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Surface Coupling between Nematic Liquid Crystals and Rubbed Polyimide Substrates for Pure Twist Deformation: Dependence on Rubbing Strength

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The optical detection of the surface coupling of nematic liquid crystals (NLCs) with rubbed polyimide substrates subjected to pure twist is described. Transmitted light beams through a cell comprised of homogeneously aligned NLC of a cyanobiphenyl, 5CB, inserted between crossed polarizers are observed as functions of applied magnetic field where the phase retardation occurring in the LC medium is measured and adjusted in advance by controlling the temperature. Torsional coupling strength has been investigated as a function of the rubbing strength which is expressed by the induced phase retardation occurring in the thin film of polyimide due to the rubbing. The torsional coupling constants A_Φ thus determined are 1.4×10^{-5} J/m^2 for strong rubbing and 5.1×10^{-6} J/m^2 for weak rubbing, respectively, at room temperature, whereas the polar coupling constants A_θ are independent of the rubbing strength and are shown to be $A_\theta > 1 \times 10^{-3}$ J/m^2.

1. INTRODUCTION

Preparation of a monodomain liquid crystal layer of a fairly large area sandwiched between two glass plates or plastic films is important both for fundamental and practical research work on liquid crystals (LCs). This process relies on the surface alignment techniques such

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as oblique evaporation of *e.g.*, SiO[1] and rubbing on, *e.g.*, polyimide films with an appropriate fabric.[2] There exist two kinds of director changes in monodomain nematic liquid crystals due to the applications of external forces; one is the polar deformation which causes a change in the angle between the director and the normal to the substrates, the other is the azimuthal or torsional (pure twist) deformation in the plane of the LC medium established in quescent condition. These director deformations give rise to changes in the capacitance or birefringence; by measuring these effects and by analyzing the data one can obtain the surface coupling strength between LC molecules and treated substrates both for polar and azimuthal deformations. A great deal of work has been devoted to the former, both in the deformation in planar (homogeneous alignment)[3] and homeotropic conformations,[4,5] but only a few papers on the anchoring strength for pure twist deformation have been published.[6–9] Nevertheless, its importance was pointed out in one published paper.[10]

This research work was done aiming at knowing torsional surface coupling strength by conducting measurements of the optical detection of the magnetic field induced by pure torsional deformation occurring in a nematic LC, 5CB (K15 from Merck or Chisso), aligned homogeneously by rubbing polyimide films (Sunever 130, Nissan Chem. Ind.) with a nylon fabric. This method is based on the analytical work described in a previous paper.[11]

The strength of the rubbing is evaluated by measuring the induced retardation ($R = 2\pi\Delta nd/\lambda$) due to the rubbing occurring in polyimide films 100 nm thick coated on ITO-coated glass plates.

2. ANALYTICAL CONSIDERATION

2.1 The optical detection of the pure twist deformation

The optical system and the configuration of the sample including other angular relationship are illustrated in Figure 1.

The method was developed originally by Gerber and Schadt[12] to evaluate the twist elastic constant K_2. The intensity of the transmitted light through the samle inserted between crossed polarizers whose axes are parallel or crossed to the optical axis of the LC medium is given by

$$I = \frac{\pi}{d}\left(\frac{n_e}{n_o}\right)\frac{d}{\Delta + \pi} E_1^2 \Phi_m (1 + \cos\Delta) \qquad (1)$$

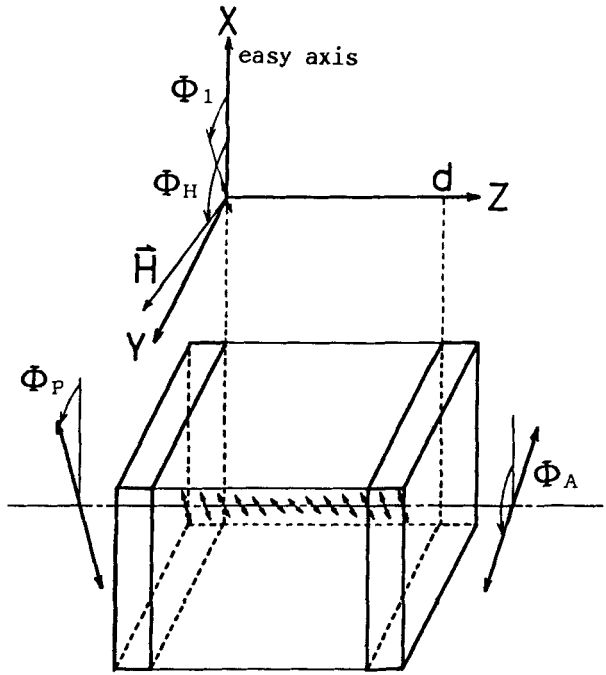

FIGURE 1 The optical system.

where d, n_e, n_o, E_1 and Φ_m are the thickness of the LC medium, the refractive index for the extraordinary ray, that for the ordinary ray, the amplitude of the optical field, and the twist angle of the director (which becomes non-zero above the threshold) at the mid-plane. And further Δ reads

$$\Delta = \frac{2\pi}{\lambda}(n_e - n_o)d \tag{2}$$

which is the phase retardation.

Equation (1) tells us that the transmitted light obviously depends on the retardation Δ occurring in the medium before the deformation takes place. The intensity of the transmitted light for $\Delta = \pi$ is zero even though the deformation takes place above the magnetic threshold, especially when the surface coupling is strong enough; on the other hand for $\Delta = 2\pi$, the transmitted light is expected to increase linearly with the magnetic field above the magnetic threshold H_c, as

approximately expressed by

$$I = 2C_1(H - H_c)/H_c \tag{3}$$

where C_1 is the proportional constant. To obtain this formula an approximate formula for Φ_m, $\Phi_m^2 = (H - H_c)/H_c$, is used.

A more detailed and accurate calculation has been done using the method of 2 × 2 matrix[13] which is simplified from that of 4 × 4 matrix[14] by ignoring the optical reflection occurring in the LC medium.

2.2 Calculation of dielectric tensor and surface coupling constant

To perform above mentioned calculation one has to know the spatial variation of the dielectric tensor of the LC medium as a function of magnetic field in advance. This is derived by performing a variational calculation of the free energy equation comprised of the elastic, magnetic, and surface energies:

$$f = f_d + f_m + f_s \tag{4}$$

$$f_d = \frac{1}{2} K_2 \left(\frac{\partial \Phi}{\partial z}\right)^2 \tag{5}$$

$$f_m = -\frac{1}{2} \mu_0 \Delta\chi H^2 \cos^2(\Phi_H - \Phi) \tag{6}$$

$$f_s = \frac{1}{2} A_\Phi \sin^2\Phi(\delta(z) + \delta(z - d)) \tag{7}$$

where Φ, $\Delta\chi$, Φ_H, A_Φ stand for the spatial variation of the azimuthal angle of the director measured from the x-axis, the anisotropy in the magnetic susceptibility, the angle between the magnetic field and the x-axis, and the torsional coupling constant. By the variational calculation one obtains the equations both for the bulk and surface as follows:

$$\frac{\partial \Phi}{\partial z} = H\left(\frac{\mu_0 \Delta\chi}{K_2}\right)^{1/2} \{\cos^2(\Phi_H - \Phi_m) - \cos^2(\Phi_H - \Phi)\}^{1/2} \tag{8}$$

$$K_2 \frac{\partial \Phi}{\partial z}\bigg|_{z=0} = A_\Phi \sin\Phi_1 \cos\Phi_1 \tag{9}$$

The threshold field H_c and relationship between applied field H and azimuthal angles at the surface Φ_1 (which is zero at $H = 0$) and Φ_m at the mid-plane are:

$$H_c = \frac{\pi}{d + 2de}\left(\frac{K_2}{\mu_0 \Delta\chi}\right) \tag{10}$$

$$\frac{H}{H_c} = \frac{2}{\pi} B(\Phi_1, \Phi_m) + S(\Phi_1, \Phi_m) \tag{11}$$

where B and S are given by

$$B(\Phi_1, \Phi_m) = \int_{\Phi_1}^{\Phi_m} \frac{d\Phi}{\{\cos^2(\Phi_H - \Phi_m) - \cos^2(\Phi_H, \Phi_1)\}^{1/2}} \tag{12}$$

$$S(\Phi_1, \Phi_m) = \frac{\sin^2\Phi_1 \cos^2\Phi_1}{\{\cos^2(\Phi_H - \Phi_m) - \cos(\Phi_H - \Phi_m)\}^{1/2}} \tag{13}$$

and where de stands for the extrapolation length which is related to the surface coupling constant A_Φ by

$$\begin{aligned} de &= \frac{K_2}{A_\Phi} \\ b &= \frac{d}{2de} \end{aligned} \tag{14}$$

the quantity b is called the coupling parameter. Then A_Φ reads

$$A = \frac{2K_2 B(\Phi_1, \Phi_m)}{d\, S(\Phi_1, \Phi_m)} \tag{15}$$

The spatial variation of $\Phi(z)$ is obtained by integrating Eq. (8); however, it is better to make a transformation,

$$\sin\beta = \frac{\cos(\Phi_H - \Phi)}{\cos(\Phi_H - \Phi_m)}$$

Then one can calculate $\Phi = \Phi(z)$ by the following equation:

$$\Delta Z = \frac{d}{2} \frac{1}{B(\Phi_1, \Phi_m)} \frac{1}{\{1 - \cos^2(\Phi_H - \Phi_m)\sin^2\beta\}^{1/2}} \Delta\beta.$$

To calculate the above equation one has to know the values Φ_1 and Φ_m which are obtained from the equation (15).

3. EXPERIMENTAL

The samples were ordinary sandwich cells which comprised two glass substrates whose inside was coated with ITO which was covered by polyimide (Sunever 130, Nissan Chem. Ind.) films 100 nm thick. The space between these glass substrates was filled with NLC 5CB which forms a homogeneously aligned phase 60 μm thick by the application of rubbing on polyimide films in advance with a nylon fabric (Y0-10-N, Yoshida Chemical Co.). The strength of the rubbing was controlled by adjusting the degree of the contact between the plates and the fabric. The rubbing strength was evaluated by observing induced phase retardation occurring in the worked polyimide film spread on the glass substrate due to the rubbing. We classify the strength of rubbing as follows: (1) strong rubbing which gives rise to retardation ($R = 2\pi\Delta nd/\lambda$) of $R = 1°$, where as (2) weak rubbing yields $R = 0.1°$. These small values of the induced retardation which appeared in the rubbed polyimide were measured with an independent instru-

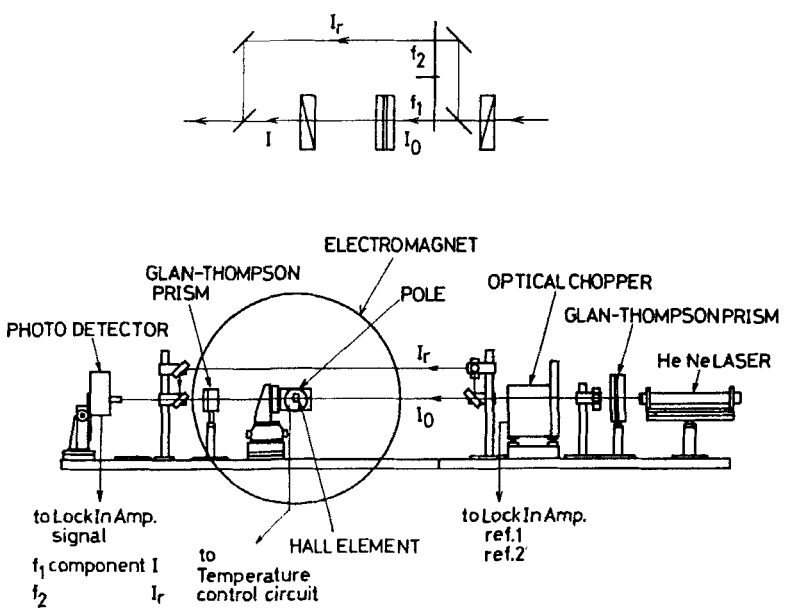

FIGURE 2 The layout of the measuring system.

ment developed by the authors.[15] Detailed work on the rubbing strength will be published elsewhere.

The pretilt angles of the NLC medium in the samples induced by the rubbing process were measured by the crystal rotation method.[16] We conducted measurements on the following two samples, one of which designated as sample A is prepared by performing strong rubbing resulting in R of 1° accompanying a pretilt angle of 3° and the other, sample B, is prepared by weak rubbing ($R = 0.1$), which had a pretilt angle of 1.8°.

The sample cell is well temperature regulated and controlled; the accuracy attained was 0.005° in the range of 20 ~ 100°C. The temperature of the cell was regulated to be at a specified temperature and kept at this temperature for over several hours in order to control the temperature-dependent birefringence of the LC medium, which makes it possible to regulate the phase retardation (Eq. (2)) precisely, prior to the application of the magnetic field. The sample temperature also has to be at this specified value throughout the duration of the measurement.

Figure 2 illustrates the layout of the measuring system. The temperature-regulated sample housing is located in a magnetic field directed in the plane of the nematic medium which is inserted between crossed polarizers (Glan-Thompson prism). The magnetic field was applied to the planar nematic medium so as to induce the pure twist even in the slightly pretilted molecular conformation. The incident light beam (He-Ne laser, 633 nm) is divided into two beams with a beam splitter after passing through the first polarizer. The beam I_0, which is the main beam, incidents normal to the nematic molecular plane, is intensity modulated at the frequency of 80 Hz and the other beam, I_r, which serves as the reference, is modulated at 800 Hz. The signal beam passes through the sample and the second polarizer. This transmitted light beam, expressed as I, is synthesized with the reference beam by a half mirror. The resultant beam is detected and mixed with a photodiode and the electrical signal from the photodiode is fed to two independent lock-in amplifiers (Model 5610, NF Electronic Instruments) tuned at the frequencies of 80 Hz and 800 Hz, respectively. Then the ratio of these detected signals, I/I_r, is taken to compensate the temporal fluctuation of the output of the laser. The flux density of the electromagnet was measured with a Gauss meter (Model 3251, Yokogawa Electric).

The retardation which occurred in the LC medium before applying the magnetic field was measured by the method of de Senarmont.[17]

In order to confirm the occurrence of the pure twist deformation

taking place in the nematic medium under the application of the magnetic field, the capacitance of the sample under the test was monitored along with the optical measurement. It was expected that the capacitance does not change even when the transmitted light does change as a function of applied magnetic field. The setting of the sample was done so that the variation of the capacitance with H would vanish.

Through independent experiments, the polar coupling constants A_θ were determined by performing measurements of the capacitance vs. electric field applied to the NLC media and also of the retardation vs. electric field.

4. RESULTS AND DISCUSSION

Figures 3(a) and 3(b) show the experimental results for samples A and B prepared by strong and weak rubbing, respectively.

The rate of the increase of magnetic field was 5×10^{-4} T/min. Figure 3(a) shows the results measured at (1) 29.02°C and (2) 29.96°C, to yield $\Delta = \pi$ and 2π, respectively. For $\Delta = \pi$, the observed behavior is almost in agreement with the analytical prediction[11] except for the slope. For $\Delta = \pi$, a fairly large amount of the leak of the transmitted light is observed above the threshold. This leak must be substantially zero when the surface coupling is infinite.[11] This may suggest that the coupling is finite even though strong rubbing was done, while Figure 3(b) shows the data for weak rubbing measured at (1) 29.21°C and (2) 30.31°C, to yield $\Delta = \pi$ and 2π, respectively. The observed light intensity for $\Delta = \pi$ exceeds the transmitted light for $\Delta = 2\pi$;

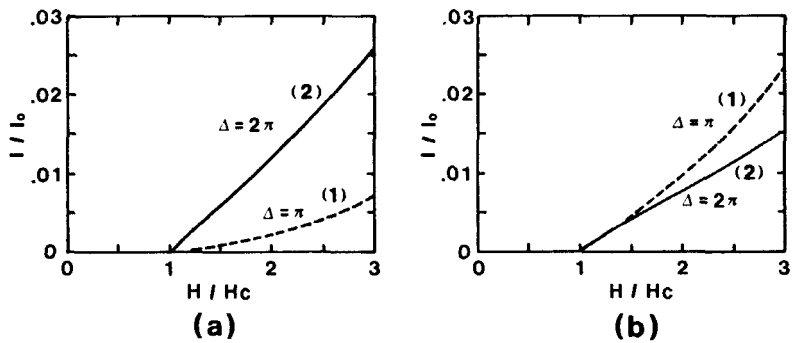

FIGURE 3 I/I_0 vs. H/H_c plots for (a) sample A (strong rubbing) and (b) sample B (weak rubbing).

a remarkable inversion in the intensity of the transmitted lights is observed in comparison with the behavior of Figure 3(a). These behavior may support the fact that strong and weak rubbing were done in the samples A and B, respectively.

Using the 2 × 2 matrix method, we made a fitting to the data of Figures 3(a) and 3(b) as shown in Figures 4(a) and 4(b), respectively, where a coupling parameter $b = 2A_\Phi/dK_2$ is adopted. The values for b giving the best fitting to observed data are $b = 150$, and 65, respectively. If we use the value of K_2 reported by N. V. Madhusudana and R. Pratibha[18] and Toyooka *et al.*,[19] the calculated values of A_Φ are 1.4×10^{-5} J/m^2 and 5.1×10^{-6} J/m^2, for strong and weak rubbing, respectively.

On the other hand, the determined values of the polar deformation A_θ's are almost 100 times larger than A_Φ and shown to be almost independent of the rubbing strength.

5. CONCLUSION

We have shown that the strength of the rubbing done on the aligning polyimide film can be evaluated and expressed by the induced optical retardation, $R = 2\pi\Delta nd/\lambda$; strong rubbing results in $R = 1°$, while a weak one is $R = 0.1°$. Further, we have succeeded in measuring the torsional coupling constant between the rubbed polyimide substrates and the nematic liquid crystal, 5CB, by observing the transmitted light through the homogeneously aligned sample which is subjected to magnetic field to yield a pure twist. The obtained torsional coupling constants are $A_\Phi = 1.4 \times 10^{-5}$ J/m^2, 5.1×10^{-6} J/m^2, for

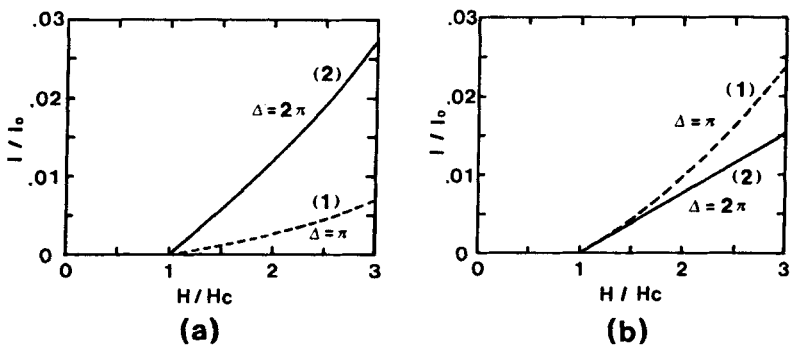

FIGURE 4 Fitting to the data of Fig. 3 (a) and (b). The fitting parameter $b = 2A/dK_2$ is taken as 150 and 65, respectively.

strong and weak rubbing, respectively; whereas the coupling constants A_θ for polar deformation of these samples were found to be almost independent of the rubbing strength and to be $A_\theta > 1 \times 10^{-3}$ J/m^2.

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