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Photonic properties of polymer-stabilized photosensitive cholesteric liquid crystal studied by combination of optical activity, transmission and fluorescence

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ABSTRACT

We report complex optical investigations of polymer-stabilised cholesteric photonic liquid crystal doped by a dichroic fluorescent dye. For the first time, we employed a combination of various experimental methods, including measurements of spectra of transmission, reflection, rotation of the plane of polarisation of light, fluorescence, to characterise the properties of the photonic crystal. The peculiarity of the reported investigations is employing a photosensitive cholesteric mixture forming the photonic crystal. The position of the photonic band could be changed by illumination with ultraviolet light and stabilised by thermopolymerisation. In this way, the position of the cholesteric band was matched with the emission band of the fluorescent dye, which enabled to perform diversified studies on the same photonic crystal. We determined the parameters, which defined the optical properties of the photonic crystal, spectral dependence of the transformation of linearly polarised light to elliptically polarised as the light passes the photonic crystal, the photonic density of states. The interpretation of the experimental data was performed using analytical expressions obtained from the solution of Maxwell's equations, numerical calculations by the Berreman matrix method.

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1. Introduction

In photonic crystals, the period of spatial ordering is comparable with a light wavelength that leads to the transformation of spatial, spectral and polarisation characteristic of light waves [1-3]. Due to their unusual structure, optical characteristics, possibilities of wide practical applications, photonic crystals during several decades attract intensive attention of researchers. A special place among photonic crystals is occupied by liquid-crystalline photonic crystals [4-6]. Among them, the most well-known and widely investigated are cholesteric photonic crystals [4]. In spite of the long history of investigations of cholesteric liquid crystals, new directions of fundamental and applied studies continue to appear [6-10]. The structure of cholesteric photonic crystals possesses two-level molecular ordering. Long molecular axes are locally oriented preferentially along a direction called the **n**-director of the liquid crystal. The degree of orientational ordering of this structure is characterised by the scalar orientational order parameter $S = 1/2(\langle 3\cos^2\theta \rangle - 1)$, where θ is the angle between the director and the long molecular axes [4]. Averaging is performed over the molecular orientational distribution function $f(\theta)$. S is the coefficient near the second term of the expansion of the orientational distribution function f (θ) over Legendre polynomials [4]. Due to molecular chirality, the **n**-director rotates along the axis perpendicular to **n** forming a helical structure with periodicity *p* of the order of light wavelength. Interaction of light with such structure is nontrivial and strongly dependent on its wavelength. A photonic stop band is formed, i.e., in a certain spectral range light cannot propagate through the cholesteric structure. Dispersion of light near the stop band is nontrivial, as well as the photonic density of states (DOS) $\rho(\omega) = dk/d\omega$, where *k* is the wavenumber of light.

The photonic density of states $\rho(\omega)$ is an important characteristic of the photonic crystal, determining its optical properties. In the direction along the helical axis, the stop band exists only for light of one circular polarisation coinciding with the direction of rotation of the cholesteric helix. The width of the photonic stop band $\Delta \lambda = p \Delta n$ depends on the optical anisotropy $\Delta n =$ $n_{||} - n_{\perp}$ in the plane perpendicular to the helix. $n_{||}$ and n_{\perp} are the refractive indices along and perpendicular to the local director. In an infinite sample $\rho(\omega)$ diverges near the long-wavelength $\lambda_1 = pn_{||}$, and shortwavelength $\lambda_2 = pn_{\perp}$ boundaries of the band, $\rho(\omega) = 0$ within the photonic band. In samples of finite thickness the photonic stop band is transformed into a quasi-stop band. The density of states $\rho(\omega)$ becomes finite inside the band and light with $pn_{\perp} < \lambda < pn_{\parallel}$ can partially transmit through the photonic crystal. Outside the band $\rho(\omega)$ oscillates acquiring maximum values near the long-wavelength λ_1 and short-wavelength λ_2 boundaries of the band. The appearance of $\rho(\omega)$ critically depends on the thickness of the photonic crystal, helical pitch, n_{\parallel} and n_{\perp} . DOS $\rho(\omega)$ defines the dispersion of light $k(\omega)$ outside the quasi-stop band, the spectral dependence of optical characteristics, including the spectra of fluorescence, optical activity.

DOS can be calculated from complex amplitude transmission coefficient of the photonic crystal $t(\omega) = X(\omega) + iY(\omega) = |t|e^{i\psi}$ [11,12]. The intensity of light $T(\omega)$ transmitted through the photonic crystal is determined by the modulus of transmission function $|t(\omega)| = (X^2 + Y^2)^{1/2}$. The phase of transmission function $\psi(\omega)$ = arctan[Y/X]gives the phase accumulated by the peak of a light pulse propagating through the photonic crystal. If the real and imaginary parts of the transmission amplitude are known, $\rho(\omega)$ can be calculated [11–18]:

$$\rho = \frac{1}{L} \frac{Y'X - X'Y}{X^2 + Y^2}$$
(1)

where *L* is the thickness of the sample. The prime denotes the derivative with respect to ω .

Recently a number of experimental methods were proposed to determine DOS of liquid-crystalline photonic crystals. The first method based on fluorescence spectra of guest molecules dissolved in the liquid crystal was developed by Schmidtke and Stille [12]. According to Fermi's Golden Rule [12,17], fluorescence intensity is proportional to the DOS and the square of the module of dipole moment of optical transition. In the range of the photonic band, the dipole moment strongly depends on frequency. Using the measured fluorescence spectra and calculated dipole moment of transition, DOS and its dependence on temperature in cholesteric were determined [19,20]. For the first time, DOS was determined experimentally in a 3D liquid-crystalline photonic crystal BPII [20]. It is however worth noting that determination of DOS by this method is conjugated to a number of difficulties. Fluorescent molecules should well orient in the liquid crystal, it is necessary to know the orientation of the dipole moment of transition with respect to the molecular long axis. Moreover, the fluorescence spectrum must be sufficiently wide to capture the whole range of spectra in which $\rho(\omega)$ is to be determined. Besides, to find $\rho(\omega)$ from the fluorescence spectra it is necessary to know the orientational order parameter S of the photonic crystal which often cannot be measured with usual methods due to helical structure of cholesteric.

In 2015 another method of determination of DOS was proposed which uses the spectra of rotation of the

plane of polarisation of light (RPPL) [21]. The abovelisted difficulties were absent in this method. Determination of DOS was made possible after the observation of steps in the spectral dependence of rotation of the plane of polarisation of light [22] which were directly connected with peculiarities of DOS. The existence of the steps was earlier predicted by analytical theory [23,24] and numerical calculations using Berreman matrix technique [25–27], but was not observed previously in experiments. Their observation enabled developing a method to determine DOS based on measurements of RPPL (optical activity).

The characteristic feature of the present work is that we performed complex investigations comprising measurements of transmission, reflection spectra, rotation of the plane of polarisation of light and fluorescence. In the investigations, we employed a photosensitive cholesteric photonic crystal in which the position of the photonic band could be shifted by ultraviolet irradiation to the spectrum of fluorescence of the dissolved dye. Eventually, the spectral position of the stop band could also be fixed by thermoinduced polymerisation of the photonic crystal. This allowed to determine various photonic characteristics using different methods and to relate them to the photonic density of states.

The article is organised as follows. In Section 2, the materials and methods employed in the investigation are described. In Section 3 we give the experimental results on measurements of transmission, reflection spectra, rotation of the plane of polarisation of light, and fluorescence. From the comparison of transmission spectra with theory, parameters characterising the photonic crystal were obtained. In Section 4 the experimental results are analysed and discussed. The obtained parameters of the photonic structure were used for the calculation of photonic density of states. The experimentally determined photonic density of states was compared with calculated. The spectral positions and intensity of peaks of fluorescence are discussed on the basis of Fermi's Golden Rule, DOS, polarisation of the light eigenmodes. In Conclusion, the main results of our work are summarised.

2. Materials and methods

A polymerisable cholesteric mixture consisting of several components shown in Figure 1(a) was prepared. Nematic mixture **E48** (Merck), nematogenic diacrylate **RM257** (Aldrich), thermoinitiator azo-bis-isobutyronitrile (**AIBN**, Aldrich), fluorescent dye **DCM** (Aldrich) were used as received. Chiral dopant **HexSorb** and chiralphotochromic dopant **CinSorb** were synthesised according to previously published paper [28]. Both dopants possess high helical twisting power and induce right-handed cholesteric helix. Chiralphotochromic dopant **CinSorb** was shown to undergo E-Z isomerisation accompanied with a decrease in molecular anisometry (Figure 1(b)) and helical twisting power [28,29].

For the sample preparation, the cholesteric mixture components were dissolved in chloroform; the solution was dried overnight at atmospheric pressure and in a vacuum (at room temperature). Samples were prepared by capillary filling of the polyimide and ITO-coated cells. Some of the samples were UV-irradiated by Hg lamp (365 nm, ~0.3 mW/cm²). UV irradiation leads to E-Z isomerisation of **Sorb** resulting in helix untwisting and shift of the stop band to the longer wavelengths. Finally, all samples were annealed at 60°C during three days for polymerisation of **RM257**. After thermopolymerisation, the sample was cooled to room temperature at which measurements were made.

In the investigations, a complex of optical methods were employed, including measurements of transmission, reflection, rotation of the plane of polarisation of light, fluorescence. We used a setup based on the Altami Lum LED optical microscope. Control of the quality of the sample was achieved by optical observations and by measurement of transmission spectra and their comparison with theoretical ones. For our measurements, we selected the region of the sample with the position of the photonic band in the range of the emission spectrum of DCM. Transmission, reflection, optical activity and fluorescence spectra were measured with the aid of Avaspec-2048 (Avantes) fibre optic spectrometer coupled to the microscope. Spectra were measured for light directed along the normal to the cell surface, that is, along the cholesteric helix. Fluorescence was excited by a KLM-473-20 DPSS laser (FTI-Optronic), emission wavelength 473 nm. Excitation was performed by the light of left (i.e. nondiffracting) circular polarisation. Fluorescence spectra were measured in light of right circular polarisation and normalised by fluorescence spectrum from the region of the sample where the spectral position of the photonic band was far from the emission band of DCM. Spectra were recorded from regions of lateral size about 200 µm. We analysed the optical properties of the photonic crystal on the basis of analytical theory [23,24] and numerical calculations using the 4×4 Berreman matrix technique optimised for uniaxial liquid-crystal structure [25-27].

3. Experiment, determination of parameters necessary to calculate DOS

The convenient feature of the cholesteric studied in this work is the possibility to tune the spectral position of its photonic band by UV illumination. This procedure was



Figure 1. (Colour online) (a) Chemical structure of components and composition of the polymerisable cholesteric mixture with photovariable helix pitch; (b) Isomerisation of the **CinSorb** molecule induced with UV-irradiation.

used in particular to match the positions of the photonic band of cholesteric and emission band of the fluorescent dye. Figure 2 demonstrates transmission (a) and reflection (b) spectra of a sample without UV treatment (blue curves) and a sample illuminated before polymerisation (red curves). The spectra were measured in light of right (diffracting) circular polarisation. The dashed line in Figure 2(a) is the fluorescence spectrum of DCM. In the nonilluminated sample the photonic band is located in the short-wavelength range (about 450 nm). UV illumination shifts the diffraction band to longer wavelength range (about 650 nm). The insets in (a) and (b) show photographs in transmission and reflection of the regions of the sample on which the spectra were measured. In transmission, the colours are complementary to reflection. The light-induced shift of the band can amount 200 nm (Figure 2). So by varying the illumination dose the band can be matched with the weighted



Figure 2. (Colour online) (a) Transmission spectra of cholesteric samples with different position of the photonic band. In the sample which was not illuminated after preparation the photonic band is located in the short-wavelength range (~450 nm). UV irradiation (5 min, 365 nm, ~0.3 mW/cm²) induces a long-wavelength shift of the photonic band (~650 nm). (b) Reflection spectra measured from the same samples as the spectra in (a). The insets in (a) and (b) show polarising optical microscope images of the regions where spectra were measured taken in transmission and reflection, respectively. The dashed curve shows the fluorescence spectrum of DCM.

centre of the fluorescence band. Form of the spectrum with the band in the long-wavelength range correlates with the theory for a perfect sample [24,30,31]. The shapes of the band in the short-wavelength range differ from the band in the long-wavelength range. The intensity in reflection band does not achieve full reflection, as in the long-wavelength range (Figure 2(b)). The band in the transmission is broadened (Figure 2(a)). This transformation can be related to Borrman effect [23,32,33] because the band in the short-wavelength range overlaps with the absorption of the components of the liquid-crystal mixture. Further, we provide the results for the sample where the position of the photonic band is in the range without absorption and close to the weighted centre of the emission band of DCM.

The solid curve in Figure 3(a) shows the transmission spectrum of the cholesteric photonic crystal measured in light of right circular polarisation. The spectrum possesses an intense band related to the photonic zone and pronounced minima and maxima on both sides of the band. The decrease in transmission in the shortwavelength region is related to absorption of DCM and photochromic additives. Well-defined photonic band and presence of oscillations allow to determine the parameters necessary to describe the properties of the photonic crystal. For cholesteric liquid crystal and light propagating along the helical axis an analytical expression for complex transmission coefficient t exists [23,24]. Namely, real and imaginary parts of t can be written as [20]

$$X(\omega) = \frac{\tau^2 \beta_3^2 \cos \beta_3 L}{\tau^2 \beta_3^2 + \kappa^4 \delta^2 \sin^2 \beta_3 L}$$
(2)

$$Y(\omega) = \frac{\tau \beta_3 (\beta_3^2 + \tau^2/4 - \kappa^2) \sin \beta_3 L}{\tau^2 \beta_3^2 + \kappa^4 \delta^2 \sin^2 \beta_3 L}$$
(3)

where $\beta_3 = \kappa \sqrt{1 + (\tau/2\kappa)^2 - \left[(\tau/\kappa)^2 + \delta^2\right]^{1/2}}$,

 $\kappa = \omega n/c, \ \tau = 4\pi/p, \ \text{and} \ \delta = (n_{||}^2 - n_{\perp}^2)/(n_{||}^2 + n_{\perp}^2).$ The transmission intensity $T = X^2 + Y^2$.

The dashed line in Figure 3(a) is the theoretical spectrum of cholesteric calculated using (2,3) with parameters p = 381.6 nm, $\delta = 0.119$. In the employed



Figure 3. (Colour online) (a) Transmission spectrum of cholesteric sample (solid curve) and the calculated transmission spectrum (dashed curve). The theoretical spectrum is calculated with parameters p = 381.6 nm, $\delta = 0.119$, nL = 5.8 µm. (b) Rotation of the plane of polarisation of light measured from the same region. Sample thickness L = 3.56 µm.

approach outside the liquid crystal, the optical cell is taken to be isotropic. Calculations employing the Berreman matrix technique give the transmission spectrum identical to the spectrum obtained using the analytical theory (2,3). Absorption of light was not taken into account. In the investigated sample the absorption is separated from the photonic band. Presence of the absorption in the short-wavelength region does not modify the optical properties in the range of the photonic band. The similarity of the experimental and calculated spectra indicates the high quality of the cholesteric structure [30,31]. Parameters p and δ obtained from fitting the transmission spectrum will be further used for modelling and analysis of the optical properties of the photonic crystal.

Now we move on to RPPL and fluorescence of the photonic crystal whose transmission spectrum is given in Figure 3(a). Figure 3(b) shows the spectrum of RPPL $\phi(\lambda)$ measured from the same region of the sample as the spectrum in Figure 3(a). Outside the photonic band the form of the RPPL spectrum practically does not depend on the orientation of incident light. RPPL has the characteristic form: pronounced peaks near the two edges of the band and smooth decrease of the absolute value of RPPL with steps on the two sides of the band. Such a form is in accordance with theory [23,31]. In the

middle of the photonic band, the polarisation of light at the exit of the sample is close to circular, so RPPL could not be measured accurately. We focus later (Section 4) on the features of RPPL and corresponding properties of DOS outside the band.

Next step is the measurement of fluorescence spectra in the range of the photonic band. The curve in Figure 4 (a) shows the fluorescence spectrum of the cholesteric sample measured in light of right circular polarisation. The spectrum is normalised by the fluorescence spectrum I^{F}_{0} measured in the same conditions on the sample where the photonic band was shifted far away from the emission of DCM. In a wide spectral range from 560 to 750 nm reflection and absorption practically do not change the fluorescence spectrum I_0^{F} which is used for normalisation. In a shorter range of $525 < \lambda < 560$ nm some decrease is observed both in I^F and $I_0^{\ F}$ spectra. This can be the reason that the normalised spectrum in this range $\lambda \le 560$ nm is somewhat less than unity. The small decrease of intensity in the short-wavelength region does not influence the obtained results and their interpretation. The main fluorescence peak is located near the long-wavelength boundary of the photonic band. Fluorescence intensity in absence of the photonic band.

The photonic crystal modifies in a complex manner the polarisation of light passing through it. Not only the plane of polarisation rotates, but also linearly polarised light becomes elliptical. Figure 5 shows the



Figure 4. (a) Normalised fluorescence spectrum $l^{F}/l^{F_{0}}$ measured in light of right circular polarisation. (b) Photonic density of states determined from the rotation of the plane of polarisation of light (dots). The solid curve is the theoretical DOS calculated with the parameters determined from the transmission spectrum. The wavelengths of peaks in fluorescence spectrum correlate with positions of the maxima in DOS. Different intensity of the two main peaks in fluorescence results from orientational ordering of dye molecules.

experimental spectrum of the ratio of minimum and maximum intensities I_{min}/I_{max} passed through the analyser at the exit of the photonic crystal. The two intensities correspond to the orientations of the analyser parallel to the short and long axes of the ellipse. I_{min} $/I_{max}$ is a quantitative characteristic of the spectral dependence of ellipticity of transmitted light in the range of the photonic band. I_{min}/I_{max} is maximal in the centre of the photonic band, that is, polarisation is close to circular. Outside the band I_{min}/I_{max} is close to zero, that is, the polarisation of light is close to linear, although its direction can change sufficiently, especially near the boundaries of the band (Figure 3(b)). I_{min}/I_{max} exhibits oscillations whose spectral positions correlate with oscillations in transmission and RPPL spectra (Figure 3). Results of calculations of I_{min}/I_{max} employing Berreman 4×4 matrix method are in agreement with the experiment. Measurements undertaken on different regions of the sample with a somewhat varying position of the photonic band give similar results.

4. Discussion

We now discuss the relations between the main optical properties of cholesteric, their dependence from DOS. Eq. (1) is valid for different types of photonic crystals. For our cholesteric photonic crystal DOS can be determined from the data of RPPL. The fact that the photonic band is present only for the light of one circular polarisation allows to link DOS and RPPL [21]. DOS and RPPL are related by a simple equation [21]

$$\rho = \frac{n}{c} + \frac{2}{L} \frac{d\varphi}{d\omega} \tag{4}$$

The first term represents DOS in absence of the photonic band ρ_0 . If the dispersion of the refractive index is small, this term can be considered constant. Symbols in Figure 4(b) show relative DOS ρ/ρ_0 determined from RPPL data with the aid of Eq. (4). The curve in Figure 4 (b) is the DOS calculated from (1–3) using the parameters determined from the fitting of the transmission spectrum (that is, no additional free parameters were used to calculate the spectra in Figure 4). DOS has pronounced maxima with close intensity near the two edges of the photonic band. Within the band, DOS abruptly decreases. The results (the points and the curve in Figure 4(b)) demonstrate good agreement between experimentally determined from RPPL and calculated DOS.

Let us now discuss similarities and differences between fluorescence and DOS spectra (Figure 4(a,b)). Whereas positions of the extremes of fluorescence correlate with those of DOS, the fluorescence spectrum essentially differs from DOS. The reason is the dependence of the spontaneous emission probability on the relative orientation of the dipole moment of transition to the polarisation of the light wave. According to Fermi's Golden Rule, the relative fluorescence intensity with respect to the intensity of emission from the structure without the photonic band is

$$\frac{I^{F}}{I_{0}^{F}} = \frac{\rho \langle |d|^{2} \rangle}{\rho_{0} \langle |d_{0}|^{2} \rangle}$$
(5)



Figure 5. Ratio of intensities I_{min}/I_{max} of light at the exit of the photonic crystal. I_{min}/I_{max} reaches the maximum value in the centre of the photonic band. I_{min}/I_{max} is close to zero and oscillates outside the band.

 $\langle |d_0|^2 \rangle$ is the average squared component of the dipole moment for the structure without the photonic band. In the employed dye DCM the dipole moment of transition is parallel to the long molecular axis. In this case with the parameters of cholesteric determined from transmission spectrum (Figure 3(a)), $\langle |d|^2 \rangle$ for the diffracting polarisation can be calculated if the degree of orientational order *S* is known [12]

$$\left\langle |d|^2 \right\rangle = \frac{2}{3} \frac{f_1^2 - \frac{1}{2}}{f_1^2 + 1} S + 1/3$$
 (6)

 f_1 is called the ellipticity of the eigenmode for diffracting polarisation [12]

$$f_1 = \frac{1 - \delta - \left(\beta_3/\kappa\right)^2 - \left(\tau/2\kappa\right)^2}{\beta_3 \tau/\kappa^2} \tag{7}$$

Inside the photonic band, f_1 becomes imaginary and $Im(f_1)$ must be substituted in (6) instead of f_1 [12]. In the isotropic medium (S = 0) the average value $\langle |d|^2 \rangle = 1/3$. The key factor which modifies the fluorescence spectrum is the spectral dependence of ellipticity f_1 (7) for the diffracting polarisation. Transformation of fluorescence intensity with respect to DOS can be qualitatively understood considering an infinite sample. At the two edges of the stop band the eigenmodes are linearly polarised with their wavelengths in medium equal to the pitch p. On the longwavelength side $(\lambda_1 = pn_{\parallel})$ the electric vector of the eigenmode rotates in space remaining parallel to the local **n**-director and to the average direction of the dipole moment of the transition in dye molecules. From (7) we get $f_1 = \infty$ at $\lambda = \lambda_1$, so $\langle |d_1(\lambda_1)|^2 \rangle =$ $\frac{2}{3}S + \frac{1}{4}$. On the short-wavelength side ($\lambda_2 = pn_1$) the electric vector of the eigenmode also rotates synchronously with the director but remains perpendicular to the average direction of the dipole moment. From (7) f_1 = 0 at $\lambda = \lambda_2$, therefore $\langle |d_1(\lambda_2)|^2 \rangle = -\frac{1}{3}S + \frac{1}{3}$. So, both $\left<\left|d_1(\lambda_1)\right|^2\right>$ and $\left<\left|d_1(\lambda_2)\right|^2\right>$ and their ratio according to (6) depend on S. These peculiarities of the resonance eigenmodes lead to an increase of fluorescence at the long-wavelength side and to a decrease at the shortwavelength side from the band gap with respect to DOS (Figure 4(a,b)). For the value of S = 0.4 [12,34–37] the ratio $\langle |d_1(\lambda_1)|^2 \rangle / \langle |d_1(\lambda_2)|^2 \rangle = 3$. In our spectrum (Figure 4(a)) the ratio $I^F(\lambda_1)/I^F(\lambda_2) \approx 2.5$. The agreement can be considered good, since for the interpretation of the transformation of the fluorescence spectrum with respect to DOS we employed the model of an infinite sample. So the characteristics of fluorescence

are in qualitative agreement with theory and correlate with other optical properties of cholesteric.

5. Conclusion

For the first time complex optical investigations including measurements of spectra of transmission, reflection, fluorescence, RPPL were performed on the same sample of cholesteric photonic crystal, which enabled to compare and interpret the peculiarities observed in the spectra. In contrast to conventional RPPL in isotropic media, in cholesteric photonic crystal linearly polarised light transforms to elliptically polarised. Full description of the state of light transmitted through the photonic crystal is performed, in particular, the spectral dependence of its ellipticity and rotation of the main axes of the polarisation ellipse were determined. In spectra of RPPL and fluorescence, peculiarities are observed which are related to the structure of DOS. We indicate the advantages of using RPPL for determination of DOS with respect to other methods. Determined from RPPL and calculated photonic density of states is in good agreement. The spectral positions of the maxima of fluorescence correlate with the maxima of DOS. Transformation of their intensity with respect to maxima of DOS is related to spectral dependence of ellipticity of photonic eigenmodes.

Disclosure statement

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References

- [1] Sakoda K. Optical properties of photonic crystals. Berlin: Springer; 2001.
- [2] Johnson SG, Joannopoulos J. Photonic crystals: the road from theory to practice. Boston (MA): Kluwer; 2002.
- [3] Soukoulis CM, editor. Photonic crystals and light localization in the 21st century. Dordrecht: Springer Science & Business Media; 2012.
- [4] de Gennes PG, Prost J. The physics of liquid crystals. 2nd ed. Oxford: Clarendon Press; 1995.

- [5] Wright DC, Mermin ND. Crystalline liquids: the blue phases. Rev Mod Phys. 1989;61:385.
- [6] Vetrov S, Timofeev IV, Shabanov VF. Localized modes in chiral photonic structures. Physics-Uspekhi. 2020;63:33.
- [7] Ortega J, Folcia CL, Etxebarria J. Laser emission at the second-order photonic band gap in an electric-fielddistorted cholesteric liquid crystal. Liq Cryst. 2019;46:2159–2166.
- [8] Folcia CL, Ortega J, Etxebarria J. Anomalous light scattering in photonic cholesteric liquid crystals. Liq Cryst. 2020;47:958–965.
- [9] Gevorgyan AH. Specific properties of light localization in the cholesteric liquid crystal layer. The effects of layer thickness. Liq Cryst. 2020;47:1070–1077.
- [10] Jeng SC. Applications of Tamm plasmon-liquid crystal devices. Liq Cryst. 2020;47:1223–1231.
- [11] Bendickson JM, Dowling JP, Scalora M. Analytic expression for the electromagnetic mode density in finite, one-dimensional, photonic band-gap structures. Phys Rev E. 1996;53:4107.
- [12] Schmidtke J, Stille W. Fluorescence of a dye-doped cholesteric liquid crystal film in the region of the stop band: theory and experiment. Eur Phys J B. 2003;31:179–194.
- [13] Blinov LM. Lasers on cholesteric liquid crystals: mode density and lasing threshold. JETP Lett. 2009;90:166–169.
- [14] Mavrogordatos T, Morris SM, Castles F, et al. Density of photon states in dye-doped chiral nematic liquid crystal cells in the presence of losses and gain. Phys Rev E. 2012;86:011705.
- [15] Gevorgyan AH, Kocharian AN. Photonic density and nonreciprocal optical properties in chiral liquid crystals. Opt Commun. 2012;285:2854.
- [16] Gevorgyan AH, Oganesyan KB, Karapetyan RV, et al. The photonic density of states and the light energy density in cholesteric liquid crystal cells. Laser Phys Lett. 2013;10:125802.
- [17] Mavrogordatos T, Morris SM, Wood SM, et al. Spontaneous emission from radiative chiral nematic liquid crystals at the photonic band-gap edge: an investigation into the role of the density of photon states near resonance. Phys Rev E. 2013;87:062504.
- [18] Furumi S, Sakka Y. Chirooptical properties induced in chiral photonic-bandgap liquid crystals leading to a highly efficient laser-feedback effect. Adv Mater. 2006;18:775.
- [19] Dolganov PV, Dolganov VK. Photon density of states in a cholesteric photonic crystal. JETP Lett. 2018;108:170–174.
- [20] Dolganov PV, Baklanova KD, Dolganov VK. Optical properties and photonic density of states in onedimensional and three-dimensional liquid-crystalline photonic crystals. Liq Cryst. 2020;47:231–237.
- [21] Dolganov PV. Density of photonic states in cholesteric liquid crystals. Phys Rev E. 2015;91:042509-1-5.

- [22] Dolganov PV, Ksyonz GS, Dmitrienko VE, et al. Description of optical properties of cholesteric photonic liquid crystals based on Maxwell equations and Kramers-Kronig relations. Phys Rev E. 2013;87:032506.
- [23] Belyakov VA, Dmitrienko VE, Orlov VP. Optics of cholesteric liquid crystals. Sov Phys Usp. 1979;22:64.
- [24] Belyakov VA, Dmitrienko VE. Optics of chiral liquid crystals. London: Harwood Academic; 1989.
- [25] Berreman DW. Optics in stratified and anisotropic media: 4x4-matrix formulation. J Opt Soc Am. 1972;62:502-510.
- [26] Wohler H, Haas G, Fritsch M, et al. Faster 4 × 4 matrix method for uniaxial inhomogeneous media. J Opt Soc Am A. 1988;5:1554–1557.
- [27] Palto SP. An algorithm for solving the optical problem for stratified anisotropic media. JETP. 2001;92:552.
- [28] Bobrovsky A, Boiko N, Shibaev V. New chiralphotochromic dopant with variable helical twisting power and its use in photosensitive cholesteric materials. Mol Cryst Liq Cryst. 2001;363:35.
- [29] Bobrovsky A, Mochalov K, Oleinikov V, et al. Electrically controlled circularly polarized emission from cholesteric liquid crystal material doped with semiconductor quantum dots. Adv Mater. 2012;24:6216.
- [30] Dolganov PV, Gordeev SO, Dolganov VK, et al. Photoand thermo-induced variation of photonic properties of cholesteric liquid crystal containing azobenzene-based chiral dopant. Mol Cryst Liq Cryst. 2016;633:14–22.
- [31] Dolganov PV, Baklanova KD, Dolganov VK. Spectral and polarization characteristics of the light passing through a cholesteric photonic crystal. JETP. 2020;130:790-796.
- [32] Etxebarria J, Ortega J, Folcia CL. Enhancement of the optical absorption in cholesteric liquid crystals due to photonic effects: an experimental study. Liq Cryst. 2018;45:122–128.
- [33] Umanskii BA, Simdyankin IV. Circular dichroism in cholesteric liquid crystals. Crystallogr Rep. 2019;64:437–442.
- [34] Penninck L, Beeckman J, De Visschere P, et al. Light emission from dye-doped cholesteric liquid crystals at oblique angles: simulation and experiment. Phys Rev E. 2012;85:041702.
- [35] Dolganov PV. Luminescence spectra of a cholesteric photonic crystal. JETP Lett. 2017;105:657–660.
- [36] Shtykov NM, Palto SP, Umanskii BA, et al. Fluorescence and lasing in an electric-field-induced periodic structure of a cholesteric liquid crystal. Quantum Electron. 2019;49:754.
- [37] Risse AM, Schmidtke J. Angular-dependent spontaneous emission in cholesteric liquid-crystal films. J Phys Chem C. 2019;123:2428-2440.