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NUMERICAL ANALYSIS OF PERIODIC PLANAR STRUCTURES ON UNIAXIAL SUBSTRATES FOR MINIATURIZATION PURPOSES

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Abstract—In this paper, a numerical analysis of a periodic planar structure using a uniaxial substrate is shown. The paper means to explore the possibility to use non-conventional substrate to reduce the size of planar radiating structure. The encouraging numerical results set the ground for a further experimental analysis. The presented results can be applied easily to the design of planar antennas, arrays and Frequency Selective Surfaces (FSS). A FSS resonating at 20.75 GHz has been analyzed. Pyrolytic boron nitrite (PBN), which has an anisotropic dielectric with a relative electric permittivity represented by a diagonal tensor, is adopted as the substrate of the designed FSS to achieve the size reduction while maintaining the FSS performance. The design is then compared with the one that uses isotropic substrate (i.e., RO4003). Comparison shows that the introduction of such a non-conventional medium allows the patch size to be reduced approximately by 20% while maintaining almost the same electromagnetic performance. Issues about size reduction and frequency shifting are further presented and discussed in the paper.

1. INTRODUCTION

Recent developments in most consumer electronic products are toward miniaturization. The technology of integrated circuit is widely applied in the field of communication baseband modules and RF modules to make communication products smaller in size. However, the technology of integrated circuits is difficult to use to design a compact antenna, antenna arrays, and FSS. Therefore, the design of compact planar structures becomes a critical technique to reduce the size of communication products.

In recent years, novel engineered materials with characteristics which may not be found in nature have been considered in the design of microwave antennas and FSS. The studies in the area showed increased directivity and bandwidth, reduced observability, and frequency shift which can be used to reduce dimensions for fixed working frequencies [1]. These encouraging results are the leading idea behind the present work.

Various terminologies have been used to classify composite materials with unique features that cannot be found in nature. The terminology would rather classify the materials according to their applications. The geometric complexity of the matter is an essential attribute, at the macroscopic as well as the micro-structural levels. A simple material, most easily exemplified by an isotropic dielectric material, affects the progress of electromagnetic waves in two ways: a delay is created with respect to propagation in matter-free space or vacuum, and absorption of electromagnetic energy occurs. Both effects are frequency-dependent (dispersive). Viewed as a continuum, an isotropic dielectric material is thus equivalent to an isotropic contraction of space with absorption overlaid. In complex materials, the progress of electromagnetic wave is additionally affected in one or more of several ways: anisotropy, chirality, non-homogeneity, and nonlinearity.

Artificial material with novel electromagnetic properties are often conceptualized and realized as particulate composite materials. If the particles are electrically small, the effective constitutive parameters and properties can be estimated via various homogenization formalisms. The synthesis and fabrication of new materials has to be matched by the development of new experimental characterization techniques.

Regarding the application of non-conventional materials to planar structures, it produces a frequency shifting with respect to the isotropic case, and a phenomenon of multi-resonance can be highlighted analogous to the one obtained using multiple patches but with the advantage being cheaper and easier the manufacture. The size of the patch can be substantially reduced and yet maintain the same electromagnetic performance. The frequency shift can be usefully employed to reduce the patch size with a corresponding improvement in terms of weight and space occupation [2]. In the present work the Method of Moments (MoM) was implemented using the sub-domain basis function in order to produce a general purpose code. In that light the patch size reduction will be expressed in terms of percentage of metallization per unit cell size.

2. ANALYTICAL FORMULATION

The periodic structure lays on an anisotropic substrate which is supposed to be infinitely extended along the x- and y-axis. The principal axis of the bianisotropic substrate is directed along the z-direction. The patches are assumed to have zero-thickness and to extend infinitely in both x- and y-directions. Anisotropic materials are characterized by a different response according to the direction of the impinging electromagnetic field. According to this behavior the dielectric permittivity of the medium can be represented by a tensor as follows:

$$\bar{\bar{\varepsilon}} = \varepsilon_0 \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix} \tag{1}$$

Or characterized by a diagonal tensorial dielectric permittivity:

$$\bar{\bar{\varepsilon}} = \varepsilon_0 \begin{bmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix} \tag{2}$$

The latter form is always possible upon an axes rotation operation (diagonalization).

Furthermore for feasible materials the elements on the diagonal fulfill the following condition:

$$\varepsilon_{ij} = \varepsilon_{ji}^{*} \tag{3}$$

which represents the well known Hermitian condition for the dielectric permittivity. If the material is also lossless the tensor is also symmetric.

A subset of interesting anisotropic materials shows anisotropicity only in one direction which is usually known as principal (or optical) axis. The material is in this case isotropic in the plane that is perpendicular to the principal axis. In that case the anisotropic material is called uniaxial and its permittivity tensor is expressed as follows:

$$\nabla \times \mathbf{H} = j\omega\varepsilon_0 \bar{\bar{\varepsilon}}_r \mathbf{E} \quad \nabla \times \mathbf{E} = -j\omega\mu_0 \mathbf{H} \tag{4}$$

According to [3] the Electric Field Integral Equation (EFIE) in the spectral domain can be written as follows:

$$\begin{aligned} -\mathbf{E}^{inc}(x,y) \;=\; & \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \underline{\tilde{G}}(\alpha_{m,n},\beta_{m,n}) \cdot \tilde{J}(\alpha_{m,n},\beta_{m,n})\, e \\ & +j(x\,\alpha_{m,n} + y\beta_{m,n}) \end{aligned} \tag{5}$$

where $\alpha_{m,n}$ and $\beta_{m,n}$ are the spectral variables associated with the Floquet (periodic boundary conditions) harmonics for the double periodic screen, $\tilde{\mathbf{J}}$ is the Fourier transform of the induced current, and $\underline{\tilde{\mathbf{G}}}$ the spectral dyadic Green's function. In order to solve the electromagnetic problem the entire field can be assumed as the superposition of TE and TM modes [4] which for a conventional substrate provides the following propagation constants:

$$\gamma_1 = \sqrt{\alpha^2 + \beta^2 - k_0^2} \qquad \gamma_2 = \sqrt{\alpha^2 + \beta^2 - \varepsilon_r k_0^2} \tag{6}$$

The previous equations can be modified to account for the uniaxial medium providing the following propagation constants:

$$\gamma_{m,n}^{TE} = \sqrt{\alpha_{m,n}^2 + \beta_{m,n}^2 - \varepsilon_{xx}\, k_0^2} \quad \gamma_{m,n}^{TM} = \sqrt{\alpha_{m,n}^2 + \beta_{m,n}^2 - \varepsilon_{zz}\, k_0^2} \tag{7}$$

Propagation constants (7) represent the difference in the evaluation of the Green's function as implemented in [4]; also the expression of incident, reflected, and transmitted fields will contain different propagation constants according to the polarization of the impinging wave. Once impinging on the patch, the incident plane wave will generate a transmitted wave (Et) and a scattered wave (Es). The overall boundary conditions on such surface will fulfill the following equations:

$$\mathbf{E}^t = \mathbf{E}^{inc} + \mathbf{E}^s \quad \mathbf{H}^t = \mathbf{H}^{inc} + \mathbf{H}^s \tag{8}$$

for the electric and magnetic field respectively. On the patch surface the transmitted electric field must be identically null; hence, the first equation returns:

$$0 = \mathbf{E}^{inc} + \mathbf{E}^s \tag{9}$$

The numerical efficiency depends upon the asymptotic behavior of the Fourier transform of the basis functions. Furthermore, if the patch geometry is unknown the use of entire-domain basis function is not recommendable. In that regard sub-domain basis functions better suit the problem scope.

3. NUMERICAL RESULTS

After knowing the electric field components it is possible to calculate the reflection and transmission coefficients that will be responsible for the electromagnetic behavior of the FSS. The reflection and transmission contributions are due either to the transmitted or reflected plane wave components on the slab for both TE and TM polarization types.

The unit cell under consideration (10×10 cm) contains a rectangular patch (0.25×0.5 cm) on a dielectric slab 2 mm thick.

As anticipated, two parallel simulations were carried out. In the first one the patch was loaded with RO4003 an isotropic dielectric having relative dielectric permittivity $\varepsilon_r = 3.38$. In the second one the dielectric layer was replaced by PBN with a dielectric permittivity given by $\varepsilon_{xx} = \varepsilon_{yy} = 3.40$ and $\varepsilon_{zz} = 5.12$. In both cases the patch layout did not change in shape.

The power reflection and transmission coefficient are reported in Figures 1 and 2 for the isotropic case and the uniaxial slab respectively.

It can be noted that the use of the uniaxial layer provides a leftward frequency shift of 1 GHz (from 20.75 GHz to 19.75 GHz) and the performance of the unit cell improves slightly. These effects allow

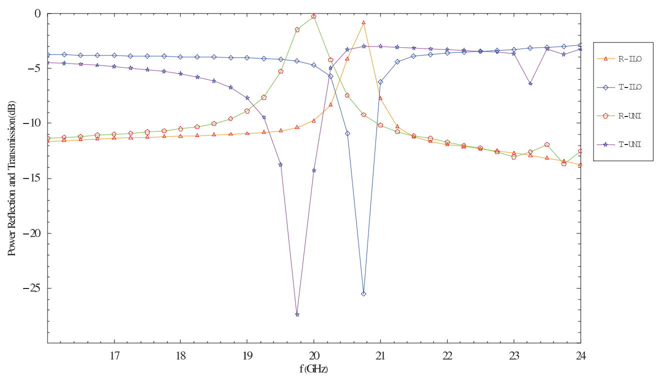

Figure 1. Power reflection and transmission coefficient for the isotropic slab and the uniaxial slab with the same metallization size.

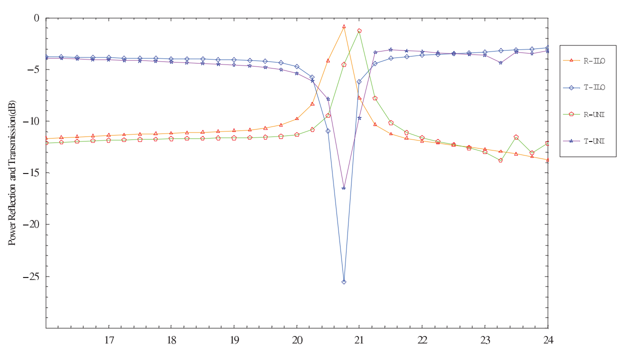

Figure 2. Power reflection and transmission coefficient for the uniaxial slab with reduced metallization area and original isotropic slab.

reduction of the patch size with a corresponding improvement in terms of weight and space occupation.

Without changing the size of the unit cell the resonant frequency of the uniaxial-loaded structure can be shifted back to the isotropic value by changing the size of the metallization. With the patch geometry being unknown a priori the size reduction effect will be shown in terms of percentage of metallization per unit cell.

In Figure 2, the unit cell presents a metallization which was reduced by 20–25% with respect to the initial size. It can be seen that the new resonant frequency coincides with the one showed in Figure 1.

4. CONCLUSIONS

The numerical scattering of electromagnetic waves from periodic metallic patches on uniaxial anisotropic layer was investigated using the spectral domain approach. The transmitted and reflected power was considered and a comparison between isotropic and anisotropic dielectric was carried out. From the results, it can be highlighted that the anisotropic dielectric generates a frequency shift which can be used to reduce the size of the patches with an improvement in weight and performance. The encouraging results are laying the foundations for an experimental analysis. This study can be applied to other periodic structures using several anisotropic layers or multiresonance planar arrays.

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