Analysis of Antennas Array with Photonic Bandgap

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***Abstract*—The use of photonic crystals is important in the theory concerning electromagnetic and optical propagation. The theory of Photonic Bandgap-PBG was first developed for lightwaves and it's fairly applicable for centimeter and millimeter waves. The presence of photonic materials as substrates of planar antennas yields some desirable features such as suppression of spontaneous emission and prevention of surface waves, thus avoiding coupling between the antenna elements and between antennas in a planar array. This work intends to perform a detailed analysis of these devices using the TTL-Transverse Transmission Line method, a efficient full wave method which gives concise results for microstrip antenna arrays with two layers PBG substrates.**

I. INTRODUCTION

THE PBG theory is based in the principle of localization of light due the presence of periodically positioned scatters. If that periodicity is equal or near a wavelength, the light wave whose frequency is within the bandgap is stuck inside the material and not allowed to propagate [1-7].

This same principle holds for microwaves. The localization is achieved by drilling periodically spaced holes in a semiconductor material thus creating a high dielectric constant contrast, such as a substrate formed by 2D photonic crystal lattice shown in Fig. 1. Some features such as the width and deepness of the bandgap may be controlled simply altering the period and the radius of the holes.

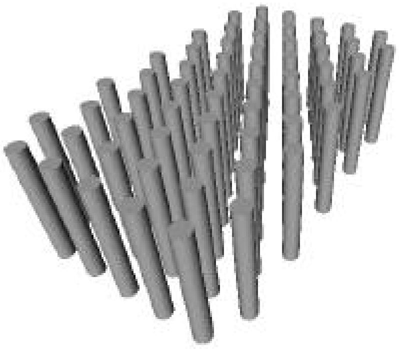

Fig. 1. 2D photonic crystal sampler (perfect hexagonal lattice).

Besides semiconductor, other materials may be used to manufacture PBG structures, such as alumina, epoxy-glass fiber, and PTFE (Teflon).

The presence of photonic materials as subtracts of planar antennas yields some desirable features such as suppression of spontaneous emission and prevention of surface waves, thus avoiding coupling between the antenna elements and between antennas in a planar array.

II. THE TTL METHOD

The TTL method is a very powerful one in the analysis of planar structures, since it allows a considerable reduction in the calculations of the E and H fields. In this method, the general equations of the electric and magnetic fields in the directions x and z are defined in function of E_y and H_y. The TTL method is described in the Fourier Transform Domain-FTD and whose definition is [8-9]:

$$\tilde{f}(\boldsymbol{a}_n, y, \boldsymbol{b}_k) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y,z)\cdot e^{j\boldsymbol{a}_n x}\cdot e^{j\boldsymbol{b}_k z}\, dxdz \qquad (1)$$

where $\boldsymbol{a}_n$ is the spectral variable.

The method and its development start from the Maxwell's rotational equations:

$$\nabla\times\vec{\mathbf{E}} = -jwm\vec{\mathbf{H}} \qquad (2)$$

$$\nabla\times\vec{\mathbf{H}} = jwe\vec{\mathbf{E}} \qquad (3)$$

According to the TTL method, these equations are written as:

$$\mathbf{E} = E_y + E_t \qquad (4)$$

$$\mathbf{H} = H_y + H_t \qquad (5)$$

where $H_t = H_x + H_z$

We obtain E_x, E_z, H_x, H_z as function of E_y and H_y, respectively. Separating the variables x and y in FTD, we obtain the following equations for the different areas:

$$\tilde{E}_{xi} = \frac{1}{g^2 + k_i^2}\left[-j\boldsymbol{a}_n \frac{\P}{\P y}\tilde{E}_{yi} + \boldsymbol{wmb}_k \tilde{H}_{yi}\right] \qquad (7)$$

$$\tilde{E}_{zi} = \frac{1}{g^2 + k_i^2}\left[-j\boldsymbol{b}_k \frac{\P}{\P y}\tilde{E}_{yi} - \boldsymbol{wma}_n \tilde{H}_{yi}\right] \qquad (8)$$

$$\tilde{H}_{xi} = \frac{1}{g^2 + k_i^2}\left[-j\boldsymbol{a}_n \frac{\P}{\P y}\tilde{H}_{yi} - \boldsymbol{web}_k \tilde{E}_{yi}\right] \qquad (9)$$

$$\tilde{H}_{zi} = \frac{1}{g^2 + k_i^2}\left[-j\boldsymbol{b}_k \frac{\P}{\P y}\tilde{H}_{yi} + \boldsymbol{wea}_n \tilde{E}_{yi}\right] \qquad (10)$$

where: $g_i^2 = \boldsymbol{a}_n^2 + \boldsymbol{b}_k^2 - k_i^2$ is the propagation constant in y direction; $k_i^2 = w^2 me = k_0^2 \boldsymbol{e}_r$.

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The boundary conditions are then applied and using the moment method one homogeneous matrix equation is obtained. The complex propagation constant is calculated numerically.

III. HOMOGENIZATION

Applying the homogenization rules it's possible to get an effective index, and consequently, the PBG substrate relative permittivity. The rods with permittivity ε_1 are embedded in a medium of permittivity ε_2. The procedure consists in dividing the structure into a superposition of homogenized layers. The layers containing the rods are broken up into cells whose *y* size (respective *x* size) is the diameter $2r$ of a rod (respective the period *d*). According to homogenization theory the effective index depends on the polarization. The effective permittivity on the *s* polarization is given by [10],

$$\varepsilon_{eq} = \beta(\varepsilon_1 - \varepsilon_2) + \varepsilon_2 \qquad (22)$$

and on the *p* polarization,

$$\frac{1}{\varepsilon_{eq}} = \frac{1}{\varepsilon_1}\left\{1-\left(\frac{3\beta}{\dfrac{\dfrac{2}{\varepsilon_1}+\dfrac{1}{\varepsilon_2}}{\dfrac{1}{\varepsilon_1}-\dfrac{1}{\varepsilon_2}}+\beta-\dfrac{\alpha\left(\dfrac{1}{\varepsilon_1}-\dfrac{1}{\varepsilon_2}\right)}{\dfrac{4}{3\varepsilon_1}+\dfrac{1}{\varepsilon_2}}\beta^{10/3}+O(\beta^{14/3})}\right)\right\} \qquad (23)$$

where β is defined as the ratio of the area of the rods over the area of the cells and α is an independent parameter whose value is equal to 0.523.

IV. SPONTANEOUS EMISSION

The presence of photonic materials as subtracts of planar antennas yields some important features such as the control of the spontaneous emission. The spontaneous emission, in accordance with the *Fermi* equation, is given by,

$$\Gamma(r) = \frac{2\pi}{\hbar}\left\langle\left\langle d.E(r)\right\rangle\right\rangle^2 \rho(r) \qquad (24)$$

where *d* is the transition dielectric dipole, $E(r)$ is the *RMS* local electric field, $\rho(r)$ is the electromagnetic mode density, and $\hbar$ is the *Planck* constant. In the bandgap, the states electromagnetic density is equal to zero, inhibiting the spontaneous emission.

V. RESULTS

The results were obtained using Fortran PowerStation, on which the initial frequency was in the gigahertz range and the patch sizes were in the millimeter dimensions. The calculations were made following the studies of the references [11-12].

Fig. 2 shows the resonance frequency for double layer resonator with Si substrate and Si PBG substrate in *s* and *p* polarization, as a function of the resonator length *L*. In this case, three substrate configurations are plotted. In the first case, both layers are manufactured of the same material (Si). In the second and third one, the second layer is manufactured of Si PBG substrate in *s* and *p* polarization, respectively. The resonator width *W* is 30mm, and the layers thickness is 0.4mm.

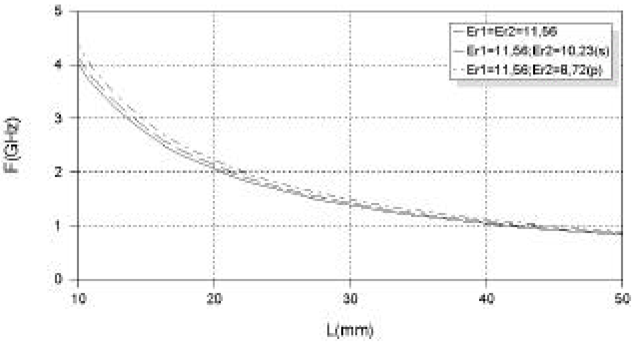

Fig. 2. Resonance frequency versus patch length for double layer resonator with Si substrate and Si PBG substrate in *s* and *p* polarization.

Fig. 3 shows the resonance frequency for double layer resonator with GaAs substrate and Si PBG substrate in *s* and *p* polarization, as a function of the resonator length *L*. In this case, three substrate configurations are also plotted. In the first case, both layers are manufactured of the same material (GaAs). In the second and third one, the second layer is manufactured of Si PBG substrate in *s* and *p* polarization, respectively. The resonator width *W* is 30mm, and the layers thickness is 0.4mm.

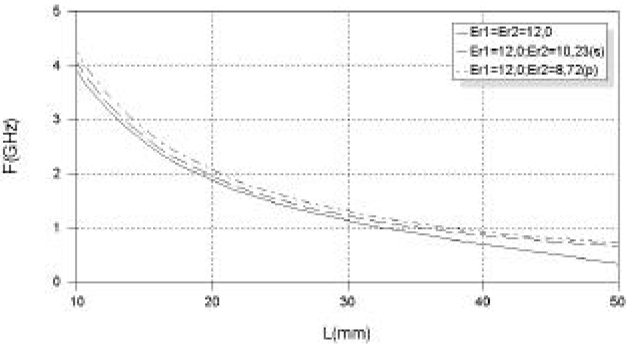

Fig. 3. Resonance frequency versus patch length for double layer resonator with GaAs substrate and Si PBG substrate in *s* and *p* polarization.

The Fig. 4 and 5 show a 3D perspective of the field pattern for a 6 x 6 and 9 x 9 elements array antenna, respectively. The operating frequency is 2.8GHz. The substrate is composed of two layers, the first of Si (ε_r=11.56) and the second of Si PBG substrate in *s* polarization (ε_r=10.233). The layers thickness is 0.4mm. Distance between the elements in the *x* and *y* direction is $\lambda/4$, and phase excitation in the *x* and *y* direction is zero. The currents in the terminals of the each antenna were normalized, for simplicity.

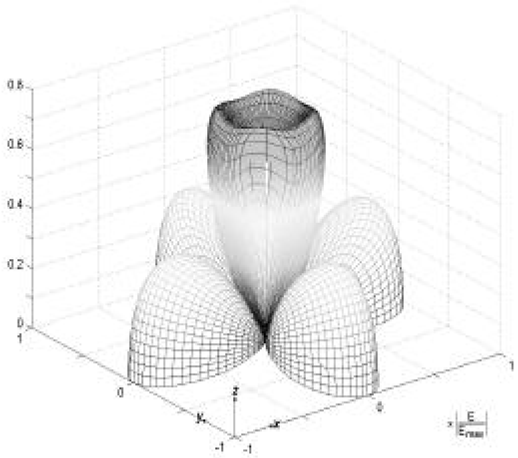

Fig. 3. A 3D graphic of the field pattern of a 6 x 6 elements array antenna.

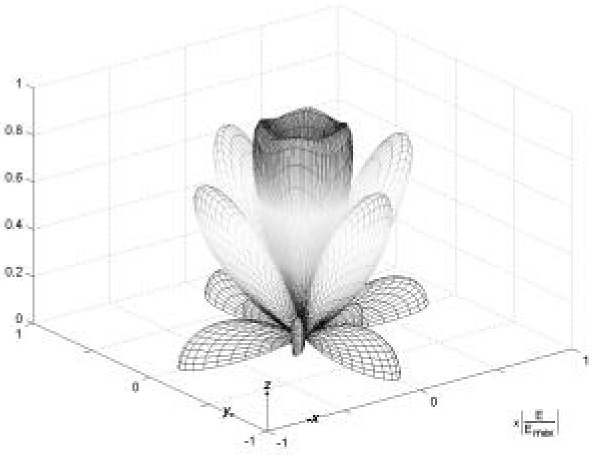

Fig. 4. A 3D graphic of the field pattern of one 9 x 9 elements array antenna.

VI. CONCLUSION

This article has shown that PBG materials represent a new paradigm in the transmission of optical and microwave signals. Theirs basic characteristics were observed, such as the signal localization, the inhibition of the spontaneous emission and the spontaneous emission control. Thus, PBG materials represent a promising horizon for the telecommunication systems. About the structure analysis structures using the TTL method, graphic results were shown and approved, enabling the use of this complete wave method for photonic materials in gigahertz range. This work received financial support of the CAPES and CNPq.

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