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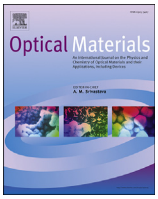

Effect of standard deviation, strength of magnetic field and electron density on the photonic band gap of an extrinsic disorder plasma photonic structure

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ABSTRACT

Transmission properties of electromagnetic waves within microwave region of the one-dimensional random extrinsic plasma photonic crystals were computed using the transfer matrix method. The layers thicknesses of the extrinsic random photonic structure follow a Gaussian distribution. Compared with the periodic extrinsic photonic crystal, wider photonic band gaps (PBGs) were found in case of random extrinsic plasma photonic crystals with few resonant peaks. The PBGs are much wider while the randomness was increased and the number and the strength of resonant peaks were enhanced. The above observations were confirmed through analysis of histogram of normalized average transmissions for four different values of standard deviation with one thousand random samples for each group. The normalized average transmission was controlled by changing the strength of external magnetic field and the electron density of magnetized cold plasma. These features of disordered extrinsic plasma photonic structures would have potential applications such as omnidirectional reflectors and random multi-channel filters with lower and higher rate of disorder.

1. Introduction

In 1987, two milestone reports on the theoretical concept and experimental validation for modulation of light using stratified structure generally referred as photonic crystals (PCs) were initialized by Yablonovitch [1] and John [2]. The fundamental of physics behind the modulation of light was originated from the Bragg scattering in the periodic structure, which leads to a forbidden frequency regions analogous to electronic forbidden band in solids. These fundamental frequency regions are popularly known as photonic band gaps (PBGs) or Bragg gaps and cause diverse interesting applications in the field of optical engineering [3–8]. The experimental validation and theoretical investigations of PCs were carried out by using different type of materials such as dielectrics, composites, semiconductors, superconductors, metals, metamaterials and plasma. These PCs are formed by two different kinds of dielectric constant material are generally referred as intrinsic PCs. On the other hand, the PCs were formed using bulk materials where dielectric function of these materials were modulated by an external periodic applied field referred as extrinsic PCs [9–12]. Now the extensive research in the field of PCs is diverted to quasi-crystals (large-order rotational symmetry but no translational symmetry) and disordered photonic structures (random mixing of refractive index domains) [13–21]. These structures show some interesting finding such as tunable cavities [15] and beam collimators [20], which help to employ for the realization of different sophisticated optical applications.

In recent, researchers are paying interest in the field of magnetized plasma based photonic crystals due to their particular characteristics than the conventional PCs. Magnetized plasma is a kind of dispersive medium and its equivalent refractive index is related with the frequency of an incident electromagnetic wave. Moreover, dielectric constant of the magnetized cold plasma can be controlled by the plasma parameters and the external magnetic

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field. Looking the usefulness of such features of magnetized plasma several reports are entitled on one-dimensional (1D) plasma photonic crystal [12,22–24]. Recently, using such features, King et al. [12] theoretically investigated a novel extrinsic plasma photonic crystal which was composed of bulk plasma system influenced by an alternating square wave like magnetic field.

Though extensive research work are carried out in the field of plasma photonic crystal; however as per our knowledge concern, there is no such study carried out on the PBG of a random plasma photonic crystal. In this manuscript, therefore, we extend the scope of our previous work i.e. the optical properties of intrinsic dielectric disordered photonic structures by controlling the distribution of the random layer thickness [19], for extrinsic magnetized cold plasma one-dimensional Gaussian distributed random layer thickness disorder photonic structures. The computational analysis of the investigation is carried out by using transfer matrix method (TMM) [12,25]. In this current work, we show that the effect of different valued standard deviation (σ) on the PBGs of the proposed extrinsic random plasma multilayer structures. In addition, the effects of strength of magnetic field and electron density on the normalized average light transmission are also examined. The outline of our paper is as follows: Section 2 presents a 1D extrinsic random structure, the characteristic matrix method and its formulation, and also the permittivity of magnetized cold plasma, Section 3 reveals the numerical results and discussions associated with our purpose, and Section 4 describes the conclusions of the investigation.

2. Physical model

Before proceeding to the results and simulated data, in this section, we are introducing the 1D extrinsic random plasma multilayer structure which was assumed to be embedded in air. The proposed extrinsic random plasma multilayer structure is a bulk cold plasma system and assumed to be divided into N number of layers. The thicknesses of the layers are random and follow Gaussian distribution. In addition to that, every odd layer of the bulk cold plasma are under uniform negative magnetic field ($-\boldsymbol{B}$) and represents the first kind of effective media (a); whereas every even sections of the bulk cold plasma are under positive magnetic field ($+\boldsymbol{B}$) and represents the second kind of effective media (b) [12]. As a result the bulk plasma system can thus be considered as Gaussian distributed random layer thickness photonic structure comprised by two effective media a and b. In the present study, we investigate the structure-property relationship of a 32 layered structure. The layer thicknesses of the proposed structure followed the Gaussian distribution centered at 15 mm with a standard deviation (σ). For the sake of example, of such statistics, a structure having standard deviation $\sigma = 6$ is sketched in Fig. 1. In which, the numerical values from 1 to 32, are correspond to the layer number of the proposed extrinsic disorder structure. In addition, it is noted here that the thicknesses of each individual layers presented in Fig. 1 are different while considering the other structures with same statistics.

In the presence of static magnetic field the frequency dependent dielectric function of the magnetized cold plasma is expressed as [12,26].

$$\varepsilon_{MCP}(\omega) = 1 - \frac{\omega_p^2}{\omega^2\left(1 - i\frac{\gamma}{\omega} \mp \frac{\omega_l}{\omega}\right)}. \tag{1}$$

where ω, ω_p, ω_l and γ are angular, plasma, gyromagnetic and effective collision frequency, respectively. In addition, the ω_l corresponds to positive and negative magnetic field referred as right-hand polarization and left-hand polarization, respectively. The value of ω_p and ω_l can be calculated by using Eqs. (2) and (3), respectively.

$$\omega_p = \frac{n_e e^2}{m\varepsilon_0}, \tag{2}$$

and

$$\omega_l = \frac{e\boldsymbol{B}}{m}. \tag{3}$$

In these equations, e, n_e, m, and ε_0 respectively represent the charge of electron, electron density, mass of electron and permittivity of free space. To compute the average light transmission of the proposed extrinsic random magnetized cold plasma multilayer structures, we shall employ the TMM which takes consideration of multilayer reflections and describes the fine spectra [12,25].

According to the TMM, the transmittance T, of a N-layer structure is calculated through the equation $T = |t|^2$, where the transmission coefficient, t, is $t = 1/m_{11}$ and m_{11} is the matrix element of the total transfer matrix M represented as

$$M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = D_0^{-1}\left(\prod_{j=1}^{N} D_j P_j D_j^{-1}\right) D_0. \tag{4}$$

Here, for normal incidence, the propagation matrix P_j in the layer j with the thickness d_j and permittivity ε_j is

$$P_j = \begin{pmatrix} e^{i\frac{\omega}{c}\sqrt{\varepsilon_j}d_j} & 0 \\ 0 & e^{-i\frac{\omega}{c}\sqrt{\varepsilon_j}d_j} \end{pmatrix}, \tag{5}$$

and the dynamic matrix D_j is

$$D_j = \begin{pmatrix} 1 & 1 \\ \sqrt{\varepsilon_j} & -\sqrt{\varepsilon_j} \end{pmatrix}. \tag{6}$$

In Eq. (5), c indicate the speed of light in free space.

3. Results and discussions

To investigate the proposed structure behavior, the computations are performed by means of Matlab R2010a environment. The frame work is hosted by desktop PC based on Intel Core i7@3.40 GHZ, with 2 GB of RAM, running on Microsoft Windows 7, 64-bit OS. In the numerical calculation, we take the parameters of the magnetized cold plasma as follows: $\gamma = 4\pi \times 10^2$ GHz and $n_e = 8 \times 10^{17}$ m^{-3}. The magnetic field, $\boldsymbol{B} = 0.5$ T. As discussed in the earlier section the number of layers is selected to be $N = 32$. The widths of the layers are assumed to follow a Gaussian distribution, centered at 15 mm with various standard deviations (σ). The incident field is assumed to be injected normally. Here, the computational study is only focused on the PBGs in the frequency domain of 2–7 GHz. Firstly, the effects of the Gaussian distributed layer thickness having four different standard deviation values on the PBG are analyzed. Then, influences of standard deviation, external magnetic field and electron density on the normalized average transmission of the PBG are discussed.

The transmissions spectra of seven random extrinsic magnetized cold plasma structures for standard deviation $\sigma = 0.5$ (seven black curves) along with the transmission spectrum of periodic extrinsic magnetized cold plasma i.e. for the standard deviation, $\sigma = 0$ (red curve) are illustrated in Fig. 2. The above seven random extrinsic magnetized cold plasma structures indicated through