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Effects of hydrostatic pressure, temperature and angle of incidence on the transmittance spectrum of TE mode in a 1D semiconductor photonic crystal

Francis Segovia-Chaves [a,b,*], Herbert Vinck-Posada [a]

[a] *Departamento de Física, Universidad Nacional de Colombia, AA 055051 Bogotá, Colombia*
[b] *Departamento de Ciencias Naturales, Universidad Surcolombiana, AA 385 Neiva, Colombia*

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ABSTRACT

In this paper, we study the effects of hydrostatic pressure, temperature and angle of incidence on the transmittance spectrum of *TE* mode of a one-dimensional photonic crystal, using the transfer-matrix method. We consider that the crystal is formed by alternated layers of air and *GaAs*, with the dielectric constant of *GaAs* as a function of the temperature and pressure applied. We found that the spectrums dependence on temperature is negligible, the optical response of the system is due mainly to the pressure applied. When increasing the hydrostatic pressure, the spectrum shifts to a short-wavelength, which is caused by the decrease of the dielectric constant of *GaAs*. These results agree with the electromagnetic variational theorem. We also found if the angle of incidence of the modes increases, the band width increases compared to the normal incidence modes.

1. Introduction

Light propagating on periodic one-dimensional structures dates back to 1887 when Lord Rayleigh discovered that when the angle of incidence varies [1], it is possible to obtain regions where the light is totally reflected. A century later, these regions were called photonic band gap (PBG). In 1987, the work of Eli Yablonovitch [2], who worked on inhibiting the spontaneous emission of electrons in semiconductors, and Sajeev Jhon [3], who studied the effects of localization of light in disordered systems, proposed making periodic structures named photonic crystals (PC), thus appearing the concept of photonic band gap in two and three dimensions. The principle of functionality in PCs is the periodic spatial variation of the dielectric constant, equivalent to a periodic potential in an atomic crystal [4]. The allowed and forbidden (PBG) states in PC are due to the Bragg diffraction, generated by the scatterers that form the crystal [5]. In PBGs no light mode with a frequency within the frequency range of PBG can propagate, regardless its polarization and angle of incidence.

PCs are formally described by Maxwell's electromagnetic theory [6]. It is possible to find the PBGs and the states of the electromagnetic field by solving the equations. To solve Maxwell's equations there are the following methods: plane waves, finite-difference frequency and time domain, transfer-matrix, scattering-matrix, among others [7–10].

The possibility of tuning the PBG by modifying the optical response of the materials that form the PC using external parameters such as electrical and magnetic fields [11,12], temperature [13,14] and hydrostatic pressure [15], allows it to be

* Corresponding author at: Grupo de óptica e información cuántica, Universidad Nacional. Departamento de Ciencias Naturales, Universidad Surcolombiana.

E-mail address: francis.segoviac@gmail.com (F. Segovia-Chaves).

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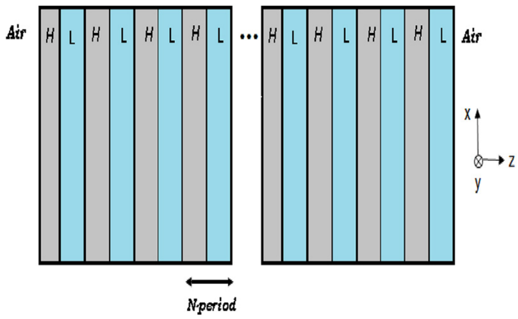

Fig. 1. Photonic crystal one-dimensional $Air/(HL)^N H/Air$.

implemented in potential applications of modern photonics such as optical switches and tunable filters, very important in wavelength-division multiplexing [16–18].

In this work, we studied the effects of the hydrostatic pressure applied, temperature and angle of incidence on the transmittance spectrum for the TE mode of a one-dimensional photonic crystal (1DPC), within the Maxwell framework and using the transfer-matrix method (TMM). We considered a 1DPC consisting of alternate layers of air and *GaAs*, in which the dielectric properties of the semiconductor depend on pressure and temperature. The work is organized as follows: Section 2, we present the theoretical framework. Section 3, we present the numerical results and discussion related to the calculation of the transmittance spectrum of the 1DPC for different temperatures, hydrostatic pressures, and angles of incidence. Finally, conclusions are presented in Section 4.

2. Theoretical model

In Fig. 1, we present a finite 1DPC surrounded by air and consisting of alternate layers of materials, with high ϵ_H and low ϵ_L dielectric constants, whose thickness are d_H and d_L respectively. The wave vector of the incident medium is k_0 and the angle of incidence is θ, the PC has a homogeneous pattern in the xy plane and a periodicity in z direction. The number of periods of HL layers is given by N.

We consider a linearly polarized electromagnetic wave propagating through the (x, z) plane with a wave vector q_x along the x-axis. For the TE modes, which will be our focus, the electric field is given by

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

where $k_{j,z} = \sqrt{\left(\omega/c\right)^2 \epsilon_j - q_x^2}$ and ϵ_j, is the z component of the wave vector and the dielectric constant in the jth layer, respectively. The transverse component of the wave vector is $q_x = k_0 sin\theta$, A_j and B_j values are calculated by the continuity conditions of the tangential electric and magnetic field components. In the TMM, each 1DPC layer may be represented by a matrix [19],

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

In Eq. (2) the propagation matrix is

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

with phase φ_j given by:

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

In Eq. (4) d_j and $n_j = \sqrt{\epsilon_j}$ are the thickness and refractive index in the jth layer, respectively. The dynamic matrix for the TE mode is given by

$$D_j = \begin{pmatrix} 1 & 1 \\ n_j \cos\theta_j & -n_j \cos\theta_j \end{pmatrix} \tag{5}$$

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

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = D_0^{-1} (M_H M_L)^N M_H D_0 \tag{6}$$