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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 $\mathbf{n}$ (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, $\lambda = 589$ 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 $\mathbf{E}$ normally to the sample plane. The planar orientation $\mathbf{n}$ 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

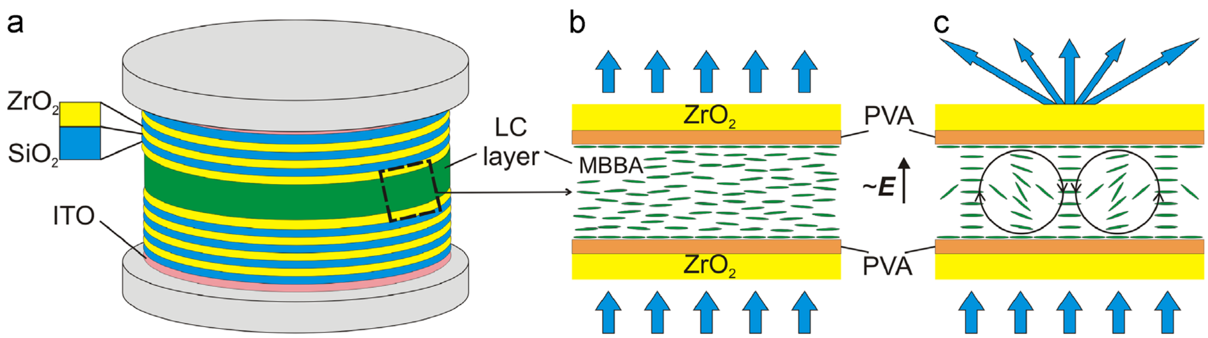

Fig. 1. Scheme of an electrically controlled PC/SEN cell with ITO coating under ZrO_2/SiO_2 multilayers (a). The LC layer is nematic MBBA with 11.7 μm thickness. Orientation of the LC director when applied ac field is less than the threshold value (b). Orientation of the LC director when applied ac field 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.

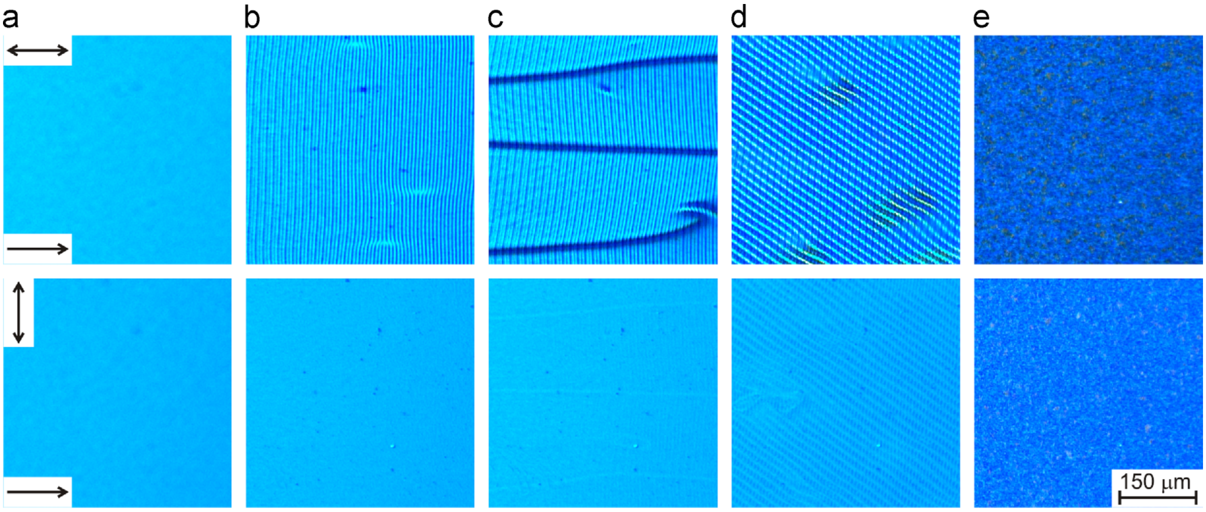

Fig. 2. Microphotographs of LC textures in photonic structure at applied ac voltage: $U=6.0$ V (a), $U=6.2$ V (b), $U=6.7$ V (c), $U=7.7$ V (d), $U=12.0$ V (e). Arrows indicate the direction of light polarization ($\leftrightarrow$) and the LC director **n** ($\rightarrow$).

nematic structure is periodically disturbed due to the electrohydrodynamic convection, which causes strong light scattering (Fig. 1c).

3. Experiment results and discussion

Microphotographs of the LC textures in the photonic structure obtained using a polarizing microscope (Fig. 2a–e) show the transformation of different electroconvection patterns in the nematic with increasing ac voltage. The upper and lower rows of the textures correspond to the parallel (‖) and perpendicular ($\perp$) polarizations of the light wave, respectively. For ‖-component, the structure remains transparent up to the threshold voltage $U_c=6.2$ V (Fig. 2a) due to the uniform alignment of nematic molecules in the defect layer. The primary electroconvective pattern, the so-called Williams domains (WD), occurs at the threshold field (Fig. 2b) [17]. Convection leads to the spatial periodicity of the LC refractive index and thus causes spatial modulation of the light field phase on an output mirror. Then, as the applied ac voltage is increased, one observes secondary instability such as oblique rolls (OR) instability (Fig. 2c) [18], which are brought to the domain grid pattern (Fig. 2d) [19]. The grid pattern is the last ordered state in the nematic liquid flow, which is followed by the chaotic dynamic scattering mode accompanied by the strong light scattering (Fig. 2e). Note that $\perp$-component remains transparent up to a voltage of 6.5 V (Fig. 2c) above which the textures of this polarization repeat the convective patterns characteristic of ‖-component, but with the much weaker contrast.

The polarized components of the transmission spectrum $T_{\parallel,\perp}(\lambda)$ and the field dependences of the spectra $T_{\parallel,\perp}(U)$ under the conditions of the discussed convection processes were studied using a Shimadzu UV-3600 spectrometer. As a polarizing element, we used a Glan prism oriented along (‖-component) or perpendicular ($\perp$-component) to the rubbing direction by its principle plane. An aperture 4 mm in diameter was placed behind the sample. Spectra were detected at a fixed temperature of 25 °C; the sample thermal stabilization accuracy was no worse than ±0.2 °C. The investigated PC structure forms a PBG in the transmission spectrum at wavelengths of 420–610 nm with a set of localized modes whose position is determined by the parameters of mirrors and defect layer and by the direction of polarization of the probing radiation. The transmission spectrum of the PC with the planar MBBA layer obtained at an applied ac voltage below threshold voltage U_c forms two sets of defect modes corresponding to components $T_{\parallel,\perp}$ (Fig. 3).

Transformation of the spectra above threshold voltage U_c in the wavelength range 500–520 nm at the PBG center, which is most sensitive to the radiation loss in real PC structures [7] is shown in Fig. 4. As one can see the field dynamics of damping of ‖- and $\perp$-modes is essentially different. In addition, in contrast to the transverse modes, the parallel modes noticeably shift to the short-wavelength range from their initial position: at an average mode half-width of 0.5 nm, the half a volt voltage increment leads to the shift by 1 nm. This is due to an increase in the depth of modulation of director orientation **n** in the LC bulk and a decrease in its refractive index $\langle n_e \rangle$ averaged over the spatial distribution $n_e(x) = (1/L)\int_0^L n_{eff}(\theta(x,z))dz$, where effective refractive index $n_{eff}(\theta(x, z))$ is a function of space point and θ is the angle between the electric field vector and local director [20]. In the discussed case, the well-known relation between the spectral position of the mode and the refractive index of the medium in a Fabry–Perot cavity is written as

$$\lambda_e = \begin{cases} 2Ln_e/m = const, & U < U_c \\ 2L\langle n_e \rangle/m, & U \geq U_c \end{cases}$$

where L is the cavity thickness and m is the defect mode number.

As an example, Fig. 5 shows field dependences of the peaks of neighboring defect modes at wavelengths of 510 (⊥-mode) and 512 nm (||-mode). It can be seen that the amplitude of ||-mode damps almost to the background PBG level in the voltage range 6.2 – 7.7 V, which involves a sequence of the convective transitions WD→OR→GP. First, the *e*-wave is scattered on WD and OR phase gratings [21]; therefore, the mode amplitude decreases due to spatial redistribution of the wave energy in the direction perpendicular to the initial propagation direction. The spatial Fourier analysis of the convective transition WD→GP for MBBA shows that the grid pattern (Fig. 2d) is the complex 3D flow of the nematic [22]. It is important that the diffraction efficiency of the domain grating in the zero diffraction maximum for the radiation whose polarization coincides with the LC orientation direction is close to unity [23]. Thus, the rapid damping of the parallel modes in the very narrow voltage range originates mainly from the diffraction loss. Then, in the dynamic scattering mode, the medium becomes strongly nonuniform for the *e*-wave. In virtue of the large birefringence of the nematic, fluctuations of refractive index n_e sharply grow and, after passing through such a medium, the direction of the *e*-wave becomes random even in a thin layer [24]. On the contrary, the behavior of transverse modes is relatively stable against convection processes (Fig. 5). For example, at a voltage of 7.7 V, the amplitude of ⊥-mode ($\lambda = 510$ nm) decreases by a factor of only 1.2, which can be caused by distortion of the initial direction of propagation of the *o*-wave, which occurs at the strongly nonuniform director orientation **n** in the LC volume, although it is weaker as compared with the *e*-wave [24].

As one can see from results presented in Fig. 5 the choice of a voltage of 7.7 V is caused by the contrast at the

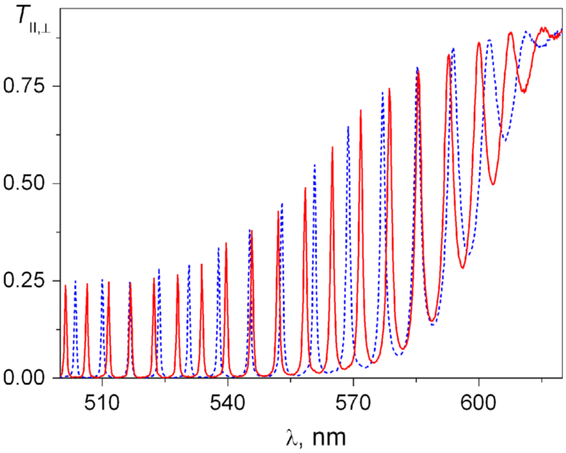

Fig. 3. Polarized components $T_{\|}$ (solid line) and $T_{\perp}$ (dashed line) of the PC/LC transmission spectrum measured at temperature $t = 25$°C. Electric field is switched off.

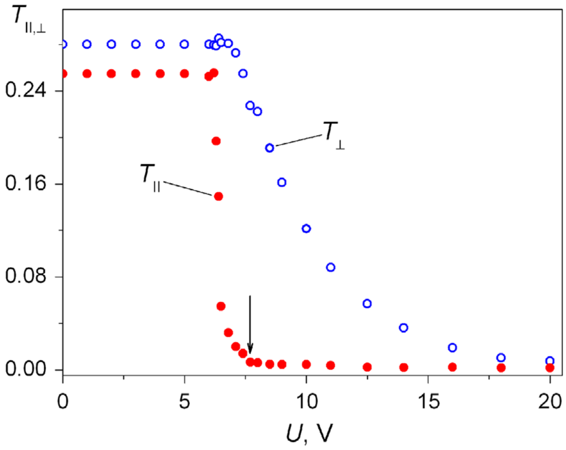

Fig. 5. The electric-field-dependence of the transmission maximum $T_{\|,\perp}$ ($\lambda = \lambda_{max}$) at $\lambda = 510$ nm (open circles) and $\lambda = 512$ nm (solid circles). Arrow indicates the voltage (7.7 V) corresponding to maximum contrast ratio $T_{\perp}/T_{\|}$.

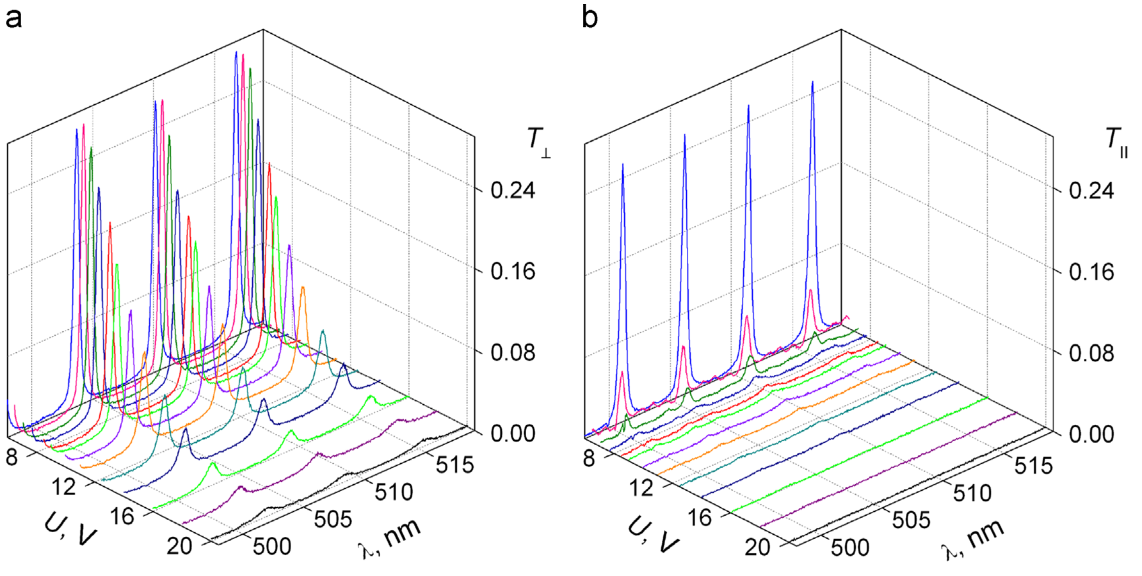

Fig. 4. $T_{\perp}$-component (a) and $T_{\|}$-component (b) of the PC/SEN transmission spectrum at different applied voltages *U*.

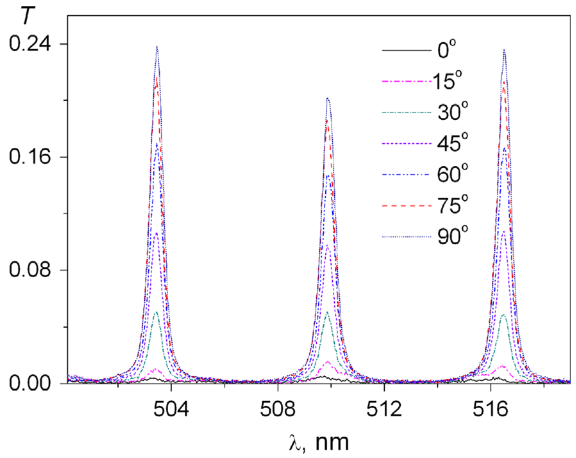

Fig. 6. Transmission spectra of the PC/SEN cell for the various angles α between the rubbing direction **n** and light polarization. Operating ac voltage is 7.7 V.

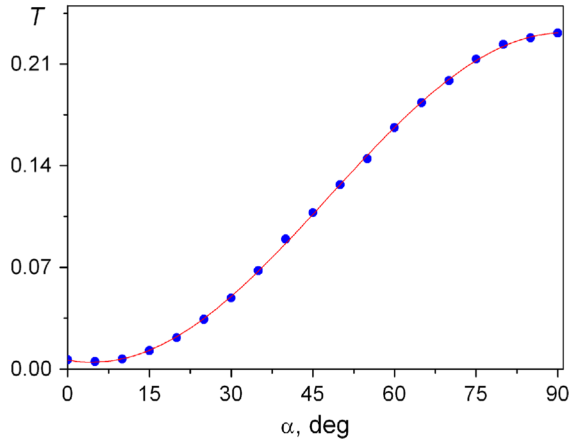

Fig. 7. Defect mode attenuation in photonic crystal cell at wavelength 510 nm as function of α. Experimental data are indicated by circles; solid line is an interpolation.

polarization switching of the defect mode from the transparent to optically closed state, which is almost optimal. At the deviation of the electric vector of the light wave from the direction parallel or perpendicular to the rubbing direction **n**, the modes of the both types are simultaneously excited in the photonic structure. The energy distribution between them depends on the value of this deviation. At the chosen voltage, transmission of the samples at the wavelengths of $\parallel$-modes is almost completely blocked by the diffraction loss. Only undamped $\perp$-modes occur in the spectrum. Their intensity is a continuous function of the angle between the rubbing direction and plane of polarization of the light normally incident onto the sample, and the fixed spectral position is caused by the stable spatial distribution of the refractive index of the medium. Fig. 6 illustrates the controlled transmission of defect modes in the PC/SEN structure at the PBG center upon variation of the light polarization direction. The experimental spectra were obtained at fixed positions of the polarizing element, which are changed with a pitch of 5°. The voltage applied to the sample (7.7 V) remains invariable. As an example, Fig. 7 shows the defect mode attenuation curve $T(\alpha)$ at the wavelength $\lambda = 510$ nm.

4. Conclusion

The spectral characteristics of the tunable photonic structure have been investigated in this paper. The tunability is achieved by infiltrating the electrically controllable spatially extended nematic as a central defect layer in the PC. Because of the three different electroconvective states of nematic layer, namely the WD, OR or GP states, the PC/SEN structure exhibits the various defect modes spectra. While low-frequency voltage above the threshold value U_c results in the typical light-scattering WD and OR states and the subsequent diminished defect modes, the operation voltage 7.7 V causes the GP domain structure and the respective disappearance only of $\parallel$-defect-mode peaks. In this case, the PC/SEN transmission spectrum consists of the undamped $\perp$-modes, whose intensity can be tuned additionally by the rotation of the light polarization plane. The proposed technique to control the defect modes spectra is promising for photonic applications of the PC/SEN structure as the light valve, spectral filter or optical modulator.

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