Birefringence effect of two directionally rubbed liquid crystal cells

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Abstract
The alignment property of liquid crystals on the two-easy axes substrate is investigated. The two-easy axes substrate frustrates the orientation of the LCs next to the substrate, and hence influences the birefringence of the LC cell. Experimental findings reveal that the ratio of the rubbing strengths in the different rubbing directions and the cell thickness substantially influence the birefringence of the LC cell. The surface anchoring energetic competition between the different rubbing directions contributes to the observed results.

1. Introduction

Liquid crystals (LCs) have been extensively investigated for display applications.[1)] Most of the LC devices use the electric, thermal or optical field-induced refractive index change to modulate light. The refractive index of LCs is determined primarily by the molecular structure, the incident wavelength and the ambient temperature.[2)] The orientation of LC molecules in a particular direction on a treated surface has been the subject of intense research in the area of manufacturing liquid crystal displays.

Recently, the alignment properties of liquid crystals on a two-easy axes surface were studied. Kim et al. reported that liquid crystals aligned along an axis between the two easy axes, and explained the observed results with the groove model.[3)] Chung et al. investigated the molecular orientation of liquid crystals on a doubly easy axes treated substrate, and determined the anchoring energies of the treated surface.[4)] In this paper, variations in the birefringence of the liquid crystal molecules on the two-easy axes cells are measured and discussed.

2. Experimental

The following steps were followed to prepare a two-easy axes substrate. First, a cleaned indium tin oxide (ITO) substrate was spin-coated with polyvinyl alcohol (PVA) and rubbed m times unidirectionally in the y direction. Then, the substrate was rotated through a rubbing angle Ω, and rubbed n times in the x direction. Such a substrate is referred as a [m, n] rubbed substrate. Figure 1 depicted the proposed substrate geometry of the experiment. In the figure, f_1 is the surface induced anchoring energy density in the first rubbing direction and f_2 is the surface induced anchoring energy density in the second rubbing direction. The two-easy axes cell was made from two identical [m, n] rubbed substrates and the substrates used were antiparallel. The empty cell was then filled with nematic E7.

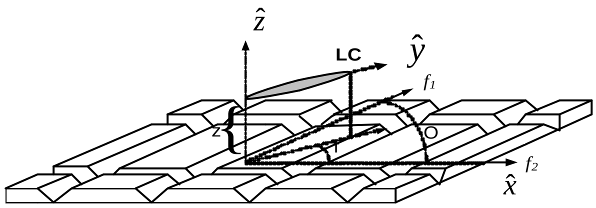

Fig. 1. Proposed geometry of the substrate rubbed in two different directions.

The angle of deviation φ from the second rubbing direction (x axis) in which the transmission was minimal, was determined after the sample was rotated between two cross polarizers. The birefringence was measured using the setup depicted in figure 2. A He-Ne laser (632.8nm) was incident on the LC cell, and a neutral density (ND) filter was used to reduce the light intensity. The polarization direction of each polarizer was ±45° from the director of the LC molecules. The transmitted intensity I was obtained by the equation,[5)]

$$I = I_0 \sin(\frac{p\Delta nd}{l}) . \qquad (1)$$

where I_0 represents the intensity transmitted through

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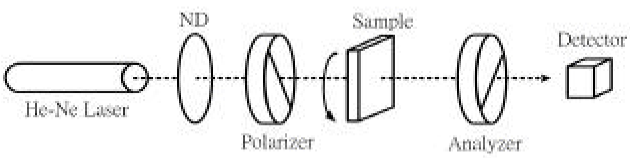
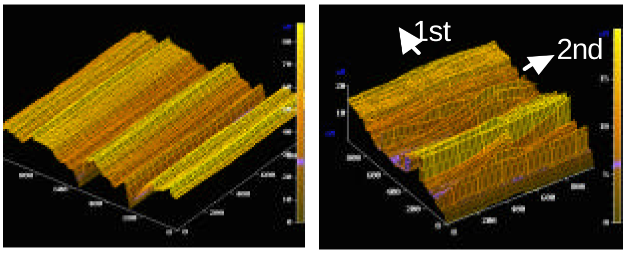


Fig. 2. Setup for measuring the birefringence of a LC cell.

parallel polarizer and analyzer without the sample, *d* is the cell thickness, *n* is the birefringence of the sample and λ is the wavelength of the incident laser light.

3. Results and Discussion



(a) **(b)**

Fig. 3. AFM surface images of (a) [0, 1] and (b) [1, 1] rubbed substrates.

Figure 3 displays the atomic force microscopy (AFM) surface images of [0, 1] and [1, 1] rubbed substrates, respectively. Clear microgrooves are generated in the rubbing direction, as shown in Fig. 3(a). For the [1, 1] rubbed substrate, it is found that rubbing in the two different rubbing directions generate microgrooves in each direction, and the microgrooves in the first rubbing direction is erased by the second rubbing. Hence, grooves in the second rubbing direction are clear than those in the first rubbing direction, as depicted in Fig. 3(b). Notably, rubbing tends to shear the top surface of the PVA-rubbed substrate. Consequently, microgrooves on a [1, 1] rubbed substrate are not as well defined as those on a [0, 1] rubbed substrate.

In the following, we attempt to analyze the relation between the rubbing strengths of the two-easy axes substrate and the orientation of the LCs. Our approach is based on the groove model developed by Berreman in 1972.[6)] Berreman suggested that the planar alignment relies on the grooves on the substrate created by unidirectional rubbing. For the orientation of the director perpendicular to the grooves, one needs to spend some additional surface induced anchoring energy density[7)]

$$f = \frac{1}{2}k(uq^2)^2 \exp(-2qz), \qquad (2)$$

due to elastic deformation, where *z* is the distance from the substrate, *k* is the elastic constant of the LCs; $q = 2p / l$, is the wave vector, l is the wavelength and *u* is the amplitude of the grooves. In a more general case, when the director lies arbitrarily with respect to the grooves, it is necessary to introduce the angle q_0 between the director and the groove. Then

$$f = \frac{1}{2}k(uq^2)^2 \exp(-2qz)\sin^2 q_0, \qquad (3)$$

and will be minimal when $q_0 = 0$ or p.

When a nematic LC is introduced into a two-easy axes cell, the anchoring energy density at a distance *z* from the substrate is given as a sum of the bulk elastic energy density and surface induced anchoring energy densities of the bottom and the top surfaces as follows,

$$f = f_{bulk} + f_{top} + f_{bottom}, \qquad (4)$$

where

$$f_{bulk} = \frac{1}{2}k(\hat{n}\cdot\nabla\times\hat{n})^2$$

$$f_{bottom} = f_{top} = f_1 + f_2$$

$$= \frac{1}{2}k(u_2 q_2{}^2)^2 \exp(-2q_2 z)\sin^2 j(z)$$

$$+\frac{1}{2}k(u_1 q_1{}^2)^2 \exp(-2q_1 z)\sin^2[\Omega - j(z)], \qquad (5)$$

In eq. (5), $\hat{n} = (\cos j(z), \sin j(z), 0)$ is the director of the LC molecules at a distance *z* from the substrate, $q_i = 2p / l_i$ is the wave vector, l_i is the wavelength and u_i is the amplitude of the grooves along the *i-th* (i=1,2) rubbing direction, Ω is the rubbing angle between the two different rubbing directions. Therefore, the free energy per unit area can be reasonably written as

$$F = 2\int_0^{d/2} f\, dz\ . \qquad (6)$$

Finally, with the assumption of $\Omega = 90^\circ$ and using the Euler-Lagrange equation, the equation of motion is obtained,

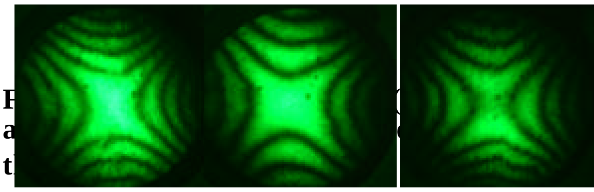
$$j''(z) + f_{tw} \sin j(z) \cos j(z) = 0\ , \qquad (7)$$

where we introduce a twist distortion factor f_{tw} ,

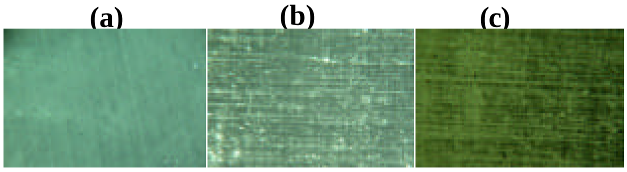
$$f_{tw} = (u_1 q_1{}^2)^2 \exp(-2q_1 z) - (u_2 q_2{}^2)^2 \exp(-2q_2 z)\ . \qquad (8)$$

This describes a twist distortion of the director at a position z from the substrate. f_{tw} is similar to the external electric field that applied parallel to the substrate in a homogeneous cell, and distorts the directors of the LCs.[8)] However, f_{tw} possesses a rapidly exponential decay factor. It indicates that the distortion of the directors can only be found next to the substrate. From eqs. (2) and (8), it is found that the influence of the surface induced anchoring energy density rapidly decay to *1/e* at position *z=1/2q*. According to the AFM image of Fig. 3(b), $l_1 \approx l_2 \approx 400nm$ in this experiment, the influence of the surface anchoring energies decays to *1/e* at *z*=0.03 µm. Therefore, the twist distortion due to the two-easy axes treatment can only be found next to the substrate and can be neglected for a thicker cell. For approximately equal rubbing strength in the two different rubbing directions, f_{tw} equals zero and the LC molecules align homogeneously; for a higher rubbing strength in one of the two different rubbing directions, the anchoring energy strength in the direction with weaker rubbing strength can be neglected and the LC molecules are assumed to be aligned homogeneously toward the direction with stronger rubbing strength. Therefore, the directors of LCs in a cell fabricated with two-easy axes treated substrates is almost homogeneously aligned along an axes intermediate between the two different easy axes. The azimuthal angle j is determined by the balance of the torques from the different rubbing directions.

Figure 4 depicts the conoscopic patterns of (a) [0, 1], (b) [1, 1] and (c) [5, 1] rubbed cells, respectively. The cells used were 75µm thick. As shown in the figure, the conoscopic patterns are different at these cells, due to variation of the birefringence in the cells.



(a) (b) (c)



(a) (b) (c)

Fig. 5. Optical microscope images of (a) [0, 1], (b) [1, 1] and (c) [5, 1] rubbed cells under cross polarizers. The rubbing angle is 90° and the cells used are 15µm thick.

The variation comes from the stochastic random distribution of the LC molecules near the orientating film.[9-10)] The stochastic random distribution originates from the anchoring energy competition between the two different rubbing directions. Figure 5 depicts the optical microscope images of (a) [0, 1], (b) [1, 1] and (c) [5, 1] rubbed cells under cross polarizers; the rubbing angle is 90°, and the cells used are 15µm thick. As shown in Figs. 5(a) and (c), the LC molecules align homogeneous due to strong anchoring energy along one of the rubbing directions. However, in Fig. 5(b), the bright spots appear in the picture, due to equal surface induced anchoring energy in the two different rubbing directions. It indicates that the orientations of the LC molecules at the bright spots are different from other area, thus the orientation of the LCs is inhomogeneous in the cell.

Following unidirectional rubbing, the LC molecules align unidirectionally with a high order parameter and birefringence. However, following rubbing in two different directions, the LC molecules receive the surface induced anchoring energies from the rubbing in different directions. The anchoring energetic competition in different rubbing directions frustrates the orientation of the LC molecules, hence reduces the order parameter and the birefringence of the LC molecules. Figure 6(a) plots the measured

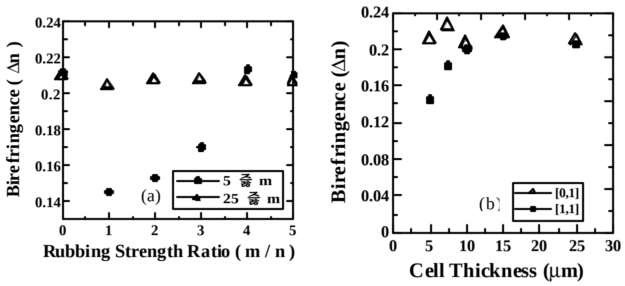


Fig. 6. (a) Birefringence of the two-easy axes LC cells with respect to the rubbing strength ratio. The rubbing angle is 90° and the cells used are 5μm thick; (b) Birefringence variation of the [1, 1] rubbed cells as a function of cell thickness.

birefringence of the LCs in the two-easy axes cells as a function of the rubbing strength ratio m/n, which is the ratio of the cumulative numbers of rub in the two different rubbing directions. The rubbing angle is 90° and the cells used are 5μm and 25μm thick, respectively. Following rubbing in the two different directions, the birefringence of the LC molecules rapidly declines due to distortion and frustration of the LCs next to the substrate. When the rubbing strength ratio m/n equals one, the frustration of the LCs becomes significant; hence, the birefringence reduction of the LC cell reaches maxima. As the rubbing strength ratio rises, the LC molecules are forced to align toward the direction in which the rubbing is stronger, and the order parameter and the birefringence of the LC molecules increase simultaneously. Therefore, the birefringence of the LC molecules increases steadily with the rubbing strength ratio and finally saturates. Figure 6(b) plots the measured birefringence variations of [1, 1] rubbed cells as a function of cell thickness. The figure demonstrates that rubbing in the different directions substantially reduces the birefringence of a thin cell because the LC molecules receive more surface anchoring energy from the substrate. Hence, the birefringence of the LC molecules falls substantially. As the cell thickness increases, the effect of the surface anchoring from the substrate decreases, and hence gradually increases the birefringence of the bulk LC molecules.

4. Conclusions

The alignment property of liquid crystals on a two-easy axes substrate is investigated. The two-easy axes substrate frustrates the orientation of the LCs next to the substrate, and hence influences the birefringence of the LC cell. The surface anchoring energetic competition between the two different rubbing directions contributes to the observed results. As the rubbing strength between the two different rubbing directions approximately equal, the orientation of the LCs is significantly frustrated, hence the birefringence of the two-easy axes LC cell decreases dramatically. Furthermore, for a thin cell, the birefringence falls markedly, due to the significant distortion and frustration of the LC molecules next to the substrate.

5. Acknowledgements

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6. References

[1] V. G. Chigrinov: Liquid Crystal Devices: Physics and Applications (Artech House, Boston, 1999).

[2] J. Li, S. Gauza and S. T. Wu: J. Appl. Phys. 96, 19 (2004).

[3] Y. J. Kim, Z. Zhuang and J. S. Patel: Appl. Phys. Lett. 24, 513 (2000).

[4] D. H. Chung, Y. Takanishi, K. Ishikawa, C. J. Yu, S. D. Lee and H. Takezoe: Jpn. J. Appl. Phys. 42 1686 (2003).

[5] C. Sanchez, R. Alcala, S. Hvilsted and P. S. Ramanujam: J. Appl. Phys. 93, 4454 (2003).

[6] D. W. Berreman: Phys. Rev. Lett. 28, 1683 (1972).

[7] A. A. Sonin: The Surface Physics of Liquid Crystals (Gordon and Breach Publisher, Singapore, 1995).

[8] P. J. Collings and M. Hird: Introduction to Liquid Crystals: Chemistry and Physics (Taylor Francis, London, 1997).

[9] A. L. Alexe-Ionescu, G. Barbero, Z. Gabbasova, G. Sayko and A. K. Zvezdin: Phys. Rev. E 49, 5354 (1994).

[10] R. Barberi, J. J. Bonvent, M. Giocondo and M. Iovane: J. Appl. Phys. 84, 1321 (1998).