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Optical characteristics of liquid-crystal domains probed by a focused laser beam

A. M. Parshin[1,2,3]

[1]L. V. Kirenskiĭ Institute of Physics, Federal Research Center "Krasnoyarsk Scientific Center of the Siberian Branch of the Russian Academy of Sciences," Krasnoyarsk, Russia
[2]Siberian Federal University, Krasnoyarsk, Russia
[3]e-mail: parshin@iph.krasn.ru

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A technique for determining the optical characteristics of the domain structures of nematic liquid crystals using a focused laser beam is presented. The dependences of the intensity of polarized light on the voltage of a separate nematic domain formed by a polycarbonate surface in the presence of a magnetic field are obtained. It is shown that the optical characteristics cannot be interpreted within the framework of the concept of light scattering, which is suitable in the case of an ensemble of domains probed by a wide laser beam. The analysis of the results is based on the assumption of gradient index optics.

OCIS codes: (160.3710) Liquid crystals; (230.3720) Liquid-crystal devices; (260.3160) Interference.

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1. INTRODUCTION

Laser radiation is widely used in liquid crystal (LC) devices for optical information processing because of its high monochromaticity and intensity [1]. An analysis of the optical transmission of a probing laser beam by an LC makes it possible to detect new effects in LC layers under the influence of orienting surfaces or external fields, which can be used to create new LC technologies. In devices with a homogeneous layer of LC, the director changes gradually from point to point, and the optical characteristics do not depend on the transverse dimensions of the laser beam. At the same time, in inhomogeneous LC structures, obtaining reliable optical characteristics when using a laser beam is a difficult task. Inhomogeneous structures include composite materials with a bulk arrangement of LC droplets in isotropic matrices [2,3]. A wide laser beam propagating through a composite passes through a significant number of microscopic volumes of an LC and carries integral information about their optical properties, which include the characteristics of light scattering and interference effects. An analysis of the optical characteristics of a composite depends on the ratio of the droplet diameter d and wavelength of light λ and is carried out for $d < \lambda$ in the Rayleigh–Gans scattering approximation, and for $d > \lambda$ in the anomalous diffraction approximation. Thus, the results of a change in the optical transmission due to electric or magnetic fields have been explained in the study of LC droplets encapsulated in a polymer matrix with a diameter $d \approx 1$–10 μm [4,5] within the framework of the indicated approximations. One study [6] showed that the scattering mechanism in the anomalous diffraction approximation remained valid in films of LC droplets encapsulated in a polymer matrix with a single-layer arrangement and size of up to $d \approx 25$ μm. In this case, the optical characteristics were determined by the phase relations of the light transmitted through the droplets and through the polymer matrix, i.e., by the difference between the refractive indices of the LC and polymer. However, to obtain them, it turned out to be necessary to use parameters that depended on the size, shape, and internal structure of the LC droplets. Recently, the domain structures of nematic LCs formed on the surface of polycarbonate (PC) have been observed and investigated [7–9]. The domains had dimensions $d \approx 50$–200 μm and were very densely packed on the PC surface. This circumstance makes it difficult to consider the characteristics of light transmitted through their ensembles within the framework of the indicated approximations. In this paper, we present a technique for determining the optical characteristics of the domain structures of an LC with the use of a focused laser beam capable of probing individual domains. Electric and magnetic fields were used to analyze the optical transmission of deformed LC structures.

2. EXPERIMENTAL PROCEDURE

To obtain the optical characteristics of an individual LC domain on the PC surface, a polarization-optical setup was assembled, the layout of which is shown in Fig. 1. The setup made it possible to transmit either white light or laser radiation through a sample and obtain its voltage-contrast characteristics. White light from a halogen lamp, reflected by a mirror, passed through a semitransparent plate, polarizer, lens, platform with a sample, objective, and analyzer. Then, after being deflected by a prism, it entered the objective of a digital camera through the eyepiece. A horizontally polarized He–Ne beam from an LGN-302 laser with a wavelength $\lambda = 0.633$ μm had its intensity weakened by a filter and then, after being reflected by a semi-transparent plate, traveled further to the objective of the camera in the same way as the white light beam. When the prism was removed from the optical path, the laser beam hit a photodiode.

A focusing lens with a focal length of 30 mm was used to focus the laser beam. It is known that a lens does not change the beam profile, but changes only the radius of curvature and spot size if the beam is Gaussian [10]. The profile of the laser beam was determined using an LBP2 laser beam profiler (Newport Corporation). The distribution of the relative intensity of the beam, I_{rel} (as a percentage of the maximum value), for the cross section located at the focus of the lens, is shown in the inset of Fig. 1 (left). It is seen from the distribution that the beam has a Gaussian shape, and its waist w_0, where the radial width w has a minimum value at $z = 0$, is approximately 25 μm. The inset in Fig. 1 (right) shows the hyperbolic contour of the beam, its waist, the surfaces of constant phase, and the energy profile of the beam.

To create a sample, a glass plate with a conductive coating of indium-tin oxide (ITO) was placed in a centrifuge, and a drop of a 2% PC solution in CH_2Cl_2 was deposited on it. After centrifugation for several tens of seconds, a PC film was formed on the substrate, onto which two 30 μm thick Teflon gaskets were placed. A glass plate with a conductive ITO coating was placed on the gaskets and washed in boiling acetone and boiling hexane. A liquid 4-*n*-pentyl-4-cyanobiphenyl (5CB) crystal with a phase transition sequence of Cr-22°C-*N*-34°C-I was introduced into the gap between the plates of the cell in the nematic phase. The LC cell was placed between the poles of an electromagnet, and a magnetic field of strength **H** was applied along the substrate plane for 20 min. After removing the magnet, an ensemble of LC domains with circular shapes and disclination lines passing through their centers along the diameters approximately perpendicular to the application direction for **H** could be observed using a polarization microscope. The obtained sample was placed on a platform capable of moving in three perpendicular directions. Moving in the vertical direction, along the light beam, the platform was set so that the layer of LC in the cell was in the focus of the lens. In addition, the platform moved in the horizontal plane until the central region of an individual domain was in the path of the laser beam. In this case, the sample was set so that the polarization vector of the light wave **e** was parallel to the application direction for **H**, and photographs were obtained. Then, the prism and analyzer were removed from the optical path, the white light source was turned off, and an alternating voltage U was applied to the cell at a frequency of 1 kHz from a generator, which was recorded by a voltmeter (*20*, Fig. 1). The voltage from the photodiode, which was proportional to the intensity of the laser beam I, was recorded with a voltmeter (*21*, Fig. 1). The signals from the voltmeters were fed to the computer through a special circuit board. The digital camera was also connected to the computer. The dependence $I(U)$ was recorded using the LabVIEW program. Then, the sample was

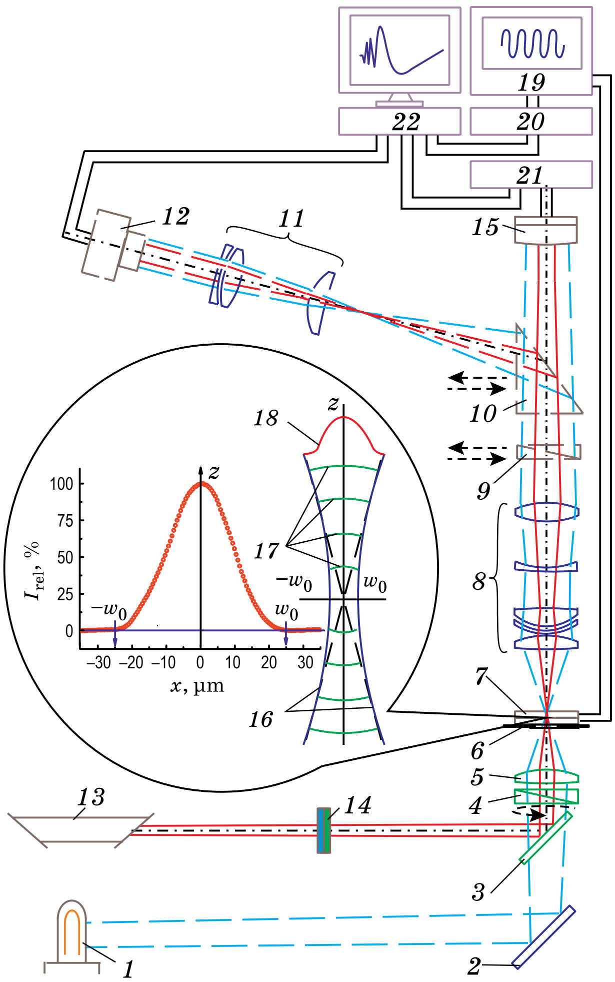

Fig. 1. Layout of the polarization-optical setup for determining the optical characteristics of light passing through separate LC domains on a PC surface: *1*—lamp, *2*—mirror, *3*—semitransparent plate, *4*—polarizer, *5*—lens, *6*—platform, *7*—sample, *8*—objective, *9*—analyzer, *10*—prism, *11*—eyepiece, *12*—digital camera, *13*—laser, *14*—filter, *15*—photodiode, *19*—generator, *20*, *21*—voltmeters, *22*—computer. The inset shows the profile (on the left) and structure of the laser beam (on the right), where I_{rel} is the relative intensity, x is the distance from the central axis z in the cross section, *16* is the hyperbolic contour, w_0 is the waist, *17* is the constant phase surface, and *18* is the energy profile.

rotated 90° so that the polarization vector of the light wave **e** was perpendicular to the application direction for **H**, and $I(U)$ was recorded again.

3. RESULTS AND DISCUSSION

A photomicrograph of the ensemble of 5CB domains formed on the surface of a PC film in the presence of a magnetic field $H = 25$ kOe is shown in Fig. 2. It can be seen from the figure that all of the disclination lines are oriented approximately perpendicular to the direction of **H**. This made it possible to simplify the orientation of the sample in the polarization-optical setup for $\mathbf{e}\|\mathbf{H}$ or $\mathbf{e}\perp\mathbf{H}$.

The dependence $I(U)$ of the intensity of the laser beam transmitted through the center of the domain for $\mathbf{e}\|\mathbf{H}$ is shown

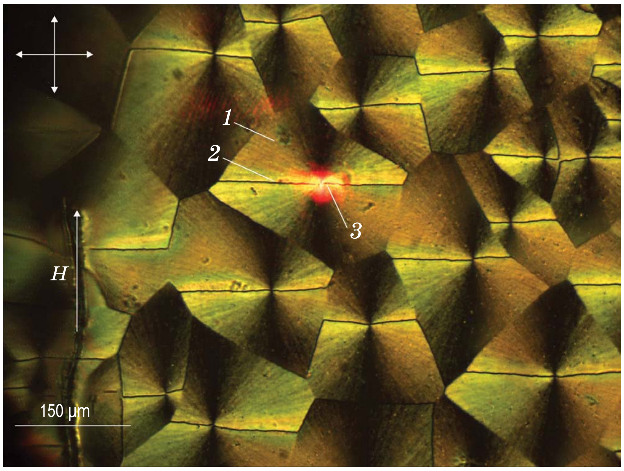

Fig. 2. Photomicrograph of an ensemble of 5CB domains formed on the surface of a PC film in the presence of magnetic field $H = 25$ kOe: *1*—individual domain, *2*—disclination line, and *3*—laser beam spot. The polarization directions of the white light are indicated by intersecting arrows.

in Fig. 3(a). The dependence is accompanied by interference effects after the beginning of the transformation of the LC layer, with a monotonic increase in intensity with increasing voltage. The analogous dependence of $I(U)$, but for $\mathbf{e}\perp\mathbf{H}$, is shown in Fig. 3(b). This curve also shows interference changes in the intensity of the laser radiation, but with a monotonic decrease with increasing voltage. It should be noted that the presented dependences remained practically unchanged when the laser beam moved relative to the domain; i.e., the contribution of the disclination lines to the optical characteristics was negligible. The following conclusions can be drawn from an analysis of the dependences shown in Fig. 3. First, the curves were obtained in the absence of an analyzer, and therefore cannot be interpreted on the basis of the birefringence effect of an LC. Second, the optical characteristics were similar to those of an ensemble of domains probed by a wide laser beam [8]. However, in this case, they could not be explained by the difference between the refractive indices of the LC and the polymer, because all of the light passed through the domain and did not enter the polymer matrix. Third, the dependences had different characteristics for different directions of the polarization vector with respect to the direction of the magnetic field vector.

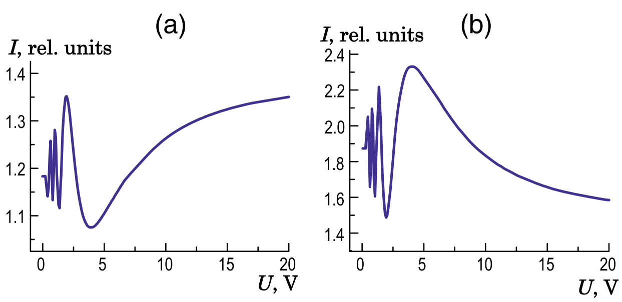

Fig. 3. Dependences of laser radiation intensity I on voltage U, with polarization vectors (a) $\mathbf{e}\|\mathbf{H}$ and (b) $\mathbf{e}\perp\mathbf{H}$, transmitted through the center of a 5CB domain formed on a PC surface.

The results obtained can be interpreted as follows. The domain structure of an LC formed by a PC surface in the presence of a magnetic field [9] is shown in Fig. 4(a). The radial configuration of the director of the LC formed on the PC surface is gradually transferred to the volume of the nematic layer and transitions at the coherence length ξ into the planar orientation. When a voltage is applied to the sample, the reorientation of the nematic molecules under the action of the electric field $\mathbf{E}$ in each domain should lead to a change in the director orientation angle with respect to the z axis at the coherence length ξ_E, along with a change in the inhomogeneous molecular

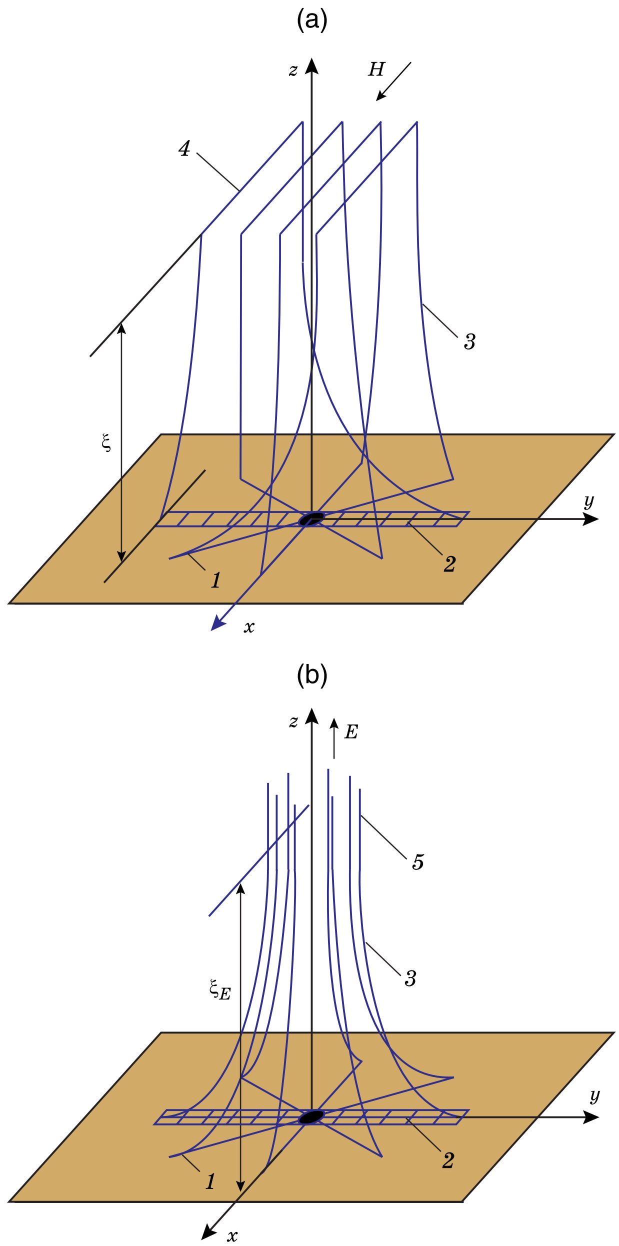

Fig. 4. Structures of the ensemble of domains of an LC formed by a PC surface (a) in the presence of a magnetic field (b) reoriented under the action of an electric field: *1*—radial structure on the PC film, *2*—disclination line, *3*—structure of the transition layer at distance z from the surface, *4*—planar orientation of the LC at coherence length ξ, *5*—homeotropic orientation of the LC at coherence length ξ_E.

distribution in the xy plane [Fig. 4(b)]. This transformation of the director will be accompanied by the refractive index of the extraordinary beam tending to the refractive index of the ordinary beam at a distance ξ_E. It can be assumed that, because of the inhomogeneous distribution of the refractive indices in the xy plane, the effect of a gradient index lens will appear in the domain, with the light beam in this lens tending to deviate toward a higher refractive index [11,12]. For $\mathbf{e}\|\mathbf{H}$, this lens will be a focusing lens, whereas it will be a scattering lens for $\mathbf{e}\perp\mathbf{H}$. In the first case, there will be an increase [Fig. 3(a)], and in the second case, there will be a decrease [Fig. 3(b)] in the intensity of the laser radiation with increasing voltage.

4. CONCLUSION

In this paper, we presented a technique for determining the optical characteristics of the domain structures of an LC with the use of a focused laser beam capable of probing individual domains. The optical characteristics of a 5CB nematic domain formed by a PC surface in the presence of a magnetic field were obtained using a polarization optical device. The setup made it possible to pass either white light or laser radiation through the sample, with either of these focused by the focusing lens. The dependences of the intensity of the laser radiation on the voltage U were obtained, with polarization vectors $\mathbf{e}\|\mathbf{H}$ and $\mathbf{e}\perp\mathbf{H}$, which passed through a nematic domain. These dependences were accompanied by interference effects after the transformation of the LC layer began, with a monotonic increase or decrease in intensity with increasing voltage. These optical characteristics could not be interpreted within the framework of the concept of light scattering suitable for an ensemble of domains probed by a wide laser beam. The results obtained can be explained if we assume that the effect of a gradient index lens arises as a result of the non-uniform distribution of the refractive indices in the section of the laser beam in the domain, with the light beam in the lens tending to deviate toward a higher refractive index.

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