Electrooptic effect in a ferroelectric liquid crystal with a small helix pitch and a large spontaneous polarization

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The distinctive features of a newly detected electrooptic effect in a helicoidal ferroelectric liquid crystal are described. This effect involves an electric-field-induced change in the refractive-index anisotropy which is averaged over time and over the light-beam aperture.

In the present letter we report the observation of the characteristic features of the dynamics of the helicoidal structure in a planar oriented layer of a ferroelectric liquid crystal[1] with a small helix pitch, $p_0 = 0.3$–$0.4\ \mu$m, and a large spontaneous polarization, $P_c = 70$ nC/cm^2. With such a small pitch in a layer of thickness up to 3 μm, the helicoidal structure remains the same, since the relation $d \gg p_0$ is satisfied.

In the experiment the planar orientation of the layer was set by rubbing the inside walls of the transparent electrodes of the cell, which were clad with a mixture of polyvinyl butyral and phenol-formaldehyde resin. For a broad light beam with a sectional diameter $D \gg p_0$, which strikes the electrode surfaces perpendicularly, the liquid-crystal layer is optically characterized by the optic $\langle \mathbf{n} \rangle$ axis, which coincides with the Z axis of the helicoid, although the locally optic axis behaves exactly like the long axes of the molecules (the director $\mathbf{n}$) and experiences continuous precession as it moves along the Z axis (Fig. 1b). After averaging the light over the beam aperture (or over the Z axis), the optics of such a liquid-crystal layer can be described by an averaged indicatrix of the refractive index, which in the cross section parallel to the electrode surfaces has a long $\langle n_e \rangle$ axis directed along the Z axis and a short $\langle n_0 \rangle$ axis perpendicular to it (Fig. 1c). We denote by $\langle \Delta n \rangle = \langle n_e \rangle - \langle n_0 \rangle$ the anisotropy of the refractive index averaged over the light beam aperture. This anisotropy is obviously weaker than that of a completely untwisted helicoid, $\Delta n = n_e - n_0$. The theoretical prediction and the description of the field dependence of $\langle n_e \rangle$ are given in Ref. 2.

The anisotropy $\langle \Delta n \rangle$, averaged over the Z axis, was determined, just as Δn, by a method described in Ref. 3 from a known thickness d of the liquid-crystal layer and from the phase delay Φ found from the relation

$$\tan 2\alpha = \tan 2\beta \cos \Phi , \qquad (1)$$

where α is the angle between the optic axis of a uniaxial plate and the polarization plane of the incident light, and β is the angle of rotation of the long axis of the polarization ellipse of the elliptically polarized light which emerges from the liquid-crystal layer. In our case we have $\Delta n = 0.248$ for a wavelength $\lambda = 0.633\ \mu$m, whereas the anisotropy averaged over the Z axis is $\langle \Delta n \rangle = 0.099$.

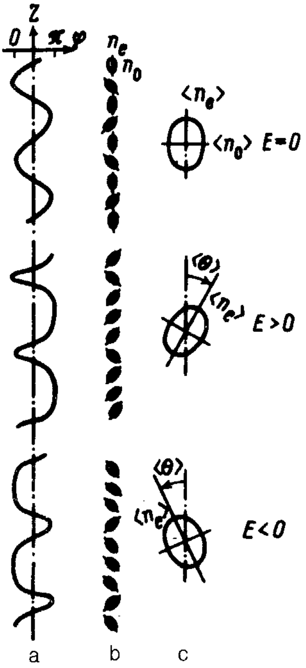

FIG. 1. (a) Distribution of the azimuthal angle φ of the slope plane of molecules in a helicoidal ferroelectric liquid crystal[8]; (b) local distribution of the refractive-index indicatrix; (c) averaged refractive-index indicatrix in a weak electric field E.

Application of a weak external electric field E perpendicularly to the electrode surfaces causes the sinusoidal distribution of the azimuthal angle $\varphi(Z) = \sin(2\pi/p_0)Z$ to be deformed. The larger the field of a given polarity in this case, the closer is the distribution $\varphi(Z)$ to one of the two homogeneous states to which the helicoidal ferroelectric liquid crystal undergoes a transition in large fields, $E \gg E_c$, where E_c is the field in which the helicoid untwists completely. The long $\langle n_e \rangle$ axis of the refractive-index indicatrix, averaged over the Z axis (or over the light-beam aperture), deviates proportionally to the applied field (the linear electrooptical effect[1,4,5]). In our case, this deviation occurred very rapidly and even at several tenths of a volt the output of the oscilloscope trace of a response at the 0.9 level was 200–250 μs for a layer thickness $d = 3.2$ μm.

As a result of application of alternating square pulses with an amplitude $U'_\Omega = \pm 1.5$ V, the angle $\langle \theta \rangle$ of deviation of the $\langle n_e \rangle$ axis reached 20° at a meander frequency of 100 Hz. An increase in the pulse frequency decreases the angle $\langle \theta \rangle$ for which the long $\langle n_e \rangle$ axis has time to diverge in a time corresponding to the meander half-period (Fig. 2). In extreme situations corresponding to the time at which the field reverses polarity, the refractive-index anisotropy averaged over the Z axis is virtually independent of the pulse amplitude, $\langle \Delta n \rangle \approx 0.1$, to within the voltage $U_\Omega = \pm 1.5$ V at $f = 100$ Hz. At this voltage the motion of dechiralization lines, which join the flat electrode surface with the helicoidal structure of the liquid crystal, becomes involved in the dynamics of deformation of the helicoid.[6] A further increase of the meander amplitude brings about a transition to a well-known effect,[5,7] wherein the director

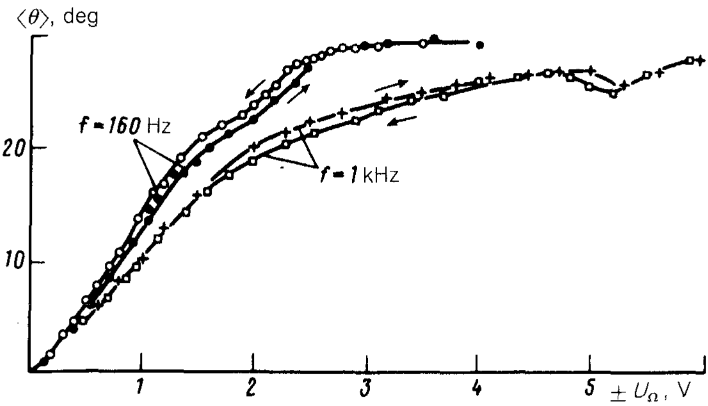

FIG. 2. The deflection angle $\langle \theta \rangle$ of the long $\langle n_e \rangle$ axis (averaged over the light-beam aperture) of the refractive-index indicatrix versus the amplitude $\pm U_\Omega$ and frequency f of the alternating control voltage (meander). The thickness of the liquid-crystal layer is 3.2 μm and the slope angle of the molecules is $\theta = 29.5°$.

switches to twice the slope angle θ of the long axes of the molecules. The Z-axis-averaged anisotropy $\langle \Delta n \rangle$ spasmodically changes to a molecular anisotropy, $\Delta n \approx 0.25$. Because of a paucity of essential experimental data, the transition from $\langle \Delta n \rangle$ to Δn at large field amplitudes is not explained here. Let us now consider the electrooptical effect, the most intriguing effect, in our view, which occurs in the structure described here. This effect is seen at low fields, $E < E_c$, at alternating-voltage frequencies higher than those seen with the naked eye, e.g., $f > 50$ Hz.

Because the direction of the long $\langle n_e \rangle$ axis, averaged over the Z axis or, equivalently, over the light-beam aperture of the refractive-index indicatrix, can be rapidly reversed, and because the amplitude $\langle \theta \rangle$ of the oscillation swing $\langle n_e \rangle$ is proportional to the pulse height U_Ω of the alternating constant-frequency voltage, we see an electrooptic effect which is associated with the response time of the observer's eye. Using a photomultiplier with an appropriate electric current, $RC \approx 0.1$ s, to simulate the eye with a time constant of ≈ 0.05 s, we were able to satisfy the condition $RC \gg f^{-1}$ and to measure the time-averaged anisotropy $\langle \Delta n \rangle$ which we denote as $\langle \overline{\Delta n} \rangle$. The doubly averaged (over time and over the light-beam aperture) refractive-index anisotropy $\langle \overline{\Delta n} \rangle$, like $\langle \Delta n \rangle$ and Δn, was measured on the basis of relation (1), using the procedure outlined in Ref. 3.

In Fig. 3 we see that, in the first place, $\langle \overline{\Delta n} \rangle$ decreases with increasing meander pulse amplitude U_Ω of a given frequency and that at a certain value of U_Ω it may vanish or even presumably change sign. This behavior indicates that the ellipse of the time-averaged refractive-index indicatrix $\langle \overline{\Delta n} \rangle$ "swells" due to the increase of the short $\langle n_0 \rangle$ axis as a result of the increase in the amplitude $\langle \theta \rangle$ (see the inset in Fig. 3). Secondly, an increase in the frequency f leads to a decrease in the variation of $\langle \overline{\Delta n} \rangle$ at a fixed pulse height U_Ω. Thirdly, the plots of $\langle \overline{\Delta n} \rangle$ versus U_Ω and f in Fig. 3 for

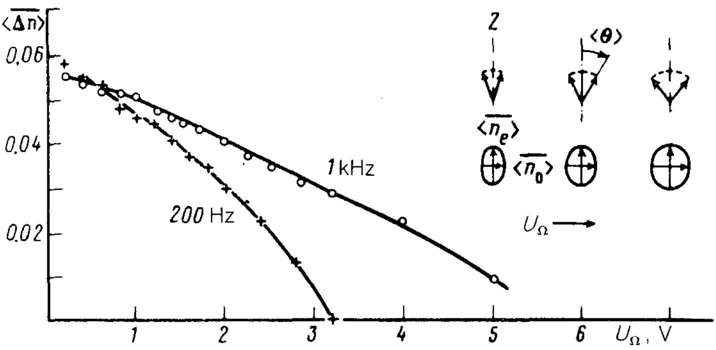

FIG. 3. Refractive-index anisotropy $\langle \overline{\Delta n}\rangle$ (averaged over the time and over the light-beam aperture) of the helicoidal ferroelectric liquid crystal versus the amplitude $\pm U_\Omega$ and frequency f of the alternating voltage (meander). The thickness of the liquid-crystal layer is 3.4 μm and the slope angle of the molecules is $\theta = 29.5°$. Inset—the evolution of $\langle \overline{\Delta n}\rangle$ as a function of the increase in the U_Ω amplitude.

various visible-light wavelengths differ from each other because of birefringence dispersion. In the case of white light, this difference is seen from the fact that a change in the amplitude or frequency of the alternating voltage in crossed polarizers leads to a visible change in the color of the light that emerges from the analyzer.

In summary, the new, experimentally observed electrooptical capabilities of thin layers of a ferroelectric liquid crystal, with a small helix pitch and strong spontaneous polarization, may be found useful in the development of high-speed, low-voltage light choppers, electrically controlled optical light filters, image converters, and other devices.

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