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Defect mode properties in a one-dimensional photonic crystal

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ABSTRACT

Based on the transfer matrix method (TMM), the interaction of electromagnetic waves with one-dimensional (1D) defective photonic crystal in ultraviolet (UV) frequency region had been studied. With the calculated transmittance characteristics in the wavelength domain, it can be found that the defect mode can be generated within the photonic band gap (PBG) at the central wavelength. Also the effects of many parameters such as the angle of incidence, the state of polarization and the defect layer thickness have been taken in account. A significant effect in generating multiple defect peaks within the PBG has been illustrated.

1. Introduction

Many of the true breakthroughs in advanced technology have resulted from a deeper understanding of the properties of materials. Advances in metallurgy, ceramics and plastics have enabled us to study the mechanical properties of materials. In this century, our control over materials has spread to include their electrical properties. Advances in semiconductor physics have allowed us to tailor the conducting properties of certain materials. In the last few decades, a new class of materials had been discovered to control the optical properties of materials that respond to light waves over a desired frequency range. These new materials had been discovered as a power result of semiconductor materials discovery due to the huge similarity between them in some properties. The control of these materials on the optical properties of the incident light waves can be described by perfectly reflecting them, or allowing them to propagate only in certain directions, or confining them within a specified volume for enormous range of technological developments [1]. Such new materials have been called the photonic crystals (PCs), or the photonic band gap (PBG) materials.

PCs are periodic, dielectric, and composite structures in which the interfaces between the dielectric media behave as light scattering centers. In general, PCs can be classified into three types, i.e., the one-dimensional (1D), the two-dimensional (2D) and the three-dimensional (3D) PCs [2–10]. The common property among these three types of PCs are the appearance of forbidden frequency regions—the so-called PBGs and photon localization [11,12]. The PBG means that electromagnetic waves of certain frequencies cannot propagate in any direction in a PC due to the inference of the Bragg scattering in this periodic structure. The photon localization presents the possibility to make some discontinuous electromagnetic waves appear in the PBG due to the presence of disorders within the structure.

The birth of PCs starting from the pioneering work of Yablonovitch [13] and John [14], walking over these steps, PCs have received considerable attention for fundamental physics studies as well as for potential applications in photonic devices [1,15,16], laser applications, the perfect mirrors, the optical communications and the filters, the eye protection, the chemical and oil sensors, and the optoelectronic circuits. All of these applications can be performed using the perfect or pure PCs, but its doped or defected versions may be more useful, as semiconductors doped by impurities are more important than the pure ones for more extensive applications.

The idea of doped PCs comes from the analogy between electromagnetism and solid state physics, which lead to the study of band structures of periodic materials and further to the possibility of the occurrence of localized modes in the band gap when a defect is introduced in the lattice. These defect-enhanced structures are called doped photonic crystals and present some resonant transmittance peaks in the band gap corresponding to the occurrence of the localized states [17], due to the change of the interference behavior of the incident waves. The defect can be introduced into perfect PCs by changing the thickness of a layer [22], inserting another dielectric into the structure [18–23], or removing a layer from it [24,25].

The introduction of the defect states within PCs has been received a huge volume, especially in 2D and 3D PCs due to the great amount of applications that can be performed using them.

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In 2D or 3D PCs, it has been also known that a point defect can act as a microcavity, a line defect like a waveguide, and a planar defect like a perfect mirror [1,7]. Similar to 2D or 3D PCs, the introduction of the defect layers in 1D PCs can also create localized defect modes within the PBGs. Due to the simplicity in 1D PCs fabrications over 2D and 3D, the defect mode can be easily introduced within 1D PCs for various applications such as in the designing of TE/TM filters and splitters [26], in the fabrication of lasers [27], and in the light emitting diodes [28].

In this paper we theoretically studied the transmittance characteristics of the defect modes introduced within 1D PCs in the UV frequency region for both TE and TM polarizations. Also the effect of the defect layer thickness, the index of refraction, and the angle of incidence on the intensity and the position of the defect state has been discussed. According to this study, such a device can be of potential use to be fabricated for many applications in UV region such as the signal processing especially in optical communication, in wavelength multiplexer, and for the design of narrowband transmittance filter based on 1D PCs [29].

2. Basic equations

Let us consider a defect layer that is immersed between two identical periodic structures, in which each of them represents a perfect 1D PC as shown in Fig. 1. The first periodic structure is repeated for N times, while the second is repeated for S times, where N and S are the integers. Both the structures are made of two dielectric materials denoted by A and B. d_1, d_2 and n_1, n_2 are the thicknesses and the refractive indices of the dielectric layers A and B, respectively. The refractive index and the thickness of the defect layer are denoted by n_D and d_D, respectively. The whole structure is situated between vacuum and a substrate. The values of refractive indices n_1 ,n_2 and n_D are available in Ref. [30].

Based on the transfer matrix method (TMM) such as the Abeles theory (AT) [31], the structure shown in Fig. 1 can be specified by the following matrix equation:

$$M_{structure}=(F)^N(G)(H)^S \tag{1}$$

The above matrix is given as a product of three matrices. The first one describes the left periodic structure, the second describes the defect layer, and the third describes the right periodic structure. According to AT, the single-period characteristic matrix that describes the left periodic structure must first be constructed and takes the following form:

$$F(a)=\begin{pmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{pmatrix}=\begin{pmatrix} \cos\delta_1 & \frac{-i}{p_1}\sin\delta_1 \\ -ip_1\sin\delta_1 & \cos\delta_1 \end{pmatrix}\begin{pmatrix} \cos\delta_2 & \frac{-i}{p_2}\sin\delta_2 \\ -ip_2\sin\delta_2 & \cos\delta_2 \end{pmatrix} \tag{2}$$

where $F(a)$ is the matrix for one period, where $a=d_1+d_2$ is the lattice constant. The elements f_{11}, f_{12}, f_{21} and f_{22} take the following forms:

$$f_{11}=\cos\delta_1\cos\delta_2-\frac{p_2}{p_1}\sin\delta_1\sin\delta_2 \tag{3a}$$

$$f_{12}=\frac{-i}{p_1}\sin\delta_1\cos\delta_2-\frac{i}{p_2}\cos\delta_1\sin\delta_2 \tag{3b}$$

$$f_{21}=-ip_1\sin\delta_1\cos\delta_2-ip_2\cos\delta_1\sin\delta_2 \tag{3c}$$

$$f_{22}=\cos\delta_1\cos\delta_2-\frac{p_1}{p_2}\sin\delta_1\sin\delta_2 \tag{3d}$$

where

$$\delta_1=\frac{2\pi d_1}{\lambda}n_1\cos\theta_1,\quad \delta_2=\frac{2\pi d_2}{\lambda}n_2\cos\theta_2 \tag{4}$$

and,

$$p_1=n_1\cos\theta_1,\quad p_2=n_2\cos\theta_2 \tag{5}$$

for TE wave, whereas

$$p_1=\frac{\cos\theta_1}{n_1},\quad p_2=\frac{\cos\theta_2}{n_2} \tag{6}$$

for TM wave.

For a system of N periods the total characteristic matrix $F(Na)$ can be obtained as follows [32]:

$$F(Na)=\begin{pmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \end{pmatrix} \tag{7}$$

With the matrix elements being related to the elements in Eq. (3), i.e.

$$\begin{aligned} F_{11}&=f_{11}U_{N-1}(\Psi)-U_{N-2}(\Psi), & F_{12}&=f_{12}U_{N-1}(\Psi), \\ F_{21}&=f_{21}U_{N-1}(\Psi), & F_{22}&=f_{22}U_{N-1}(\Psi)-U_{N-2}(\Psi), \end{aligned} \tag{8}$$

where

$$U_N(\Psi)=\frac{\sin((N+1)\cos^{-1}\Psi)}{\sqrt{1-\Psi^2}} \tag{9}$$

where $U_N(\Psi)$ are the Chebyshev polynomials of the second kind with the argument equal to the half trace of the single period matrix, i.e., $\Psi=(f_{11}+f_{22})/2$ [33].

Next, the matrix that can be used for describing the electromagnetic waves interactions through the defect layer can be written by

$$G(d_D)=\begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{pmatrix}=\begin{pmatrix} \cos\delta_D & \frac{-i}{p_D}\sin\delta_D \\ -ip_D\sin\delta_D & \cos\delta_D \end{pmatrix} \tag{10}$$

where

$$\delta_D=\frac{2\pi d_D}{\lambda}n_D\cos\theta_D,\quad p_D=n_D\cos\theta_D \tag{11}$$

Then the matrix that describes the right periodic structure is similar to that obtained for the left one. We use the parameter S to be the period number instead of N, so we can write the matrix of

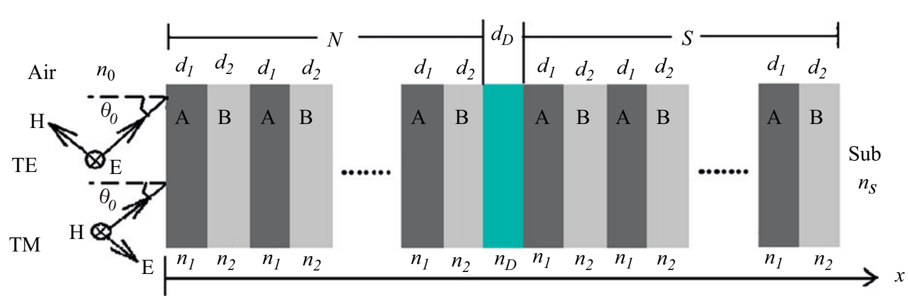

Fig. 1. A defective 1D PC structure, in which the thicknesses of the dielectric layers are denoted by d_1 and d_2, respectively, and that of defect layer, is d_D. The corresponding refractive indices are separately indicated by n_0, n_1, n_2, n_D, and n_s, where n_0=1 is taken for free space and n_s is for the substrate.