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Invited Paper

Elastic dependence of defect modes in one-dimensional photonic crystals with a cholesteric elastomer slab

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A B S T R A C T

We studied the transmission spectra in a one-dimensional dielectric multilayer photonic structure containing a cholesteric liquid crystal elastomer layer as a defect. For circularly polarized incident electromagnetic waves, we analyzed the optical defect modes induced in the band gap spectrum as a function of the incident angle and the axial strain applied along the same axis as the periodic medium. The physical parameters of the structure were chosen in such a way the photonic band gap of the cholesteric elastomer lies inside that of the multilayer. We found that, in addition to the defect modes associated with the thickness of the defect layer and the anisotropy of the elastic polymer, two new defect modes appear at both band edges of the cholesteric structure, whose amplitudes and spectral positions can be elastically tuned. Particularly, we showed that, at normal incidence, the defect modes shift toward the long-wavelength region with the strain; whereas, for constant elongation, such defects move toward larger frequencies with the incidence angle.

1. Introduction

Photonic crystals (PCs) are artificial structures whose fascinating properties have been the subject of theoretical and experimental studies. Their optical properties have been conveniently exploited in the fabrication of new devices for numerous applications including control of optical radiation in laser engineering and information transfer systems [1,2]. Owing to the periodic modulation of their refractive index, the most attractive attribute of these structures is the existence of photonic band gaps (PBGs) in which the propagation of electromagnetic waves is prohibited for a specific wavelength range and photon group velocity is suppressed at the edge of the PBG [3]. In one-dimensional structures, this phenomenon is usually called Bragg reflector or Bragg mirror. The simplest one-dimensional PC is a multilayer structure consisting of alternate layers of two dielectric materials with different refractive indices.

Localization of photons can be achieved by inserting a defect in a PC [4]. Application of photon localization has been exposed in low-threshold lasers and microwave guides [5–7]. Such a defect is commonly composed of a Fabry-Pérot microcavity structure sandwiched between two Bragg mirrors. The defect layer acts as a microcavity where standing waves with a huge energy density are localized in the proximity of the defects (defect modes). The defect modes are transmission bands localized inside the PBGs, whose amplitude and position depend on the geometric and physical parameters of the designed periodical structure.

In many technological applications, active tuning and switching of defect modes is desirable. This can be achieved by taking advantage of the susceptibility of the optical properties of certain materials with pressure, temperature, electric or magnetic fields. Appropriate combination of these materials, acting as defect layers, with PCs provides an useful way for the external control of optical defect modes. Liquid crystals (LCs) are anisotropic intermediate phases between the solid and liquid states of matter whose physical properties can be easily controlled by external stimuli [8,9]. In a series of papers, the authors of Refs. [10–12] investigated for the first time the optical properties of a one-dimensional multilayer PC containing a nematic LC as a defect layer. They revealed the wavelength tuning of the extraordinary components of the defect modes by externally applied voltage. In Ref. [13] it was studied the thermal dependence of the spectra of defect modes for parallel and perpendicular polarizations to the director of the nematic LC At normal incidence of light by considering planar alignment of the defect layer. Particularly, it was demonstrated the spectral shift of defect modes due to the variation of the refractive index of the

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LC slab. In a similar system placed between crossed polarizers, the authors of Ref. [14] showed the spectral shift of defect modes corresponding to the extraordinary light wave and its superposition with the ordinary one, resulting in the control of the intensity of interfering optical modes by the applied magnetic field. By considering a twisted-nematic LC as a central defect layer, in Ref. [15] it was shown that the defect modes not only shift with the applied voltage but also switch between two mayor modes when the linear polarization angle of the incident light is altered. Cholesteric LC (CLCs) are periodic materials with a helical structure which display the circular Bragg phenomenon (CBP) whereby a normally incident, circularly polarized plane wave of a specific handedness is highly reflected in a certain wavelength regime, whereas a similar plane wave of the reverse handedness is not. A one-dimensional PC infiltrated with a cholesteric LC defect layer has been previously considered in Ref. [16]. It was found one additional peculiar mode with a high Q factor at the band edge of the cholesteric LC which exists necessarily under any set of conditions as long as the PBG of the CLC is inside that of the multilayer. The authors experimentally demonstrate single-mode laser action with low pumping threshold based on the additional defect mode. In Ref. [17] it is reported a multichannel PC device with a polymer-stabilized cholesteric texture as central defect slab whose defect mode is switchable among three major stable states by various appropriate frequency-modulated voltage pulses and its intensity can be electrically tuned in multi-metastable states.

Cholesteric liquid crystals elastomers (CLCEs) are structurally chiral materials where the CBP is displayed [18,19]. CLCEs are soft solids formed by anisotropic molecules incorporated into a polymer network whose helicoidal symmetry is similar to that of CLCs. They possess unusual properties because they combine mechanical characteristics of polymers with variable optical properties of CLC. Tunability of defect modes using CLCEs was demonstrated in Refs. [20,21] by imposing a uniaxial strain in the direction orthogonal to the helical axis on a structure composed of CLCEs in a three-layer configuration, where an isotropic layer containing a laser dye is sandwiched between two CLC elastomers. Singlet and multiplet structure of the optical defect modes generated within the band gap by a finite number of twist defects in axially elongated CLCEs are shown in Refs. [22,23], where it is also demonstrated the mechanical tunability of the defect modes induced by the twist defects when the structure is deformed parallel to the helical axis.

In this paper we study elastic tunable defect modes in a one-dimensional PC which consists of a finite set of alternate layers of two dielectric materials with different refractive indices and a central microcavity of a CLCE which acts as a defect layer. The tunability of defect modes is performed by applying an elongation parallel to the periodicity axis of the structure and by varying the incident angle of the electromagnetic radiation impinging on the system for circularly polarized waves. We demonstrate the appearance of similar defect modes as shown in Ref. [16] whose amplitudes and spectral positions can be elastically tuned. The structure proposed here constitutes an elastic tunable device of easy fabrication that, as it will be shown later, operates at visible wavelength spectrum. Additionally, our results motivate the fabrication of elastically tunable devices using single-mode laser action with low pumping threshold based on the additional defect modes.

The outline of our paper is as follows. In Section 2 we write the basic equations governing the propagation of electromagnetic waves throughout the periodic structure in a 4×4 matrix representation and we establish the transfer matrix technique to obtain the transmittance and reflectance as function of axial elongation of the CLCE layer and angle of incidence of light. Numerical results for the transmittance and reflectance for circularly polarized incident waves as function of strain and angle of incidence are obtained in Sections 3 and 4. Finally, our conclusions are presented.

2. Electromagnetic propagation in a layered medium

We are focused in the elastic tunabililty of reflection and transmission spectra due to a one-dimensional photonic structure immersed in free space containing a layer of CLCE sandwiched between two multilayer PCs. Each of these multilayer mirrors consisting of N alternate layers of two dielectric materials with different refractive indices. (see Fig. 1(a)). For this purpose, we regard that an electromagnetic wave is obliquely incident parallel to the xz-plane on the system from the half-space $z \le 0$. To study this system we use a matrix formalism in which a boundary-value problem has to be established in order to determine the reflection and transmission coefficients [24].

2.1. 4×4 matrix representation

The linear interaction between the structure and the optical field is governed by the Maxwell equations and their corresponding constitutive equations. If we define the time-harmonic transversal four-component-vector

$$\Psi(x,z,t)=\psi(z)e^{ik_x x-i\omega t}=\begin{pmatrix} e_x(z)\\ e_y(z)\\ h_x(z)\\ h_y(z)\end{pmatrix}e^{ik_x x}e^{-i\omega t}, \tag{1}$$

with ω the angular frequency of the propagating wave and k_x the transversal component of wavevector, we can express Maxwell's equations, inside a non-magnetic medium, in the following matrix form:

$$\frac{\partial\psi(z)}{\partial z}=ik_0\mathbf{A}(z)\cdot\psi(z), \tag{2}$$

where the 4×4 matrix $\mathbf{A}(z)$ is given by

$$\mathbf{A}(z)=\begin{pmatrix} -\dfrac{k_x\varepsilon_{zx}}{k_0\varepsilon_{zz}} & -\dfrac{k_x\varepsilon_{zy}}{k_0\varepsilon_{zz}} & 0 & 1-\dfrac{k_x^2}{k_0^2\varepsilon_{zz}}\\ 0 & 0 & -1 & 0\\ -\varepsilon_{yx}+\dfrac{\varepsilon_{yz}\varepsilon_{zx}}{\varepsilon_{zz}} & \dfrac{k_x^2}{k_0^2}-\varepsilon_{yy}+\dfrac{\varepsilon_{yz}\varepsilon_{zy}}{\varepsilon_{zz}} & 0 & \dfrac{k_x\varepsilon_{yz}}{k_0\varepsilon_{zz}}\\ \varepsilon_{xx}-\dfrac{\varepsilon_{xz}\varepsilon_{zx}}{\varepsilon_{zz}} & \varepsilon_{xy}-\dfrac{\varepsilon_{xz}\varepsilon_{zy}}{\varepsilon_{zz}} & 0 & -\dfrac{k_x\varepsilon_{xz}}{k_0\varepsilon_{zz}}\end{pmatrix}, \tag{3}$$

where $k_0=2\pi/\lambda=\omega/c$ is the wavenumber in free space, λ and c are the wavelength and the speed of light in vacuum, respectively. In writing Eq. (2) we have defined the fields $\mathbf{e}(z)=(e_x(z), e_y(z), e_z(z))$ and $\mathbf{h}(z)=(h_x(z), h_y(z), h_z(z))$, related to the electric $\mathbf{E}(z)$ and magnetic $\mathbf{H}(z)$ fields, as $\mathbf{e}(z)\equiv Z_0^{-1/2}\mathbf{E}(z)$ and $\mathbf{h}(z)\equiv Z_0^{1/2}\mathbf{H}(z)$, with $Z_0=\sqrt{\mu_0/\varepsilon_0}$ the free space impedance and μ_0, ε_0 the permeability and permittivity in vacuum, respectively. Finally, $\varepsilon_{ij}(z)$ with $(i, j=x, y, z)$, represents the elements of dielectric matrix in the structure.

2.2. Dielectric matrix of structure

Because the multilayer mirrors consist of homogeneous and isotropic dielectric films, the matrix $\boldsymbol{\varepsilon}(z)$ is diagonal and independent of the position, whereas for the polymeric slab $\boldsymbol{\varepsilon}(z)$ depends on the local orientation of the principal axis of the CLC molecules, which in turn is a function of the elongation of the periodic structure. The constitutive equation for the CLCE is

$$\varepsilon_{ij}(z)=\varepsilon_\perp\delta_{ij}+\varepsilon_a n_i n_j, \tag{4}$$