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Light transmission of liquid crystal domains formed by polycarbonate surface

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Abstract: We investigate the optical transmission of a monochromatic laser beam passing through an individual domain of a nematic liquid crystal formed by the polycarbonate surface. The domain has the radial orientation structure with a disclination line on the polymer surface, which gradually transforms to "pseudoplanar" alignment at the coherence distance ξ from the surface. The dependence of the optical transmittance on an electric field applied to the domain are different at various light polarization directions relative to the disclination lines and, in the absence of an analyzer, are accompanied by interference oscillations. To explain the results obtained, a domain is considered to be a gradient lens with the refractive index variable in the plane perpendicular to the laser beam and the resulting deflecting effect that was collected at the beam path through the liquid crystal layer.

OCIS codes: (160.3710) Liquid crystals; (260.1440) Birefringence; (260.3160) Interference.

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1. Introduction

Homogeneous planar, homeotropic, and twisted nematic liquid crystal (LC) layers and nematic dispersions included in capsules, pores, or other limited volumes find application in fundamental research and are used in electrooptical devices, including displays. The most wide-spread technique for optical probing of homogeneous layers is birefringence analysis, when an LC layer in the plane-parallel cell is placed between the polarizer and analyzer. The former polarizes the light and the latter, analyzers the phase difference between the ordinary and extraordinary beams integral over the nematic layer thickness. The optical transmission of LC cells significantly depends on electric or magnetic fields applied to them, which change the preferred orientation of nematic molecules. The field dependences of the optical transmission are characterized by threshold Fredericks fields, interference extrema, and exponential behavior in the saturation region [1].

In LC dispersions, the change in the optical transmission can be observed without the analyzer. The optical characteristics of such objects are usually studied in the framework of the theory of light scattering by small particles [2], when it is necessary to take into account the refractive indices of an LC and its homogeneous environment. In particular, in study of LC droplets with a diameter of d ~1–10 μm in a polymer-dispersed matrix (PDLC) [3, 4], some results of the optical transmission variation under the action of electric or magnetic fields were described using this theory in the Rayleigh–Gans and anomalous-diffraction approximations. Further investigations showed [5–8] that the scattering mechanism in the anomalous diffraction approximation is suitable for describing the light propagation through the PDLC of a film with a droplet size of up to d ~25 μm. In most cases, in an external electric field, the transmission of the light passed through the PDLC film with the single-layer droplet alignment is accompanied by interference oscillations and described by the parameters depending on the droplet size, shape, and internal structure and on the refractive indices of the LC and polymer.

Lately, we found and investigated the nematic LC domains with the radial-planar structure grown on the polycarbonate (PC) surface using solution technique [9–11]. Transmission of polarized light by domain ensembles significantly changes in applied electric and magnetic fields and is accompanied by even deeper interference extrema than in the PDLC films. However, domains have a size of d ~50–200 μm and are closely packed on the PC surface, which complicates the study of the characteristics of light passed through their ensembles in the framework of the theory of scattering on small particles [2]. To clarify the features of light propagation in such objects, here we investigate the optical transmission of the monochromatic laser beam passed through an individual domain with the use of electric field.

2. Experimental

The samples to be investigated were LC cells with two plane-parallel glass plates with ITO electrode coatings. The upper plate was washed with boiling acetone and hexane; the lower plate was coated with a 2% PC solution (Bisphenol A carbonate, Sigma-Aldrich Co. LLC, St. Louis, MO, USA) in dichloromethane deposited by centrifuging. Two Teflon spacers with a thickness of 30 μm ensured a gap in the cell.

To study the optical transmission of one domain, the cell was placed on an adjustable platform of a polarization-optical setup (Fig. 1). The setup allowed the white light or monochromatic laser radiation to be transmitted through the cell. White light of a halogen lamp passed through the polarizer, semi-transparent plate, focusing lens, sample, and objective, and after deflection by the lens, arrived at a Micropublisher 3.3 RTV digital camera (Canada) though a viewing length. The He-Ne laser beam with a wavelength of λ = 633 nm (R-39727, Newport Corporation) attenuated by the light filter passed in the same way after reflection by the semi-transparent plate. The lens was set so as to its focus distance f = 3 cm coincided with the cell center. The focus distance and intensity distribution in the laser beam cross section were determined in an additional experiment with the use of an LBP2-HR-VIS Laser Beam Profiler (Newport Corporation). The 4-n-pentyl-4′-cyanobiphenyl (5CB) nematic LC (Merck, Darmstadt, Germany) with the sequence of phase transitions *Cr*-22°C-*N*-34°C-*I* was introduced in a gap between the cell plates at a temperature of 24°C. In the cell filled in this manner, one can choose areas of uniform planar or oblique alignment of the direction $\boldsymbol{n}_0$, which is caused by the flux of LC. In a few seconds, one could observe the occurrence and growth of circular LC domains with the disclination lines passing through their centers and perpendicular to $\boldsymbol{n}_0$ within the area chosen on the PC surface [9–11]. After 1–2 minutes, the cell was replaced on a platform so as to an individual domain appeared on the laser beam path. The polarizer was oriented so as to the light wave polarization vector $\boldsymbol{e}$ was parallel or perpendicular to $\boldsymbol{n}_0$. Then, the prism and analyzer were removed from the optical path, the white light source was switched off, and the intensity of the transmitted laser beam was detected by a photodiode, in front of which a diaphragm 3 mm in diameter was set. After ten minutes, when the grown domains covered the entire substrate surface, an electric voltage with a frequency of 1 kHz was applied to the cell. The transmission T vs voltage dependence have been a result of the averaging over the photodiode area limited by the diaphragm.

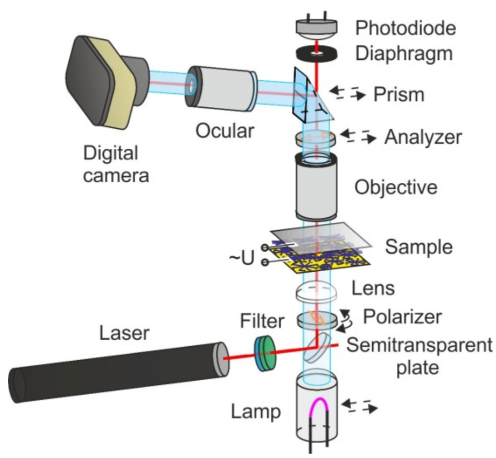

Fig. 1. Experimental setup for determining the transmission of light passing through the nematic domain formed by the polycarbonate film.

3. Results and discussion

Figure 2(a) shows the laser beam intensity distribution in the beam cross section located in the lens focus in dependence on distance x from the center. It can be seen that the beam distribution is Gaussian and the beam waist is $w_0 \cong 25$ μm. Figure 2(b) presents a microphotograph of the domain ensemble formed by the PC surface in the LC cell. One can see a spot of the laser beam L passing through the center of an individual domain.

Upon probing one domain, two types of the dependences of optical transmission T on domain growth time t and electric voltage U were observed (Fig. 3). When the light polarization vector $\boldsymbol{e}$ was set parallel to the direction $\boldsymbol{n}_0$, then, in $t \cong 10$ min the transmission increased by a few percent. When the voltage was applied to the cell after the structure formation, the optical transmission of the domain after U > 1.2 V first oscillated in the range of 0 < U < 4V and then, at U > 4V, decreased exponentially to the value of $T \cong 75\%$ similar to the transmission of the initial homogeneous LC layer (on the top of Fig. 3). When the vector $\boldsymbol{e}$ was perpendicular to $\boldsymbol{n}_0$, the transmission T decreased during the domain growth and then, in an electric field, after interference oscillations, increased exponentially to the initial T value (in the bottom of Fig. 3).

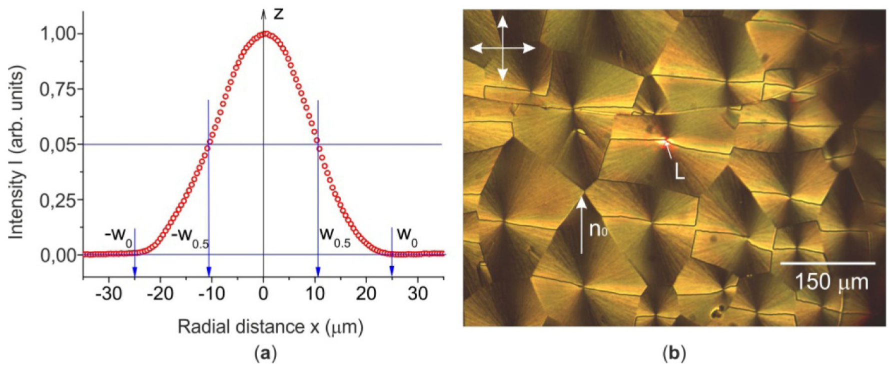

Fig. 2. Characteristics of the He-Ne laser and its propagation through LC domains. (**a**) Distribution of intensity I over the radius in the beam cross section, x is the distance from the beam center along the radius, and w_0 and $w_{0.5}$ are the waists at $I = 0$ and $I = 50\%$ from the maximum I, respectively. (**b**) Microphotograph of 5CB formed by the PC surface; L is the spot of a beam passing through an individual domain; $\boldsymbol{n_0}$ is a direction of LC flux during the filling process.

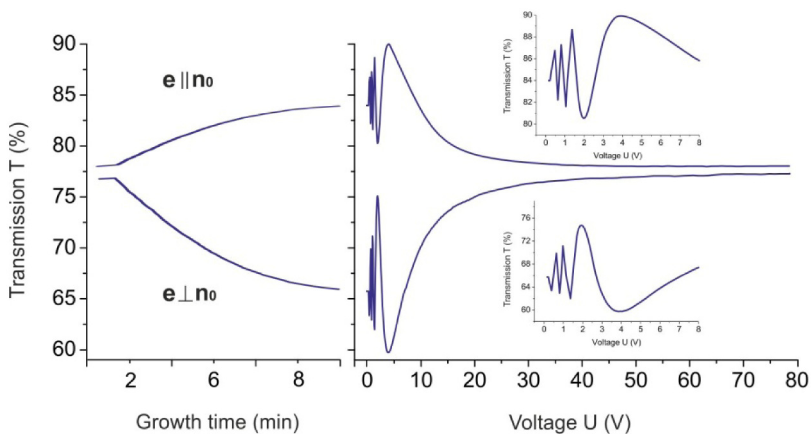

Fig. 3. Regimes of variation in optical transmission T of the 5CB domain formed by the PC surface with time t (on the left) and electric voltage U applied to the domain (on the right): the polarization vector $\boldsymbol{e}$ is parallel (on the top) and perpendicular (in the bottom) to the nematic direction $\boldsymbol{n_0}$. Insets: enlarged portions of the $T(U)$ dependences.

The results obtained can be interpreted as follows. As we demonstrated in [9–11], the LC director field configuration in the domain (Figs. 4) results from the competition of three factors. The radial nematic director configuration formed from the nucleus on the PC film extends in the bulk of domain. These nucleus determine the location of the radial structure center [9]. The homogeneous planar alignment is also transferred in the bulk of domain from the surface disclination line passing through the radial structure center (Fig. 4(a)).

The coherence length ξ, i.e., the distance from the PC surface at which the radial configuration transforms to the planar alignment can be estimated as [11]:

$$\xi = \sqrt{\frac{\pi(\pi-3)+12}{24\pi\ln\left(\frac{2r}{b}\right)}}r \tag{1}$$

where r is the domain radius and b is the surface disclination line width.

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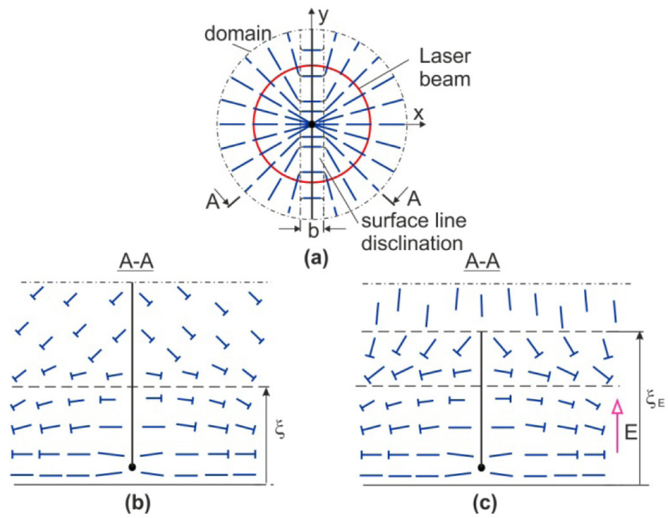

Fig. 4. LC director field distribution in the domain formed by the PC surface. (**a**) In the *xy* plane at the distance z > ξ from the PC film surface. (**b**) In the A-A cross section in zero external field. (**c**) In external field *E*.

In this case, domains have a texture with two extinction bands (Fig. 1(b)), which replaces the texture with four extinction bands when the planar LC layer is superimposed on the radial structure. The LC director ***n*** alignment also propagates from the upper cell boundary in the bulk of the domain. At the cell thickness $d > \xi$, the texture with two extinction bands is retained even when the upper plate in the LC cell is treated to form an tilted or homeotropic alignment of ***n***. In other words, at $d > \xi$, the effect of the radial configuration from the PC film and uniform orientation from the surface disclination line significantly exceeds the effect of the outer interfacial surface. However, at the distance ξ, where the radial structure vanishes, the slope of LC molecules at their tilted or homeotropic alignment at the upper domain boundary should remain. We will call such a configuration of the LC director field in a domain the «pseudo-planar» orientation (Fig. 4(b)), which, in our opinion, is caused by the chosen method of processing of the LC cell upper plate. In addition, the contribution to the tilted alignment should be made by a narrow (~2 μm) wall extended from the surface disclination line in the bulk of the domain. The electric field *E* applied perpendicular to the substrates tends to align the nematic director homeotropically in the bulk of the domain on the electrical coherent length ξ_E [10] (Fig. 4(c)) and, thus, at $\xi_E < \xi$ induces the degenerate hybrid-aligned nematic structure [12] with a texture containing four exctinction lines.

Since the formation of the LC structure starts from the domain center and surface disclination line, we may assume that along the radial direction ρ in the *z*ρ plane, the nonuniform distribution of the director field arises. This is stimulated by the fact that, in our case, the LC is interfaced only by the upper and lower substrates rather than from every side as in the PDLC films [3–8]. The refractive index n_e of the extraordinary light beam passing through a domain along the *z* axis should depend on the angle of director orientation ***n*** relative to *z*. It will tend to the refractive index $n_{\parallel}$ or $n_{\perp}$ of the uniform LC layer near the surface disclination line, depending on the direction of polarization vector ***e*** relative to the direction $\boldsymbol{n_0}$. The nonuniform distribution of the refractive indices of the light beam in the *xy* plane can lead to the gradient lens effect [13, 14]. Since the beams in such a lens are deflected toward the larger refractive index, the lens will be focusing at $\boldsymbol{e} \parallel \boldsymbol{n_0}$ and defocusing at $\boldsymbol{e} \perp \boldsymbol{n_0}$. This explains the variations in the optical transmission *T* observed during the domain growth for time *t* (Fig. 3), which correspond to the resulting deflecting effect accumulated upon laser beam transmission over the nematic layer thickness.

The variation in the angle of director $\boldsymbol{n}$ relative to z in an electric field is accompanied by the trend of the refractive index n_e of the extraordinary beam to the refractive index n_o of the ordinary beam at the transition of the LC layer to the homeotropic alignment. At the LC layer output, the extraordinary and ordinary beams passed through the neighboring domain parts have the phase difference, which results in the interference. The phase difference will be collected mainly at the distance ξ. In the range of $z > \xi$, the refractive indices at the orientation in a strong electric are leveled, which leads to disappearance of the interference oscillations (Fig. 3). Thus, the phase difference between n_e and n_o will be determined by the integration over the coherence length ξ

$$\delta(U)x,y = \frac{2\pi}{\lambda}\int_0^{\xi}\left[n_e(x,y,z)-n_o\right]dz \approx \frac{2\pi}{\lambda}\left\langle\left[n_e(x,y,z)-n_o\right]\right\rangle\xi, \tag{2}$$

where

$$n_e(x,y,z) = \frac{n_{\parallel}n_{\perp}}{\left(n_{\parallel}^2\sin^2\theta(x,y,z)+n_{\perp}^2\cos^2\theta(x,y,z)\right)^{1/2}}, \tag{3}$$

where θ is the deviation of the nematic director from the bounding surfaces and $n_{\parallel}$ and $n_{\perp}$ are the limit values of n_e corresponding to the uniform planar or homeotopic LC alignment. It is assumed that the intensity of light transmitted through the domain depends on the phase difference as $I \sim \sin^2\delta\,(U)/2$ [1].

The maximum number of extrema in the $T\,(U)$ dependences in Figs. 3 is $N = (n_e - n_{\perp})\,\xi/\lambda$ $N \approx 3.5$. Substituting the values $\lambda = 0.633$, $r = 85$ µm (Fig. 2), $b = 10$ µm [9–11], and the refractive indices $n_{\parallel} = 1.7081$ and $n_{\perp} = 1.5276$ for 5CB at a temperature of 24°C [15], we obtain the average angle $\langle\theta\rangle \approx \pi/4$.

4. Conclusions

The radial-planar domains formed during the growth on the polycarbonate surface [9–11] have a size of d ~50–200 µm and are closely packed on the polycarbonate surface. To disclose the features of light propagation in such objects, we studied the optical transmission of the monochromatic laser beam passing through an individual 5CB nematic domain using electric field. It was experimentally established that the optical transmission T as a function of electric voltage U depends on the light polarization direction $\boldsymbol{e}$ relative to the direction $\boldsymbol{n_0}$ of the domain planar layer. At $\boldsymbol{e}\|\boldsymbol{n_0}$, during the domain growth, the T value first grew and then, after transmission of the laser beam through the formed domain, oscillated under the action of U and decreased to its initial value. At $\boldsymbol{e}\perp\boldsymbol{n_0}$, the inverse $T\,(U)$ dependences were obtained. We succeeded in explaining the obtained dependences considering the domain to be a gradient lens with the resulting deflecting effect collecting on the coherence length ξ upon propagation of the laser beam through the domain. Interference oscillations on the $T\,(U)$ dependences were caused by the phase difference between the extraordinary and ordinary beams passed through the neighboring domain parts.

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