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OPTICAL PHYSICS

Interference oscillations in the optical response of a hybrid-aligned nematic with a surface disclination line to a pulsed magnetic field

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The propagation of light through a hybrid-aligned nematic layer with a surface disclination line is investigated in a pulsed magnetic field. The experimental dependences of light intensity I on time t accompanied by interference oscillations are presented. The shift and expansion of the interference extrema as functions of the magnetic field pulse length during the reaction are shown. The $I(t)$ dependence for the relaxation process is calculated with allowance for scattering. The calculated $I(t)$ dependence agrees well with the experimental dependence over the entire hybrid-aligned nematic layer, except for the surface layer.

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1. INTRODUCTION

Investigations into the dynamics of liquid crystals (LCs) via optical methods are currently performed based on both theory and application [1,2]. In the first key studies [3,4], the basic dynamic characteristics of nematic LCs in homogeneous layers were determined. It was discovered that the optical transmission changed exponentially upon the deformation of a homogeneous nematic layer in a magnetic field. The oscillations induced by the birefringence of an LC in crossed polarizers were analyzed, and equations for the reaction and relaxation times were derived. Subsequently, the optical response of the LC director was investigated with allowance for scattering under the alignment of the LC by electric [5,6] and magnetic [7] fields. The reaction and relaxation times in a homogeneous LC layer with regard to the finite energy of LC anchoring with the surface in an electric field were determined [8]. Precision optical measurements of the dynamic characteristics of planar nematic cells in an electric field were recently performed in [9]. The stages of initialization, orientation, and relaxation are studied considering light scattering in thin and thick layers of nematics near the threshold field of Freedericksz transition. By observing the change in the color of light transmitted through planar and twist nematic cells, the phenomenon of balance between fluctuations and the relaxation processes was investigated in [10]. Subsequently, nonuniformly oriented LC layers in nematic droplets encapsulated in polymer matrices in electric [11] and magnetic [12] fields were investigated. A magnetic field was used to avoid side effects induced by the possible emergence of charges in an electric field caused by significant deviations of the LC director [13,14]. In addition, the dependence of the electric field on the thickness of the LC layer within the electric coherent length with a strong inhomogeneity of the director profile in hybrid-aligned nematic with surface disclination line (HANL) significantly complicates its use. Along with this, it becomes difficult to take into account the voltage drop across the polymer film and in the near-surface region of the HANL layer. These factors made it possible to reliably determine the phase difference between ordinary and extraordinary waves only after the experimental establishment of the correspondence between the electric field and the magnetic field in the static regime [15]. One should expect even greater manifestation at strong deformations of the LC in the pulsed regime. Therefore, to study the dynamic characteristics of the HANL layer, it is necessary to give preference to a pulsed magnetic field. A significant disadvantage of all the above-cited studies was the complexity in obtaining analytical expressions for describing the dynamic characteristics, which were analyzed using small-angle approximations or numerical methods [16]. Recently, we analyzed the interference of light propagating in HANL layers of an LC in slowly scanned electric [15] and magnetic [17] fields. The interference was caused by the superposition of ordinary and extraordinary beams due to their deviation on a radial LC structure, which formed the basis of the HANL, and was detected as extrema in the field dependence of light intensity.

The aim of this study was to investigate the optical transmission of an LC based on the dynamics of the HANL layer in a strong pulsed magnetic field. Model investigations were

performed via analytical methods in the small-angle approximation and in a wide range of LC director deviations from the equilibrium orientation using semi-empirical methods.

2. MODEL

Figure 1 shows the LC director field distribution over the domain of the HANL layer that was affected by the magnetic field H. Initially [(Fig. 1(a)], $H=0$, and the magnetic coherence length [1] is $\xi_H = 1/H(K/\Delta\chi)^{1/2} = \infty$, where $K=(K_{11}+K_{22}+K_{33})/3$ (K_{11}, K_{22}, and K_{33} are the elasticity modules for the splay, twist, and bend distortions, respectively) is the modulus of elasticity of the nematic in the one-constant approximation, and $\Delta\chi$ is the anisotropy of the magnetic susceptibility. The director exhibits an equilibrium configuration corresponding to a planar radial structure with a disclination line on the lower surface, which changes gradually to a uniform planar alignment at a distance ξ in the bulk of the LC [18]. This effect competes with the homeotropic alignment specified on the upper surface of the LC cell; additionally, in the HANL layer, an ordering with a director field distribution angle of θ_0 occurs. When the magnetic field H is switched on, the LC director of length ξ_H orients along H [1]. If the H value corresponds to the case where $\xi_H=\xi$, then the homeotropic orientation should be implemented using this length [(Fig. 1(b)] because the effects of the upper surface and the magnetic field on the LC director are matched, and the effect of the lower surface in a thick LC cell decays rapidly. In the range of $z<\xi$, the director extends an angle θ along the z axis. In a strong magnetic field, $\xi_H \ll \xi$, and the entire nematic layer, except for a thin surface layer, becomes homeotropic [Fig. 1(c)].

The free energy of the LC with director $\boldsymbol{n}$ in domain volume V can be written as follows [1]:

$$F=\frac{1}{2}\int\left\{K\left[(\mathrm{div}\boldsymbol{n})^2+(\mathrm{rot}\boldsymbol{n})^2\right]-\Delta\chi H^2\cos^2\theta\right\}\mathrm{d}V. \quad (1)$$

By specifying the director components $n_\rho=-\sin\theta$, $n_\varphi=0$, and $n_z=\cos\theta$ in the cylindrical coordinates (ρ,φ,z) and determining the minimum free energy using the variational method, we obtain the balance equation for the elastic and magnetic moments. When a pulsed magnetic field is used, these moments should be compared with the LC frictional torque. Disregarding the inertial and hydrodynamic terms [2], we have

$$\nabla^2\theta-\left(\frac{A^2}{\xi^2}+\frac{1}{\xi_H^2}\right)\sin\theta\cos\theta=\frac{\gamma_1}{K}\frac{\partial\theta}{\partial t}, \quad (2)$$

where $\nabla^2\theta=\partial^2\theta/\partial\rho^2+(1/\rho^2)(\partial^2\theta/\partial\varphi^2)+\partial^2\theta/\partial z^2$ is the Laplacian; $A=[(\pi^3/12-\pi^2/4+1)/2\pi\ln(l/b)]^{1/2}$ [18]; l and b are the length and width of the disclination line, respectively; γ_1 is the LC rotational viscosity coefficient. Assuming that $\rho=r$ is the domain radius as well as $\partial\theta/\partial\rho=0$ and $\partial^2\theta/\partial\varphi^2=0$, in the approximation of small angles θ, we can write Eq. (2) in the following form:

$$\frac{\partial^2\theta}{\partial z^2}-\left(\frac{A^2}{\xi^2}+\frac{1}{\xi_H^2}\right)\theta=\frac{\gamma_1}{K}\frac{\partial\theta}{\partial t}. \quad (3)$$

This equation was solved via the separation of variables over the coordinate and time as a standard task for the heat equation under inhomogeneous boundary conditions $\theta(0,\ t)=\pi/2$, $\theta(d,\ t)=0$ in the $0\le z\le d$ range. Solving this task for the case $H=0$ [(Fig. 1(a)] with the corresponding Fourier coefficients for the function $\theta(z,\ t)$ and limiting the consideration to the first term of the series, we obtain

$$\theta(z,t)=\frac{\pi}{2}\left(1-\frac{z}{d}\right)-\exp\left(-\frac{\pi a}{d}\right)^2\sin\left(\frac{\pi z}{d}\right). \quad (4)$$

After determining the parameters $a=(K/\gamma_1)^{1/2}$ and solving Eq. (3), as well as applying Eq. (4), we obtain the following equations for the time of the LC reaction to the magnetic field:

$$t_R=\frac{\gamma_1}{K\left(\frac{A^2}{\xi^2}+\frac{B^2}{\xi_H^2}-\frac{\pi^2}{d^2}\right)}, \quad (5)$$

where $B^2=1-\pi/2(1-z/d)/e\sin(\pi z/d)$ at $t=t_R$.

The relaxation time of the nematic director to the equilibrium distribution [Fig. 1(a)] from the homeotropic alignment [Fig. 1(c)] after switching off the magnetic field is expressed as follows:

$$t_D=\frac{\gamma_1}{K\left(\frac{\pi^2}{d^2}-\frac{A^2}{\xi^2}\right)}. \quad (6)$$

The small-angle approximation allows one to obtain expressions only for the reaction and relaxation times. However, to investigate the dynamics of the optical response to a magnetic field pulse, the change in orientation angle θ of the LC director $\boldsymbol{n}$ over the entire range of its deviation must be determined. It can be assumed that the investigated system is characterized by the relaxation property, i.e., the rotational speed at which $\boldsymbol{n}$ approaches the equilibrium state is proportional to the degree of deviation from it. This assumption is confirmed by the experimental results from [3,4] and this study. In this case, we can write $\partial\theta/\partial t=-\kappa\theta$, which correlates the coefficient κ to the rate of relaxation of the LC director for time $t=\ln(\theta_0/\theta)/\kappa$ on angle θ specified by magnetic field H to the equilibrium value θ_0 at $H=0$. Such an assumption will be fulfilled for the reaction, since the speed of rotation of the LC director is determined by the magnetic moment, which is proportional to angle θ. This is consistent with the data reported in [3,4]. Under these

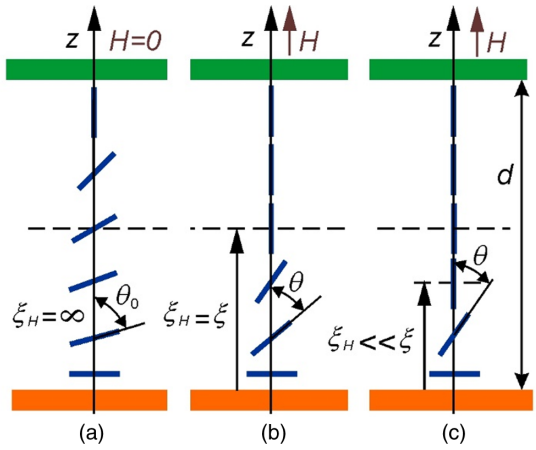

Fig. 1. Distribution of the LC director field in the HANL layer at magnetic coherence lengths. (a) $\xi_H=\infty$. (b) $\xi_H=\xi$. (c) $\xi_H \ll \xi$.

assumptions and retaining the same Laplacian approximations after differentiating Eq. (2), we obtain

$$\left(\frac{d\theta}{dz}\right)^2 = \left(\frac{A^2}{\xi^2} + \frac{1}{\xi_H^2}\right)\sin^2\theta + \frac{\gamma_1}{K}\kappa\theta^2. \quad (7)$$

The ordinary and extraordinary waves $\boldsymbol{E}_{o1}$ and $\boldsymbol{E}_{e2}$ transmitted through the HANL layer interfere [15,17]. The phase difference arising between the waves has the integral value

$$\delta = \frac{2\pi}{\lambda}\int_0^{\xi_H}\left[n_e^*(z) - n_o\right]dz, \quad (8)$$

where λ is the wavelength of light, and $n_e^*(z) = n_e n_o (n_e^2\cos^2\theta + n_o^2\sin^2\theta)^{-1/2}$ is the effective refractive index for the extraordinary (n_e) and ordinary (n_o) waves. Substituting dz from Eq. (7) into (8), we obtain

$$\delta = \frac{2\pi n_o}{\lambda}\int_0^{\theta}\left[\left(1 - \nu\sin^2\theta\right)^{-1/2} - 1\right] \times \frac{1}{\sqrt{\left[\frac{A^2}{\xi^2} + \frac{1}{\xi_H^2}\right]\sin^2\theta + \frac{\gamma_1}{K}\kappa\theta^2}}d\theta, \quad (9)$$

where $\nu = (n_e^2 - n_o^2)/n_e^2$.

The intensity $I = \Sigma < (\boldsymbol{E}_{o1} + \boldsymbol{E}_{e2})^2 >$ of light with wave vector $\boldsymbol{k}$ transmitted through the HANL layer as a result of the superposition of the waves should contain the interference term $J = 2\Sigma < \boldsymbol{E}_{o1}\,\boldsymbol{E}_{e2} >$, which changes periodically as a function of the phase difference and decreases monotonically because of scattering. In [17], to account for scattering by the HANL inhomogeneities, J was added with an exponential factor containing the magnetic (ξ_H) and structural (ξ) coherence lengths; this is consistent with the analytical and experimental dependences of the light intensity on the magnetic field in the static regime. In dynamics, the changes in ξ_H and the rotation of the LC director occur at different rates; therefore, it is more appropriate to consider the scattering using the director orientation angle θ, rather than the parameter ξ_H associated with the magnetic field. In [19], to account for the scattering of nonuniformly oriented layers in nematic droplets encapsulated in polymer matrices, intensity I was added with a term containing the scattering cross section associated with the order parameter of the droplet axes through Legendre polynomials. Scattering in the HANL layer due to the spatial nonuniformity of the optical anisotropy of the nematic $\Delta n = n_e - n_o$ is determined by the arrangement of disclination lines $\boldsymbol{l}$ on the polycarbonate (PC) surface and is transferred in the bulk by distance ξ [17]. The magnetic field eliminates the nonuniformity after attaining $\xi_H = \xi$ by reorienting the LC to the homeotropic state and specifies the angle θ in the HANL layer at $\xi_H < \xi$. In this case, we can introduce the scattering cross section $\sigma = f(\boldsymbol{l}\,\boldsymbol{k}) = \sin\theta$ averaged over the HANL layer because the nematic director $\boldsymbol{n}$ aligns perpendicular to the disclination lines [18]. It is convenient to expand the scattering cross section in terms of Legendre polynomials $\sigma = \sum n = 1 n a_{2n} P_{2n}(\sin\theta)$, and add the factor $\exp(-\sigma z)$ to J. The expansion coefficients can account for scattering associated with the distortion of the domain shape and other scattering types, e.g., scattering by the fluctuations of the order parameter [1] or scattering caused by the interaction of the nematic with the surface [20,21]. In this case, the equation for light intensity is of the following form:

$$I = \frac{1}{2}I_0\left(1 + \frac{2}{\pi}\exp(-\sigma z)\cos\delta\right), \quad (10)$$

where I_0 is the intensity of the light transmitted through the HANL layer at $H = 0$. In this case, $I_0 = I_0'\exp(-\sigma_0 d)\cos\delta_0$, where I_0' is the intensity of the light incident on the LC cell, and σ_0, δ_0 are the scattering cross section and phase difference, respectively, for the initial state of LC orientation at $H = 0$ [(Fig. 1 (a)]. The parameter σ_0 takes into account the light scattering on a polymer film with an inhomogeneous surface, scattering at domain boundaries (since the HANL layer in reality is not an ensemble of regular cylindrical domains, but a polygonal structure), and scattering at the intermediate regions between the line disclination and radial structure in the domain. All these scattering components may be considered as stationary, since the structures are determined mainly by the azimuthal angle φ, and the magnetic field does not affect it, but only changes the polar angle θ. We believe that the inclusion of a magnetic field does not result in the formation of a wall, since microscopic observations of the LC reorientation process under the action of an electric field (which we carried out earlier on the same samples [22]) did not show this effect. Apparently, this is due to the noncritical change of LC director profile under the action of the field, when there is a planar anchoring on the bottom surface of the LC cell and homeotropic anchoring on the top surface, which is assumed in our experiment. The parameter δ_0 is also independent of the angle φ, since the refractive index n_e^* does not depend on it and determines the initial value of the phase difference for the HANL layer.

3. EXPERIMENT

To conduct the investigations, we fabricated an LC cell comprising two plane-parallel glass plates measuring 10 mm × 12 mm. A PC film was deposited on the lower plate in a centrifuge from a 2% solution in dichloromethane, and the upper plate was coated with a 4% lecithin solution film to set the homeotropic orientation. The plates were bunched with a shift through two 30-μm-thick Teflon strips and adhered along their edges using epoxy resin. The gap between the plates was filled with a well-known 4-*n*-pentyl-4′-cyanobiphenyl nematic with positive anisotropy of magnetic susceptibility; subsequently, we observed the formation of an ensemble of LC domains on the PC film with a radial structure and a disclination line and a planar LC orientation on the PC surface under a polarizing microscope for ∼20 min [23,24] (Fig. 2). The average domain radius was $r \approx 75$ μm.

The cell was placed in a thermostat installed in the cylindrical channel of a multilayer pulse solenoid [25] such that the plates were perpendicular to the magnetic field lines. A He–Ne laser beam with a wavelength of $\lambda = 0.633$ μm was directed along the solenoid axis through the cell, and its intensity was detected using a photodiode, the signal from which was supplied to one of the oscilloscope channels. The magnetic field value was detected using a Hall sensor on another oscilloscope channel.

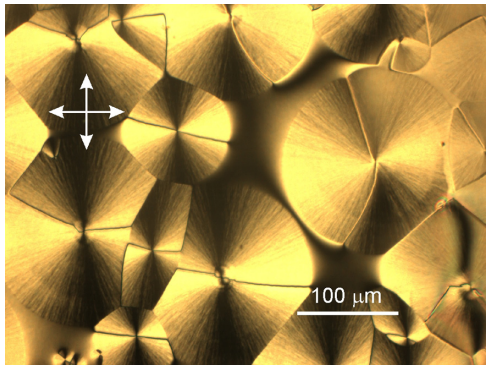

Fig. 2. HANL texture observed in a polarizing microscope in crossed polarizers.

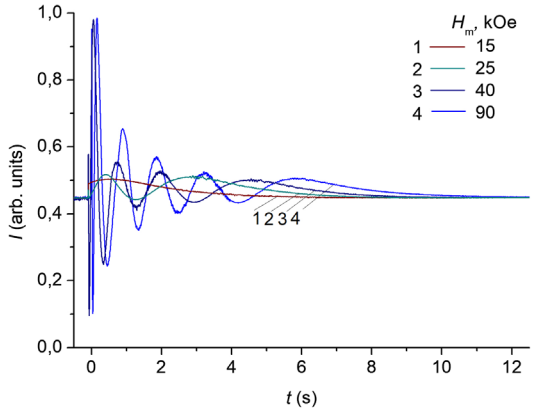

Fig. 3. Set of dependences of intensity I of light transmitted through the HANL layer on time t at different magnetic field pulse amplitudes of $H_m = 15, 25, 40$, and 90 kOe.

To obtain a pulse, the solenoid was connected to a capacitor bank, which can be charged to any voltage U up to 1000 V and discharged through a thyristor. Cell preparation and all measurements were performed at 23°C.

4. RESULTS AND DISCUSSION

Figure 3 shows the $I(t)$ dependencies obtained at magnetic field pulse amplitudes H_m from 14 to 90 kOe. The $I(t)$ curves detected at $H_m > 90$ kOe almost coincided; therefore, the experiment was limited to a value of $H_m = 90$ kOe. The dependences exhibited the following features: at any H_m value for determining the degree of deviation θ of the nematic director, its relaxation time to the equilibrium orientation remained the same, i.e., the relaxation rate of $\boldsymbol{n}$ is proportional to the degree of its deviation. This allows us to use Eq. (5) for the reaction times and Eq. (6) for the relaxation times obtained using the small-angle approximation and for significant deviations of the LC director from the equilibrium alignment. In addition, it allows us to use the approximation $\partial\theta/\partial t = -\kappa\cdot\theta$ for the relaxation, excluding the time from the dynamic equation shown in Eq. (2), as well as calculate the $I(t)$ dependences using Eqs. (6)–(10). In the calculation, we used values from the literature, i.e., $K = 6.21 \cdot 10^{-7}$ dyn [17], $\Delta\chi = 0.97 \cdot 10^{-7}$ [26], $n_e = 1.7103$, $n_o = 1.5271$ [27], and $\gamma_1 = 1\ P$ [28] for the temperature of 23°C and a cell parameter of $d = 30$ μm, as well as domain structure parameters of $r = 75$ μm, $l = 150$ μm, $b = 10$ μm, $\xi = r[(\pi^3/12 - \pi^2/4 + 1)/2\pi\ln(l/b)]^{1/2} = 22.3$ μm, and $A = 0.297$. Using these data in Eqs. (5) and (6), a reaction time of $t_R = 1.3 \cdot 10^{-3}$ s and a relaxation time of $t_D = 2$ s were obtained, which differed by more than three orders of magnitude. This difference was caused by the simultaneous effect of the increasing magnetic field on all molecules in the bulk of the LC and the sequential transfer of the wall effect to the bulk from one molecule to another during relaxation.

The initial range of the curve of the nematic response to a magnetic field pulse is shown in Fig. 4. The curve was accompanied by the interference maxima and minima characteristics of the HANL. However, the LC reaction time $t_R = 10$ ms was longer than $t_R = 1.3$ ms calculated using Eq. (5) for the case of involving an abrupt switching of the field. Its value is even higher than the rise time of the magnetic field $t_H = 5$ ms. Hence, we can conclude that the field pulse governs the LC response. The interference extrema that should have been enclosed in a narrow millisecond range of time t_R appears to expand over a wider range. For a more detailed consideration of this issue, the following should be noted. It can be seen from expression (5) that t_R depends on the parameters of the HANL layer and $t_R \sim \xi_H^2 \sim 1/H^2$. Consequently, as the magnetic field increases, the reaction time decreases rapidly. If the field was abruptly turned on and kept on for a long time (that is, when a rectangular pulse was used), the experimental value of t_R would most likely coincide with the calculated $t_R = 1.3$ ms. This is confirmed by the results of [11], obtained in the study of nematic droplets encapsulated in a polymer matrix under a pulsed electric field. Unfortunately, we cannot provide for comparison a rectangular magnetic field pulse due to the inductance of the solenoid [25]. If the rise time of the magnetic field became very long, $t_H \to \infty$, a static regime would arise for which the nematic director would follow the magnetic field at $t_R = t_H$. A regime close to this was observed in [12] when studying the optical response of nematic droplets encapsulated in a polymer matrix under a pulsed magnetic field. In our case, the rise time of the magnetic field $t_H = 5$ ms is longer than the calculated value of t_R, so the director of the nematic manages to track a front of the control pulse, that is, a static regime is implemented. Interference oscillations accompany the experimental curve. In this regime, the $I(t)$ dependence cannot be estimated by the calculated curve obtained from expressions (9) and (10) but is determined by the $H(t)$ dependence for the pulse. However, the delay t_R exceeds t_H at 5 ms. We assume that the delay associated with an additional inertia HANL layer is due to the restructuring of domain structures affecting each other.

For coefficients $a_2 = -0.6$, $a_4 = -0.075$, and $z = d$ in Eq. (10), as well as by changing θ from zero to $\pi/2$ with a step of 0.001 rad, we obtained a sequence of δ values and calculated the $I(t)$ dependence for the relaxation (Fig. 5). In addition, Fig. 5 shows the experimental $I(t)$ dependence depicted in Fig. 3. As shown, the calculated and experimental curves in the t range of 0.2 to 12 s indicated good agreement. At $t < 0.2$ s, the calculated curve began deviating from the experimental curve. It is interesting to note that Eq. (10) has a form that describes damped oscillations. However, the nonlinear character of the phase difference δ, which follows from Eq. (9), transforms the

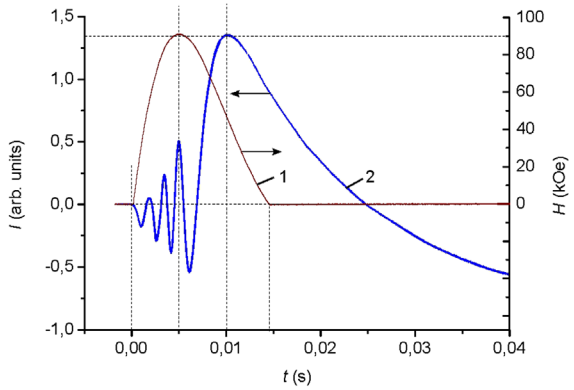

Fig. 4. (1) Dependence of pulsed magnetic field H on time t and (2) reaction of $I(t)$ of the LC to the field effect.

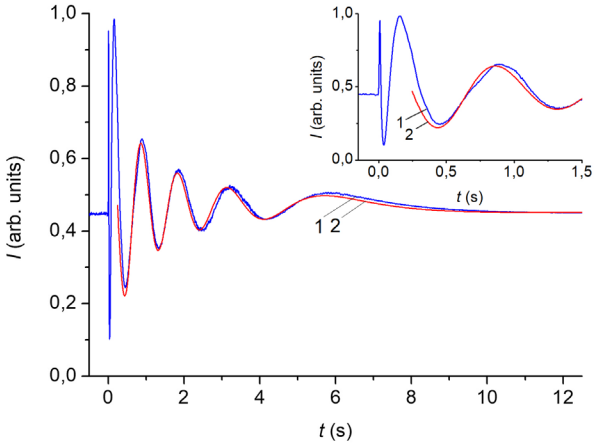

Fig. 5. Experimental (1, blue line) and calculated (2, red line) time dependences of the intensity of laser radiation transmitted through the HANL layer at a pulsed magnetic field amplitude of $H_m = 90$ kOe.

cosδ in Eq. (10) so that the $I(t)$ curve gradually expands with increasing time t. The extrema on the curves are due to the interference of ordinary and extraordinary waves [15,17].

Figure 6 shows the initial ranges of $I(t)$ dependencies obtained at magnetic field pulse amplitudes H_m from 14 to 90 kOe, in which, for the convenience of comparison, the amplitudes of the interference extrema were smoothed using a filter. As shown, the amplitudes of the optical response maxima, which presumably correspond to the maximum deviation angle θ per pulse, showed the same value on the time scale. This justifies the use of the approximation of proportionality for the change in the angle θ with time to the angle for the reaction, as well as for the relaxation. However, the dependence of t_R on H at the nonlinear $H(t)$ function prevented us from obtaining the calculated $I(t)$ dependence for the reaction, similar to the case for the relaxation, which coincides with the experiment. The $I(t)$ curves in Fig. 6 can be categorized into three ranges (I, II, and III). Range I corresponds to the LC response to a magnetic field pulse. Range II characterizes the transition layer between the bulk and LC/PC interface. In this layer with a thickness of $\xi_H = 0.2$ μm, at $H_m = 90$ kOe, we observed a violation in the exponential property when decreasing the amplitude during relaxation, which in fact occurred in range III. This is

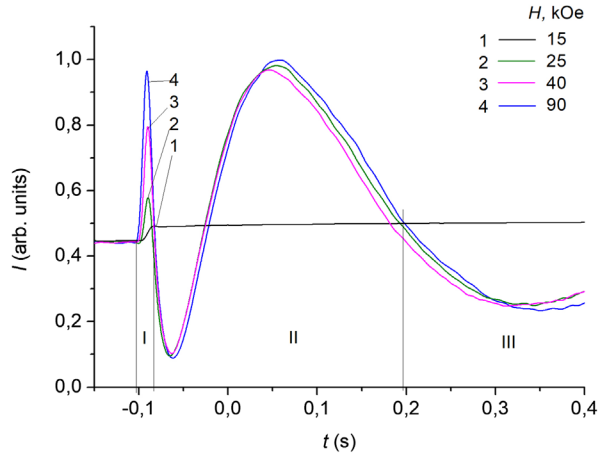

Fig. 6. Dependences of intensity I of light transmitted through the HANL layer on time t at different magnetic field pulse amplitudes of $H_m = 15, 25, 40$, and 90 kOe with the reaction (I), transition layer (II), and relaxation (III) range.

possible because of the effect of the magnetic field pulse shape on the response, the manifestation of the HANL structure inhomogeneities formed at the physicochemical interaction of LC molecules with PC polymer chains [23,24,29], and the backflow effect [2–4].

The one-constant approximation is often used for estimating calculations when studying the structure and properties of LCs. This term was introduced in [1] and is used in many studies of LCs. Disregard for the difference in elasticity constants is one of the possible reasons for the discrepancy between the calculation results and experimental data, including in this work. LC orientation structures with proper optical texture are the same as in Fig. 2 and were considered and explained convincingly early in [18,23,24,29] in the framework of physicochemical interactions of LC molecules with polymer chains without using the macroscopic parameters of nematic. In this regard, the discrepancy between the temporal characteristics in Fig. 4 is explained by the change in the ordering of the LC due to the process of such formation. Good agreement between the theoretical and experimental dependences of the light intensity on the pulsed magnetic field confirms the validity of using this approximation. An exception is the thin near-surface layer of the domain structure, in which the backflow effect caused by the difference in the elastic moduli K_{11} and K_{33} is possible. We believe that this effect is still small mostly manifesting itself in thick planar-oriented LC layers [2] and hides in the HANL layer against the background of other surface effects. The backflow effect was experimentally observed during the relaxation of the nematic director from the homeotropic orientation imposed by an external field to the initial homogeneous planar aligning [2]. This is caused by a strong curvature of the director lines of different signs on the interface. In our case, the backflow in the LC layer should be much less due to the smoother curvature of the director lines. The effect is associated with the movement of nematic, so we should have observed an anomalous behavior of the $I(t)$ dependence [2]. In fact, the relaxation curve in Fig. 5 remains monotonic (with its inherent interference extrema) including the region corresponding to the propagation of light through the near-surface layer, on which it expands only along

the time scale. In any case, the solution of this issue presupposes further studies using fine optical methods for probing LC structures, for example, those presented in [9,10].

5. CONCLUSION

In this study, the propagation of light from a He–Ne laser with a wavelength of $\lambda = 0.633$ μm through a HANL layer in a pulsed magnetic field was investigated. Based on the minimum LC free energy, the dynamic equation for the distribution of the director field $\boldsymbol{n}$ was derived and used to determine the LC reaction and relaxation times in the approximation of small orientation angles θ. Under the assumption that the investigated system is characterized by the relaxation property, based on which the angular velocity at which $\boldsymbol{n}$ approaches the equilibrium state is proportional to the degree of deviation from it, the director field distribution at any θ was obtained. The expression for the integral phase difference δ over the HANL layer thickness was derived. Using these δ values, the dependence of the light intensity I on time t was obtained. To account for scattering by the HANL layer inhomogeneities, I was added with an exponential factor containing the scattering cross section related to the degree of ordering of disclination lines in an ensemble of domains via Legendre polynomials. As the magnetic field at the beginning of the curve increased for t ranging from 0 to 0.015 s, the course of the $I(t)$ dependence was affected by the pulse length, i.e., the magnetic pulse governed the LC response. During relaxation, the calculated $I(t)$ dependence was compared with the experimental one; it was discovered that the values agreed well with other, albeit only in the t range from 0.3 to 12 s. In the intermediate t range from 0.02 to 0.3 s, which corresponds to the laser beam probing of a thin (∼0.2 μm) surface layer, the $I(t)$ dependence is not explained herein using the investigated model. For further development of the model, the effect of the magnetic field pulse shape on the optical response, the structuring of the HANL at the PC surface, and the backflow effect using a viscosity coefficient γ_2 should be considered.

In this study, we used a one-constant approximation. The obtained satisfactory agreement between the experimental and theoretical dependences of the light intensity on time confirms the possibility of using this approximation. We believe that the discrepancy between the dependences near the boundary of the HANL layer is associated with the specific physics of LC surface, where it is necessary to consider the dispersion, polar, and adsorption interactions of a nematic with a structured polymer surface. Consideration of these issues requires special research.

We believe that the presented results will be useful both from fundamental and applied points of view. First, the dynamics of nontrivial self-organized composite structures with attractive optical properties was investigated in this work. The experiments were carried out using a magnetic field that excludes the influence of parasitic effects inherent in an electric field. Further development of the topic is expected in the direction of searching for new polymer and LC materials suitable for similar self-organization effects. Second, the structures under study are a promising optical material with a large modulation depth of transmitted light. This material and modulators based on it do not require the use of polarizers and can be easy to fabricate. The use of LCs with negative diamagnetic anisotropy can significantly expand the variety of forming structures, types of orientational transitions, and observed optical effects.

Disclosures. The authors declare no conflicts of interest.

Data Availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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