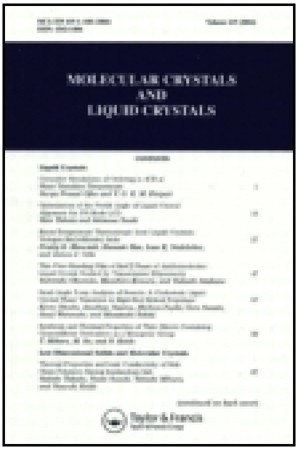

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Electrooptical Switching in a One-Dimensional Photonic Crystal

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An electrooptical narrow-band switch within wide spectral range on the base of photonic crystal/liquid crystal cell has been designed. The cell consists of thin layer of a planar oriented nematic which is confined by two identical multilayer dielectric mirrors. Presence of defect layer in the center of periodic structure induces the origin of the spectral windows (defect modes) inside the photonic crystal bandgap of the transmission spectrum. The transmittance of the cell placed between crossed polarizers depends on the matching of wavelengths for the defect modes of two polarizations and their relative phase retardation. In turn the spectral position of defect modes and the phase retardation were controlled by applied voltage that may result both in the addition and diminution of the defect modes intensities.

Keywords: defect modes; electrooptical switching; interference; nematic liquid crystals; photonic crystals; polarization

INTRODUCTION

The photonic crystal (PC) materials with spatial modulation of dielectric properties have been under intensive discussion [1–3]. The modulation period is comparable to the wavelength of electromagnetic radiation. An important feature of PC is the presence of the photonic bandgaps (PBGs) which are characterized by the low density of the photon states and therefore by the high reflectivity (low transmittance)

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in some directions of light propagation. If a defect breaking the periodicity is introduced into the PC structure, the localized states of light are arisen and the transmission bands, which are called defect modes, appear within the PBG. One-dimensional (1D) PCs usually constitute the multilayer periodic structures consisting of the alternate layers of two dielectric materials with different refractive indices. In contrast to the three-dimensional photonic crystals they do not have a complete PBG. Nevertheless, 1D-PC materials are of interest in view of their multifunctionality. Such structures have been long studied and widely applied as interference filters, light polarizers, multilayer dielectric reflectors, and antireflecting coatings [4–6].

Application of the liquid crystals (LC) as a defect unit allows designing the PC structures with the tunable optical properties. In this relation, PCs that contain liquid crystal layers as their structural elements are quite promising. The properties of LCs, such as a wide range of optical transparency, high birefringence, large optical nonlinearity and high susceptibility to external perturbations (temperature, electric and magnetic fields, etc.) make LCs a quite promising means for the effective control of the spectral and optical characteristics of PCs [2,3,7]. Originally, LCs for controlling the spectral properties of PCs were proposed in [8,9]. Intensive investigations of PCs in combination with LCs started in the end of nineties (see [2,7]). The transmission spectra of the 1D-PC systems infiltrated with LCs have been theoretically studied in [10]. Recently an electrical tuning of defect modes in a one-dimensional PC with a nematic LC as a defect layer, as well as tuned-wavelength lasing was demonstrated in [11]. Brief view shows that by controlling is mainly meant the spectral tuning of the defect modes. It would be interesting to use this spectral tuning for controlling amplitude intensities of the defect modes and in turn for the development of the electrically controlled optical narrowband switches based on the one-dimensional photonic crystal with a planar oriented nematic layer used as a defect of the multilayer structure. The aim of the present paper is to study an opportunity to switch on (off) the transmittance of 1D-PC cell placed between crossed polarizers within spectral range of a single defect mode using interference of ordinary and extraordinary light waves propagated across the anisotropic layer of LC due to the electrically induced coincidence of their wavelengths.

EXPERIMENT

A one-dimensional photonic crystal lattice under study has the $(HL)^N H(D)H(LH)^N$ periodic structure. Here H and L are the various dielectric layers with the high n_1 and low n_2 refractive indices and the thicknesses t_1 and t_2, respectively. A lattice spacing is $t = t_1 + t_2$. The symbol D denotes the defect layer with the refractive index n_d and the thickness t_d. N is the number of the HL and LH bilayers. Two identical multilayer mirrors are combined so that a sandwich-like cell with a gap of about $t_d = 7.4\,\mu\text{m}$ is fabricated. Each mirror consists of six zirconium dioxide (ZrO_2) layers with the refractive index $n_1 = 2.04$ and the thickness $t_1 = 55\,\text{nm}$ of each layer and five silicon dioxide (SiO_2) layers with the refractive index $n_2 = 1.45$ and the thickness $t_2 = 102\,\text{nm}$. The layers were alternatively deposited on the fused quartz substrate with ITO electrode [12]. The nematic liquid crystal 4-n-pentyl-4′-cyanobiphenyl (5CB) with the sequence of phase transitions Cr – 22.5°C – N – 34°C - I between the crystalline, nematic and isotropic liquid phases was used as a defect layer. The refractive indices of 5CB are $n_{||} = 1.720$, $n_{\perp} = 1.536$, where indices ($||$) and ($\perp$) refer to the direction parallel or perpendicular to the nematic director **n**, respectively [13]. The values $n_{||,\perp}$ refer to the wavelength $\lambda = 589\,\text{nm}$, as well as the refractive indices $n_{1,2}$ of the mirror dielectric layers presented above. To induce the homogeneous alignment of the director **n** along the plane of mirror the polyvinylbutyral surfactant film rubbed unidirectionally was used. The cell thus obtained was infiltrated with the nematic 5CB heated to temperature of 36°C. The quality of the planar orientation of samples was controlled by texture patterns under conoscopic observation using a polarizing microscope. This 1D-PC cell with an electrically controlled nematic defect layer placed between two crossed polarizers is shown in Figure 1. Right in the figure an optical indicatrix of the nematic LC is presented.

The polarized transmission spectra as well as an electric-field-induced response of the cell placed between two crossed polarizers were measured by a spectrometer KSVU-23. Probe radiation was normally incident on the cell. Initial orientation of the liquid crystal

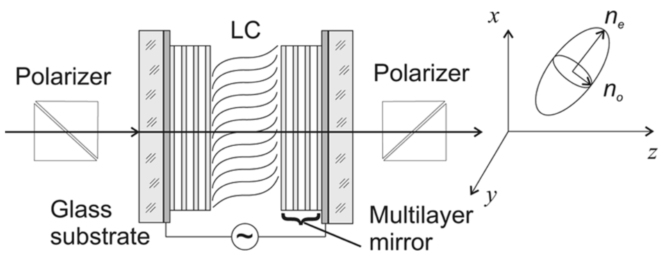

FIGURE 1 Experimental cell of the one-dimensional photonic crystal with an electrically controlled nematic defect layer between crossed polarizers.

was a planar one with the director **n** aligned along the x-axis. First the x- and y-polarized spectra of 1D-PC were obtained. A 800-Hz AC voltage was applied to the ITO electrodes to reorient the liquid crystal. The direction of **n** was varied in xz-plane.

The first polarizer placed between the light source and the cell was oriented at 45° to the x-axis. The second polarizer is arranged after the cell and crossed with the first one. Ordinary refractive index n_o is a characteristic of the light polarized along the y-axis. The refractive index n_e of the liquid crystal is extraordinary when the vector of light wave $\mathbf{e}||x$. In this geometry, an optical anisotropy of the nematic is expected to result in different behavior of the dependencies for the x- and y-polarized waves.

A nematic deformation caused by the applied voltage (see Fig. 1) reveals in the decrease of extraordinary refractive index n_e of LC defect layer

$$n_e = \frac{n_{||} n_{\perp}}{\sqrt{n_{||}^2 \cos^2 \theta(z) + n_{\perp}^2 \sin^2 \theta(z)}}, \tag{1}$$

where $\theta(z)$ is the angle between the wave vector of the extraordinary beam $\mathbf{k}||z$ and the local direction of **n**. Ordinary refractive index $n_o = n_{\perp}$ is independent of the director tilt angle θ. The change of n_e under the action of external field results in the shift of the spectral position of defect modes for the extraordinary wave. At the same time, the spectrum of ordinary wave remains invariable.

RESULTS AND DISCUSSION

The transmission spectra of the PC/LC cell proper to the nematic phase of 5CB at a fixed temperature $t = 23$°C are shown in Figure 2. As seen, the photonic bandgap with two different sets of defect modes corresponding x- and y-polarized waves is formed within the visible range of the spectrum. The spectral positions of the defect mode peaks depend on the polarization of probe light. The different number of x- and y-polarized modes in the spectra and the various intermode spacing are resulted from the difference of $n_{||}$ and $n_{\perp}$ refractive indices of 5CB.

We note that the defect modes have maximal amplitude near the edge of PBG. The discrepancy in the amplitudes of defect modes in the center and near the edges of photonic bandgap was earlier found to be related to the losses inside the defect layer of real photonic crystal [14].

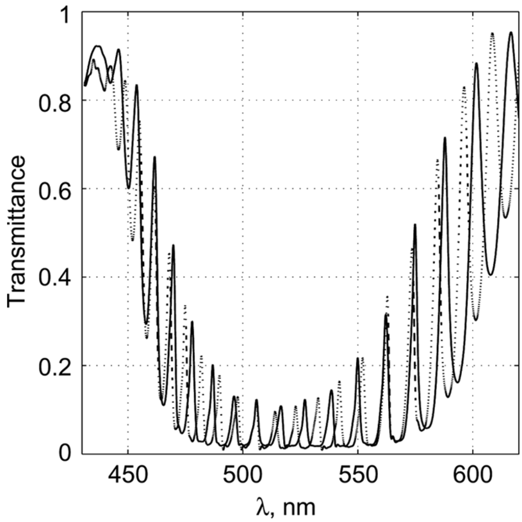

FIGURE 2 The transmission spectra of the 1D PC with a planar oriented 5CB layer for x- (dotted line) and y-polarized (solid line) light at a fixed temperature $t = 23^{\circ}$C.

To demonstrate clearly the effect of light switching we have chosen the 560÷600 nm spectral range close to the long-wavelength edge of PBG, which is included a set of high-intensive peaks (see Fig. 2).

A voltage dependence of the transmission spectrum of defect modes T_e(U) corresponding to x-polarized light is presented in Figure 3. According to the specific feature of Freedericksz transition [15], the spectrum does not change up to the threshold voltage which is $U_c = 0.74$ V for nematic layer under study. The further increase of voltage causes the shift of the spectral position of defect modes.

Figure 4 shows the spectral positions of the defect mode peaks of PC/LC in considered range as a function of the applied voltage. All peaks of x-polarized defect modes (open circles) are shifted towards the shortwave part of spectrum. As seen from the figure some peaks arise from long-wavelength edge of PBG at the voltage $U > U_c$.

On the other hand, the spectral positions of the peaks of y-polarized modes are independent of the applied voltage in contrast to x-polarized ones. So, some parallel modes shifting subject to the external field can be superposed with perpendicular ones. The extraordinary and ordinary waves with the same wavelengths and orthogonal polarizations may interfere passing through the analyzer.

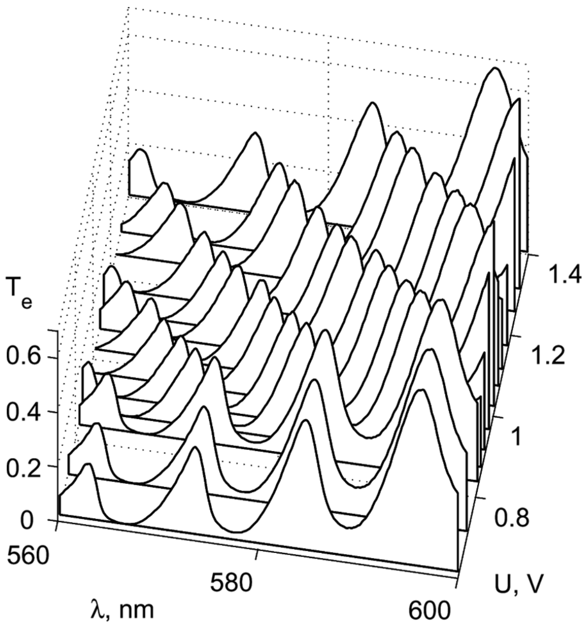

FIGURE 3 Spectral shift of defect modes of the 1D PC with a planar oriented 5CB layer for x-polarized light in the vicinity of Freedericksz transition.

Figure 5 shows the optical states T_{OFF} and T_{ON} of the tunable 1D-PC cell with the nematic director in the defect layer aligned at 45° relative to crossed polarizers. The optical state T_{OFF} with the minimal transmittance is realized when the applied voltage $U_1 = 1.01\,\mathrm{V}$. In this case the first nearest parallel mode located initially at $\lambda_{||1} = 596\,\mathrm{nm}$ shifts to the spectral position of the chosen perpendicular mode at $\lambda_{\perp} = 588\,\mathrm{nm}$. The increase of voltage up to $U_2 = 1.30\,\mathrm{V}$ results in the optical state T_{ON}, when the next parallel mode initially located at $\lambda_{||2} = 609\,\mathrm{nm}$ overlaps with considered perpendicular mode. Maximal transmittance of overall curve coincides with the perpendicular mode peak at $\lambda_{\perp} = 588\,\mathrm{nm}$.

Observed phenomenon can be qualitatively understood using the analogy between one-dimensional PC with a defect layer and Fabry-Perot interferometer. Resonant wavelengths of such interferometer are given by

$$\lambda = \frac{2nL}{m}, \tag{2}$$

where L and n are the length and the refractive index of the interferometer, respectively; integer m corresponds to the order number of the

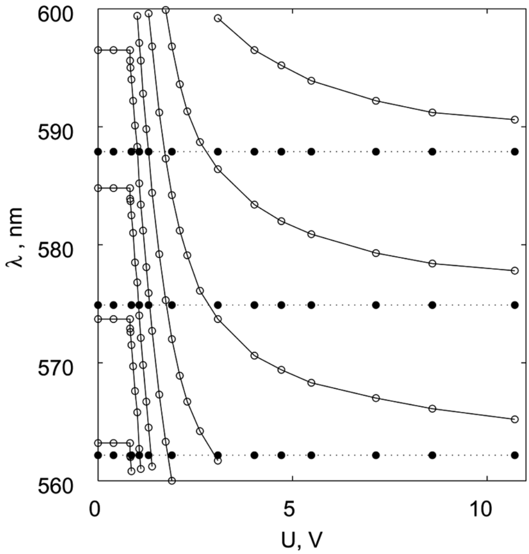

FIGURE 4 Voltage dependence of the defect mode wavelengths for the x-(open circles) and y-polarized (closed circles) light. The solid and dotted lines are the interpolation of experimental data.

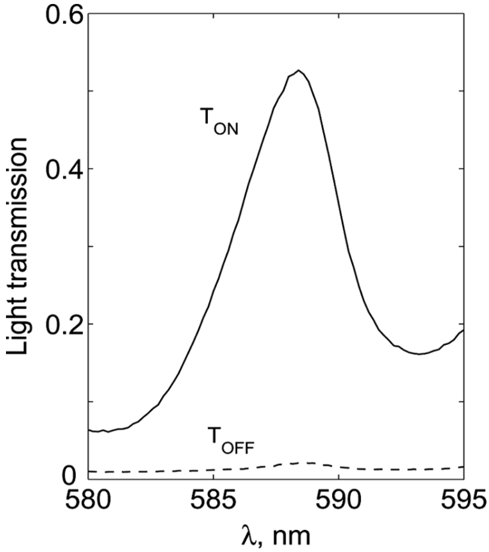

FIGURE 5 The optical states T_{OFF} (dashed line) and T_{ON} (solid line) of the 1D-PC cell.

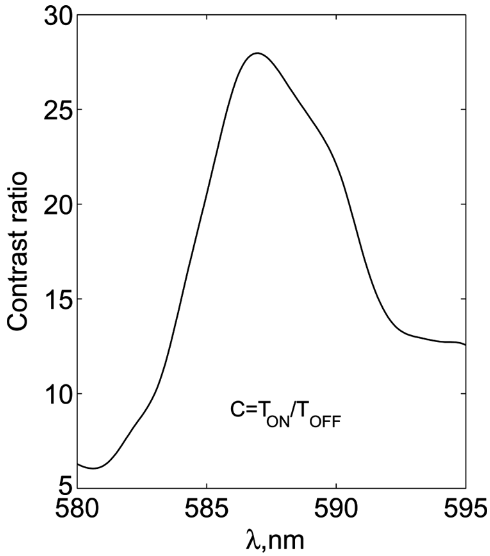

FIGURE 6 The contrast ratio of the transmittance curves $C = T_{ON}/T_{OFF}$ for the tunable 1D-PC cell as a function of wavelength.

defect mode. In our case a cavity of interferometer is filled by a liquid crystal. As seen from formula (2), the electric-field-induced change of the refractive index n of LC can result in a coincidence of the wavelengths position of defect modes with different m. One can see that the result of interference of x- and y-polarized waves passed across analyzer depends cardinally on the parity of order numbers of the interacting modes. If the defect modes have the same parity (odd-odd, even-even), the interfering modes quench each others. And vice versa, in the case of the different parities (odd–even, even–odd), it takes place the constructive interference and output intensity is maximal. The spectral dependence of the contrast ratio of transmittance curves $C = T_{ON}/T_{OFF}$ is shown in Figure 6. As can see, the contrast ratio is related with the wavelength and reaches the maximal value $C = 28$ at $\lambda = 587\,\text{nm}$.

CONCLUSION

It has been experimentally demonstrated that the one-dimensional photonic crystal cell is able to switch over the transmittance within the defect modes. It is related to the interference of the ordinary and extraordinary light waves passed through the cell due to the electrically induced coincidence of their wavelengths. Thus, the 1D-PC cell with the controllable nematic liquid crystal defect layer placed between crossed polarizers can be effectively used as an optical narrow-band switch.

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