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Flexoelectrically controlled twist of texture in a nematic liquid crystal

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Résumé. — Nous décrivons un nouvel effet flexoélectrique de volume en champ électrique homogène, dans la phase némotique du MBBA. Une texture de flexion-divergence est créée entre deux plaques de verre, traitées pour induire des orientations antagonistes homéotrope et planaire. Il en résulte une polarisation flexoélectrique en volume. Un champ électrique continu transverse induit une torsion de la texture, mesurée par une rotation de la polarisation de la lumière en mode guide d’onde. La constante flexoélectrique de volume $e_1 - e_3 = +1.0 \pm 0.2 \times 10^{-4}$ stat C/cm à 20 °C. La rotation de polarisation de la lumière, continûment contrôlable sur une amplitude $\sim \pm 45^\circ$, peut être utile pour des applications.

Abstract. — We describe a new flexoelectric volume effect in homogeneous electric field, in the nematic phase of MBBA. An initial splay-bend texture is created by strong antagonistic planar and homeotropic anchoring on two glass plates. This results in a volume flexoelectric polarization. A transverse DC electric field creates a twist of the texture, which can be measured by the resulting wave guided rotation of light polarization. We obtain the volume flexoelectric constant $e_1 - e_3 = +1.0 \pm 0.2 \times 10^{-4}$ stat C/cm at 20 °C.

The continuously controllable light polarization rotation on a total amplitude $\sim \pm 45^\circ$ may be useful for applications.

Most nematic liquid crystals are flexoelectrics [1], i.e. they build an electric polarization $P$ when submitted to a curvature strain. As shown by the Bordeaux Group [2], the flexoelectric effect is mostly quadrupolar i.e. $P \sim e \nabla_{\lambda} Q$, where $Q$ is the electric quadrupole density, proportional to the nematic order parameter. In the « isotropic » case $e$ is a scalar and the coupling of $P$ with an applied uniform electric field $E$ results only in surface effects, which imply the use of weak surface anchoring difficult to control [3]. People have induced flexoelectric texture distortions by use of inhomogeneous electric fields [4, 5].

In the so-called « hydrodynamic » limit, it was argued [2] that there exists no bulk flexoelectric effect. In fact this statement was misleading, at least for us. The « hydrodynamic » assumption was really the « homogeneous » assumption [5], i.e., the case of small angular distortions from an

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initially homogeneous sample. In non-homogeneous situations, this statement is not valid [6]. The reason is due to the fact that $e$ is a tensor, which rotates in space as the nematic order parameter itself. For arbitrary angular distortions, there must be a bulk flexoelectric effect. The volume induced flexoelectric polarization can be coupled to an applied uniform electric field [7, 8]. Such an effect has been indirectly observed from the threshold of a texture instability [9]. In this paper, we describe the first direct observation of a new volume flexoelectrooptic effect, from an external uniform $E$ field, acting on a permanent flexoelectric polarization created by a non uniform bend and splay texture. The result is an $E$ field controlled twist of texture, which may be useful for practical applications.

The sample geometry is shown on figure 1. A nematic liquid crystal is placed in between two glass plates $a$ and $b$, coated to induce respectively a parallel ($x$) and perpendicular ($z$) orientation.

![Sample geometry](image)

Fig. 1. — Sample geometry. The unperturbed director line is in the $xz$ plane. Under the action of $E$, this line (dashes) twists continuously along $y$. The twist $\phi(z)$ is visible on the $xy$ projection (dots). An optical beam, linearly polarized along $x$ on plate $a$, shows at the output of the sample (plate $b$) a linear polarization along the maximum twist $\phi(0)$.

A single domain will present a state of permanent splay and bend. The « non isotropic » permanent polarization created by this distortion can be visualized as

$$ P = e^* \mathbf{n} \text{div} \mathbf{n} \frac{e^* \mathbf{n}}{d}, $$

where $\mathbf{n}$ is the director, $d$ the sample thickness and $e^* = e_1 - e_3$ is the anisotropic flexo volume effect in classical notations [1, 10]. $P$ is parallel to $x$ and localized close to the plate $a$. Using two parallel electrodes one can apply an electric field $E$ along $y$, parallel to the plates, and perpendicular to $P$. The result is an electric torque proportional to the applied field. At equilibrium, the texture is continuously twisted compared to the rubbing direction on plate $a$. To calculate this twist we first assume that the volume polarization charges $- \text{div} P$ are just cancelled by ionic conductivity. We keep only a static problem of torque equilibrium. We call $\theta$ and $\phi$ the usual Euler angles which define the orientation of $\mathbf{n}$ compared to the normal to the plates $z$, and the rubbing direction on plate $a$ ($x$) (see Fig. 1). The elastic free energy density in absence of field is simply:

$$ f_{el} = \frac{K}{2} \left[ \left( \frac{d\theta}{dz} \right)^2 + \sin^2 \theta \left( \frac{d\phi}{dz} \right)^2 \right], $$

where $K$ is the assumed isotropic Frank curvature constant. The bend-splay texture is defined by $\phi = 0$ and $d^2\theta/dz^2 = 0$, or $\theta = \pi z/2d$. The coupling energy between the permanent flexo pola-
rization and the electric field is \(- \mathbf{P} \cdot \mathbf{E} = e^* E \sin^2 \theta \sin \phi \frac{d\theta}{dz}\). The equilibrium equations write:

\[ K \frac{d^2 \theta}{dz^2} - \sin \theta \cos \theta \left( \frac{d\phi}{dz} \right)^2 = -e^* E \sin^2 \theta \cos \phi \frac{d\phi}{dz} \]  

(1)

\[ \frac{d}{dz} \left( K \sin^2 \theta \frac{d\phi}{dz} \right) = e^* E \cos \phi \sin^2 \theta \frac{d\theta}{dz} \]  

(2)

the azimuthal equation (2) for low \(E\) field, will give a twist \(\phi\) linear in \(E\). The bend equation (1) describes the change in the initial bend-splay due to the field. One sees immediately that this correction is second order in applied field, and can be neglected for low twist. We then calculate the azimuthal equation (2) in \(\phi\) and using for \(\theta\) the unperturbed splay-bend \(\theta = \pi z/2d\). Equation (2) becomes

\[ \frac{d\phi}{d\theta} = \left( \frac{e^* E d}{\pi K} \right) \left[ \theta - \frac{1}{2} \sin 2\theta \right] \sin^{-2}\theta. \]  

(3)

We are interested by the largest value \(\phi(0)\) close to the lower plates \((z = 0)\). Equation (3) can be integrated exactly [11] as:

\[ \phi(0) = -e^* \frac{Ed}{\pi K}. \]  

(4)

In practice, to measure \(\phi(0)\), one can use the wave guide property of the twisted texture. We send for instance a light beam normal to the sample and polarized along \(x\) \((\phi = 0)\) on the upper plate. We observe the polarization of the transmitted beam outside the sample. The criterion for the wave guide regime [1] is \(\Delta n, p > \lambda\) where \(\Delta n\) is the apparent birefringence of the nematic sample, \(p\) is the pitch of the twisted texture and \(\lambda\) the wave length of the light beam. In our case, \(p = 2 \pi \frac{dz}{d\phi}\) and because of the tilt, close to the lower plate, \(\Delta n = \Delta n_0 \theta^2\) with \(\Delta n_0 \sim 0.2\). Using equation (3), one gets the condition:

\(\theta > \frac{\lambda e^* E}{3 K} \sim \frac{\lambda}{d} \phi(0).\)

The resulting error for \(\phi(0)\) is:

\[ \frac{\Delta \phi(0)}{\phi(0)} \sim \frac{\lambda^2}{d^2} \phi(0). \]

This error is negligible in the linear regime where \(\phi(0)\) is smaller than 1, and for thick samples. In practice a sample of thickness \(d\) larger than \(\lambda\) should behave as an optical wave guide for linear polarization, from the upper plate till the lower plate.

To observe the effect, we use a nematic sample of MBBA (Methoxy Benzylidene Butyl Aniline) at room temperature (20 °C). The plate \(a\) is coated with polyvynil alcohol, to induce a planar orientation. The plate \(b\) is silane coated, to induce an homeotropic orientation. The electrodes are two Al foils, 2.5 mm apart, oriented along the rubbing direction of plate \(a\). The thickness is \(d = 40 \mu m\). The sample is observed on the stage of a polarizing microscope. For convenience, the planar plate \(a\) is placed close to the condenser side, so that we have just to rotate the analyser to measure an eventual rotation of polarization.

In absence of \(E\) field, we observe that the sample behaves optically as a birefringent slab, with the neutral lines along (and perpendicular to) the rubbing direction. Sometimes, domains are observed, delimited by a disclination line. Applying an oblique magnetic field in the \(xz\) plane one can make these domains grow independently. One identifies these domains as the expected twins for the splay-bend geometry (see Fig. 2).
We now apply a DC electric field $E$. We obtain at the output of the sample a light linearly polarized along a direction rotated by an angle $\phi(0)$ compared to the rubbing (and polarizer) direction. Rotating the polarizer compared to the rubbing direction results in an elliptical polarization at the output. This proves that the director remains aligned along $x$ close to the plate $a$, i.e. that the planar anchoring is strong. We have measured $\phi(0, E)$ on one single domain. The results are plotted on figure 3. We do find a linear dependence as expected, with positive and negative values according to the sign of $E$. We now observe the corresponding rotation on the twin domain. For the same value of the field, the polarization rotation is exactly the opposite, as expected. From the slope of the $\phi(0, E)$ plot, we can derive

$$\frac{|e^*| d}{\pi K} = 0.31 \text{ cgs}, \text{ i.e. } \frac{|e^*|}{K} = 250 \text{ cgs}.$$ 

With $K \sim 5 \times 10^{-7}$ cgs, we find $|e^*| \sim 1.2 \times 10^{-4}$ cgs, which is the correct order of magnitude. Taking into account the anisotropy of the elastic constants [1] ($K_1 = K_3, K_3/K_2 = 2.5$), equation (3) can now be integrated numerically as

$$\phi(0) = 0.8 \frac{e^* E d}{\pi K_2}$$

Fig. 2. — The twin domains of splay-bend. Under the action of the magnetic field $H$, the (+) domain grows. This indicates the polarity $n(\text{div} \ n)$ of the domain (in the opposite direction of $n$).

Fig. 3. — $\phi(0)$ versus $E$, for the two twin domains (+) and (−). The linearity and the symmetry of the two plots prove the existence of a volume flexoelectric polarization $p = e^* n(\text{div} \ n)$. 
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(K_3 is the bend and K_2 the twist Frank curvature constant). The flexo constant is now

| e^* | = (1.0 \pm 0.2) \times 10^{-4} \text{ stat C/cm}.

From our magnetic field effect, we can check the direction along which the director lines drop from plate a to plate b, i.e. the direction of \( n(\text{div} \ n) \). We have verified that the director lines oriented along \( n(\text{div} \ n) \) rotate toward the direction of \( E \), as shown on figure 1, i.e. that \( e^* = e_1 - e_3 \) is positive.

An important parameter is the maximum value of \( \phi \) that can be achieved. This value is in the range of \( \pm 45^\circ \). For higher fields, we observe the onset of electrohydrodynamical instabilities, as usual in flexoelectric experiments when effects in \( E^2 \) dominate the effects linear in \( E \). Within our present accuracy, we have not observed any flow in the linear regime.

Other features of this effect are now being studied. We have checked for instance that the maximum twist \( \phi(0) \) increases with \( d \). The response time of the texture twist is nematic-like (slow, of the order of 100 ms in our sample), but can be decreased using stabilizing fields. The effect is also visible in other bend-splay geometries, above a Freedericks transition for instance from homeotropic to planar textures, with a symmetrical distortion resulting in a total twist 2 \( \phi(0) \). All these points will be described in forthcoming papers.

In conclusion, we have observed the volume flexoelectric effect from uniform electric field, using strong plate anchoring, in the nematic liquid crystal MBBA. We have created a permanent splay-bend distortion, which results in a permanent volume density electric polarization. A transverse homogeneous electric field induces a continuous twist of this texture. Using the wave guide property of this twisted texture for linearly polarized light, we have measured the twist. This allows us to give the first direct measurement of the bulk flexoelectric constant

\[ e_1 - e_3 = 1.0 \times 10^{-4} \text{ (dyn.)}^{1/2} \text{ in MBBA at 20 }^\circ\text{C}. \]

This value compares reasonably with the only data available of \( e^* = 1.7 \times 10^{-4} \text{ cgs units for BMAOB from the instability experiment of the Russian group [9]. With the accepted result that the quadrupolar volume effect in electric field gradient measures the quantity } e_1 + e_3, \text{ we have now two independent experiments to determine the constants } e_1 \text{ and } e_3, \text{ in strong anchoring, i.e. without the problems due to the uncontrolled weak anchoring.} 

References

[10] Because the isotropic part of \( P \) can be integrated out as a surface effects, the choice of the « effective » \( P \) is arbitrary. One could obviously have taken \( -e^*(\text{rot} \ n) \times n \) as well.
[11] This was pointed to us by the referee. We had previously found the same result using a numerical integration...