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Thermooptical Switching in a One-Dimensional Photonic Crystal

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Abstract—The temperature dependence of the optical transmission spectrum of a one-dimensional multilayer photonic crystal structure with a central defect layer has been studied. The defect was represented by a nematic liquid crystal (5CB) layer with a homeotropic orientation. It is shows that the defect modes exhibit a 10-nm spectral shift due to a change in the refractive index of the liquid crystal in the course of heating-induced transition to the isotropic phase. A comparison of the experimental data to the results of numerical analysis shows the importance of allowance for the decay of defect modes.

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The growing interest in photonic crystals (PCs), representing structures with dielectric properties spatially modulated over a scale on the order of an electromagnetic radiation wavelength, is related to good prospects for their application in optoelectronics and microwave technology [1–5]. The presence of inhomogeneities (defects) in the periodic lattice leads to the localization of electromagnetic waves in the form of defect modes with discrete frequencies falling within the photonic band gaps of the unperturbed PC spectrum. This phenomenon can be used for the creation of narrowband spectral filters, low-threshold lasers, highly effective nonlinear optical converters, etc. The functional possibilities of PCs can be considerable expanded using highly labile materials such as liquid crystals (LCs) for the formation of structural defects. The rich variety of magneto-, acousto-, and thermooptical effects revealed in LCs makes possible the development of principally new electronic devices with tunable characteristics [1, 3–7]. For example, Ozaki et al. [6] controlled the spectral characteristics of a one-dimensional PC by means of the electric-field-induced reorientation of an LC defect layer. Schuller et al. [7] studied the temperature dependence of the transmission spectrum of a two-dimensional optical waveguide with a PC structure formed by cylindrical LC micropores.

This Letter reports the possibility of a thermooptical control over the transmission spectrum of multilayer PC structures with LC defect layers.

The defect layer in the PC structures studied was formed by nematic LCs of 4-*n*-pentyl-4'-cyanobiphenyl (5CB), which is characterized by the sequence of phase transitions C–22.5°C–NLC–34°C–I between the solid crystalline (C), nematic LC (NLC), and isotropic liquid (I) states. We have studied variations of the transmission spectrum of the PC, which were related to a change in the dielectric characteristics of the LC in the course of heating, especially in the vicinity of the phase transition from NLC to the isotropic phase, where the refractive index exhibits a sharp change [8].

The structure of the one-dimensional PC with a central defect (LC) layer is schematically depicted in the inset in Fig. 1. Two identical multilayer mirrors were assembled to form a plane-parallel sandwich type cell. Each mirror in this cell comprised eleven layers of zirconium dioxide (ZrO_2) having a refractive index of n_1 = 2.04 and a thickness of $t_1 \simeq 55$ nm alternating with ten layers of silicon dioxide (SiO_2) having a refractive index of n_2 = 1.45 and a thickness of $t_2 \simeq 102$ nm, which were sequentially deposited onto a glass substrate. The values of $n_{1,2}$ (as well as the refractive indices $n_{\perp, i}$ of the LC layer presented below) refer to a wavelength of λ = 589 nm. The cell was assembled with a gap of $L \simeq$ 5.8 μm between the mirror surfaces, which was set by a teflon film spacer. The sandwich structure was heated to 36°C, and the LC in the isotropic state was introduced into the gap. It was found that the ZrO_2 dielectric layer contacting with the LC induces a uniform homeotropic (perpendicular to the substrate surface) orientation of the NLC director, which was identified using the corresponding texture patterns revealed by conoscopic examination in a polarization microscope (POLAM P-113).

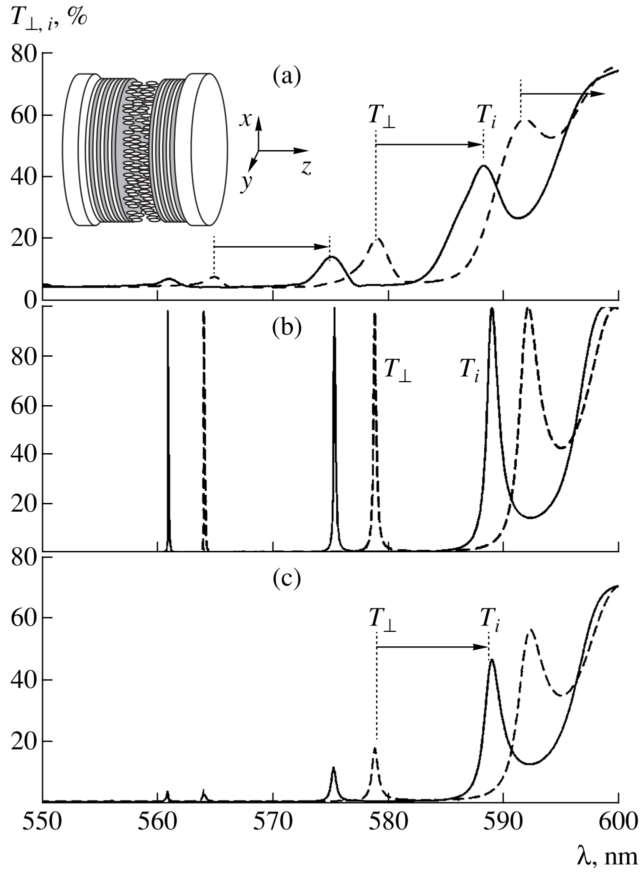

Fig. 1. Transmission spectra of a PC structure with a homeotropically oriented LC defect layer: (a) experimental data; (b, c) results of numerical calculations of the same spectra without and with corrections, respectively, for the decay of defect modes ($\mathrm{Im}\,n_{ZrO_2, SiO_2} = 2 \times 10^{-3}$, $\mathrm{Im}\,n_{LC} = 2.5 \times 10^{-4}$).

Using a controlled-temperature cell equipped with a thermostat, it was possible to measure the transmission spectra of a PC with the LC defect layer in the interval from 20 to 40°C with a temperature controlled to within ±0.2°C.

The transmission spectra were measured with a KSVU-23 spectrometer, which ensured a spectral resolution on a level of 0.1 nm. The cell was arranged so that the primary light beam was incident along the normal to the mirror surface. This experimental scheme with a homeotropic orientation of the NLC director provides the measurement of a perpendicular transmission component ($T_\perp$).

The PC structure under consideration exhibits the first photonic band gap in the transmission spectrum in a wavelength interval from 460 to 595 with a set of localized modes. The spectral positions of these modes are determined by parameters of the LC defect layer and the multilayer dielectric mirror structure. Figure 1a shows the spectra of the transmission components with perpendicular polarization for the nematic ($T_\perp$, dashed curve) and isotropic (T_i, solid curve) phases measured near the long-wavelength edge of the photonic band gap at a temperature in the vicinity of the NLC–I phase transition, where the refractive index of the LC exhibits a jumplike change from $n_\perp = 1.551$ to $n_i = 1.588$. As can be seen, the defect modes corresponding to the nematic phase also exhibit a jumplike shift toward longer wavelengths upon the heating-induced transition to the isotropic state. The main long-wavelength mode goes behind the edge of the photonic band gap. The arrows in Fig. 1a indicate the direction of the defect mode shift with increasing temperature. The change in the wavelengths of the defect modes at the phase transition temperature is about 10 nm. The defect mode peaks exhibit a maximum intensity near the edges of the photonic band gap, while at the center of this gap, the defect mode transmission drops to background level.

The transmission spectra of PCs with LC defects were modeled using the method of recurrent relations [9], which also describes the field distribution inside the PC. In these model calculations, we assumed that the structure occurs in vacuum ($n = 1$ on the left and right boundaries). The field in an arbitrary jth layer is represented by a superposition of waves propagating in opposite directions:

$$E(z) = [A(z)\exp(is(z)z) + B(z)\exp(-is(z)z)], \quad (1)$$

where $s(z) = kn(z)$ and $k = 2\pi/\lambda$. Let us subdivide all PC layers into sufficiently large number M of thin sublayers, so that the field E_m in each mth sublayer can be considered constant. The conditions of continuity of the electric and magnetic field components at the interface between the mth and $(m + 1)$th layer yield a system of equations,

$$A_m + B_m = g_{m+1}^{-1}A_{m+1} + g_{m+1}B_{m+1}, \quad (2)$$

$$s_m(A_m - B_m) = s_{m+1}(g_{m+1}^{-1}A_{m+1} - g_{m+1}B_{m+1}), \quad (3)$$

where $g_m = \exp(is_m t_m)$ and t_m is the thickness of the mth sublayer. Using these equations, it is possible to calculate the field amplitudes in each mth sublayer and to determine the reflection and transmission coefficients for the whole structure. Equations (2) and (3) yield the following recurrent relations for the amplitude reflection coefficients $R_m = B_m/A_m$, which relate the R_m and R_{m+1} values for the adjacent sublayers:

$$R_m = \frac{r_m + g_{m+1}^2 R_{m+1}}{1 + r_m g_{m+1}^2 R_{m+1}}, \quad (4)$$

where $r_m = (s_m - s_{m+1})/(s_m + s_{m+1})$. Equation (2) yields the following expression for A_m in an arbitrary mth sublayer:

$$A_{m+1} = A_m \frac{1 + R_m}{g_{m+1}^{-1} + g_{m+1}R_{m+1}}. \quad (5)$$

Using recurrent relations (4), we can determine all R_m values, starting from the right-hand PC boundary and using the boundary condition $R_{M+1} = 0$. Then, using expression (5), we calculate all A_m values, starting from the left-hand PC boundary, and determine the backward wave amplitude as $B_m = A_m R_m$. The transmission (T), reflection (R), and absorption (A) coefficients are defined as

$$T = |A_{M+1}/A_0|^2, \quad R = |B_0/A_0|^2 \quad \text{and} \quad A = 1 - T - R. \tag{6}$$

These calculations were performed with allowance for the dispersion of refractive indices of all components of the PC structure under consideration.

Figure 1b presents the transmission spectra of the PC structure calculated as described above for the parameters corresponding to the sample studied in experiments. As can be seen, the results of calculations agree well with the experimental data on the positions of defect modes. However, there is a significant difference in shapes of the resonance lines: the amplitudes of experimentally observed defect modes are markedly smaller, while their widths are significantly greater than the corresponding calculated values. This discrepancy can be related to certain features of the real PC structure, including fluctuations in the thicknesses of layers, imperfect mirror surfaces, etc. In addition, inhomogeneities of the medium can lead to losses for the light scattering, which decreases the quality of the PC resonator. To the first approximation, such losses can be effectively taken into consideration by introducing corrections into the imaginary parts of the refractive indices of the PC structure components and selecting these additives so as to provide the best fit to experiment. Figure 1c shows the transmission spectra of the PC structure calculated with such corrections.

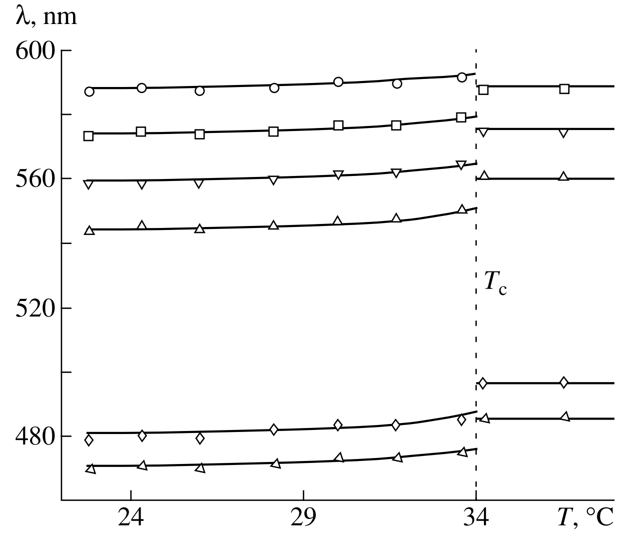

Fig. 2. The temperature dependences of the wavelengths of the defect mode peaks in the transmission spectrum of a PC structure. Symbols represent experimental data, solid curve show the results of calculations using formula (6).

Figure 2 shows the temperature dependences of the wavelengths of defect modes. As can be seen, the modes weakly shift toward longer wavelengths in the region of existence of the mesophase, which is related to a relatively small increase in the refractive index $n_\perp$ for the ordinary wave [8]. At the point (T_c) of the NLC–I phase transition from the nematic to isotropic phase, all peaks exhibit a sharp "red" shift. As the heating is continued, the positions of the defect mode peaks remain virtually unchanged, because the refractive index of the isotropic phase is practically independent of the temperature. As can be seen, the spectral positions of experimental peaks agree well with the calculated values in the entire temperature range studied.

In conclusion, we have demonstrated that a small change in the refractive index of a defect-forming material leads to a significant transformation of the transmission spectrum of a one-dimensional PC structure. This result points to the principal possibility of using the observed thermooptical effect for the creation of various optoelectronic devices.

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