Analysis of the Phased Antenna Array With Photonic Material

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Abstract — The use of photonic material is applied to millimeter waves, microwaves and planar antenna frequencies. The phased array formed by microstrip antennas is analyzed using the full wave Transverse Transmission Line (TTL) method. For the microstrip patch resonator a set of equations that represents the electromagnetic fields in the *x* and *z* directions as function of the fields in the *y* direction are obtained applying the TTL method. The PBG (Photonic Band Gap) structure is analyzed using the homogenization theory, where the objective is obtain the equivalent permittivity of structure. Numerical results of the radiation pattern for some phase excitation in a phased array are shown.

Key-Words:- TTL Method, Phased array, PBG, Microstrip.

1 Introduction

The phased antenna array is composed of a group of individual radiators that are distributed and oriented in a linear or two-dimensional spatial configuration. The magnitude and phase excitations of each radiator can be individually controlled to form a field radiation of any desired shape in space. Phased antennas array have properties that make the best choice for directivity in modern mobile communication. They are well suited for use in the microwave frequencies [1]-[4].

The PBG structure is added as dielectric material in antenna that impede the propagation of electromagnetic waves in some frequency, producing photonic band gap (PBG).

Photonic band gap materials are similar to semi-conductors in that they exhibit gaps in the energy structure for photons (instead of electrons). In a photonic crystal if a photon has energy in the photonic band gap it will be unable to propagate through the material no matter the direction the light. This photonic gap comes about from a periodic array of air pores with diameters and inter-pore spacing of less than the wavelength of light [5]-[8], as shown in Fig. 1.

This work is devoted for various applications of rectangular microstrip phased antenna array by using the dynamic TTL method. In the Fig. 2 a planar microstrip array of 3x3 elements is shown. The microstrip antenna consists of a radiating structure spaced a small fraction of wavelength (0.01 to 0.05 free-space wavelength) above a conducting ground plane.

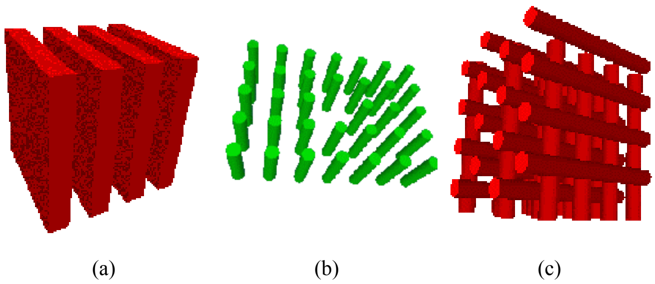


Fig. 1. PBG structures: (a) One-dimensional (b) Two-dimensional (c) Three-dimensional

Antenna arrays of this type have found applications where low cost, lightweight, reduced dimensions, and high efficient are necessary requirements for wireless communications and can be used in many applications over the broad range of frequencies.

Recently several works using the TTL method were published, being shown the efficiency of this method in several structures by H.C.C. Fernandes et al. [9]-[11].

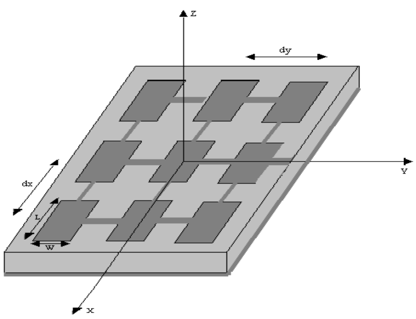


Fig. 2. Planar microstrip phased antenna array of 3x3 elements.

2 Theory

2.1. TTL Method

Considering the microstrip antenna resonator of Fig. 3, the equations that represent the electromagnetic fields in the **x** and **z** direction as function of the electric and magnetic fields in the **y** direction are obtained applying the TTL method.

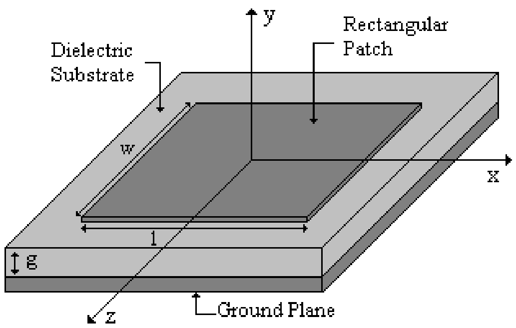


Fig 3. Microstrip patch antenna resonator

Starting from the Maxwell's equations and after various algebraic manipulations the general equations for the structure in the Fourier Transform Domain-FTD are obtained, for the **x** direction as:

$$\tilde{E}_{xi} = \frac{1}{\gamma_i^2 + k_i^2}\left[-j\alpha_n \frac{\partial}{\partial y}\tilde{E}_{yi} + \omega\mu\beta_k \tilde{H}_{yi}\right] \quad (1)$$

$$\tilde{H}_{xi} = \frac{1}{\gamma_i^2 + k_i^2}\left[-j\alpha_n \frac{\partial}{\partial y}\tilde{H}_{yi} - \omega\varepsilon\beta_k \tilde{E}_{yi}\right] \quad (2)$$

and for **z** direction as:

$$\tilde{E}_{zi} = \frac{1}{\gamma_i^2 + k_i^2}\left[-j\beta_k \frac{\partial}{\partial y}\tilde{E}_{yi} - \omega\mu\alpha_n \tilde{H}_{yi}\right] \quad (3)$$

$$\tilde{H}_{zi} = \frac{1}{\gamma_i^2 + k_i^2}\left[-j\beta_k \frac{\partial}{\partial y}\tilde{H}_{yi} + \omega\varepsilon\alpha_n \tilde{E}_{yi}\right] \quad (4)$$

where i = 1, 2 are the regions dielectric of structure, $\gamma_i^2 = \alpha_n^2 + \beta_k^2 - k_i^2$ is the propagation constant in **y** direction, α_n is spectral variable in **x** direction, β_k is spectral variable in **z** direction, $k_i^2 = \omega^2\mu\varepsilon = k_0^2\varepsilon_{ri}^*$ is wave number of *ith* dielectric region and $\varepsilon_{ri}^* = \varepsilon_{ri} - j\frac{\sigma_i}{\omega\varepsilon_0}$ is the relative electric permissive of material, α_n is the spectral variable, k is the wave number , $\Gamma=\alpha+j\beta$ is the complex propagation constant, α is the attenuation constant, β is the phase constant and γ is the propagation in the y direction in the FTD-Fourier Transform Domain.

After the application of the boundary conditions, the Moment method is used to eliminate the electric fields and to obtain the homogeneous matrix equation for the calculation of the complex resonant frequency. The roots of this matrix are the real and imaginary resonant frequencies.

2.2 Phased Array

To provide radiation in two angular dimensions, a planar array of radiating elements is used. The complete field of the array is the field of one element positioned at the origin multiplied by the factor array. This is function of the geometry of the array and of the phase excitation. Changing the distance and the phase of the elements, the characteristics of the factor array and of the complete field can be controlled [11-12]. A planar array of *M x N* uniformly spaced identical microstrip antenna elements localized along the any axis of the coordinate system is considered. The pattern field of the planar array, is given by:

$$E(\theta,\phi) = F(\theta,\phi)\cdot T_x T_y \quad (5)$$

where $F(\theta,\phi)$ is the element pattern, T_x and T_y are the factors array in the x and y directions, respectively.

The element pattern is:

$$F(\theta,\phi) = \frac{sin\left(\frac{k_0 h}{2} sin\theta cos\phi\right)}{\frac{k_0 h}{2} sin\theta cos\phi} \frac{sin\left(\frac{k_0 W}{2} cos\theta\right)}{\frac{k_0 W}{2} cos\theta} sin\theta \quad (6)$$

In these equations *h* is the dielectric substrate thickness and *W* is the width of the antenna element.

The factor array is calculated, considering the excitation, phase and the relative displacement between the elements as well as the dimensions and number of elements. The factor array of a rectangular planar array of *M* x *N* elements is then given by

$$T_x = \sum_{m=-N_x}^{N_x} I_{m0}\, exp\left[j\left(mk_0 d_x sin\theta cos\phi + \beta_x\right)\right] \quad (7)$$

$$T_y = \sum_{m=-N_y}^{N_y} I_{n0}\, exp\left[j\left(nk_0 d_y sin\theta sin\phi + \beta_y\right)\right] \quad (8)$$

where β_x is the phase excitation and I_{m0}, is the *real* current gain, in this x direction, β_y is the phase excitation and I_{n0}, is the *real* current gain in the y direction, and, the current in the surface is [13]

$$I_{mn} = I_{mo}.I_{no} \tag{9}$$

Considering the phase excitation uniform, the total excitation can be defined by Imn=Io, then the array factor will be expressed as:

$$T = I_o \sum_{m=1}^{M} e^{j(m-1)(kd_x sin\theta \cos\phi + \beta_x)} \sum_{n=1}^{N} e^{j(n-1)(kd_y sin\theta \cos\phi + \beta_y)} \tag{10}$$

Techniques for maximize the output power in adaptive antenna have been developer [14].
Normalizing (10), it is obtained the factor array [13]:

$$T(\theta,\phi) = \left\{ \frac{1}{M} \frac{sin\left(\frac{M}{2}\psi_x\right)}{sin\left(\frac{\psi_x}{2}\right)} \right\} \left\{ \frac{1}{N} \frac{sin\left(\frac{N}{2}\psi_y\right)}{sin\left(\frac{\psi_y}{2}\right)} \right\} \tag{11}$$

where

$$\psi_x = kd_x sin\theta \cos\phi + \beta_x \tag{12}$$

$$\psi_y = kd_y sin\theta \cos\phi + \beta_y \tag{13}$$

In the planar array, the element spacing and lattice must be chosen so that the total number necessary of elements in the planar array is minimized.
For a rectangular lattice, the principal maximal and grating lobes can be located by

$$sin\theta \cos\phi - sin\theta_0 \cos\phi_0 = \pm \frac{m\lambda}{d_x}, \; m = 0,1,2,... \tag{14}$$

$$sin\theta \cos\phi - sin\theta_0 \cos\phi_0 = \pm \frac{n\lambda}{d_y}, \; n = 0,1,2,... \tag{15}$$

and the element spacing must be chosen so that

$$\frac{\lambda}{d_x} = \frac{\lambda}{d_y} = 1 + sin\theta_m \tag{16}$$

where θ_m is the maximal scan angle.

2.3 PBG Structure

One of the problems that emerge when we worked with photonic material it is the determination of the effective dielectric constant. For being a non-homogeneous structures and that submit the incident sign at the process of multiple spread. A solution can be obtained through of numerical process called of homogenization [15].
The process is based in the theory related the diffraction of a plane electromagnetic wave incident imposed by the presence of cylinders of air immerged in a homogeneous material [7].
Chosen a Cartesian coordinates system of axes (*O, x, y, z*), shown in the Fig. 4. Consider firstly a cylinder with relative permittivity ε_1, with traverse section in the xy plane, embedded in a medium of permittivity ε_2. For this process the two-dimensional structure is sliced in layers whose thickness is equal at the cylinder diameter. In each slice is realized the homogenization process.

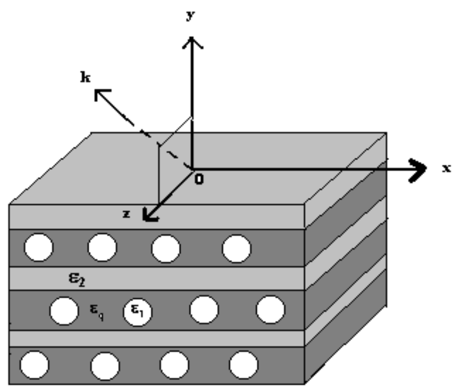


Fig. 4. Homogenized two dimensional crystal

According to homogenization theory the effective permittivity depends on the polarization [8]. For *s* and *p* polarization, respectively, are:

$$\varepsilon_{eq} = \beta(\varepsilon_1 - \varepsilon_2) + \varepsilon_2 \tag{17}$$

$$\frac{1}{\varepsilon_{eq}} = \frac{1}{\varepsilon_1}\left\{1 - \frac{3\beta}{A_1 + \beta - A_2\beta^{10/3} + O(\beta^{14/3})}\right\} \tag{18}$$

where

$$A_1 = \frac{2/\varepsilon_1 + 1/\varepsilon_2}{1/\varepsilon_1 - 1/\varepsilon_2} \tag{19}$$

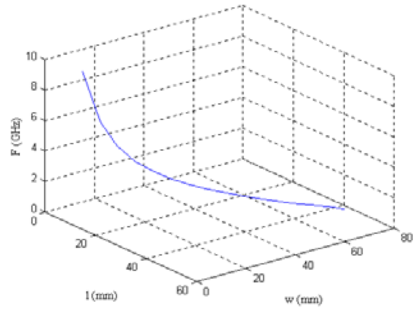
$$A_2 = \frac{\alpha(1/\varepsilon_1 - 1/\varepsilon_2)}{4/3\varepsilon_1 + 1/\varepsilon_2} \tag{20}$$

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

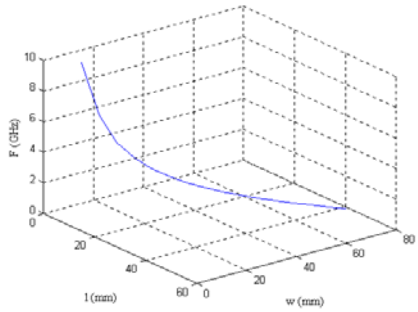
0.523. The A_1 and A_2 variables in (19) and (20) were included only for simplify (18).
The process of homogenizing involves a particular choosing direction, the results obtained are for small variation de incidence angle of wave vector, usually these values are between 70° and 90° degrees [8].

3 Numerical Results

The Fig. 5 shows the real frequency of a patch antenna as function of width and length. The relative permittivity is 10.233 for s polarization and 8.7209 for p polarization. The substrate thickness is 0.7 mm.



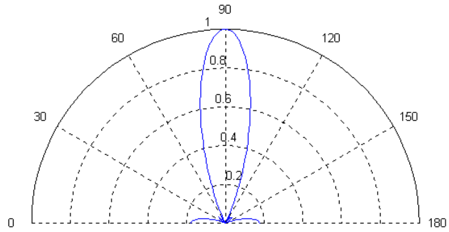
(a)



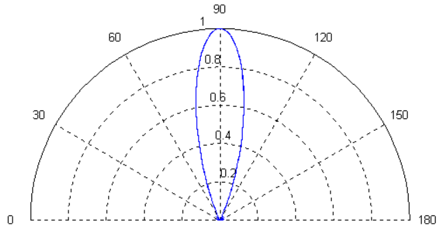
(b)

Fig. 5. Resonant frequency of microstrip patch (a) s polarization and (b) p polarization.

For the radiation patterns is considered the microstrip antenna with resonant frequency of 9.14 GHz, the width and length of patches are 10 and 5 mm, respectively, the substrate have an thickness of 0.7 mm and relative permittivity equal to 10.233 (s polarization), number of elements disposed in the x and y direction are 5 and distance between the elements radiator is $\lambda/2$, where λ is wavelength.
The Fig. 6 shows the E-plane and H-plane of microstrip antenna with the incidence angles $\theta_0 = 90^o$ and $\phi_0 = 90^o$.



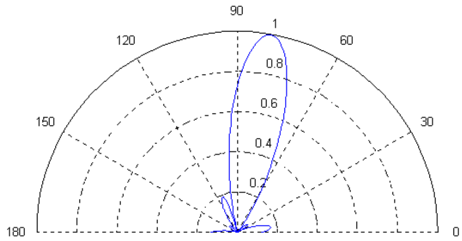
(a)



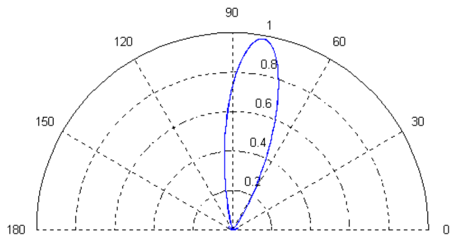
(b)

Fig. 6 Radiation patterns (a) E-Plane (b) H-Plane.

In the Fig. 7 the incident angles are $\theta_0 = 85^o$ and $\phi_0 = 80^o$. The modification in phase excitation has the objective of adjusting the antenna for new transmission or reception conditions.



(a)



(b)

Fig. 7 Radiation patterns (a) E-Plane (b) H-Plane.

In Fig. 8 is plotted a 3-D graph of the frequency operation as a function of the width (w) and length (l) of the conductive strip, for a PBG sample of LiNbO3. Little variation of the frequency operation is observed with the variable width (w).

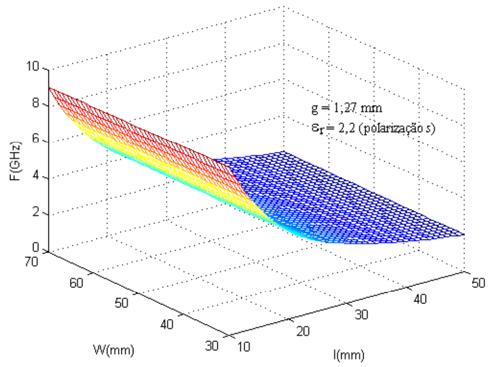


Fig 8 – Resonance frequency as function of the length and of the width of the patch resonator for a PBG sample of LiNbO3 (εr =2.2, ***s*** polarization).

Fig. 9 shows a 3-D graph of the propagation of the electric field in the θ and ϕ directions, of an antennas array with 3 x 3 elements. The parameters used were: frequency of 2.0 THz, effective dielectric constant equal to 4.04, substrate thickness equal to 0.0154 mm, relative permittivity equal to 10.233, number of elements

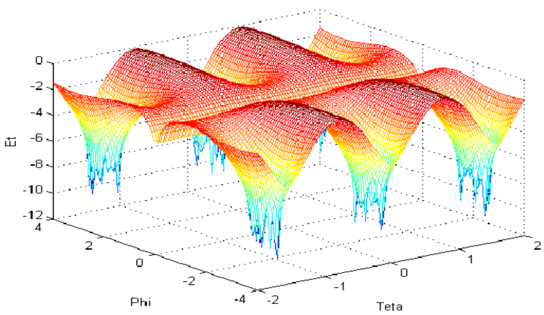


Fig 9. 3-D results of the electric field as a function of the θ and ϕ directions, for a 3 x 3 elements antennas array.

the x and y directions equal to 3, distance among the elements in the directions x and y equal λ /4, delay in the x and y directions equal to 0.

4 Conclusions

The Transverse Transmission Line (TTL) method was used for analysis of the microstrip phased antenna array. The TTL is an efficient and accurate method applied to the analysis and design of rectangular microstrip antenna arrays. This is a very versatile method that can be used with losses less, semiconductor or PBG substrate in various planar structures. The photonic structure was analyzed using the homogenization method. The antenna phased array has been shown very efficient and used in several applications. Radiation diagrams were presented for the array of microstrip antenna. It was observed that the variation of the phase excitation in the control of the array. The computational programs were developed in FORTRAN PowerStation and in MATLAB 6.0 using one 800 MHz PC microcomputer.

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