THE FORMATION AND PROPAGATION OF FRONTS AT THE ELECTRIC FIELD INDUCED BEND FREEDERICKSZ TRANSITION

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ABSTRACT

The electric field induced bend Freedericksz transition in 5CB is first order. At the threshold value of the applied voltage, the deformed and undeformed states can coexist in equilibrium. The width of the front separating the two states gives a measure of the abruptness of the transition. If the applied voltage differs from its threshold value, the stable state invades the metastable one, and the front separating the two states moves. We present data for the velocity of front propagation in 5CB, and compare results with the predictions of theory.

INTRODUCTION

A nematic liquid crystal sample aligned between parallel glass plates can undergo a transition from a uniform state to an elastically deformed one under the influence of external fields. If the transition is first order, then, at the transition, the undeformed and deformed states can coexist in equilibrium. These two states are separated by an interface, or a front. At the transition, this interface does not move, but if the electric field is increased above the threshold value, the interface starts to move: the region where the director field is deformed expands into the undeformed domain. Upon decreasing the field below the threshold, the interface moves in the other direction. The problem of front propagation into unstable and metastable states has received considerable theoretical[1] and experimental[2] attention recently.

We have recently studied the electric field induced bend Freedericksz transition[3] and shown that this transition in the nematic liquid crystal 5CB (4-cyano-4'-n-pentylbiphenyl) is first order. Furthermore, we found that the phase behaviour of this system is well described by an approximate Landau free energy

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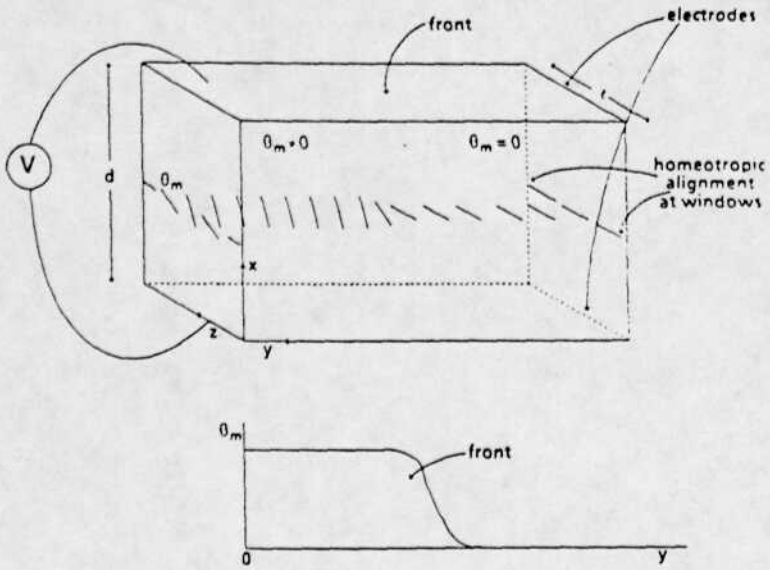

Figure 1. Schematic of the cell and director configuration.

expansion. This system therefore appeared well suited to the study of front propagation, since the material properties of 5CB are well known.

The cells used are sketched in Fig. 1 and consist of a rectangular slab of 5CB between parallel glass windows with initial uniform alignment of the nematic director perpendicular to the windows. A voltage applied to a pair of planar electrodes perpendicular to the windows gives rise to an elastic deformation of the liquid crystal such that the director away from the windows makes a nonzero angle with the window normal. Since this transition is first order, distorted and undistorted domains can coexist in equilibrium. The transition may be made more strongly first order by applying a magnetic field perpendicular to the windows. Because of the large refractive index anisotropy of the material, the two states are readily distinquishable, and the interface is easily seen by illuminating with polarized light. The free energy density difference between the distorted and undistorted states is determined by the voltage applied to the electrodes. Changing this voltage causes one state to invade the other, giving rise to front propagation.

THEORY

In the electric field induced bend Freedericksz transition, the orientation dependent part of the energy density associated with the electric field is[4]

$$\mathcal{E}_{EL} = -\frac{1}{2}\frac{\epsilon_\perp (\frac{V}{d})^2}{(1-u\, n_x^2)}\,, \quad \text{where} \quad u = 1-\frac{\epsilon_\perp}{\epsilon_{||}}\,,$$

$\epsilon_\perp$ and $\epsilon_{||}$ are the principal values of the dielectric tensor, V is the voltage applied to the electrodes, d is the separation between two electrodes, and n_x is the component of the director $\hat{n}$ in the x direction (see Fig. 1). Because of the form of $\mathcal{E}_{EL}$, this transition can be first order[3,4]. Assuming that the director field has the form $\hat{n}=(\sin\theta,\ 0,\ \cos\theta)$, where $\theta=\theta_m(y)\sin(\pi z/l)$ is the angle between director and the z axis, and expanding the free energy density in powers of θ_m, we get[5] up to terms of order $\theta_m{}^6$

$$\mathcal{F} = \frac{a}{2}\theta_m{}^2 + \frac{b}{4}\theta_m{}^4 + \frac{c}{6}\theta_m{}^6 + \frac{d}{2}\left(\frac{\partial\theta_m}{\partial y}\right)^2\,, \qquad (1)$$

where the Frank free energy is measured in units of $\pi^2 A K_3/(4 l)$, A is the area of the sample, l is the thickness between the glass plates, K_1, K_2, and K_3 are the splay, twist, and bend elastic constants. The constants a,b,c, and d depend on material parameters and the applied fields.

We note that as the transition turns out to be relatively strongly first order, there is no priori reason to expect the power series expansion in Eq.(1) to be accurate. Fortunately, both numerical studies of $\mathcal{F}$ and the experiments[3] show that (1) is surprisingly accurate, and this allows us to compare our dynamical measurements directly with theoretical results derived from (1). For 5CB we have $b<0$, and a first order transition takes place at $16ac=3b^2$. At this value, θ_m jumps from the $\theta_m=0$ to the $\theta_m=\sqrt{-\frac{3b}{4c}}$ state.

From Eq.(1), the torque balance condition gives

$$\gamma_{eff}\frac{\partial\theta_m}{\partial t} = d\frac{\partial^2\theta_m}{\partial y^2} - a\,\theta_m - b\,\theta_m^3 - c\,\theta_m^5. \qquad (2)$$

the time dependent Ginzburg-Landau equation. Here $\gamma_{eff}=\gamma/2$ with γ the twist viscosity. In the two phase region $a>0$, $b<0$, the uniformly propagating solution describing the motion of an interface with boundary conditions $\theta_m(y=-\infty)=\theta_0$ and $\theta_m(y=+\infty)=0$ is[1]

$$\theta_m = \left[\sqrt{\frac{c}{a}}\, e^{2(y-vt)\,\theta_o^2\sqrt{\frac{c}{3d}}} + \frac{1}{\theta_o^2}\right]^{-\frac{1}{2}}, \qquad (3)$$

and it propagates with velocity v given by

$$v = \frac{b}{\gamma_{eff}}\sqrt{\frac{d}{3c}}\left[-1 + 2\sqrt{1-\frac{4ac}{b^2}}\right]. \qquad (4)$$

The width w of the front, from Eq.(3), is given by $w=(1/2\theta_o^2)(3d/c)^{1/2}$. At the transition, $16ac=3b^2$ and $v=0$, we get $w=-(2/b)(dc/3)^{1/2}$. Indeed, the width of the front is finite and inversely proportional to $|b|$, which measures the strength of the first order transition. If the voltage differs from its threshold value, the stable phase displaces the metastable one and the front moves with a velocity given by Eq.(4). This behaviour is analogous to that described by Cladis et al.[2] in their 'dynamical test of phase transition order'.

EXPERIMENT

We studied front propagation in a homeotropically aligned 5CB cell. In this alignment, the nematic director at the windows is perpendicular to the glass. The aligment was achieved by surface treatment of the glass by a silane compound prior to assembing the cell. The cell dimensions were 30mm x 4mm x 0.5mm. The cell was slightly wedge shaped in the y direction, with a wedge angle of 0.05 radians to allow localization of the front. The electrodes were stainless steel plates, 1cm in width to minimize fringe effects. Because the physical properties of liquid crystals sensitively depend on temperature, the cell was placed in a temperature controlled housing and the sample temperature was thermostatted at 24.847 ± 0.001 °C in this experiment. A 0.17 T magnetic field in the z direction was applied used to make the transition more strongly first order. [The magnetic field was taken into account in evaluating the constants a, b and c in Eq.(1)]. In our experiment, the electrode separation (and hence a, b and c) varied linearly with y, and on varying the applied voltage, the front moved to its equilibrium position with an exponentially decaying velocity.

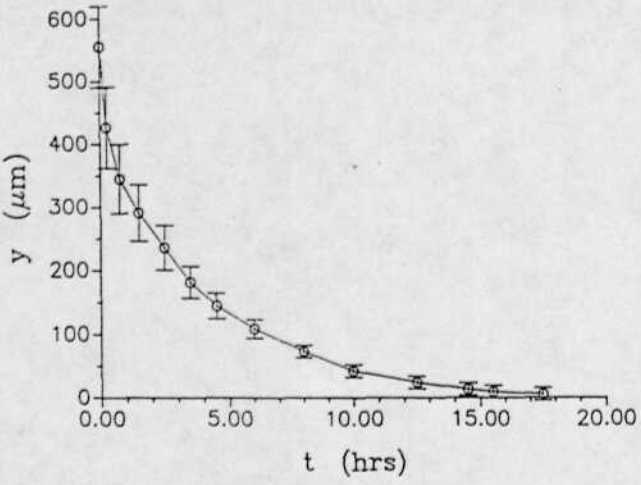

Figure 2. Front position y versus time t.

The cell was observed through holes in the magnet pole pieces via a specially constructed microscope. The resulting images were recorded on vidotape and photographed. The direction of motion of the front was observed to change depending on whether the applied voltage was increased or decreased.

From Eq.(4), we obtain that in our slightly wedge shaped cell the velocity should decay as $v = v_i\, e^{-t/\tau}$ with time constant

$$\tau = -\frac{2\,\gamma_{eff}}{3\,\alpha\,b}\sqrt{\frac{3\,c}{d}} \quad . \tag{5}$$

Here α is defined by $4ac/b^2 = 3(1+\alpha\, y)/4$ and, as stated, $\gamma_{eff} = \gamma/2$ with γ the usual twist viscosity of 5CB.

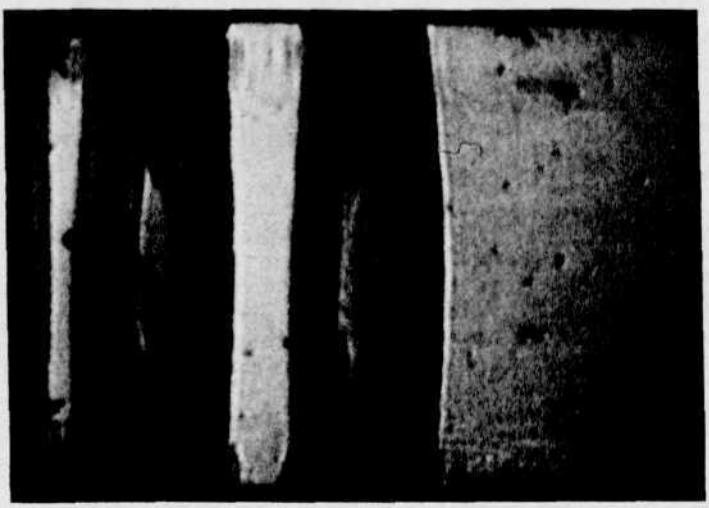

Figure 3. Photograph of the cell with transmitted light polarized along the x direction. The dark domains are the deformed regions and the white domains are the undeformed regions.

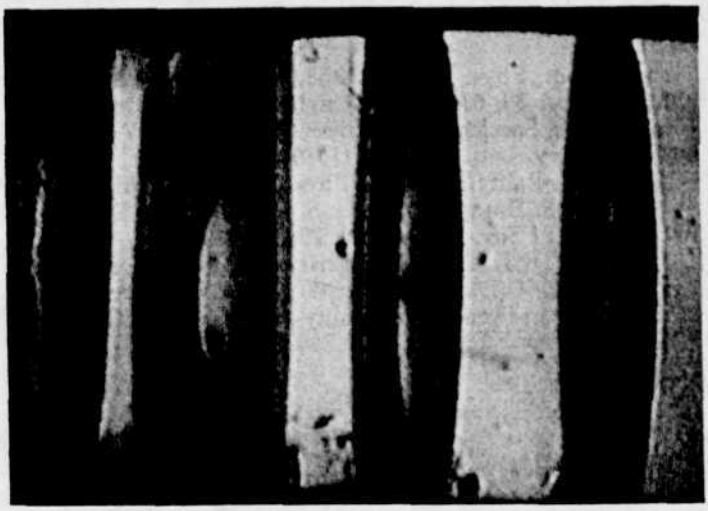

Figure 4. Photograph of the cell showing the spacing of domains near the equilibrium position.

The front position as a function of time was measured and is shown in Fig.2. From the plot of ln y vs. time, we estimate τ=3.6 hrs. The time constant τ calculated from Eq.(5) shows a strong dependence on the values of the dielectric and diamagnetic susceptibility anisotropies. Using values for the material constants of 5CB which are within the uncertainties published in the literature, we get values in excellent agreement with experiment. The details of these comparisons will be published elsewhere[5].

As can be seen from the photograph in Fig. 3, instead of observing two homogeneous states, we observed a periodic modulation in the deformed region of the cell. This periodic modulation has been reported elsewhere[3,6]. We view each domain as being bounded by two fronts, one on either side. As the applied voltage is changed, the two fronts on the two sides of each domain move in opposite directions. We assume that the domain walls of adjacent domains are prevented from merging by the opposite sense of director deformation in the domains. As expected, the width of the undeformed region (white region in the pictures) between the black domains decreases away from the equilibrium position of the front. This effect can be seen in Fig. 4. When the applied voltage was increased so that only the deformed state was stable, then we observed nucleation and growth of new domains. When the applied voltage was decreased so that only the undeformed state was stable, we observed melting of domains.

CONCLUSIONS

We have observed front propagation in a nematic cell in the vicinity of the electric field induced bend Freedericksz transition. The existence of a stable front separating undeformed and deformed domains is additional evidence that the transition is first order. The time constant of the propagating front calculated from theory using the material parameters of 5CB was found to be in good agreement with the experimentally observed value.

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REFERENCES

1. See W. van Saarloos, Phys. Rev. Lett. 58, 2571 (1987); Phys. Rev. A37, 211 (1988); Phys. Rev. A 39, 6367 (1989), and references therein.
2. P.E. Cladis, W. van Saarloos, D.A. Huse, J.S. Patel, J.W. Goodby and P.L. Finn, Phys. Rev. Lett. 62, 1764 (1989).
3. B.J. Frisken and P. Palffy-Muhoray, Phys. Rev. A 39, 1513 (1989).
4. S.M. Arakelyan, A.S. Karayan and Yu. S. Chilingaryan, Dokl. Akad. Nauk. SSSR 275, 52 (1984) [Sov. Phys.-Dokl. 29, 202 (1984)].
5. P. Palffy-Muhoray, H.J. Yuan, B.J. Frisken, and W. van Saarloos, (to be published).
6. D.A. Allender, B.J. Frisken and P. Palffy-Muhoray, Liq. Cryst. 5, 735 (1989).