Measurement of the surface-tension anisotropy of a nematic liquid crystal

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The surface tension anisotropy factor of the nematic liquid crystal MBBA σ_a is determined experimentally. The magnitude of σ_a, which is measured for the first time, is $\sigma_a \approx 10^{-5}$ erg/cm^2.

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1. The free surface of a nematic liquid crystal (NLC) contains an easy axis of orientation of the director.[1] This axis arises due to the interaction of molecules in the surface layer of the NLC with the medium adjacent to it. In this case, when this medium is isotropic, for example, air, the orienting action of the free surface is described by the orientation-dependent part of the surface free energy[2,3]

$$\Lambda(\mathrm{erg/cm^2}) = \frac{1}{2}\sigma_a(\mathbf{n}\mathbf{e}_z)^2. \tag{1}$$

The following notation is used in (1): σ_a is the anisotropy of the surface tension, and $\mathbf{e}_z$ is the unit vector normal to the free surface.[1)]

The possibility of measuring the magnitude of σ_a with the help of self-focusing of light in NLC by an orientation mechanism was demonstrated in Ref. 3. In this work, σ_a is determined by investigating the light-induced Freedericksz transition (LFT) in the NLC layer with two free, i.e., adjacent to air, surfaces. The interaction of laser radiation with such layers was first studied in Ref. 4.

2. As is well known,[1] for the nematic MBBA $\sigma_a < 0$, i.e., the surface strives to orient the director homeotropically. However, in relatively thick layers $L \sim 100\ \mu\text{m}$, good orientation can be attained only by applying an external, homogeneous magnetic field with intensity $|\mathbf{H}| \sim 1$ kG perpendicular to the layer. Let a linearly polarized light wave be normally incident on such an NLC layer filling the space $0 \leqslant z \leqslant L$,

$$\mathbf{E}_{\text{real}} = 0.5\{\mathbf{E}\exp(-i\omega t + i\mathbf{kr}) + \mathbf{E}^*\exp(i\omega t - i\mathbf{kr})\}.$$

When the power density of the wave exceeds some threshold value P_{cr}, reorientation of the director occurs $\delta\mathbf{n} = \mathbf{n} - \mathbf{n}^0$, i.e., the Freedericksz transition, whose theory for the layer with rigid orientation of the director on substrate surfaces is worked out in Ref. 5. In the case examined by us the variational equations of motion for the perturbations of the director $\delta\mathbf{n}$ have the form

$$K_{33}\frac{\partial^2 \delta n}{\partial z^2} + \left(\frac{\epsilon_a\epsilon_\perp}{8\pi\epsilon_\parallel}|\mathbf{E}|^2 - \chi_a H^2\right)\delta\mathbf{n} = \eta\frac{\partial\delta\mathbf{n}}{\partial t}, \tag{2a}$$

$$\left[K_{33}\frac{\partial\delta\mathbf{n}}{\partial z} + |\sigma_a|\delta\mathbf{n}\right]_{z=L} = 0, \tag{2b}$$

$$\left[K_{33}\frac{\partial\delta\mathbf{n}}{\partial z} + |\sigma_a|\delta\mathbf{n}\right]_{z=0} = 0, \tag{2c}$$

where K_{33} is the Frank constant, $\epsilon_a = \epsilon_\parallel - \epsilon_\perp$ is the anisotropy of the dielectric constant of the NLC at the frequencies of light, χ_a is the diamagnetic anisotropy, and η (poise) is the relaxation constant.

Separating out the time-dependent part in $\delta\mathbf{n}$ as $\delta\mathbf{n}(z,t) = \delta\mathbf{n}(z)\exp(\Gamma t)$, we write the solution of Eq. (2a) in the form

$$\delta\mathbf{n}(z) = c_1\sin\kappa z + c_2\cos\kappa z, \tag{3}$$

where c_1, c_2 are constants

$$\kappa^2 = \frac{1}{K_{33}}\left(\frac{\epsilon_a\epsilon_\perp}{8\pi\epsilon_\parallel}|\mathbf{E}|^2 - \chi_a H^2 - \eta\Gamma\right). \tag{4}$$

Perturbations of the director increase exponentially with time, if $\Gamma > 0$. As follows from (4), this occurs for

$$P_{\text{cr}} = \frac{c\sqrt{\epsilon_\perp}}{8\pi}|\mathbf{E}|^2_{\text{cr}} = A(B\kappa^2 + H^2), \tag{5}$$

where

$$A = c\epsilon_\parallel\chi_a/\epsilon_a\sqrt{\epsilon_\perp}, \qquad B = K_{33}/\chi_a.$$

The quantities c_1, c_2 and κ^2 are determined by substituting (3) into Eqs. (2b) and (2c) and using the condition for the existence of a nontrivial solution for δn.

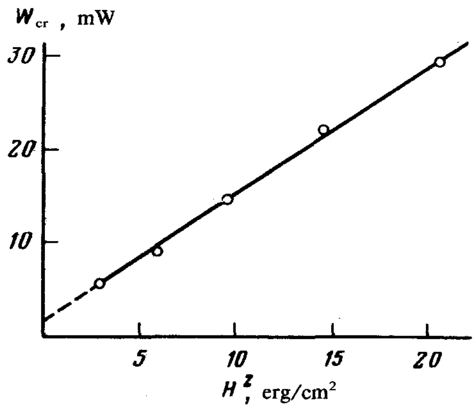

FIG. 1. The threshold power for LFT as a function of the square of the magnetic field intensity.

$$\tan \kappa L = 2\xi \frac{\kappa L}{(\kappa L)^2 - \xi^2}, \tag{6}$$

$$c_2/c_1 = \kappa L/\xi, \quad \xi = L(|\sigma_a|/K_{33}). \tag{7}$$

3. In the experiment, we used a continuous argon-type $ILA = 120$ laser ($\lambda = 0.51$ μm) with a single transverse mode with width 1.5 mm. The radiation, focused by a lens with a 50-cm focal length, is incident normally on an MBBA layer with two free surfaces, located in a static magnetic field. The magnetic field, whose intensity varied up to 5 kG, is necessary to create a uniform orientation of the director in the volume of the layer. We used layers with a diameter of 1.5 or 3 mm and thickness of 200 μm with homeotropic orientation. The reorientation of the director induced by the light field leads to the appearance of aberrational rings in the far zone, recorded visually on the screen.

The dependence of the threshold power W_{cr} on H^2 is shown in Fig. 1. This dependence is linear, consistent with the theory. The value of $AB\kappa^2$ can be determined by extrapolating this line to the point of intersection with the ordinate axis. The slope of the line gives the value of A. The coefficient $B = K_{33}/\chi_a$ is determined from the threshold for the Freedericksz transition in a static magnetic field in a cell with rigid boundary conditions and with homeotropic orientation of the NLC.[6] For the liquid crystal used by us (MBBA) B was equal to 8.4 dynes. The necessity for independent measurements of all parameters entering the theory stems from the fact that the values available in the literature have a certain spread.[6,7]

The quantity κ^2 is determined from the known values of A, B, and $AB\kappa^2$ and the quantity $\xi, \xi \approx 0.21$ is determined from Eq. (6). Since the thickness of the layer $L = 200$ μm, the ratio $|\sigma_a|/K_{33}$ is equal to $|\sigma_a|/K_{33} \approx 10.5$ cm^{-1}. Using the value of the constant K_{33} 7.5×10^{-7} dynes,[6] we obtain $\sigma_a \approx -0.8 \times 10^{-5}$ erg/cm^2. We note again that the value of σ_a obtained corresponds to an NLC surface that borders on air.

The accuracy of the method is limited primarily by thermal effects and the finiteness of the transverse dimensions of the NLC layer and of the light beam, and it is also related to the accuracy with which the LFT threshold is measured.[8] In addition, we should point out that the quantity σ_0 was recalculated using the given value of the Frank constant. In our experiment, σ_0 was measured to within 20%.

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[a] The expression actually obtained in Ref. 1 for the surface free energy has a more complex form, involving transverse gradients of the director field. In the present work, we shall ignore them due to the assumed smoothness of the intensity distribution in the light beam acting on the NLC layer.

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