Selective scattering of polarized light by an oriented nematic liquid crystal

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The propagation of an ordinary wave has been found to differ substantially from that of an extraordinary wave in thick oriented samples of nematic liquid crystals. In particular, a beam whose extraordinary wave is polarized transforms from a coherent beam into a diffuse beam without appreciable beam expansion and without affecting its polarization. A theoretical explanation for the observed picture is proposed.

Nematic liquid crystals (NLC) are characterized by strongly developed fluctuations of the director. The intensity of light scattering by these fluctuations is proportional to $(\mathbf{k}_i - \mathbf{k}_s)^{-2}$ where $\mathbf{k}_i$ and $\mathbf{k}_s$ are the wave vectors of the incident and scattered light. For this reason, the integral over all scattering angles, which, according to the optical theorem, determines the extinction coefficient σ, diverges logarithmically as $\mathbf{k}_s \to \mathbf{k}_i$.[2] Since NLC are uniaxial crystals in terms of their optical properties, two types of waves can propagate in them: an ordinary wave (o) and an extraordinary wave (e). We note that the contribution to σ from a scattered wave polarized oppositely to the incident wave is finite, since we have in this case $|\mathbf{k}_i - \mathbf{k}_s| = |k_i - k_s| \neq 0$ for forward scattering. Using the expression for the correlation function of fluctuations of the director[1] and the Green's function for the electromagnetic field in an anisotropic medium,[3] we can show that if the incident and scattered waves are ordinary waves, the intensity of scattering in any direction is zero (compare Ref. 4). For an ordinary incident beam the integral therefore converges, and we obtain

$$\sigma^{(o)}(\varphi) = \sigma_0 f = \pi k_B T \epsilon_a^2 f / \lambda^2 K_{33} \sqrt{\epsilon_\parallel \epsilon_\perp}\,, \tag{1}$$

where $\epsilon_a = \epsilon_\parallel - \epsilon_\perp$; $\epsilon_\parallel$ and $\epsilon_\perp$ are the dielectric constants in a direction parallel and perpendicular to the director $\mathbf{n}$; $f = f(\varphi, t_1, t_2, \epsilon_a/\epsilon_\perp)$ is an angular factor ($f \sim 1$–2); $t_1 = K_{11}/K_{33}$, $t_2 = K_{22}/K_{33}$, K_{ii} are the Frank moduli; λ is the wavelength of light in a vacuum; and φ is the angle between $\mathbf{k}_i$ and $\mathbf{n}$. The angular dependence of $\sigma^{(0)}(\varphi)$ is shown in Fig. 1. For the case in which the incident and scattered beams are extraordinary and φ differs from 0 and 90°, the divergence remains the same.[1)] However, the extinction coefficient is finite in this case only because the correlation radius of fluctuations of the director is limited by the dimensions of the sample, L. In calculating σ the integral must be cut off at angles on the order of the diffraction angle $\theta_{\min} \sim \lambda / L^2$. If, on the other hand, the extinction length is $\sigma^{-1} < L$, then it can become the cutoff parameter in the integral. To calculate σ in this case, we must use a more general optical theorem, taking into account the damping in the Green's function.[5] For the imaginary part of the polarization-operator kernel, both approaches in the single-loop approximation give the same expressions for the expansion in terms of the small pa-

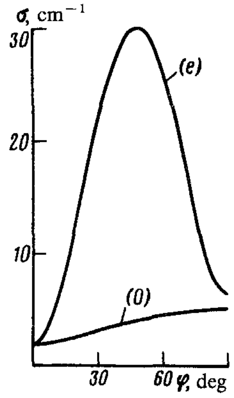

FIG. 1. The coefficients of extinction of the ordinary beam (*o*) and the extraordinary beam (*e*) in the NLC *N*-106 ($\epsilon_{\parallel} = 2.644$, $\epsilon_{\perp} = 2.2$, $t_1 = 0.863$, $t_2 = 0.273$, $K_{33} = 1.1 \times 10^{-6}$ dynes and $T = 23$ °C).

rameter $\delta = (2k_i\, l)^{-1}$, where l is the cutoff parameter ($L/2\pi$ or σ^{-1}). To lowest order in δ, we obtain

$$\sigma^{(e)}(\varphi) = \frac{\sigma_0 (\epsilon_{\parallel} \epsilon_{\perp})^{3/2} \sin^2 2\varphi}{2(\epsilon_{\parallel} \cos^2\varphi + \epsilon_{\perp} \sin^2\varphi)^2} \frac{t_1}{F_1} \frac{F_1 + F_2}{t_1 F_2 + t_2 F_1} \ln \delta^{-1}, \tag{2}$$

where $F_i = (t_i^2 \epsilon_{\parallel}^2 \cos^2\varphi + t_i \epsilon_{\perp}^2 \sin^2\varphi)^{1/2}$. The calculation based on Eq. (2) for $l^{-1} = \sigma^{(e)}$ with allowance for higher-order corrections with respect to δ, is shown in Fig. 1. We see that $\sigma^{(e)}$ has a sharp angular dependence and exceeds $\sigma^{(o)}$ by approximately an order of magnitude.

An extremely elongated scattering indicatrix for the extraordinary incident and scattered beams leads to a specific effect in reasonably thick samples with $L^{-1} < \sigma^{(e)}$. Because of multiple forward rescattering, a coherent laser beam transforms into a diffuse beam without appreciable beam expansion and without a significant change in the total intensity.

To check the validity of this picture of the propagation of light in an NLC, we prepared a cell with an N-106 liquid crystal about 2 mm thick and 3 cm long. The director vector was oriented parallel to the glass surfaces (planar orientation). The quality of the single crystal was monitored with a polarization microscope. Upon appearance of disclinations, the sample was placed into a magnetic field with an intensity of $\sim 3 \times 10^3$ Oe and kept there until they completely disappeared ($\sim$3–5 min). A He–Ne laser beam ($\lambda = 6328$ Å) was passed through the cell at different angles to the director axis; the polarization of the incident light corresponded either to (*o*) or (*e*) polarization. The beam that passed through the crystal impinged on the screen and was photographed.

As is evident from the photographs in Fig. 2a, in the case of an ordinary beam, the picture is essentially independent of the angle φ. A bright spot with (*o*) polarization, surrounded by a weak, flickering, (*e*)-polarized background, is seen at the center.

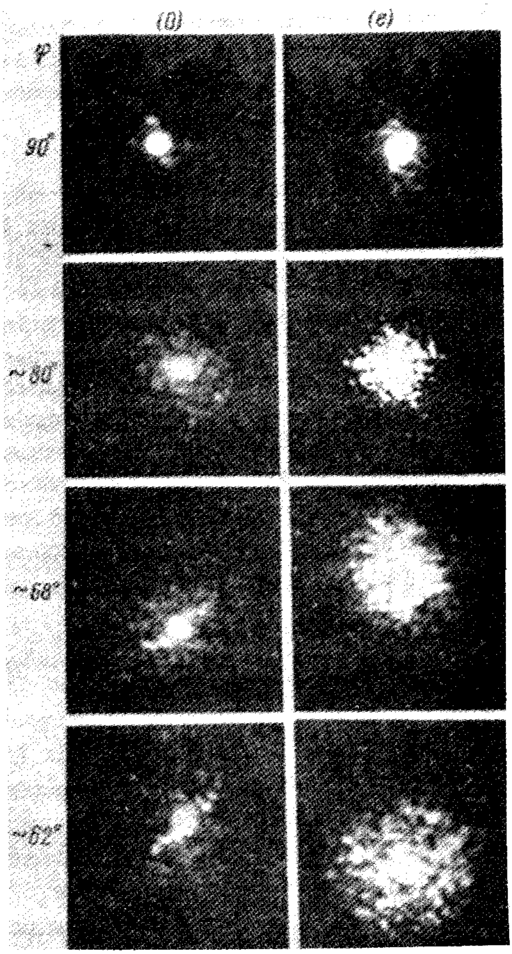

FIG. 2.

This result is entirely understandable, since the extinction of the ordinary beam is comparatively small and there is no scattered, (*o*)-polarized light.

In the case of an extraordinary beam, the picture is entirely different (Fig. 2b). A diffuse, (*e*)-polarized, central spot, whose angular size increases to 1° upon changing the angle φ from 90 to 60° (the limiting refraction angle in our case is 52°) is observed. The spot consists of regions with different brightness, whose structure varies slowly with time. The scintillating background surrounding the spot has (*o*) and (*e*) polarizations.

These circumstances confirm our assumption that energy is transferred from a narrow laser beam into a wider diffuse beam due to scattering by long-wavelength fluctuations of the director. The increase in the spot size is explained by the increase in the number of scatterings in the diffuse beam as $\sigma^{(e)}$ is increased. The weak background corresponds to the light scattered at large angles. In the case of an extraordinary incident beam, this light has both types of polarizations. The scintillation of the background is accounted for by the kinetics of the fluctuations of the director for scattering at angles $\lesssim 3°$, whereas the slower change at the center of the spot corresponds to scattering at very small angles.

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[1)] The total scattering cross section is finite at $\varphi = 0.90°$. The quantities is $\sigma^{(e)}(0) = \sigma^{(o)}(0)$, $\sigma^{(e)}(90°)$, and also $\sigma^{(o)}(90°)$ were calculated in Ref. 3.

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