Flexoelectric effect in twisted liquid-crystal structures

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The flexoelectric effect is investigated in cholesteric and 90°-twisted nematic liquid crystals. It is manifest as a domain instability. The flexoelectric instability is a unique example of a polar electro-optical effect in nonpolar media. The dependences of the threshold characteristics on the parameters of liquid crystals are studied experimentally for various degrees of twisting of the director. The sign of the difference of the flexoelectric coefficients $e^* = e_1 - e_2$ is determined. The results are in quantitative agreement with theoretical computer calculations.

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1. INTRODUCTION

The flexoelectric instability in liquid crystals (LC) is a unique analog of the piezoelectric effect in solids and is the result of a linear connection between the polarization induced by the electric field and the orientational deformation of the molecular structure of the mesophase.[1] In planar layers of nematic liquid crystals (NLC), the flexoelectric instability manifests itself as a static spatially periodic deformation of the director, observed in the form of a domain structure with the domain lines parallel to the initial direction of the director. Domains of this type were first described in Refs. 2, and their flexoelectric nature was established as a result of subsequent experimental[3,4] and theoretical[5,6] studies.

In cholesteric liquid crystals (CLC) and in twisted NLC structures there is likewise a domain instability of flexoelectric character,[7] but one with a large number of peculiarities compared with the instability in planar NLC layers. A consistent interpretation of the peculiarities in the manifestation of the flexoelectric effect in twisted structure can be possible only by resorting to rigorous theoretical calculations, in which it is necessary to take into account the natural (cholesteric) or stimulated (for example, by the cell wall) helical periodicity of the distribution of the LC director.

In the present paper we present the results of an investigation of the threshold characteristics of the flexoelectric effect in NLC structures twisted through 90° and in various Grandjean bands made up by the CLC. The threshold voltage and the period and orientation of the domain lines are experimentally investigated as a function of the dielectric anisotropy of the LC, the pitch of the cholesteric helix, and the polarity of the constant electric field. A theoretical calculation of the threshold characteristics of the flexoelectric domain instability was carried out within the framework of a linear model developed in Refs. 5 and 6 with account taken of the peculiarities of the twisted liquid-crystal structure.

2. THEORETICAL CALCULATIONS

The flexoelectric instability in twisted LC structures can be described by solving the variational problem for the free energy of the twisted LC, with allowance for the flexoelectric polarization:

$$F=\int\Big\{{}^1/_2K_{11}(\operatorname{div}\mathbf{n})^2+{}^1/_2K_{22}(\mathbf{n}\operatorname{rot}\mathbf{n}+t_0)^2+{}^1/_2K_{33}[\mathbf{n}\operatorname{rot}\mathbf{n}]^2 -\frac{\varepsilon_a}{8\pi}(\mathbf{E}\mathbf{n})^2-e_1(\mathbf{E}\mathbf{n})\operatorname{div}\mathbf{n}+e_2\mathbf{E}[\mathbf{n}\operatorname{rot}\mathbf{n}]\Big\}d^3r, \tag{1}$$

where n is the LC director, e_1 and e_2 are the flexoelectric coefficients, ε_a is the anisotropy of the dielectric constant, K_{ii} are the elastic moduli, $t_0 = 2\pi/P_0$, and P_0 is the equilibrium pitch of the cholesteric helix.

We introduce a right-hand Cartesian coordinate frame (x, y, z) such that the z axis coincides with the direction of the cholesteric helix, and the x axis coincides with the direction of the director on the lower bounding surface of the LC. The director distribution, which characterizes the given instability, will be sought in the form

$$\mathbf{n}=\{\cos(\psi+\varphi)\cos\theta,\ \sin(\psi+\varphi)\cos\theta,\ \sin\theta\},$$

where φ and θ are the small deviation angles ($|\varphi|, |\theta| \ll 1$) of the director from the unperturbed uniformly twisted orientation of the director:

$$\mathbf{n}_0=\{\cos\psi,\ \sin\psi,\ 0\},\quad \psi=tz,\quad t=2\pi/P.$$

Here P is the real (induced) pitch of the helix. We represent the periodic variation of φ and θ in the xy plane in the form $\varphi = \tilde{\varphi}(z)\cos(k_x x + k_y y)$, $\theta = \tilde{\theta}(z)\sin(k_x x + k_y y)$, where the instability wave vector k for the domains making a certain angle α with the director at the center of the layer of the LC satisfies the condition $k_x\cos(\alpha + tL/2) + k_y\sin(\alpha + tL/2) = 0$.

Minimizing the functional (1) and confining ourselves to terms linear in the perturbations of φ and θ, we obtain the following equations, which determine completely the distribution of the director in the twisted modulated structure of the LC layer:

$$\begin{gathered}K_{11}\frac{d^2\theta}{dz^2}=\Big\{k^2(K_{22}\cos^2\Phi+K_{33}\sin^2\Phi)+K_{33}t^2-2K_{22}t\,\Delta t-\frac{\varepsilon_a E^2}{4\pi}\Big\}\theta\\ +k\{[2K_{22}\Delta t-(K_{11}+K_{33})t]\sin\Phi+e^*E\cos\Phi\}\varphi+k(K_{11}-K_{22})\cos\Phi\frac{d\varphi}{dz},\\ K_{22}\frac{d^2\varphi}{dz^2}=k^2(K_{11}\cos^2\Phi+K_{33}\sin^2\Phi)\varphi\\ +k\{[2K_{22}\Delta t-t(K_{22}+K_{33})]\sin\Phi+e^*E\cos\Phi\}\theta-k(K_{11}-K_{22})\cos\Phi\frac{d\theta}{dz};\\ \Phi=\psi-\alpha-\frac{tL}{2},\quad e^*=e_1-e_2,\quad \Delta t=t-t_0=2\pi\left(\frac{1}{P}-\frac{1}{P_0}\right).\end{gathered} \tag{2}$$

The boundary conditions in the case of a rigid coupling of molecules with the surface are of the form

$$\varphi=\theta=0 \quad \text{at} \quad z=\pm L/2, \tag{3}$$

where L is the thickness of the LC layer.

The procedure for solving equations of this type was considered in detail in Ref. 8. By determining for each value of the wave number k the corresponding value of the voltage $U=EL$ at different values of α, we obtain a dispersion relation that connects the electric-field voltage U with the wave number k and with the angle α. The minimum value

$$U_n(k_n,\alpha_n)=\min_{k,\alpha} U(k,\alpha)$$

is the threshold voltage of the flexoelectric domain instability which arises with a period $T_n=2/k_n$ at an angle α_n to the direction of the unperturbed director at the center of the LC layer.

A. Analytic estimates

For the zeroth Grandjean band formed by the CLC, in which the total twist angle of the director $\psi=tL=0$, in the particular case of zero dielectric-constant anisotropy, $\varepsilon_a=0$, Eqs. (2) simplify and admit of an analytic solution in the form

$$\theta(z)=\sum_{j=1}^{4} A_j e^{iq_jz}, \quad \tilde{\varphi}(z)=\sum_{j=1}^{4} B_j e^{iq_jz},$$

where the q_j ($j=1,\ldots,4$) are obtained from the boundary conditions (3) and are connected with the wave-number instability k by the dispersion equation for the system (2), which ensures that the complex coefficients A_j and B_j are not trivial.[6] It can be shown that in our case, when $\psi=0$, $\varepsilon_a\sim 0$, $|\alpha|\ll 1$, the relations $q_{1,2}=\pm q$, $q_{3,4}=\pm iq$ are valid, where

$$q=\pi L^{-1}(1+x), \quad |x|\sim(K_{22}/K_{11}-1)^3\ll 1.$$

The dispersion equation that determines the value of $U(k,\alpha)$ is of the form

$$[K_{11}q^2+k^2(K_{11}\cos^2\alpha+K_{33}\sin^2\alpha)][K_{22}q^2+k^2(K_{22}\cos^2\alpha+K_{33}\sin^2\alpha)]=(e^*E\cos\alpha-2K_{22}\Delta t\sin\alpha)^2k^2. \tag{4}$$

The minimum value

$$U_n=\min_{k,\alpha} U(k,\alpha) \quad (|k|\ll 1)$$

is reached at

$$k_n\approx\frac{\pi}{L}\left[1-\left(\frac{L}{P_0}\right)^2\frac{1}{y^2}\left(\frac{K_{33}}{K_{11}}+\frac{K_{33}}{K_{22}}-2\right)\right], \tag{5}$$

$$\alpha_n\approx\frac{2L}{P_0y}\operatorname{sign}(e^*U) \tag{6}$$

and takes on the form

$$U_n=U(k_n,\alpha_n)=\frac{2\pi(K_{11}K_{22})^{1/2}}{|e^*|}\left[1-\frac{K_{22}^2}{K_{33}(K_{11}+K_{22})}\left(\frac{2L}{P_0}\right)^2\right], \tag{7}$$

$$y=\frac{K_{33}}{K_{22}}\frac{(K_{11}+K_{22})}{2(K_{11}K_{22})^{1/2}}\approx\frac{K_{33}}{K_{22}}.$$

We see therefore that at the threshold voltage the wave number k_n remains practically unchanged along the zeroth Grandjean band ($0\leqslant 2L/P_0\leqslant 1/2$): the threshold voltage U_n of the flexoelectric instability decreases somewhat with increasing thickness of the LC, and the angle α_n has a linear dependence on the reduced thickness $2L/P_0$, with the slope of the plot approximately equal to the ratio K_{22}/K_{33}. As $L\to 0$ or $P_0\to\infty$ the threshold voltage is $\tilde{U}_n=2\pi K/|e^*|$, and agrees with the well-known formula (8) of Ref. 5, at $\varepsilon_a=0$ and $K_{11}=K_{22}=K$.

The qualitative character of the dependences of the threshold voltage, of the wave vector, and of the angle of inclination of the flexoelectric domains on the dielectric anisotropy in the considered zeroth Grandjean band can be analyzed by generalizing Eqs. (5)–(7) to include the case of small values of ε_a, when $U_0/U_F\ll 1$, where $U_0=2\pi(K_{11}K_{22})^{1/2}/|e^*|$ is the threshold of the flexoelectric instability in a planar NLC at ($\varepsilon_a=0$, $U_F=2\pi(K_{11}/\varepsilon_a)^{1/2}$ is the threshold voltage of the Freedericksz transition (S effect) at $\varepsilon_a>0$. Then

$$U_n(\varepsilon_a)=U_n(0)\left[1-\frac{\operatorname{sign}(\varepsilon_a)}{4}\left(\frac{U_0}{U_F}\right)^2\right], \tag{8}$$

$$k_n(\varepsilon_a)=k_n(0)\left[1-\frac{\operatorname{sign}(\varepsilon_a)}{4}\left(\frac{U_0}{U_F}\right)^2\right], \tag{9}$$

$$\alpha_n(\varepsilon_a)=\alpha_n(0)\Big/\left[1-\frac{\operatorname{sign}(\varepsilon_a)}{4}\left(\frac{U_0}{U_F}\right)^2\right]. \tag{10}$$

It is seen from these equations that the threshold voltage U_n of the domains increases, while their period $T_n=2\pi/k_n$ and the angle α_n that they make with the initial direction of the director in the LC midlayer decreases with increasing dielectric anisotropy of the LC.

B. Numerical calculation

In the general case, the threshold characteristics U_n, k_n, and α_n of the flexoelectric instability are calculated with a computer with the aid of the algorithm described in Ref. 8. The solution of the system (2) was sought in the form

$$\mathbf{Y}(z)=\{\theta_i,\ (d\theta/dz)_i,\ \varphi_i,\ (d\varphi/dz)_i\},$$

where $\mathbf{Y}_i(z=-L/2)=\varepsilon\mathbf{e}_i$, $\varepsilon=\text{const}\neq 0$, and $\mathbf{e}_i$ is the ith row of a fourth-order unit matrix. The threshold voltage U_n of the flexoelectric domains and the wave number k_n corresponding to it are defined as the minimum of the lowest branch of the solutions $U(k)$ of the dispersion equation

$$\theta_2(z=L/2)\varphi_4(z=L/2)-\varphi_2(z=L/2)\theta_4(z=L/2)=0, \tag{11}$$

which follows from the boundary conditions (3). The calculations were performed for the first three Grandjean bands $0\leqslant 2L/P_0\leqslant 5/2$ for parallel $\mathbf{n}(z=-L/2)\parallel\mathbf{n}(z=L/2)$ and perpendicular $\mathbf{n}(z=-L/2)\perp\mathbf{n}(z=L/2)$ boundary conditions, and for an NLC twisted 90° under perpendicular boundary conditions. In the calculations we used the elastic constants $K_{11}=0.78\cdot 10^{-6}$ dyn, $K_{22}=0.55\cdot 10^{-6}$ dyn, and $K_{33}=1.13\cdot 10^{-6}$ dyn, the flexoelectric coefficient $e^*=\pm 1.8\cdot 10^{-4}$ dyn$^{1/2}$; the dielectric anisotropy was varied in the range $-0.25\leqslant\varepsilon_a\leqslant 0.25$.

3. EXPERIMENTAL PROCEDURE

In the experimental investigations of the flexoelectric instability in twisted NLC structures we used p-butyl-p-methoxyazooxybenzene (BMAOB), whose dielectric anisotropy is $\varepsilon_a=-0.25$ at $t=25$ °C.[3] The CLC were mixtures of BMAOB with cholesteryl caprinate (CCN) up to 1%. The dielectric constants of the investigated LC were varied by adding to them small amounts (up to

1.5%) of p-cyanphenyl ester of p-heptylbenzoic acid (CEHBA) with $\varepsilon_a \sim 29$ at $t = 25\,^{\circ}\mathrm{C}$. At these concentrations of the added substances, only the required parameters were altered, namely the pitch P_0 of the cholesteric helix, from 44 to 8 μm, and the dielectric anisotropy ε_a in the range -0.25 to 0.25. The changes of the remaining parameters were negligible and could be neglected within the experimental errors.[9]

The liquid crystals were placed between two glass plates, on the inner surface of which were deposited transparent electrodes of SnO_2. The thickness of the LC layer was set by means of teflon liners. The CLC were investigated in wedge-shaped cells whose thickness ranged from 0 to 22 μm. The direction of the LC director on the bonding surfaces was set by rubbing in the electrodes.

The flexoelectric instability was observed and the threshold voltages were measured with the aid of a polarization microscope. The period T and the deflection angle α of the domain lines were measured by diffraction of an He–Ne laser beam. The experimental error for small directed twist angles $\psi \leq \pi$ and for nonnegative angles of the dielectric anisotropy $\varepsilon_a > 0$ amounted to 5%. At twist angles $\psi > \pi$ and at $\varepsilon_a > 0$ the experimental error increases to ~10%. All the experimental investigations were performed in a constant electric field.

4. RESULTS AND THEIR DISCUSSION

A. Instability of twisted NLC structures

Since the flexoelectric effect is a bulk phenomenon[3,6] and the binding energy of the molecules with the bounding surfaces is quite high (~0.1 erg/cm^2—Ref. 10) the molecules of the surfaces are hardly deflected from the initial directions when instability sets in, and the maximum deformation of the director takes place at the LC midlayer. A similar deformation of the director (maximum at the LC midlayer and tending to zero on the surfaces) occurs also in other instabilities, such as Williams domains or pre-chevron domains.[9] The domain lines for these instabilities are perpendicular to the direction of the unperturbed director in the center of the LC layer.[11-13] It can therefore be expected that the direction of the flexoelectric domains in the twisted LC layers is also determined by the direction of the unperturbed director at the center of the layer, and these directions should coincide, just as in planar LNC layers. In fact, the flexoelectric domains in twisted structures are deflected a certain angle α from the direction of unperturbed director in the LC midlayer (see Fig. 1 and Fig. 3 below).

Figure 1 shows photographs of the flexoelectric instability in an NLC twisted 90°. The orientation of the director coincides with the x axis, on the lower bounding surface of the cell ($z = -L/2$) and with the y axis on the upper surface ($z = L/2$). Since the liquid crystal is twisted in this case by the orienting action of the bounding surfaces, left-hand ($t < 0$) and right-hand ($t > 0$) twisting of the director can occur with equal probability. Regions with opposite twist directions are separated by a disclination line. The upper left parts of the photographs in Fig. 1 correspond to regions with right-hand twisting of the director. In the remaining part, the director is twisted to the left. If the field is perpendicular to the plane of the layer in the upward direction, as shown in Fig. 1(a) (positive field direction), then the angles between the domain line and the x axis are

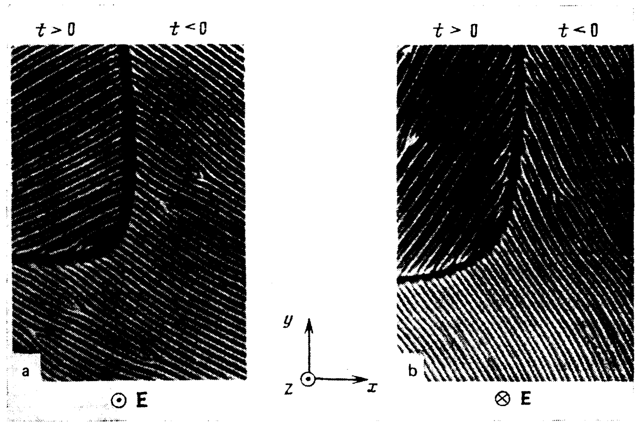

FIG. 1. Domain picture of flexoelectric instability for positive (a) and negative (b) field directions in an NLC twisted 90°.

$$\varphi < \pi/4 \text{ for } t > 0 \text{ and } \varphi > \pi/4 \text{ for } t < 0,$$

i.e., the angle of inclination of the domain lines from the unperturbed director $\mathbf{n}_0$ at $z = 0$ has a sign opposite to that of the twist direction t. When the polarity of the field is reversed (Fig. 1b, negative field direction), a symmetrical rearrangement of the domain picture takes place, so that the angle of the direction $\mathbf{l}$ of the domain lines relative to the direction n_0 of the director in midlayer reverses sign: $-\alpha \rightarrow \alpha$.

Figure 2 shows the dependence of the threshold of the flexoelectric domains on the angle α, calculated numerically with a computer using Eqs. (2) for an NLC

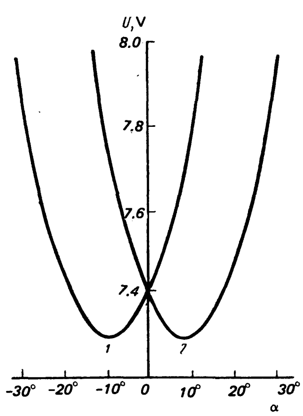

FIG. 2. Dispersion dependence of the voltage at which the flexoelectric instability set is in an NLC twisted 90° on the angle between the direction of the domain lines 1 and the direction of the unperturbed director $\mathbf{n}_0$ in the LC midlayer, obtained by numerical computer calculations at $\varepsilon_a = 0$ for flexoelectric-coefficient difference values: 1) $e^* = -1.8 \cdot 10^{-4}$ dyn$^{1/2}$; 2) $e^* = 1.8 \cdot 10^{4}$ dyn$^{1/2}$.

with zero dielectric anisotropy, twisted through 90°. Curve 1 corresponds to a flexoelectric coefficient $e^* = -1.8\cdot 10^{-4}$ dyn$^{1/2}$, and curve 2 to $e^* = 1.8\cdot 10^{-4}$ dyn$^{1/2}$. Both plots have minima at definite angles α_n. These minima determine the threshold of the onset of flexoelectric domains and the angles that they make with the director at midlayer. As seen from the figure, the threshold voltage U_n in an NLC twisted 90° amounts to 7.3 V. The threshold voltage U_n in a planar NLC layer is given by Eq. (7) at $P_0 = \infty$ and is equal to 6.9 V. Thus, the threshold voltage of the flexoelectric domains is higher in twisted NLC structures than in planar layers, as is confirmed also by experiment.

The reversal of the sign of the flexoelectric coefficient e^* is equivalent to a change in the direction of the electric field, i.e., domain patterns with opposite inclination angles of the domain lines (6) correspond to electric fields of opposite polarity, as is indeed observed in experiment (Fig. 1). On the other hand, if the field is assumed in both cases to be positive (as shown in Fig. 1a), and the signs of the flexoelectric coefficients are assumed to be opposite, then it follows from a comparison with the experiment for which the sign of the angle of inclination of the domains is negative at a positive direction of the field (Fig. 1a), that the real case corresponds to curve 1. This determines uniquely the sign of the flexoelectric coefficient e^*, namely, $e^* < 0$ for the investigated BMAOB.

B. Instability of planar CLC structures

In the zeroth Grandjean band, the cholesteric helix is completely untwisted. The distribution of the director in it coincides with the distribution of the director in a planar NLC layer. The flexoelectric instability in a cholesteric, however, has substantial peculiarities compared with the planar nematic. Hereas in a planar NLC layer the flexoelectric domains are strictly parallel to the initial direction of the director, in an untwisted CLC they make an angle with the direction (Fig.

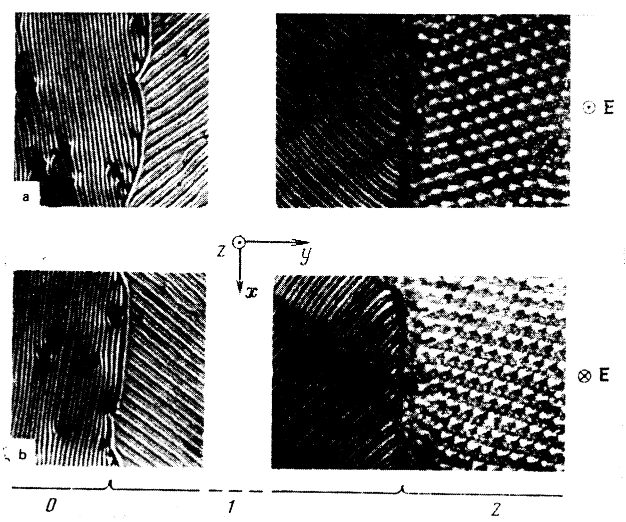

FIG. 3. Form of the flexoelectric domain instability in different Grandjean bands produced by a CLC in a wedge-shaped cell at positive (a) and negative (b) field directions.

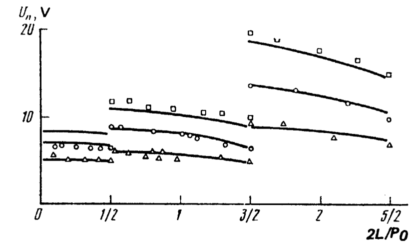

FIG. 4. Dependence of the threshold voltage of the onset of the flexoelectric instability in the first three Grandjean bands on the radio of the LC layer thickness L to the equilibrium half-pitch of the cholesteric helix $P_0/2$ at different values of the dielectric anisotropy: □) $\varepsilon_a = -0.1$, ○) $\varepsilon_a = 0$, △) $\varepsilon_a = 0.25$. The solid lines show the dependence of the threshold voltage, obtained by numerical computer calculation, for the corresponding values of ε_a.

3). At a positive field direction in a left-hand cholesteric (such as CCN), the domains are inclined to the right, i.e., the angle of inclination of the domains $\alpha < 0$, and consequently $e^* < 0$. When the field polarity is reversed, $\mathbf{E}_n \to -\mathbf{E}_n$, the domain inclination angle also reverses sign: $-\alpha \to \alpha$ (Fig. 3b).

Figure 4 shows the experimental and computer-calculated dependences of the threshold of the flexoelectric instability for different values of ε_a on the reduced thickness of the LC layer $2L/P_0$. The zeroth Grandjean band corresponds to a change of the parameter $2L/P_0$ from 0 to 1/2. As seen from the figure, the threshold voltage decreases slightly with increasing layer thickness, in full agreement with expression (7). When the dielectric anisotropy is decreased, the instability threshold increases [Eq. (8)], in agreement with the known theoretical premises concerning the nature of the flexoelectric effect in LC.[3-6] The reduced instability wave vector $k_n\pi/L$ is practically independent of the layer thickness within the limit of the zeroth Grandjean band (Fig. 5). Indeed, the second term in (5), which determines the dependence of the wave vector on L, is very small (~0.02). As seen from Fig. 5, the dependence of the wave vector k_n on the dielectric anisotropy ε_a is qualitatively described by the approximate formula (9). The angle of inclination of the domains from the initial direction of the director depends linearly on the reduced thickness of the layer $2L/P_0$ (Fig. 6). The slope of this plot at $\varepsilon_a = 0$, as follows from (6), is de-

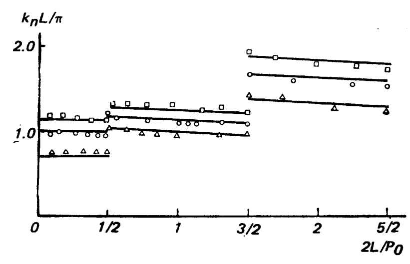

FIG. 5. Reduced wave vector of flexoelectric instability $k_n\pi/L$ in the first three Grandjean bands vs. the reduced thickness of the LC layer $2L/P_0$ at different values of ε_a: □) $\varepsilon_a = -0.1$, ○) $\varepsilon_a = 0$, △) $\varepsilon_a = 0.25$. The solid lines are obtained by numerical computer calculations.

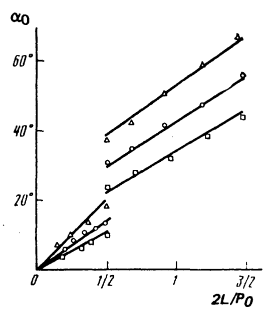

FIG. 6. Dependence of the angle between the direction of the domain lines and the initial direction of the director in an LC midlayer in the first Grandjean bands on the reduced thickness $2L/P_0$ of the LC layer at different values of the dielectric anisotropy: □) $\varepsilon_a=-0.1$, ○) $\varepsilon_a=0$, △) $\varepsilon_a=0.25$.

termined by the factor $y\approx K_{33}/K_{22}$.

In the first Grandjean band $1/2\leqslant 2L/P_0\leqslant 3/2$ of the CLC, which spans half the pitch of the cholesteric helix, the flexoelectric instability manifests itself in the same way as in a nematic twisted 90°. The total twist angle of the director for this band is $\psi = tL = 180°$. Thus the directions of the director on the bounding surfaces are equal and perpendicular to the direction of the director in the midlayer. In accordance with this director distribution, domains are produced at an angle to the initial orientation of the director in the midlayer. Their direction changes symmetrically when the polarity of the electric field is changed (Fig. 3). Compared with the instability in a twisted NLC, however, in the first band of a CLC the flexoelectric instability has higher thresholds and larger domain inclination angles. The qualitative character of the threshold curves in the first Grandjean band (Figs. 4, 5, 6) remains the same as in the zeroth band, but these dependences manifest themselves more strongly.

Figure 7 shows the numerically calculated dispersion dependence of the voltage at which the flexoelectric instability sets in on the domain orientation angle for the second Grandjean band, where the total twist angle of the director is 360°. The dispersion curve has two minima, i.e., at threshold voltage there should be produced two systems of linear domains positioned at different angles. In experiment, the instability is observed in the form of a domain grid (Fig. 3), which is a superposition of these two systems of linear domains. The theoretical and experimental dependences of the threshold voltage and of the wave vector on the reduced thickness of the LC layer are shown in Figs. 4 and 5. The qualitative character of these dependences is the same as in the zeroth and first bands.

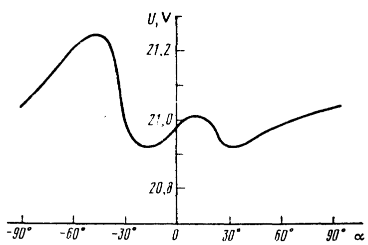

FIG. 7. Dispersion dependence of the voltage of the onset of flexoelectric instability U in the second Grandjean band on the angle α between the direction of the domain lines and the direction of the unperturbed director in the LC midlayer, obtained by numerical computer calculation at $\varepsilon_a=0$ and $e^*=-1.8\cdot 10^{-4}$ dyn$^{1/2}$.

The threshold voltage U_n and the wave vector k_n decrease, while the domain inclination angle α_n increases with increasing thickness of the CLC layer within the limits of each Grandjean band, owing to the decrease of the "stress" of the twisted structure from $\pi/2L$ to $-\pi/2L$. The values of all the threshold characteristics, other conditions being equal, increase with increasing director twist angle. On the boundary between the bands, where the twist angle experiences a jump of 180°, and the "stress" of the structure changes jumpwise from $-\pi/2L$ to $\pi/2L$, the values of all the threshold characteristics also increase jumpwise (see Figs. 4, 5, 6).

It was shown in Refs. 3 and 5 that the flexoelectric instability in NLC takes place when the condition $|\varepsilon_n| < 4\pi e^{*2}/K$ is satisfied. The threshold voltage U_n and the wave vector k_n of the instability increase with decreasing dielectric anisotropy ε_a and diverge when the critical value $\varepsilon_a = -4\pi e^{*2}/K$ is approached. As seen from Figs. 4 and 6, the larger the director twist angle, the sharper the increase of the threshold characteristics with decreasing dielectric anisotropy. Thus, the interval of the values of ε_a in which flexoelectric instability can exist decreases with increasing director twist angle.

5. CONCLUSIONS

The flexoelectric instability in twisted LC structures is a unique example of a polar electro-optical effect not connected with surface phenomena and observable in nonpolar media with high point-group symmetry. Flexoelectric domains in twisted structures differ from all other known domain systems in that the domain lines are directed at an arbitrary angle to the initial orientation of the director at the center of the LC layer. The magnitude of the angle depends on the anisotropy of the dielectric and elastic properties of the liquid crystal, and the sign of the angle is reversed with changing polarity of the field, i.e., a symmetrical rearrangement of the domain picture takes place. By investigating the threshold characteristics of the flexoelectric instability it is possible to determine the absolute value and the sign of the difference of the flexoelectric coefficients, as well as the elastic moduli of the LC. All the investigated peculiarities of the flexoelectric instability in twisted LC structures are qualitatively and quantitatively explained within the framework of the linear model of the flexoelectric effect.

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