Azimuthal Anchoring Energy Using the Splay Deformation in a Polarization Grating Configuration

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Received March 17, 2010; accepted April 23, 2010; published online June 7, 2010

We propose a simple method of measuring the azimuthal anchoring energy of liquid crystals by splay deformation in a binary polarization grating based on the linearly distorted director approximation. Under crossed polarizers, the splay-distorted regions near domain boundaries produce dark stripes whose widths represent distortion lengths, corresponding to the extrapolation lengths. The azimuthal anchoring energy was directly derived from the splay-distortion length. In addition, since the distortion lengths were measured at all domain boundaries, the azimuthal anchoring energy based on the statistical consideration could be estimated for a single sample. © 2010 The Japan Society of Applied Physics

DOI: 10.1143/JJAP.49.060204

The deformation at the dual-domain boundary plays an important role in the performance of liquid crystal (LC) devices, such as binary gratings, since the diffraction properties of the LC gratings strongly depend on the modulating profiles of the polarization states and/or refractive indices. Especially, the splay deformation in the LC polarization grating without defect-line, where the oppositely twisted LC domains are used for the polarization-invariance, originated from the azimuthal surface anchoring energy due to elastic continuity of the LC molecules. In addition, the azimuthal surface anchoring energy is one of the key parameters for the performance of LC devices, including LC displays, where the LC molecules switch on a plane parallel to the substrate. To estimate or measure azimuthal anchoring energy, a variety of techniques such as a constraining geometry technique, an external field technique, a rubbed alignment distribution method, and a defect analysis were proposed. In most methods, however, little statistical consideration of the estimated anchoring energy was reflected since only a single value was obtained for a single sample with the same conditions. It might be possible to take a temporal average through repeated measurements at the same sample in these methods or to take a case average at the different samples with different external parameters.

In this work, we propose a simple method of measuring an azimuthal anchoring energy of the LCs by splay deformation in an oppositely twisted polarization grating based on the linearly distorted director (LDD) approximation. Under the assumption of the linear deformation of the LC director near domain boundaries according to the continuum theory, the extrapolation length corresponding to the azimuthal anchoring energy can be analytically obtained. In the LC binary polarization grating as shown in Fig. 1, the LC molecules are twisted alternatively in opposite directions. In the optically adiabatic limit, the polarization of incident light through the uniformly aligned surface becomes rotated by an angle of either +45° or −45° with respect to the x-axis on passing the other surface with two oppositely twisted domains.

In the oppositely twisted domains, the azimuthal anchoring energy of the LCs in two oppositely twisted domains influence significantly the director distribution near domain boundary as shown in Fig. 2(a). Under the assumption that the LC molecules lie on the xy-plane parallel to the substrate, the azimuthal (twisted) angles of the LC molecules are continuously deformed near domain boundaries with forming splay regions on the top substrate. For simplification, assume that the LC directors are linearly distorted into two oppositely twisted regions along the y-axis and into bulk along the z-axis near domain boundary. Under the assumption that no molecular tilt angle exists in the whole region considered, the distribution of the molecular azimuthal (twisted) angle near the domain boundary between two oppositely twisted domains is shown in Fig. 2(b). The −45°-rotated alignment with respect to the x-axis was produced in the region of −w/2 ≤ y ≤ 0 and the +45°-rotated one in the region of 0 ≤ y ≤ w/2 on the top substrate at z = d. In the whole region on the bottom substrate at z = 0, the planar alignment was prepared parallel to the x-axis. Here, the regions of y < −w/2 and y > w/2 correspond to the intrinsically −45°- and +45°-twisted domains, respectively. As a result, the LC director was linearly twisted along the y-axis in the range of −w/2 ≤ y ≤ w/2 because of the curvature elasticity. As shown in Fig. 2(b), the azimuthal angle φ of the LC director in the yz-plane is expressed as

\[ \phi(y, z) = \frac{\pi y z}{2 w d}. \]  

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Fig. 1. Schematic diagram of our LC polarization grating with two oppositely twisted domains. At one substrate, the LC director is uniform along the x-axis and at the other, two directors in the two domains make angles of ±45° with respect to the x-axis.
where \( d \) and \( w \) represent the cell thickness and the distortion length, respectively.

We now discuss the total free energy with the LC director distribution shown in Fig. 2(b). In the case of the tilted and/or homeotropic anchoring surfaces, the polar and azimuthal anchoring strengths are indistinguishable.\(^{17–19} \) In our configuration, however, all directors lie parallel to the substrates and thus the only azimuthal anchoring effect is considered in the splay deformation regions. Using the Rapini–Papoular anchoring energy,\(^{20} \) the total free energy within the distorted region in the \( yz \)-plane is described as

\[
F_{\text{tot}} = \frac{\pi^2 K_{\text{eff}}}{24w^2d} \left( d^2 + \frac{w^2}{4} \right) + \frac{w W_a}{2} \left( \frac{1}{2} - \frac{1}{\pi} \right),
\]

where \( K_{\text{eff}} \) and \( W_a \) are the relevant elastic constant and the azimuthal anchoring energy, respectively. Minimizing eq. (2) with respect to \( w \), the length \( w \) is readily obtained as

\[
w = 2d \left[ 1 + \frac{24(\pi - 2)}{\pi^3} \cdot \frac{d}{\xi} \right]^{-1/2},
\]

where \( \xi = K_{\text{eff}} / W_a \) representing the extrapolation length. Finally, we derive the azimuthal anchoring energy as

\[
W_a = \frac{(4d^2 - w^2)\pi^3}{24(\pi - 2)w^2d} K_{\text{eff}}.
\]

As a consequence, the azimuthal anchoring energy is directly determined from measuring the distortion length \( w \).

For fabricating the oppositely twisted domains, the substrate with alternatively aligned LC domains was prepared using a single-masking process through two-step linearly polarized ultraviolet (LPUV) illumination of a photopolymer LGC-M2 (LG Cable).\(^{6} \) The LGC-M2 aligns the LC molecules homogeneously under the illumination of the LPUV light and repeatedly altering the direction of the LC alignment depending on the polarization of the LPUV light. After the first LPUV exposure on the whole substrate along the direction of 45° with respect to the \( x \)-axis (step 1), the second LPUV exposure was subsequently carried out through an amplitude photomask to align the LC along the direction of \(-45° \) to the \( x \)-axis (step 2). The grating period was 100 \( \mu \)m. The cell thickness was maintained using glass spacers of 9.48 \( \mu \)m. The nematic LC material of MLC-6012 (E. Merck) was used for this study. The microscopic textures of our LC polarization grating with oppositely twisted LC domains are shown in Fig. 3. The photographs showing two alternating stripes in our LC polarization grating were taken with a polarizing optical microscope (Nikon Optiphot-pol II) under the analyzer rotated by ±45° with respect to the polarizer. In bright domains, the LC molecules are aligned parallel to the analyzer, while in dark domains they are perpendicular to the analyzer. All the measurements were carried out at room temperature.

We measured the widths of the dark stripes between two adjacent domains shown in Fig. 4(a) to determine the azimuthal anchoring energy using eq. (4). Figure 4(a) shows the transmittance profile at a position denoted by a white-dashed line on the microscopic texture. The distortion lengths were determined by the widths of valleys in the intensity profiles of the transmittance along the grating vector. In this texture (480 × 210 pixels, while 480 × 320 pixels in original image), we can gather about 4,000 distortion lengths (about 7000 in original image) through scanning the transmittance profiles along the vertical direction. For 500 distortion lengths, the statistical distribution of the distortion length was shown in Fig. 4(b). Here, solid line represents a Gaussian-curve-fit of the distortion length. The central distortion length and the standard deviation were 8.59 and 1.48 \( \mu \)m, respectively. As a result, the corresponding anchoring energy was determined to be \((4.62 \pm 2.67) \times 10^{-6} \) J/m\(^2 \) for the cell thickness of \( d = 9.48 \mu \)m and the relevant elastic constant of \( K_{\text{eff}} \approx 10^{-11} \) N.

In summary, we proposed the simple method of measuring an azimuthal anchoring energy of the LCs using splay deformation in an oppositely twisted polarization grating configuration with the statistical consideration. According the LDD approximation, the azimuthal anchoring energy
was derived from the splay-distorted length, corresponding to the extrapolation length, into both twisted regions. Under crossed polarizers, the splay-distorted regions near domain boundaries produce dark stripes whose widths represent the distortion lengths. From measuring the domain boundaries in whole texture area, we could gather a lot of the distortion lengths in a single cell and thus the azimuthal anchoring energy was determined to be $(4.62 \pm 2.67) \times 10^{-6} \text{J/m}^2$ under statistical consideration.

Acknowledgment This work was supported by a grant (F0004121-2009-32) from Information Display R&D Center, one of the Knowledge Economy Frontier R&D Program funded by the Ministry of Knowledge Economy of Korean government and the research fund of Hanyang University (HY-2007-5932).

Fig. 4. (a) The intensity profile of the transmission at a position depicted by a white-dashed line on the microscopic texture and (b) the statistical distribution of the distortion length. The solid line in (b) represents the Gaussian-curve-fit.