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A new type of layer structure defects in chiral smectics

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Under a low frequency AC electric field applied to the S_A phase an apparently homogeneous planar structure is obtained which is in fact composed of a system of parallel stripes perpendicular to the smectic layers. This texture persists even in the S_C^* phase. The stripes are explained as a contrast on elongated focal conics originating from undulations of smectic layers. Such undulations are formed as a consequence of a reduction in the smectic layer thickness due to the electroclinic effect. The deformation of smectic layers has been calculated on the basis of the elastic free energy associated with their deformation.

1. Introduction

In experimental investigations of liquid crystals as well as in their technical applications planar glass cells are mostly used. The form and dimensions of the samples and the boundary conditions introduce particular structural defects, which can influence the macroscopic properties of the samples significantly.

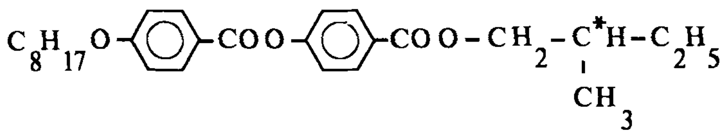
In chiral smectic C (S_C^*) planar samples, with smectic layers perpendicular to the major sample plane, a net of dechiralization lines exists near both major surfaces when the sample thickness d is sufficiently high ($d > p$, where p is the pitch of the helicoidal S_C^* structure) [1–3]. These lines are parallel to the smectic layers [1–3] and their spacing near one sample surface is equal to p [2, 3]. They have proved to be decisive in switching the ferroelectric sample [2, 3] and can also influence the dielectric properties of the planar sample [4]. In thin samples ($d < p$), the helicoidal structure is unwound by homogeneous boundary conditions, and so the net of dechiralization lines is not present [5, 6]. In that case, another type of defect becomes important. These are zig-zag defects connected to a smectic layer bend (chevron) structure [7, 8]. Both chevrons and zig-zag defects [9, 10] play an important role in switching thin samples. They have been studied intensively because thin unwound samples can be used as very fast electrooptic displays with a memory [5].

In both thin unwound [11] and thick helicoidal S_C^* samples [12] another type of defect in the layer structure can be present which has not been discussed so far in detail. The relevant texture observed in polarized light under a microscope takes the form of stripes perpendicular to the smectic layers. The same texture can also be found in the smectic A phase, above the ferroelectric $S_C^* \leftrightarrow S_A$ transition temperature.

In this paper we intend to describe the smectic layer structure producing the stripe-shaped texture and to present a model of its origin.

2. Texture observation

The liquid crystal material used was 4-*n*-octyloxy benzoic acid 4′-[(2-methylbutyloxy)carbonyl]phenyl ester



with the phase sequence

$$\mathrm{C}\quad 34^{\circ}\mathrm{C}\quad (\mathrm{S}_C^*\quad 32^{\circ}\mathrm{C})\quad \mathrm{S}_A\quad 56^{\circ}\mathrm{C}\quad \mathrm{I}.$$

The cells were made of two glass plates with a conducting ITO layer. The sample thickness was defined by a 25 μm thick mylar spacer. The electrode area was 3×3 mm. The indium tin oxide (ITO) transparent electrode was either covered by a thin polyimid layer which was rubbed with a velvet cloth or it was rubbed directly without the polyimid coating. This procedure resulted in planar alignment after the sample had been cooled from the isotropic phase. This alignment was not homogeneous, but formed a fan-shaped structure. The fan shaped structure was reconstructed under an AC electric field of 20 Hz, 4×10^3 kV m^{-1}, in the S_A phase. After about 1 hour in the applied field an apparently homogeneous texture was obtained. Near the optical extinction between crossed polarizers a stripe-shaped texture became visible with rather weak and diffuse contrast (see figure 1). The width of the stripes was 20–25 μm. This texture persisted even when the aligning field was switched off. In fact the stripes appeared shortly after the applications of the field when the fans became sufficiently large. In a very dense fan-shaped texture the faint contrast on the stripes was lost. The stripes were parallel to the fans radii. With the fans disappearing under the action of the field the stripes became mutually parallel through the whole sample treated by the field. In the S_C^* phase the dechiralization lines appeared perpendicular to the stripe direction and mutually, strictly parallel. The optical contrast on the dechiralization lines overwhelmed the contrast of the stripes, which became invisible. When the helicoidal structure was unwound under the action of a DC electric field, the dechiralization lines disappeared [2, 3] and the stripes again became

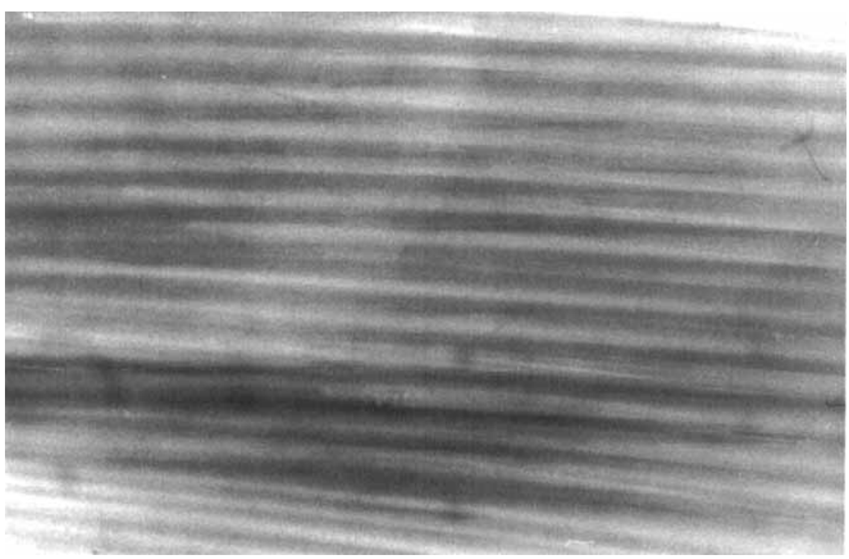


Figure 1. The texture of focal conics observed in the S_A phase in an aligned sample ($E = 0$).

visible. In the process of disappearance and reapparance of the dechiralization lines no interaction was observed between the lines and the underlying structure of the stripes.

3. Model of smectic layer deformation

When an electric field is applied to the S_A phase of a ferroelectric liquid crystal perpendicular to the director, the tilt of the director from the smectic layer normal is induced; this is known as the electroclinic effect [13]. The induction of the tilt angle θ is connected with the reduction of the smectic layer thickness. To avoid a dilation in a finite sample, the smectic layers are locally inclined, which may result in the deformation of the smectic layers in the form of undulations. Such undulations were observed by Helfrich and Hurault in the experiment in which the director tilt was induced by an external magnetic field (see [14]).

To calculate the equilibrium deformation in the S_A phase under the applied electric field we introduce a coordinate system in such a way, that the x axis is parallel to the applied electric field and perpendicular to the smectic layer normal, the y axis is parallel to the glass surface and the z axis is the smectic layer normal in the non-deformed state. Due to the induced tilt angle θ, the smectic layer will deform as shown in figure 2. It is supposed that the director can rotate freely at the sample surface (parallel to the yz plane) and so the deformation does not depend on the z and x coordinates. The deformation can be described by an angle ψ, which is the angle between the z axis and the smectic layer normal in the deformed state. The smectic layers can be inclined either to the right or to the left from the z axis with a molecular splay in between (see figure 2). The angle $\delta = \theta + \psi$ describes the orientation of the

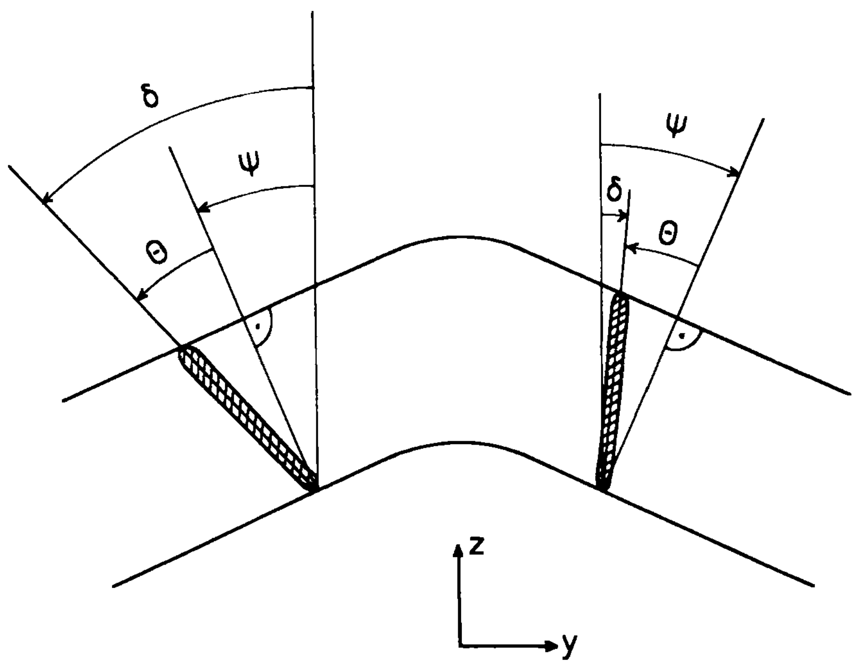


Figure 2. The deformation of smectic layers under an applied electric field. The angle θ is the induced tilt, ψ is the inclination of the smectic layer normal, δ is the inclination of director from the position at $E = 0$.

director with respect to the z axis. The splay is non-symmetric about the z axis because all of the directors are inclined from the layer normal in the same direction determined by the electric field polarity (see figure 2).

The elastic energy associated with the deformation of smectic layers can be written [14]

$$F_{el} = \tfrac{1}{2}\bar{B}\gamma^2 + \tfrac{1}{2}K_1\left(\frac{d\psi}{dy}\right)^2, \tag{1}$$

where γ is the dilation of the layers, $\bar{B}$ and K_1 are elastic constants. The dilation γ represents the relative change of the layer thickness t along the z axis

$$\gamma = (t - t_0)/t_0,$$

where

$$t = t_0 \cos\theta/\cos\psi$$

(see figure 2). For small θ and ψ it gives

$$\gamma = \tfrac{1}{2}(\psi^2 - \theta^2). \tag{2}$$

To minimize the elastic energy (1) we solve the equilibrium equation

$$\tfrac{1}{2}\bar{B}\psi[\psi^2 - \theta^2] - K_1\frac{d^2\psi}{dy^2} = 0, \tag{3}$$

with respect to ψ. Two solutions of this are $\psi = \theta$ and $\psi = -\theta$ which give the absolute minimum of F_{el} and represent two equivalent domains. Further we suppose that these two domains take place at infinity, i.e. $\psi = \theta$ for $y \to \infty$ and $\psi = -\theta$ for $y \to -\infty$. For these boundary conditions we find another solution of equation (3) as

$$\psi = 2\theta/[1 + \exp(-y\theta/\lambda)] - \theta, \tag{4}$$

where $\lambda = (K_1/\bar{B})^{1/2}$ is an associated length, usually comparable to the layer thickness [14]. Solution (4) is only a theoretical solution because it results in an infinite displacement of layers at infinity. Using solution (4) we can construct a periodic multidomain solution

$$\psi = -\theta + 2\theta\sum_{k=-\infty}^{k=+\infty}(\{1 + \exp[(2kb - y)\theta/\lambda]\}^{-1} - \{1 + \exp[(2kb + b - y)\theta/\lambda]\}^{-1}), \tag{5}$$

which is an approximate solution under the condition $2\lambda/\theta \ll b$ (b is the domain width). This condition expresses the fact that the domain width is much larger than the intermediate region between two adjacent domains. Solution (5) is shown in figure 3. The periodicity $2b$ of solution (5) cannot be determined from the elastic energy in equation (1).

The tilt angle θ is given by the electroclinic effect [13]

$$\theta = \frac{C\chi E}{\alpha(T - T_c) + Kq^2}, \tag{6}$$

where C is the piezoelectric constant in the linear interaction between the polarization P and the tilt angle θ, χ is the temperature independent dielectric susceptibility deep in the S_A phase, K is the director curvature elastic constant, q is the wavevector of the

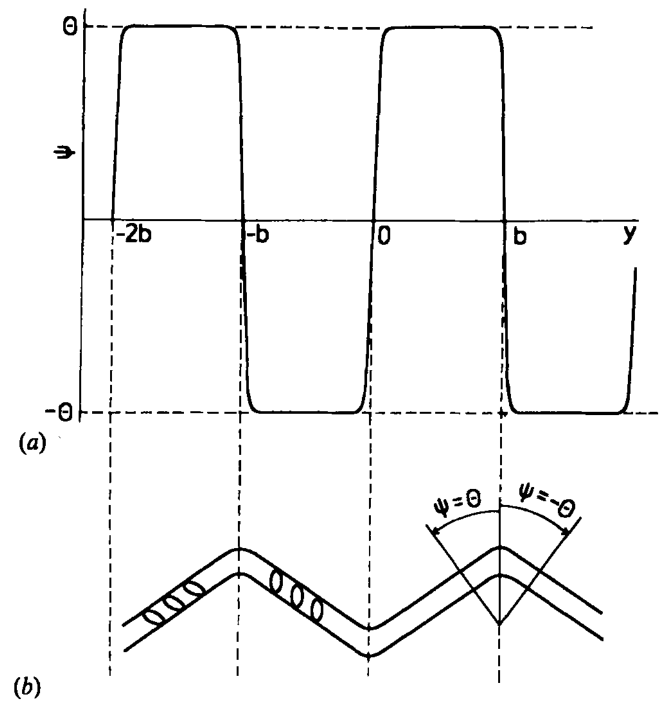


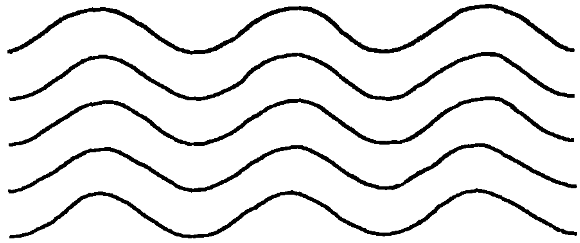
Figure 3. (*a*) Periodic inclination of the smectic layer normal at static equilibrium. (*b*) The corresponding deformation of smectic layers.

helical modulation and α is the soft mode susceptibility. T_c is the transition temperature from the S_C^* to the S_A phase. As the tilt is a linear function of E we find the change of director orientation $\delta = 2\theta$ in one domain and $\delta = 0$ in the other domain, both for one polarity of E (see figures 2 and 3).

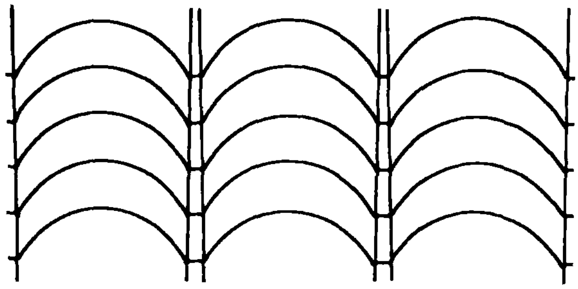
4. Discussion

Our model of smectic layer deformation is confirmed by the texture observed with planar samples which were aligned by applying an AC electric field (see figure 1). We suppose that under the aligning field undulations are induced, the amplitudes of which are proportional to the applied field (cf. equation (6) and figure 3 for small E). The periodicity b of the undulations is not determined from the model used. It is supposed that the undulations are immediately transformed to very long parabolic focal conics with their axes parallel to the sample plane (see figure 4 (*b*)). This is the reason why a contrast on undulations is not observed. We see only the focal conic texture which is stable even when $E = 0$. A similar transformation of undulations has been reported [15], where the undulations in cholesterics were caused by a mechanical dilation. In that case due to the different direction of dilation the focal conics' axis was perpendicular to the sample plane.

The width of long focal conics seems to be correlated with the sample thickness. With our samples, 25 μm thick, it is 20–25 μm. In studies of the texture of surface stabilized chiral smectic C samples (a few micrometres thick), stripes with a width of a few micrometres were found [11]. We can suppose that the width of the resulting focal conics corresponds to the periodicity of undulations which result just after the



(a)



(b)

Figure 4. A model for the transformation of smectic layer undulation (a), to parabolic focal conics [15] (b).

field is switched on (cf. figure 4). The model of smectic layer deformation improved by taking into account the finite sample dimensions and boundary conditions could yield the periodicity of undulations probably depending on the sample thickness.

The present model has been developed for the deformation of smectic layers in the S_A phase. The creation of a similar layer deformation under the applied field was also reported for the surface stabilized chiral smectic C samples [16]. It was shown that this structure could be responsible for the memory effect in those samples [16].

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