ISSN 1063-7850, Technical Physics Letters, 2015, Vol. 41, No. 1, pp. 86–89. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © V.A. Gunyakov, M.N. Krakhalev, V.Ya. Zyryanov, V.F. Shabanov, 2015, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2015, Vol. 41, No. 2, pp. 70–78.

Modulation of Defect Modes Intensity by Controlled Light Scattering in a Photonic Structure with a Liquid-Crystal Component

V. A. Gunyakov*, M. N. Krakhalev, V. Ya. Zyryanov, and V. F. Shabanov

Kirensky Institute of Physics, Krasnoyarsk Scientific Center, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia

Siberian State Aerospace University, Krasnoyarsk, 660014 Russia

**e-mail: gun@iph.krasn.ru*

Received August 4, 2014

Abstract—We describe a new method of defect modes intensity modulation in a multilayer photonic structure containing liquid crystal (LC) inclusions. The proposed method is based on using the regime of electroconvective instability in a nematic LC, which leads to the appearance of a scattered mode sensitive to the polarization type in the optical response. The defect mode intensity is controlled by variation of the angle between the initial planar orientation of the director and the polarization plane of light normally incident onto the photonic structure.

DOI: 10.1134/S1063785015010241

Photonic crystals (PCs) exhibit unique dispersion properties and are capable of localization and directed transmission of light, which opens new prospects in the creation of base elements for nanophotonic and optoelectronic devices [1]. Much interest has been devoted to PCs containing liquid crystal (LC) inclusions that are capable of effectively controlling the spectral properties of defect modes (i.e., narrow resonances in the photonic bandgap) [2].

Recently, we have developed a method of high-contrast modulation of the intensity of defect modes in a multilayer PC/LC structure confined between crossed polarizers [3–5]. According to the proposed scheme, the electric- or magnetic-field-induced spectral matching of the extraordinary (*e*) and ordinary (*o*) components of defect modes with various ordinal numbers can lead to either amplification by interference or mutual quenching of both components. However, this method is not related to direct action upon the amplitude of modes, since the effect is achieved due to the field-induced tuning of their spectral position. In some cases, it may be also important to directly control the amplitude of defect modes at their fixed positions in the spectrum. In this respect, it is of interest to study the behavior of defect modes related to the decay of propagating light waves on optical inhomogeneities in the periodic structure of PCs [6–8]. The presence of controlled optical inhomogeneity in a defect layer, which arises, e.g., under the conditions of electroconvective instability of a nematic LC (NLC) [9] and is accompanied by a strong scattering of light, can be used for realization of the regime of controlled mode damping. In addition, the hierarchy of convective structures with increasing complexity (Williams domains, zig-zag rolls, domain grids, etc.) observed in LCs upon increasing control field strength [10] allows one to select the optimum conditions of light scattering as dependent on the polarization of probing radiation.

In this Letter, we describe a new method of defect modes intensity modulation in a multilayer PC/LC structure, which employs the domain grid regime of standard electroconvective instability in an NLC where the defect modes intensity can be smoothly controlled by variation of the angle between the initial planar orientation of the director and the polarization plane of light normally incident onto the photonic structure.

Figure 1 shows the scheme of an electrically controlled PC/LC cell used to study the effect of various regimes of electroconvective instability in LC on the transmission spectra of the PC structure. The cell is formed by two identical dielectric mirrors and cavity, which is filled with a nematic LC of 4-methoxybenzylidene-4'-butylaniline (MBBA) possessing a negative anisotropy of dielectric permittivity ($\varepsilon_a < 0$) and a positive anisotropy of conductivity ($\sigma_a > 0$). MBBA has nematic–isotropic phase transition temperature $T_c = 45°C$ and refractive indices $n_e = 1.765$ and $n_o = 1.552$ for the light with wavelength $\lambda = 0.589\ \mu m$ polarized parallel and perpendicular, respectively, to NLC director **n**. Multilayer coatings of the mirrors consisted of six 55-nm-thick layers of zirconium dioxide (ZrO_2) with refractive index 2.04 and five 102-nm-thick layers of silicon dioxide (SiO_2) with refractive

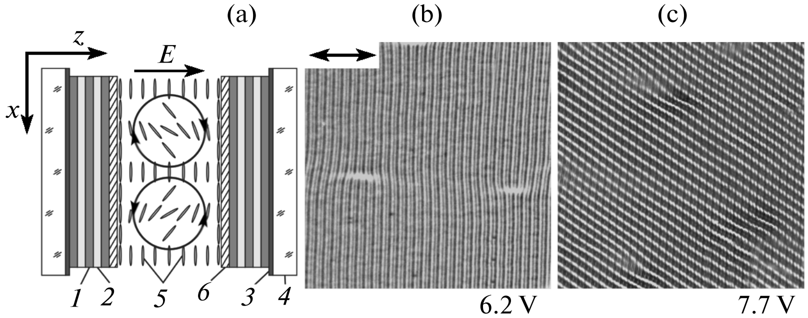

Fig. 1. (a) Scheme of an electrically controlled PC/LC cell: (*1*) ZrO_2 layers, (*2*) SiO_2 layers, (*3*) ITO coating, (*4*) substrates, (*5*) LC molecules (NLC layer thickness, 10 μm), and (*6*) rubbed polymer film. (b, c) Micro photographs of cell texture at U = 6.2 and 7.7 V, respectively (arrows indicate the direction of light polarization).

index 1.45. These layers were alternately deposited onto the surface of quartz substrates covered by ~150-nm-thick ITO electrode layers, which allowed electric field **E** to be applied along the normal to the cell plane. The initial homogeneous planar orientation ($\mathbf{n} \parallel x$) of the NLC was set by a rubbed polymer coating. The quality of orientation was checked by monitoring the pattern of visual field extinction between crossed nicols in a polarization microscope. The application of a low-frequency (in this work, 80 Hz) electric field to the NLC with planar orientation leads (beginning with a certain critical value) to the appearance of a convective instability in the form of closed flows (indicated by circular arrows in Fig. 1a), which form a one-dimensional grating of rolls aligned in the *y* axis direction.

Microphotographs of the PC/LC cell textures observed in a polarization microscope (Figs. 1b and 1c) show the transformation of various regimes of electroconvective instability in a defect layer of the NLC with increasing electric field. The light is polarized along the direction of initial director orientation (*e* wave). The "transparent" state of the cell observed up to a critical voltage of $U_c = 6.2$ V is due to a homogeneous NLC ordering in the substrate plane. Note that, in this geometry, orientational effects of the Freedericksz transition type are excluded due to a negative anisotropy of the dielectric permittivity of MBBA. At voltages above the critical value, the cell exhibits a periodic pattern of alternating bright and dark strips (Williams domains, Fig. 1b) perpendicular to director **n**. This alternation is related to a periodic variation of the refractive index of *e* wave in the NLC, which is caused by modulation of the director orientation in the polarization plane of incident light. The modulation is induced by the ordered vortex motion in the NLC [11]. As the applied voltage is increased further, the Williams domains first transform into zig-zag rolls [12] and then these rolls form a domain grid (Fig. 1c). In this case, the cell becomes turbid, which is indicative of a strongly inhomogeneous director orientation in the LC bulk. Under exposure to light polarized along the *y* axis (*o* wave), the cell transparency is close to that in the initial state at $U = 0$ V.

Polarized transmission components $T_{e,o}(\lambda)$ and field dependences of the transmission spectra under conditions of convective processes have been studied using a Shimadzu UV-3600 spectrophotometer. The polarizing element was a Glan prism oriented with its main plane either along the *x* axis (*e* component of spectrum) or along the *y* axis (*o* component of spectrum). Past the cell, the probing beam was passed via a aperture with a 4-mm-diameter. The spectra were measured at a fixed cell temperature of 25°C that was maintained constant to within ±0.2°C. The transmission spectrum of the structure studied represents the photonic bandgap in a 420–610 nm interval with a set of defect modes. In the general case, the defect modes for *e* and *o* waves have different wavelengths because the corresponding refractive indices are not equal [4–6].

Figure 2 shows the field dependences of the polarized transmission components $T_{e,o}$ of the PC/LC cell measured in a 500–520 nm wavelength interval, which corresponds to the center of the bandgap that is most sensitive to the modes damping. As can be seen, the *e* and *o* modes exhibit different characters of response to the field application at voltages above the critical value $U_c = 6.2$ V. In a narrow interval of $\Delta U = U - U_c \sim 1.5$ V, the *e* mode amplitude exhibits a sharp drop and decays almost completely at about 7.7 V (Fig. 2a). The *e* wave first exhibits diffraction on a one-dimensional phase grating formed by a set of Williams domains [13], so that the defect mode amplitude decreases as a result of the spatial redistribution of the wave energy in the *xz* plane. In addition, *e* modes exhibit a significant shift toward shorter wavelengths, which reaches 1 nm at $\Delta U = 0.6$ V (at an average modes half-width of 0.5 nm). This weak change in the field increases the modulation depth of the direction of **n**, which leads to a significant decrease in effective refractive index $n_{\text{eff}}(\theta)$ of the LC layer, where $\theta(x, z)$ is the angle between the electric field and local director [13].

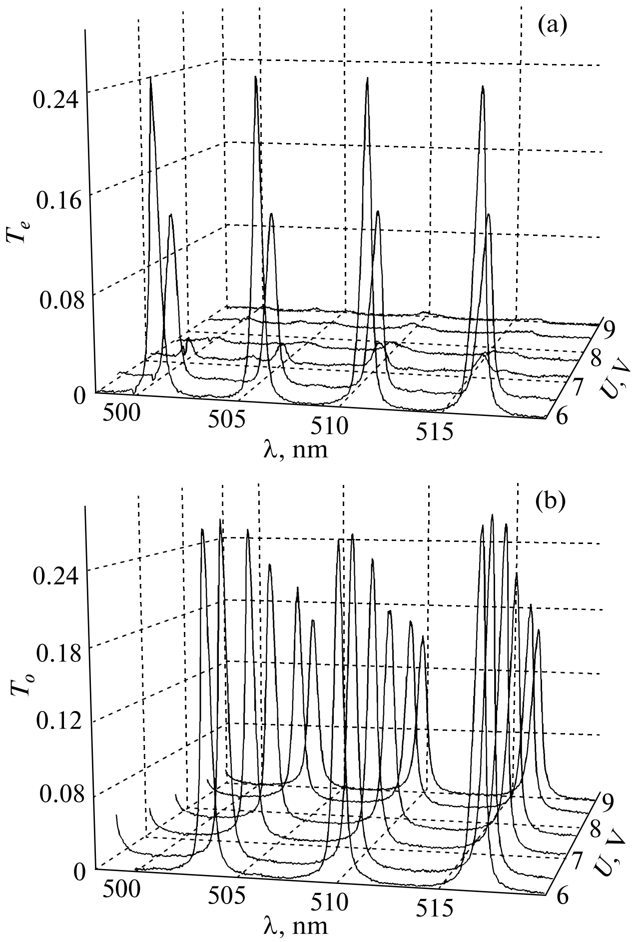

Fig. 2. Field dependences of polarized transmission $T_{e,\,o}(\lambda)$ of the PC/LC cell, corresponding to (a) *e* wave and (b) *o* components of spectrum.

The well-known relationship between the mode wavelength and refractive index of the medium in the resonator cavity, which has been derived in the Fabry–Perot interferometer theory, can be written in the case under consideration as follows:

$$\lambda_e = \begin{cases} 2Ln_e/m = \text{const}, & U < U_c, \\ 2Ln_{\text{eff}}(\theta)/m, & U \geq U_c, \end{cases}$$

where L is the cavity (i.e., LC layer) thickness and m is the integer determining the defect mode order number. The regime of domain grid (Fig. 1c) observed when the applied voltage is increased to 7.7 V corresponds to a more complex structure of flow in the nematic liquid. However, the LC layer still represents an optically anisotropic medium with regularly distributed refractive index [14]. Then, due to a large birefringence of the NLC, the fluctuations of refractive index of *e* wave propagating in a strongly inhomogeneous LC become large and passing across this medium produces chaotization of the propagation direction even in a thin layer [15], so that *e* modes in the PC structure exhibit damping.

In contrast, the behavior of *o* modes is characterized by relative stability with respect to convective processes in a defect layer of the LC (Fig. 2b). First, the *o* modes are fully insensitive to NLC transition from the static to dynamic regime at critical point U_c. Second, the mode amplitude decreases on the average only by a factor of 1.2 even at $U = 7.7$ V, while their half-width and positions remain stable. A small decrease in the *o* mode amplitude can be related to the fact that, for inhomogeneous director orientation appearing in the LC bulk in a regime of domain grid, the *o* wave is also distorted, albeit to a much lower degree than the *e* wave [15].

Using a significantly different character of optical responses to the applied field observed for differently polarized components of the PC/LC cell spectrum, it is possible to control the defect mode amplitude by changing the angle between the initial director orientation and the polarization plane of light normally incident onto the photonic structure. Figure 3 illustrates the transmission of defect modes controlled by variation of the direction of electric vector in the light wave at $U = 7.7$ V. Any deviation of the polarization plane from the direction of *o* component leads to the appearance of *e* modes, which effectively decay in the LC layer for the reasons indicated above. A change in the deviation angle affects the light wave energy distribution between the polarized components and, hence, makes it possible to control the amplitude of *o* modes at fixed spectral positions.

Rotation of the polarization plane of probing radiation at frequency ω leads to modulation of the intensity of defect modes in the LC layer and, hence, to modulation of cell transmission $T(\omega)$. At the same time, rotation of the polarization plane by 90° relative to the NLC director provides, e.g., for the mode with $\lambda = 0.510$ μm (Fig. 3), a modulation depth of $K = (T_{\max} - T_{\min})/(T_{\max} + T_{\min}) = 92\%$. A finite response speed of devices rotating the polarization plane places certain limitations on maximum modulation frequency $\omega_{\max}$ of modes in the given PC. In particular, the polarization angle can be controlled by a multistable magneto-optical polarization rotator based on the Faraday effect, representing a thin plate of orthoferrite containing inhomogeneities [16]. In the visible spectral range and part of the near-IR range (including a wavelength of 1.55 μm, which is important for applications related to optical data transmission), orthoferrites possess the best magneto-optical quality factor, reaching 14°/dB, which is many times the values for other magnetic materials [17]. The minimum switching times of orthoferrite-based rotators are limited predominantly by the minimum duration of separate control magnetic field pulses and fall in a nanosecond range. This circumstance makes it possible to reach a modes modulation frequency of $\omega_{\max} \sim 1$ GHz, which is comparable with the characteristics of modulators of

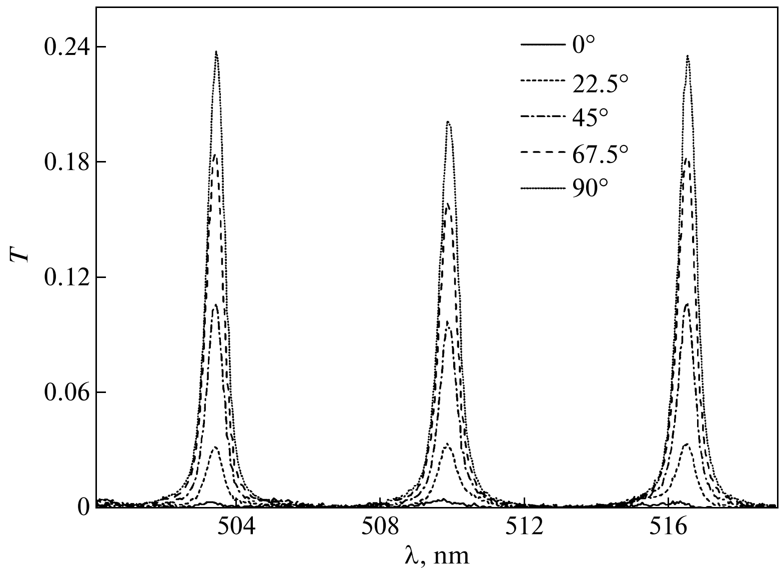

Fig. 3. Change in PC/LC cell transmission T at stable frequencies of defect modes induced by applied voltage $U = 7.7$ V at 80 Hz observed for various angles between the initial director orientation and the polarization plane of light normally incident onto the photonic structure.

another type based on an MOS structure embedded in a silica optical fiber [18], albeit significantly lower than the modulation frequencies accessible with electro-optical [19] and quantum-confined electroabsorption [20] modulators.

Thus, the proposed method of defect modes modulation in a photonic structure with a nematodynamic component as a defect layer may find application in photonic devices for the filtration, switching, and optical modulation of light fluxes.

Acknowledgments. This study was supported in part by the Siberian Branch of the Russian Academy of Sciences (projects nos. 43 and 101) and by a Joint Project of the Siberian Branch of the Russian Academy of Sciences and the National Science Council of Taiwan.

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Translated by P. Pozdeev