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Modulation of defect modes intensity by controlled light scattering in photonic crystal with liquid crystal domain structure

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ABSTRACT

A method to modulate the defect modes intensity in a multilayer photonic crystal with a nematic liquid crystal layer arranged midmost has been proposed. The various electrohydrodynamic domain structures (Williams domains, oblique rolls and grid pattern) were formed in the nematic layer under the action of ac electric field. The domains cause a polarization-sensitive light scattering which leads to an anisotropic reduction of the defect modes intensity. Thus by varying the applied voltage, we can tune gradually the transmittance spectrum of photonic crystal. In addition, the spectrum strongly depends on the light polarization direction above threshold voltage.

1. Introduction

Photonic-crystal (PC) structures attract much attention as new optical materials whose permittivity periodically changes in one, two, or three dimensions with the spatial scale comparable with the light wavelength [1,2]. An important property of these structures is the presence of photonic band gaps (PBGs) with the low density of photonic states and low transmittance. The band gaps exhibit extraordinary dispersion characteristics, which allow implementing some regimes of propagation of light waves in the PC structures that are interesting for both fundamental research and application [1–3]. One-dimensional (1D) photonic crystals are multilayer periodic structures consisting of alternating layers of dielectric materials with different refractive indices [4]. In contrast to 3D-PCs, they do not have a complete PBG; however, they are multifunctional and simple to fabricate. Such structures are widely used as interference filters, antireflection coatings, mirrors with high reflectance in a wide frequency range, etc. In band gaps of the photonic crystals with a lattice defect, i.e., broken periodicity, transmission bands occur that are called the defect or localized modes. Combining PCs and liquid crystals (LCs) as a defect layer, one can obtain photonic structures with controllable spectral characteristics [3,4]. High sensitivity of LCs to external factors (temperature and electric or magnetic fields) in combination with high birefringence, transparency in the visible and near-infrared ranges, and optical nonlinearity make it possible to control the spectral position and transmittance of defect modes in these structures. The multilayer PC structures with the tunable spectrum have been well-studied [5–7], but there is a lack of works devoted to the methods for controlling the defect mode amplitude and related intensity modulation. High-contrast modulation of defect modes in a PC/LC structure controlled by

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electric or magnetic field was experimentally demonstrated in [8–10]. The proposed technique is based on the field-induced matching of the tunable *e*-modes, corresponding to extraordinary light waves, with fixed *o*-modes, corresponding to ordinary light waves. The matching can lead to both interference amplification of their intensity and mutual quenching of the modes of two types. These interference effects cannot be implemented without additional polarization elements. On the other hand, of interest are recent studies on 1D-PCs characterized by scattering of light waves on optical inhomogeneities arisen [11] or inserted [12] in defects of the periodic structure. The authors of [11] developed the electric-field-controlled photonic device with no polarization elements on the basis of a 1D-PC infiltrated with a double-frequency cholesteric LC as a defect layer. The device allows using different frequency-modulated voltage pulses for controlling defect modes and switching the stable states. The authors of [12] theoretically and experimentally investigated transmission of light through a Fabry–Perot microcavity consisting of distributed mirrors and containing a dielectric cylindrical rod as a defect. It was shown that the light transmitted through this system is scattered at different resonance angles and undergoes the angular resonance transformation. As controlled defects in PCs, the so-called spatially extended systems can be used, including nematic LCs characterized by the electroconvective instabilities. It is caused by the spatial inhomogeneity of optical anisotropy of LC in the originally homogeneous nematic liquid crystal caused by the applied field over the threshold value [13]. The approach to describe scattering processes in the domains generated by the electric field is similar to the approach for description of light scattering by a LC droplet in polymer [14,15]. The difference is that formed domains change their dimensions and they are in an anisotropic “matrix” of liquid crystal.

The hierarchy of convective structures easily switched by electric field and the dependence of the optical response of spatially extended nematics (SEN) on light polarization make it possible to control the amplitude of modes in the PC spectrum [16].

In this study, we propose a new way of modulation of the mode intensity based on controlled light scattering in a multilayer PC/SEN structure. The electrohydrodynamic convection, which manifests itself as a domain grid pattern (GP) in nematic, is used. In addition the continuous variation in the transmittance of defect modes in the spectrum of the photonic structure is initiated by changing the angle α between orientation of the nematic director **n** (unit vector characterizing a preferred molecular alignment for a local volume of a LC layer) on the substrates and light polarization via rotation of a polarizing element.

2. Photonic structure

A scheme of the photonic structure used for studying the effect of different electroconvective instabilities on its spectral characteristics is presented in Fig. 1a. A sample consists of two dielectric mirrors with a gap of 11.7 μm filled with the 4-metoxybenzylidene-4′-butylaniline (MBBA) nematic LC, which has the negative permittivity anisotropy ($\varepsilon_a < 0$) and positive conductivity anisotropy ($\sigma_a > 0$). The clearing temperature of nematic is T_c=45 °C and the refractive indices are n_e=1.765 and n_o=1.552 (t=23 °C, λ=589 nm) for the light polarized parallel and perpendicular to the director, respectively. The multilayer coating of the mirrors consists of six 55-nm-thick zirconium dioxide (ZrO_2) layers with a refractive index of 2.04 and five 102-nm-thick silicon dioxide (SiO_2) layers with a refractive index of 1.45 alternately deposited onto the surface of quartz substrates preliminary coated with a thin (~150 nm) ITO layer, which serves as an electrode for applying electric field **E** normally to the sample plane. The planar orientation **n** of the LC director was specified by an unidirectionally rubbed polymer coating (the *x*-axis of the *x*, *y*, *z* frame). The orientation was controlled on a polarization microscope by extinction of the field of view in crossed polarizers. Hereinafter, the light wave polarizations parallel and perpendicular to the rubbing direction in all the microscopic, spectral, and electrooptical measurements are denoted by indices ∥ and ⊥, respectively. The applied ac field along the *z*-axis with a frequency of 80 Hz below a certain threshold value cannot modify the optical response of the photonic structure with the uniformly ordered nematic LC (Fig. 1b). Above the threshold, the

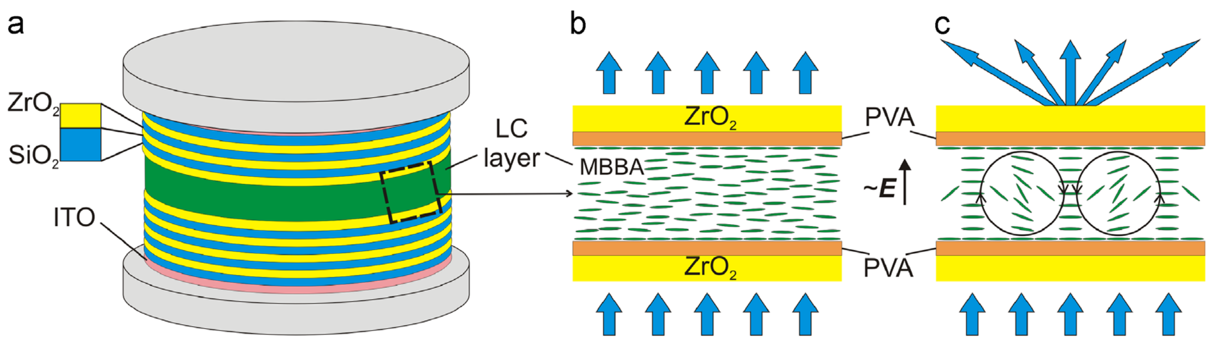

Fig. 1. Scheme of an electrically controlled PC/SEN cell with ITO coating under ZrO_2/SiO_2 multilayers (a). The LC layer is nematic MBBA with 11.7 μm thickness. Orientation of the LC director when applied ac field is less than the threshold value (b). Orientation of the LC director when applied ac field is more than the threshold value (c). In case (b) there is a planar orientation and scattering is absent, in case (c) electroconvective instability is implemented which causes light scattering. The thick short lines in (b) and (c) display the LC molecules.