A CLOSELY SPACED WAVEGUIDE PHASED ARRAY INTEGRATED WITH A FREQUENCY SELECTIVE SURFACE. MODELING AND DESIGN.

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1. Introduction

Frequency Selective Surfaces (FSS) are two-dimensional arrays of patch or aperture elements, showing a particular filtering behavior. Historically FSS have been designed as standing alone elements and, just in a second phase, associated to the antenna [1]. However, the stringent constraints in terms of low Radar Cross Section (RCS), Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) in phased array antenna development for military applications lead to a structural integration of the antenna with the platform itself. Moreover, the design of efficient multiple beam antennas for multimedia and broadband space applications requires the capability of modeling the presence of spatial filters and polarization or frequency selective structures at the array aperture. Therefore, the traditional approach, based on independent design of the FSS and the antenna, is not always appropriate. The implementation of the Integrated Antenna Design concept becomes an essential requirement for an efficient production process. Moreover, combining different FSSs, having different frequency and angle selectivity properties, in order to obtain a particular filtering behavior, gives one more degree of freedom in the design of the multilayer array structure.

A very general and flexible tool has been developed, that gives the possibility of designing structures integrated with the array antenna, having an arbitrary number of dielectric layers and FSSs with different layouts, as well as tuning/matching elements in the waveguide feed [2], [3]. This paper illustrates the theoretical formulation of the problem and the design of an array of dielectric loaded open-ended waveguides integrated with a patch based frequency selective surface. The results obtained with our tool are compared with the ones of commercial tools. Measurements with a waveguide simulator will be used as further validation.

2. Theoretical formulation

The structure under analysis is an infinite array of patches on a dielectric slab placed on the top of a phased array of open-ended waveguides (Fig. 1). The analysis of such a structure is based on a Multimode Equivalent Network (MEN) approach [2], [3], which allows an efficient representation of the FSS structure coupled to an equivalent representation of the waveguide array. A review of the theoretical formulation for the derivation of the FSS equivalent network is presented hereafter.

The infinite array Green's function for the tangent electric field (z= 0) can be expressed as a superposition of Floquet's modes:

$$\mathbf{G}^{et}(x,y;x',y') = \sum_{i=1}^{\infty} Z_i \mathbf{e}_i(x,y)\mathbf{e}_i^{*}(x',y') = \sum_{i=1}^{\infty} \mathbf{G}_i(x,y;x',y') \tag{1}$$

For the purpose of deriving an equivalent network representation of the patch transition, we separate the Floquet's modes in accessible and not accessible (or localized) modes.

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This concept was already used in [2], [3]. The accessible modes are lower order modes, propagating or below cut-off, which reach the next discontinuity and are therefore responsible for the energy exchange. The localized modes are higher order modes, below cut-off and with high attenuation constant, which do not reach the next junction. We can now introduce the definition of the "not-accessible-part" of the Green's function, as the difference between the total Green's function and the part due to the accessible modes:

$$\mathbf{G}_{\mathbf{na}}^{et}(x,y;x',y') = \mathbf{G}^{et}(x,y;x',y') - \sum_{i=1}^{Nacc} \mathbf{G}_i(x,y;x',y') \tag{2}$$

The boundary condition to be imposed is the vanishing of the total tangent electric field on the patch. This field can be written as linear combination of localized and accessible Floquet's modes. In particular, the electric field associated to the non accessible modes can be expressed as a function of the equivalent current distribution on the patch $\boldsymbol{J}(x,y)$ and the non accessible part of the Green's function $\boldsymbol{G}^{na}(x,y;x',y')$ as defined in (2):

$$\mathbf{E}t = \mathbf{E_a} + \mathbf{E_{na}} = 0 \Rightarrow \sum_{i=1}^{Nacc} V_i \mathbf{e}_i(x,y) = -\mathbf{E_{na}} = -\int_{Patch} \mathbf{G}_{\mathbf{na}}^{et}(x,y;x',y') \cdot \mathbf{J}(x',y')dx'dy' \tag{3}$$

We introduce now a non conventional representation of the equivalent electric current density on the patch $\boldsymbol{J}$, in terms of unknown modal currents on the two sides of the patch $\boldsymbol{J}_i^d(x,y)$, weighted by the modal voltage amplitudes V_i of the accessible modes:

$$\mathbf{J}(x,y) = \sum_{i=1}^{Nacc} V_i \mathbf{J}_i^d(x,y) = \sum_{i=1}^{Nacc} V_i \left(\mathbf{J}_i^1(x,y) - \mathbf{J}_i^2(x,y)\right) \forall x,y \in \mathit{patch} \tag{4}$$

Substituting (4) in (3) and then equating similar addend terms, we obtain the final set of N_{acc} integral equations (IE):

$$\mathbf{e}_i(x,y) = -\int_{Patch} \mathbf{G}_{\mathbf{na}}^{et}(x,y;x',y') \cdot \mathbf{J}_i^d(x',y')dx'dy' \quad \forall\, x,y \in \mathit{patch} \tag{5}$$

The kernel of this IE consists of the non accessible spectral components of the Green's function (reduced kernel), while the unknowns $\boldsymbol{J}^d{}_i$, obtained for each different forcing term, are the currents associated by this kernel to the patch.

Finally, in order to derive an equivalent network representation of the FSS to be connected to the equivalent network of the array (Fig. 2a), we can write the relation between the magnetic field discontinuity and the equivalent current distribution on the patch. Representing the total tangent magnetic field on the two sides of the patch as a linear combination of Floquet's modes and using the expansion (4) for the equivalent electric current, we obtain

$$\left(\mathbf{H}_{t1} - \mathbf{H}_{tn}\right) = -\mathbf{n} \times \mathbf{J}_s \Rightarrow \left(I_i^1 - I_i^2\right) = \sum_{j=1}^{N} Vj \int_{Patch} \mathbf{J}_j^d \cdot \mathbf{e}_i{}^* \qquad \forall\, i = 1..N \tag{6}$$

Equation (6) directly provides the expression for the multimode admittance matrix:

$$Y_{ij} = \int_{Patch} \mathbf{J}_j^d \cdot \mathbf{e}_i^* \quad \forall\, i = 1..N \tag{7}$$

3. Integrated antenna design

The above mentioned approach has been applied to the design of an open-ended waveguide phased array integrated with a patch based FSS. Although an extensive research has been done about Frequency Selective Surfaces [1], the problem of the integration of a generic array antenna with a multilayer FSS has never been addressed in a systematic way and few scientific papers are available in literature [4]. At TNO Physics and Electronics Laboratory we designed an antenna system, which is presently being manufactured, in order to validate our tool in its most important and distinctive feature, that is the capability of analyzing a generic waveguide array integrated with a multilayer frequency selective structure.

The array, operating at X band, consists of open-ended waveguides 8 x 8 mm filled with a dielectric of permittivity 8 and distributed in a triangular lattice of 10 by 10 elements. The filling of the radiating elements with a dense dielectric allows reducing the size of the element itself and the inter-element distance, resulting in a very compact configuration and in a large scanning area. On the other side, this configuration requires the design of an appropriate iris, 4.72 mm long, 1.5 mm wide and 0.5 mm thick, filled with the same dielectric of the radiating element and a dielectric-matching layer of permittivity 12 and thickness 2.54 mm. This structure has been cascaded with a dipole based FSS printed on foam of dielectric constant 1.08. Each dipole is 8 mm long and 1 mm wide.

These different elements can be modeled using the same tool thanks to the flexibility of the MEN approach. In particular, the single parts (array antenna and FSS) can be first analyzed and designed separately and then integrated for a final accurate design, which can account and optimize the effects of the mutual interactions.

As first validation, Fig.3 shows the reflection coefficient of the waveguide simulator predicted using our tool compared with the result obtained with HFSS. An experimental validation of the design will be performed using a waveguide simulator for the case of rectangular lattice and afterwards a complete array panel of 100 radiating elements will be manufactured and measured. A comparison between the experimental data and the theoretical design together with some design considerations will be presented at the conference. The geometry of the simulated array is illustrated in Fig.1. A side view of the waveguide simulator is shown in Fig. 2b. The dimensions of the unit cell are the ones of the waveguide housing the multilayer FSS in the waveguide simulator, a standard WR90.

4. Conclusions

In this paper the mathematical formulation for patch FSS integrated with a waveguide array has been presented. This formulation has been implemented in a tool that is able to analyze various configurations of FSS integrated antennas, both screen or patch based, having arbitrary layout and element shape and different periodicity for the FSSs and the array. An experimental validation of the theoretical results will be presented at the conference.

5. References

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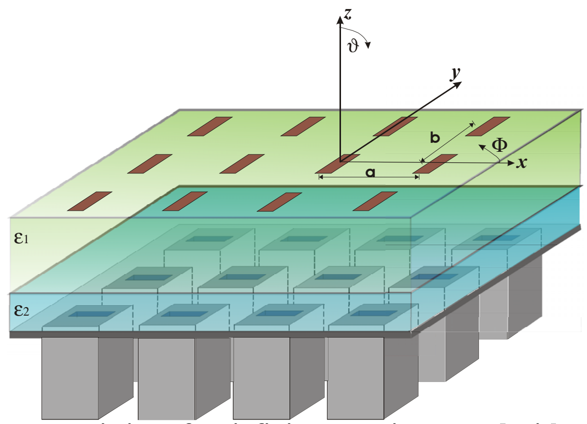
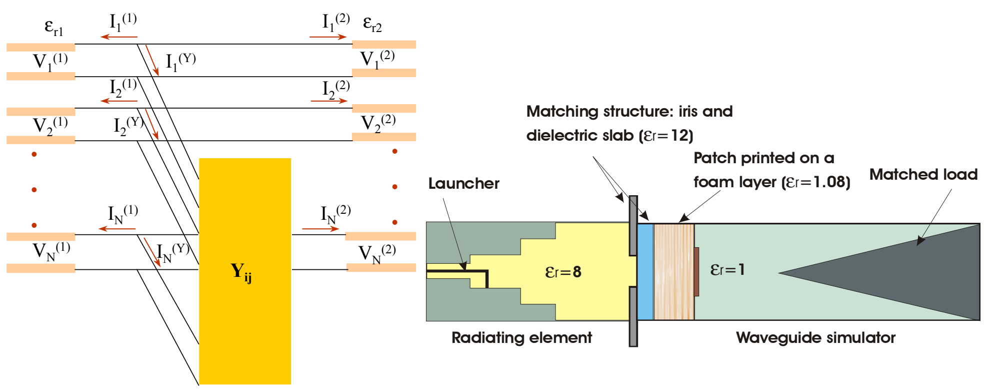


Fig.1 Array structure consisting of an infinite array integrated with a multilayer FSS



(a) (b)

Fig.2 (a) Multimode Equivalent Network for a patch based FSS.
(b) Side view of the waveguide simulator

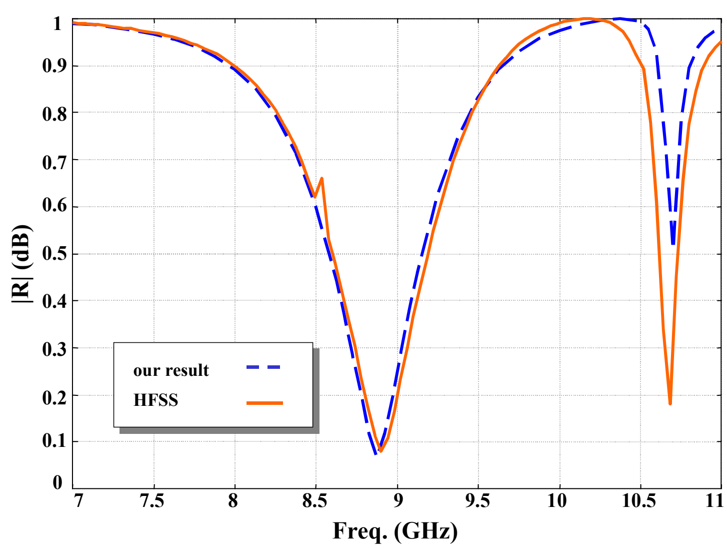


Fig.3 Reflection coefficient for the structure in Fig.1 (normal incidence). Comparison with HFSS