Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

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Version of record first published: 23 Sep 2006.

To cite this article: Antal Jákli & Alfred Saupe (1995): Mechanical Vibrations of Smectic Cells Under Fast Field Reversal, Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 263:1, 103-111

To link to this article: http://dx.doi.org/10.1080/10587259508033574

Mol. Cryst. Liq. Cryst. 1995, Vol. 263, pp. 103–111
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MECHANICAL VIBRATIONS OF SMECTIC CELLS UNDER FAST FIELD REVERSAL

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Abstract: It is known that ferroelectric liquid crystal cells vibrate mechanically under the effect of ac fields. The vibrations are mainly due to the backflow and electroclinic effects. For small director oscillations the effect is mainly linear and goes with the frequency of the field. For larger oscillations higher harmonics appear too. We studied the practically interesting case when, due to rectangular excitation, the director switches fully between two stable positions. In the experiments bookshelf textures of (R)-MHPOBC and FLC6430 (from Hoffmann La Roche) were used. The accelerations of the cover plates due to the reversal of the field were detected in three orthogonal directions. The switches cause strong vibrations of the plates (lasting less than a millisecond,. acceleration ~10m/s^2). The vibration is largest at the SmC_α*-Sm A phase transition indicating that the dominating effect is electroclinic in origin.

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 coupling between electric field and flows (linear electromechanical effects[5,6]). Ferroelectric liquid crystals have a layer structure with the director tilting away from the layer normal (e.g. SmC*). The layer distance is determined by the director tilt angle. The director tilt angle also influences the value of the polarization and therefore couples linearly to the electric field (electroclinic effect[7]). This can also yield electromechanical effects[7]. Experiments show that, in first approximation, the coupling between ro-

tation and flow induces a flow parallel to the smectic layers and the film surfaces. The electroclinic effect results in vibrations of the glass plates normal to the film[8], while the backflow causes a horizontal motion. For weak fields (when the director oscillates only by a small value around the equilibrium position) both lead to linear effects, with the backflow dominating[8].

In this paper we studied the mechanical vibrations of smectic samples while the polarization was switched by 180°. Strong vibrations of the plates lasting a few tenths of millisecond with accelerations in the order of $10m/s^2$ were detected. The measurements indicate that here the electroclinic effect plays the dominating role.

EXPERIMENTAL DETAILS

The experimental setup is schematically shown in Fig.1. We measured smectic liquid crystal films with uniform bookshelf textures sandwiched between glass plates with ITO coatings on their inner surfaces. The plates were placed horizontally and only the lower one was fixed. The motion of the upper plate was monitored using accelerometers (BK4375 from Bruel&Kjaer) in vertical direction (x) and two horizontal directions, parallel and perpendicular to the smectic layers (y and z axis). Rectangular voltage waveforms, of periods much larger and of rise times much shorter than the switching time of the liquid crystal, were applied using a waveform generator (Keathley 3910, rise time=120ns). The time dependent signals of the accelerometers were measured by a digital scope (HP 54601A) and then were processed by a computer. The sample temperatures were controlled with an accuracy of 0.1°C.

The uniform bookshelf alignment was achieved by transforming a homeotropic texture (coating: octadecyl triethyloxysilane) to a bookshelf in the SmC^* phase by electric field and shear. Details of the alignment method is described in Ref.9.

Two materials, (R)-MHPOBC and FLC6430 (from Hoffmann La Roche) were used. (R)-MHPOBC /4-(1-methylheptiloxycarbonyl) phenyl 4'-octyloxybiphenyl-4-carboxylate/ has various antiferroelectric and ferrielectric phases below the smectic A phase. It has been extensively studied in the last few years[10]. According to our observations[11] the phase sequence of our 8μm samples in cooling is the following:

$$\text{Sm A} \text{ ---- } \text{Sm}C_{\alpha}^{*} \text{ ---- } \text{Sm}C_{\beta}^{*} \text{ ---- } \text{Sm}C_{\gamma}^{*} \text{ ---- } \text{Sm}C_{A}^{*}$$
$$115.8^{\circ}C \quad 114.7^{\circ}C \quad 112.7^{\circ}C \quad 111.6^{\circ}C$$

SmC_{α}^{*}, SmC_{β}^{*} and SmC_{γ} are different ferrielectric phases, SmC_{A}^{*} denotes an antiferroelectric phase[10]. The measurements were carried out in the temperature range between 100°C and 125°C.

With FLC 6430 we made 5μm thick films of areas: $2x2cm^2$ and $3x3cm^2$ and studied them at room temperature in the SmC* phase. FLC 6430 has a polarization of $90nC/cm^2$ and helical pitch of 0.43μm.

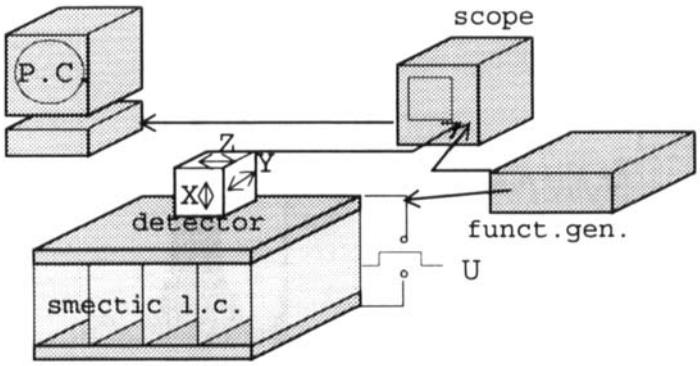

FIGURE 1 Experimental set up.

EXPERIMENTAL RESULTS

We observed that the glass plates start to vibrate right after the polarity of the electric field is reversed. The acceleration reached its maximum level after about 100μs, then it decayed in a few hundred microseconds. A typical time dependence and the corresponding Fourier spectrum of the acceleration for (R)-MHPOBC is shown in Fig.2. The spectral

density shows resonance like peaks in the 1, 20, 40 and 70 kHz ranges. The peaks at 72kHz correspond to the resonance frequency of the accelerometers. The resonances at around 20 and 40kHz were not present on FLC 6430 samples which were not placed in the oven. An analysis of the vibration modes indicates that these resonances are due to the sample holder (oven). The low frequency resonances changed with to the size of the glass plates, which suggests that they are connected to the bending mode of the glass plates. We have no evidence that any resonance correspond to modes of the liquid crystal.

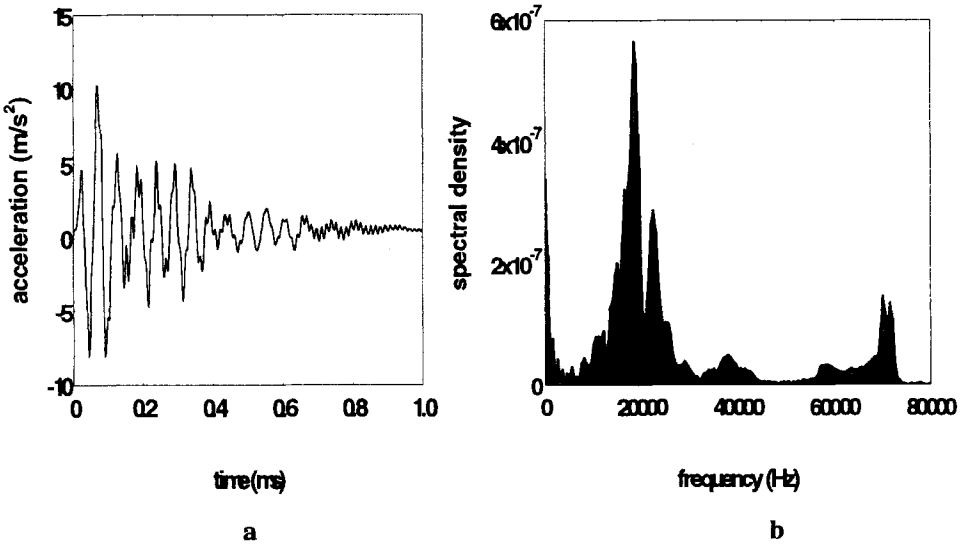

FIGURE 2. Vertical vibration of the cover glass after reversing at t=0 the sign of the voltage (10 V) applied on the sample. Sample: (R)-MHPOBC, T=116.7°C
a.) Time dependence of the acceleration. b.) The corresponding Fourier spectrum.

For both materials the dominating acceleration as measured at moderate fields is vertical (normal to the film). At high fields, however, the horizontal accelerations become comparable. For a 2x2cm^2 FLC 6430 sample the time dependencies and the frequency spectra of the vibrations in different directions are seen in Fig. 3.

The signals do not depend on the direction of the field reversal: first the film thickness always decreases. For FLC 6430 we measured the vibrations at different places on the glass and observed that the amplitude of the vibration varies along the glass plate.

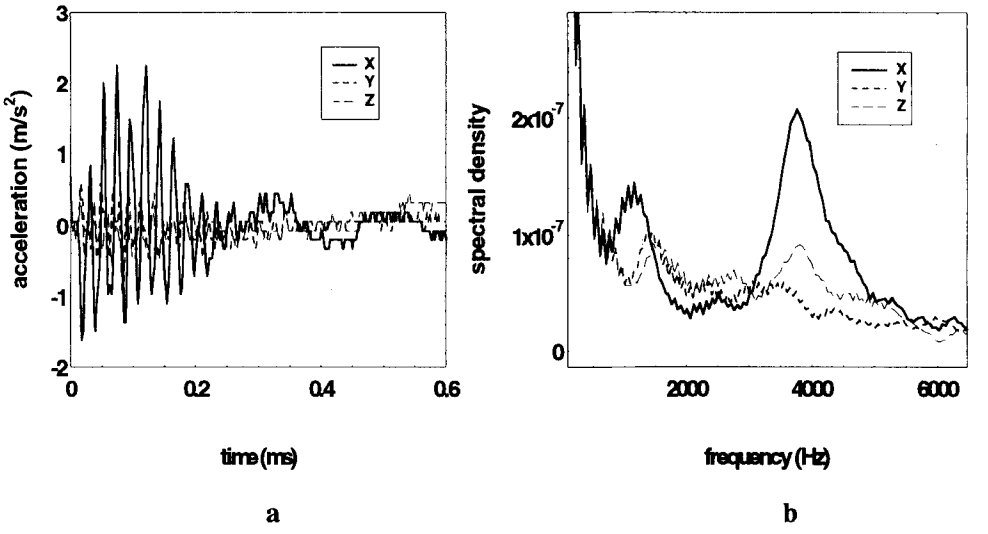

Figure 3. Acceleration of the vibration of the top plate in three orthogonal directions after sign reversal at t=0 of the voltage (10V) applied on the SmC^* film. Sample: FLC 6430, thickness: d=5μm, area=2x2cm^2, T=23°C. a.) time dependencies; b.) corresponding Fourier spectra.

The temperature dependence of the vibration showed a maximum at the SmC_α^*-SmA phase transition for all directions. The temperature dependence of the maximum acceleration of the vertical vibration for a constant voltage is shown in Fig.4. The signal drops to zero in the antiferroelectric SmC_A^* state, but the phase transition temperature depends on the voltage. The vibration starts where the field induced antiferroelectric ferroelectric transition occurs. We observed mechanical vibrations only when the sample optically switched.

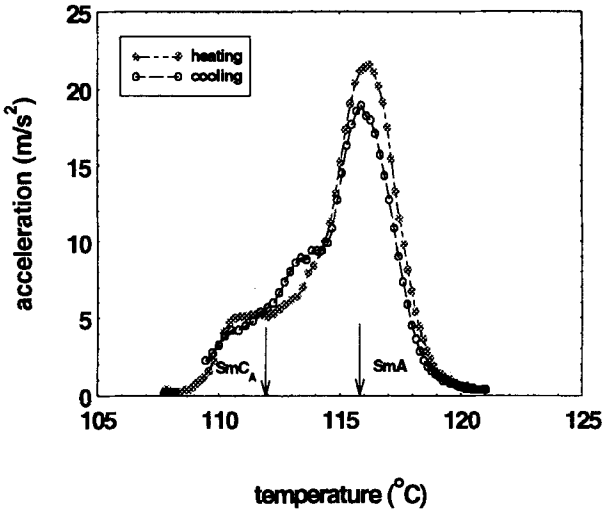

FIGURE 4. Temperature dependence of the maximum acceleration of the vertical vibration of the (R)-MHPOBC sample. The applied voltage is ±10V. Arrows indicate phase transition temperatures at zero field

DISCUSSION

The temperature dependence of the vibration amplitude suggests that the vibration is mainly caused by the electroclinic effect. Based on this, our model for the proper SmC* range is the following. At the applied voltage the polarization is uniformly along the direction of the field. When the field direction is reversed quickly (in 120ns) the polarization has two mechanisms to respond. (i) The director can rotate on a cone with constant tilt angle, thus the polarization can turn around by 180°. The rotation of the director is relatively slow (in the studied voltage range t_r ~ 0.2-0.5ms). (ii) The director tilt angle, θ, can also decrease (electroclinic response). This effect is much faster (t_e ~ 10 μs). Accordingly, we suppose that, after field reversal, the director tilt angle and the magnitude of the polarization decreases first. The rotation of polarization occurs only later. The variation of the

director tilt angle leads to a variation of the smectic layer spacing. The material can be considered to be incompressible, i.e. the density does not want to change. This results in a change of the extensions along the smectic layers. Therefore, the decrease of the director tilt angle causes the smectic layer spacing to increase and the sample thickness to decrease. Later the polarization rotates, thus the director tilt angle and the sample thickness can eventually relax to their original values. This mechanism is schematically represented in Fig.5.

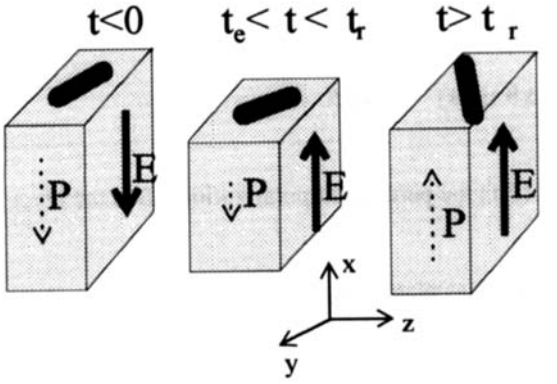

FIGURE 5. Schematic representation of the variation of the dimensions of a volume element containing one smectic layer. a.) relaxed state before switching; b.) transient state shortly after switching; c.) relaxed state after switching

As the SmC^*-SmA transition is approached, ϑ can change to $-\vartheta$ directly going through zero without director rotation on a cone. During this direct change thickness will first increase and then decrease again. Consequently, the film thickness will first decrease and subsequently increase again. This will be particularly strong at the transition, but then decay rapidly in the smectic A range since the induced $\Delta\vartheta$ decreases with $\frac{1}{T-T_c}$.

To estimate the force on the cover plate in the smectic C^* range we make the following assumptions.

1.) The coupling between the director tilt, ϑ ,and the smectic layer spacing, l, is given by

$$l = l_o \cos\vartheta \tag{1}$$

2.) The layers extend isotropically and the number of layers does not change.

For the decrease of the sample thickness, Δd, we get

$$\Delta d = \frac{1}{2} d \Delta\vartheta \sin\vartheta \tag{2}$$

The variation of the tilt angle, $\Delta\vartheta$, due to an electric field, E, can be obtained from the free energy. In the SmC* range we can write the free energy in the form[7]:

$$F = F_o + \frac{1}{2} B (\Delta\vartheta \sin\vartheta)^2 - c\Delta\vartheta E \tag{3}$$

here $c = \left(\frac{\partial P}{\partial \vartheta}\right)\Big|_{E=0}$ (P is the permanent polarization); B is the layer compression modulus.

The vertical force on the glass plate using Eqs. (2) and (3) is:

$$-\Omega d \frac{\partial F}{\partial (\Delta d)} = e - b\Delta d \tag{4}$$

here, Ω is the film area (~2cm^2), e is the force due to the field , and $b = \frac{4B\Omega}{d}$ is the restoring force due to layer compression. For small tilt angles

$$e = \frac{2cE\Omega}{\vartheta} \tag{5}$$

In equilibrium ($t \leq 0$) $\Delta d = -\frac{e}{b}$. The vertical force acting on the glass plate at the field reversal ($t = 0$) is $2e$. Note that the force varies as $\frac{1}{\vartheta}$ when the SmC*-SmA transition is approached. This explains the peak of the observed acceleration at the transition.

To estimate the magnitude of the acceleration experienced by the glass and the detectors (total mass ~30g) we use P~10^{-3}C/m^2, E=10^6V/m and ϑ ~20° . For the value we get: ~100m/s^2. This is larger by an order of magnitude than the measured one because of the low frequency eigenmodes of the system, but the estimation supports the idea that the

electroclinic effect causes the observed strong vibrations.

To demonstrate the importance of the mechanical effect we consider a display of A4 size with 1000x1000 pixels. When it is addressed as a TV (in sequence of rows from top to bottom and the pictures are updated every 20ms) the electroclinic effect may accumulate over 10 rows. It can result considerable vertical force (~8N) which at a time acts on 1% of the screen and shifts downward. This might result in a pumping of the substance out of the plates and should be considered designing a display.

We are grateful to Prof. H. Takezoe and Dr. M Schadt for providing the materials (R)-MHPOBC and FLC 6430, respectively.

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