ISSN 1063-7842, Technical Physics, 2010, Vol. 55, No. 10, pp. 1484–1489. © Pleiades Publishing, Ltd., 2010.
Original Russian Text © V.A. Gunyakov, S.A. Myslivets, A.M. Parshin, V.Ya. Zyryanov, V.G. Arkhipkin, V.F. Shabanov, 2010, published in Zhurnal Tekhnicheskoĭ Fiziki, 2010, Vol. 80, No. 10, pp. 95–100.

OPTICS, QUANTUM ELECTRONICS

Magnetic-Field Control of the Transmission of a Photonic Crystal with a Liquid-Crystal Defect

V. A. Gunyakov*[a, b], S. A. Myslivets[a, b], A. M. Parshin[a, b], V. Ya. Zyryanov[a, b, c], V. G. Arkhipkin[a, b], and V. F. Shabanov[a, b, c]

[a] *Kirenskii Institute of Physics, Krasnoyarsk Research Center, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia*

[b] *Siberian Federal University, Krasnoyarsk, 660041 Russia*

[c] *Siberian State Aerospace University, Krasnoyarsk, 660014 Russia*

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

Received December 1, 2009

Abstract—The method of modulation of transmittance of a multilayer photonic crystal with a nematic liquid-crystal defect upon the orientational transition from the homeotropic to the planar state is investigated. The orientation of the director of the nematic is controlled by a magnetic field in the *B*-effect mode. The method of recurrent relations is used for numerical simulation of transmission spectra of the photonic crystal structure under investigation.

DOI: 10.1134/S1063784210100142

INTRODUCTION

Photonic crystals (PCs) are basic materials for designing the next-generation optical instruments [1–3]. For this reason, these materials have been of special interest during the last two decades for researches both from fundamental and practical points of view. PC structures with tunable parameters are of considerable importance. In this respect, PCs containing high-sensitivity materials such a liquid crystals (LCs) as structural elements are quite promising. Various electro-, magneto-, and thermo-optical effects manifested in liquid crystals make it possible to develop a number of basically new elements in optoelectronics and nanophotonics on their basis [1–3].

Practically all possible technical applications of multilayer PCs are based on spectral tuning of defect modes in temperature [4], electrical [5], and optical fields [6]. For example, a multilayer photonic crystal with a nematic defect layer can be used in designing narrow-band optical filters with an electrically controlled spectral position of defect modes [7]. It should be noted that field investigations of spectral properties of multilayer PCs with an LC defect are mainly limited by the orientational transition of the nematic layer from the planar to the homeotropic state. At the same time, it would be interesting to analyze the inverse effect [8], in which a nematic in a PC/LC cell is reoriented from the homeotropic to the planar state. This may lead to switching of the cell from an optically closed state in the entire spectrum to a state with open spectral transparency windows (defect modes) at the minimal value of the controlling field. The application of a magnetic field would make it possible to avoid difficulties associated with the formation of structural defects in such a transition, which is a necessary condition for observation of field-induced variations in the defect mode spectrum.

In this connection, we study experimentally the features of magnetically controlled modulation of transmittance in a multilayer PC/LC cell in the inverse orientational effect emerging in the nematic defect layer.

EXPERIMENTAL

A PC/LC cell with the structure shown at the center of Fig. 1 is formed by two identical dielectric mirrors. The multilayer coating of the mirrors consists of six layers of zirconium dioxide (ZrO_2) with a refractive index of 2.04 and a thickness of 55 nm and five layers of silicon dioxide (SiO_2) with a refractive index of 1.45 and a thickness of 102 nm, deposited one by one on the surface of a fused quartz substrate. A nematic 4-metoxybenzylidene-4'-butylaniline (MBBA) liquid crystal in the isotropic state was introduced as a defect into a cavity of the cell. The thickness of the cavity was $L = 13.8$ μm. To produce a homeotropic alignment of MBBA molecules (director $\mathbf{n} \parallel z$), the surface of the mirrors was coated with a thin film of 0.6% of alcohol solution of lecithin. The quality of orientation was controlled by a polarization microscope from conoscopic figures. The refractive indices of MBBA were $n_e = 1.765$ and $n_o = 1.552$ ($T = 23$°C, $\lambda = 589$ nm) for light with polarization parallel and perpendicular to the director, respectively, were measured by the wedge method.

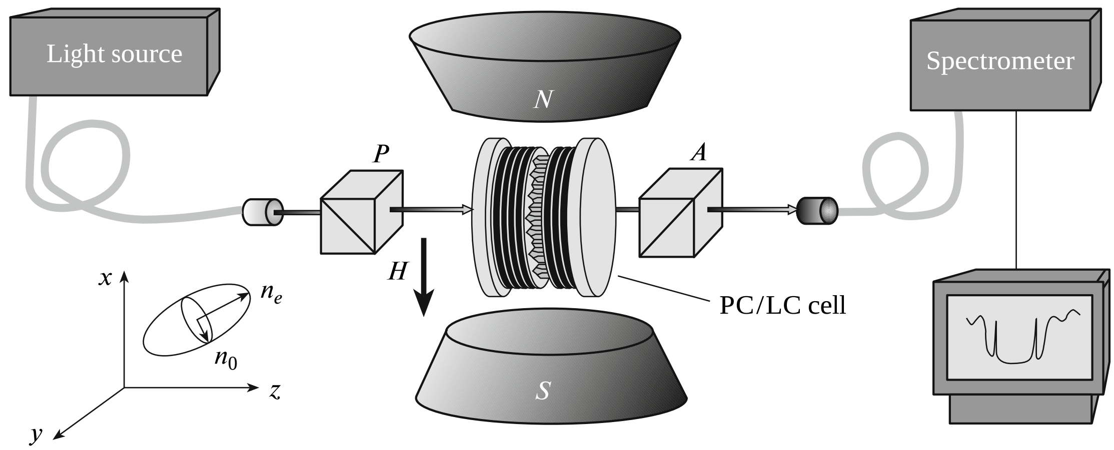

Fig. 1. Schematic diagram of experiments on the transmission spectra of a PC/LC cell with a homeotropically oriented nematic layer in a magnetic field.

The transmission spectra of the photonic crystal were recorded by the Ocean Optics HR4000 spectrometer using the magneto-optical device shown in Fig. 1, which was assembled on the basis of a FEL magnet. The samples were placed between the poles of the magnet so that the planes of the substrates remained parallel to the field lines. The power source of the magnet, generating a static magnetic field, made it possible to smoothly vary the field in the limits $0 < H < 1.6 \times 10^6$ A/m. Fiber optics of the Ocean Optics spectrometer ensured the detection of variation in the spectra of the PC/LC cell placed into the narrow gap of the magnet. The spectra were recorded at a fixed temperature of $T = 23°C$ and the error in thermal stabilization did not exceed ±0.2°C. For this purpose, the sample was placed into a sealed cell connected to a thermostat. Glan prisms whose principal planes formed an angle of $\beta = \pm 45°$ with the x axis were used as polarizing elements **P** and **A** in measurements in the geometry of crossed polarizers. In another version, a single polarizer **P** oriented either along the x axis or along the y axis was used for measuring the polarized components of the transmission spectrum.

Under the action of a magnetic field $\mathbf{H} \parallel x$ exceeding a certain critical value, director $\mathbf{n}$ is smoothly reoriented through an angle up to 90° in the (xz) plane. The effective refractive index $\langle n_e \rangle$ of the extraordinary (e) wave varies from n_o for $\mathbf{n} \parallel z$ to n_e for $\mathbf{n} \parallel x$. Here, the angle brackets indicate averaging over the thickness of the LC layer. The refractive index n_o of the ordinary (o) wave remains unchanged. In this experimental geometry, it is significant that the final orientation of nematic director $\mathbf{n} \parallel x$ defined by the direction of magnetic field lines remains uniform, and special methods of processing of the supporting surfaces of PC/LC cell, which remove the degeneracy of azimuthal anchoring of nematic molecules with the substrate as in the electric analog of the effect, are not required [9].

RESULTS AND DISCUSSION

Figure 2 shows the dependences of spectral positions of the peaks of defect modes for polarization $\mathbf{P} \parallel x$ of probe radiation on reduced magnetic field H/H_c, where H_c denotes the threshold field of the Freedericksz transition [10]. For the LC layer under investigation, $H_c = 0.5 \times 10^6$ A/m. Below the Freedericksz threshold $H/H_c < 1$ in the resonator, only ordinary waves with refractive index n_o appear for any polarization of light ($\mathbf{P} \parallel x$ or $\mathbf{P} \parallel y$). For this reason, the transmission spectrum of the PC/LC cell is a set of defect modes with the spectral position insensitive to field variations (horizontal lines in Fig. 2).

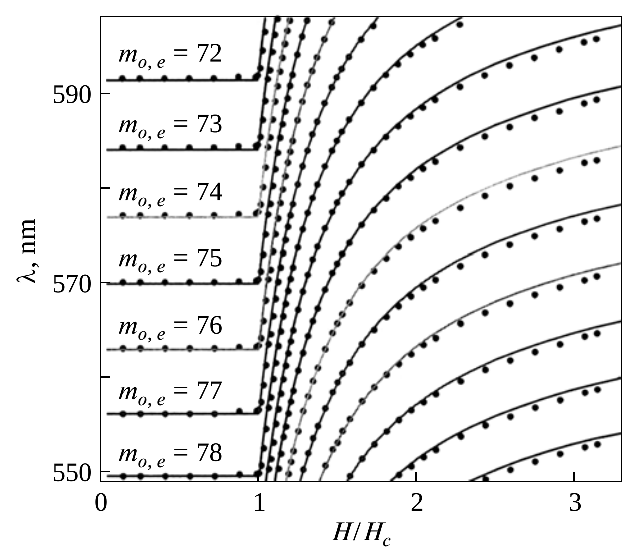

Fig. 2. Experimental (circles) and calculated (solid curves) field dependences of the spectral positions of the defect mode maxima in a PC/LC cell for polarization $\mathbf{P} \parallel x$. Temperature is $T = 23°C$, the thickness of the LC layer is $L = 13.8$ μm.

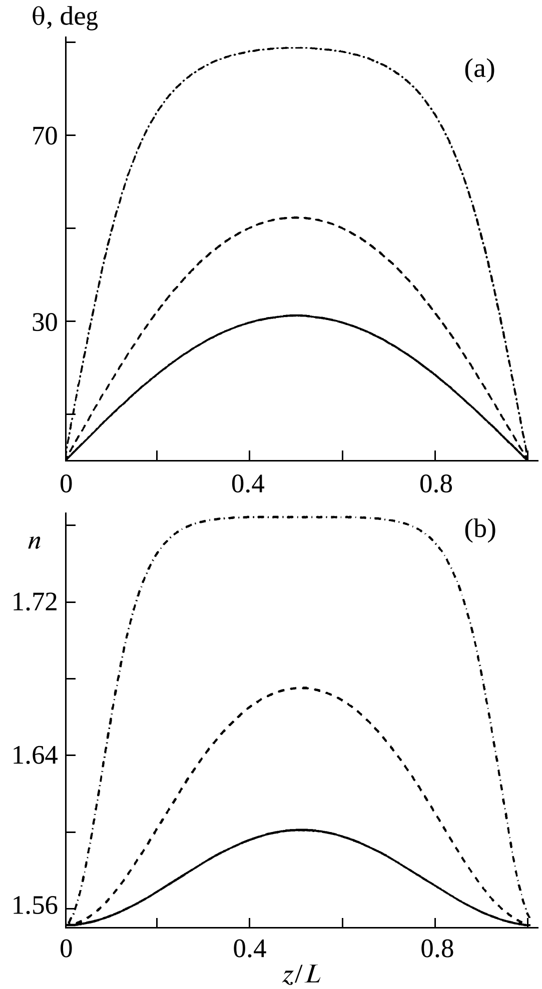

Fig. 3. Distributions of orientation angle $\theta(z)$ of the nematic director calculated by formulas (2)–(4) (a) and of refractive index $n(z)$ of a deformed LC (b) in the defect layer of the PC cell for several values of the magnetic field (H/H_c = 1.07 (solid curve), 1.22 (dotted curve), and 3.00 (dot-and-dash curve)).

Under the action of orientation perturbations of the director field $\mathbf{n}(\mathbf{r})$ of the nematic layer above the Freedericksz threshold $H/H_c > 1$, the defect mode spectrum splits into two orthogonally polarized components with a wavelength satisfying the relation from the theory of Fabry–Perot interferometer:

$$\lambda_e = 2\langle n_e\rangle L/m_e \ (\mathbf{P} \parallel x, e\text{-modes}),$$
$$\lambda_o = 2n_oL/m_o \ (\mathbf{P} \parallel y, o\text{-modes}). \quad (1)$$

Integers $m_{e,\,o}$ determine the serial numbers of defect modes. It should be noted that for the sake of simplicity, we disregard the phase change upon reflection from the mirrors [11]. Reorientation of the nematic by the magnetic field does not affect the ordinary component of the spectrum, but substantially transforms the extraordinary component. It can be seen from Fig. 2 that with increasing magnetic field, the *e*-modes are monotonically displaced to the long-wavelength spectral range. Conversely, in the reorientation of the planar-oriented nematic defect layer in the PC cell (*S*-effect), a shift of *e*-modes to the short-wavelength range was observed [7].

It can be seen from Fig. 2 that in the case of PC structures with a small interval between the modes, any horizontal line λ_o = const with number m_o has several intersections with the curves $\lambda_e(H)$ of spectral positions of peaks of the *e*-modes with numbers $m_e = m_o + 1, m_o + 2, \ldots$. For example, upon an increase in the field, the horizontal line λ_o = 584.4 nm corresponding to the 73rd defect mode of the *o*-wave intersects in turn the defect modes of the *e*-wave with numbers of 74, 75, 76, etc. At the points of intersections of the curves corresponding to spectral coincidence $\lambda_e = \lambda_o$ of orthogonally polarized modes, using an analyzer, it will be possible to observe their interference, the result of which depends on the parity of serial number m_o and m_e (see below).

The spectra of the multilayer structure under investigation were simulated by the method of recurrent relations [12, 13]. The essence of this method is that the light field in each layer is represented by a superposition of counterpropagating incident and reflected waves. The resultant recurrent relations connecting the amplitude reflectance in adjacent layers make it possible to calculate the transmission spectra of the photonic crystal as a whole. Figure 2 illustrates good agreement between the experimental and calculated spectral positions of defect modes in the entire range of magnetic fields.

The distributions of angle $\theta(z)$ between local director $\mathbf{n}$ and vector $\mathbf{H} \parallel x$ used for simulating the transmission spectra were obtained from the minimization of the total free energy per unit volume, which in the case of the *B*-effect in a magnetic field has the form

$$F = \frac{1}{2}(k_{11}\cos^2\theta + k_{33}\sin^2\theta)\left(\frac{d\theta}{dz}\right)^2 - \frac{1}{2}\chi_a H^2\cos^2\theta. \quad (2)$$

This expression is used for deriving the following differential equation:

$$(k_{11}\cos^2\theta + k_{33}\sin^2\theta)\frac{d^2\theta}{dz^2} + \frac{k_{33}-k_{11}}{2}\sin 2\theta\left(\frac{d\theta}{dz}\right)^2 + \frac{1}{2}\chi_a H^2\sin 2\theta = 0, \quad (3)$$

which can be solved numerically with the boundary conditions $\theta(0) = \theta(L) = \pi/2$.

Figure 3 shows the distributions of orientation angle $\theta(z)$ (a) and of the refractive index

$$n(z) = \frac{n_e n_o}{\sqrt{n_e^2\sin^2\theta(z) + n_o^2\cos^2\theta(z)}} \quad (4)$$

(b) in the defect layer for various values of the reduced field, which were calculated using the values of k_{11} =

6×10^{-12} N, $k_{33} = 7.5 \times 10^{-12}$ N [14], and $\chi_a = 0.97 \times 10^{-7}$ [15] taken at a temperature of 25°C. Integration of expression (4) over the thickness L of the defect layer makes it possible to determine the effective refractive index of the LC medium for any field value:

$$\langle n_e \rangle = (1/L)\int_0^L n(z)dz.$$

In the geometry of crossed polarizers above the Freedericksz threshold, orthogonally polarized o- and e-waves appear due to field-induced optical anisotropy of the defect layer. The phase difference between these waves in the case of spectral coincidence $\lambda_e = \lambda_o$ is defined by the relation

$$\delta = 2\pi(\langle n_e \rangle - n_o)L/\lambda.$$

Using relations (1), we can express phase delay δ in terms of the difference in the serial numbers of combining defect modes:

$$\delta = \pi(m_e - m_o). \quad (5)$$

Taking into account this relation, we can then write the transmittance of the PC structure under investigation in the form

$$T = \sin^2[\pi(m_e - m_o)/2]. \quad (6)$$

This expression leads to the conditions for the interference minima and maxima for light transmitted through the PC/LC cell placed between crossed polarizers:

$$(m_e - m_o) = 2k \text{ (minimum)};$$
$$(m_e - m_o) = 2k + 1 \text{ (maximum)}. \quad (7)$$

Here, integers $k = 0, 1, 2, \ldots$ indicate the serial number of intersections of combining e- and o-modes.

Figure 4 shows the distribution of transmittance of light in the λ vs. H/H_c coordinates, which is a set of the transmission spectra of the PC/LC cell in crossed polarizers, which were measured with a step of 1.6×10^3 A/m in the range of fields $H/H_c = 1.0$–1.4. It can be seen from the figure that prior to the Freedericksz threshold $H/H_c = 1$, the degeneracy of the e and o-modes with the same serial number $(m_e - m_o)$ takes place; in accordance with expressions (7), a close-to-zero transmittance is observed in the entire spectrum. For $H/H_c \geq 1$, the degeneracy is removed, and the two sets of polarized transmittance components corresponding to the o and e-modes appear in the spectrum. The spectral position of the o-modes remains unchanged, while the e-modes are displaced to the long-wavelength range of the spectrum. Their gradual coincidence with the o-modes leads to alternation of the set of the minima (optically closed T_{off} states) and maxima (transparent T_{on} states) of the transmittance in the direction of reduced field coordinate H/H_c, which is caused by periodic alternation of parity of $(m_e - m_o)$.

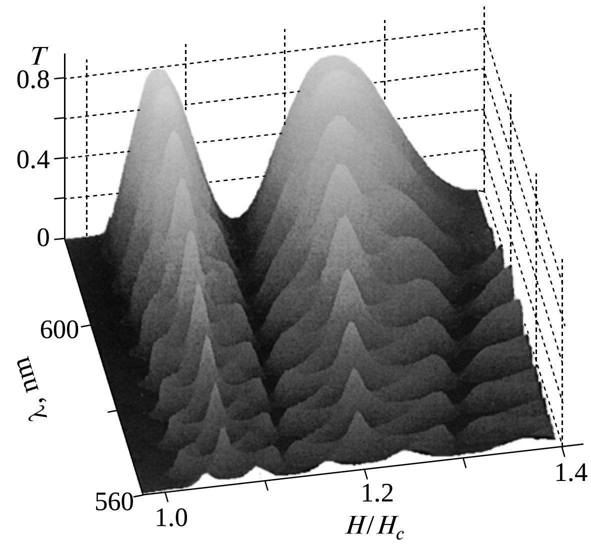

Fig. 4. Distribution of the transmittance of a PC/LC cell placed between crossed polarizers in the B-effect regime.

In contrast to the S-effect [16], the oscillating field dependence of the transmittance of the PC/LC cell is of consistent nature. Upon a change in the effective refractive index $\langle n_e \rangle$ of the LC medium, two opposite tendencies appear in the behavior of the e-modes: on the one hand, the red shift of all e-modes takes place, while on the other hand, a decrease in intermodal interval $\Delta\lambda_e$ in the transmission spectrum takes place due to the well-known relation $\Delta\lambda = \lambda^2/2Ln$. The simultaneous effect of these factors leads to consecutive emergence (disappearance) of transmittance peaks from the short-wavelength to the long-wavelength edge of the photonic band gap (PBG). Upon an increase in the field, the process is repeated periodically.

In PC structures with a small intermodal interval, it is possible to implement the switching regime from the opaque state in the entire spectrum to a state with open spectral transparency windows. Such a situation takes place, for example, in the PC/LC cell under investigation in a wavelength range of 560–620 nm in the field $H/H_c = 1.07$ corresponding to the first intersection of modes. In this case, the change in the interval between the nearest o- and e-modes does not exceed their spectral width, and transmission at all resonances is switched on practically simultaneously (solid curve in Fig. 5). For higher values of the field, the modes are switched on consecutively. Indeed, in the field of $H/H_c = 1.22$ corresponding to the maximal transmittance of the chosen mode $\lambda = 584.4$ nm (dashed curve), it can be seen that the profiles of short-wavelength modes have passed by the transmittance peak, while the long-wavelength modes have not reached the peak. In addition, Fig. 5 demonstrates the advantage of the method of crossed polarizers used here in the

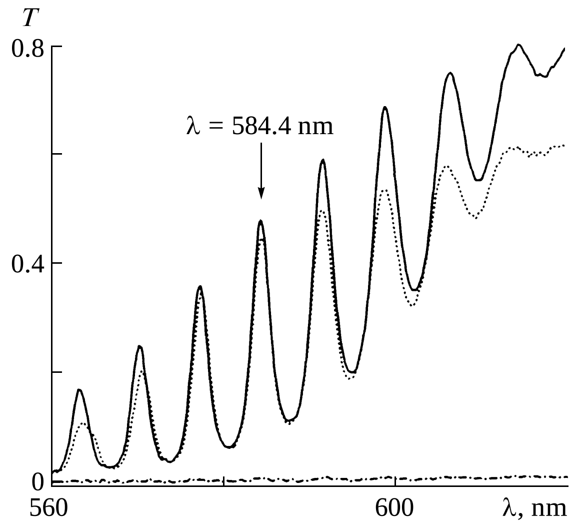

Fig. 5. Magnetooptical switching of the spectrum of the PC/LC cell. The dot-and-dash curve shows the transmittance in a field $H < H_c$; the solid curve corresponds to the first intensity maximum of the defect mode for H/H_c = 1.07; the dotted curve corresponds to the second maximum for H/H_c = 1.22. All curves correspond to the extrema for $\lambda_0 = 584.4$ nm.

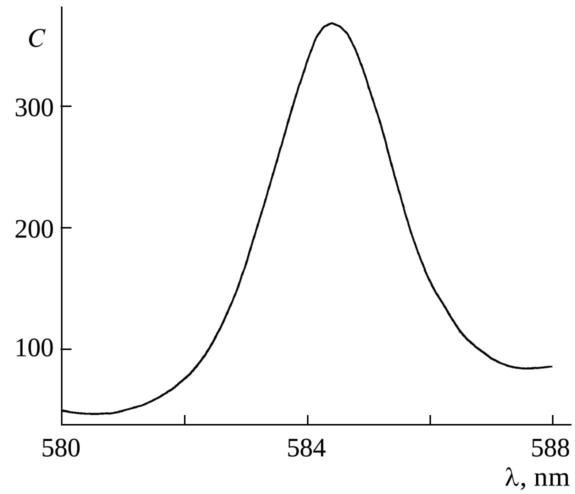

Fig. 6. Contrast ratio $C = T_{\text{on}}/T_{\text{off}}$ of the transmittance curves as a function of wavelength of light in the range of the 73rd *o* mode with a peak at $\lambda_0 = 584.4$ nm.

vicinity of the PBG edge. It can be seen that in the state T_{off}, not only modes, but also the background level are switched off. This leads to a considerable increase in the contrast ratio $T_{\text{on}}/T_{\text{off}}$.

The spectral dependence of contrast ratio $C = T_{\text{on}}/T_{\text{off}}$ in the limits of the profile corresponding to the 73rd *o*-mode is shown in Fig. 6. It can be seen that the contrast ratio is a function of the wavelength and attains its maximal value $C_{\max} = 380$ at the peak of the mode. It should be noted that the contrast ratio in the case of defect mode switching as a result of *B* deformation is an order of magnitude larger than in the case of the *S*-effect [16].

In probing the samples by monochromatic radiation at a wavelength corresponding to any *o* mode in the geometry of crossed polarizers, we can observe modulation of the transmittance of the PC/LC cell due to periodic variation of phase delay (5). Figure 7 shows experimental and calculated dependences *T*(*H*) of the PC structure under investigation at a wavelength of 584.4 nm.

In contrast to the case of an anisotropic LC film placed between crossed polarizers, this dependence is nontrivial. The maxima and minima of the transmittance correspond to the coincidence of resonant wavelengths of defect *e*-modes with the wavelength of the 73rd o mode. The maximum at $H/H_c = 1.07$ corresponds to the first intersection of modes, the minimum at $H/H_c = 1.12$ corresponds to the second intersection, while the maximum for $H/H_c = 1.22$ corresponds to the third intersection of the modes. The broadening of oscillations is associated with slowing down of the increase in the effective refractive index $\langle n_e \rangle$ far from the Freedericksz threshold field. The "arms" observed on both sides of the maximum correspond to the transmittance level for the *o* mode which does not overlap with the *e*-modes. The switching of the PC/LC cell from the closed to the first transparent state requires a change in the field by 3.2×10^4 A/m. Figure 7 also demonstrates the calculated modulation curve for transmittance of the PC/LC cell. It can be seen that the results of the experiment and computer calculations are in good agreement.

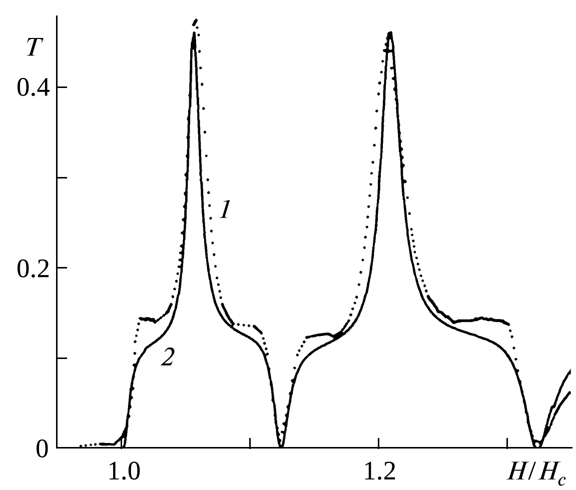

Fig. 7. Experimental (*1*) and calculated (*2*) modulation curves of the transmittance of the PC/LC cell at a wavelength of 584.4 nm.

CONCLUSIONS

Our analysis of spectral properties of a multilayer PC/LC structure upon the orientation transition in a nematic defect layer from the homeotropic to the planar state revealed a number of features associated with the specific geometry of crossed polarizers used in this study. It has been shown both experimentally and theoretically that the oscillating field dependence of the transmittance of the PC/LC cell is of consistent nature. The behavior of extraordinary defect modes in the spectrum is determined by opposite tendencies associated with the variation in the effective refractive index of the LC medium upon reorientation of the director.

It is found that for PC structures with a small intermodal interval, the cell can be switched from the state closed in the entire spectrum to the state with open spectral transparency windows. In addition, modulation of transmittance of the PC/LC cell associated with periodic alternation of the parity of serial numbers of combining defect modes is implemented at frequencies of ordinary defect modes. The method of recurrent relations is used for numerical analysis of the spectra and modulation curves for the transmittance of the PC structure. Good agreement with experimental data was obtained. It should be noted that the magnetic field was used only for convenience of measurements. Analogous results can be obtained by applying an electric field instead of the magnetic field for reorientation of the nematic layer.

ACKNOWLEDGMENTS

This study was supported by the Russian Academy of Sciences (grant nos. NSh-3818.2008.3, RNP.2.1.1.3455, 27.1, and 9.1), Siberian Branch, Russian Academy of Sciences (grant nos. 5 and 144), State contract no. 02. 740.11.0220, and the Federal program "Scientific Manpower and Pedagogical Staff of Innovative Russia."

REFERENCES

1. H. Kitzerov, Liq. Cryst. Today **11**, 3 (2002).
2. K. Busch, R. B. Wehrspohn, and S. Lolkes, *Photonic Crystals: Advances in Design, Fabrication, and Characterization* (Wiley, Berlin, 2004).
3. V. F. Shabanov, S. Ya. Vetrov, and A. V. Shabanov, *Optics of Real Photonic Crystals: Liquid Crystal Defects and Inhomogeneities* (Sib. Otd. RAN, Novosibirsk, 2005) [in Russian].
4. V. A. Gunyakov, V. P. Gerasimov, S. A. Myslivets, et al., Pis'ma Zh. Tekh. Fiz. **32** (21), 76 (2006) [Tech. Phys. Lett. **32**, 951 (2006)].
5. J. S. Patel, M. A. Saifi, D. W. Berreman, et al., Appl. Phys. Lett. **57,** 1718 (1990).
6. A. E. Miroshnichenko, I. Pinkevich, and Yu. S. Kivshar, Opt. Express **14**, 2839 (2006).
7. R. Ozaki, T. Matsui, M. Ozaki, and K. Yoshino, Jpn. J. Appl. Phys. **41**, L1482 (2002).
8. M. F. Schiekel and K. Fahrenschon, Appl. Phys. Lett. **19**, 391 (1971).
9. L. M. Blinov, *Electro- and Magneto-Optics of Liquid Crystals* (Nauka, Moscow, 1978) [in Russian].
10. V. K. Freedericksz and V. Zolina, Trans. Faraday Soc. **29**, 919 (1933).
11. W. Demtroder, *Laser Spectroscopy: Basic Concepts and Instrumentation* (Springer-Verlag, Berlin, 1981; Nauka, Moscow, 1985).
12. V. A. Bushuev and A. D. Pryamikov, Kvantovaya Élektron. (Moscow) **33**, 515 (2003).
13. V. G. Arkhipkin, V. A. Gunyakov, S. A. Myslivets, et al., Zh. Eksp. Teor. Fiz. **133**, 447 (2008) [JETP **106**, 388 (2008)].
14. M. H. Stephen and J. P. Straley, Rev. Mod. Phys. **46**, 617 (1974).
15. W. H. De Jeu, W. A. P. Claassen, and A. M. J. Spruijt, Mol. Cryst. Liq. Cryst. **37**, 269 (1976).
16. V. Ya. Zyryanov, V. A. Gunyakov, S. A. Myslivets, et al., Mol. Cryst. Liq. Cryst. **488**, 118 (2008).

Translated by N. Wadhwa