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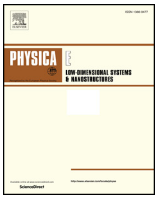

Dependence of photonic defect modes on hydrostatic pressure in a 2D hexagonal lattice

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ABSTRACT

The plane wave expansion method is used to investigate the effects of hydrostatic pressure on the photonic band structure in a two-dimensional hexagonal lattice composed cylindrical air holes embedded in a GaAs background. We found that the hydrostatic pressure modifies the optical response of the crystal. While increasing the pressure, the photonic band structure for both transverse electric (TE) and transverse magnetic (TM) polarizations, exhibit a shift to high-frequency regions due to a decrease in the dielectric constant of the semiconductor. Using the supercell technique, the numerical results exhibit that both the position and width of the photonic band gap for both polarizations remain unchanged while eliminating a cylindrical air hole. Additionally, we observe defective modes whose energies increase with an increase in hydrostatic pressure inside the photonic band gap.

1. Introduction

In the previous decades, photonic crystals (PC) and their optical properties have given rise to interest in the scientific community regarding their suitability as candidates to be applied to applications in various fields of optics and optoelectronics [1]. Since the pioneering works of E. Yablonovitch and S. John about the inhibition of spontaneous emission and the localization of light in periodic dielectric structures [2,3], PC has been the denomination for structures characterized using a dielectric function, which is periodic in one, two, or three dimensions, with spatial periods of a fraction of the optical wavelength. This is analogous with the atomic crystals in which the allowed (valence and conduction bands) and forbidden states are produced by constructive and destructive interference of the electronic wave function [4]. These PC states are caused due to the interference phenomena of the light scattered by the crystal constituents. The frequency bands at which propagation of light is not allowed are referred to as the photonic band gaps (PBG) [5]. In fact, one of the most attractive characteristics of PCs and their main technological applications are based on the existence of PBGs [6,7]. However, there are considerable differences between atomic crystals and PCs. The description of electronic dynamics is governed by the Schrödinger scalar equation, whereas PCs are formally described using Maxwell's electromagnetic theory [8]. The solution of Maxwell equations in PCs allows to find the photonic band structure (PBS) and the respective states of the electromagnetic field. Additionally, when the periodicity of PC is broken by the insertion of defects (geometric or compositional), the location of the electromagnetic field around the defect is induced, allowing the confinement or guidance of light modes with a high efficiency [9].

The study of two-dimensional photonic crystals (2DPC) can be dated back to the early nineties because of the enormous possibilities that are offered by these structures for controlling the transmission and absorption of light. These phenomena are dependent on PBS, which can be determined by the dielectric and magnetic permeability functions of the constituents of PC as well as the crystalline structure [10]. The most common 2DPCs comprise lattices with triangular, square, and hexagonal geometries, including square and circular cross-section rods. In Refs. [11,12], a PBG is observed to be absent in the configurations of dielectric rods that are embedded in air, whereas a PBG is generated in the configurations of air holes in a dielectric background. As an example, we can refer to the works of R. Meade et al. [13] and J. Wendt et al. [14]. These authors observe that, in a hexagonal lattice of air rods in a dielectric material, a PBG can be produced for any polarization if the dielectric exhibits a refractive index of greater than 2.7. This can be confirmed using the direct-write techniques of electron-beam lithography and reactive-ion-beam etching in case of 2DPC nanofabrication for a hexagonal lattice of air rods, recorded on a semiconductor surface with a refractive index contrast of 3.54. The point defects that are

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caused by eliminating the air rods in 2DPC serve as resonant cavities that trap photons of certain frequencies [15]. The quality factor, *Q*, of the cavity can be determined by comparing the energy loss per cycle against the stored energy [16]. K. Hennessy et al. [17] observed that the quality factor exhibited values as high as 4000 while investigating the optical emission of InAs quantum dots that are embedded in a microcavity of a square lattice 2DPC. Y. Taguchi et al. [18] observed that *Q* is 3.9 million while considering a 2DPC triangular lattice of circular air holes with a radius of 110 nm, which was formed in an Si slab having a thickness of 220 nm. In this structure, the nanocavity is formed by a linear defect while removing 17 air holes. However, the theoretical *Q* factor of this structure exceeds 10 million. The discrepancy in experimental *Q* can be attributed to the imperfections, such as the structural variations in the air holes and the losses of absorption related to the surface, while manufacturing the nanocavities [19]. K. Venkatachalam et al. [20] used the plane wave expansion (PWE) and finite difference time domain (FDTD) methods to calculate *Q*. Additionally, they calculated the PBG and the normalized transmission spectra in a ring resonator that was designed to introduce both linear and point defects. They observed that the *Q* factor can be controlled by varying the size of the cavity, the periods, and the coupling between the cavity and the waveguide. The coupling of defects in one-dimensional PC (1DPC) and 2DPC of GaAs rods in a square lattice has been theoretically investigated by S. Lan et al. [21] using the transfer matrix (TMM) and FDTD methods. These authors have observed that the coupling behavior of the defects is reflected in the spectra of PC molecules formed by two identical PC atoms (single defects). The PC atoms are classified in accordance with the spectral shape of the PC molecules; a PC atom generates the bonding and antibonding states in the spectra of the molecules, whereas the other type of atom creates PC molecules with spectra that are almost flat on top. Due to the advantages associated with manufacturing and modeling in 2D, the experimental and theoretical studies related to 2DPC that contain defects has received research attention due to the possibilities that are offered by these structures in optical waveguides [22], defect-mode PC lasers [23], optical switches [24], and filters [25].

The tuning of PBG opens a new perspective in scientific research. A tunable PBG can be obtained by externally controlling the response functions of the constituent materials of PC. The response function can be modified according to the temperature, hydrostatic pressure, and magnetic and electric fields. Manzanares–Martínez et al. [26] considered a 2DPC with air rods in an InSb background. In this study, they observed that, due to the dependence of the concentration of intrinsic carriers in the semiconductor on the temperature, the temperature can be used as a tool for tuning the PBG and the transmission spectra. H. Elsayed et al. [27] investigated the simultaneous effects of thermal and thermo-optical expansion in a 2DPC composed Si rods in a square lattice in an air background. They demonstrate that temperature variations exhibit an influence on PBG in case of the TE and TM modes. PBG enhancement can be achieved when the temperature is increased to become more than the room temperature due to the variation in contrast between the refractive indices of the rods and the background material. A. Aly et al. [28] used the TMM to observe a defect mode shift to short wavelengths in a 1DPC containing a defective layer of a nanocomposite material in case of infrared radiation. The effects of hydrostatic pressure, temperature, and angle of incidence on a 1DPC composed a superconductor and semiconductor have been reported by A. Herrera et al. [29] and F. Segovia et al. [30]. These authors observed that, by increasing the temperature and angle of incidence and by maintaining both the thicknesses of the materials as well as the pressure constant, there is a shift of the transmittance spectrum to lower frequency values with an increase in the bandwidth of the gaps and with a decrease in the cutoff frequency. The PBG can be tuned without modifying the structure of PC by considering the variations in the intrinsic properties of the materials that constitute the PC. As an example, N. Porras and C. Duque [31] report the dependence on temperature and hydrostatic pressure of the PBS in a two-dimensional honeycomb lattice composed cylindrical GaAs rods embedded in air. They observe a shift in PBS due to the variation of the dielectric constant of GaAs with the temperature and the applied hydrostatic pressure. The shift to higher energies is related to the decrease in dielectric constant by increasing the pressure for a given temperature value. In Ref. [32], the effects of the magnetic field on the PBS in a metallic 2DPC are investigated based on the Faraday Effect. Using the PWE method, they observe that the PBG can be adjusted because the dielectric constant of metals is affected by the external magnetic field, especially below the plasmon frequency. C. Duque and M. Mora [33] report the combined effects of the magnetic field, hydrostatic pressure, and temperature in a 2DPC square and triangular lattice composed cylindrical GaAs rods. The general effect of the hydrostatic pressure causes the PBG to shift toward high frequency values. The temperature slightly affects the location and width of the gaps; the shift is observed to be toward regions of short frequencies both in the square photonic and triangular crystal lattice. The application of magnetic field gives rise to new PBGs in both the types of lattice. A. Ahmed et al. [34] investigated the effects of the external electric field on the reflectance spectrum in a 1DPC composed lithium niobate and polymer materials. They observe that, by increasing the applied electric field, the contrast of refractive indices can be increased and the edges of the PBG can shift to short wavelengths that will be accompanied by a linear increase in the width of the PBG. Another method for tuning the PBG is by concentrating the doping impurities from the dielectric constant of a semiconductor layer. Recently, H. Elsayed [35] considers a 1DPC that is composed of an extrinsic semiconductor (InSb) and a dielectric (MgF_2). Using the TMM, we can observe that the concentration of doping impurity significantly affects the transmittance spectrum of the PC. This parameter controls the number, position, and width of the PBG. For 2DPCs, the dependence of the PBS and PBG on the variations in the concentration of doping impurities has been further studied in Ref. [36]. The authors consider the Si-doped rods that are embedded in a square air lattice. The numerical results exhibit a large width of PBG with a shift to high frequencies while increasing doping.

However, Tefelska et al. [37] experimentally investigated the effects of hydrostatic pressure on the polarization and propagation properties in photonic liquid crystal fibers. They concluded that the effect of hydrostatic pressure narrows the PBG and the variations in the polarization state. Similar results are reported by Wolinski et al. [38] while experimentally considering the influence of temperature, external electric field, and hydrostatic pressure on the propagation properties in photonic liquid crystal fibers. They observe that there was a shift in the wavelength of the PBG as the temperature changed. This shift of PBG in the transmittance spectrum is used to determine the thermal characteristics of the ordinary refractive index of the liquid crystal. By increasing the pressure from 0 to 73.2 MPa, the position of the PBG was dependent not only on the refractive index of the material but also on the geometry. The effect of hydrostatic pressure and the modification of the polarization properties in the PC altered the phase birefringence. Martynkien et al. [39] experimentally investigated the polarimetric sensitivity at the hydrostatic pressure and temperature in two PC fibers guided by a highly birefringent index. They observed that the polarimetric sensitivity to temperature is less than that in case of conventional highly birefringent fibers by at least two orders of magnitude. In Ref. [40], the effects of hydrostatic pressure on the transmittance spectrum in a dual-core PC fiber have been experimentally investigated. By increasing the pressure from 0 to 45 MPa, a shift can be observed in the transmittance spectrum to short wavelengths. S. Olyaee and A. Dehghani [41] presented a pressure sensor, which comprised a PC waveguide coupled to a nanocavity. The waveguide can be configured by eliminating a row of Si cylindrical rods, whereas the nanocavity can be configured by inserting a point defect as it is to modify the radius of an Si rod of the 2DPC. By varying the optical properties of Si, the refractive index is observed to alter and, therefore, the resonant