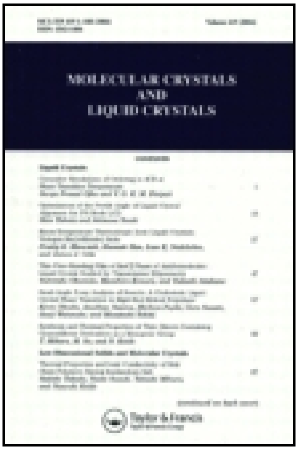

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New Scenarios in the Electroconvection of a Homeotropic Nematic Liquid Crystal

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Unusual electroconvection scenarios have been found in a homeotropic nematic liquid crystal subjected to a small magnetic field: two Lifshitz frequencies, oscillations between pattern free state and chaos, and CRAZY rolls. The variation of the azimuthal angle of the director has been measured around the normal roll – abnormal roll transition at various frequencies. Experimental results agree well with theoretical expectations. A model is proposed to describe the structure of CRAZY rolls.

Keywords: nematic liquid crystal; electroconvection

INTRODUCTION

Nematic liquid crystals with negative dielectric anisotropy may exhibit electroconvection scenarios in planar as well as in homeotropic geometry [1]. The homeotropic texture becomes unstable first due to the well known bend Freedericksz transition occurring above $V = V_F$. Electroconvection sets in on this Freedericksz distorted state at another threshold $V_c > V_F$. When the degeneracy of the azimuthal angle of the tilted

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director is resolved by a small magnetic field parallel to the surfaces of the cell, electroconvection scenarios similar to those in planar cells are expected. [1]

It has been pointed out recently both experimentally [2-4] and theoretically [4-6] that increasing the voltage above V_c may result in change of the azimuthal angle of the director away from the roll normal (abnormal rolls). The homeotropic geometry offers exceptional possibilities for studying this rotation, as the surfaces do not express a constraint on the azimuthal angle of the director. Consequently the change in the azimuthal angle results in a net rotation of the optical axis, in contrast to the planar case, where light propagation is characterized by wave guiding due to the twist deformation.

In this paper we present an experimental method developed to measure the azimuthal angle as a function of the control parameters (voltage and frequency) and the results obtained. Preliminary descriptions of two new electroconvection scenarios are also reported.

EXPERIMENTAL RESULTS

Electroconvection (EC) patterns have been studied at 30.0 °C in a 31 μm thick homeotropic cell of Nematic Phase 5A (Merck) [7] subjected to a small magnetic field $H=H_F/3$ along x (H_F is the magnetic Freedericksz threshold). The sample was illuminated by polarized white light and was observed, either with parallel or with crossed polarizers, by a long-range microscope equipped with a CCD video camera. A frame grabber in a PC allowed a digital processing of the x-y images with a resolution of 512*512 pixels with 256 gray levels. The polarizers could be rotated independently by step motors (200 steps/full rotation) synchronized to the video frames.

The frequency dependence of the electroconvection threshold voltage (Fig. 1, left) was found similar to that in planar cells.

The EC pattern at onset changes from normal rolls (NR, $f > f_{L2} \approx 725$ Hz) to oblique rolls (OR, $f < f_{L2}$) as the frequency is reduced. At even lower frequencies, however, the roll angles decrease again, as it is illustrated in Fig. 1 (right), and normal rolls seem to be preferred at very low frequencies. Thus there are two Lifshitz points ($f_{L1} \approx 180$ Hz and $f_{L2} \approx 725$ Hz). Theoretical calculations [8] using amplitude equations and the material constants of Nematic Phase 5 have led to the same conclusions. Such an unusual behavior has not been reported before either in planar or in homeotropic cells of other substances.

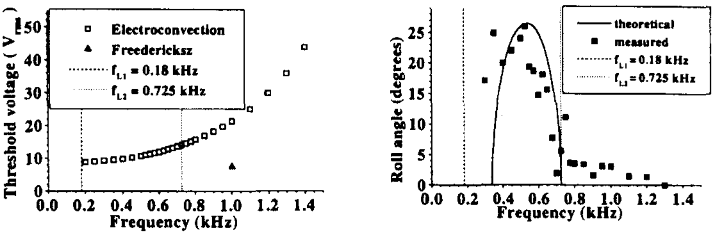

FIGURE 1 Frequency dependence of the electroconvection threshold voltage (left), and the angle between the roll normal and the magnetic field (right), for a homeotropic cell of Nematic Phase 5A. The solid line corresponds to the theory.

Patterns at low frequencies

At frequencies below 200 Hz another, oscillatory scenario has been observed. At some voltage there is a nucleation of a turbulent, chaotic pattern, which extends over the image. When it fills the space, this pattern decays spontaneously without further change of the applied voltage, and a partially homogeneous (pattern free) texture is recovered. The process then repeats itself on the time scale of some ten seconds. These oscillations states prevented us to measure the threshold voltage and the roll angles precisely at such low frequencies.

Measurement of the azimuthal angle of the director

The local optical axis (the local azimuthal angle φ of the director) can be determined from analyzing the intensity variations of the recorded images of the patterns while rotating the polarizers (i.e. changing the angle α between light polarization and the magnetic field). In the case of parallel polars the pattern cannot be seen at ordinary light polarization ($\alpha = \varphi \pm 90^o$), while with crossed polars a full extinction is observed both for extraordinary and ordinary illumination ($\alpha = \varphi$, $\alpha = \varphi + 180^o$ and $\alpha = \varphi \pm 90^o$).

Spatial variations of φ can easily be visualized by the x-α images where subsequent rows correspond to the same line of the real x-y image taken at subsequent polarizer settings. Figure 2 shows a sequence of snapshots and x-α images taken at a frequency slightly above the upper

Lifshitz point ($f_{L2} < f = 900$ Hz). It can be seen that just above the onset of electroconvection (NR regime) the optical axis lies along the magnetic field ($\varphi = 0^{\circ}$), just as in the subcritical regime (Freedericksz distorted state without pattern), since the extinction lines in the x-α images are straight and horizontal. However, when the reduced control parameter $\varepsilon = V^2/V_c^2 - 1$ exceeds the value ε_{AR}, φ becomes spatially modulated, i.e. the director deviates from the magnetic field, without change in the roll direction. This scenario is called abnormal rolls (AR).

The weakly nonlinear analysis of the homeotropic electroconvection [6,8] has shown that the NR-AR transition should correspond to a supercritical pitchfork bifurcation, i.e. the azimuthal angle behaves according to

$$\varphi_{\pm} = \begin{cases} 0 & \text{if } \varepsilon < \varepsilon_{AR}, \\ \pm\Phi\,(\varepsilon - \varepsilon_{AR})^{1/2} & \text{if } \varepsilon < \varepsilon_{AR}, \end{cases} \qquad (1)$$

where Φ diverges as the frequency approaches f_{L2}. This formula predicts the existence of AR domains with opposite sign of φ.

Our observations have proved that two types of AR domains with excursion of the director from x in opposite directions do exist. However, there are no sharp domain boundaries, instead, φ varies smoothly along x. Near ε_{AR} the AR domains are large and patchy, but at increasing ε they become smaller and more 'periodic', as it can be seen in the bottom image of Fig. 2.

The ε dependence of the maximum excursions of $\varphi(x)$ in Fig. 3 fits well to Eq. 1. Measurements at higher frequencies also yield a pitchfork behavior, although, with smaller opening angles (smaller Φ), which agrees with theoretical predictions too.

CRAZY rolls

The sudden jump of φ at $\varepsilon_{CY} = 0.057$ in Fig. 3 indicates the appearance of a new structure, the CRAZY rolls. It nucleates at $\varepsilon > \varepsilon_{CY}$, when the excursion of the director exceeds $|\varphi| \approx 20$-30°, and grows along the roll direction into the AR domains. Due to the smaller opening angles at higher frequencies such transition is observed only up to frequencies just slightly above f_{L2}. Figure 4 shows a snapshot and the related x-α image of this structure.

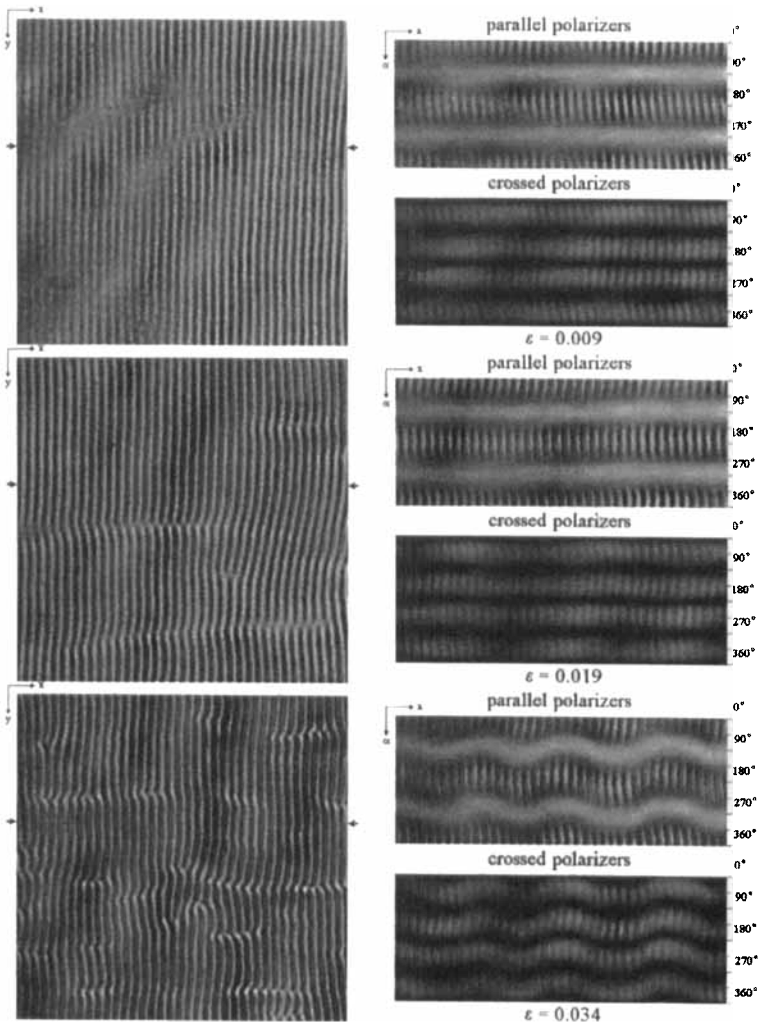

FIGURE 2 Snapshots (left side) at parallel polars and x-α images at parallel as well as at crossed polars in a homeotropic cell of Nematic Phase 5A. Images taken (from top to bottom) at $\varepsilon = 0.009$ (NR), $\varepsilon = 0.019$ (patchy AR) and $\varepsilon = 0.034$ ('periodic' AR) respectively (f = 900 Hz).

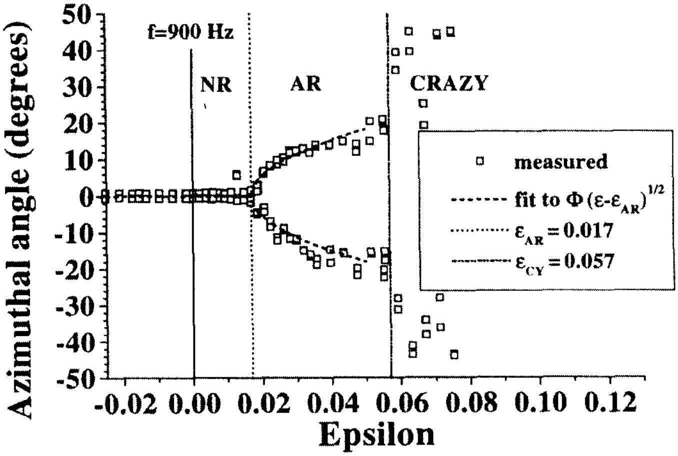

FIGURE 3 ε dependence of the maximum and minimum of the azimuthal angle of the director. The dashed line corresponds to the fit to Eq. 1. The vertical lines mark the critical ε values separating various scenarios.

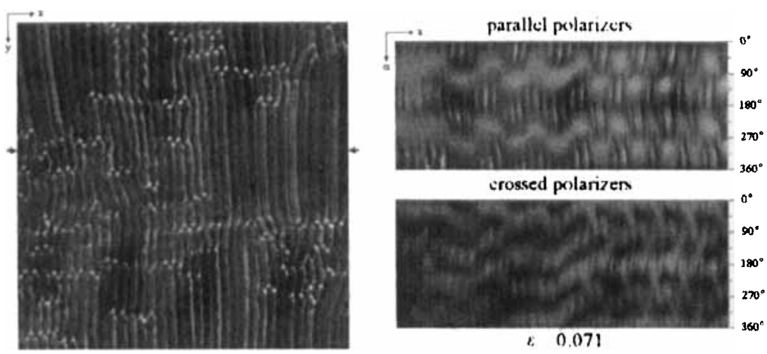

FIGURE 4 Snapshots (left side) at parallel polars and x-α images at parallel as well as at crossed polars of CRAZY rolls in a homeotropic cell of Nematic Phase 5A at $\varepsilon = 0.071$ (f = 900 Hz).

The width of a CRAZY roll equals that of a Williams domain (an abnormal roll). In contrast to the smooth φ variation in AR domains, in CRAZY rolls the x-α images indicate a net rotation of $\approx\pm 90^\circ$ across the roll, either from $\varphi = +45^\circ$ to $\varphi = -45^\circ$, or vice versa. CRAZY rolls with opposite direction of rotation occasionally form pairs which can fill the space densely, the actual wavelength of the resulting periodic structure is twice the original wavelength of the NR or AR patterns, similarly to the striped pattern described in [9]. Otherwise CRAZY rolls are separated by the conventional (AR) domains.

CRAZY rolls have an apparently hysteretic feature. Their decay time depends on their length (along y). Fully evolved (long) CRAZY rolls may persist for minutes even after reducing the voltage to below V_c. Decay of CRAZY rolls often leads to the appearance of disclination lines associated with walls separating domains with opposite Freedericksz tilt, however, this tilt direction does not change in the CRAZY roll itself. The coexististence of ARs and CRAZY rolls with little or no mutual distortion suggests, that the convection might not be influenced too much by the AR-CRAZY transition.

Based on the observations above the following model is proposed for the structure of CRAZY rolls (CRAZY=convection in a regular array of z-y disclination loops). Each CRAZY roll contains two disclination lines running along the roll (in the z-y plane along y) at the surfaces. These lines close to a loop at the tips of the CRAZY roll. The rotation of the azimuthal angle from $\varphi = +45^\circ$ to $\varphi = -45^\circ$ ($\equiv 135^\circ$) occurs through the $\varphi = 90^\circ$ ($\equiv -90^\circ$) position as we cross the CRAZY roll along x (around the tip outside of the CRAZY roll the same rotation occurs through the $\varphi = 0^\circ$ position). On both sides of the CRAZY roll the director tilts in the same direction as given by the Freedericksz profile, however in the plane of the disclination loop there is a jump from undefined tilt (at the surfaces) to a planar configuration (inside the loop).

Further detailed studies of the phenomenon are in progress.

CONCLUSIONS

As at low frequencies the electroconvection threshold voltages are not much larger than the Freedericksz threshold value, the maximum tilt angle of the director do not exceed 50-60° if $f < 200$ Hz. Thus in homeotropic cells the electroconvection sets in on a Freedericksz basic state with continuous variation of the director tilt across the cell (i.e. being far from the planar configuration). This may be responsible for the unusual scenarios (oscillations, two Lifshitz points) observed at low frequencies.

Mapping the local azimuthal angle of the director with the rotating polarizer technique allowed us to determine the main characteristics of the NR-AR transition which represent good qualitative and partially quantitative agreement with the predictions of the weakly nonlinear theoretical analysis.

The same technique allowed us to reveal the structure of a new pattern containing disclination loops, the CRAZY rolls. Their decay requires a contraction of the length of the disclination loop before it annihilates which explains their apparently hysteretic behavior.

Acknowledgments

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