One-dimensional photonic crystals based polarization compensation approach

Guo-Lun Hong [2], Kuei-Jen Lee [1], Bin Li [3], Hsi-Tseng Chou[2], Ya-Wei Yin [3]

[1]Department of Communication Engineering, Oriental Institute of Technology, 58, Sec.2,Sichuan Rd.,Pan-Chiao City,Taipei County 22061,Tawian, R.O.C. E-mail: cathylgr@gmail.com

[2]Department of Communications Engineering, Yuan Ze University, Chung-Li 320, Taiwan

[3]Key Laboratory of Optical Communication and Lightwave Technologies, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing 100876

Abstract: This paper proposes an approach based on a one-dimensional photonic crystal structure to compensate the circular-polarization (CP) discrimination as encountered in many antenna's applications. The goal is to widen the beamwidth of radiation that has a less than 3dB axial ratio. A transfer matrix method was developed to represent the multilayer film and characterize its performance. Simulation using HFSS shows that a crossed-dipole, as an example, can achieve a beamwidth of more than 30 degrees at the frequency of 12.45GHz after compensation.

Key Words: crossed-dipole; photonic crystals; compensation; 3dB-region

Ⅰ Introduction

Applications of circularly polarized (CP) antennas are widely used in the wireless communications. Unless the antenna is used only for point-to-point communications, where the CP performance at the boresite direction is of major concern, it is desirable to design the antenna structure that radiates fields with an as wide beamwidth of a good CP as possible, which potentially provides better reception performances such as in the applications of global positioning system (GPS) where a single antenna is used to receive signals from various satellites in different angular locations. Such examples can be easily found in the satellite communications. Although in many antenna designs, such as using cross-dipoles, a good CP can be obtained in the antenna's boresite direction, the polarization discrimination of TE and TM modes grows while the angle of incident waves increased[1] with respect to the antenna’ s boresite. That means more signal amplifications in the system are compulsory which will increase the cost accordingly.

In order to improve the efficiency of antenna and keep the polarization discrimination at a lowest level in a wide range of angular region, we introduce a compensation method using one-dimensional (1D) photonic crystals to broaden the beamwidth that has a less than 3dB TE/TM ratio region

The concepts of the photonic crystals were first brought forward by E. Yablonovitch and S.John [2]. Photonic crystals are periodically structured using dielectric materials that can be recognized as multilayer films. If the structures show a periodicity in the range of the wavelength of the light, interferences appear which affect the propagation of light in these materials strongly and allow the energy re-distributing in the angular space. The photonic crystals have been shown a wide range of applications, such as the area of laser, glass fibers and pigments, also photonic crystal can be used in the newly emerged area of integrate optics and sensing[3]. In this application the different mechanisms of energy re-distribution in the TE and TM modes may be used to make their ratio become smaller if the structure is designed properly.

This paper is organized in four parts. In Section Ⅱ, the theory of photonic crystals is summarized, including the transfer matrix method used in this compensation approach. Section Ⅲ presents the simulation environment in HFSS 9.0. Two criterions are proposed to evaluate the performance of compensation. Section Ⅳ show the simulation result using a cross-dipole antenna as a demonstrating example, and explanation for the results are given. Section Ⅴ presents some conclusive discussions for further studies.

Ⅱ Theory of photonic crystals

In the case of 1D photonic crystals, the amendment of Maxwell's equation can be expressed as

$$-\frac{\partial^2 E}{\partial x^2}=\frac{\varepsilon(x)}{c}\varpi^2 E. \tag{1}$$

Figure 1 gives a representative structure of 1D photonic crystals. The width of the incident beam is assumed to be large compared with its lateral displacement such that the incident fields illuminating the structure exhibit the characteristics of local plane waves and can be characterized by TE/TM modes. The fields of incidence will experience many reflections and transmissions in the structure, which contribute significantly to the resultant reflected and transmitted beams. There are several approaches that can be used in the optical film computations. The analytical resolution is rather complex while calculating the electromagnetic field layer-by-layer within the multilayer films. We introduce a transfer matrix method that can provide a great deal of flexibility in designing interference coatings with almost any specified frequency-dependent reflectance or transmittance characteristics.

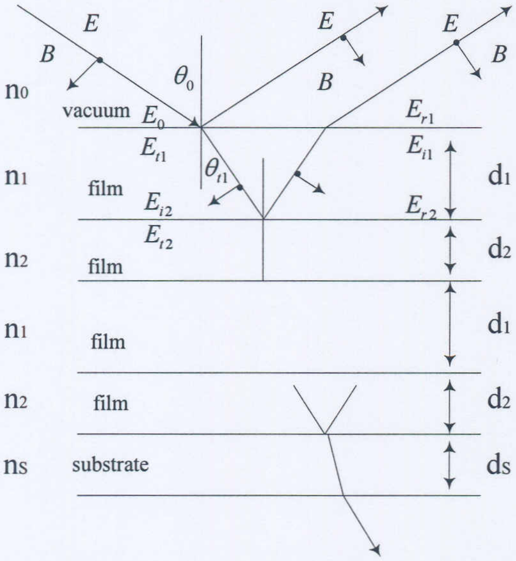

Fig.1 Reflection and transmission

The electric and magnetic fields of the incident wave must obey the boundary condition restrictions, that is, the tangential components of the resultant E- and B-field are continuous across the interface and their magnitudes on either side are equal. Under this restriction of the boundary condition[4], we get the relation of the electric and magnetic fields between the adjacent layers of the crystal:

$$\begin{bmatrix} E_k \\ B_k \end{bmatrix}=\begin{bmatrix} \cos\delta_k & i\sin\delta_k/\gamma_k \\ i\gamma_k\sin\delta_k & \cos\delta_k \end{bmatrix}\begin{bmatrix} E_{k+1} \\ B_{k+1} \end{bmatrix} \tag{2}$$

where $\delta_k=\frac{2\pi}{\lambda}n_k d_k\cos\theta_k$, $1\le k\le N$, and

$$\begin{bmatrix} E_1 \\ E_1 \end{bmatrix}=M\begin{bmatrix} E_N \\ E_N \end{bmatrix} \tag{3}$$

where M is the compound matrix, $M=M_1M_2.....M_N$. We generally represent the M-matrix as the following form:

$$M=\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \tag{4}$$

We define the reflection and transmission coefficients as:

$$r=E_{r1}/E_0 \text{ and } t=E_{tN}/E_0 \tag{5}$$

Substituting the expression of t, r, and M in (4) and (5) into the boundary condition, (3) can be solved for the transmission and reflection coefficients in terms of the transfer-matrix elements to give:

$$t=\frac{2\gamma_0}{\gamma_0 m_{11}+\gamma_0\gamma_s m_{12}+m_{21}+\gamma_s m_{22}} \tag{6}$$

$$r=\frac{\gamma_0 m_{11}+\gamma_0\gamma_s m_{12}-m_{21}-\gamma_s m_{22}}{\gamma_0 m_{11}+\gamma_0\gamma_s m_{12}+m_{21}+\gamma_s m_{22}} \tag{7}$$

Equation (6) and (7) , together with the transfer-matrix elements, enable us to evaluate the reflective and transmissive properties of the single or multilayer film represented by the transfer matrix.

Ⅲ Simulation environment

Simulation was performed using HFSS 9.0. In this case, a cross-dipole antenna is employed as an example to demonstrate this concept, which can be however employed to the treatment of many other CP antenna in a similar fashion. Also in this example we design the compensating 1-D photonic crystal using the KP (Kronig-Penney) model[2], and the structure of the crystal is ranged in the ABAB alternate form as can be seen in figure 2. Based on the front-fed arrangement described in literature[5], we design the reflector of the crossed-dipole a parabolic structure so that the backward radiation of the crossed dipoles can be directed into the forward direction and thus increase the gain of the antenna. Note that a paraboloid is used because as shown in geometrical optics that if a beam of parallel rays is incident upon a parabolic reflector, the reception will converge at its focus, where thus the crossed-dipole is placed at the focus to enhance a parallel beam.

We use a glass substrate (n_s=1.52) at the top of the photonic crystal and allow incidence from air (n_0=1). The relative permittivity of the 4 layers below the substrate is 1.44, 1.172, 1.44, 1.172 respectively while the relative permeability of all the layers is 1. The thickness of each layer is a quarter of the effective wavelength. All the film is assumed to be both homogeneous and isotropic.

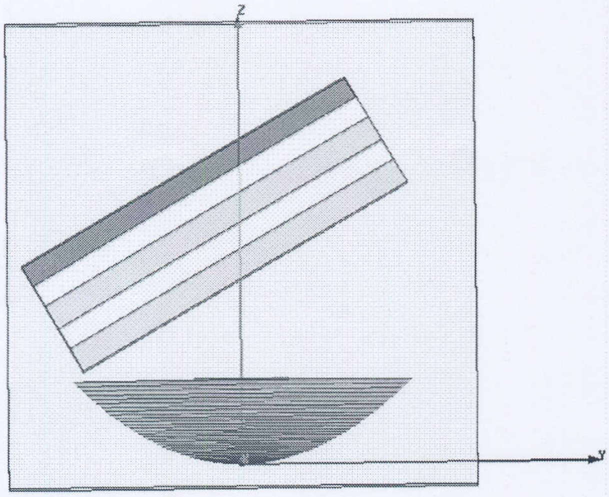

Fig.2 1D photonic crystal polarization compensation for antenna

In order to evaluate the performance of the compensation approach, we introduce a 3dB region as criterion. If the remote signal receiver can recognize the antenna easily, the axial ratio must fulfill the following constriction:

$$20\log|TE/TM|<3dB \qquad (8)$$

The minimal angle of transmission that can not meet the requirement of (8) is recorded as $\theta_{\min}$; in the same way, the maximal angle of transmission is recorded as $\theta_{\max}$. The 3dB region is defined as the degrees of the angle that range from $\theta_{\min}$ to $\theta_{\max}$.

Ⅳ Experimental Result

The simulation results are shown in figure 3. The three curves denote the results under different conditions, that is, the dipole without lens, dipole with a lens located parallel to the dipole plane (indicated by "lens00") and the dipole with a lens of 30 degree lean (indicated by "lens30"). In these cases, the dipole's excitations can be adjusted, if desired, to obtain better results. From the results we can see that in the third case we can get a widest 3dB region by adjusting the excitation of the crossed-dipole. The abscissa represents the axial ratio of the magnitudes of the two perpendicular modes of the crossed dipole's excitations. While adjusting the magnitude ratio to about 1:0.75, the maximal 3dB region of 38 degree obtained. Both in the first two cases the maximal 3dB regions were reached at the ratio of 1:1, this proves that the parallel lens do not change the proportion between TE and TM mode and the 3dB region. Although the average 3dB region of third case is not broader than the other two, the maximal region can be obtained, this is very useful in the many applications of satellite communication since the magnitude ratio of the perpendicular mode can be easily modified in crossed-dipole antenna[6].

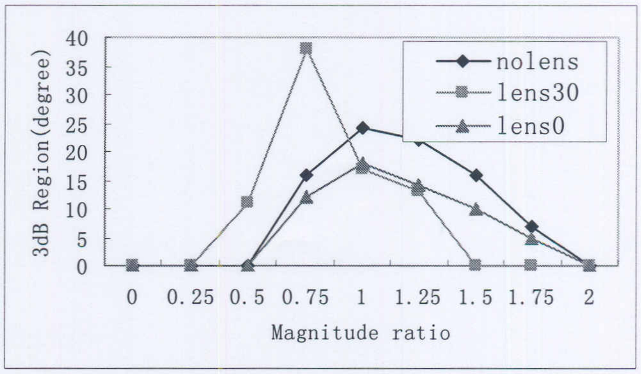

Fig.3 The 3dB region with different magnitude ratio

Figure 4~6 give the 3-D far-field gain patterns of all three cases. The red color denotes the highest gain in dB while on the other hand, the dark-blue denote the lowest gain.

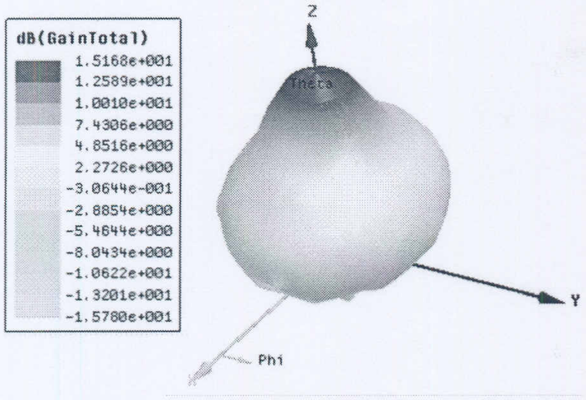

Fig.5 The far-field of the 3D polar plot without lens

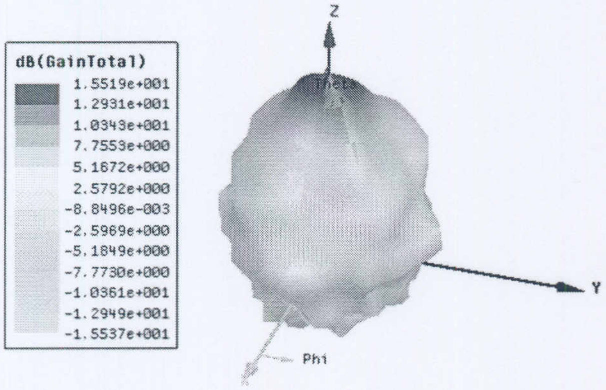

Fig.6 The far-field of the 3D polar plot with lens00

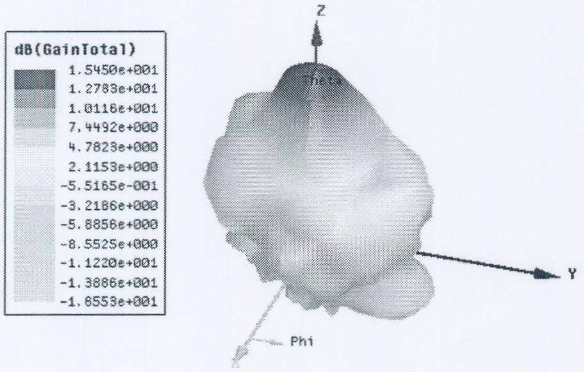

Fig.4 The far-field of the 3D polar plot with lens30

(ratio=1:0.75)

V Conc lusion

In this paper, a pilot study on the CP compensation methods is performed using 1-D photonic crystals. As shown in the simulation, a rotated photonic crystal can broaden the 3dB axial ratio beamwidth with low reflectance. Further study will focus on establishing a simulation software that allows designing the structure to compensate the polarization discrimination in an automatic fashion using intelligent controlling algorithms.

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