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SURFACE POLAR ELECTRO-OPTIC EFFECT INDUCED BY IN-PLANE TWIST IN NEMATIC LIQUID CRYSTALS

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Abstract A finite degree of in-plane twist is predicted to produce a surface polar electro-optic (EO) effect in nematic liquid crystals (NLCs). It is found that the flexoelectric coupling with an external electric field essentially renormalizes anchoring energies at the solid-NLC interfaces. Because of the anchoring renormalization by out-of-plane tilt and/or in-plane twist the symmetry of the system is broken, and the polar EO effect is thus induced. The EO modulation exhibits a peak near the Fredericks transition, which agrees well with numerical simulations.

INTRODUCTION

Anisotropic interfacial interactions of liquid crystals (LCs) are of great importance for a basic understanding of surface phenomena as well as for practical applications. For instance, subtle change in the interfacial interactions leads to variations in both molecular orientation and pretilt at surfaces.[1] Because of the inversion symmetry of a uniform nematic system, the coupling of LC molecules with an electric field should be necessarily quadratic in nature, which is known as the dielectric effect.[2] In a deformed state, however, the orientational distortions can induce a flexoelectric polarization which produces a polar electro-optic (EO) effect through a linear coupling with the field.

Recently, several flexoelectrically induced EO effects have been reported in a homeotropic[3] and a hybrid[4] aligned LCs. No polar EO modulation can be achieved in a homogeneous geometry except for a cell with asymmetrical interfaces.[5,6,7] One of the interesting questions might be then what would be expected for a homogeneously aligned cell with a finite degree of in-plane twist. In this paper, we predict that this in-plane twist can produce a polar EO effect through the anchoring renormalization at interfaces by means of the flexoelectricity[8] in twisted NLCs.

This prediction is experimentally confirmed by introducing a finite in-plane twist into a planar cell with symmetrical interfaces.

In a non-zero twisted NLC cell, the polar effect should exist as a result of the broken symmetry. The underlying physical mechanism is essentially the renormalization of the anchoring energies at the substrate-NLC interfaces. Numerical simulations are performed to obtain the director profiles and the resultant EO modulation, starting with a full description of the free energy of a twisted NLC.

RENORMALIZED ANCHORING ENERGY

In predicting the phenomenon described above, let us first construct the free energy of a twisted NLC cell with the thickness d under an electric field $\mathbf{E}$ in the z direction. Taking the molecular director as $\mathbf{n} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$ and denoting partial derivatives by subscripts, the free energy density F per unit area is written as

$$F = \int_0^d \left[\frac{1}{2}K_1\cos^2\theta\theta_z^2 + \frac{1}{2}K_2(\cos^2\theta\phi_z - q)^2 + \frac{1}{2}K_3(\sin^2\theta\theta_z^2 + \sin^2\theta\cos^2\theta\phi_z^2) - \frac{e^*D\sin\theta\cos\theta}{\varepsilon_\perp + \Delta\varepsilon\sin^2\theta} + \frac{1}{2}\frac{D^2}{\varepsilon_\perp + \Delta\varepsilon\sin^2\theta}\right]dz + f_{sur}, \quad (1)$$

where $q = 2\pi/p$ with p the natural pitch, K_i ($i = 1, 2$ and 3) the relevant elastic constants, e^* the effective flexoelectric coefficient, D the electric displacement, $\varepsilon_\perp$ the dielectric constant perpendicular to the director, and $\Delta\varepsilon$ the dielectric anisotropy. Here, f_{sur} represents the surface anchoring energy which consist of a polar and an azimuthal parts, $W_p\sin^2\theta$ and $W_a\sin^2\phi$, respectively.[9]

Minimizing the free energy, Eq. (1), the Euler-Lagrange equations for θ and ϕ are given by

$$\begin{aligned}(K_1\cos^2\theta &+ K_3\sin^2\theta)\theta_{zz} + (K_3 - K_1)\sin\theta\cos\theta\theta_z^2 + [2K_2\cos^2\theta \\ &+ K_3(\sin^2\theta - \cos^2\theta)]\sin\theta\cos\theta\phi_z^2 - 2K_2q\sin\theta\cos\theta\phi_z \\ &+ \Delta\epsilon D^2\sin\theta\cos\theta/(\varepsilon_\perp + \Delta\varepsilon\sin^2\theta)^2 = 0, \quad (2)\\ (K_2\cos^2\theta &+ K_3\sin^2\theta)\cos^2\theta\phi_{zz} + 2K_2q\sin\theta\cos\theta\theta_z \\ &+ 2[2(K_2 - K_3)\sin^2\theta - (2K_2 - K_3)]\sin\theta\cos\theta\theta_z\phi_z = 0. \quad (3)\end{aligned}$$

Two boundary conditions at the surfaces can be written as

$$\begin{aligned}(K_1\cos^2\theta_{1,2} &+ K_3\sin^2\theta_{1,2})\theta_{z1,2} \pm (W_{p1,2} \mp e^*E)\sin\theta_{1,2}\cos\theta_{1,2} = 0, \quad (4)\\ (K_2\cos^2\theta_{1,2} &+ K_3\sin^2\theta_{1,2})\cos^2\theta_{1,2}\phi_{z1,2} - K_2q\cos^2\theta_{1,2} \\ &\pm W_{a1,2}\sin\phi_{1,2}\cos\phi_{1,2} = 0, \quad (5)\end{aligned}$$

where the subscripts 1 and 2 denote the lower and upper surfaces, respectively. Note that no flexoelectric coupling terms appear in the bulk equations as well as the surface one for ϕ. We will discuss numerical simulations later on. Qualitatively, the flexoelectricity makes the polar anchoring energy larger at one surface and smaller at the other. This can be described in terms of the concept of the renormalization as $W_p^* = W_p \pm e^* E$ at the two surfaces. Moreover, the effective extrapolation length is given by $d^* = K/(W_p \pm e^* E)$ with K the relevant elastic constant. Therefore, the renormalization effect will be profound in a weakly anchored geometry.

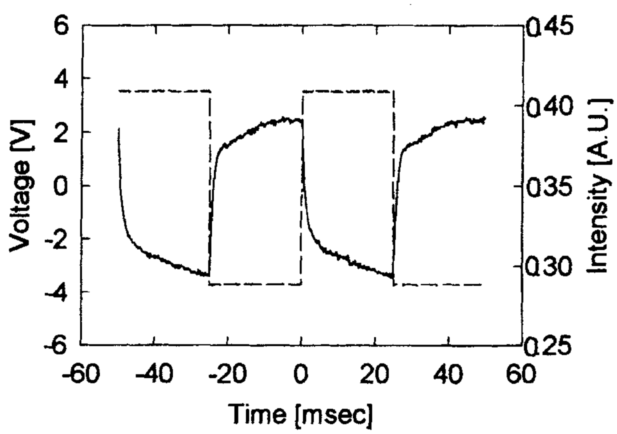

Figure 1: The ac transmitted intensity through a twisted NLC cell under a square wave voltage at 20Hz. The solid and dashed lines represent the ac transmitted intensity and the applied voltage.

RESULTS AND DISCUSSION

Based on the above idea, we made the EO measurements on a commercial NLC doped with a chiral additive which produces an appropriate twisting power. A twist angle of 180° were achieved in planar NLC cells from one surface to the other. The cell gap was maintained by glass spacers of $7\mu m$. The LC and the chiral additive used were ZLI-2293 and S-811 of E. Merck, respectively. The concentration of S-811 was varied to produce a proper ratio of the cell gap to the pitch, $d/p = 0.5$, so that the twist angle of 180° was naturally obtained.

The transmitted intensity was measured through the sample cell placed between a polarizer with an angle of 45° and an analyzer with 90° to the rubbing axis. In this configuration, the strongest polar EO effect was observed. A He-Ne laser of 632.8nm was used as a light source. A square wave voltage with an arbitrary amplitude was applied to the cell to avoid any systematic error involved. Total transmitted intensity was monitored with a photodiode in conjunction with a digitizing storage oscilloscope and a lock-in amplifier.

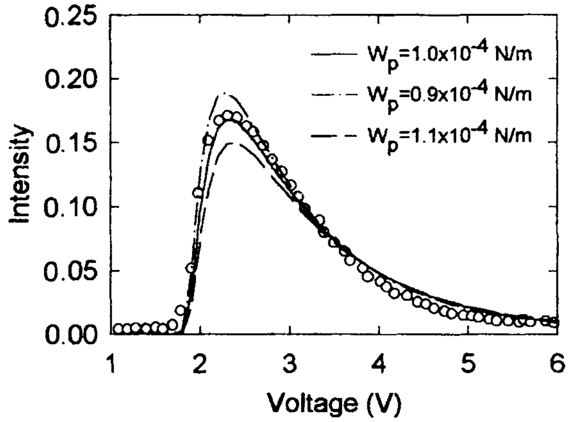

Figure 2: The ac modulation of the transmitted intensity as function of the applied voltage. The open circles are experimental data.

Fig. 1 shows a typical EO modulation trace measured at 20Hz. A polar EO effect is clearly seen in our twisted NLC cell. In Fig. 2, the ac component (ΔI) of the transmitted intensity, normalized with respect to the dc one (I), is shown as a function of the applied voltage V. The open circles represents experimental data and three lines denote theoretical fits for different polar anchoring energies. The magnitude of the polar EO modulation is simply the difference in the transmitted intensities between two polarities of the field. Since the dc component I results from the dielectric anisotropy, it is independent of the polarity of the field and becomes to saturate in the high field regime. However, the ac component ΔI originates from a linear coupling of the flexoelectric polarization with the field. This flexoelectric modulation has a peak around the Fredericks threshold and becomes less dominant than the dielectric one in the high field limit.

Numerical simulations for the observed polar effect were carried out using Eqs. (2), (3), (4), and (5). Once the director profiles of $\theta(z)$ and $\phi(z)$ are obtained, the transmitted intensity through the twisted NLC can be readily computed by employing an extended version of the 2×2 Jones matrix method. Some of the material parameters used for numerical simulations were taken from the literature provided by E. Merck. The effective flexoelectric coefficient is assumed to be $e^* = 5 \times 10^{-11}$C/m, and the anchoring energies are varied. In Fig. 2, the three lines represent numerical results for different polar anchoring energies. In the weak anchoring regime, the higher flexoelectric modulation was achieved as discussed before. The polar modulation was found to exhibit a peak near the Fredericks threshold.

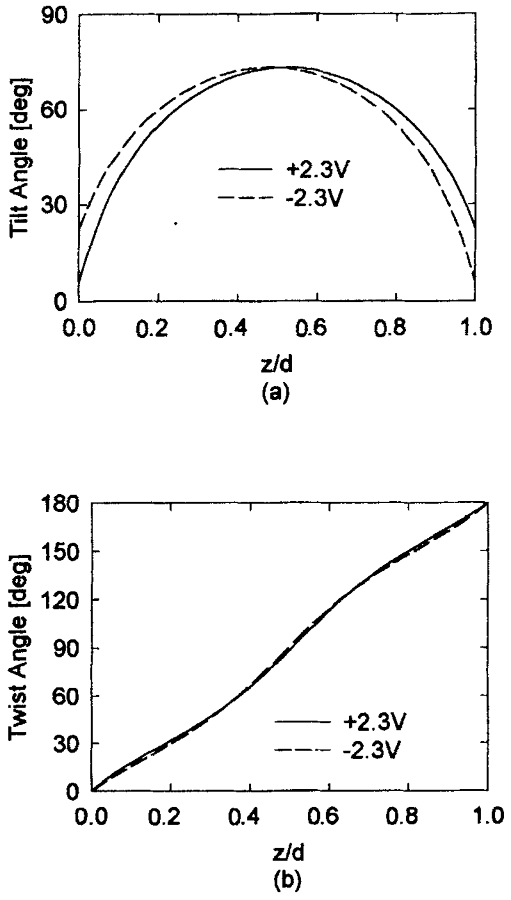

Figure 3: The director profiles of (a) tilt and (b) twist as a function of the spatial coordinate. The solid and dashed lines represent +2.3V and −2.3V, respectively.

The calculated tilt and twist profiles are shown in Fig. 3. Because of the renormalization of the polar anchoring energies, the tilt profiles depend on the polarity of the field. The polar anchoring at one surface is enhanced by the flexoelectric coupling and the LC molecules are strongly pinned at the boundary. The anchoring at the other, however, is reduced and the molecular orientation is easily deformed. Unlike the tilt profiles, the twist profiles are not directly associated with the flexoelectricity but is affected through the elastic deformations. This symmetry-breaking at the surfaces in a form of out-of-tilt and/or in-plane twist induces the polar EO modulation. It should be emphasized that for a zero-twisted NLC with symmetrical interfaces, the optical path difference exactly cancels out by the in-plane symmetry of the system although the out-of-tilt depends on the polarity of the electric field.

CONCLUDING REMARKS

We have demonstrated theoretically and experimentally that any finite in-plane twist produces a polar EO effect in NLCs which have symmetrical interfaces. It was found that the flexoelectric coupling with the electric field renormalizes anchoring energies at the solid-NLC interfaces. The observed polar effect, associated with this anchoring renormalization, exhibits a peak near the Fredericks threshold, which is in good agreement with our numerical simulations.

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