Measurement of polar anchoring coefficient for nematic cell with high pretilt angle

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A method to determine the surface anchoring energy of a nematic liquid crystal is proposed. The technique implies the measurements of optical retardation of a nematic cell as a function of a strength and direction of the applied magnetic field. It enables one to get both pretilt angle α and anchoring coefficient W_a in the course of the same experiment. As an example, both parameters ($\alpha=10.9°$ and $W_a=1.5\times10^{-5}$ J/m^2) are measured at the interface between the nematic 5CB and rubbed polyimide film. © *1995 American Institute of Physics.*

Molecular interactions at the interface between a nematic liquid crystal and an ambient medium establish a definite orientation (so-called easy axis) of the director **n**. Two basic parameters characterize this anchoring phenomenon: (1) polar tilt angle θ between **n** and the surface normal **k** (or pretilt angle $\alpha=\pi/2-\theta$); (2) anchoring coefficient W_a which measures the work needed to deviate **n** from $\theta=\bar{\theta}$.

The values of α and W_a are measured by different techniques which are based usually on dielectric or diamagnetic anisotropy of liquid crystals.[1–8] The most popular method to define α is the magnetic ''null'' method.[1] One rotates a flat cell with uniform **n** between the poles of a magnet and measures a response of the cell to the applied field **H**. There is only one orientation, $\mathbf{H}\|\mathbf{n}$, which does not produce such a response (in most materials, the anisotropy of diamagnetic susceptibility is positive, $\chi_a=\chi_\parallel-\chi_\perp>0$, where the subscripts refer to **n**). The angle between the cell and **H** defines α.

To determine W_a, one usually uses the Yokoyama–van Sprang technique,[3–6] which implies simultaneous measurements of the birefringence and capacitance of a cell as a function of the applied electric field. Besides the necessity to measure two parameters, the method is of practical use only for rather thick cells, $d\geqslant50$ μm.[3,4] However, many practical applications require thinner cells, $d\cong5$ μm. This circumstance might be important, since W_a can depend on d (Ref. 7). in the presence of long-range forces caused, e.g., by electric double layers.[9]

In many applications, **n** is required to be slightly tilted from the plane of a cell: $\alpha=1-10°$. Different α can be set by adjusting the rubbing technique (rubbing provides uniform in-plane orientation) or by choosing different orienting substrates. Evidently, a practical method would be the one where both α and W_a are determined within the course of the same experiment. Such a method is described in this letter.

A magnetic field **H** is applied to the cell. First, α is found by the magnetic ''null'' method.[1] Then **H** and **n** are misaligned. The field sets spatially nonuniform director configuration $\mathbf{n}(\mathbf{r})$ whiwch depends on **H**, χ_a, surface anchoring, and elastic constants. The configuration $\mathbf{n}(\mathbf{r})$ defines optical retardation Φ of the cell, which can be determined both experimentally and theoretically. With known **H**, χ_a and elastic constants, the comparison of experimental and calculated Φ restores the whole surface anchoring energy as a function of both polar and azimuthal angles. Here, to illustrate the method, we restrict ourselves only to the measurements of α and W_a that characterize the polar part of anchoring potential.

Consider a nematic cell with plates located at $z=d/2$ and $z=-d/2$; **n** is confined to the (x,z) plane of Cartesian coordinates. The magnetic field is applied in the (x,z) plane at some angle β (Fig. 1). The free-energy per unit area of the cell is

$$F=\frac{1}{2}\int_{-d/2}^{d/2}\left[(K_{11}\sin^2\theta+K_{33}\cos^2\theta)\left(\frac{d\theta}{dz}\right)^2+\chi_a H^2\sin^2(\theta-\beta)\right]dz+W(\theta-\bar{\theta})\Big|_{-d/2}^{d/2}, \tag{1}$$

where $\theta(z)$ describes director distortions, $W(\theta-\bar{\theta})$ is the anchoring energy, K_{11} and K_{33} are the splay and bend elastic constants, respectively.

If the field direction is close to the easy axis, $\beta\approx\bar{\theta}$, the director deformations are small and it is appropriate to introduce small angles $\bar{\Psi}=\bar{\theta}-\beta$ and $\Psi(z)=\theta(z)-\beta\ll1$. In this case, the anchoring energy is well represented by $W(\Psi-\bar{\Psi})=\frac{1}{2}W_a(\Psi-\bar{\theta}+\beta)^2$, and the equilibrium $\Psi(z)$ is found from Eq. (1) as

$$\Psi(z)=\Psi_0\cosh qz/\cosh u, \tag{2}$$

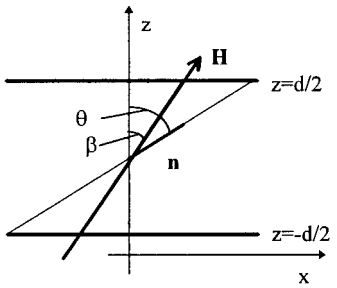

FIG. 1. Cell geometry.

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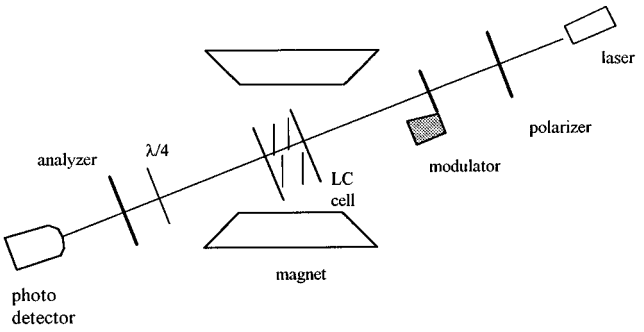

FIG. 2. Experimental setup.

where $\Psi_0=(\bar{\theta}-\beta)/g$, $g=1+lq\ \tanh u$, $l=K/W_a$, $q^2=\chi_a H^2/K$, $u=qd/2$, and $K=K_{11}\sin^2\beta+K_{33}\cos^2\beta$.

The field-induced distortions change the retardation Φ of the cell. For a normally incident (along z-axis) laser beam of wavelength λ,

$$\Phi=\frac{4\pi n_0}{\lambda}\int_0^{d/2}\left(\frac{n_e}{n}-1\right)dz, \tag{3}$$

where $n[\theta(z)]=[n_0^2\sin^2\theta(z)+n_e^2\cos^2\theta(z)]^{1/2}$, n_0 and n_e are the ordinary and extraordinary refractive indices, respectively. The change in Φ caused by the field, $\Delta\Phi=\Phi|_H-\Phi|_{H=0}$, is calculated from Eqs. (2) and (3). Retaining leading terms (linear and quadratic in the small angle $\bar{\Psi}$), one gets

$$\Delta\Phi=\frac{4\pi A}{\lambda qg}\left[B\bar{\Psi}(\tanh u-ug)+C\bar{\Psi}^2\times\left(ug-2\tanh u+\frac{2u+\sinh 2u}{4g\cosh^2 u}\right)\right], \tag{4}$$

where $A=\bar{n}_0 n_e(n_e^2-n_0^2)2\bar{n}^5$, $B=\bar{n}^2\sin 2\bar{\theta}$, $C=\bar{n}_e^2\cos^2\bar{\theta}-n_0^2\sin^2\bar{\theta}+(n_e^2-n_0^2)\cos^2\bar{\theta}\sin^2\bar{\theta}$, and $\bar{n}=n(\bar{\theta})$.

The anchoring coefficient W_a can be obtained by fitting experimental values of $\Delta\Phi$ with theoretical curves [Eq. (4)] in two independent ways; either from the dependence $\Delta\Phi(H)$ when $\beta=$const or from the dependence $\Delta\Phi(\beta)$ when $H=$const.

Experiments were performed for the liquid crystal 5CB (K15, EM Industries) at fixed temperature 25.0 °C. Glass substrates were spin coated with polyimide SE-610 (Nissan Chemical Ind., Ltd. solvent NMP/Butyl cellosolve), which is used in display industry for high-pretilt orientation. The plates were cured at 250 °C for 1 h and rubbed with rotating velvet wheel. The cells were formed by a pair of plates treated in antiparallel directions (to set nondistorted **n**). Variation in the rubbing force resulted in different pretilt angles ($\alpha=3°-13°$). Here, we report results for the cell of thickness $d=4.5$ μm (measured by interference method) with $\alpha=10.9°$.

The cell was placed between the poles of electromagnet Varian V3400 (Fig. 2). Newport rotary stage 495 with programmable motion controller (model PMC200-P) was used to set different rotations of the cell with respect to the magnetic field.

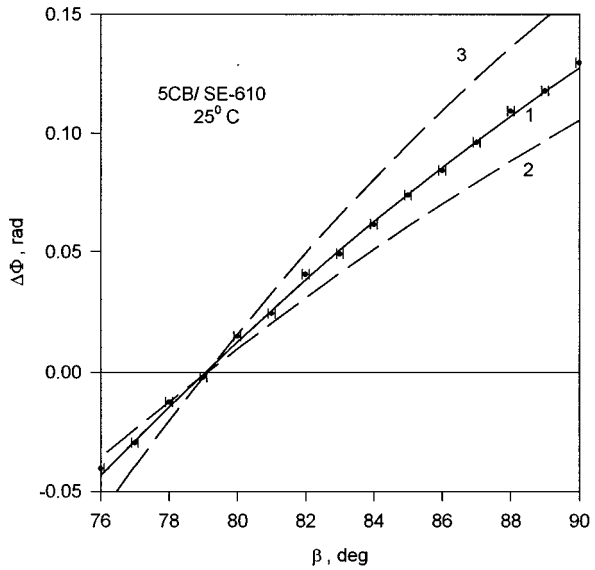

FIG. 3. Phase retardation $\Delta\Phi$ as a function of angle β between the magnetic field **H** and the normal to the cell. $H=8.5$ kGs. (1) fitting curve, $W_a=1.47\times10^{-5}$ J/m^2; (2) $W_a=3.0\times10^{-5}$ J/m^2; and (3) $W_a=0.7\times10^{-5}$ J/m^2.

The linearly polarized (45° with respect to the rubbing direction) He–Ne laser beam of diameter 1.5 mm was modulated by a chopper ($f=400-800$ Hz) and directed normally to the cell. The retardation was determined by Senarmont technique. Elliptic polarization of the beam passing through the sample was transformed into the linear one by a $\lambda/4$ plate; the angle of this linear polarization was defined by rotating the analyzer to find the extinction position.

Figure 3 shows the measured and calculated $\Delta\Phi(\beta)$. Each point represents a separate measurement; for each β, the field H was gradually increased to $H=8.5$ kGs and then $\Delta\Phi$ was measured. β was determined with accuracy of 0.1°, and $\Delta\Phi$ with accuracy better than 10^{-3} rad. The pretilt angle ($\alpha=10.9°$) corresponded to $\Delta\Phi=0$. The fitting of the experimental data with Eq. (4) resulted in $W_a=1.47\times10^{-5}$ J/m^2 (standard error 0.15×10^{-5} J/m^2). We used the values of K_{11}, K_{33}, and χ_a from Ref. 10 and refractive indices from Ref. 11.

Figure 4 shows $\Delta\Phi(H)$ for fixed $\beta=90°$. The fitting gives $W_a=(1.54\pm0.15)\times10^{-5}$ J/m^2, which is in good agreement with W_a obtained from $\Delta\Phi(\beta)$. Comparison of two independent W_a's provides an estimate of the goodness of the method. Note that the experimental conditions (accuracy in $\Delta\Phi$, chosen cell thickness d and magnetic field strength H) allow measurements of W_a up to 10^{-3} J/m^2. This limit can be exceeded by using, e.g., stronger magnetic field.

To conclude, we illustrated the method to determine the angular and energetic parameters of anchoring potential. The basic advantages of the method include the following: (1) both α and W_a are measured; (2) W_a is measured for any α and for any dielectric anistropy of liquid crystal; (3) W_a can

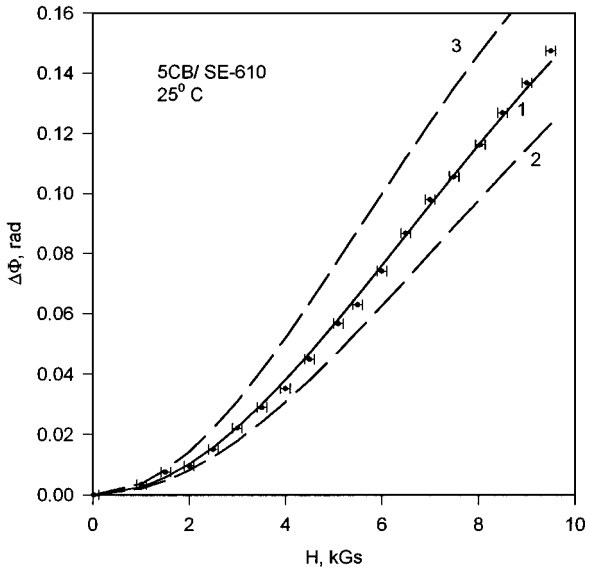

FIG. 4. Phase retardation $\Delta\Phi$ as a function of the magnetic field **H** with fixed orientation $\beta=90°$. (1) fitting curve $W_a=1.54\times10^{-5}$ J/m^2; (2) $W_a=3.0\times10^{-5}$ J/m^2; and (3) $W_a=0.7\times10^{-5}$ J/m^2.

be measured for thin cells; (4) two W_a's values can be obtained independently to check the reliability of the result.

The technique can be expanded to yield the whole profile of the anchoring potential; that generally would require numerical analysis similar to the one performed by Gleeson and Palffy-Muhoray.[8] If unknown, the necessary parameters such as χ_a or elastic constants can be measured with practically the same magneto-optical setup. The technique is sensitive to the errors in the measured cell thickness d. To reduce this sensitivity, one can consider the ratio $\Delta\Phi/\Phi|_{H=0}$ rather than $\Delta\Phi$; $\Phi|_{H=0}$ can be determined independently, e.g., from the temperature dependence of phase retardation. Another way to improve the accuracy is to use reflected light[12] or total internal reflection mode.[13] The reflection modes allow one, in addition, to eliminate the influence of a possible difference in α at the opposite plates; on the other hand, a special setup (e.g., wedge-shaped samples or high-index prizms) is required. The method of measurements should be defined on the basis of particular practical or research needs.

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