonance index of N, and the solid curve is the suppression condition of the parasitic mode. Based on the diagram, the width and radius of the ring resonator can be decided in the intersection point between the solid and dotted curves. Figure 2 shows the photograph of the fabricated ring resonators whose sizes are very small compared with that of the quarter. These dimensions are summarized in table 1. Good agreements between the theory and measurement are quite satisfactory when the resonance index is set to be lager than 2, though the slight discrepancy was obtained in case of N=1 because of the influence among the evanescent decay fields on the inside of the ring. Figure 3 shows the measured band rejection performance of the ring resonator, designed by N=2. Good rejection of more than 30dB can be performed at the center frequency of 60GHz

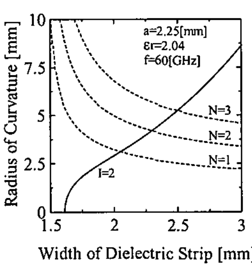

Fig. 1 Design diagram of NRD guide ring resonator at 60GHz

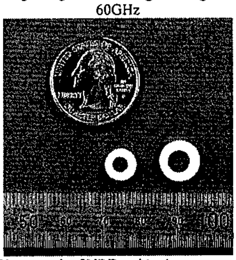

Fig.2 Photograph of NRD guide ring resonators designed by N=1 (left side) and N=2 (right side)

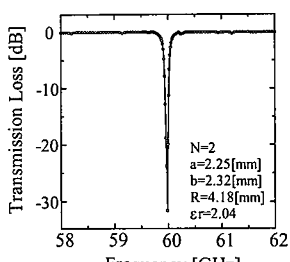

Fig.3 Measured band rejection performance of NRD guide ring resonator

Table 1 Dimensions of fabricated ring resonators and calculated and measured resonant frequencies

N	Rudius [mm]	Width [mm]	Resonant Frequency [GHz] Theory	Resonant Frequency [GHz] Measurement
1	3.11	2.05	60.00	60.41
2	4.18	2.32	59.95	60.00
3	5.31	2.50	59.87	59.61

Experiment on Giga Bit Class Ultra High Speed Data Transmission Using NRD Guide Transmitter/Receiver at 60GHz

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NRD guide transceiver, fabricated for wireless LAN at 60GHz, has great advantages such as high speed operation beyond 400Mbps as well as small size less than that of the name card (F.Kuroki, M.Sugioka, S.Matsukawa, K.Ikeda and T.Yoneyama, IEEE Trans. Microwave Theory Tech., Vol.MTT-46, No.6, 1998). Having this fact in mind, Giga-bit based transmitter and receiver have been developed for applications to the IEEE 1394 and SDI systems. The performances are summarized in Table 1. The transmitter consists of Gunn diode oscillator with the output power of 12dBm, ASK modulator made by Schottky barrier diode, and circulator, while the receiver consists of local Gunn diode oscillator with the LO power of 10dBm and balanced mixer with the conversion loss of 12dB. Figure 1 shows the system configuration of the data transmission test. Millimeter-wave with the frequency of 59.75GHz is modulated by the 1Gbps clock in the NRD guide ASK transmitter, and the demodulated wave which is received by the NRD guide receiver is down-converted to the intermediate frequency (IF) of 2.25GHz. And then the IF wave is amplified and detected. The comparison between the modulating and demodulated waveforms, observed by oscilloscope, is shown in Fig.2, where the transmitter and receiver are separated by a distance of about 5m in a narrow hall. The two patterns are identical in shape, thus, it is confirmed that the transmitted signal can be clearly recovered in the receiver. The transmitter and receiver can be applied to wireless portion in IEEE1394 systems and SDI-based HDTV signal distribution systems.

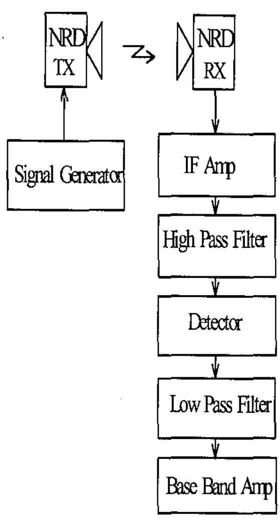

Fig.1 System configuration of high speed data transmission test

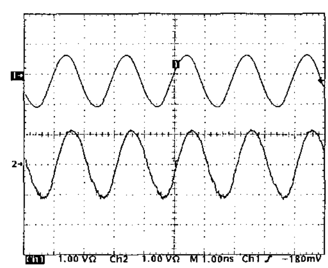

Fig. 2 Comparison between modulating (top) and demodulated (bottom) waveforms with 1Gbps clock (vertical axis: 1V/div; horizontal axis: 1ns/div)

Table 1 Performance of NRD guide transmitter/receiver

Transmitter	
Frequency	59.75GHz
Transmitting Power (Average)	10 dBm
Modulation	ASK
Bit Rate	1Gbps
Antenna Gain	19dBi
Receiver	
LO Frequency	62GHz
Intermediate Frequency	2.25GHz
Conversion Loss (Average)	12dB
Antenna Gain	19dBi

LINEARIZATION OF RF POWER AMPLIFIER

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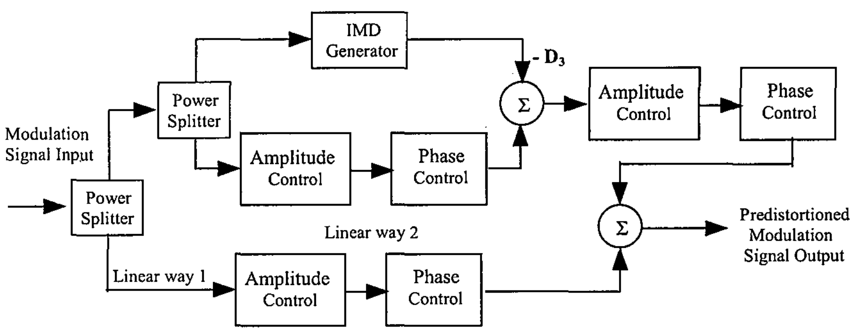
There is a growing need for high-level power RF amplifiers able to handle complex wideband signals without adding significant distortion. The primary goal in the high power amplifier design is to improve its dynamic linearity range. For a Class A amplifier, the upper limit is the 1-dB compression point, P_{1dB}. In Class AB the gain varies and hence the concept of compression point, defined in terms the maximum envelope power (rated *PEP*) for a given linearity, is more difficult to apply. It is common, in practice, to specify the linearity level as -30 dBc for a two-tone signal. Amplification of a single carrier with a true constant envelope presents the least problems with respect to linearity and high power amplifier design and it is possible to using class C or other kind of amplification that have good efficiency. If the envelope of the signals changes, the linearity becomes much more important and a more linear amplifier must be used. Therefore, a number of techniques have been developed that attempt to linearize an inherently nonlinear amplifier, like feedback, pre-distortion, feedforward, etc. This paper presents the results of the pre-distortion implementation to linearize an UHF medium power amplifier. The *Intermodulation Rate* (*IMR*) was measured using two modulating signal patterns: a complex digital TV 8-VSB and COFDM. The diagram below shows the designed pre-distortion module and the experimental results. The *IMR* improvement was near of 6 dB.



EXPERIMENTAL RESULTS (UHF Power Amplifier @ 200 W)			
Power Output (*W*)	**Modulation Signal Pattern**	**Measured IMR (*dBc*)**	
		without pre-distortion	**with pre-distortion**
200	***TV 8-VSB***	**42**	**48**
250		**46**	**46**
115	***TV COFDM***	**41**	**46**

Transmitter Linearization Using Digital Predistortion

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Nonlinearity is the most known feature of the RF Power amplifier (*PA*). One way to reduce the effects of nonlinearity is to back off from the nonlinear region, which adds low power efficiency. A usual solution would be the combination of nonlinear *PA* with a predistortion technique enough to compensate the nonlinear distortion. Digital predistortion will provide a highly linear output. For example, on Digital TV system channel coding such as the *8-VSB* and *COFDM* are very sensitive to nonlinear distortions, where the digital predistortion is used in order to achieve accepted intermodulation distortion. One of most innovative contribution of this paper is to explore the idea of works on the base band independent of three essential points: the modulation type, the output frequency and the signal bandwidth. Figure 1 depicts a classic nonlinearity of the amplifier with both ideal and realized gain.

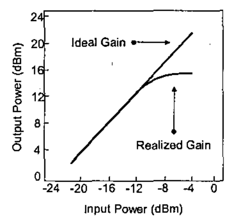

Fig. 1

The main idea of the predistortion is to introduce a device on the system which its transfer function can be superposed with the corresponding transfer function of the amplifier, such that the convolution of them results in a linear one. Our choice to do the treatment of the problem digitally takes into account the device flexibility and its extraordinary performance. All the process is accomplished using an Analog-to-Digital Conversion (*ADC*), a fast memory, and a Digital-to-Analog Conversion (*DAC*), where the processing of the signal digitally allow us to reproduce the desirable transfer function. Figure 2 can give us some idea of the hardware implementation already done.

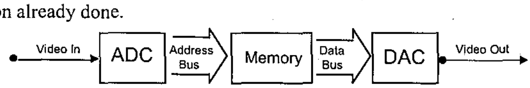

Fig. 2

The memory works like a one-to-one corresponding table between the input and the output. It is on read operation and the *ADC* output bits are tied on the memory's address bus. Thus, the data stored at a memory location determined by the address pins are asserted on the data bus, which is tied on the *DAC* inputs. Note that, if the data stored in an address was its own address, the transfer function satisfies: $H(S) = 1$.

In this case, every signal presents in the input appears at the output too. It takes an important hole when the data stored at a memory location do not coincide with its address. In this case, the transfer function becomes different from 1 and so it can have the amplitude level we should manipulate. There is no compromise to work with the more significant bits, because the system is not completely confuse, and the engineering designer should works only with the less significant bits.

The future of the digital predistortion technique advantages is very clear. The simplicity to operate with sequences of binary digits makes the process described above a great solution for the nonlinearity of the transmitter. This is a great contribution in the next step of the research, and our work in progress.

Patch Antennas

Co-Chairs: *P. Mohanan, Cochin University of Science & Technology, India*
W. Wiesbeck, University of Karlsruhe, Germany

Stacked Patch Antenna with Shorting Pins

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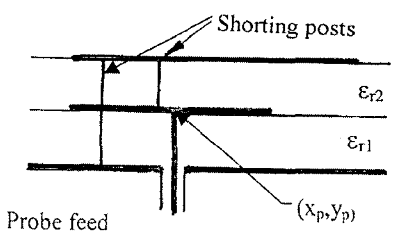
There have recently been extensive researches into the design of microstrip patch antennas that are wideband (> 15%) and small size (longest dimension of patch < 0.3 λ_o where λ_o is free space wavelength), which are required in a number of wireless communication systems. One approach is to combine the bandwidth widening techniques employing the U-slot patch, L-probe fed patch, and stacked patches, with the size reduction techniques using shorting wall and shorting pins.

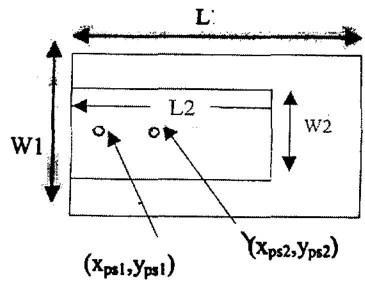
This paper is concerned with the geometry using two stacked patches and shorting pins. It appears that to realize the specifications, it is necessary to use two shorting pins, one connecting the upper and lower patches and another connecting the top patch to the ground plane through the lower patch, as shown below. In Ref. 1 (R.Waterhouse, Electron Lett., Vol. 35, pp. 98-100, 1999), this design was tested for the case of foam substrates in both the upper and lower layers. An impedance bandwith of 32-34% was reported, with the longest dimension of the patches about 0.19λ_0.

The stacked patch antenna with shorting pins involves many parameters, making the design of this antenna somewhat complicated. In this paper, we present a number of design data for this antenna, using the ENSEMBLE 6.0 simulation software. Four combinations of substrates are used for the upper and lower substrate layers: (a) $\epsilon_{r1} = \epsilon_{r2}$ =1.07 (foam); (b) $\epsilon_{r1} = \epsilon_{r2}$ =2.33; (c) ϵ_{r1} =1.07, ϵ_{r2} = 2.33; (d) ϵ_{r1} =2.33, ϵ_{r2} =1.07. In each case, the antennas are designed for operating at four center frequencies: 2 GHz, 3 GHz, 4 GHz and 5 GHz. It is found that, for case (a), bandwidths of 27-28% are obtained, with the longest dimension of the patches about 0.2 λ_o. Cases (b)-(d) reduce the longest patch dimension to about 0.12 λ_o while maintaining bandwidths in the range 17-22%. Details of the designs will be presented in the meeting.

Side View



Top View



DUAL TAPERED MEANDER SLOT ANTENNA FOR RADAR APPLICATIONS

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Abstract: A dual tapered short loaded meander slot antenna is designed for operation at the X-band. The antenna is excited by a coplanar waveguide (CPW) feed. The present antenna operates at a center frequency of 10.6 GHz with 2.2 GHz bandwidth.

1. Introduction

Antennas for radar applications require wideband and high gain. Usually these antennas are constructed from two or three dimensional arrays of individual antennas for gain improvement. The bandwidth, in many cases, is more dependent on the individual element of the array. In this study, we introduce a new type of antenna that exhibits wide band characteristics for X-band operation and 50 Ω matching network.

2. Design Parameters

The antenna is constructed by making meander slots in a perfectly conducting plane supported by a dielectric substrate of 1 mm thickness and relative dielectric constant of 2.17. Figure 1, shows the top view of the antenna and the design parameters. The spacing between the parallel slots is 0.5 mm, the width of the slot is 1 mm, the number of turns in each of the tapered meanders is 4, and the angle of the taper is 75°. The ends of the meander slots are connected by a vertical slot with additional horizontal tuning slots. The antenna was first designed with square edges at the corners of the meander lines, however, to improve the antenna performance the square edges were cut at 45 degree angles.

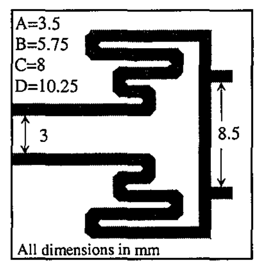
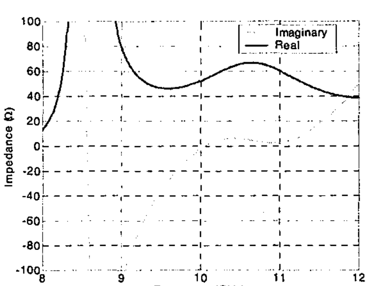


Fig. 1. Antenna geometry.

3. Simulation and Results

Momentum, a 2.5D full wave simulator using the method of moments for layered structures is used to analyze this type of antenna. The design presented in Fig. 1, yields a bandwidth of about 2.2 GHz with 50 Ω input impedance, as shown in Fig. 2, and a directivity of 4.69 dB.



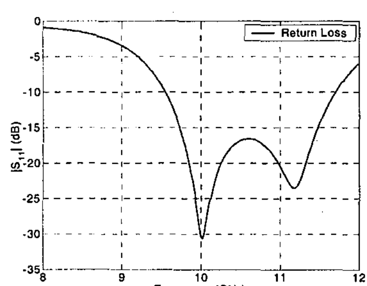


Fig. 2. Input impedance and return loss.

Simple Loading Techniques for Size Reduction of Circularly-polarized Microstrip Antennas

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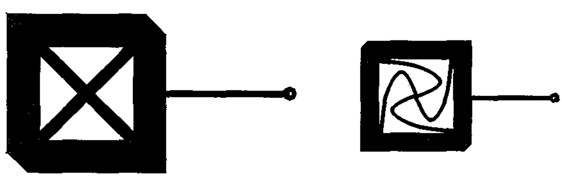
A number of authors have investigated reactive loading of microstrip antennas to reduce their size for a specified frequency of operation. Many schemes combine different modes to extend the impedance bandwidth of the configuration; this often produces antennas with varying pattern and polarization characteristics. The simple loading techniques investigated here not only produce good impedance characteristics but also maintain good pattern characteristics. That is, they minimize the decrease in efficiency while maintaining pattern shape and polarization characteristics. Furthermore, simple techniques that are straightforward to match are a particular goal of the study.

In a previous study, the configuration shown on the left-hand side of the figure below produced linear size reductions on the order of 23% (a 41% decrease in the footprint area of the radiating structure itself) on a substrate with $\varepsilon_r = 3.05$, $\tan\delta = 0.003$ and a thickness of h = 0.060" compared to an unloaded, trimmed-corners patch. The efficiency of the unloaded patch was $e_{rad} = -2$dB while that of the reduced-size version was –6 dB. Subsequent to the measurements, simulations have shown that these efficiencies would have been –1 dB and –4 dB, respectively had a lower loss substrate been used.



The primary problem with the simple X-patch structure was that for linear size reductions greater than about 25% the amount of copper removed made the antennas difficult to match and limited their bandwidth. Simulations have demonstrated that linear size reductions on the order of 35 to 40% (64% area decrease) are possible with the configuration shown on the right. Additional configurations will be identified and the most promising ones will be fabricated. Full radiation distribution plots will be measured on the selected antennas and efficiency, pattern characteristics, axial ratio bandwidth and impedance bandwidth will be determined and reported.

Corrugated Patch Antennas On Plastic Substrates

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This work investigates the use of corrugated dielectric substrates in order to reduce the length of rectangular patch antennas. Using this new type of design, reductions of antenna length by 50% at a frequency of 2.0 GHz are possible. Decreasing the size of antennas is motivated by the need to incorporate small form factor antennas into handheld devices. Several techniques have been previously demonstrated to reduce the size of the patch antenna, including: modifying the patch antenna shape (J. George and K.G. Nair, *Elect Lett.*, *32*, 508-509, 1996) use of high permittivity substrates, and the use of shorting posts. We present a new type of patch antenna where the radiating metallic surface is deposited on a corrugated dielectric substrate, which reduces the effective phase velocity of the propagating wave. Our fabrication approach is based on using PDMS (Polydimethylsiloxane- a moldable thermoplastic with a dielectric constant of 2.75) as the substrate material and sputtered copper metallization for the ground plane and radiator material. The corrugated antenna geometry is shown in Figure 1, where the length L of the baseline patch antenna is 4.65 cm. The reduced antenna has four periods, each with length of 0.58 cm., for an overall length of 2.4 cm. To verify its performance, far-field radiation patterns and input return loss are simulated and compared to the classical rectangular patch antenna. As shown in Figure 2, the return loss and radiation patterns degrade only marginally at up to a 50% reduction in length. The corrugated antenna also shows a bandwidth increase of x2 over the reference structure. The results suggest that non-planar substrates and antenna structures may offer new design opportunities for low-cost compact devices.

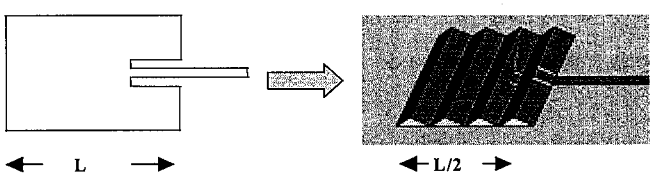
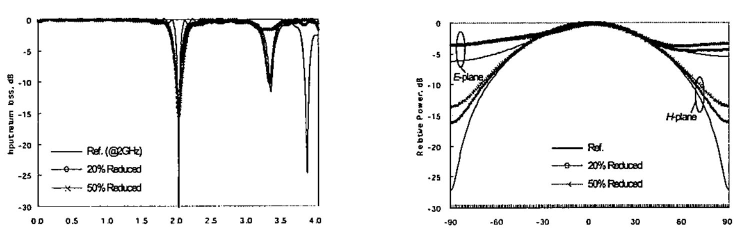


Fig.1 Proposed Antenna



(a) Input Return Loss (b) Radiation Patterns

Fig. 2 Simulated Effects of Corrugated Antenna

Grounded Multifinger Patch Antenna

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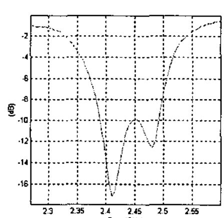
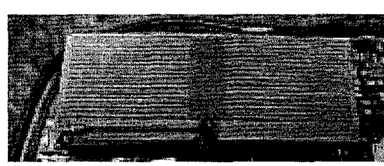
Abstract:

Regular patch antenna bandwidth usually hardly covers data transmission applications. In order to improve the bandwidth, different solutions exist. Some of them use capacitively coupled parasitic elements that are excited by a driving element like stack patches. In some other cases, the optimization method consists in exciting the same mode over the same element in which several inclusions can be found. As the device aspect ratio tends to shrink, the classical application bandwidth requirements are even more challenging to meet. To address this size reduction, one solution consists in changing the patch antenna profile in a set of slits, which corresponds to inductive load [S. Reed et al. APS/URSI UTAH 2000]. The authors have demonstrated a 50% size reduction using the same TM001 regular patch antenna mode. Moreover, efficiency is the most important parameter in order to keep up with data communication link performances. Unfortunately, as the patch gets smaller, the efficiency tends to drop and the working bandwidth gets smaller. These physical rules have been demonstrated [Thiele and Stutzman, antenna theory and design, Wiley and Sons 1998]. In this work, a new technique [US 6,323,810, poilasne and Desclos] is presented in order to obtain a small and efficient antenna. On one hand, inductively loading slits on the side of the patch allow to reduce the patch dimensions -fig.1-. On the other hand, we place a shunt to ground connected to the feeding point. This will create a second resonance that will allow to have a broader bandwidth –Fig.1-. At the same time it creates a good isolation from outside components. This full solution allows one to obtain a 10% bandwidth antenna with an efficiency of nearly 100% (efficiency compared to the dipole). Examples will be shown in the ISM and PCS bands using some RO4003 materials. The size of the grounded multi-finger patch in this case is about 35mm by 8mm by 2.5mm and the evaluated efficiency is 90% for both. Some more investigations with the antenna placed within enclosures will be shown -fig.2-



-Fig. 1-



-Fig.2-

Multilayer Meander Loop Antennas

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The use of conventional microstrip antennas and arrays is widespread due to their inherent advantages such as being low cost, low profile, lightweight, conformal, and suitable for integration. These antennas are generally narrowband because they are resonant-type antennas. Since the antenna is usually one of the bulkiest elements of transmitters and receivers, there is always a need to develop smaller, efficient antennas amenable for integration, particularly at lower frequencies where antenna size can be very large. Antenna designs for multifrequency, multiband operation is also of interest. The most common microstrip patch shapes used are the rectangular and circular patches. In this paper, we investigate a new geometry, namely, the meander loop antenna. A single-layer microstrip meander loop antenna is narrowband producing broadside radiation similar to rectangular and circular patch antennas. However, the area occupied by the meander loop is much smaller than conventional patches operating at the same frequency. This makes them very attractive for integration with active devices and for applications at lower frequencies where the size of conventional patches can be prohibitively large. The characteristics of microstrip meander loop antennas are investigated. Input Impedance, bandwidth, efficiency, and radiation patterns in relation to antenna geometry, dimensions, and substrate parameters are studied. Various feeding techniques including gap coupling and aperture coupling using microstrip lines are considered. Since the bandwidth of this type of antennas is small, multilayer configurations are studied to obtain broad bandwidth and/or to realize multifrequency operation. Methods for obtaining circular polarization using geometry perturbations are also investigated. Finally, research concerning the scanning ability and limitations of two-dimensional arrays of meander loops is conducted.

This research uses theoretical as well as experimental methods. Theoretical simulations are based on a full wave method of moment approach. In the experimental component, various antenna prototypes are designed, built, and tested.

CPW - Fed Microstrip Antenna using a Slot/Loop Combination

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Microstrip antennas have been the subject of extensive research for their low cost, light weight, low profile, being conformal, and compatibility with integrated circuits. Using coplanar waveguides as feed transmission lines offers the advantage of ease of integration with active devices due to their uniplanar design. In the literature, some feeding methods for single-layer microstrip antennas using coplanar waveguides, mainly inductive or capacitive coupling via a rectangular a slot, have been explored. The coplanar waveguide allows for easier integration with active devices than microstrip lines since the need for via holes is eliminated. Furthermore, since the CPW conductors are also used as the ground plane for the microstrip patches, the feed substrate used in conventional microstrip aperture coupling is no longer needed. Reconfigurability, tunability, as well as bandwidth improvements without detracting from the major advantages of microstrip antennas are very important subjects of research. The most common technique for increasing the impedance bandwidth has been the use of multilayer configurations. However, using multilayers increases the overall thickness of the microstrip antenna resulting in stronger surface waves, which in turn lower efficiency, distort radiation patterns, and can cause scan blindness in microstrip arrays. In this research, we propose a two-layer configuration that offers a bandwidth similar or better than conventional three layer configurations. One layer of the proposed antenna consists of a high dielectric constant feed substrate with a coplanar waveguide and a slot/loop combination on one side and a rectangular patch on the other. The second layer is a low dielectric constant substrate having one patch only. In addition to the bandwidth advantage, the proposed configuration offers easy tunability with the ability to include switches in the slot/loop combination part of the feed. It also has an advantage in realizing active antennas. The slot/loop combination allows biasing of active devices without disturbing the RF circuitry, as it can be used for both antenna excitation as well as isolation of DC bias. Theoretical simulations using method of moments as well as experimental results concerning the proposed antenna's performance will be presented.

Cavity-fed patch antenna arrays

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Abstract

Conventional 2-dimensional passive antenna arrays are fed by complex network of transmission lines. These transmission lines not only pose a serious challenge to antenna designers but also cause degradation in performance. Approaches to reduce the complexity of feed network have been proposed. For instance, series fed arrays in which one transmission line passes through each antenna element in the same row or column, thus reducing the complexity in one dimension only. Another example is reflectarrays. A reflectarray usually consists of a planar patch antenna array which is fed, instead of through feed network, by another source above the surface of the planar array. The arrangement is very similar to a conventional reflector antenna except that the costly metallic reflector is replaced with a cheaper planar patch antenna array, therefore reducing the cost. However, the source is not integrated to the planar circuitry, which causes inconvenience in construction and installation.

We propose a new approach toward complete removal of feed network and yet retaining the easy of manufacturing of planar circuitry. In this approach, the patch antenna array is placed on top of a rectangular cavity which is very thin in height. The cavity can be manufactured by micromachining if it is in an MMIC, or be constructed separately and bond with the planar array such that the whole package remains a low profile. Coupling is achieved through the slots under the patch antenna elements by the electromagnetic fields of a particular higher order mode of the cavity. The position and size of each slot will determine the strength and phase of the excitation. Metallic post can be inserted in the cavity at the nulls of the higher order mode to suppress lower order cavity modes. At the opposite side of the cavity surface, a slot is opened to allow another microstrip line to supply power to this cavity. In previous work of the authors, simulations have shown that higher order modes of a rectangular cavity can be excited by a microstrip line through slots on the cavity. The numerical method used in the simulation is a hybrid technique which employs the method of moment in the planar circuits and the finite element method in the cavity to implement an equivalent Green's function of the cavity itself. Although the Green's functions of a rectangular cavity can be derived analytically, the finite element method is used such that the simulation will not be restricted to limited canonical cavity shapes which have analytical Green's functions. This hybrid technique has been verified by comparing to FDTD and measurement data in previous work.

Simulation and measured data of the radiation pattern and input impedance of an 4×4 cavity-fed uniform patch antenna array will be presented to demonstrate the plausibility of this concept. The date of the same array excited by Chebyshev distribution will also be shown.

A SIMPLE APPROACH FOR EDGE FEEDING OF MICROSTRIP RING ANTENNAS

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Abstract

Microstrip antennas are widely used for portable applications. Changing the patch shape and or loading can give rise to a substantial size reduction. For example, microstrip ring antennas, H-shaped patch, etc. may give rise to a reduction factor of 2.0.. However, cross-polarization and gain charactertstics of the antenna suffer considerably when loaded. On the other hand, ring shaped microstrip antennas provide a good compromise between size reduction and antenna characteristics. For example, a square ring antenna is one of the smallest unloaded circularly polarized microstrip antenna with size $\lambda/4 \times \lambda/4$ without incurring loss of gain.

The resonant wavelength for the dominant mode of operation of a microstrip ring antenna is nearly equal to the average circumference of the ring. The input impedance is large at the edge of the strip and varies across the strip width. Therefore a wider strip is necessary to achieve $50\,\Omega$ input impedance. Otherwise, one has to increase the substrate thickness or use stacking of resonators (P. Moosavi and L. Shafai, AP-S Int. Symp., 944-947, 1997). Howecer, a narrow strip is needed to achieve compactness, but the impedance matching problem increases. In this paper we present a simple solution to the feeding problem, retaining the compactness of the antenna. The idea is to use circumferential variation of current. In most of the patch shapes this property has already been exploited, e.g. non-radiating edge feeding of a rectangular patch antenna. The circumferential variation of field in these geometries is pre-fixed by the patch shape. However, in ring geometries the field distribution, although full-wave in nature, is not pre-fixed and is determined by the feed or load. In the absence of load, the electric field becomes maximum at the feed and gives rise to maximum input impedance, which may be higher than the feed line impedance.

If we load the ring antenna, the field at the load will fix the field distribution on the rest of the ring. The input impedance will vary accordingly along the periphery. By properly choosing the position of feed with respect to the load, $50\,\Omega$ matching at four points on the circumference may be found. This concept for edge feeding for the square ring microstrip antenna has been verified theoretically and experimentally. The loadings tried are stubs and notches. It has been found that the cross-polar level of radiation, due to the degenerate mode of the ring can be reduced by using a narrow strip ring antenna.

Thursday AM *AP/URSI B Session 109 Rio Grande East*

Special Session

Fractal Antenna Engineering

Organizer(s): *D. H. Werner, Pennsylvania State University, USA*

Co-Chairs: *D. H. Werner, Pennsylvania State University, USA*
J. M. Rius, Polytechnic University of Catalonia, Spain

The Q of fractal antennas: Can space-filling geometries lower the Q of antennas?

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Introduction: The limitation of the bandwidth of an antenna is set by the size of a sphere that can completely enclose the antenna. Efficient use of the space inside the sphere can maximize the bandwidth. This work includes the investigation of various fractal geometries, including Koch curves, Sierpinski triangles, and 2D and 3D Fractal trees, as proposals of efficient configurations.

Space filling curves to lower the Q: There are ample reasons given in published works concerning maximizing bandwidths for one to look at space filling geometries to lower the Q of an antenna. R.C. Hansen writes "*..it is clear that improving bandwidth for an electrically small antenna is only possible by fully utilizing the volume in establishing a TM or TE mode, or by reducing efficiency.*" (R.C. Hansen. *Proceedings of the IEEE.* v. 69 no. 2. Feb 1981.) Furthermore, C.A. Balanis writes "*...the bandwidth of an antenna (which can be closed within a sphere of radius r) can be improved only if the antenna utilizes efficiently, with its geometrical configuration, the available volume within the sphere.*" (C.A. Balanis. *Antenna Theory: Analysis and Design*. 2nd ed. John Wiley & Sons, Inc. New York. 1997.) Fractals and other space-filling curves fill spaces more efficiently than one-dimensional antenna structures. From the two quotes above, it cannot be directly concluded that fractal and space-filling curves can efficiently couple waves to free space, but their geometries are worth investigating.

Calculation of the Q of a small antenna: The Q of an antenna is a measure of the stored energy to its radiated energy. For resonant antennas, the Q is approximately the inverse of its fractional bandwidth. For a fractal antenna, the input impedance can be computed using the moment method and the Q can be found from

$$Q = \frac{\omega}{2R_{in}}\left(\frac{dX_{in}}{d\omega} + \left|\frac{X_{in}}{\omega}\right|\right),$$

where ω is the angular frequency and R_{in} and X_{in} are the real and imaginary input impedances, respectively, as employed by Puente, *et al.*, (Carles Puente, J. Romeu, and A. Cardama. "Fractal-Shaped Antennas." ch 2. *Frontiers in Electromagnetics*. D. Werner and R. Mittra, ed. IEEE Press, New York. 2000). A plot of the of the Q for a thin (h/a=242) and thicker (h/a=50) dipole, computed with an estimated formula given below as well as the moment method, a 3D fractal tree dipole, and the fundamental limit, as given by Balanis in the reference above, is shown in Fig. 1. The estimation, used by R.C. Hansen in the reference above, estimates the Q from $Q \cong \left(6(\ln h/a - 1)\right)/\left(k^2h^2 \tan kh\right)$, where h is the half-length of the dipole, a is its radius, and k is the wavenumber. The plot shows that a 3D fractal tree more efficiently utilizes the space in a unit sphere compared to a dipole and therefore has a lower Q in the small antenna regime ($kh < 1$).

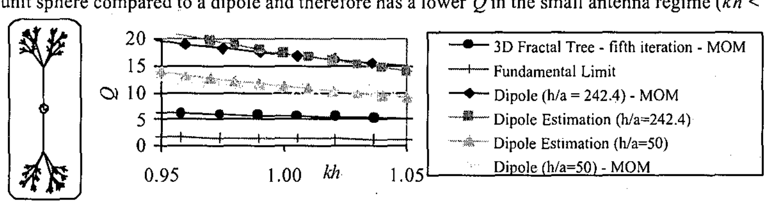

Figure 1: A 3D fractal tree in a dipole configuration and a plot of the computed Q of a thin and thicker dipole, the fractal antenna, and the fundamental limit of a small antenna.

Feed-point Effects in Hilbert-Curve Antennas

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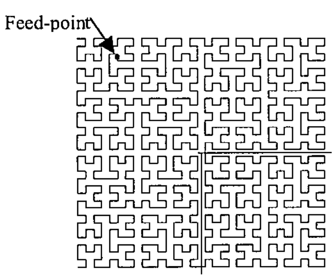
Space–filling curves are, in general, a continuous mapping from a normalized [0,1] interval to a two-dimensional regions, $[0.1]^2$ that passes through every point in the region. Since G. Peano in 1890 demonstrated the construction of the first space-filling curve, many such curves have been suggested over the years [Hans Sagan,"Space- Filling Curves", Springer- Verlag, 1994]. The most widely used of these curves is the one proposed by David Hilbert in 1891. From the electromagnetics and antenna viewpoints the Hilbert-curve (and for that matter all other space-filling curves) are very attractive since they offer a resonant structure that could have a very small footprint as one increases the step-order in iterative filling of a 2-D region [see e.g., Vinoy, *et al.*, "Hilbert curve fractal antenna: a small resonant antenna for VHF/UHF applications," MOTL, Vol 29, No. 4, pp. 215-219, May 2001]. The questions naturally arises as whether a Hilbert-curve antenna is an efficient radiator, i.e., can it be matched to a feed line with a given characteristic impedance as one increases the step-order, n, in order to form a planar resonant antenna with an electrically small footprint? In addition, for a given feed-point, such issues as bandwidth, radiation pattern and polarization performance of Hilbert-curve antennas should be fully understood before one can consider these antennas as candidates in practical applications.

In this work, we have applied a moment-method based simulation code to perform a detailed parametric study of Hilbert-curve antenna in order to address some of the above issues. In particular, we have investigated the effect of the feed-point location on the input-impedance of a Hilbert-curve antenna as the step-order increases from n=1 to n=5. It is shown that while a center-fed antenna may result in a very small radiation resistance, a properly chosen off-center feed point can always provide, regardless of how high n is, a 50-ohm match required for most applications. In general, for an antenna occupying a fixed square surface area of L x L, increase of n from 1 to 5 drastically lowers the resonant frequency by a factor of three or higher. This reduction in the resonant frequency, however, is achieved at the expense of an input impedance bandwidth that is very small when n=5. The geometry of the antenna, together with the feed location for a fifty-ohm match, is shown in Figure above for n= 5. For comparison, a microstrip patch antenna with an air-substrate, and with an identical footprint, has a resonant frequency, which is much larger, albeit with a higher bandwidth. Numerical results for radiation pattern, gain, and current distribution on the surface of the Hilbert-curve antenna for various values of order n will be given in the presentation. In addition, a printed microstrip implementation of the Hilbert-curve antenna, fed by a coaxial probe, will be discussed.



A fifth step Hilber-curve Antenna

Nature-based Antenna Design: Interpolating the Input Impedance of Fractal Dipole Antennas via a Genetic Algorithm Trained Neural Network

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Over the years engineers have often looked to nature for inspiration when seeking new and innovative ways to solve complex design problems. For instance, the development of fractal geometry was originally inspired by studying the shapes of natural objects such as trees, leaves, ferns, terrain, coastlines, snowflakes, and cloud boundaries. Neural Networks (NN) have been developed to mimic the human decision-making process. Similarly, Genetic Algorithms (GA) are based on the Darwinian notion of survival of the fittest and evolution. In fact the origin of several commonly used analysis techniques of modern day electromagnetics may be traced to processes found in the natural world. This paper will focus on developing a powerful nature-based antenna engineering design tool that combines together for the first time aspects of fractal geometry, neural networks and genetic algorithms. More specifically, an efficient method will be introduced for interpolating the driving point impedance of fractal dipole antennas using a genetic algorithm trained neural network.

A versatile as well as efficient approach based on Iterated Function Systems (IFS) is used to generate the candidate fractal dipole antenna geometries (D. H. Werner et al.; *IEE Electronics Letters*, **37**, pp. 1150-1151, Sept. 2001). The GA trains the NN over a set of data which contains the IFS parameters and the corresponding input impedances. Once the NN is trained, it is used to interpolate the input impedances for IFS parameters that are not contained in the training data. The IFS parameter space is discretized such that the training set is extremely small when compared to the actual data set of IFS parameters. This training set of various fractal geometries with their respective driving point impedances is calculated from a numerically rigorous Method of Moments (MoM) simulation. Once the neural network has been trained, the IFS parameters for any fractal dipole antenna geometry belonging to a particular class may be specified and passed on to the neural network. The NN will then interpolate the driving point impedance corresponding to any specific IFS parameters that lie within the parameter space. One of the main advantages of this IFS-GA-NN approach is that it is more computationally efficient than a direct MoM technique.

Time Domain Numerical Methods

Co-Chairs: *D. J. Riley, TRW, USA*
J. B. Schneider, Washington State University, USA

Accuracy Analysis of ADI-FDTD algorithms

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Alternative direction implicit (ADI) based Finite Difference Time Domain (FD-TD) method has received a lot of research attention recently (T. Namiki and K. Ito, IEEE Trans. On MTT, Vol 49, 665-670, 2001). In this implicit scheme, the Courant time step constrain is removed. In principle, the time domain sampling rate of the algorithm can reach the Nyquest sampling rate. However, in realistic electromagnetic simulations, the size of the time step could be closely related to simulation environments and could be constrained by the algorithm accuracy.

In this work, we will perform a comprehensive accuracy analysis of ADI-FDTD algorithms. First, an analytical time domain solution will be constructed and serve as the benchmark for accuracy comparisons. Then, a higher order ADI-FDTD algorithm in which the spatial discretization is performed using high order approximations will be developed. After the high order model is developed, the errors of ADI-FDTD algorithms as a function of the time step size, the order used in the spatial discretization, and the medium loss will be studied. The error analysis from the traditional FD-TD algorithm will also be included.

It is expected that the higher order ADI-FDTD algorithm will have better accuracy with some computational overhead. The merit of figure based on the traditional FDTD algorithm will be proposed to study the ADI-FDTD for different orders. Based on this comprehensive analysis, discussions and suggestions will be given during the presentation.

Investigation, Analysis, and Elimination of ABC-Induced Instability in FDTD Simulation

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When using the Finite Difference Time Domain (FDTD) method to solve open-region electromagnetic problems, the truncation of the computational domain is required to simulate the outgoing EM waves. The stability of FDTD simulation depends on both the differencing scheme used in the interior region *and* on the truncation technique, or absorbing boundary condition (ABC), used at the perimeter of the computational domain. These two differencing schemes are completely independent and their numerical compatibility has never been a subject of serious research. For the classical Yee scheme, the instability due to the interior scheme can be resolved by applying the Courant-Friedrichs-Lewy criterion. However, the instability that arise due to the truncation technique, which may be constructed either analytically or numerically, is harder to control and seems to be elusive. In this work, we focus on the instability arising from the application of analytical absorbing boundary conditions.

Previous work has shown that there are several mechanisms that give rise to instability when an absorbing boundary condition is applied [Ramahi, IEEE Trans. Antennas Propagat., vol. 47, no. 4, 593-599, 1999]. In this work, we address two types of instabilities. The first one arises from the numerical incompatibility inherent to the computational grid of the corner region of a Cartesian computational domain. The second type of instability arises from the differencing scheme used to discretize the ABC. The corner region instability arises from the cross-talk of the ABC finite difference stencil in the close proximity of the corners. To address this numerical incompatibility, we propose the use of a convex perimeter for terminating the computational domain in lieu of the corners. A second instability source is related to the space and time averaging procedure that is almost always used whenever analytical boundary conditions are converted into discrete forms. To the best of our knowledge, the weighing coefficients used to discretize boundary conditions have been used without any strong mathematical foundation. To predict the relationship between these weighting coefficients and instability, we turn to discrete system stability analysis. By examining the system function, which is determined by the ABC differencing scheme, it would be possible to manipulate, or in a sense, optimize the differencing scheme to resolve the instability problem without loss of accuracy.

Surface Current Density on Conductors Using FDTD and the Current Diffusion Equation

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The current density flowing on conductors can be computed from the tangential magnetic fields using the FDTD method. This, however, requires a full wave solution to the problem and is very demanding in terms of memory and computational resources. Moreover, the FDTD stability criterion is too stringent, resulting in a time step much lower than required for accurate representation of the current density (i.e. the current density is oversampled). This is a severe limitation, especially for low frequency applications where the number of time steps may eventually be of the order of millions.

An alternative approach that is valid for good conductors and low frequencies, whereby the displacement current density can be neglected, is to solve the current diffusion equation directly. This has some distinct advantages over FDTD. At first, standard finite difference schemes, either explicit or implicit, can be used with a more relaxed stability criterion than FDTD. Memory requirements are reduced since only the three components of the electric current density need be computed instead of the six field components. Additionally, only the surface of the conductor needs to be discretized instead of the fully volumetric discretization of FDTD.

The only drawback of the diffusion equation method is that the sources in the problem must be impressed current sources. This is ideal for applications such as lightning strikes, where there is an actual attachment point through which current flows, but may be inapplicable to other cases, such as scattering from an incident wave. In this paper, the current diffusion equation is solved for simple geometries, such as rectangular plates, and comparisons with FDTD are performed so that the advantages of the former method can be determined.

An Embedded Technique for a Highly Accurate FDTD Method

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Abstract

The finite-difference time domain (FDTD) method has enjoyed widespread applications in computational electromagnetics. However, in spite of its flexibility and its 2nd-order accuracy in a homogeneous medium, the FDTD method suffers from a serious degradation in accuracy when treating material interfaces, greatly reducing its accuracy in inhomogeneous media and for perfect conductors. This problem has attracted significant attention in recent years.

In this work, a multidimensional embedded FDTD scheme has been developed for the solution of Maxwell's equations. In this scheme, an embedded technique is utilized based on the popular Yee method to represent the location and physical conditions of material and metallic boundaries correctly, hence eliminating problems caused by staircasing which may lead to local divergence and loss of global convergence. Accuracy analysis has been made to show that the embedded FDTD method is at least 1st-order accurate near the local material and metallic interfaces and accordingly maintains a 2nd-order accuracy globally. The entire problem is embedded into a simple staggered grid similar to that employed by the Yee method. An extra effort is only needed when treating the grid points close to the interfaces to represent the boundary conditions correctly. Therefore no significant additional computation cost is needed over the Yee method. In addition, a perfectly matched layer (PML) is used to absorb outgoing waves at the truncated boundaries of an unbounded medium. The embedded FDTD scheme has been validated by the analytical solutions for the TM wave propagation in the presence of a dielectric sphere and a PEC sphere. Comparison of error has been made to show an improvement of typically 1-2 orders of accuracy over the Yee method with little additional computation cost. More applications will be illustrated to show that the embedded FDTD is a useful tool for computational electromagnetics.

A 3-D Multidomain Pseudospectral Time-Domain Algorithm

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A 3-dimensional multidomain pseudospectral time-domain (PSTD) method is developed as an accurate and flexible tool for the modeling of electromagnetic scattering problems. In this scheme, we employ the Chebyshev polynomials to calculate spatial derivatives, and incorporate a well-posed perfect matched layer for the truncation of the computational domain.

Previously, we have developed the 3-D Fourier PSTD method for EM modeling, which uses FFT to calculate spatial derivatives. The Fourier PSTD method requires only 2 cells per minimum wavelength, but it encounters staircasing error when applied to curved objects and Gibbs' phenomenon when applied to perfect conductors, resulting in a degradation of solution accuracy. We have also developed a 2.5-D Chebyshev PSTD algorithm applied in problems with two-dimensional inhomogeneities but three-dimensional fields.

In this work, we extend the multidomain Chebyshev PSTD to three dimensional problems. We use a recently developed 3-D well-posed PML (G.-X. Fan, Q. H. Liu, *IEEE Antennas and Propagat. Soc. Intl. Symp.,* vol. 3, pp. 2–5, 2001) to truncate the outgoing waves. Different from the previous schemes, which use characteristic waves to perform patching at the interface between two adjacent subdomains with the same material, this 3-D algorithm uses only physical boundary conditions as the patching conditions, which avoids the complexity of calculating characteristic variables in 3-D subdomains. A low-storage 5-stage 4th-order Runge-Kutta scheme is employed for the time integration.

Applications of this 3-D multidomain PSTD method will be shown for (1) homogeneous and inhomogeneous dielectric resonators with perfect conductor walls, (2) wave scattering from arbitrary 3-D objects, (3) transmission characteristics of photonic band gap structures. Both analytical solutions and experimental results will be used for validation.

Numerical Simulation of Electromagnetic Fields in Complex Borehole Environments

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We describe a new finite-difference time-domain (FDTD) algorithm for the simulation of electromagnetic field propagation and induction in complex borehole environments with applications to subsurface prospecting. The FDTD algorithm utilizes a cylindrical grid that conforms to the geometry of the drilling equipment and measuring antennas. The surrounding geophysical formation can have an arbitrary spatial distribution of constitutive parameters. The method can be used to model a large class of technologically important borehole-prospecting problems. Typically, these problems involve a layered formation traversed by a borehole in an arbitrary direction, with the near-borehole region of the formation invaded by the borehole fluid.

The FDTD grid can be made very compact around the formation by employing a perfectly matched layer (PML) absorbing boundary condition directly in cylindrical coordinates. Moreover, the disparate cell sizes inherent to the cylindrical grid are avoided by employing a mesh refinement (sub-gridding) scheme along the radial coordinate. As a result, the number of grid points along the azimuthal direction becomes a function of the radial coordinate and the overall cell size distribution becomes more uniform. This is particularly desirable in view of the CFL condition for hyperbolic partial differential equations (PDE).

Electromagnetic logging instruments operate in CW mode. Given the low-Q value of the problem, the CW response of the instruments can be extracted easily from the early time-domain data by simulating a ramp sinusoidal excitation at the source.

The algorithm is validated against the numerical mode matching (NMM) results and it is used to estimate tool responses in various complex geophysical environments.

STABILITY ANALYSIS OF THE GREEN'S FUNCTION METHOD (GFM) AS A GENERAL DIAKOPTIC FDTD-BASED METHOD

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The GFM [Holtzman & Kastner, "On the time domain discrete Green's function at the FDTD grid boundary", *IEEE T-AP*, July 2001] facilitates the characterization of a certain spatial region $\bar{\Gamma}$ in terms of the Green's function G defined over its boundary $\partial\Gamma$. The GFM can be used as an ABC when $\bar{\Gamma}$ is an external free space region, such that $\partial\Gamma$ engulfs the computational domain Γ. However, one can apply it equally well as a diakoptic Green's function that models the effect on Γ due to a non-free-space "external" region $\bar{\Gamma}$ with obstacles and arbitrary boundary shapes. A pre-processing stage is required, whereby G is computed as a solution to an artificial Dirichlet problem in $\bar{\Gamma}$, wherein $\partial\Gamma$ is perceived as either PEC or PMC, depending on the location within the Yee grid. Although conceptually the GFM is a global boundary condition, practical implementations reveal that G may be truncated in space-time accounting only for the interaction between nearby points on $\partial\Gamma$. Several numerical experiments have shown that indeed the GFM is stable when used as an ABC in the free space case, however when an obstacle is present beyond the boundary, instabilities are bound to occur. Instabilities can also arise when $\bar{\Gamma}$ has concave (re-entrant) portions. The physical mechanism behind these instabilities is identified as an artifact of spurious reflections generated by the interaction between the (physical) obstacle and the aforementioned (artificial) PEC/PMC-like boundary conditions at $\partial\Gamma$, or between different portions of the boundary. In principle, given a large number of terms in the Green's function series, these reflection should be offset by the interaction with Γ. However, the practical implementation of the algorithm with a truncated Green's function and the numerical dispersion effect fails to eliminate this effect, thereby leading to long term instabilities. These instabilities are demonstrated here by representing the FDTD/GFM algorithm in state-space format which lends itself to a straightforward stability analysis via the inspection of its eigenvalue and eigenvector behavior. Numerical verification is also presented.

As follows from the discussion above, the Dirichlet approach for the construction of the diakoptic decomposition and the associated Green's function is not deemed natural for some compositions of $\bar{\Gamma}$. The usage of a new formulation is suggested in this work, one that involves alternative forms of the Shelkunoff equivalence theorem that do not impose Dirichlet conditions on $\partial\Gamma$. Like the former formulation of the GFM, this diakoptic boundary condition is global but in practice it may be truncated in space-time. If the external domain is uniform and only one term is preserved, then it reduces to the Mur condition. The stabilizing effect of this formulation is demonstrated via the state-space eigenvalue/eigenvector analysis.

FDTD Method without Marching-On in Time Scheme using Laguerre Polynomials

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ABSTRACT

The finite difference time domain (FDTD) method, as first proposed by Yee 1966, has been widely used for the numerical analysis of transient electromagnetic problems. The FDTD method is very simple so that it can be applied to various electromagnetic problems, such as antenna and planar circuit problems. The electromagnetic fields are updated by a leapfrog scheme, which leads to a recursive marching-on-time (MOT) algorithm. But, the FDTD method has a limit on the size of time step that is dependent on the minimum grid size. Recently, to remove the temporal stability constraint, the alternating-direction-implicit FDTD (ADI-FDTD) was proposed, which is free of the Courant stability conditions. In the ADI-FDTD method, the size of time step is no longer restricted by stability but by accuracy.

In this paper, we propose a new algorithm for the FDTD method without the MOT scheme using the Laguerre polynomials that are used for temporal basis functions, which is also no longer restricted by stability. The Laguerre polynomials $L_p(t)$ are orthogonal with respect to the following weighting function $\int_0^\infty e^{-t} L_p(t) L_q(t) dt = \delta_{pq}$ where δ_{pq} is a delta function. When we choose the basis function as like $\phi_p(t) = e^{-t/2} L_p(p)$, the electric and magnetic fields can be expanded in terms of the orthogonal functions as $\vec{E}(\vec{r},t) = \sum_{p=0}^{\infty} \vec{E}_p(\vec{r}) \phi_p(t)$ and $\vec{H}(\vec{r},t) = \sum_{p=0}^{\infty} \vec{H}_p(\vec{r}) \phi_p(t)$. Considering the bandwidth and the time interval, we can obtain approximately the minimum order of Laguerre polynomials. Integrating the updating equations over $t = [0, \infty)$ with respect to the above orthogonal basis function, we can obtain the linear sparse matrix equations without marching-on-time (MOT), which becomes a recursive equation between the orders of Laguerre polynomials. We call this procedure a temporal testing. Then, we use the same spatially staggered cell as conventional FDTD. Numerical results are presented to illustrate the validity of this algorithm.

Integral Equation Methods

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Using SVD to Compress Loop-Star EFIE Matrix for Scattering Problems

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An electric field integral equation (EFIE) using loop-star basis functions has been formulated for electromagnetic scattering by perfect conducting objects. However, it is well known that the traditional integral equation methods suffer both the storage and computational complexity problems. Significant progress has been made in using the FMM (N. Engheta et al., IEEE-AP,40,634-641,1992) to circumvent these difficulties. Another approach which has not attract much attention yet is the SVD method (S. Kapur and D. E. Long, "IES^3", IEEE/ACM,448-455,1997). This paper exploits the possibility of employing the SVD method to achieve a highly efficient integral equation method for electomagnetic scattering problems.

Unlike "IES^3", our approach is the combination of SVD and iterative matrix solution technique such as preconditioned conjugate method. A highly efficient preconditioner based on mesh near method has been derived previously and is used in this work. The SVD method is employed just like the FMM, that is to reduce the complexity of matrix vector multiplication. Our approach starts by partitioning the unknowns into roughly $\sqrt{N}$ groups with roughly equal number of unknowns using a recursive octree ordering algorithm. The system matrix is then divided into two categories: self and coupling matrix blocks. The group self matrix blocks will be assembled in a classical way, namely dense and requires total of $N^{1.5}$ computation. As for the group coupling blocks, they will be the ones that subject to SVD compressions. The critical issues in driving a SVD algorithm without actually assembling the system matrix are develpment of an efficient "ranking" method to pivot the QR factorization process, and a robust reduced order system to represent the system matrix. Details of varios attempts will be presented and discussed at the presentation.

ANALYTICAL EVALUATION OF FAR INTERACTIONS IN THE VOLUME INTEGRAL EQUATION BY MOM

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Electromagnetic scattering from arbitrarily shaped inhomogeneous dielectric bodies has been an interesting topic due to its importance to problems that include propagation through inhomogeneties. Volume integral equation techniques can be applied to solve this type of problems. In this study, the volume integral equation is obtained through the mixed potential integral equation and solved by the method of moments. Tetrahedral volume elements, which are the 3-D simplex geometries, allowing solution for arbitrary shape are chosen to be the discretization elements. The 3-D H(div) conforming basis function, which assumes constant electric flux density through each face of a tetrahedral volume element, (Schaubert D. H. et al., IEEE Trans. Antennas Propagat., vol. AP-32, pp. 77-85, Jan. 1984) is used and exact Galerkin testing procedure is implemented.

One of the major drawbacks of this approach is the rapid increase in computation time of evaluating matrix entries with an increase in the dielectric object size due to numerical integrals over volume elements. Hence an acceleration technique to speed up the matrix-fill process is required for large-scale problems. In this study, as an extension to previous studies, the Taylor expansion of the free space Green's function is formulated and proposed for evaluating far interactions. This allows analytical integration in simplex coordinates, thus expected to lower the matrix-fill time. The error estimate of the Taylor expansion of the free space Green's function, which depends on separation distance and volume element size, is also derived.

Numerical results that validate the numerical efficiency and accuracy of this approach will be discussed.

Evaluation of the Electromagnetic Interaction Between Neighbouring Bodies of Revolution with the Moment Method

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Moment Method (MoM) solutions for perfectly conducting objects of complex shapes usually require a fine subdivision of the object surface and hence a large amount of computations to build the MoM matrix. When the object has a body of revolution (BoR) symmetry a very efficient set of basis functions can be defined: these are separable as subdomain functions of the curvilinear coordinate t describing the contour generating the BoR surface and as entire domain functions in the azimuthal coordinate ϕ. More specifically, the complete set $\sin(m\phi)$, $\cos(m\phi)$, with m integer is chosen (Harrington, Mautz, "Radiation and scattering from bodies of revolution", *Appl. Sci. Res.*, 20, pp. 405–435, 1969). Figure 1 shows a classic triangular rooftop bases for a generic body and a BoR basis function.

When two or more BoRs are considered revolution symmetry is lost (unless the two BoRs are co-axial) and conventional MoM has been used in the literature.

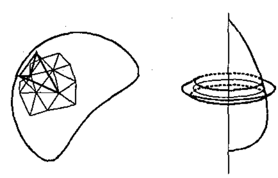

Figure 1 - *a) Rooftop bases over a generic body; b) rotationally symmetric basis function for a BoR.*

In this contribution a different approach is presented. The BoR bases are still used on each BoR, therefore allowing an easy and fast computation of the self-impedance matrices of each BoR. These matrices will constitute the diagonal blocks of the full MoM impedance matrix. The off-diagonal blocks, describing the mutual-coupling, are then computed using the same basis functions.

The approach is particularly suitable for circular horn coupling analysis. This problem is of high interest in modern applications (http://astro.estec.esa.nl/SA-general/Projects/Planck/lfi/lfi_top.html), where cluster of feeds are more and more used in antenna systems to increase efficiency. In these cases, coupling between feeds may have undesired effects on the system performances. Horns can be efficiently modeled via a mode matching/combined field integral equation hybrid technique, the latter equation being solved via a BoR MoM. The proposed technique allows an accurate modeling of the coupling between neighbouring circular horns.

Numerical Modeling of Coupling into Cavities via Apertures and Thin-Slots

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Many systems are designed to operate in complex electromagnetic environments. To predict and assess system performance the field coupling mechanism must be understood and predicted. An important class of problems that reveal salient features of the general problem is coupling into a cavity via an aperture. The purpose of this talk is to examine the algorithms that are appropriate for this class of problems and reveal the accuracy and robustness of the algorithm for a number of complex test cases. For this talk the slot models have been implemented in EIGER (Electromagnetic Interactions GenERalized) an object oriented frequency-domain method of moments code.

The first step toward the solution of the cavity-backed aperture problem is the canonical problem of the coupling into a sphere with an aperture. For this problem the aperture or slot is gridded explicitly. The analytical solution was obtained using a dual series approach and this is compared to numerical results obtained using different field equation formulations on the outside of the sphere. Once an appropriate numerical approach is identified we then shift our focus to a cavity with a thin-slot.

The thin-slot modeled is not gridded directly but is described using a sub-cell modeling technique. The sub-cell modeling technique takes into account the depth of the slot as well as the loss that may be present in the slot. The results using the sub-cell algorithm in EIGER are compared to experimental results obtained at Sandia National Labs as well as the University of Missouri at Rolla for a number of different geometries. In addition some analytic results are presented for certain modes of the cavity of interest.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy under Contract No. DE-AC04-94A185000.

Simulation of 3-Dimensional Near-Field Optical Circuits by Boundary Integral Equation Method

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It is considered that the physical phenomenon in near-field optical circuits, such as a near-field microscope and an optical manipulator and so on, is interaction between electromagnetic waves and dielectric/metallic objects. In order to simulate the physical phenomenon in near-field optical circuits, we have to solve the full set of Maxwell's equations with high accuracy. Computational electromagnetics are very useful approach to uncover the physical phenomenon in near-field optical circuits.

The finite-difference time-domain (FD-TD) method and the volume integral equation method have been applied to solve the Maxwell's equations. However, it is difficult to solve the problem involved an infinite substrate, because the computation space is discretized in those methods.

Since the unknown field is only on the surface of objects in the boundary integral equation method, the boundary integral equation method is more appropriate to simulate near-field optical circuits than the FD-TD method and the volume integral equation method. However, there is no paper to apply the boundary integral equation method to 3-dimensional near-field optical ciruits to our knowledge.

In this presentation, we apply the boundary integral equation method to a near-field optical circuit. We will consider the scattering problem of subwavelength size objects deposited on an infinite substrate. We assume that the objects are illuminated by the evanescent wave which has been created by the totally reflection of the incident plane wave.

The boundary integral equations are solved by the method of moment, where the Rao-Wilton-Glisson (RWG) functions for triangle patches is used as the basis and testing functions, and the matrix equation is solved by the generalized minimum residual (GMRES) method. The numerical results are checked by the optical theorem. We will discuss some field distributions comparing with non-substrate case and a static case.

HIGHER-ORDER DIVERGENCE CONFORMING VECTOR BASIS FUNCTIONS IN THE SOLUTION OF VOLUME INTEGRAL EQUATION BY MOM

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Higher-order vector basis functions are attracting attention due to their ability to represent vector distributions and geometries more accurately, hence to provide better convergence. In this study, this type of basis functions is implemented in the solution of electromagnetic scattering from an arbitrarily shaped inhomogeneous dielectric body problem. The problem is formulated in the form of a volume integral equation through the mixed potential integral equation and solved by the method of moments. Tetrahedron, which is the 3-D simplex geometry, is chosen to be the volume element. 3-D divergence conforming (H(div)) vector basis functions are used to expand the electric flux density, which is normally continuous across each face of a volume element.

In this study, we propose to use the family of Nedelec type basis functions due to its completeness and conformity to the divergence operator (J. C. Nedelec, Numer. Math., vol. 35, pp. 315-341, 1980). The first and second order H(div) vector basis functions, which model the constant and linear variation of electric flux density with position within a volume element, can be expressed in volume coordinates as below, which may give more physical insight:

First Order Basis Functions (4)

Face Based Functions (4)

$$W_{jkl} = \zeta_j \nabla\zeta_k \times \nabla\zeta_l + \zeta_k \nabla\zeta_l \times \nabla\zeta_j + \zeta_l \nabla\zeta_j \times \nabla\zeta_k$$

Second Order Basis Functions (15)

I. Face Based Functions (12)

1. $W_{jkl} = \zeta_j \nabla\zeta_k \times \nabla\zeta_l + \zeta_k \nabla\zeta_l \times \nabla\zeta_j + \zeta_l \nabla\zeta_j \times \nabla\zeta_k$
2. $W_{jkl,m} = \zeta_m \left(\zeta_j \nabla\zeta_k \times \nabla\zeta_l + \zeta_k \nabla\zeta_l \times \nabla\zeta_j + \zeta_l \nabla\zeta_j \times \nabla\zeta_k\right)$

   $W_{jkl,n} = \zeta_n \left(\zeta_j \nabla\zeta_k \times \nabla\zeta_l + \zeta_k \nabla\zeta_l \times \nabla\zeta_j + \zeta_l \nabla\zeta_j \times \nabla\zeta_k\right)$

for face i, where $\{i, j, k, l\}$ form a cyclic index notation and ζ_m and ζ_n are the independent area coordinates on face i.

II. Volume Based Functions (3)

$$W_m = \zeta_m \left(\zeta_j \nabla\zeta_k \times \nabla\zeta_l + \zeta_k \nabla\zeta_l \times \nabla\zeta_j + \zeta_l \nabla\zeta_j \times \nabla\zeta_k\right)$$

for m = j, k, l where ζ_j, ζ_k and ζ_l are the independent volume coordinates.

Numerical results that validate the better convergence property of the use of higher-order H(div) vector basis functions will be discussed.

Mesh and discretization issues in the Dual-Isoscalar Multiresolution Technique

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The EFIE-MoM approach is largely used in the simulation of large and complex structures, like antenna arrays, and circuits. It is well known that matrix size and condition number involved in the problems of interest are the key limitations of this approach. In these problems, the structure of the solution exhibits very different scales of variation. For examples, local interactions in sub-wavelength details, edges and discontinuities, generate small-scale details of high spatial frequency; on the other hand, distant interactions - as well as resonant lengths - are responsible for the low-frequency, slow spatial variations. To avoid the difficulties associated with very different scales, an effort can be done to keep these different scales directly into the formulation and solution process, a typical Multi-Resolution (MR) instance.

The dual-isoscalar (DIS) multiresolution approach has been recently introduced by the authors (P. Pirinoli, G. Vecchi, L. Matekovits, IEEE Trans. on Ant. and Prop., pp. 858-874, June 2001) to address the above issues. It has been shown to be capable of handling real-life structures, drastically improving the condition properties of the associated MoM matrix, with clear advantages on the matrix sparsity and speed of convergence of iterative solvers (e.g.the CG).

In the DIS-MR scheme, the generation of the MR basis is approached first by dividing the unknown surface current into its solenoidal (TE) and quasi-irrotational (quasi-TM, qTM) components: they can be mapped to scalar quantities that posses the same degree of regularity in both spatial directions, on which the introduction of wavelet-like constructs is easier. More specifically, the qTM part is related to the charge density, and the TE part is derived from the grid of a "solenoidal potential". The splitting of the current allows separating the singular, near-field behaviors that are of key importance for the conditioning of the MoM system matrix.

This communication deals with recent improvements of the scheme - notably a generation scheme for hierarchical MR bases - and the application of DIS-MR to test problems meshed with a triangular grids. The above-mentioned reference dealt in detail with rectangular grids; extension to triangular grids can be obtained almost directly by application of the described algorithms. However, Rao-Wilton-Glisson (RWG) functions are known to allow continuity of only one current component (the longitudinal one), a fact that renders bases defined over nested meshes (as obtained from h-refinement) not directly hierarchical. This opens interesting possibilities and an option that is absent in rectangular grids.

Analysis of Transient Scattering from Conducting Objects by Using The Magnetic Field Integral Equation

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In the past, several formulations have been presented by various researchers for the solution of the time-domain integral equation to calculate the electromagnetic scattering from arbitrarily shaped, three-dimensional structures using triangular patch modeling techniques. Recently an implicit scheme has been proposed to solve two- or three-dimensional scattering problems to overcome late-time instabilities. Most of papers, however, have used a time-domain electric field integral equation (TD-EFIE), and a small number of researchers have considered a time-domain magnetic field integral equation (TD-MFIE) for only two-dimensional problem. In this paper, we present a time-domain magnetic field integral equation to obtain the transient response from three-dimensional closed conducting bodies. A matrix equation is derived for both the explicit and implicit solutions. The structure to be analyzed is approximated by planar triangular surface patches.

The numerical results have been compared with those from a TD-EFIE and the inverse discrete Fourier transform (IDFT) solution of the frequency domain result. The agreement with the result from the IDFT solution calculated using EFIE and MFIE in frequency domain have been very good except for the difference in peak values of the current between the TD-EFIE and TD-MFIE. However, as the size of the patch is reduced, the agreement becomes better. The interesting point is that the time domain solution and the IDFT solution coincide with each other. Transient responses computed by the TD-MFIE have been found to be very accurate and quite stable. However, even the implicit TD-MFIE blows up if one continues the solution procedure.

A Time-Domain Surface-Integral Formulation for General Coupled Electromagnetic-Circuit Simulation

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The Partial Element Equivalent Circuit (PEEC) approach is a popular method for coupled electromagnetic-circuit simulation in both frequency and time domains. In the classical PEEC approach, volumetric filament structures are used to model directional conduction current flow within a conductor. For arbitrarily-shaped, non-orthogonal structures such as those found on systems-on-chip, including inductors and RF components, a more natural description is based on using surface-equivalent currents and a surface-integral formulation, as has been accomplished with great success for scattering problems in both the time and frequency domains.

The coupling of a surface-integral equation approach to a circuit simulator is normally carried out through S-parameter models, or through semi-infinite ports. The PEEC approach, on the other hand, uses an intuitively simple and direct connection to circuit nodes owing to the fact that all electromagnetic interactions are represented in terms of equivalent circuits which can directly be linked to circuit nodes. Time or phase-delays are accounted for by controlled sources placed between two circuit nodes.

In this work, we apply the equivalent-circuit-based coupling idea of the classical PEEC formulation for time-domain surface-integral equations. In a coupled time-domain system, the electromagnetic interactions are represented in terms of equivalent circuits, and connections to circuit equations are facilitated through modified nodal analysis. This coupled system is then reduced back to a form where it can be represented as a time-domain surface electric field integral equation coupled to modified nodal analysis in the time domain through sparse coupling matrices obtained from the connections of underlying equivalent circuits. Thus equivalent circuits are used to formulate the connections between the electromagnetic and circuit problems only.

The resulting coupled matrix system can be interpreted as both a generalized time-domain PEEC approach, as well as a coupled time-domain surface integral equation and circuit solver. The coupling mechanisms includes an inductor-based equivalent model for planar connections to a two-dimensional structure, and a continuity equation-based model for a planar facial terminal on a three-dimensional structure. The advantage of this approach is that it can be incorporated into a SPICE-like solver without altering the modified nodal analysis submatrix. Furthermore, the sparse coupling mechanism enables a variety of direct and iterative solution methods, fast matrix-vector schemes, as well as design iteration on sub-sections of the circuit schematic. Numerical examples and application include transient simulations, impedance computations, and time-domain crosstalk simulation.

Volume/Surface-Integral-Equation-Based Analysis of Transient Scattering from Periodic Perfectly Conducting Structures with Dielectric Media

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A novel scheme for analyzing transient scattering from doubly periodic, combined penetrable and perfect electrically conducting structures, is described. The proposed method relies on a novel marching on in time (MOT) scheme for solving a hybrid volume-surface time domain integral equation.

Transient scattering from doubly periodic structures traditionally has been analyzed using finite-difference time-domain methods. Efficient schemes for analyzing scattering from periodic structures should restrict the computational domain to a single cell. Within the finite difference time domain framework, this is achieved by imposing periodic and absorbing boundary conditions along directions in, and normal to, the plane of periodicity, respectively. While this approach is trouble free when a normally incident field excites the periodic structure, difficulties arise for obliquely illuminated structures because the periodic boundary conditions involve non-causal time shifts. Most fixes to this problem are either hard to implement or limited in scope.

The proposed MOT-based volume-surface time domain integral equation solver for doubly periodic structures is devoid of the problems inherent to its FDTD cousins. A classically constructed MOT solver, when applied to the analysis of obliquely illuminated doubly periodic structures, requires knowledge of time-advanced current values to solve for present ones. Our earlier work on the analysis of transient scattering from perfect electrically conducting doubly periodic structures [N.-W. Chen, B. Shanker and E. Michielssen, *Applied Computational Electromagnetics Society*, 2002, in press], resolved the issue of noncausality through the introduction of time-shifted temporal basis functions and a prolate-like extrapolation scheme for bandlimited signals [Cadzow, *IEEE Trans. ASS*, 27, 4-12, 1979]. Here, this scheme is extended to hybrid volume-surface structures, thereby enabling the simulation of realistic structures. By invoking the equivalence principle, fields scattered from dielectric bodies and conducting surfaces are modeled in terms of volume polarization and surface currents, respectively. Spatial variations of volume polarization and surface currents are approximated in terms of standard RWG and volumetric rooftop basis functions that are defined on triangles and tetrahedrons, respectively. Time-shifted cubic polynomial interpolation functions are chosen to represent temporal variations. The hybrid volume-surface integral equations are discretized using a Galerkin testing procedure. Because fields in dielectric regions are modeled in terms of polarization currents, the proposed scheme is applicable to the analysis of structures with nonplanar interfaces. Numerical results that demonstrate the accuracy and effectiveness of the proposed scheme will be presented.

Novel Modeling Techniques

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On Single Scattering Theory for Estimation of Coherent Attenuation Through Dense Foliage at Millimeter-wave Frequencies

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Abstract

A forest canopy which consists of many branches, twigs, and leaves can be considered a random medium for an electromagnetic wave. These constituents attenuate and scatter an electromagnetic field depending upon the canopy particle density, foliage moisture content, and the wave frequency and polarization. For most deciduous forest, leaves usually cluster rather densely at the end of branches, and form a lossy dielectric cover which can attenuate high microwave and millimeter-wave signals significantly. Hence for a precise prediction of wave propagation in a forest, scattering properties of leaf clusters must be investigated.

Foldy's approximation has been widely used for the calculation of mean-field in random media like a forest because of its simplicity. Foldy's formulation is based on forward scattering theorem and is valid for sparse random media, in which interactions among scatterers can be ignored. Therefore for a dense random medium like a deciduous tree, the accuracy of this formulation based on single scattering is questionable. To address this issue in this paper the accuracy of single scattering theory for estimation of field attenuation is tested by several numerical experiments. A numerical method (MoM) is used to exactly calculate the scattering from a cluster of leaves that are placed very closely, and the result is compared with a solution based on coherent sum of scattering from individual scatterers by ignoring multiple scattering. It is shown that single scattering formulation overestimates signal attenuation through a layer of closely spaced leaves.

In examining the accuracy of single scattering theory approximate analytical formulation for the calculation of scattering from a single leaf based on commonly used Rayleigh-Gans approximation is also examined. Using the MoM solution it is shown that, unless all dimensions of leaf (dielectric disk), are very small compared to the wavelength, a scattering solution based on volumetric physical optics approximation (VIPO) provides much more accurate results.

Reconstruction of Cavity Shapes Using Genetic Algorithm Combined with Gradient Search

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Genetic algorithm (GA) has been widely used as a global optimizer in electromagnetic design and inverse scattering problems. For inverse problems, GA is well suited in searching for the global optimum, but usually suffers from slow convergence. Gradient-based local search methods can quickly converge to a minimum, but the results are strongly dependent on the initial condition. In this paper, we combine the genetic algorithm with a gradient-based method to speed up the convergence rate of GA. We apply the algorithm to reconstruct the interior shapes of cavity structures that contain strong multiple scattering effects.

In the cavity inversion problem, the objective is to reconstruct the interior cavity shape from the available scattered field data collected from outside of the cavity. A cost function is defined as the difference between the scattered field from an assumed shape and the collected field data. The problem is then cast into an optimization problem to minimize the cost. In our GA-gradient procedure, in each GA iteration some members with low cost values are picked out as initial guesses and a gradient search is carried out for each of them to obtain the optimal solution. This set of optimal solutions is then placed into the GA population pool by displacing some randomly chosen members. The members from the gradient search have lower cost values and thus tend to speed up the convergence rate of GA. This iterative process is continued until the stopping criterion is met.

A two-dimensional cavity under different sensor scenarios is studied based on this hybrid GA-gradient scheme. The search space consists of N points and the cavity interior is described by the spline interpolation of these points. A method-of-moments solver is used as the forward solver. The results from the simple GA and the hybrid GA-gradient scheme are compared and analyzed. It is found that the GA-gradient scheme retains the advantage of a global optimizer while achieving a faster convergence rate than the simple GA. High-frequency ray tracing is also attempted in place of the moment method solver to reconstruct the interior structure of electrically large cavities using multiple frequency data.

A Surface-Based 3D Coupled Circuit-Electromagnetic Simulator with Accurate Lossy Conductor Modeling

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With the increase in working frequencies for mixed signal ICs to GHz range, the accurate modeling of the on-chip and package-level electromagnetic (EM) effects becomes imperative for successful single-pass chip design. The Partial Element Equivalent Circuit (PEEC) method addresses the problem of coupled EM circuit simulation by deriving equivalent circuit elements like capacitors, inductors and resistors from the EM interactions. The equivalent circuit can then be fed into a SPICE-like simulator to obtain the performance of the circuit including EM effects.

Classical PEEC uses a filament discretization, which is not necessarily efficient for accurate modeling of skin effects in arbitrarily-shaped structures. This is because at high frequencies the current tends to flow on the surface of the conductor, with the magnitude of current reducing exponentially away from the surface. Hence volumetric modeling of the current needs a finer discretization near the surface. In order to accurately model the decaying current an appropriate filament meshing is required near the surface. However the skin depth, which determines the rate of decay of the current, is frequency dependent, which in turn necessitates frequency-adaptive meshing. Such dynamic meshing is computationally expensive for frequency domain analysis. Previous surface-based attempts to solve this problem employ the surface impedance formulation (Y. Wang et. al. Proc. *IEEE Meeting on Elec. Perf. of Electron. Packaging,* pp. 233-236, Sept. 2001). However this method is accurate only at high frequencies, where cross sections are larger than twice the skin depth. Thus at relatively lower frequencies, when the current flows through the entire cross section of the conductor, surface impedance is a poor approximation to the interior lossy problem.

In this work we propose a surface based formulation for coupled circuit EM analysis with simultaneous solution of interior and exterior problems. The skin depth is modeled accurately by solving the interior problem based on the frequency-domain lossy medium Green's Function. Since this discretization is surface based, the need for dynamic volumetric meshing for different frequencies is avoided. The solution of the interior problem with the lossy medium Green's function accurately models the skin depth at all frequencies, and reduces to the surface impedance at sufficiently high frequencies.

For 3D problems, the EM structure is coupled to the circuit by enforcing electrical field integral equations for the EM part, KVL and KCL for the circuit unknowns and electrical field continuity for circuit EM coupling. The unknowns in this formulation include the surface equivalent current, and circuit quantities like voltage and current. Both circuit and electric field excitations can be modeled by proper formulation of the right hand side. The interior problem is solved using the lossy medium Green's function. For the lossy medium, the wave number is complex and thus the Green's function falls exponentially away from the excitation region. Hence instead of the normal singularity extraction procedure, which is applied for the integration of free space Green's function, an analytical singularity cancellation method is implemented for accurate modeling. Results presented at the conference will include applications of the simulator in real design problems, comparison with surface impedance formulation and impedance frequency response of lossy conductors.

ANALYSIS OF ELEMENT PHASE CENTER DISPLACEMENTS IN AN ARRAY ANTENNA

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Future phased array systems will digitize signals at the element level to achieve superior sidelobes performance, beam pointing accuracy and interference suppression. The usual assumption is that the array element patterns are identical. However, mutual coupling and edge diffraction are known to distort the element patterns. Previous work examined the effects of element pattern differences on sidelobe performance (H. Aumann, "Eigenvalue Analysis of Phased Array Element Patterns," Proc. 1994 IEEE AP-S Symposium). In this paper, we consider the effects of element phase center displacements.

The phase center location of an antenna is usually determined by a least squares fit of the phase measured in the far-field, on an antenna range, to a theoretical phase derived from the range geometry. However, many of the range geometry parameters have similar effects on the measured phase, resulting in an ambiguous phase center determination. By measuring antenna patterns on a relatively short antenna range, with the antenna offset from the center of rotation, we will show that the electrical phase center can be accurately located in three dimensions.

From the measured element patterns of a 224 element L-band phased array, element phase center locations were numerically determined. Figure 1 illustrates that the electrical locations of the elements in a phased array are measurably displaced from their physical locations. This displacement results in a systematic array beam pointing bias that can be corrected. Furthermore, the displacement is such as to make the array appear to be electrically larger. However, there is no increase in array gain, because the elements phase centers also move so as to defocus the array.

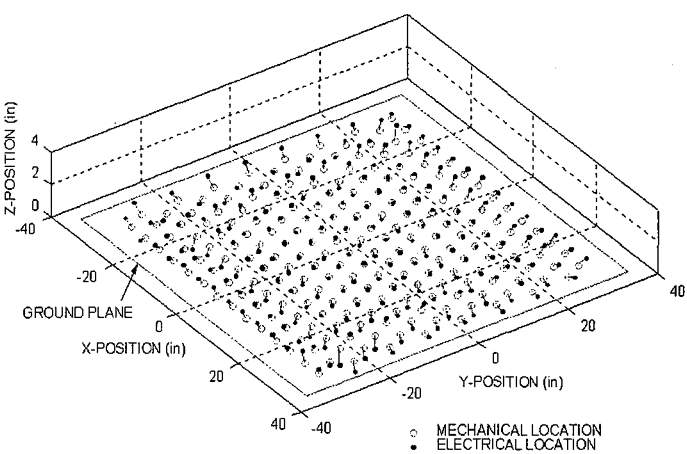

Fig. 1: Element Locations and Phase Center Displacements

One-dimensional and Two-dimensional Scattering Center Extraction Using Evolutionary Programming-based CLEAN

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One-dimensional (1-D) and two-dimensional (2-D) scattering centers have been used as important features for automatic target recognition (ATR). Therefore, many researchers have developed various scattering center extraction techniques until now. The well-known techniques are model-based methods and a FFT (fast Fourier transform)-based CLEAN method. The model-based method has the high resolution, but is not robust to random noise. The FFT-based method has the robustness, but does not have the high resolution. In this work, we propose a novel method, called evolutionary programming (EP)-based CLEAN, which has the high resolution and robustness at the same time.

The 1-D and 2-D EP-based CLEAN use the 1-D and 2-D undamped exponential models and EP for an optimization of cost function. The EP-based CLEAN algorithm has many advantages compared to conventional methods. First, it takes advantage of the FFT-based CLEAN method and model-based methods simultaneously. Second, it is very fast compared to genetic algorithm (GA)-based method (Q. Li *et. al.,* IEEE Trans. Ant. & Prop. 44, 198-207, 1996) since it extracts the parameters of each scattering center step-by-step. Third, false estimation of the number of scattering centers does not affect the accuracy of parameter extraction, as does the model-based methods. Forth, extracted parameters of the scattering centers are very accurate since it does not have a bias, as is the case with the model-based methods. Fifth, it does not require transforming of the coordinates of the measured data from polar to Cartesian in 2-D scattering center extraction.

For the verification of the proposed algorithm, we use the synthesized data composed of several ideal point scatterers. We will show the high-resolution characteristic and the robustness to random noise through simulations. We will also show the accuracy of extracted parameters comparing with the matrix enhancement and matrix pencil (MEMP) method, one of the high-resolution methods.

Analytical Modeling of Dense Arrays of Planar Dipole Scatterers

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An analytical effective boundary condition for modeling electromagnetic properties of planar regular dense arrays of dipole particles for oblique incidence of waves is developed. This is a generalization of the case for normally incident plane waves given in (S.A. Tretyakov, A.J. Viitanen, " Electromagnetic properties of periodical arrays with small nonreciprocal inclusions," Journal of Electromagn. Waves Applic., Vol. 14, pp. 1159-1177, 2000). A regular array is assumed to be dense, although the period is not necessary very small compared ot the wavelength. More precisely, the restriction is $ka < 1$, where the distance between the dipoles is denoted by a and k is the wave number. Full-wave electromagnetic interactions between the dipole particles are taken into account by the dynamic interaction constant. The expression for the interaction constant is written in analytical form for obliquely incident plane waves. For oblique incidence the equivalent model is different for perpendicular (TE) and parallel (TM) polarizations. Finally, this procedure leads to a model where the regular dense array is given as a shunt impedance, different for the two polarizations. The reflection coefficients can then be solved using the transmission-line model. As an example, the reflection and transmission for a dense array of metal circular disks are considered. In this example the equivalent model for the array impedance is capacitive. The reflection problem for a thin dense array for oblique incidence is important for studying surface waves propagating along the array and for material modeling of layered dense arrays of dipoles.

Simulation of a hybrid Geolocation Method for UMTS Location Service (LCS)

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Abstract - The location finding techniques of mobile stations can be classified into Network and Handset Based methods. In Network Based methods, receivers located at the base stations measure the timing or multipath characteristics of the uplink signals. The comparison of the uplink signals measured at the base stations yields the information to locate the mobile station. For example, if the base stations are synchronized or the timing offset is known between the base stations, the base stations can measure the time of arrival (TOA) of the uplink signals, and use three of the TOA measurements to find the location of the mobile station. In Handset Based methods, the timing or signal strength measurements are performed at the mobile station. The mobile station can measure the TOA of the downlink signals from different base stations. The mobile station can also measure the GPS (Global Positioning Sytem) signals, if it is equipped with a partial or full GPS receiver, and calculate its own position.In this paper, we will present simulation of an hybrid approach, which combines the merits of the Network Based and the Handset Based approaches. The timing from the wireless network and GPS satellites will be measured both at the base station and the mobile station.

The wireless network elements involved in a UTRAN (UMTS Terrestial Radio Access Network) geolocation system include a user equipment (UE), base stations (BSs), GPS satellites, a Radio Network Controller (RNC) and a Geolocation Server. In a typical scenario for geolocation, the timing measurements at the UE and the UTRAN are used to estimate an initial position. The UE can detect the TOA of the downlink UTRAN signals from1, 2 , 3 or more base stations, which is referred to as visibility 1, 2 or 3 at the UE, respectively. The BS measures the round trip time (RTT) from the UE. For the 1 BS visibility case, the UE's position can be calculated from the information of the RTT and the angle of arrival (AOA), estimated from the ratio of the energies of the uplink signal received at different sectors at the base station. For the case of 2 BS visibility, time difference of arrival (TDOA) information is obtained from the measurement of relative TOA of the base stations at the UE, and RTT is measured at the serving base station. For the case of 3 BS visibility, the TDOA measurements at the UE, obtained from TOA measurements from 3 base stations, can be used to calculate the UE position. If the UE is able to detect signals from more than 3 GPS satellites with adequate SNR, the UE position fix is mainly derived from GPS satellite signals. If the UE is only able to detect signals from 3 or less GPS satellites, the UTRAN signals are combined with GPS signals to get the location fix. If the UE cannot detect signals from any satellites, the UE location fix will be derived solely from UTRAN signals. The hybrid approach will offer advantages over any of the network only or handset only methods. In areas where GPS signal strength is weak, there will be extended service coverage through the combination of GPS and UTRAN signals or improved accuracy over TDOA or TOA based methods. Indoor operation will also be possible since operation is not reliant on a permanent adequate GPS link margin. Furthermore, the GPS signals will be acquired rapidly at the UE with network assistance data, which is essential for emergency applications such as E911.

MIX OF HEAT TRANSFER METHODS, EKG TRANSMISSION AND MOLECULAR EFFECTS IN AN EUNIVERSAL LINK

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In a closed-loop communication link, the received data is estimated to obtain the transmitted data as close or as soon as possible, e.g. via media equalization. In Emistical closed-loop systems as the cardiovascular system, pure red cells are circulated through arteries as does cluttered blood in veins is purified for recirculation by the heart pump. This problem (and the corresponding mathematics) is defined in this paper as stable chemical extraction from the cluttered blood for optimal retransformation to red blood cells for recirculation. Similar situations also occur in heat transfer by known conduction (analogues to electrical conduction in wires), convection and radiation (analogues to EM propagation in media), and by Emistical collidation technique [1] in the Euniverse. The body can heat up or cool down by normal body temperature fluctuations, body infections, emotional mood swings as excitement? and self-stimulation. Similar to convection heat transfer, a device is needed to transfer EM by convection and by collidation, possibly by data pulling, Emistical spontaneous oxidation [2, A. K. Gupta (1999); IEEE Information and Communication Theory Workshop, South Africa.], process media conditioning (as in air flow by fan) and/or Emistical transport of waves.

Rather than pulse wave transmission in a media, similar to pulse transmission analysis (analogues to known blood flow method) in the cardiovascular system by the author in 1973, one can analyze chemical reactions induced [2] EKG signal distortion in a multipath media from multichannel EKG reception. Previously, the EKG signal was modeled by complex exponentials in 1960's at John Hopkins University, MD. In this paper, we propose chemical reactions induced EKG waveform synthesis and transmission to analyze deterministic or ripple media effects. The problem, thus, can be defined as the synthesis of the cascade of a chemical filter and the electrical transmission filter for the analysis of the dynamic heart conditions. Similar to author proposed general multidimensional media [1], multidimensional EKG waveform split, the heart as the media traffic model and corresponding GAMA dynamics are intriguing ideas in the synthesis of no sidelobe EKG waveform [the process reasons are explained in [1] via overlap) and in closed-loop monitor of heart as variable media conditions.

Repetitive contraction of the heart muscle is analyzed in this paper by a Emistical molecular effect [E. Gupta, 4/7/1994]. 'If you are to put a heater or any heat-warming machine inside the center of the molecules, the center molecules would start to move and bump into the next circle set which would cause them to collapse or fall down. This is the domino effect. Since when molecules are cooled, they pack down for a great mass. If you were to put something cool in the center, the molecules would be the way they were before.' In other words, molecular effect is explained by forward-backward motion via expansion or contraction (and the base floor of the contraction), rather than one-way domino effect. A paper is in preparation for its application in super high-speed systems.

[1] e.g., A. K. Gupta (1998); "Super High Resolution, Novel Equalization and Arbitrary Multidimensional Pattern Synthesis," IEEE Radar Conference, Texas. Appendices.

Furtivity and masking problems in acoustic and electromagnetic scattering

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We consider "furtivity" and "masking" problems in time dependent acoustic and electromagnetic obstacle scattering. Roughly speaking a "furtivity" ("masking") problem consists in making "undetectable" ("unrecognizable") an object immersed in a medium where an acoustic or an electromagnetic wave that scatters on the object is propagating. The detection (recognition) of the obstacle must be made through the knowledge of the acoustic field or of the electromagnetic field scattered by the object when hit by the propagating wave. These problems are interesting in several application fields. We formulate a mathematical model for the "furtivity" and "masking" problems considered consisting in optimal control problems for the wave equation or for a vector wave equation. Using the Pontryagin maximum principle we show that the solution of these control problems can be characterized as the solution of a suitable exterior problem for a system of two coupled wave equations or of two coupled vector wave equations. The numerical solution of these systems involving partial differential equations in four (space, time) independent variables is a critical issue when reliable and efficient procedures to solve the furtivity or masking problem are required. High performance parallel algorithms are desirable to solve these systems. We suggest a computational method well suited for parallel computing and based on an adapted version of the operator expansion method developed by the author and some co-authors. In the acoustic case some numerical results in the form of computer animations can be found in the websites: http://www.econ.unian.it/recchioni/w6, http://www.econ.unian.it/recchioni/w8.

Scattering from a Two-Face Impedance Strip Grating Analyzed by the Method of the Dual Series Equations and Analytical Regularization

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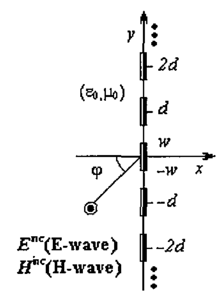

Fig.1. Geometry of the Problem

The problem of the plane wave scattering from a zero-thickness impenetrable two-face impedance flat strip grating is considered. This structure can be regarded as a model of electromagnetic wave absorbing sheet or screen made of dielectric-coated metal strips.

The problem formulation involves a set of generalized boundary conditions, relating tangential fields to effective electric and magnetic currents. The strip coating are characterized by two surface impedances $Z^{\pm}$ on their different sides. Notations can be seen in Fig.1.

Accurate numerical solution is based on the Floquet-Rayleigh field expansions, which lead to the coupled pair of the dual-series equations for the series coefficients. Further, we make an extraction and analytical inversion of the static part of the full-wave dual-series equations. This results in a rapidly convergent numerical algorithm, which has a controlled accuracy. Numerical computations have been carried out for the reflected, transmitted, and absorbed power fractions as a function of the electrical and material parameters of the grating.

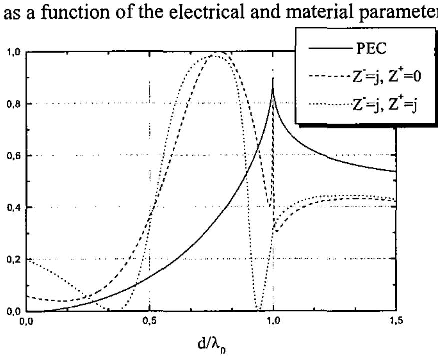

Fig.2. Frequency dependence of the reflected powers. 2w/d=0.5, $\varphi=0^0$

As an example, we present the plots of the reflected power fraction versus normalized frequency (Fig. 2). Here, we compare three identical in period and filling factor gratings illuminated by a normally incident H-polarized plane wave: PEC, single-face-coated and two-face-coated gratings. As can be seen, the presence of the lossless coating with the reactance equal to the free-space impedance changes power plots significantly. Here, the curves for the single-face and two-face coated gratings are closer to each other than to the PEC (not coated) grating curve. This indicates that coating the illuminated face of the strips plays a leading role in the modification of the wave scattering.

Planar Inverted F Antennas

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Compact Dual Band Circular PIFA With Integrated Feed Line For Wireless Applications

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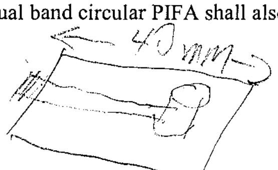
Apart from extensive utility of PIFA in commercial cellular communications, PIFA continues to find its usefulness in many other systems applications such as WLAN. In wireless RF data communications, there is a shift in the requirement from the existing single band operation to dual ISM band operation covering the (2.4-2.5/5.15-5.35) GHz range. The analytical and design studies of potential internal or external wireless antennas operating in the 5 GHz range are rather limited in open literature. The primary focus of this paper is the design of a compact dual ISM band internal PIFA with single feed. In the majority of the research papers on PIFA, the contour of the radiating element has mostly been restricted to either rectangular or square shape. In conventional microstrip antennas, circular contour is also very common for its radiating element. PIFA can possibly be considered as a class of microstrip antenna with shorting post. One of the objectives of this paper is thus to consider the radiating element of the PIFA with a circular shape also. This paper presents three different design configurations of dual ISM band circular PIFA for wireless applications.

In the first configuration of the circular PIFA design, a horse-shoe slot on the radiating element accomplishes the dual band operation. A 50 Ohm inverted micro-strip line at a position away from the center of the antenna contour feeds such a circular PIFA. The feed post and the shorting post of the PIFA as well as the bases of the horse shoe slot structure are located on a common straight line. The slot with larger arc radius, which is farther away from the feed and shorting post, has the pronounced effect of controlling the upper frequency band than the slot with smaller arc radius. A small matching stub of chosen dimensions and placed at the selective location on the circumference of the PIFA facilitates the tuning of the lower resonant band. The circular PIFA with a horse-shoe slot (r=7.5 mm, h= 7.5 mm) showed a VSWR <2.0 across the dual ISM bands. In the second design configuration, the dual frequency operation is realized using a U-shaped slot. The U-slot is designed such that the slot contour is positioned away from the center of the circular PIFA. The circular PIFA with a U-slot (r=7.5 mm, h= 7.5mm) also exhibited a VSWR < 2.0 across the dual ISM bands. In both of these PIFA designs, the radiating element and the micro-strip feed line of the PIFA are on the opposite sides of the ground plane. A conductive post suitably drawn through a via hole at the desired position connects the feed post of the PIFA and the microstrip feed line. In the last design configuration of this paper, the dual frequency response is achieved through an L-shaped open slot. Such a circular PIFA with an L-slot (r= 5 mm, h= 7.5 mm) is designed to be fed by a 50-ohm CPW line. In the last design configuration, there is no need for a via hole to connect the feed post of the PIFA with the microstrip feed line. This simplifies the fabrication process of the antenna assembly. The impedance band-width of the third design configuration of PIFA is slightly narrower with a VSWR <2.5 across the dual ISM bands. However, such a design with an L-Shaped slot also resulted in a dual band operation with a much more compact volume of the circular PIFA. The bandwidth, the radiation and the polarization characteristics of all the proposed design configurations of dual band circular PIFA shall also be presented in the paper.



3X30X12/3X43 mm GP 1.4dB gain
Stamp + S&H construction

DUAL ISM BAND PIFA FOR WIRELESS COMMUNICATION

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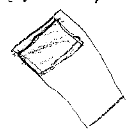
The wireless communication has witnessed a rapid progress in the recent past. The emerging technology of short range radio link (Bluetooth) and LAN system applications have lead the renewed focus of attention to ISM frequency band of 2.4- 2.5 GHz. Keeping in pace with the advancement of antenna technology of Mobile Voice communication, the ISM band RF data communication has also utilized the inherent advantages of the internal antenna. PIFA has proved to be the most widely used internal antenna for commercial wireless systems of both the Mobile Voice and RF data communications. In many research publications pertaining to the single ISM band PIFA technology, the thrust has been on optimal performance despite the miniaturization in the sizes of both the antenna and the ground plane [G.R.Kadambi et. al, URSI Symposium, 2000, Salt Lake City, pp. 224]. In view of the ever-growing demand for further expansion of personal wireless communication system, there is a gradual shift of the emphasis from the existing single ISM band operation to dual ISM band covering the frequency range of 2.4-2.5 /5.15 –5.35 GHz. This calls for the development of dual ISM band antennas for possible applications in wireless communication. There exists a continued interest and requirement for the compact dual ISM band PIFA for emerging applications of RF data wireless systems comprising Laptop and other hand held communication devices. This paper presents some of the design case studies of dual ISM band PIFA for wireless system applications. In particular, the case studies cover the design of single feed dual ISM band PIFAs with very narrow width of the order of 3 mm.

Unlike the case of PIFA for cellular applications, in Wireless RF data communication systems, there is a large degree of variations as regards to the constraints on the sizes of radiating element, ground plane as well as on the choice of preferred placement of the PIFA within the communication device. In majority of the single feed cellular dual band PIFAs, the dual frequency operation is realized by the quasi-physical partitioning of the original single band structure. The slot (straight or inclined or L shaped) on the radiating element facilitates the desired partitioning of the PIFA structure. When the system requirements impose stringent restrictions on the allowable width of the radiator/ground plane (of the order of 3 mm), the conventional dual band PIFA design invoking hitherto proven slot technique can not be applied. Alternate techniques of realizing a dual ISM band performance without the conventional slot techniques are of immense help to overcome the seemingly common constraint on narrow linear dimensions of PIFA. Invoking the concept of parasitic element, this paper presents the design of Dual ISM band PIFAs devoid of a slot on its radiating element. The primary role of the parasitic element in the presented design of this paper is mainly to control the resonant frequency and the bandwidth characteristics of a particular resonant band of the dual ISM frequency of operation. The location, the size (height and width) and the relative orientation of the parasitic with respect to the radiating element control the tuning performance of the parasitic element. This paper demonstrates the implementation of the proposed concept of parasitic element in the successful design of dual ISM band PIFAs of varying sizes. All the design case studies of this paper deal with an identical width for both the radiating element and the ground plane. This paper also presents a feasibility of applying the slot technique in the design of compact dual ISM band PIFA (17X9X8mm) on a ground plane of 22X9 mm. The bandwidth and the gain characteristics of Dual ISM band PIFA design case studies are also dealt in this paper.

Three narrow bands PIFA similar to previous paper - stamp and fold.



SINGLE FEED MULTI BAND PIFA FOR CELLULAR AND NON CELLULAR APPLICATIONS

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With the rapid progress of the Cellular Communication Technology and the ever increasing demand for multi systems application, there is a growing trend towards the design of Multi purpose Cellular Handset. Of late, there is also an enhanced thrust for internal Cellular antennas to harness its inherent advantages. PIFA has proved to be the most widely used internal antenna in commercial applications of cellular communication. In most of the research publications/ patents on multiband PIFA technology, the major success has been the design of a single feed PIFA with Dual Resonant Frequencies resulting essentially a Dual Band PIFA. Depending upon the achievable bandwidth around the resonant frequencies, the dual resonant PIFA can potentially cover more than 2 bands. However, system applications such as GPS and Bluetooth or IEEE 802.11 have frequency bands that are significantly off from the cellular bands (AMPS/GSM, DCS/PCS). Enhancing the bandwidth of Cellular Dual Band PIFA to additionally cover the GPS/Bluetooth applications can prove to be a very difficult task. As a result, a practical recourse to design a single feed Tri band PIFA that covers both the Cellular and Non Cellular bands lies in the realization of **three** distinct resonant frequencies at the respective bands and to achieve the requisite bandwidths centered around the resonant frequencies of interest. In this paper, a new method for the design of a single feed Multiband PIFA operating in the Cellular and Non Cellular Bands (GPS/Bluetooth) is presented. Such a PIFA design falls into the Multiband Category.

In the proposed scheme, the resonant frequencies of the Cellular bands are generated via the design technique of conventional Dual Band PIFA [G.Kadambi et.al, URSI Symposium, 2000, Salt Lake City, pp. 221]. The third distinct resonant frequency of the non Cellular band (GPS or Bluetooth), which is distinctly **far off** from the Cellular bands, is generated by the shorted parasitic element placed in between the radiating element of the PIFA and the ground plane. The size, the position of the parasitic element as well its separation distance from the radiating element of the PIFA primarily determine the resonant frequency of the Non Cellular Band. Because of the close proximity of the parasitic element to the radiating element, the design of such a multi (Tri) band PIFA involves the optimization of the coupling to generate the desired multiple (more than two) resonant frequencies as well as the bandwidth centered around them. In conventional designs of Microstrip antenna with a parasitic element or a PIFA with a parasitic element, the parasitic element is usually placed adjacent to the radiating element resulting in the increase of the linear dimension of the antenna. Further, in most of the reported designs of planar antennas, the parasitic elements are primarily employed to improve the bandwidth of the antenna. In this paper, the placement of parasitic element in between the radiating element and the ground plane results in neither the increased volume nor the increased linear dimensions thus accomplishing the compactness of the multiband PIFA structure. This clearly is a distinct advantage of the design proposed in this paper. The simultaneous realization of multiple resonant frequencies at Cellular and Non Cellular Bands of a single feed PIFA with parasitic element seems to have not been reported in the open literature. The proposed concept of internal parasitic element of this paper has been successfully implemented in the design of AMPS/PCS/GPS band and GSM/DCS/ISM band PIFAs. The single feed Multiband (Cellular and Non Cellular bands) PIFA designs based on the proposed concept of internal parasitic element exhibit satisfactory gain and reasonable bandwidth at the respective bands of interest. It is inferred that the new design technique of single feed Multiband PIFA proposed in this paper is likely to find useful applications in Mobile communication.

Mobile Antennas, Devices, and Processing

Co-Chairs: *P. Kabacik, Wroclaw University of Technology, Poland*
H. Foltz, University of Texas Pan American, USA

Estimating DOA by Exploiting Cyclostationarity Based on a D^3 Approach

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ABSTRACT

In an adaptive process, the goal is to extract the signal of interest (SOI) embedded in other interfering signals and noise. Generally, this adaptive process is carried out by using the available information on the direction of arrival (DOA) of the SOI. This is true for RADAR applications where that information is available, as we know apriori to which direction a beam was transmitted. However, in a mobile communication when the information about the DOA of the SOI is not available, the problem is then how to implement an adaptive process. However, to implement an adaptive process we first need to estimate the DOA of SOI. Hence, we propose to use the concept of cyclostationarity to achieve that goal. The term cyclostationarity implies that the signal displays characteristic spectral properties and this property is shared by almost all man made communication signals. The novelty of this paper is that we implement a direct data domain approach to carry out the DOA estimation exploiting cyclostaionarity. Thus we avoid the formation of a covariance matrix, which is always problematical when we have short data lengths or the environment is quite dynamic. In this paper we consider the problem of estimating the DOA for the SOI embedded in noise and other interfering signals whose characteristics are unknown. The DOA of the SOI may coincide with the DOA of one of the interferers. In this approach, the various signals impinging on the array can have different carrier frequencies, which are unknown. In the proposed algorithm, while the estimation of the cyclic array covariance matrix is avoided, we develop a new matrix form using extremely short data samples. As a result, the computational load in the proposed approach is relatively reduced and the robustness of the estimation of SOI is significantly improved when the number of available snapshots is extremely limited. Numerical results are presented to illustrate the efficiency and accuracy of this method.

COST- AND TIME-EFFICIENT AND ACCURATE MEASUREMENTS OF ACTUAL AND EFFECTIVE DIVERSITY GAINS OF WIRELESS TERMINALS IN SMALL REVERBERATION CHAMBER

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The performance of mobile and wireless terminals can be significantly improved by making use of two separate antennas for spatial, polarization or pattern diversity by combining the signals from them in an optimum way. Diversity studies are normally done by moving antennas and equipment around in an urban or indoor environment, which is expensive both in terms of cost and time. In addition, the results may not be repeatable in other environments. We will in the present paper describe how to measure diversity gain in a small reverberation chamber, without the need of moving neither the phone nor the measurement equipment away from the laboratory. We have previously shown that radiation efficiency and total radiated power can be measured efficiently in such chambers, see www.bluetest.se.

Published recent measurements of diversity gain do not agree well with theoretical formulas for simple reference cases such as two parallel halfwave dipoles. From our measurements we have found that this is caused by the reduced efficiency of the dipoles, due to the mutual coupling between them. Each of the two dipoles will have a reduced efficiency due to the power absorbed in the neighboring dipole. We have defined an **effective diversity gain** relative to a single lossless reference antenna. The measured effective diversity gain turns out to be very close to the theoretical maximum calculated without considering neither efficiency nor mutual coupling. Thus, the physical limitations due to reduced efficiency and coupling through the radiation patterns are strongly related, which we know also from other types of antennas.

In real situations, such as the antenna of a phone when the phone is in talk position close to the head, the efficient diversity gain will not be representative as a measure of the quality of the diversity antenna. In such cases the improvements are better characterized in terms of the diversity gain relative to a single lossless reference antenna in the same position relative to the head. We refer to this as the **actual diversity gain** in the talk position. This diversity gain will be significant, even if the effective diversity gain is low, because we cannot avoid some losses in the head and therefore have included these in the reference case. The radiation efficiency of the reference antenna is reduced due to the losses in the head. Measured results show that two parallel dipoles can be located significantly closer when they are close to the head than in free space, and still obtain a significant diversity gain.

In the presentation we will show experimental results for two parallel dipoles in free space and in position close to a head phantom, all measured in a small reverberation chamber of 0.8m x 1m x 1.6m size. We will even show theoretical results for the effective diversity gain of two dipoles in free space. This has been calculated from the equivalent circuit of two parallel dipoles including mismatch and mutual coupling. Such results have not been presented previously. The agreement with measurements is striking.

A Transmission-Line Matrix Model for Smart Antenna

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An electromagnetic modeling system based on the Transmission Line Matrix (TLM) method has been introduced in this article to predict the performance of adaptive antenna . Unlike some other numerical techniques, the TLM algorithm does not involve any convergence criteria, a property that makes it an inherently stable method. This stability is reflected in the flexibility of the TLM method to deal with various types of input signals. This ability will be explored in this paper by changing the input excitation such that a required field pattern is obtained at a given point in time.

Beam steering capability is introduced in model by properly weighting the input of each array element. The results given by proposed model are compared with the analytical relationships that exist in literature for dipole arrays An adaptive procedure to change the inputs of the model in order to track the source of maximum power received based on the Lagrange's formula is added to the model. The response of numeric adaptive antenna model to changes of the parameters of the propagation medium (ε,μ) is investigated. A multi-layered structure is tested and scattering by different shaped reflectors is studied

A comparison between numerical results and experimental data in similar configurations is provided to validate the model.

Antennas Isolation for Wireless Communications Devices.

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Abstract:

Cellphone, laptop or hand held computer manufacturers are implementing wireless capability inside their products. Aesthetics and mechanical needs are forcing them to use internal antennas. Antennas embedded inside an enclosure have to be optimized in order to limit the interaction with their surroundings.

The antenna isolation is therefore a very important feature for new wireless communications system. The isolation can be analyzed at different levels. The first one corresponds to the antenna and system performance level. In this case, either the antenna or the overall system efficiency can be measured respectively by measuring the radiation pattern or the bit rate. Even if this solution is very demonstrative, it does not give any information on the potential antenna isolation improvement. A more accurate solution consists in doing implementation tests where the electromagnetic parameters of the antenna (return loss and efficiency) are analyzed when the antenna surroundings are changed. Finally, the antenna isolation can be analyzed in a very precise way by simulating or measuring (Hindman, G., *Anechoic Diagnostic Imaging,* AMTA Symposium, Antenna Measurement Techniques Association, Columbus, OH, 1992.) the current distributions due to the antenna radiated near field.

One benefit of the isolation is to improve the antenna efficiency, when implemented inside a handheld device. Here we study two kinds of antenna, respectfully poorly and highly isolated. Results in terms of performances are shown in Fig.1 in which we see that the non isolated antenna radiation pattern (red) is more affected. Fig.2 shows the current distributions. It is clear that the current of the non isolated antenna (2.a) is a lot less confined than in the highly isolated case (2.b). Globally, the isolation improvement has shown an efficiency increase that permits to improve the global link by 3dB. Several experiments and simulations (Ansoft, Ensemble, V8.0) will be described during the conference.

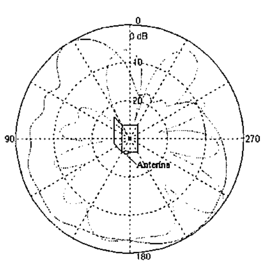

Fig.1: Isolated (blue) and none-isolated (red) antenna radiation pattern mounted on a laptop

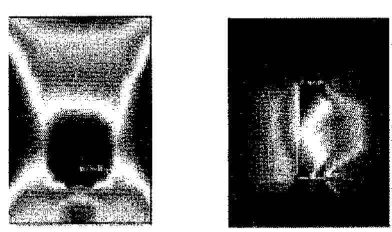

Fig.2: Current distribution showing the antenna isolation,
- on the left, for a PIFA with very low isolation and a lot of current on the edges.
- on the right, for an Ethertronics antenna with very little current on the edges.

COMPARISON OF SWITCHING DECISION METHODS FOR MOBILE SPATIAL AND PATTERN DIVERSITY ANTENNAS

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Beam forming smart antenna systems for base station usage can use multiple receiver front ends combined with complex signal processing to obtain mitigation of fading and interference. However, at the mobile end of a communications link, power, size, and cost considerations often make simpler schemes such as switching diversity with a single receiver desirable. The antennas used may provide spatial or pattern diversity, or a combination of the two. In such systems the switching decision must be made without direct knowledge of the signal levels in the other diversity antenna channels. The problem is further complicated in packetized data systems, where it is desirable to be able to schedule packets ahead of time, and avoid switching in the middle of a packet.

There is significant work in the literature on single-channel prediction techniques for small-scale fading, with prediction times of 10 ms or better at vehicular speed. Some techniques are based on direct application of linear prediction techniques while others attempt to extract and then recombine the multipath components. By incorporating these techniques into the switching decision one can not only predict signal strength for the current antenna but possibly obtain an estimate of that in the other antenna channels). Direct linear prediction techniques have some benefit for spatial diversity antennas displaced along the line of motion; however, techniques which estimate the multipath components allow one to sum the field at points on and off the path of motion, thus allowing the possibility of estimating strength for pattern diversity and for spatial diversity with antenna displacement transverse to the direction of travel.

In this work, we will compare the effectiveness of existing algorithms for single-channel prediction as applied to selecting switch times and channels, for both measured and simulated data at 1.9 and 2.45 GHz. In the measured data, three and four element spatial (omnidirectional) and pattern (sector beam) diversity arrays were rapidly multiplexed with a narrowband receiver to provide essentially simultaneous data for all channels. Thus each algorithm can be compared to the known optimum with respect to (1) average signal level, (2) fade distribution, and (3) accuracy in next antenna selection. Also, we can look at the performance drop-off with increasing prediction lead time, and with decreasing baseline data length, which is critical in packetized systems. In the simulated data, we can also examine the case of wideband data, where some of the benefits of spatial diversity are obviated, but pattern diversity is expected to still yield significant gains by concentrating the available gain on the strongest multipath components.

Modeling Antennas on Automotive Vehicles at VHF and Lower Frequencies

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This paper discusses the modeling of antennas on automotive vehicles at VHF and lower frequencies. Intelligent Transportation Systems are planning to broadcast information to automotive vehicles in the FM broadcast band (88 to 108 MHz). Some public safety communication systems use some VHF (162 to 174 MHz) and lower frequencies . The military uses the SINCGARS communication system in the 30 to 88 MHz frequency band, and also uses the HF frequency band of 2 to 30 MHz for other communication systems. An antenna on a vehicle in a roadway environment does not behave as if it were in free space or over a perfectly conducting ground plane. Accurate antenna modeling is necessary to determine the elevation and azimuth gain variability for prediction of the actual gain to be used in launching the electromagnetic wave at the appropriate elevation angles. The gain of the antenna is a function of the antenna geometry, materials used, antenna height above ground, ground conductivity, ground dielectric constant, frequency, elevation angle, and azimuth angle. The performance of an antenna near or on the surface of the Earth is very dependent on the interaction with the lossy Earth and the automotive vehicle. The Numerical Electromagnetics Code (NEC-4) was used to model these antennas with method-of-moments techniques. Conventional methods involving the use of free-space antenna gain performance for the antennas could not be used here due to the close proximity of the antennas with respect to a lossy Earth and the metallic automotive vehicle. Investigation results show that depending on the relative geometry of the communication scenario, differences between free-space antenna gain and the actual gain can be on the order of 8 to 20 dB for a typical antenna and vehicle over real Earth. These lower gains occur at the low elevation angles (less than 3 degrees) typical of a scenario involving a geometry for broadcasting to a vehicle, or for two-way communications between vehicles, or between vehicles and the roadside. By including the correct antenna gain in the propagation loss predictions, a good agreement with measurements was obtained. Some of the results will be presented here with correlation to measurements. This antenna analysis work was originally performed to supplement a measurement and prediction of coverage study that determined the service area of an FM Subcarrier Broadcast System. Recently, the antenna analysis was expanded to cover other frequency bands of interest above and below the FM broadcast band, where antennas would be used on automotive vehicles.

RF Performance Characteristics of a 4.6 m, shaped dual-offset, C-/X-/Ku-Band, low PIMP mobile antenna system

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This paper presents the RF performance characteristics of a unique mobile reflector antenna design: a 4.6 m, dual-offset shaped, C-, X-, and Ku-Band antenna with low passive inter-modulation product (PIMP) characteristics in X-Band operations. In this presentation, two topics are addressed in greater detail, namely (a) to compare measured versus simulated gain performance improvement due to a dual-offset shaped reflector optics and (b) to exhibit the low PIMP antenna design and performance of this mobile antenna system.

To achieve a higher gain performance in the same available surface area, a shaped dual reflector antenna was pursued. The measured gain performance improvement based on this dual-shaped offset reflector surface versus a purely Gregorian surface is presented. For all three frequency bands, stretching in total from 3.625 GHz to 14.5 GHz, simulated gain values are compared to measured gain values based on the pattern integration method. Additionally, measurements of the G/T performance using the sky noise method are presented to detail the figure-of-merit of this antenna system.

For an antenna of this size to become mobile and meet the dimensional requirements for transport, it was necessary to fold the main reflector into a stow position. This reduction in size was accomplished by dividing the main reflector into three tiers and folding the outer panels into the middle panel. In order for this antenna system to have low PIMP characteristics, the folding mechanism (hinges, locking mechanism, ...) had to be especially designed to avoid non-linearities in its RF path. Some aspects of this design, the measurement procedure of the low PIMP characteristics, and representative results are presented in detail in the second part of this presentation.

TCAD of Mobile Phones: Guidelines for MTE Design using FDTD

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Introduction

The last two decades have shown tremendous growth within the MTE sector. Additional increasing consumer demand for attractive performance/price ratios as well as international mandatory safety guidelines addressing RF related possible health effects confront engineers with the development of highly efficient devices. The use of numerical simulation techniques and the FDTD method in particular have been chosen by many research institutions in order to efficiently support product R&D processes. However, applications to real-world engineering needs are often restrained by limited FDTD grid resolution and poorly implemented graphical user interfaces.

Objective

The objective of this study was to evaluate the suitability of FDTD based simulation tools for supporting RF engineers in the design of mobile phones. This poses the clear demand to simulate not only the outer shape of the device, but all embedded electromechanical components which are RF relevant and moreover require resolutions down to $100\,\mu$m or less.

Methods

The study was performed using one of the latest commercially available multi-band mobile phones, observing the two main bands, namely GSM and DCS. Simulations were conducted by application of the FDTD based platform SEMCAD (SPEAG, Zurich, Switzerland, www.semcad.com) which provides a 3-D ACIS based solid modeling environment, further enhanced by a local refinement scheme (Chavannes N., et al., IEEE Trans. on MTT, submitted, 2002) and combined with semi-automated non-homogeneous grid generation. The detailed CAD dataset of the phone consisted of about 40 distinguished main electromechanical parts, moreover the PCB was modeled by 5 PEC/dielectric layers interconnected using more than 50 vias. The application of combined graded mesh subgridding enabled FDTD grid resolutions of $100\,\mu$m (helix antenna, PCB) embedded within computational domains extended by 0.5 m. All measurements were conducted with the near-field scanning system DASY4 which is the forth generation of the system described in (Schmid T., et al., IEEE Trans on MTT, 44, 105-113, 1996) and equipped with the latest probes providing the required isotropy, sensitivity and spatial resolution.

Results

The numerical and experimental characterization was conducted in free space and with various dielectric loads (flat phantom, SAM standard phantom, anatomical human head), whereby different parameters were evaluated such as impedance, efficiency, far-fields, as well as near-field distributions of E- and H-fields and the SAR. Good to excellent agreement between measurement and simulation was obtained for all examined parameters. An initial investigation of the multiband antenna itself lead to small deviations in gain and resonance frequencies ($\approx$1%). For the averaged SAR, deviations from measurements smaller than 10% were obtained. In addition, mechanical design issues which show a significant influence on the EM field behavior could be predicted by simulations and were experimentally reproduced.

Discussion

The obtained accurate prediction of all essential performance parameters by straightforward simulations suggests that state-of-the-art software packages are suitable for device design in industrial R&D environments with hardly any limitations, provided the availability of excellent and flexible user interfaces and the applicability of graded meshes combined with robust subgrids.

Dielectric Embedded Switched Active and Switched Parasitic Antenna for 2.4GHz ISM SDMA Applications

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Space Division Multiple Access (SDMA) technology is becoming more important in mobile radio environments where the probability of a strong interferer is high, especially in the unlicensed ISM bands. Coupled with the recent increase in use of WLAN's, Bluetooth and other applications, there is a growing need for small directional antennas for WLAN terminals and basestations.

Small directional monopole arrays with a large groundplanes were analysed by Lu et al. (J. W. Lu, D. V. Thiel, B. Hanna and S. Saario, Electronics Letters, 5th July, 871-872, 2001). Significant directionality and good return loss were obtained for these antennas, however, the requirement for a large groundplane makes the application of these antennas impracticable.

Our work in this paper focuses on the design of these antennas for practical applications with the removal of the large groundplane as a primary objective. The structure that we propose is a Dielectric Embedded Switched Active Switched Parasitic Antenna (DE-SASPA) antenna with an approximately quarter-wave metal skirt below the dielectric block. This allows the antenna to operate effectively as an asymmetrically balanced antenna structure.

A full-wave numerical analysis of a nine-element DE-SASPA with a metal skirt was performed using the FDTD method with PML boundary conditions. The physical dimensions for the DE-SASPA from Lu's paper were applied in defining the dielectric embedded component of the antenna. The antenna was placed on a small groundplane of radius equal to that of the dielectric cylinder. A vertically oriented, 30-mm-long metal skirt was connected to the outer edge of the groundplane on the opposite side of the antenna.

The broadband impedance of the antenna was calculated from the current and voltage ratio at the base of the feeding element. From this, the return loss for the antenna was calculated to be -10.3dB at 2.45GHz. The radiation pattern was calculated in the elevation and azimuthal planes using a frequency domain near-to-far field transformation. At an elevation of 10 degrees, the antenna had maximum gain with a beamwidth of 138 degrees. The inclination of the beam being could be controlled by varying the length of the skirt. The azimuthal plane front-to-back (FB) ratio was 11dB.

The addition of a RG-402 feed cable through to the base of the antenna had no appreciable effects on return loss or radition patterns.

These initial numerical results and insensitivity to feed-cables indicate that this structure is a promising candidate for SDMA base, or mobile terminal applications.

RADIATION PATTERN OF CELL PHONE ANTENNAS USING NEUROCOMPUTING

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ABSTRACT: A new method of using Artificial Neural Networks (ANNNs) for the accurate determination of radiation pattern of cellular telephone antennas has been adopted in this paper. The results using ANNs are compared with the experimental findings and simulated results. The ANNs results are more in agreement with the experimental findings.

The current focus on electronics packaging and interconnects in wireless technology has led to design of efficient, wide band, low cost, low SAR and small volume antennas which can readily be incorporated into a broad spectrum of systems. The calculation of radiation pattern of these antennas in the presence of telephone handset, human head and hand are challenging and emerging areas of research. The radiation pattern of an isolated antenna gets severely affected in the presence of cell-phone body, human head and hand. Methods such as FDTD etc. have been used and are in use to simulate the radiation patterns of these antennas. However, the simulations techniques are still suffer deviations from experimental values and at the same time involve large computational time. In the present paper, an attempt has been made to explore the ability and adaptability to learn, generalizability small information requirement, fast real time operation and ease of implementation features of ANNs to simulate the radiation patterns of these cell phone antennas in free space and in the presence of human head. 130 patterns have been taken for training and 50 patterns have been tested to see the accuracy. The testing time is less than a second for all the patterns where as the training time is below 8 minutes in P-III (853 MHz) HP Brio Pc. The average error is less than 1% in both the cases(i.e. in free space and in the presence of head).

Application of ANNs for the determination of radiation pattern of cellular telephone antennas is a simple, inexpensive and accurate method having a very good agreement with the experimental findings.

Acknowledgement: Thanks are due to MHRD. Govt. of India for sponsoring the Project.

Direction Finding, Multipath, and Smart Antennas

Co-Chairs: *J. Grimm, Nokia, USA*
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Efficient Ray-tracing Propagation Prediction Methods for Indoor Wireless Communications

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Abstract

Indoor wireless communication such as personal communications (PCs) and wireless local area networks (LANs) are exploding rapidly. Radio propagation prediction for indoor environments has become an important research topic. The ray-tracing technique has been used widely to predict radio propagation in indoor environments.
In this paper, the application of several ray-tracing techniques in combination with the uniform theory of diffraction is presented, for efficient prediction of propagation in the UHF (communication) band in an indoor environment. The process of ray-tracing is a complicated program of recursion. In the 3D model, there are so many rays that need to be traced. But in fact there are only a few rays that will reach the receiver. It is advantageous to sift out the rays that will probably reach the receiver for tracing. Firstly, we improve the computational efficiency of the two-dimensional (2D) ray-tracing method by reorganizing the objects in an indoor environment into irregular cells. The result indicates that our irregular cell method can save almost 60% of CPU time on the average over to traditional methods and the accuracy of prediction does not degrade. Secondly, by making use of the 2D ray-tracing results, a new three-dimensional (3D) propagation prediction model is developed, which can save 99% of the computation time of traditional 3D model. This new hybrid model is more accurate than 2D model and more efficient than traditional 3D model in computing the path loss to any point in the building. In this model, reflection and refraction by layered materials and diffraction for the corners of the wall are considered. A patched-wall model is used to improve the accuracy of prediction in the method. Finally, comparison between simulation and measurement shows a good agreement.

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