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Research article

Complete light polarization control using a chiral-nematic cell with tangential-conical boundary conditions

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ABSTRACT

Light polarization control by the chiral-nematic cell with hybrid tangential-conical boundary conditions has been studied by means of photo- and electrically induced transformations of the orientational structure. The polarization azimuth changes due to the power ratio of ultraviolet and blue radiations, at which the director twist angle in the chiral nematic varies smoothly. The light polarization ellipticity is controlled by an electric field applied perpendicular to the liquid crystal cell changing the effective anisotropy of the refractive index. The optical material under study is promising to develop the devices for the light polarization converter over the entire visible range, as well as for photo-controlled rotators of linear polarization of white light.

1. Introduction

Chiral-nematic (or cholesteric) liquid crystals (CLC) are widely used in the optoelectronic devices due to their unique physical properties caused by an intrinsic helicoidal orientational structure [1]. Light polarization transmitted through such a twisted structure changes depending on the propagation direction as regards the helix axis, the ordinary $n_\perp$ and extraordinary $n_\parallel$ CLC refractive indices, the cholesteric helix pitch p and the light wavelength λ. For instance, the polarization plane of linearly polarized light passed along the helicoid axis rotates by the angle equal to the director rotation angle when the radiation wavelength $\lambda \ll p(n_\parallel - n_\perp)$ (the Mauguin regime) [2]. According to the effect of selective light reflection, the circularly polarized light with the rotation direction opposite to the twist cholesteric helix passes through CLC cell under $pn_\perp < \lambda < pn_\parallel$, and the circularly polarized light with the rotation direction coinciding with the twist cholesteric is completely reflected [3]. When $\lambda \gg pn_\parallel$ or $p(n_\parallel - n_\perp) \ll \lambda \ll pn_\perp$, the cholesteric structure exhibits an optical activity, i.e., the light polarization plane rotates passing through the CLC layer, while the rotation angle depends on the wavelength, the helix pitch and the refractive CLC indices [3]. Such features of CLC allows applying them to control a light polarization, for example, as achromatic [4,5] or monochromatic [6] electrically controlled rotators of the linear polarization, as well as to change the azimuth and ellipticity of a light polarization [7].

To control the light polarization, the homogeneous cholesteric structure under strong tangential (planar) anchoring must be formed. However, such boundary conditions limit the range and/or ability of a change in the light polarization. So, despite the large optical activity of a cholesteric, the electro- controlled change of the linear polarization direction is slight, that is revealed by the appearance of the Helfrich domain structure [6,8]. This drawback can be eliminated by using the photosensitive cholesteric changing the helix pitch under radiation [9] or a helicoidal cholesteric [7]. At using photosensitive cholesteric, the strong tangential anchoring leads to a discontinuous change of the helix pitch and, hence, the light polarization [10,11]. In addition, the methods used to control the light polarization by the cholesteric do not allow adjusting independently both its azimuth and ellipticity, i.e. a change in one parameter leads to the transformation of another characteristic. In this work, we consider the liquid crystal cell based on the photo- and electro-sensitive chiral nematic with tangential-conical boundary conditions allowing to control independently the azimuth and ellipticity of the transmitted light polarization.

2. Materials and methods

The nematic mixture LN-396 (Belarusian State Technological University) doped with the left-handed chiral dopant S5011 (Macklin) at concentration of 0.45%, and the right-handed composite photosensitive chiral dopant cChD (ICNM NAS, Belarus) [12] at concentration of 1.20% was used as the cholesteric. The melting temperature of LN-396 is $T_m = -20$ °C, the clearing point is $T_c = +66$ °C, the dielectric conductivity anisotropy is $\Delta\varepsilon = +10.2$. The CLC cell consisting of two glass substrates with transparent ITO electrodes was fabricated. One substrate was covered with the polyvinyl alcohol (PVA) film to

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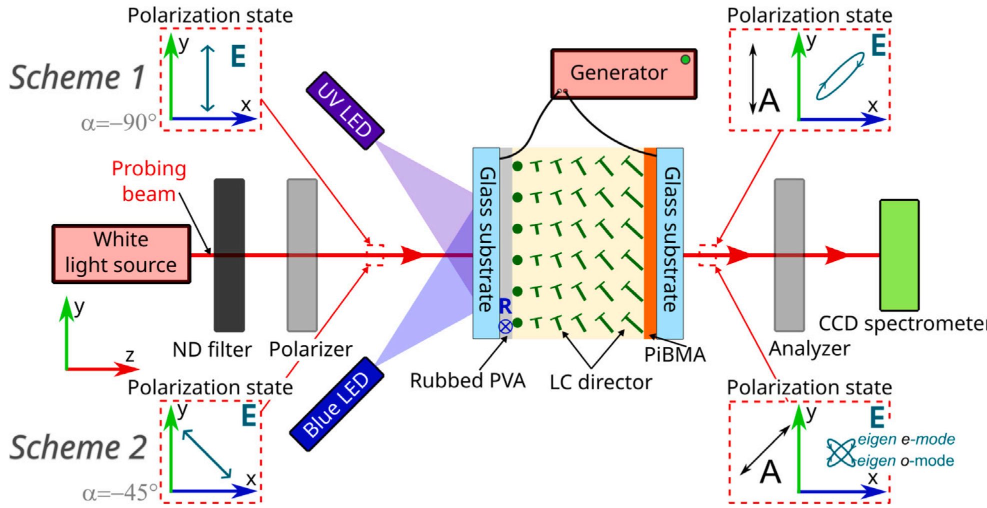

Fig. 1. Optical setup to control and measure the light polarization transmitted through the CLC layer. The light polarization before (linear) and after (elliptical) the CLC cell are marked in the dashed red rectangles.

provide the strong tangential anchoring. Another substrate was covered with the polyisobutyl methacrylate (PiBMA) film specifying the conical boundary conditions with the director tilt angle $\theta_{0,C} = 47.7°$ [13]. The polymer films were deposited by spin coating. The films were dried at 60 °C temperature for 1 h, then the PVA film was rubbed unidirectionally. The substrates were glued by the photosensitive compound NOA61 (Norland Products) with added glass microspheres 17.3 ± 1.4 μm diameter (Duke Scientific). The cell gap thickness $d = 20.9$ μm was measured by the interference method. Then, the cell was filled with the CLC by the capillary method at room temperature.

The helical twisting power of the cChD dopant increases at λ = 420–460 nm (blue radiation) and decreases at λ = 360–380 nm (ultraviolet radiation) [12]. The cholesteric pitch (the director twist angle) in the CLC cell was controlled by simultaneously illuminating the sample with the LEDs M365LS (λ = 365 nm) and M430LS (λ = 430 nm) combined with the collimators SM1U25-4 (ThorLabs). The intensity of UV and blue light was adjusted by the diodes current and measured by PDA100A2 Si Switchable Gain Detector (ThorLabs). Light polarization transmitted through the CLC layer was determined by the spectral method at the parallel polarizers oriented along the Oy axis (*Scheme 1*) or at $\alpha = -45°$ angle to the Ox axis (*Scheme 2*), α is the angle between the polarizer axis and the Ox axis (Fig. 1). The spectra were measured with CCD spectrometer CCS200 (ThorLabs). The rubbing direction **R** of the PVA film was parallel to the Ox axis. The probing beam was incident normally along the Oz axis on the CLC cell from the substrate side covered with PVA film. AC voltage of 1 kHz frequency was applied to the sample.

3. Results and discussion

3.1. Complete control strategy of the light polarization

Let us consider a cholesteric layer with a linear twisted structure, where the director is tilted uniformly throughout the LC layer thickness. A director distribution of this CLC structure can be represented as $\mathbf{n}_{dir} = (\cos\phi(z)\cos\theta_s, \sin\phi(z)\cos\theta_s, \sin\theta_s)$, where θ_s is the uniform tilt angle of director equal to the pretilt angle on the substrates, $\phi(z) = \phi_{dir} z/d$, and ϕ_{dir} is the twist angle of director along layer thickness d. It is known, when the linearly polarized light propagates along z-axis through CLC with $p(n_\parallel - n_\perp) > \lambda$ the polarization becomes elliptical with an ellipticity angle $-45° \le \xi \le 45°$ and the polarization azimuth $-90° \le \psi \le 90°$ equal to [14]:

$$\xi = \tan^{-1}\frac{|\chi| - 1}{|\chi| + 1} \tag{1}$$

$$\psi = -\frac{1}{2}\arg(\chi) \tag{2}$$

where

$$\chi = \frac{\chi_0\beta\cos\beta + i\left(\frac{\pi d\Delta n_{eff}}{\lambda} + \chi_0\phi_{dir}\right)\sin\beta}{\beta\cos\beta + i\left(\chi_0\frac{\pi d\Delta n_{eff}}{\lambda} - \phi_{dir}\right)\sin\beta}e^{-2i\phi_{dir}}, \tag{3}$$

$$\beta = \sqrt{\left(\frac{\pi d\Delta n_{eff}}{\lambda}\right)^2 + \phi_{dir}^2}, \tag{4}$$

$$\Delta n_{eff} = \frac{n_\perp n_\parallel}{\sqrt{n_\perp^2\cos^2\theta_s + n_\parallel^2\sin^2\theta_s}} - n_\perp, \tag{5}$$

d is the LC layer thickness, ϕ_{dir} is the azimuth director angle on the substrate with conical anchoring, λ is the light wavelength, Δn_{eff} is the effective anisotropy of refractive index, $\chi_0 = \cos 2\alpha - i\sin 2\alpha$ is the χ at $z = 0$. According to the equations, the azimuth and ellipticity of the transmitted light polarization depend both on the effective optical anisotropy of CLC Δn_{eff} and the structure twist angle ϕ_{dir}. The effective anisotropy of refractive index can be changed by an electric field applied perpendicular to the liquid crystal layer [3], and the structure twist angle can be varied using the photosensitive cholesteric provided changing of its helix pitch. It should be noted that the structure twist angle can be controlled smoothly specifying the hybrid tangential-conical boundary conditions when the strong tangential anchoring is set on the one substrate, and the conical anchoring is on the other one [15,16]. Under conical anchoring the director on the substrate reorients in azimuthal plane (change in the angle ϕ_{dir}) causing a transformation entire CLC bulk [17] or change in the helix pitch p [15]. For CLC with hybrid tangential-conical anchoring, the director tilt angle $\theta(z)$ is not the same through the layer thickness, yet the nearly linear dependence $\phi(z)$ is satisfied at $\phi_{dir} \le 200°$ [4,15]. In this case, the optical properties of cholesteric layer with a non-uniform director tilt angle are equivalent to that of a CLC layer with the uniformly tilted director at angle $\theta_s = (1/d)\int_0^d \theta(z)\,dz$ and the linear twist structure at angle ϕ_{dir} [18]. According to the optical scheme (Fig. 1), the transmittance T depends on the azimuth and ellipticity of the light polarization as follows [19]:

$$T = \frac{1}{2}(1 + \cos 2\xi\cos 2(\alpha - \psi)) \tag{6}$$

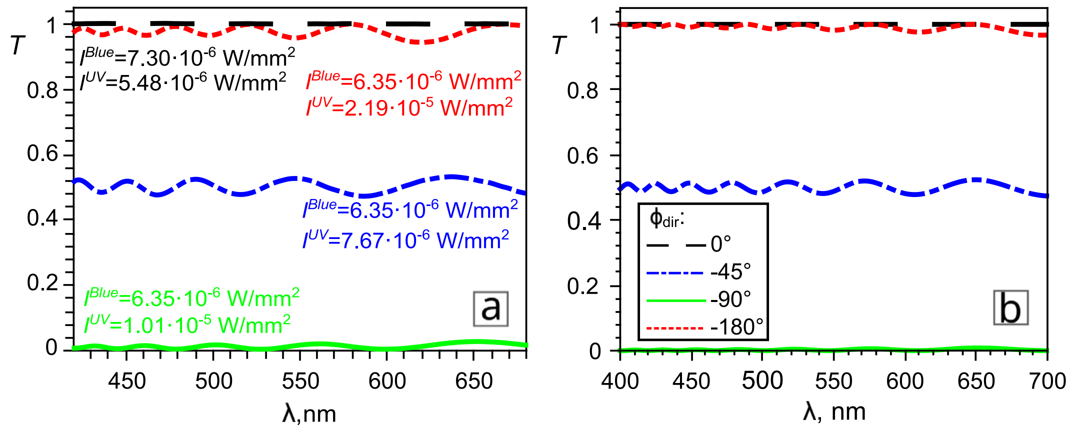

Fig. 2. The measured (a) and calculated (b) transmission (T) spectra of the CLC cell obtained at the optical *Scheme 1* shown in Fig. 1. The spectra were measured under simultaneous illumination by UV (I^{UV}) and blue (I^{Blue}) radiations. The intensity ratio of the LEDs was such that the transmittances corresponded to director twist angles of $\phi_{dir} = 0°$ ($\theta_s = 25.80°$), $\phi_{dir} = -45°$ ($\theta_s = 23.02°$), $\phi_{dir} = -90°$ ($\theta_s = 20.24°$), $\phi_{dir} = -180°$ ($\theta_s = 14.68°$).

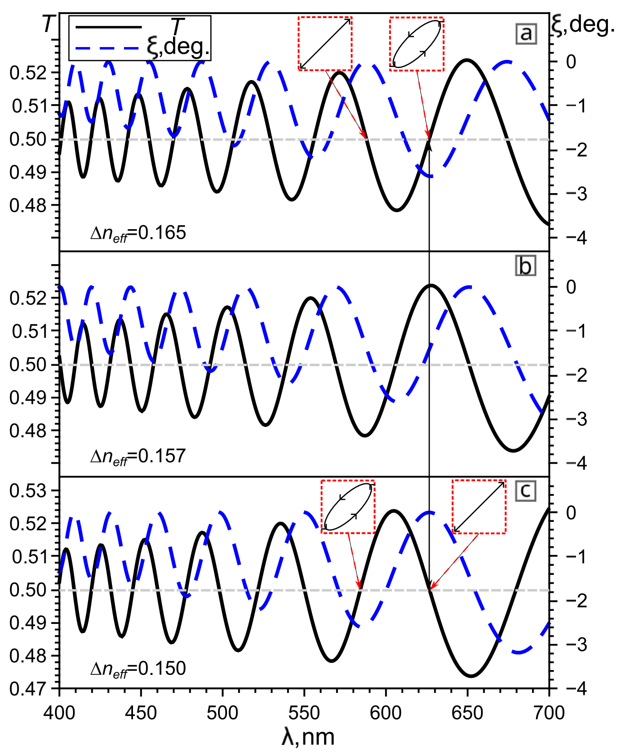

Fig. 3. Calculated transmission (T) spectra and the ellipticity angles ξ of the CLC layer at the director twist angle $\phi_{dir} = -45°$ and thickness $d = 20,9$ μm. Dependencies were obtained at $\theta_s = 23.02°$ (a), 25.50° (b), and 27.95° (c). Δn_{eff} are indicated for the $\lambda = 627$ nm, the red dotted arrows indicate points with maximal and zero ellipticity.

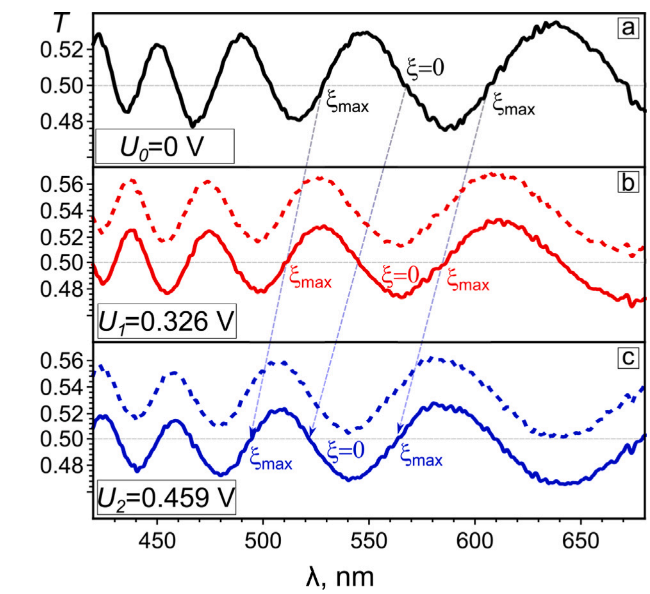

Fig. 4. Transmission spectra T of the CLC cell at voltages $U_0 = 0$ V and the intensity of UV light $I_0^{UV} = 1.75 \cdot 10^{-5}$ W mm^{-2} (a); $U_1 = 0.326$ V, $I_0^{UV} = 1.75 \cdot 10^{-5}$ W mm^{-2} (dotted line) and $I_1^{UV} = 1.81 \cdot 10^{-5}$ W mm^{-2} (solid line) (b); $U_2 = 0.459$ V, $I_1^{UV} = 1.81 \cdot 10^{-5}$ W mm^{-2} (dotted line) and $I_2^{UV} = 1.87 \cdot 10^{-5}$ W mm^{-2} (solid line) (c). The intensity of the blue light is $I_0^{Blue} = 1.10 \cdot 10^{-5}$ W mm^{-2}.

3.2. Control of light polarization azimuth (Scheme 1)

As shown in *Scheme 1*, $\alpha = -90°$, therefore $T = 100\%$ from Eq. (6), that corresponds to light transmission of the optical system with the nematic cell ($\phi_{dir} = 0$). The angles ϕ_{dir} and ψ are measured off the positive direction of Ox axis. The ellipticity angle sign ξ coincides with the sign of cholesteric twist direction. It can be seen from the Eqs. (2) and (6), T is extremely sensitive to ψ angle or ξ changes at the angles $\phi_{dir} = 45° \pm 90°$ m.

Fig. 2a demonstrates the spectra measured at various intensities of UV and blue LEDs. The spectra are characterized by an oscillating dependence $T(\lambda)$, while the average transmittance T_{mean} varies from nearly 0 to 1. The variation of T_{mean} is caused by a change in the structure twist angle ϕ_{dir} that is transformed from the right-handed to the left-handed cholesteric at increasing of UV light intensity. The structure twist angle in the considered CLC layer can be set in the range of $-225° \le \phi_{dir} \le +150°$. The CLC orientational structure is a defect-free for this range of the director twist angle. Specifying the wider twist angle the inhomogeneous structure appears. So, the linear defects arise in the sample with $d \cong 20$ μm at the director twisting $|\phi_{dir}| > 270°$. The transmittance oscillations T resulted from the oscillating behavior of the angles $\psi(\lambda)$ and $\xi(\lambda)$ [20]. Fig. 2a shows the spectra measured at the various structure twist angles ϕ_{dir}. The calculations were made for the CLC layer of $d = 20.9$ μm thickness using the approximation of uniform director tilt angle θ_s(Fig. 2b) [18]. The tilt angles θ_s defined by the director twist angle ϕ_{dir} were obtained by the data interpolating given in [4,15]. The effective anisotropy of refractive index Δn_{eff} was found considering the dispersion of refractive index LN-396 [4].

Fig. 3a demonstrates the transmission spectrum T and the oscillating dependence of the ellipticity angle ξ on the wavelength λ calculated for the cholesteric with the $\phi_{dir} = -45°$. In this case, the transmittance

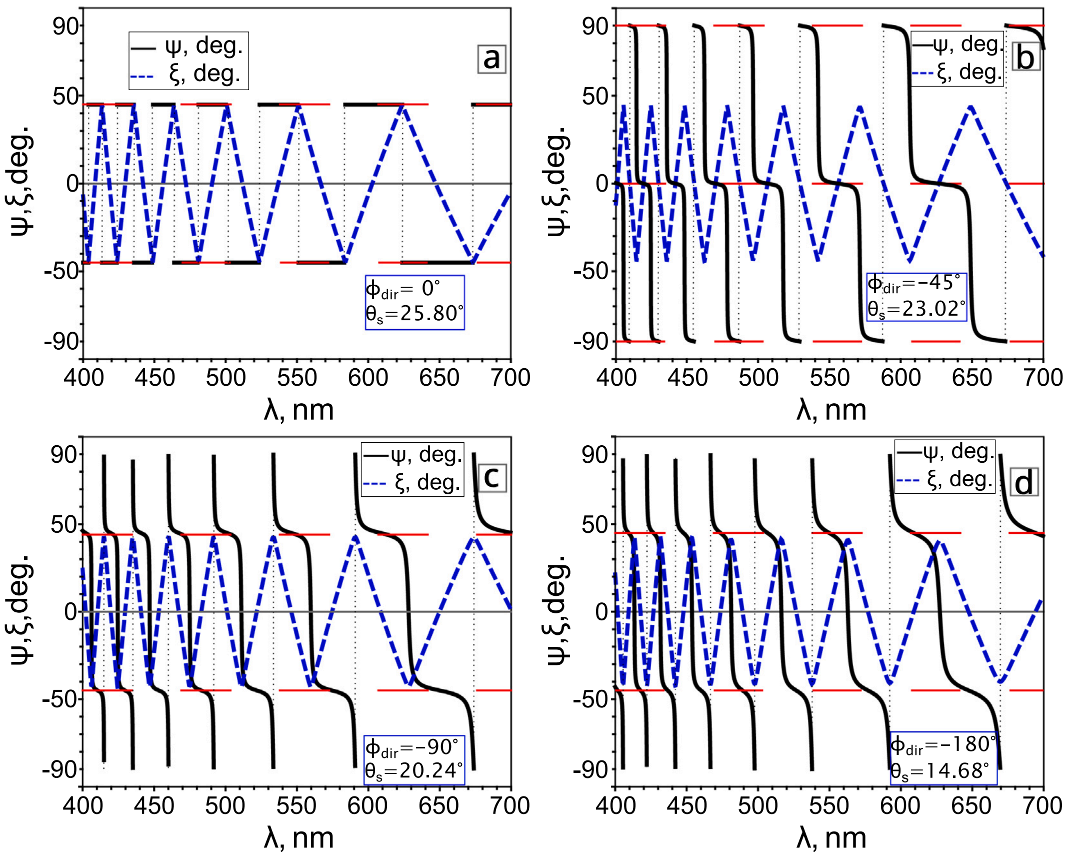

Fig. 5. The calculated azimuthal angle and ellipticity angle of the light polarization passed through CLC cell obtained at the optical setup shown in Fig. 1 at $\alpha = -45°$ (*Scheme 2*). The director twist angles are: (a) $\phi_{dir} = 0°$ ($\theta_s = 25.8°$), (b) $\phi_{dir} = -45°$ ($\theta_s = 23.02°$), (c) $\phi_{dir} = -90°$ ($\theta_s = 20.24°$), (d) $\phi_{dir} = -180°$ ($\theta_s = 14.68°$). The levels $\psi \approx \phi_{dir} \pm 45°$ are noted by the horizontal red dotted lines.

average $T_{mean} = 0.5$. The curve $T(\lambda)$ crosses the average value line $T_{mean} = 0.5$ at points where the ellipticity angle is equal to $\xi = 0$ or takes the maximum in absolute value. If the director twist angles ϕ_{dir} are within the first or third quadrant of the xOy plane, then the value $\xi = 0$ corresponds to the intersection points being in the increasing parts of dependence $T(\lambda)$. If the angles ϕ_{dir} are within the even quadrants of the xOy plane, then $\xi = 0$ corresponds to the intersection points being in the decreasing parts of the curve $T(\lambda)$ (Fig. 3a).

3.3. Control of light polarization ellipticity (Scheme 1)

Decreasing Δn_{eff}, for example, by increasing the average angle θ_s, does not change $T_{mean} = 0.5$, but leads to a blue-shift of the dependence T along with the increase in the oscillations amplitude and period (Fig. 3b,c). It allows changing the light polarization ellipticity at the selected wavelength from zero to maximum, and vice versa. The values Δn_{eff} in Fig. 3 were chosen so that the change in the angle ξ from the maximum to zero occurs at $\lambda = 627$ nm.

Fig. 4a demonstrates the transmission spectra measured under voltage-off at intensities of the control UV and blue lights equal to $I_0^{UV} = 1.75 \cdot 10^{-5}$ W mm^{-2} and $I_0^{Blue} = 1.10 \cdot 10^{-5}$ W mm^{-2}, respectively. There is an oscillating dependence with the transmittance average value $T_{mean} = 0.5$, which corresponds to the director twist angle $\phi_{dir} \cong -45°$. Noticeable changes in the transmission spectra are observed in the CLC cell under studied at $U \gtrsim 0.2$ V, at that any defects or structure undulations do not appear. Applied voltage $U_1 = 0.326$ V causes to the blue-shift of curve T and the average transmittance changes to $T_{mean} \cong 0.54$ (Fig. 4b, the dotted line). A rise in T_{mean} is conditioned by an electrically induced decreasing of the structure twist angle to $\phi_{dir} \cong -42.7°$ [4], that is compensated by increasing of the intensities of UV light to $I_1^{UV} = 1.81 \cdot 10^{-5}$ W mm^{-2} (Fig. 4b, the solid line). An increase in voltage to $U_2 = 0.459$ V and UV light intensities to $I_2^{UV} = 1.87 \cdot 10^{-5}$ W mm^{-2} results in further blue-shift in the spectrum T (Fig. 4c). Therefore, the light polarization ellipticity at $\lambda \cong 608$ nm decreases from the maximum ($U = 0$ V) to zero ($U = 0.459$ V). Similar changes of the light ellipticity are observed at other λ. However, the λ at which the ellipticity angle is $\xi = 0$ ($\xi = \xi_{max}$) decreases monotonically at increasing voltage. After switching off voltage and reset of power I_0^{UV} and I_0^{Blue}, the structure reverts to the initial state (Fig. 4a). The characteristic response times (switching on or switching off) of the investigated CLC at voltage are hundreds of milliseconds. At that, the director structure under light illumination is transformed for the tens of seconds at the used intensities of LEDs.

To explain the observed oscillating dependences of $T(\lambda)$ and the ellipticity of light polarization, let us consider the polarization eigenmodes of cholesteric. Far from the selective reflection region, two orthogonal elliptically-polarized o-eigenmode and e-eigenmode propagate and their orientation follows the director orientation [20]. Consequently, the light polarization azimuth passed through CLC cell depends on the angle ϕ_{dir} and deviates slightly from the director orientation in opposite directions, depending on the phase difference between the eigenmodes. The maximal ellipticity of eigenmodes increases as the CLC layer thickness d and the effective anisotropy of refractive index Δn_{eff} decrease, and the twist angle ϕ_{dir} rises. The Δn_{eff} makes a main contribution into ellipticity of eigenmode for the investigated cell. It allows controlling the light polarization ellipticity after its passing the CLC cell and the maximal value of this parameter increases as the voltage decreases. As the ellipticity of transmitted light depends on d and Δn_{eff}, a phase change by the same value can be reached at decrease in d and increase in Δn_{eff} resulting in increasing the operating voltage. The change in polarization ellipticity angle at high voltages can be $\Delta\xi = 45°$ [4]. At that, the noticeable deformations of director

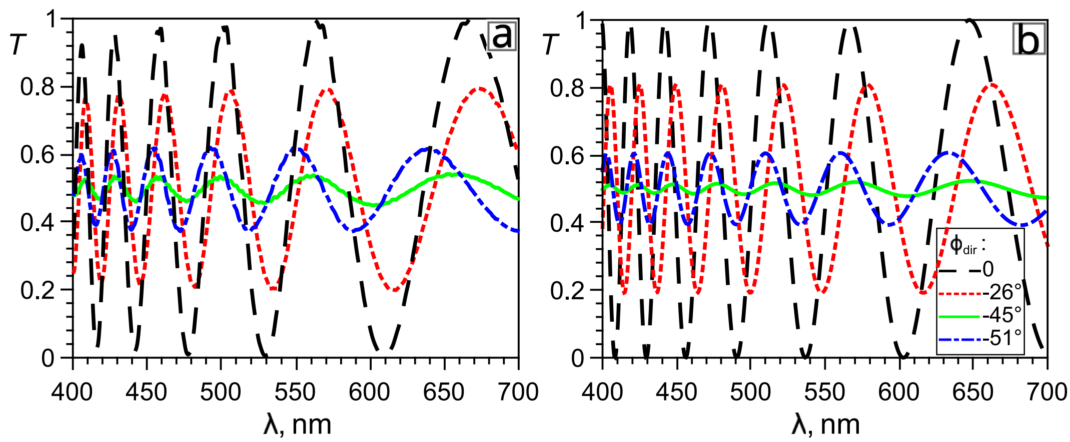

Fig. 6. The measured (a) and calculated (b) transmission (T) spectra of the CLC cell obtained according to the *Scheme 2* of the optical setup shown in Fig. 1. The director twist angles are $\phi_{dir} = 0°$ ($\theta_s = 25.8°$), $\phi_{dir} = -26°$ ($\theta_s = 24.2°$), $\phi_{dir} = -45°$ ($\theta_s = 23.02°$), $\phi_{dir} = -51°$ ($\theta_s = 22.65°$).

field appear and the used linear approximation of the director twist angle along the layer thickness cannot be applied. Especially, it means the polarization azimuth of light transmitted through the CLC layer does not follow the azimuthal director orientation [17], making the proposed control algorithm of polarization state more complicated.

The more effective and convenient control method of the light ellipticity can be realized when the polarization of incident light is oriented at $\alpha = -45°$ ($\alpha = 45°$) (*Scheme 2*). In this case the intensities of the o-eigenmode and e-eigenmode are equal and, consequently, the maximal ellipticity angle can be $\xi_{max} = \pm 45°$ (at $\phi_{dir} = 0$). As the orientation of the o-eigenmode and e-eigenmode follows the director orientation, the polarization azimuth of transmitted light will be caused by the ϕ_{dir}.

3.4. Complete light polarization control (Scheme 2)

Fig. 5 shows the dependences of ellipticity angle and light polarization azimuth on a wavelength calculated for the different twist angles ϕ_{dir} at $\alpha = -45°$. The oscillating dependence of ellipticity angle on a wavelength (values $2\pi d \Delta n_{eff}/\lambda$) is observed, the $\xi_{max} = \pm 45°$ at $\phi_{dir} = 0$ and the amplitude change decreases to $\xi_{max} = \pm 42°$ at $\phi_{dir} = -180°$ and $\lambda = 447$ nm. Two series of plateau at levels $\psi \approx \phi_{dir} \pm 45°$ are seen in the dependences of polarization azimuth on $2\pi d \Delta n_{eff}/\lambda$. The level values $\psi \approx \phi_{dir} \pm 45°$ in Fig. 5 are reduced to the condition $-90° \leq \psi \leq 90°$. The plateau slope is equal to zero at $\phi_{dir} = 0$ and it increases as rise of director twist. Transition between adjacent plateaus with $\psi \approx \phi_{dir} + 45°$ and $\psi \approx \phi_{dir} - 45°$ occurs sharply at λ at which the ellipticity reaches the maximal values. Transition abruptness decreases as the twist angle increases.

The oscillating about the level 0.5 dependence of the transmittance $T(\lambda)$ taken in the parallel polarizers (Fig. 6) corresponds to the dependence of the ellipticity and polarization azimuth. The oscillation amplitude is determined by the structure twist angle ϕ_{dir} while the position of maximum and minimum $T(\lambda)$ depends on ϕ_{dir} and Δn_{eff}. For example, the maximum and minimum T at angle $\phi_{dir} = -45°$ will fit the maximal light polarization ellipticity and the linear light polarization will satisfy $T = 0.5$.

As the ellipticity angle depends on $2\pi d \Delta n_{eff}/\lambda$, it can be controlled within $-45° < \xi < 45°$ by an electric field varying the effective anisotropy of refractive index (Fig. 7). Unlike the case when the polarization of incident light is orthogonal to the rubbing direction (*Scheme 1*), the ξ angle can be varied applying minor voltage at which the linear approximation of the director twist angle along the layer thickness is applicable (Eq. (3)). Varying the ratio of blue and UV control radiations, it can change the twist angle ϕ_{dir} and, consequently, specify the required polarization azimuthal angle within $-90° \leq \psi \leq 90°$ or correct the twist angle ϕ_{dir} to save the polarization azimuth under polarization ellipticity changing by an electric field as shown in Fig. 4.

4. Conclusion

We have proposed and implemented mutually independent control of the azimuth and ellipticity of the light polarization using the CLC cell with tangential-conical boundary conditions. Such a control can be realized for monochromatic light throughout the entire visible spectral range. The light polarization azimuth is tuned by simultaneously illuminating the photosensitive CLC with the UV and blue light, while the polarization ellipticity is controlled by the electric field. The eventual range of the twist angle (and, accordingly, the light polarization azimuth) depends on the concentrations of the left- and right-handed chiral dopants, as well as the CLC layer thickness d and it can be several thousand degrees [9]. In particular, a change in the structure twist angle is possible in the range of $-225° \leq \phi_{dir} \leq +150°$ for CLC cell under study. In turn, the change in the light polarization ellipticity is determined by the CLC layer thickness, the twist angle ϕ_{dir}, as well as by the variation of effective birefringence Δn_{eff} (i.e. by the magnitude of applied voltage) and it can reach the value $\Delta\xi = 90°$. The sign of ellipticity angle ξ can be controlled by the twist direction of CLC structure or by switching the polarizer orientation by 90° relative to the rubbing direction [20] (in *Scheme 1*), or by the magnitude of applied voltage (in *Scheme 2*).

Using two control factors allows realizing all light polarization states, at that, the low applied voltages and weak control light fields are required. By comparison, when using a heliconical cholesteric liquid crystal to control the polarization state, the electric or light fields increase by several orders of magnitude [7]. The change in ellipticity and polarization azimuth occurs simultaneously and interdependently for similar CLC systems with conical boundary conditions, when only electrical control of the structure is used [4]. It should be noted that this system can be considered as a photo-controlled achromatic light polarization rotator if the Mauguin condition is fulfilled for the light passing through the CLC cell. In our case, the light polarization can easily rotate in the range $-180° \leq \psi \leq +180°$ and is not limited by the CLC cell design [5] or the violation of the Mauguin regime as a result of a decrease in Δn_{eff} [4].

The results obtained are of interest for the development of a light polarization converter over the entire visible spectral range, as well

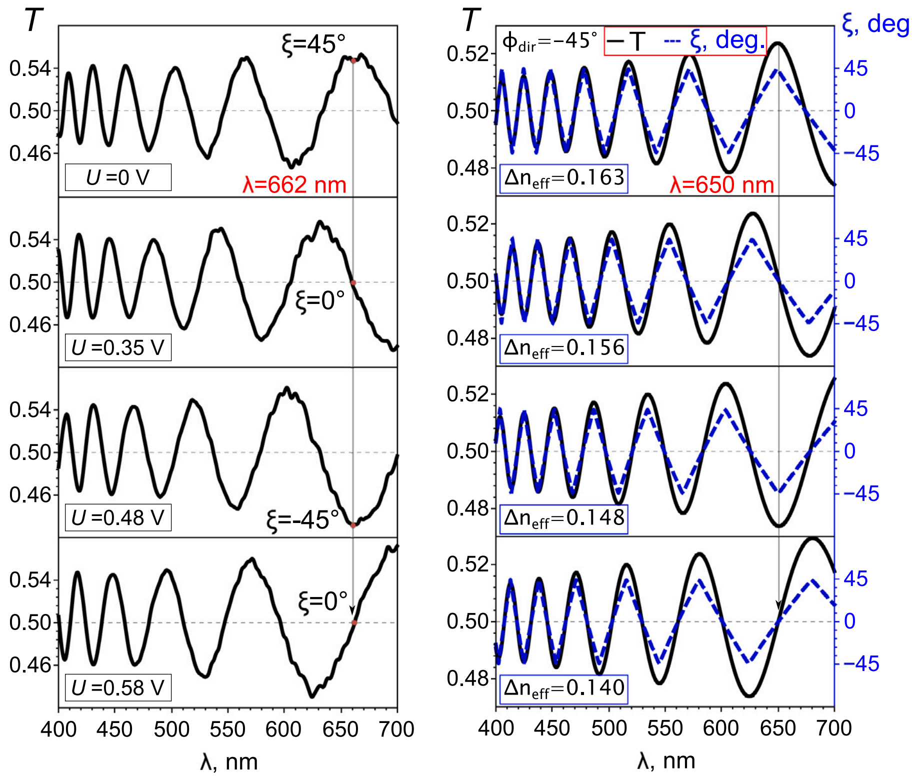

Fig. 7. The measured (left column) transmission (T) spectra of the CLC cell at voltages $U = 0$ V, 0.35 V, 0.48 V and 0.58 V obtained using *Scheme 2* of the optical setup shown in Fig. 1. The transmission (T) spectra (right column) calculated for the director twist angle $\phi_{dir} = -45°$ with $\Delta n_{eff} = 0.163$, 0.156, 0.148 and 0.140 for the wavelength $\lambda = 650$ nm.

as photo-controlled achromatic rotator of linear light polarization. In this case, the standard CLC cell design is used, which simplifies a manufacture of the converter.

CRediT authorship contribution statement

Abylgazy S. Abdullaev: Methodology, Investigation, Validation, Visualization, Formal analysis, Writing – review & editing. **Denis A. Kostikov:** Investigation, Validation, Visualization, Formal analysis, Writing – review & editing. **Mikhail N. Krakhalev:** Conceptualization, Validation, Formal analysis, Writing – original draft. **Victor Ya. Zyryanov:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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