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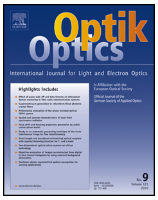

Original research article

Dependence of the defect mode on the temperature and the angle of incidence in a one-dimensional photonic crystal

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ABSTRACT

In this work, by using the transfer matrix method, it was theoretically studied the dependence on temperature and the angle of incidence of the transmittance spectrum for the TE mode in a defective one-dimensional photonic crystal. We found that there is only one defect mode within the photonic band gap, where the height of the transmittance peak and the position depend on the angle of incidence. By increasing the angle of incidence there is a shift to short wavelengths of the photonic band gap and the defect mode. Additionally, we found that when considering the simultaneous effects of thermal and thermal-optical expansion, the defect mode shows a shift to long wavelengths with the increase in temperature.

1. Introduction

Photonic crystals (PC) are a new kind of optical materials which facilitate control of light propagation [1,2]. In analogy to the periodic quantum potential of atomic crystals, in PCs the dielectric function is periodic in space. In this way, the allowed states (valence and conduction bands) and forbidden (band gaps) that in atomic crystals are produced by phenomena of constructive and destructive interference of the electronic wave function [3], in PCs it arises as interference phenomena of the electromagnetic waves scattering in the crystal [4]. PCs are characterized by having a photonic band gap (PBG) that forbidden the light propagation in a specific range of frequencies, the permitted values for which light is allowed to propagate are known as modes, whose groups form the bands [5]. The existence of PBG gives rise to optical phenomena such as the inhibition of spontaneous emission, the guidance of light through optical circuits, waveguides with low losses and Fabry Perot resonators [6–8].

By breaking the spatial periodicity of the PC by introducing impurities or defects (geometric), it is originated the presence around the impurity of defect modes located within the PBG, allowing the confinement or guidance of light modes with high efficiency [9,10]. It is in this scope where PCs are important, since with these systems it is possible to manufacture TE/TM filters, splitters, laser making and light emitting diodes [11–13]. Additionally, the possibility of tuning the PBG by modifying the optical response of the constituent materials of the PC by an external agent such as operating temperature [14,15], hydrostatic pressure [16,17], electric and magnetic fields [18–20], allow its implementation in multiplex devices by wavelength division in communication systems [21,22].

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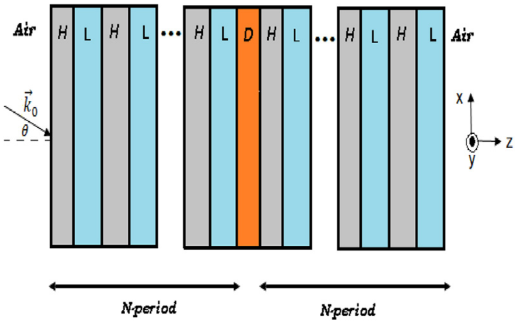

Fig. 1. Structure of 1DPC $Air/(HL)^N D(HL)^N/Air$.

In this work we are interested in studying the dependence on the temperature and the angle of incidence for the TE mode of the transmittance spectrum, of a defective one-dimensional photonic crystal (1DPC) constituted by alternating layers of TiO_2 and SiO_2 by the transfer-matrix method (TMM). We consider that in the 1DPC the defect is SiO_2, and both the refractive indexes of the means and their thicknesses depend linearly on the changes in temperature [23]. This paper is organized as follows: Section 2 is the theoretical model for calculating the transmittance spectrum by the TMM [24,25]. In Section 3, the numerical results of the transmittance spectrum of the defective 1DPC for different values of the angle of incidence and changes in temperature. The conclusions are presented in Section 4.

2. Theoretical model

In Fig. 1 we present a finite 1DPC surrounded by air composed of alternating layers of materials of high refractive index n_H and low n_L, whose thicknesses are d_H and d_L, respectively. The defect layer D has refractive index n_D and thickness d_D. The number of periods of the two-layer HL is given by N. The wave vector of the incident medium is $\vec{k}_0$, θ the angle of incidence, the PC has an homogeneous pattern in the xy plane and the direction of periodicity in z.

For the TE modes that will be the focus of our attention in the present work, the monochromatic electric field is linearly polarized propagating in the plane (x, z):

$$\vec{E}_j(x,z) = \vec{e}_y \left(A_j e^{ik_{j,z}z} + B_j e^{-ik_{j,z}z} \right) e^{-iq_x x} \tag{1}$$

where $k_{j,z} = \sqrt{\left(\frac{\omega}{c}\right)^2 \epsilon_j - q_x^2}$, ϵ_j and ω, is the z component of the wave vector, the dielectric constant in the jth layer and the angular frequency, respectively. The transversal component of the wave vector is $q_x = k_0 \sin\theta$. The values of A_j and B_j are calculated by the continuity conditions in the tangential components of the electric and magnetic fields. In the TMM each layer of the 1DPC is represented by a matrix [24]:

$$M_j = \mathfrak{D}_j P_j \mathfrak{D}_j^{-1} \quad j = H, L, D \tag{2}$$

where P_j is the propagation matrix given by,

$$P_j = \begin{pmatrix} e^{i\varphi_j} & 0 \\ 0 & e^{-i\varphi_j} \end{pmatrix} \tag{3}$$

with the phase $\varphi_j = k_{j,z} d_j = \frac{2\pi d_j}{\lambda} n_j \cos\theta_j$. In Eq. (2) the dynamic matrix for the TE mode is given by:

$$\mathfrak{D}_j = \begin{pmatrix} 1 & 1 \\ n_j \cos\theta_j & -n_j \cos\theta_j \end{pmatrix} \tag{4}$$

The total transfer matrix for the 1DPC $Air/(HL)^N D(HL)^N/Air$, is defined as

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \mathfrak{D}_0^{-1} (M_H M_L)^N M_D (M_H M_L)^N \mathfrak{D}_0 \tag{5}$$

with $\mathfrak{D}_0$ the dynamic matrix of air. The transmittance $\mathfrak{I}$ is calculated with the matrix elements M_{11} of Eq. (5),

$$\mathfrak{I} = \left| \frac{1}{M_{11}} \right|^2 \tag{6}$$