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Dependence of optical microcavities coupled with temperature in one-dimensional photonic crystals

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ABSTRACT

In this work, by the transfer matrix method we calculated the transmittance spectrum of two defects coupled in a one-dimensional photonic crystal composed of alternating layers of $Bi_4Ge_3O_{12}$ and SiO_2 with defects of SiO_2. We consider the simultaneous effects of thermal and thermal–optical expansion. It was found the presence of two defect modes within the photonic band gap, where the position of the modes changes to long wavelengths when increasing the temperature. Additionally, as we increase the separation of defects and temperature, the confinement of the modes is greater with a shift of the central wavelength.

1. Introduction

In the atomic crystals the electrons suffer multiple scattering, the constructive interference gives rise to allowed electronic states such as conduction or valence bands, while the destructive interference originates prohibited electronic states [1]. The allowed electronic energies are represented by bands and those prohibited are represented by electronic bandgaps. Analogously, photons or electromagnetic waves suffer multiple scattering in a photonic crystal (PC). PCs are a new class of artificial optical materials with a periodic modulation in the space of the refractive index with a period comparable to the wavelengths of electromagnetic waves, and in the same way as in an atomic crystal, the constructive interference gives rise to bands or allowed states and destructive interference gives rise to photonic band gaps (PBG) [2,3]. However, there are important differences: the description of the electronic dynamics in an atomic crystal is governed by Schrödinger's scalar equation, while the description of the electromagnetic dynamics in a PC is governed by Maxwell's vector equations [4]. Additionally, the possibility of tuning the PBG by the optical response of the constituent materials of the PC by an external agent such as operating temperature [5,6], hydrostatic pressure [7,8], electric and magnetic fields [9,10], attracts the attention of researchers in their implementation in devices such as TE/TM filters, splitters, laser manufacturing and light-emitting diodes [11–13].

The insertion in the PC of geometric or compositional defects that break the spatial periodicity of the crystal, originates the presence of electromagnetic modes within the PBG [14]. In this way, it is possible to produce a cavity in low absorption dielectric materials through a confinement mechanism called distributed Bragg-reflection. This generates a large increase in the quality factor Q of the cavity, defined as the ratio between the stored energy and the energy dissipated in a cycle [15]. These heterostructures allow the confinement of light of great interest in the solid state and quantum optics, the construction

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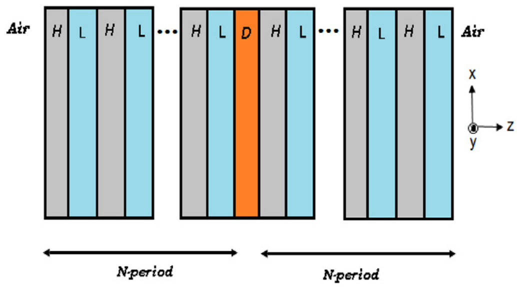

Fig. 1. Structure of 1DPC $Air/(HL)^N D(HL)^N/Air$.

of waveguides with higher quality factors than those of fiber optics, optical filters, optical switches, resonant cavities and Fabry–Perot resonators [16–19].

The wide variety of functionalities offered by photonic devices has its origin in the interaction between the basic constituents of the system. Particularly the coupling of the electromagnetic modes associated with the defects in the heterostructure with the capability of those constituents to transfer information between them. The coupling in PC attracts attention because it provides some important functionalities which cannot be reached with a single defect, as in the waveguides made of coupled defects which are referred to as coupled cavity waveguides and in optical switches [20,21].

In this work, we are interested in studying the dependence on the temperature of the transmittance spectrum for the case of normal incidence, in the coupling of defects in a one-dimensional photonic crystal (1DPC). The crystal is composed of alternating layers of $Bi_4Ge_3O_{12}$ and SiO_2 with defects of SiO_2. We will assume a linear dependence on the temperature of the refractive indices and the thicknesses. The work is organized as follows: Section 2 presents the theoretical model for calculating the transmittance spectrum by using the transfer matrix method (TMM). In Section 3, the numerical results of the transmittance spectrum for different temperature values. The conclusions are presented in Section 4.

2. Theoretical model

In this work we studied the propagation of electromagnetic waves with normal incidence on a defective finite 1DPC surrounded by air, and with a homogeneous pattern in the *xy* plane as shown in Fig. 1. The crystal is composed of alternating layers of non-magnetic and isotropic materials, with H and L the materials of refractive indexes n_H, n_L and thicknesses d_H and d_L, respectively. The defect is given by D with refractive index n_D and thickness d_D, the number of periods of layers HL is N.

The monochromatic electric field of frequency ω linearly polarized propagating in the plane (x, z) is given by:

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

with $k_{j,z} = \sqrt{\left(\frac{\omega}{c}\right)^2\epsilon_j - q^2}$ the z component of the wave vector, ϵ_j the dielectric constant in the jth layer and q the wave vector along the x axis. 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 H, L and D of the 1DPC is represented by the matrix [22]:

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

with P_j the propagation matrix,

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

of phase φ_j given by:

$$\varphi_j = k_{j,z}d_j = \frac{2\pi d_j}{\lambda} n_j \tag{4}$$

In Eq. (4) d_j and $n_j = \sqrt{\epsilon_j}$, is the thickness and the refractive index in the jth layer, respectively. In Eq. (2) the dynamic matrix is,

$$\mathfrak{D}_j = \begin{pmatrix} 1 & 1 \\ n_j & -n_j \end{pmatrix} \tag{5}$$