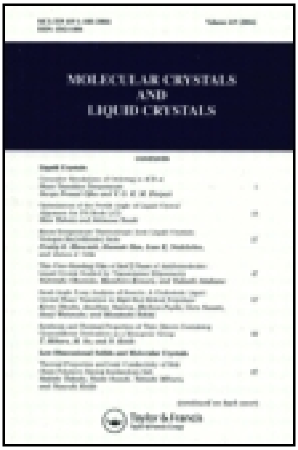

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Electrically Induced Flows in Ferroelectric Liquid Crystal Films

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We review six different physical mechanisms that lead to alternating electric field induced flows in ferroelectric liquid crystals. *Linear electromechanical effects* are mainly caused by director rotation induced flows and by electroclinic induced variation of the layer spacing. *Transient vibrations* occur at fast field reversal due to "inverse electroclinic" which attracts the plates before the collective director rotation is activated. During full rotation of the director around a cone *the pressure varies* yielding vertical vibrations with higher harmonic components. Periodic fields also induce *"pumping" effects.* A pumping can be caused either by a flow parallel to the plates, or by an increase of the sample thickness. The unidirectional flow reflects the chirality of the system, whereas the increase of the sample thickness cannot be connected to the chirality.

Keywords: Liquid crystal; ferroelectricity; flow; electromechanical effects

PACS numbers: 61.30.-v, 62.20.-x, 77.65.-j

INTRODUCTION

One of the characteristic properties of liquid crystals is that the rotation of the director is linearly coupled to viscous flow (backflow) [1, 2]. In case of ferroelectric liquid crystals the director linearly couples to the external electric field [3]. It results in faster switching [4] and a strong linear relation between electric field and flows. The first example of this kind of effect was demonstrated by Pieranski *et al.* [5] in 1975. They observed on a homeotropic (smectic layers are parallel to the substrates) helical sample that shear flow results in the appearance of electric polarization. As explained, in the undistorted helix the polarization is averaged out, but the shear flow distorts the helix and yields a net polarization normal to the helix axis and the direction of the shear. Similar effects were found later on films with planar geometries too [6].

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In this paper we concentrate on the inverse situations and summarize electric field induced mechanical effects.

A. Linear electromechanical effects

Electric field induced mechanical vibrations were first reported in 1985[7]. It was observed that applying AC fields on SmC* films of bookshelf geometry (smectic layers are perpendicular to the substrates) periodic flows at the frequency of the applied field appeared parallel to the plates and to the smectic layers. In the audio frequency range the vibrations result in audible acoustic effects and imply their possible use as electromechanical transducers[8]. For quantitative analysis of the effects open cells (plates were not glued together) were made and the vibration of the plates were detected mainly by tiny piezoceramics fixed on one of the plates (Fig. 1).

The resulting vibration is very sensitive to the overall alignment of the liquid crystal, so it has to be controlled very precisely in order to obtain useful informations. Our studies revealed the followings[9]. For bookshelf geometries the vibrations are essentially parallel to the smectic layers with amplitudes typically in the range of 10–100 nm. In the direction parallel to the substrates the frequency dependence is relatively smooth and the effect is largest when the polarization is parallel to the plates. Vibrations normal to the plates are induced when the polarization has a component perpendicular to the film surface. The frequency dependence of such vibrations consist of resonances in the kilohertz range. The resonances correspond to the bending modes of the glass plates. Based on studies on different alignments it was proposed that basically two independent mechanisms dominate the linear responses[9]. Those are related to the different director oscillation modes as shown in Figure 2. The smectic layers lay in the xy plane, the field is applied in the x direction. The average molecular direction makes an angle θ with the smectic layer normal, and its projection to the smectic layers (c-director) is characterised by the azimuthal angle ϕ measured from the y direction. The spontaneous polarization is parallel to the layers and perpendicular to the director. Under an AC field the director can oscillate around the cone by an amplitude of $\Delta\phi$ (Goldstone mode) and θ can vary by $\Delta\theta$ (electroclinic mode). In the former case the magnitude of the polarization is constant, only its direction changes. This mode is excited mostly if the polarization is perpendicular to the field and induces a flow parallel to the plates. The electroclinic mode is excited only when the polarization has a component parallel to the field and leads to a variation of the magnitude of the polarization. Due to the layer structure and

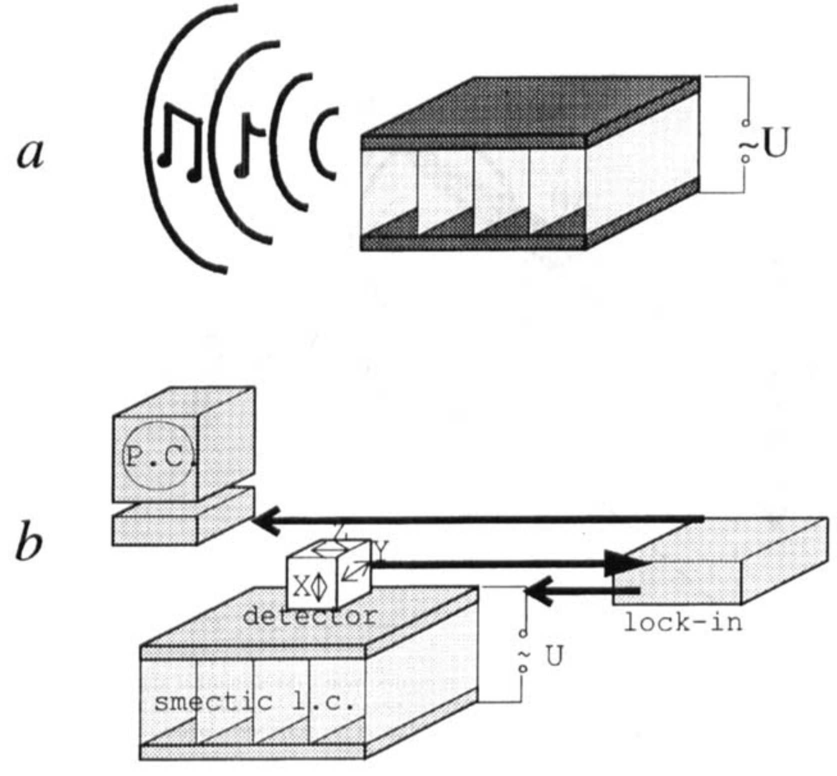

FIGURE 1 a) Ferroelectric liquid crystal films in bookshelf geometry work as speakers due to linear electromechanical effects. b.) Experimental set-up for studying electromechanical effects. The detector consist of 3 piezoelectric "accelerometers" (BK 4375 from Bruel and Kjaer) that are sensitive in different directions. Above 100 Hz the sensitivity of the vibration amplitudes is 0.1Å.

the incompressibility of the material the electroclinic effect also has mechanical consequence. A variation of the tilt angle results in a change of the layer distance which, in turn, tends to alter the sample thickness. When the tilt angle increases the layer distance shrinks and a vertical force appear which tries to lift up the cover plate.

B. Quadratic electromechanical effects

For larger fields the amplitude of the director oscillation increases and higher order (quadratic, etc.) effects appear too [10]. Besides them we also observed two other kind of quadratic effects [11, 12].

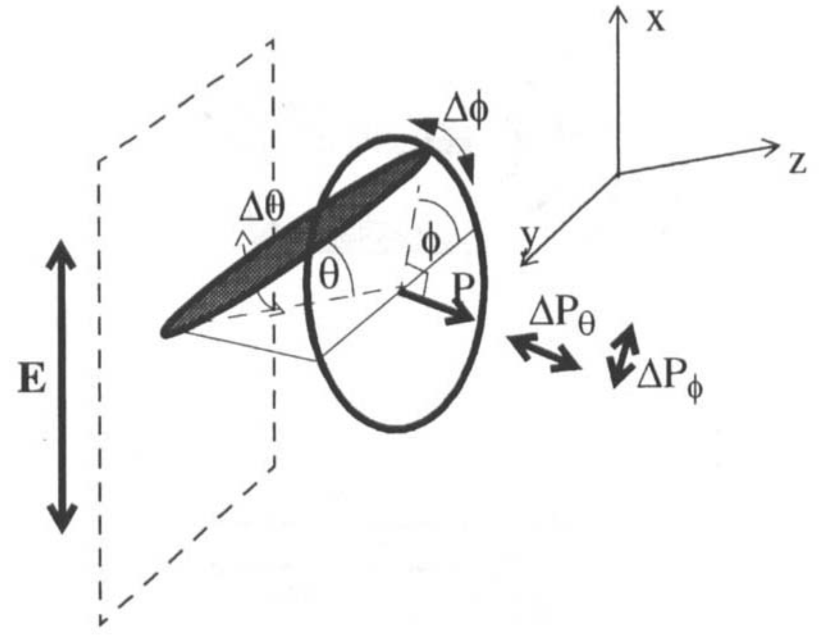

FIGURE 2 Field induced director rotation modes. When the azimuthal angle varies by $\Delta\Phi$ (Goldstone mode) the permanent polarization changes by $\Delta P_\phi \sim \sin(\Phi)$ so that its magnitude is unaltered. When the tilt angle varies the magnitude of the permanent polarization changes by $\Delta P_\theta \sim \cos(\Phi)$.

A transient vibration occurs under fast field reversal[11]. The phenomenon is sketched in Figure 3. Rectangular voltage waveform is applied and the polarization switches between "up" and "down" positions. The glass plates start to vibrate right after the polarity of the electric field is reversed. The acceleration reaches its maximum level (of about $10\,m/s^2$) after about $100\,\mu s$, then it decays in a few hundred microseconds. Independent of the direction of the field reversal the plates are attracted at first. We explain the effect as follows[11]. After the field direction is reversed quickly (in 120 ns) the polarization remains in the opposite direction. The rotation around the cone is a slow process (takes a few hundred microseconds) and has a considerable delay due to the initial absence of the torque. Since the polarization is proportional to the tilt angle, the magnitude of the polarization showing in the opposite direction can be decreased by decreasing the tilt angle. This "inverse electroclinic" process has no delay and takes only a few microseconds. Accordingly it will be excited before the rotation around the cone starts. The decrease of the tilt angle leads to an increase of the layer spacing and thus to the decrease of the sample

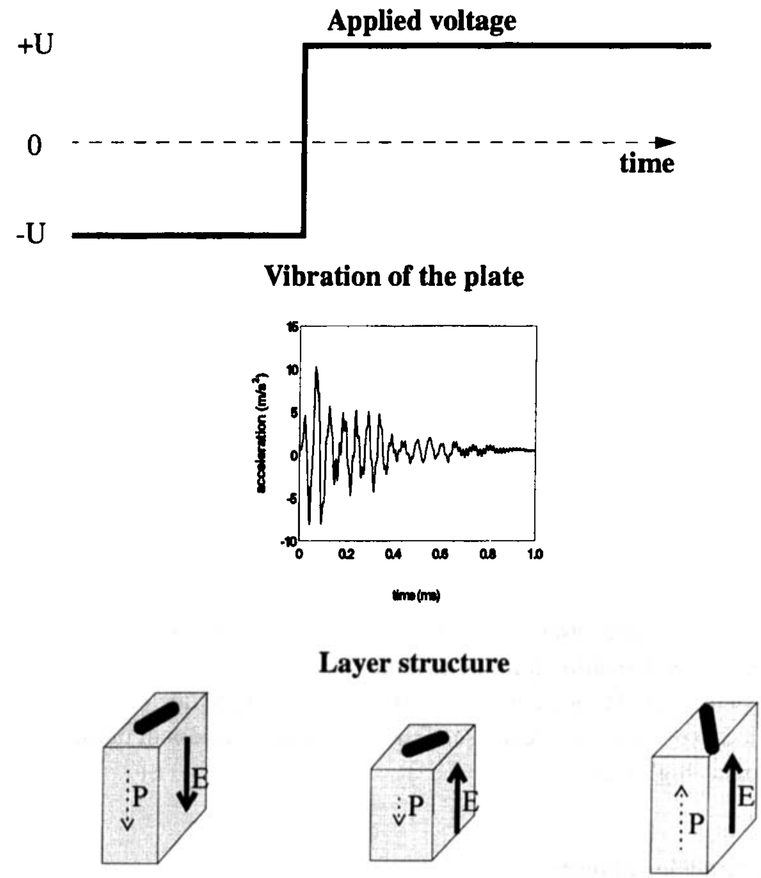

FIGURE 3 Schematic representation of the transient vibration of the cells under fast field reversal and of the smectic layer structures before field reversal, during the vibration and after switching.

thickness. It was calculated that the vertical force acting on the glass plate at the field reversal is $4cE\Omega/\theta$ (Ω is the sample area and $c = \delta P/\delta\theta$ is the electroclinic coefficient). To demonstrate the effect let us consider a A4 size display filled with a typical SmC* material ($P \sim 10^{-3}C/m^2$, $\theta = 25°$). At the field reversal of $1V/\mu m$ a force of about 500 N appears (as if a lady stepped on it!). Regarding that in displays short pulses are applied and are addressed as a TV (in sequence of rows from top to bottom and the pictures are updated in every 20 ms) the above effect can accumulate over 1% of the screen and shift downward. This may lead to a pumping of the material and has to be suppressed in displays.

An other kind of quadratic effect appears for any waveform at the threshold for full switch (Fig. 4). It can be attributed to the collective rotation of the molecules around a cone. During the switching process the director rotates from position **u** (upward polarization) to position **d** (downward polarization) through position **h** (polarization is horizontal). In position **h** the director is sticking out from the plane of the glass plates and the molecules occupy larger distance along the sample thickness. Accordingly, for free boundary conditions, the sample thickness would change approximately by $x = l \cdot \sin\theta$ (l is the molecular length, ~ 2nm, and θ is the cone angle, 27°). Experimentally we indeed observe that the maximum of the quadratic component is in the range of 1 nm. This value is reached near the unwinding, then it decreases rapidly with increasing fields. The pressure that causes the periodic vibrations can be calculated using the continuum theory of Leslie *et al.*[15]. Neglecting backflow (it is justified if the anchoring is negligible, so the switching is uniform) the time dependence of the pressure is

$$p(t) = PE\frac{\lambda_2}{2\lambda_5}\sin(\Phi)\sin(2\Phi) \tag{1}$$

Here λ_2 and λ_5 are viscosity coefficients and Φ is the angle between the spontaneous polarization and the external field. The pressure is not zero only during switching. At increasing fields the switching time decreases relative to the period explaining the decrease of the quadratic component of the periodic vibration at high fields.

C. Unidirectional flows

AC field induced mass flow (pumping) was first reported by Zou and Clark [13]. The pumping occurs at sufficiently high frequencies when the director only rotates about its equilibrium position. Depending on the direction of the stable state the liquid crystal flows in one direction parallel to the smectic layers and the substrate. As it was explained the unidirectional flow is due to the chirality and the backflow.

Very recently we observed an other kind of pumping induced by AC fields which switch the director uniformly and fully[12]. The effect is due to the increase of the thickness of a ferroelectric liquid crystal film. It occurs at sufficiently high frequencies. The sample thickness could be increased by as large as 0.3 μm in a few minutes. Due to the separation of the plates the area of the liquid crystal decreases, and at the edge of the cell air channels form and flow inside parallel to the smectic layers. Simultaneously the plates periodically vibrate at double frequency with a maximum amplitude of almost 1 nm. This vibration is the same as shown schematically in Figure 4 and expected by

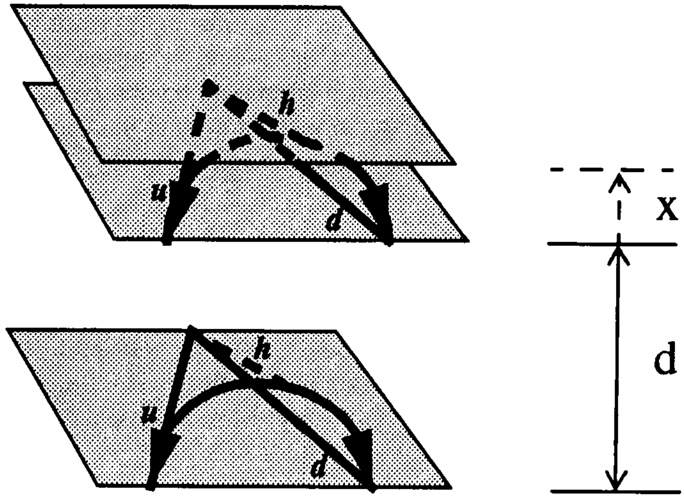

FIGURE 4 Simplified explanation of the sample thickness variation with frequency twice of the applied field due to uniform director rotation around a cone.

the continuum theory of Leslie *et al.*[15]. To obtain a pumping, however, an asymmetry in the switching mechanism is needed. For example if the surface is anisotropic, than the orientation corresponding either to the "up" or "down" state can be more favourable and the switching is asymmetric provided that the surface allows anchoring transitions. The reason for the anisotropy is not clear yet, but some of the characteristics of this pumping effect are understood qualitatively. At low frequencies the threshold for unwinding is small. Since the pressure is proportional to the applied field (see Eq. (1)), the time average of the pressure is also small. As there is a threshold for the lifting (due to surface tension and weight) there is a critical frequency where $\langle p \rangle$ reaches the threshold. The saturation of the lifting motion in time is due to the increased surface tension, by forming air channels and the reduced area where pumping occurs.

As a summary we outlined 6 different effects that lead to electric field induced mechanical vibrations or unidirectional flows. The piezoelectric type linear electromechanical effects may have practical applications as electromechanical transducers. Such transducers are the key elements of the so called "Intelligent Materials" which can anticipate failure, repair themselves and adapt to the environment[14]. Flows in SmC* films also have important impact on the electrooptical effects. The effect of the "backflow" on the reorientation dynamics was calculated by Zou *et al.*[16]. The electroclinic may lead to the destruction of the alignment[9, 11]. The pumping effects have to be considered in display applications. Vibration analysis can yield useful informations about the structure and the symmetry of the samples. For example small linear electromechanical effects can be observed in the SmA phase above the ferroelectric phase, or even in normal SmA materials, like 8CB, indicating reduced symmetry at the film surfaces[17].

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