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A. Jákli[a]; N. Éber[a]; L. Bata[a]
[a] Central Research Institute for Physics, Budapest, Hungary

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Electromechanical effect in surface stabilized and unwound S_C^* liquid crystals

by A. JÁKLI, N. ÉBER and L. BATA
Central Research Institute for Physics, H-1525 Budapest P.O.B. 49, Hungary

Applying an A.C. electric field to a planar oriented S_C^* liquid crystal sample, a shear flow occurs parallel to the bounding plates and perpendicular to the helical axis. We have investigated this so-called electromechanical effect by applying different D.C. bias electric fields superposed on a constant A.C. field. The amplitude of the mechanical vibration was measured versus the bias field in different samples. From the results, structural models of the surface stabilized and unwound samples were tested.

1. Introduction

In the last decade the investigation of ferroelectric liquid crystals has become the most rapidly growing branch of liquid crystal physics and chemistry. The main reason for this development results from their delicate electrooptical effects [1–5]. These offer the possibility of constructing fast switching bistable electrooptic devices.

However, ferroelectric liquid crystals may possess other delicate properties. For example, the electromechanical effects found by us in 1985 [6] may be interesting in fundamental as well as in practical respects. According to this effect, applying an A.C. electric field to a planar oriented S_C^* sample, a shear flow occurs parallel to the bounding plates and perpendicular to the helical axis [6]. When one of the bounding plates (A) is fixed while the other (B) can move parallel to A, this shear flow causes a vibration of plate B with the frequency of the applied field. This electromechanical effect has previously been investigated [7] in samples with thickness, d, larger than the helical pitch, p, and has been interpreted within the framework of an electrohydrodynamic continuum theory [8].

In this paper we report measurements on unwound samples of two types:

(i) $d < p$, i.e. when the helix is unwound by the surface (surface stabilized structure),
(ii) $d > p$, i.e. when, in the absence of electric field, a helix is present which is unwound by applying a large D.C. bias field.

2. Experimental set-up

The behaviour of planar S_C^* liquid crystals in an applied A.C. and superposed D.C. bias electric fields was investigated. The experimental set up is shown in figure 1. Sandwich cells were used with teflon spacers in two slightly different arrangements. The lower glass plate (A) was always fixed, whereas the upper one (B) was allowed to move either freely or against a spring (the membrane of a loudspeaker) in a direction parallel to the lower plate and perpendicular to the helical axis. The amplitude of the vibration was detected by a Brüel & Kjaer No. 4375 type accelerometer fixed to plate B. Its signal was amplified by a No. 2635 charge preamplifier and then analysed by a lock-in amplifier.

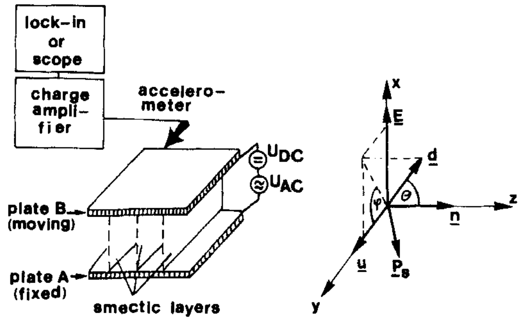

Figure 1. Experimental set-up. The orthogonal vectors **n**, **E**, and **u** indicate the direction of the helical axis, the electric field and the displacement of the upper plate, respectively. The unit vector director **d** makes an angle θ with the smectic layer normal being in the z direction; its projection onto the smectic layer (xy plane) makes an azimuthal angle φ with the y axis.

All the experiments were carried out at room temperature ($T = 23°C$) on planar oriented samples of three liquid crystal mixtures. The materials with their main parameters such as phase sequence, pitch p, spontaneous polarization P_s and the sample thickness, d, are

(1) FK4 [9]

$$S_I^* \xrightarrow{16°C} S_C^* \xrightarrow{29°C} S_A \xrightarrow{69°C} Ch \xrightarrow{67°C} I$$

$p = 5\,\mu m$ and $P_s = 1{\cdot}2 \times 10^{-5}\,C\,m^{-2}$ at room temperature; $d = 15\,\mu m$.

(2) CS-1011 [10]

$$S_C^* \xrightarrow{56°C} S_A \xrightarrow{78°C} Ch \xrightarrow{91°C} I$$

$p = 3{\cdot}2\,\mu m$ and $P = 1{\cdot}5 \times 10^{-4}\,C\,m^{-2}$ [11] at room temperature; $d = 45\,\mu m$.

(3) BW1 [12]

$$S_C^* \xrightarrow{39°C} S_A \xrightarrow{58°C} Ch \xrightarrow{65°C} I$$

$p > 50\,\mu m$ and $P_0 = 1{\cdot}7 \times 10^{-5}\,C\,m^{-2}$ [13] at room temperature; $d = 15\,\mu m$ and $d = 45\,\mu m$ (two samples)

For our investigations we prepared planar aligned samples. The samples containing FK4 and BW1 were aligned simply by shear [14] while to obtain homogeneous alignment in the whole CS–1011 sample we had to use in addition to shear a PVA coating on the surfaces with unidirection rubbing perpendicular to the shear direction.

The A.C. voltages applied were much smaller than the unwinding threshold values, thus for CS–1011 and FK4 the initial structures were helical. Since for BW1 $d < p$ initially no helix was present.

3. Experimental results

In the absence of a D.C. bias field the amplitudes of the vibration and their frequency dependence were different for the two experimental arrangements (with and without a spring). This behaviour will be discussed in detail in a forthcoming paper. Here we focus on the common features of samples subjected to a D.C. bias field.

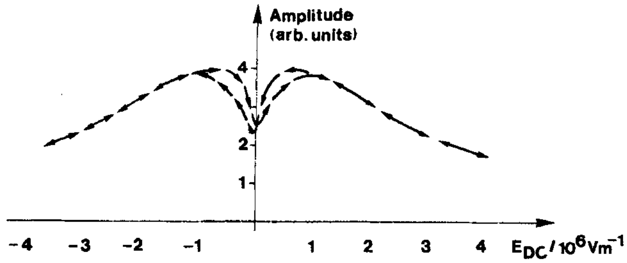

Figure 2. The vibrational amplitude of plate B measured in the y direction versus the applied D.C. bias electric field for the 15 μm thick planar oriented FK4 sample (f = 524 Hz, T = 23°C, E_{AC} = 1·33 × 10^5 V m^{-1}).

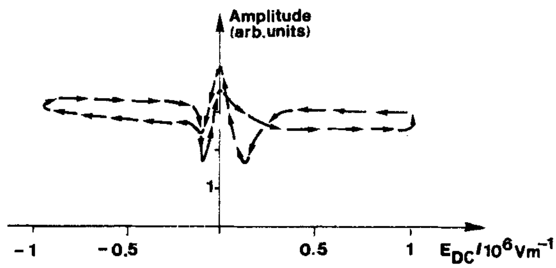

Figure 3. The vibrational amplitude of plate B measured in the y direction versus the applied D.C. bias electric field for the 45 μm thick planar oriented CS–1011 sample (f = 4·61 Khz, T = 23°C, E_{AC} = 1·57 × 10^5 V m^{-1}).

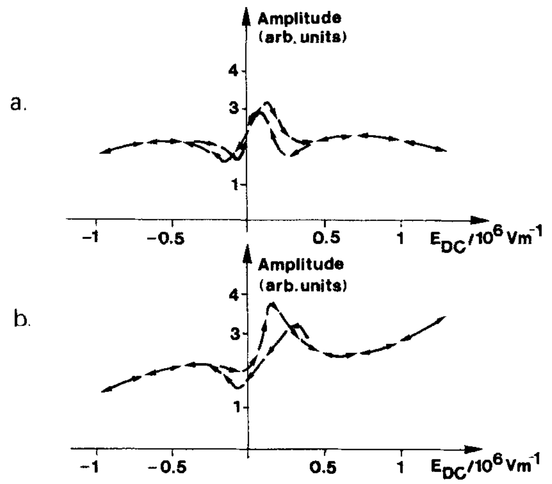

Figure 4. The vibrational amplitude of plate B measured in the y direction versus the applied D.C. bias electric field for two BW1 samples. (a) d = 15 μm (f = 3·0 kHz, T = 23°C, E_{AC} = 2·0 × 10^5 Vm^{-1}); (b) d = 45 μm (f = 2·3 kHz, T = 23°C, E_{AC} = 2·2 × 10^5 V m^{-1}).

Figures 2–4 show the dependence of the vibration amplitudes on the D.C. bias electric field at constant A.C. fields for the three compounds. The shape of the curves were found to be independent of frequency (100 Hz < f < 10 kHz), and also of whether plate B was connected to a spring or was free to move.

For FK4 (see figure 2) the electromechanical response did not depend on the sign of the D.C. bias field. This indicates that the boundary conditions for the director were symmetric on both plates. Furthermore a hysteresis was found in bias fields $E_{DC} < E_0 \sim 10^6\,\mathrm{V\,m^{-1}}$. Increasing E_{DC} above E_0 and then decreasing it back to zero the vibrational amplitudes were found to be different. Comparing E_0 to our former results on FK4 [15] we can see that $E_0 - E_{AC} \sim E_c$ (E_c is the static unwinding critical field). Our microscopic observations confirmed that for $E_{DC} < E_0$ disclination lines were present due to the helical structure. During the disappearance and reappearance of these lines, which took a considerable time, the structures are different and this may lead to a hysteresis in the observed curve. Increasing E_{DC} further no hysteresis was seen, indicating that in this stage the director field variation due to the electric field had a short relaxation time and was not accompanied by the creation and disappearance of any disclination walls or lines. Finally the most remarkable result of the measurement is that, when $E_{DC} > E_0$ and no electrooptical response was found, the electromechanical effect still existed.

Similar characteristics can be seen in figure 3 which shows the behaviour of a 45 μm thick CS-1011 sample. Here the curve is less symmetrical than for FK4, but the difference is not crucial. However, the hysteretic behaviour was much more pronounced and was also observed above the unwinding threshold. We have found that this hysteresis is the result of the inability of the equilibrium textures to develop between successive measurements (the texture relaxation times were of the order of an hour even for unwound samples).

The samples containing the substance BW1 show only a slightly different behaviour. In the initial state their structures were composed of domains with spontaneous polarizations pointing in different directions (UP and DOWN states). As we can see from figure 4(*a*) and 4(*b*) the curves are not symmetric about the $E_{DC} = 0$ vertical axis, indicating asymmetrical boundary conditions and domain structure. As for the former two compounds, samples of BW1 also showed hysteresis in the range when domains still existed ($E_{DC} < 4 \times 10^5\,\mathrm{V\,m^{-1}}$), and furthermore the electromechanical effect was present even in high D.C. bias fields when the electrooptical response vanished (thus when there was no measurable director rotation).

4. Discussion

In analyzing the strength of the electromechanical effect as a function of the applied D.C. bias electric fields the following statements can be made.

Statement 1. The electromechanical effect exists both in samples with helical structure ($d > p$), and in surface stabilized samples ($d < p$).

Statement 2. The amplitude of the mechanical vibration depends on the D.C. bias electric field, which also modifies the actual director configuration.

Statement 3. An apparent hysteresis can be observed. According to our simultaneous microscopic observations this is always connected with the slow appearance and disappearance of dechiralization lines and/or domain walls. (The creation of domains and dechiralization lines may take as long as several hours.)

Statement 4. If $E_{DC} \gg E_C \gg E_{AC}$, the sample is unwound by the field. Due to the bias there is no field reversing, however the electromechanical effect still exists.

In order to explain these observations we have to analyse our earlier theoretical considerations concerning the electromechanical effect [7, 8]. According to the notation and approximations used in [7], the induced flow of a planar ordered S_C^* liquid crystal film can be described by the equation

$$\varrho \frac{\partial v}{\partial t} = -\frac{\partial}{\partial x}\left[-\mu(x)\frac{\partial v}{\partial x} - \gamma(x)\frac{\partial E}{\partial t}\right], \tag{1}$$

where ϱ is the mass density, v is the flow velocity of the substance inside the sample, which varies only along the sample thickness ($v = v(x)$),

and

$$\left.\begin{aligned} \mu(x) &= \mu_{11} + \mu_5 \sin^2 \varphi(x) \cos^2 \varphi(x) \\ \gamma(x) &= [\gamma_5 - (\gamma_2 + 2\gamma_5)\cos^2 \varphi(x)] \sin \varphi(x) \end{aligned}\right\} \tag{2}$$

are the effective viscosity and the effective electro-mechanical coefficients, respectively. Here $\varphi(x)$ is the azimuthal angle of the C director (projection of the director $\mathbf{d}$ on the smectic layers) with respect to the y coordinate axis (see figure 1). According to equation (2) the effective coefficients $\mu(x)$ and $\gamma(x)$ depend on the actual director configuration in the sample. Statements 2 and 3 are thus evident consequences of these equations. From equation (1) we can deduce that a flow can exist in the sample if and only if the effective viscosity and electromechanical coefficients have a gradient along the sample thickness. (We emphasize, that static gradients are sufficient for the existence of the electromechanical effect, there is no need for any temporal change of the director configuration.) Thus in a homogeneous state ($\varphi(x)$, $\mu(x)$ and $\gamma(x)$ are all constant) there is no flow ($v = 0$) and hence no electromechanical effect is expected for samples completely unwound either by fields or by surface interactions. However, such a behaviour was not observed in our samples. Therefore, in accord with equations (1) and (2) we can conclude from Statements 1 and 4 that even in unwound and surface stabilized samples the director configuration is not homogeneous along the sample thickness. Though imperfect alignment of the samples may lead to such inhomogeneities, it is a typical observation that deterioration of the alignment (more inhomogeneities, more focal conics, etc.) results in a decrease of the vibrational amplitude. Our findings suggest therefore that the presumption about the bookshelf geometry [16, 17] of unwound and surface stabilized samples cannot be true. If the smectic layers are bent in the sample as has been proposed recently [18–21] (chevron structure), a director gradient is always present in the unwound samples and consequently the electromechanical effect can be observable. We would like to point out finally that owing to symmetry considerations no linear electromechanical effect is expected in the non-chiral S_C phase. However this prediction has not yet been checked experimentally.

5. Summary

Experimental investigations of the electromechanical effect have shown that the vibrational amplitude depends strongly on the actual director configuration and hence is influenced by D.C. bias fields. The non-vanishing vibration of unwound samples seems to be a novel proof of the chevron structure of the S_C^* phase. A more detailed interpretation of the experimental curves would need an essential improvement of our model in order to take into account the bent layer structure.

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