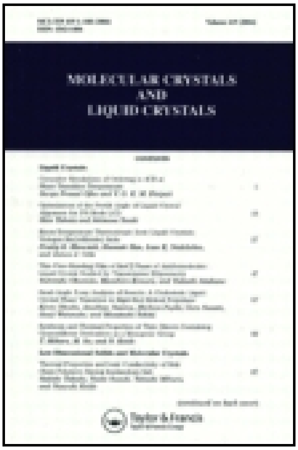

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The Birefringent Texture of Nematic Liquid Crystals Confined to Capillary Tubes with Square Cross-Section

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The structure of nematic liquid crystal director fields in supramicrometer capillary tubes with square cross-section is studied using polarizing optical microscopy. Frank elastic theory is used to determine theoretical director configurations for this geometry.

Keywords: nematic liquid crystal; birefringence; Frank elastic theory

INTRODUCTION

Previous studies of optical birefringence patterns of nematic liquid crystals constrained to supramicrometer capillary tubes with circular cross-sections enabled the determination of important parameters which dictate the director configuration of nematic liquid crystals [1,2]. Namely, the bend-to-splay bulk elastic constant ratio, K_{33}/K_{11}, for strong anchoring conditions, and the saddle-splay surface elastic constant, K_{24}, and the molecular anchoring strength, W_0, when strong anchoring conditions were relaxed, was also determined.

In this paper, we present the nematic liquid crystal structure confined in capillary tubes with square cross section for both homeotropic and parallel concentric surface boundary conditions.

EXPERIMENT

The samples are prepared using commercial liquid crystal materials K-15, ZLI-5400-100, and ZLI-4792 commercially available from EM Industries. Square glass tubes with varying side length are employed in this study. In order to enforce homeotropic surface anchoring of liquid crystal molecules at the tube surface, the tubes were treated with lecithin, a well known homeotropic surface alignment layer. Parallel surface anchoring of liquid crystal molecules at the tube surface was achieved using polyimide and an UV polarized laser beam. This non-contact technique is currently being developed for the liquid crystal display industry to bypass the archaic rubbing technique [3]. At first the tubes were treated with polyimide and cured at a high temperature (~180^{0}C). After temperature cure, the tubes were ready for UV exposure. In order to enforce the homogeneous parallel anchoring conditions on each surface of the square tube, the tube was rotated in the laser beam perpendicular to the direction of polarization. Only 2mm region of the tube was exposed to UV. The power of laser emission was 100 mW.

THEORY

In the strong anchoring limit, and absence of an external field, the free energy density [4] is given by:

$$f = \frac{1}{2}\left[K_{11}(div\mathbf{n})^2 + K_{22}(\mathbf{n}\cdot curl\mathbf{n})^2 + K_{33}(\mathbf{n}\times curl\mathbf{n})^2\right] \qquad (1)$$

where $\mathbf{n}$ represents the director-field and the surface elastic terms are ignored. The director field $\mathbf{n}$ is described by:

$$\mathbf{n} = \sin\theta\cdot\cos\varphi\cdot\mathbf{i} + \sin\theta\cdot\sin\varphi\cdot\mathbf{j} + \cos\theta\cdot\mathbf{k} \qquad (2)$$

where $\theta = \theta(x,y)$ and $\varphi = \varphi(x,y)$ are azimuthal and polar angles respectively, and $\mathbf{i}$, $\mathbf{j}$ and $\mathbf{k}$ are unit vectors along the x, y and z directions respectively (see Figure 1).

Using the one constant approximation ($K_{11} = K_{22} = K_{33} = K$) we derive the free energy density to be:

$$f = \frac{K}{2}\left[\theta_x^2 + \theta_y^2 + \left(\varphi_x^2 + \varphi_y^2\right)\cdot\sin^2\theta + \left(\theta_x\varphi_y - \theta_y\varphi_x\right)\cdot\sin 2\theta\right] \quad (3)$$

where θ_x, θ_y, φ_x, φ_y are the first derivatives of corresponding angles with respect to x and y. This is accomplished by substituting equation (2) into equation (1). Minimization of equation (3) results in the following differential equations:

$$\theta_{xx} + \theta_{yy} - \left(\varphi_x^2 + \varphi_y^2\right)\cdot\sin\theta\cdot\cos\theta = 0 \quad (4)$$

$$\varphi_{xx} + \varphi_{yy} + 2\cdot\left(\theta_x\varphi_x + \theta_y\varphi_y\right)\cdot\cot\theta = 0 \quad (5)$$

where θ_{xx}, θ_{yy}, φ_{xx}, φ_{yy} are the second derivatives of corresponding angles with respect to x and y.

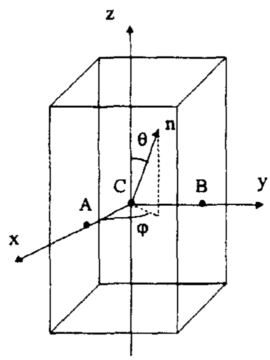


FIGURE 1 Schematic representation of the coordinate system used in the text.

It is not trivial to find the solutions of equations (4) and (5) because they depend on two angles, and in addition they are coupled. In this paper we solve the capillary problem with square cross-section numerically. In our method, we assumed the escaped radial solution [5] for circular capillary tubes as a condition for angles along CA and CB directions in the tube (see Figure 1):

$$\tan\frac{\theta}{2} = \frac{\sqrt{x^2 + y^2}}{a} \tag{6}$$

where $2a$ is a side length of the tube.
Solutions for director field configurations with the different boundary conditions are presented on Figure 2.

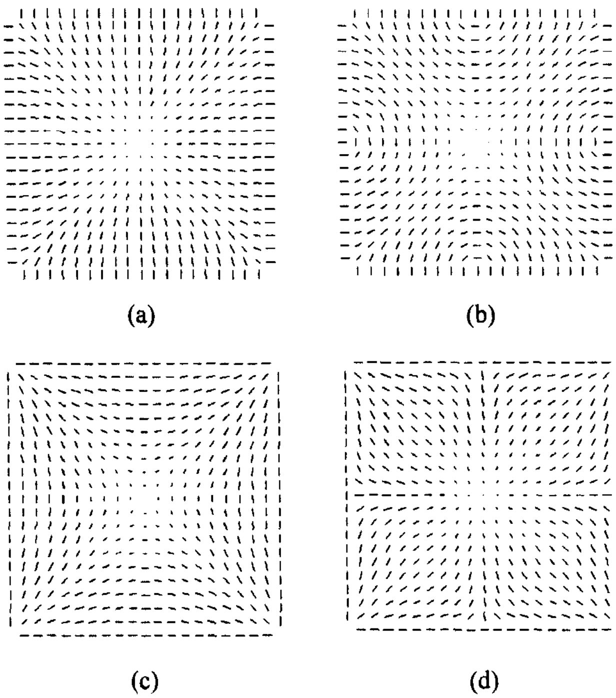
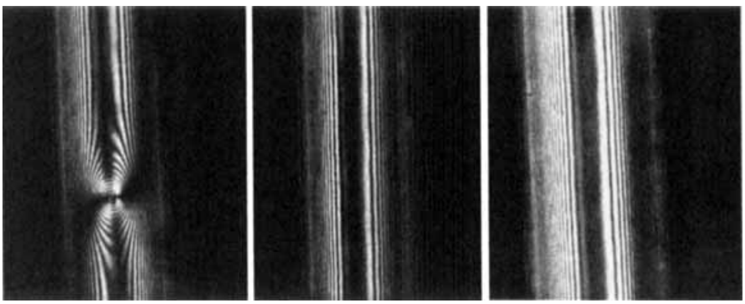


FIGURE 2 Nematic director field of escape radial configuration in a capillary with strong anchoring conditions: (a) and (b) perpendicular to the surface, (c) and (d) parallel to the surface.

The fraction of the energies calculated using (3) reveals that F_b/F_a=1.3 for homeotropic boundary condition and F_d/F_c=2.7 for homogeneous boundary condition, where F_a, F_b, F_c, F_d are the calculated free energies for configurations presented on Figure 2 (a), (b), (c), and (d) respectively.

EXPERIMENTAL RESULTS AND DISCUSSION

In our experiments we viewed samples between cross polars of an optical microscope. Observation of nematic birefringence pattern is performed using a mercury lamp equipped with an interference filter to obtain monochromatic light. The wavelength of the incident light is 435 nm.

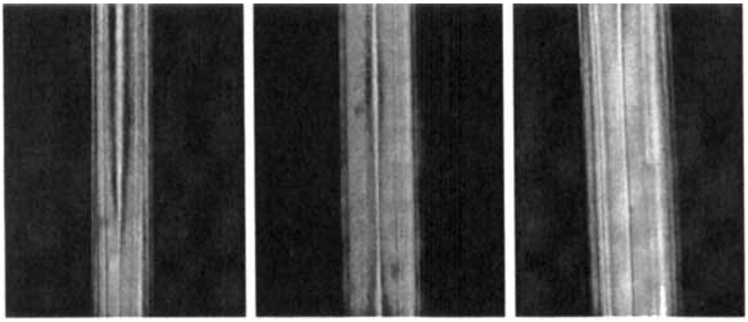


(a) (b) (c)

FIGURE 3 Interference pattern of 50μm square capillary filled with ZLI 5400-100 with and without defect (a), (b); 100μm square capillary filled with ZLI 5400-100 (c); (a)-(c) were observed through cross polarizers.

Figures 3 and 4 show the birefringence patterns with the perpendicular and parallel director orientation respectively on the surface of the tube obtained in 50μm, 80μm, and 100μm square tubes using ZLI-5400-100. The ZLI mixture is a room temperature nematic. All experiments were performed at room temperature.

The microscope features clearly reveal the escaped radial director field. This observation is the reason why in our computer simulation we used the escaped radial solution along CA and CB directions in the tube (see Figure 1).



(a) (b) (c)

FIGURE 4 Interference pattern of 80μm square capillary filled with ZLI 5400-100 (a), (c); 100μm square capillary filled with ZLI 5400-100 (b); in (a)-(c) the orientation of the tube axis is 45^0 with respect to the initial polarization vector.

On Figure 4 (a) the boundary between exposed and unexposed regions of the tube is observed. The persistence of the aligned structure beyond the exposed region can be explained if we take into account the anchoring strength on the surface of the tube.

CONCLUSION

We have presented our initial studies on nematic filled capillary tubes with square cross-sections. We have also presented nicely aligned configuration obtained from parallel concentric boundary conditions using UV polarized light, a technique used in displays to eliminate rubbing. Based on the theoretical director fields in Figure 2, we believe that these configurations will be more sensitive to surface elastic constants, which will be a subject of future study.

ACKNOWLEDGEMENT

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