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Measuring electric-field-induced birefringence in polymer stabilized blue-phase liquid crystals based on phase shift measurements

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A simple optical method to measure the electric-field-induced birefringence and Kerr constant of polymer-stabilized blue-phase liquid crystals (PSBP-LC) is demonstrated. By measuring the phase shift of PSBP-LC and the averaged refractive index of PSBP-LC at the voltage-off state, the ordinary refractive index and extraordinary refractive index of PSBP-LC as function of applied voltage can be obtained experimentally. As a result, the electric-field-induced birefringence and Kerr constant can be determined as well. The method we proposed can help in designing PSBP-LC-based photonic devices. © 2011 American Institute of Physics. [doi:10.1063/1.3583572]

I. INTRODUCTION

Blue-phase liquid crystals (BPLC) have attracted much attention recently since polymer-stabilized technology has widened their temperature range.¹ The advantages of polymer-stabilized BPLC (PSBP-LC) include that they are alignment-layer-free and have a fast response time and wide viewing angle.² The photonic applications of PSBP-LC are as displays, photonic crystal lasers, and tunable focusing microlens arrays.^{3–6} Based on Meiboom *et al.*'s model, PSBP-LC is an optically isotropic medium at the voltage-off state due to the structure of the double twist cylinders and is an optically anisotropic medium under an applied voltage.⁷ The capability of changing from optical isotropy to anisotropy of PSBP-LC can be quantified by the Kerr constant and electric-field-induced birefringence, which are also important parameters for designing photonic devices. To measure the Kerr constant, the electric-field-induced birefringence of BPLC or PSBP-LC is usually measured first and then is converted into the Kerr constant according to the Kerr equation.^{8–10} Moreover, many researchers proposed methods to obtain electric-field-induced birefringence of BPLC or PSBP-LC. For example, Haseba *et al.* proposed a method to measure the phase retardation of BPLC and then converted the phase retardation into the electric-field-induced birefringence and the Kerr constant.⁸ However, this method requires a corrected factor of 2.7 which is a material-dependent factor.⁸ Khoshshima *et al.*⁹ proposed a conventional method for measuring electric-field-induced birefringence of the Kerr cell, but it requires a large thickness of the Kerr cell and a high electric field. As a result, the structure of PSBP-LC is not easily developed and the material is easily damaged, owing to the large thickness of the Kerr cell.⁹ Yan *et al.* proposed a method based on a Michelson interferometer,¹⁰ but some assumptions were made to obtain the induced birefringence. Recently, Yan *et al.* proposed a direct measurement to measure the phase retardation, phase shift, and refractive index at the voltage-off state of PSBP-LC in order to obtain

the electric-field-induced birefringence and Kerr constant of PSBP-LC.¹¹ However, this method requires many individual optical setups, such as the Senarmont method, Michelson interferometer, and Abbe refractometer, to complete the measurement. Although many methods are proposed, the proposed methods still need to be improved. Therefore, an accurate and simple method to measure the Kerr constant and electric-field-induced birefringence of PSBP-LC is an urgent need.

In this paper, we developed a simple method to measure the electric-field-induced birefringence and Kerr constant of PSBP-LC by measuring phase shift of PSBP-LC. The principles and optical setup are simple. We first measured the phase shifts of PSBP-LC as functions of applied voltage at different incident angles of polarized light and measured the averaged refractive index of PSBP-LC at the voltage-off state. According to the results of phase shifts and the averaged refractive index, the ordinary refractive index of PSBP-LC and extraordinary refractive index of PSBP-LC as a function of applied voltage were obtained. As a result, the electric-field-induced birefringence of PSBP-LC was obtained as well. The Kerr constant was then determined according to the Kerr equation. The measurement of electric-field-induced birefringence and the Kerr constant of PSBP-LC we proposed can help designing and optimizing PSBP-LC-based photonic devices.

II. MECHANISM AND PRINCIPLES

The theoretical principle for measuring the electric-field-induced birefringence of PSBP-LC is described as follows. When light is incident on a PSBP-LC cell and the electric field is perpendicular to the glass substrates, the phase shift ($\Delta\delta$) of PSBP-LC between a high voltage (V) and no voltage can be expressed as:¹¹

$$\Delta\delta(\theta, V) = \frac{2\pi \times d}{\lambda \times \cos(\theta)} \cdot [n_i - n_{\text{eff}}(\theta, V)], \quad (1)$$

where d is cell gap, λ is wavelength of the incident light, n_i is the averaged refractive index of PSBP-LC at $V=0$, θ is

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the angle between the incident light and normal direction of PSBP-LC and $n_{\text{eff}}(\theta, V)$ is effective refractive index of PSBP-LC at θ at V which can also be expressed as:¹²

$$n_{\text{eff}}(\theta, V) = \left(\frac{\cos^2(\theta)}{n_o^2(V)} + \frac{\sin^2(\theta)}{n_e^2(V)} \right)^{-0.5}. \quad (2)$$

According to the multiple beam interference at different wavelength of incident light, n_i in Eq. (1) can be expressed as:¹²

$$n_i = \frac{m}{2 \times d} \cdot \frac{\lambda_1 \times \lambda_2}{\lambda_1 - \lambda_2}, \quad (3)$$

where λ_1 and λ_2 are the wavelengths of the light, and m is the number of the interference cycles between λ_1 and λ_2 . From Eq. (1), at $\theta = 0$, $\Delta\delta(\theta, V)$ can be simplified as:

$$\Delta\delta(\theta = 0, V) = \frac{2\pi \times d}{\lambda} \cdot (n_i - n_o(V)). \quad (4)$$

That means we can obtain $n_o(V)$ when we measure the phase shift of PSBP-LC at the normal incidence. At $\theta \neq 0$, we can obtain $n_e(V)$ according to Eq. (1), Eq. (2), and Eq. (4). In addition, the birefringence ($\Delta n(V)$) induced by the Kerr effect equals to $(n_e(V) - n_o(V))$, and $\Delta n(V)$ also equals to $\lambda \times K \times E^2$, where E is the external electric field and K is Kerr constant.¹¹ Thus, after replacing E by V/d , the Kerr constant can be expressed as:

$$K = \frac{d^2}{\lambda \times V^2} [n_e(V) - n_o(V)], \quad (5)$$

Therefore, we can obtain the electric-field-induced birefringence by measuring the phase shift of the PSBP-LC at different angles of polarized incident light at different voltages and then find the Kerr constant of PSBP-LC by Eq. (5).

III. EXPERIMENTS AND DISCUSSIONS

To prepare the sample of PSBP-LC, we mixed a positive nematic LC ($\Delta n = 0.142$) with two UV-curable monomers EHA (2-Ethylhexyl, Fluka) and RM257 (Merck), a chiral molecules CB15 (Merck), and photoinitiator DMPAP (Aldrich) at 56.9: 3.33: 3.42: 35.85: 0.5 wt. % ratios. The mixture at isotropic state was filled into an empty liquid crystal (LC) cell consisting of two Indium Tin Oxide (ITO) glass substrates without any alignment layers. The cell gap was $5.5 \mu\text{m}$. We then cooled down the cell at the cooling rate of $0.1 \text{ }^\circ\text{C}/\text{min}$, and the blue phase appeared at the temperature $T < 30 \text{ }^\circ\text{C}$. The cell was then exposed by UV light at $28.5 \text{ }^\circ\text{C}$ with intensity $\sim 3 \text{ mW}/\text{cm}^2$ for 30 min for photopolymerization. After photopolymerization, the temperature range of PSBP-LC was between $20 \text{ }^\circ\text{C}$ and $41 \text{ }^\circ\text{C}$. According to the results of the Kossel diagram, the structure of the sample is blue phase II (BPII). The morphology of PSBP-LC was then observed under reflective polarizing microscopy, as shown in Fig. 1. Figure 1 shows the typical selective Bragg reflection and the Mozaic platelet structure of PSBP-LC. The domain size is around $20\text{--}50 \mu\text{m}$.

To measure the electric-field-induced birefringence of PSBP-LC, we measured the phase shift of the sample of

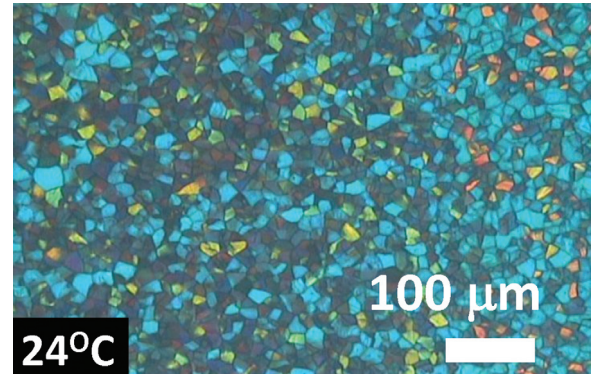


FIG. 1. (Color online) The morphology of PSBP-LC observing under a reflective polarizing optical microscopy at $24 \text{ }^\circ\text{C}$.

PSBP-LC. The experimental setup is depicted in Fig. 2. The incident light source was an unpolarized He–Ne laser (JDSU model 1122, $\lambda = 633 \text{ nm}$). The incident light passed through a polarizer and then was split into two arms by a beam splitter. The light of one arm, the signal arm, was incident on the sample driven by a square-wave voltage at frequency $f = 1 \text{ kHz}$ and then reflected by a dielectric mirror (M_2). The other arm, the reference arm, was incident on a dielectric mirror (M_1) and then was combined with the signal arm by another beam splitter. The interference fringes were magnified by a lens and recorded by a digital video camera (SONY, DCR-HC40). In Fig. 2, the direction of the incident polarization is x-linearly polarized. In fact, the angles of the incident linearly polarized lights do not affect the overall phase shift. We measured the phase shift at the different rotation angles (θ) of the sample according to the position shift of the interference fringes.¹² We also used a white light source and spectrometer (Shimadzu, UV-210 A) for measuring the averaged refractive index of PSBP-LC at $V = 0$ and $\theta = 0$ based on the multiple beam interference. The whole system was built on a floating optical table to avoid any environment-induced fluctuation. In this setup, we can measure both the phase shift and averaged refractive index of PSBP-LC at the voltage-off state.

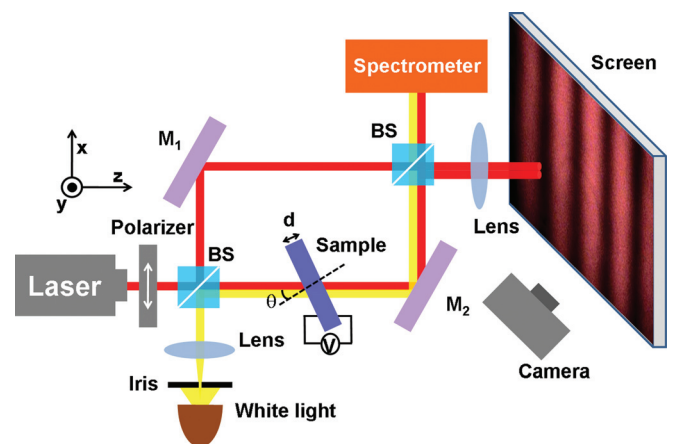


FIG. 2. (Color online) The experimental setup for measuring the phase shift of PSBP-LC and the averaged refractive index of PSBP-LC at the voltage-off state. M_1 is a dielectric mirror, M_2 is a dielectric mirror, BS is a beam splitter, and d is the cell gap of the sample. The arrow of polarizer indicates the transmissive axis of the polarizer.

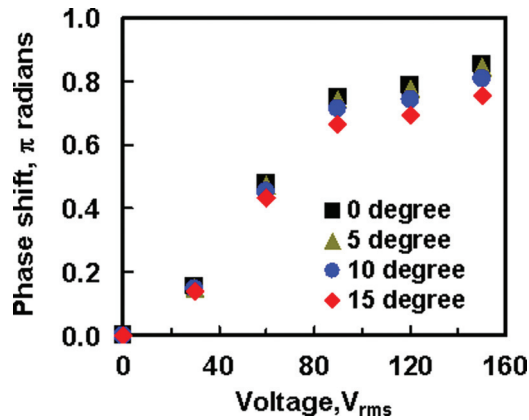


FIG. 3. (Color online) The measured voltage-dependent phase shifts at different rotation angles: 0°, 5°, 10°, and 15°. The temperature was 24 °C.

The measured voltage-dependent phase shifts at different rotation angles (i.e., θ in Fig. 2) were shown in Fig. 3. The phase shift increases with the applied voltage because of the increase of the birefringence induced by Kerr effect. The maximum phase shift at $\theta=0$ at 150 V_{rms} is around 0.85 π radians. At a fixed voltage, the phase shift decreases with the rotation angle. That is because the effective refractive index of PSBP-LC increases. From the results of the spectrum and Eq. (3), the measured averaged refractive index n_i is around 1.5596. (The data are not shown here). From Eq. (4), n_i , and the measured data at 0° in Fig. 3, we can obtain the $n_o(V)$ as a function of voltage, as plotted in Fig. 4 (black squares). From Eq. (1), Eq. (2), and the measured data at 5°, 10°, and 15° in Fig. 3, the $n_e(V)$ as a function of voltage at 5 degree, 10 degree, and 15 degree are plotted in Fig. 4 as well. In Fig. 4, $n_o(V)$ decreases with an applied voltage while $n_e(V)$ increases with an applied voltage because the increase of birefringence induced by Kerr effect. At different rotation angles, we obtain the same extraordinary refractive index $[n_e(V)]$ as a function of voltage. From $n_o(V)$ and $n_e(V)$, we also plotted $n_i(V) = [2 \times n_o(V) + n_e(V)]/3$ in Fig. 4 (gray dots with gray line). As one can see, the $n_i(V)$ decreases from 1.5596 to 1.5499 with voltage.

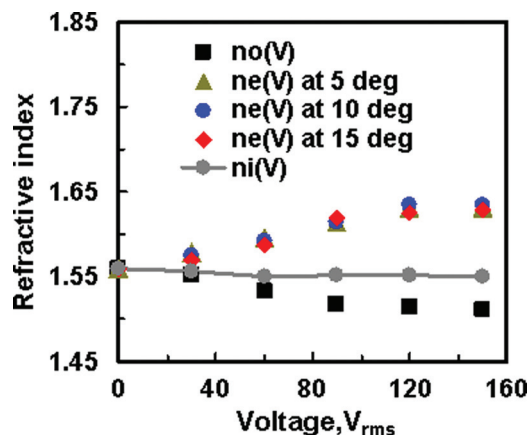


FIG. 4. (Color online) The ordinary refractive index (squares) as a function of voltage, and extraordinary refractive index as a function of voltage at rotation angles of 5° (triangles), 10° (dots), and 15° (diamonds). The gray dots with gray line indicate the averaged refractive index of PSBP-LC as a function of applied voltage.

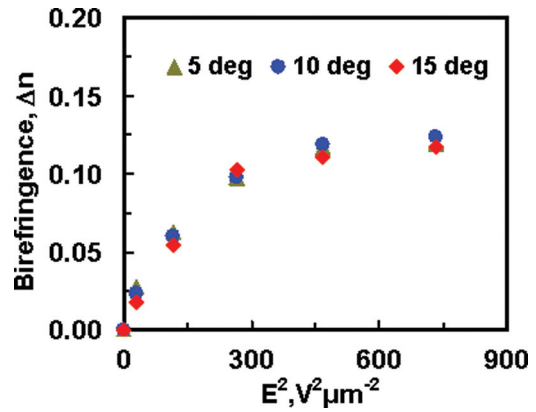


FIG. 5. (Color online) The birefringence of PSBP-LC as a function of the squared electric field at rotation angles of 5° (triangles), 10° (dots), and 15° (diamonds).

We then converted Fig. 4 into Fig. 5 which is the birefringence $[n_e(V) - n_o(V)]$ of PSBP-LC as a function of the squared electric field at different rotation angles. The maximum birefringence is around 0.117, which is smaller than the host BPLC (~ 0.142). That is because the concentration of BPLC is not 100% and some LC molecules are tangled with the polymer chains as well. In Fig. 5, the Kerr effect which follows the equation: $\Delta n(V) = \lambda \times K \times E^2$ holds only when the electric field is small. We can calculate the Kerr constant $K = \Delta n(V)/\lambda \times E^2 \sim 7.93 \times 10^{-10} m/V^2$ after putting in the experimental parameters: λ is 633 nm and the slope in the small electric field is $\sim 5.02 V^2 m^{-2}$ at 60 V_{rms} in Fig. 5. Compared to the extended Kerr effect proposed by Yan *et al.*,¹⁰ Kerr constant can be expressed as: $K = 3 \times [n_i - n_o(V)] / (\lambda \times E^2) \sim 10.8 \times 10^{-10} m/V^2$ after putting in the experimental parameters: $n_i \sim 1.559624$, $n_o(E) \sim 1.53232$ at 60 V_{rms} . The Kerr constants are close to each other by the different methods. The error mainly comes from the ratio of $\Delta n(V)$ to $[n_i - n_o(V)]$. Instead of 3, the ratio of $\Delta n(V)$ to $[n_i - n_o(V)]$ in our experiment is less than 3. We averaged the ratio of $\Delta n(V)$ to $[n_i - n_o(V)]$ at all voltages and the ratio is around 2.42. The reason why the ratio is less than 3 might be because the lattice distortion accompanies the local orientation of molecules.¹¹

IV. CONCLUSION

In conclusion, we developed a simple method to measure the electric-field-induced birefringence and Kerr constant of PSBP-LC by measuring phase shift of PSBP-LC. The optical setup is simple. The related optical principle is introduced. In our method, the ordinary refractive index of PSBP-LC and extraordinary refractive index of PSBP-LC as a function of applied voltage can be determined, and then the electric-field-induced birefringence of PSBP-LC and the Kerr constant are obtained. We also measured a sample of PSBP-LC as an example. The measured electric-field-induced birefringence at high voltage is around 0.117 and the Kerr constant is $7.93 \times 10^{-10} m/V^2$. The measurement of the electric-field-induced birefringence and the Kerr constant of PSBP-LC we proposed can help in designing and optimized PSBP-LC-based photonic devices, such as displays, electro-optical switches, and tunable focusing lens arrays.

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