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Fringing field-induced monodomain of a polymer-stabilized blue phase liquid crystal

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The influence of fringe electric field applied during photopolymerization on the electro-optic properties of polymer-stabilized blue phase liquid crystals (PS-BPLCs) was investigated. It has been found that the thermal stability would not degrade if the electric field was less than a critical value. The contrast ratio of PS-BPLC can be improved significantly because the uniformity of blue phase liquid crystal domain was enhanced by the electric fields, which were applied during photopolymerization. Meanwhile, with the electric filed, the potential energy of the BPLC molecules may lower the anchoring energy of the polymer network resulting in the improvement of electro-optic response properties. With optimized electric field during polymerization, the contrast ratio and the Kerr constant of PS-BPLC can be improved by 4.1 times and 15%, respectively, and the hysteresis can be decreased by 10%, while the response time and residual birefringence have no degradation. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4938072]

Blue phase liquid crystals (BPLCs) are self-assembled photonic crystals, which consist of a regular array lattice of double twist cylinders (DTCs) with disclination lines in a narrow temperature range between the isotropic phase and the chiral nematic phase. The BPLCs have attracted great interest for their potential applications in field sequential displays, phase modulator devices, and tunable photonics,[1–6] due to the interesting features including sub-millisecond response time, macro optical isotropic status, and self-assembled photonic crystal structures on the order of visible wavelength, since the temperature range has been broadened to more than 60 °C by stabilizing the disclination lines with polymer networks.[7,8] However, there are still some issues, such as high driving voltage, low contrast, hysteresis, and residual birefringence, which should be solved prior to the wide application of polymer-stabilized blue phase liquid crystals (PS-BPLCs).[9–11] The light diffraction from Bragg refection and polarization rotation effect in PS-BPLC degrade the dark state and lead to a poor contrast ratio.[11–14] These issues can be solved by rotating analyzer,[11] compensation film design,[13] and circular polarizer,[14] but the optical structure becomes more complicated and the rotation angle is wavelength dependent. The reflective display using surface alignment and vertical electric field-induced monodomain BPLC with high reflectance and vivid colors was demonstrated.[15,16] It exhibits narrow reflection bandwidth (~25 nm), analog grayscales, sub-millisecond response time, and selective reflect of right-handed circularly polarized light, when chiral dopant is right-handed.[16] However, the alignment layer shields the voltage, and the contrast ratio is relatively low due to surface reflection.[17] Xu *et al*. proposed a stabilization method of PS-BPLCs which reduced the hysteresis significantly and improved response time. By polymerizing photopolymers with linear polarized ultraviolet (UV) light, anisotropic polymer networks are formed and electrostriction effect is suppressed.[18] To improve the driving capacity of PS-BPLC device, several approaches have been demonstrated, including the large Kerr constant BPLC material,[19] polymer system with reactive diluent,[20] and the device structure optimization.[21–23] In spite of the remarkable achievements in reducing the driving voltage, the fabrication process becomes complicated and additional optical components are needed.

In this paper, a stabilization process by applying horizontal electric field to the PS-BPLCs is demonstrated to improve the contrast ratio and electro-optic properties of PS-BPLCs. The electric field applied during polymerization may enhance the uniformity of blue phase domains resulting in a good dark state. Meanwhile, the potential energy of the BPLC molecules may offset the anchoring energy of the polymer network with the electric field, which can improve the electro-optic properties of PS-BPLC device.

In our experiment, a nematic liquid crystal (LC) (BP006, Jiangsu Hecheng Display Technology Co., Ltd. (HCCH)) was used as a LC host, whose properties are listed as follows: $\Delta n = 0.158$ at $\lambda = 633$ nm and $T = 20$ °C, $\Delta\varepsilon = 34.2$ at 1 kHz and 20 °C, and $T_c = 80.5$ °C. The BPLC precursors were composed of 88.67 wt. % LC host (BP006, HCCH), 3.16 wt. % chiral dopant (R5011, HCCH), 3.53 wt. % UV-curable monomer (12A, HCCH), 3.80 wt. % cross-linker (RM257, HCCH), and 0.84 wt. % photo-initiator (IRG184, HCCH). After mixing, the precursors were filled into in-plane switching (IPS) cells without alignment layer at isotropic phase in a temperature controller (HCS302, Instec Co.). The cell gap of IPS cell was 7.5 μm. The indium tin oxide (ITO) electrode width was 7.5 μm and the electrode gap was 12.5 μm.

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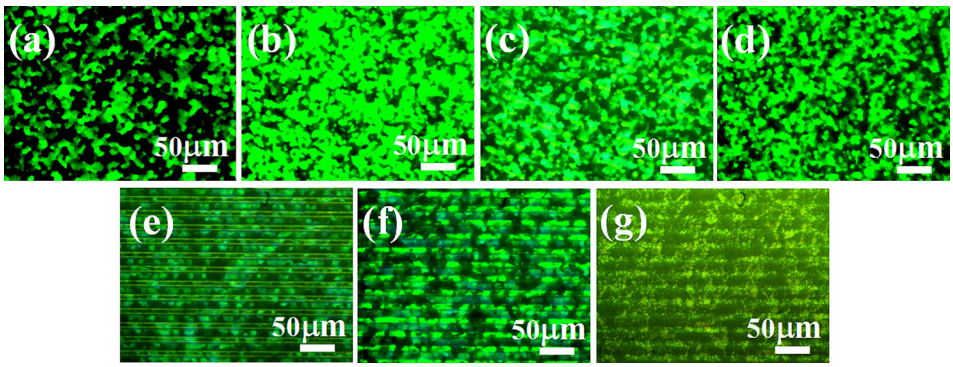

FIG. 1. Texture of BPLC after polymer stabilization with different electric fields: (a) 0 V/μm, (b) 0.18 V/μm, (c) 0.37 V/μm, (d) 0.55 V/μm, (e) 0.74 V/μm, (f) 0.92 V/μm, and (g) 1.1 V/μm.

At a cooling rate of 0.5 °C/min, the blue phase platelet textures of the BPLC precursor without electric field could be observed from 64.0 °C to 58.9 °C under a polarized optic microscope (POM, XPL-30TF). To investigate the electric field effect on the polymerization of PS-BPLC, several kinds of 1 kHz square-wave AC signal were applied to the test cells during polymerization process. The electric fields induced by the electrodes of the IPS cell were highly inhomogeneous.[24] The electric fields in different areas of the IPS cell were simulated by simulation software, TechWiz LCD 3D (Sanayi System). Then, by calculation, we could get the average electric field of the IPS cell, 0.18 V/μm, 0.37 V/μm, 0.55 V/μm, 0.74 V/μm, 0.92 V/μm, and 1.1 V/μm with different voltages, 4 V, 8 V, 12 V, 16 V, 20 V, and 24 V applied during polymerization, respectively. Then, the cells were exposed to ultraviolet irradiation (UV, $\lambda = 365$ nm) with intensity of 3 mW/cm^2 for 10 min. After polymerization, the temperature range of blue phase was broadened to more than 80 °C when the average electric field was less than a critical value of 0.92 V/μm, but the blue phase would transit to chiral nematic phase if the electric field during polymerization was higher than 1.1 V/μm. As shown in Fig. 1, compared to the PS-BPLC cell without electric field during photopolymerization, more uniform texture of monodomain BPLC is formed after polymer stabilization with electric field. The strong electric field at the electrode edge leads to the local lattice orientation of BPLC and induces stripe textures. If high voltages are applied during polymerization, light scattering will be induced by the local lattice variation of BPLC and the locally fixed LC birefringence.

To measure the electro-optic properties of the PS-BPLC, a 7 in. pad backplane, a uniform light source with white light-emitting diodes (LEDs) whose spectrum may cover all the visible light spectrum, was used to avoid diffraction of IPS cell. The IPS cell applied with a 1 kHz square-wave signal was placed between two crossed linear polarizers. The angle of the polarization direction and the electrode stripe was 45°. As the PS-BPLC reflected green light from Bragg reflection, the reference wavelength of the IPS cells was set to 633 nm to avoid the effect of Bragg reflection. Without the sandwiched LC cell, the extinction ratio of the crossed polarizers was 17 000:1.

Figure 2(a) depicts the normalized voltage-dependent transmittance (V-T) curves of the IPS cells after polymerization with different electric fields. The contrast ratio and the Kerr constant of the PS-BPLC are shown in Fig. 2(b). With the electric field during polymerization increasing from 0 V/μm to 0.18 V/μm, the contrast ratio increases from 116 to 1000. However, if the electric field keeps increasing from 0.18 V/μm to 0.92 V/μm, the contrast ratio decreases from 1000 to 3. Therefore, with the optimized electric field 0.18 V/μm, the contrast ratio of PS-BPLC cell can be increased by a factor of 8.6 compared with the PS-BPLC cell without electric field during polymerization. The BPLC device is supposed to have a high contrast ratio due to its macro optical isotropic status. However, scattered light from the non-uniform lattice planes and domains on microscopic state in BPLCs may cause light leakage which leads to a low contrast ratio.[12,25] As a proper electric field during polymerization induces a uniform domain orientation of the blue phase liquid crystal, the light leakage is reduced and high contrast ratio can be achieved, as shown in Fig. 3. However, if the electric field is higher than a critical value, the dark status of the PS-BPLC devices will degrade due to the electric field-induced birefringence. The birefringence can be easily induced with large dielectric anisotropy LC host. The narrow electrode gap may lead to relatively high horizontal electric fields, which can lead to unwanted

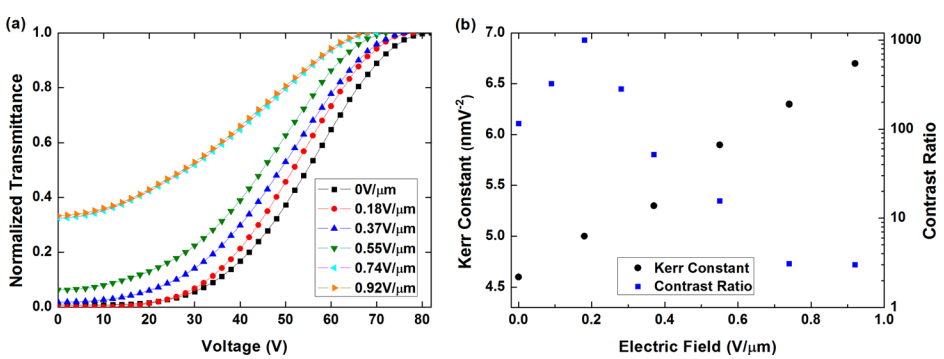

FIG. 2. (a) Normalized voltage-dependent transmittance (V-T) curves of PS-BPLC cells with different electric fields during polymerization at $\lambda = 633$ nm and (b) contrast ratio and Kerr constant of PS-BPLCs with different electric fields during polymerization at $\lambda = 633$ nm.

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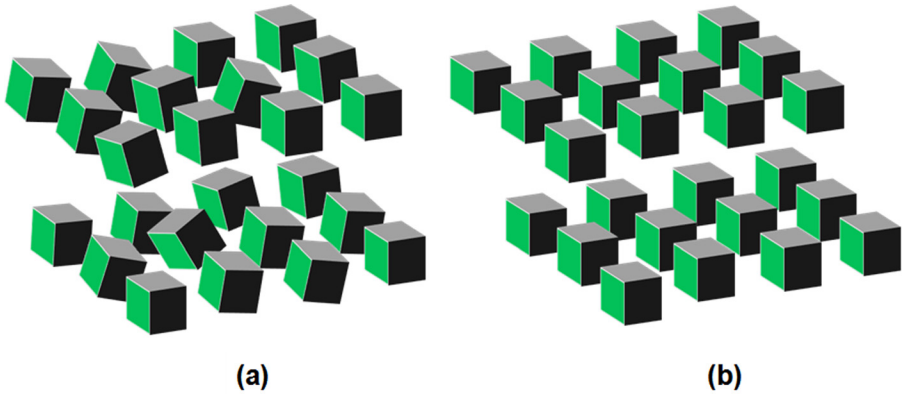

FIG. 3. Orientation of the blue phase liquid crystal domain (a) without electric field during polymerization and (b) electric field-induced uniform crystal domain.

appearance of nematic domains and cause residual birefringence. Therefore, the optimal average electric field that leads to uniform monodomain samples will be lower in a LC host of large dielectric anisotropy and narrow electrode gap IPS structure.

The Kerr constant can be extracted from the V-T curves with the extended Kerr effect model.[26] As shown in Fig. 2(b), with optimal electric field of 0.18 V/μm, in addition to significantly enhanced contrast ratio, the Kerr constant is increased by 8.7% compared with the PS-BPLC cell without electric field. According to previous research, the Kerr constant of PS-BPLC can be improved by polymer network with low anchoring energy.[19,27–30] The potential energy of the BPLC molecules increases with the electric field, which may offset the anchoring energy of polymer network. Therefore, the Kerr constant can be increased, and the electro-optic properties of PS-BPLC can be improved.

As illustrated in Fig. 2(b), when the electric field is higher than 0.18 V/μm, the Kerr constant increases while the contrast ratio decreases. Therefore, the frequency effect of the electric field in polymerization process is investigated to improve the contrast ratio of PS-BPLC with large Kerr constant. Figures 4(a), 4(b), and 4(c) depict the V-T curves of the BPLCs after polymerization with electric fields of 0.37 V/μm, 0.55 V/μm, and 0.74 V/μm at different frequencies, respectively. The BPLC cell with the high electric field of 0.74 V/μm at high frequency, 500 kHz, cannot be stabilized.

The contrast ratio and the Kerr constant of the PS-BPLCs with electric fields during polymerization at different frequencies are shown in Figs. 4(d) and 4(e). As the frequency increases, the contrast ratio of the PS-BPLC cell with electric field of 0.37 V/μm, 0.55 V/μm, and 0.74 V/μm increases from 52 to 595, 16 to 116, and 3 to 10, respectively. The electric field-induced birefringence during polymerization is governed by Kerr effect as follows:

$$\Delta n_{ind} = \lambda K E^2, \tag{1}$$

where λ is the wavelength, K is the Kerr constant, and E is the electric field. According to Gerber's model,[31] K is governed by the birefringence (Δn), dielectric anisotropy ($\Delta\varepsilon$), average elastic constant (k), and chiral pitch length (P) as

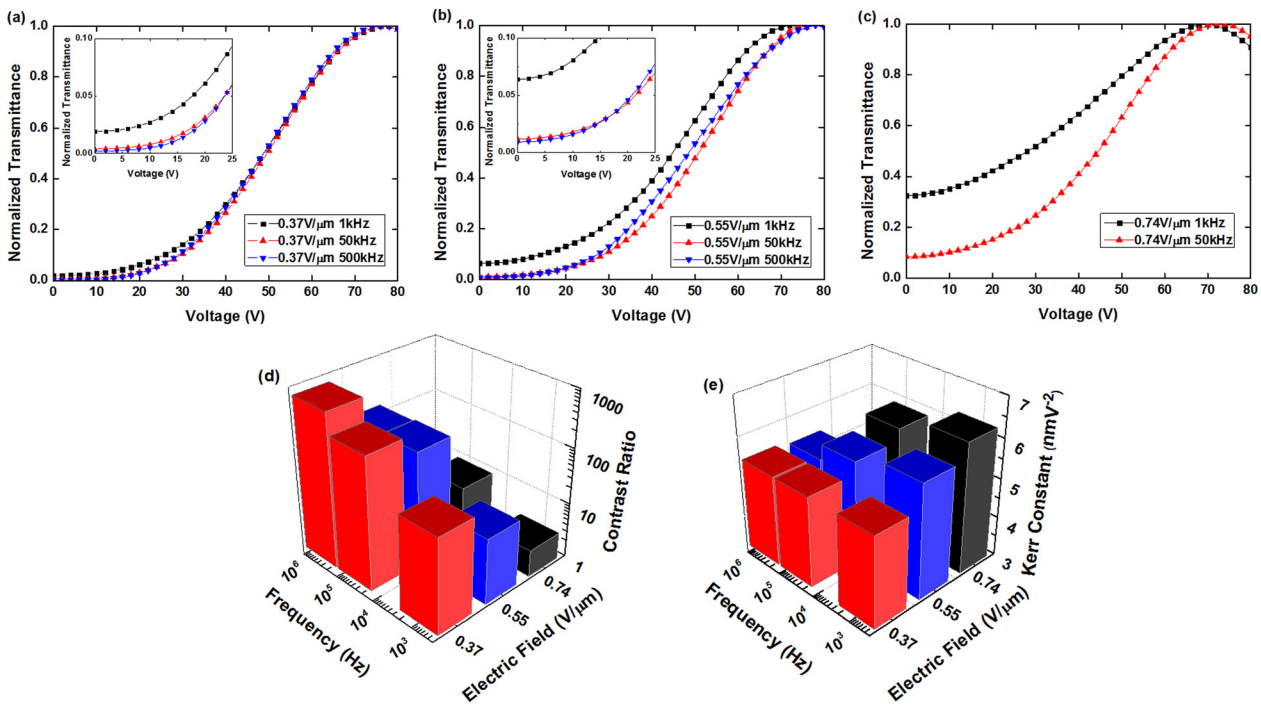

FIG. 4. Normalized V-T curves with electric fields during polymerization at different frequencies of (a) 0.37 V/μm, (b) 0.55 V/μm, and (c) 0.74 V/μm. (d) The contrast ratio and (e) the Kerr constant of the PS-BPLCs with different electric fields during polymerization of 0.37 V/μm, 0.55 V/μm, and 0.74 V/μm.

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$$K \sim \frac{\Delta n \Delta\varepsilon \varepsilon_0 P^2}{k\lambda(2\pi)^2}. \quad (2)$$

From the Debye relaxation model, $\Delta\varepsilon$ is frequency dependent as the following:[32]

$$\Delta\varepsilon = \Delta\varepsilon_\infty + \frac{\Delta\varepsilon_0 - \Delta\varepsilon_\infty}{1 + (f/f_r)^2}, \quad (3)$$

where $\Delta\varepsilon_\infty$ and $\Delta\varepsilon_0$ represent the dielectric anisotropy at high and low frequency limits, respectively, f is the driving frequency, and f_r is the relaxation frequency. By the Kerr effect, the birefringence induced by the electric field with high frequency during polymerization is smaller than that of PS-BPLC with low frequency as the $\Delta\varepsilon$ and Kerr constant decrease with the frequency.[33,34] However, when the electric field during polymerization is high, the PS-BPLC cell still has low contrast ratio as the induced birefringence is proportional to E^2. The Kerr constant of the PS-BPLCs decreases slightly when the frequency of the electric field increases, as the effect of offsetting the anchoring energy by the electric field decreases in high frequencies.

Hysteresis and residual birefringence are the key issues to affect the grayscale in LCDs which should be solved before the wide application of PS-BPLCs. The effect of electric field applied during polymerization on hysteresis and residual birefringence is shown in Fig. 5. With the electric field of 0.92 V/μm during polymerization, the hysteresis is decreased by 52% compared to that without electric field. As the voltage applied during polymerization decreases the operation voltage, the lattice deformation induced by strong driving electric field will be degraded resulting in the low hysteresis. The residual birefringence increases gradually when the electric field during polymerization is higher than 0.37 V/μm, as shown in Fig. 5. The residual birefringence increases because the polymer network with low anchoring energy cannot easily recover to its initial state. According to the measurement results, with the optimized electric field, 0.37 V/μm at frequency of 500 kHz, the contrast ratio and the Kerr constant of PS-BPLC can be improved by 4.1 times and 15%, respectively, and hysteresis can be decreased by 10%, while the residual birefringence shows no degradation. Although the direction of electric field is not uniform in the entire space of IPS cell, the uniform horizontal electric field may occupy most of the area in the IPS

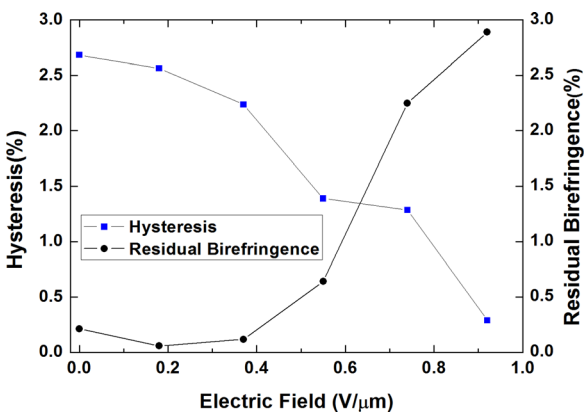

FIG. 5. The hysteresis and residual birefringence of PS-BPLCs with different electric fields during polymerization.

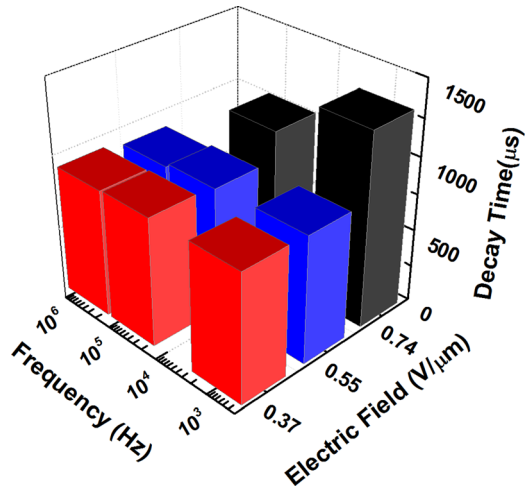

FIG. 6. The decay time of the PS-BPLCs with different electric fields during polymerization of 0.37 V/μm, 0.55 V/μm, and 0.74 V/μm.

cell, which induces the uniform domain and improves the contrast ratio of the PS-BPLC cells. Meanwhile, compared to the vertical electric field, the horizontal electric field can improve the electro-optic properties of the IPS-BPLCs. The strong electric field near the electrode edge may induce a large birefringence during polymerization process which degrades the dark status of the PS-BPLC cells.

For PS-BPLC, the fast response time is an attractive feature. As the rise time depends on the driving voltage, we only evaluate the decay time in this paper. As shown in Fig. 6, the decay time of the PS-BPLC cells with low electric field during polymerization is in the sub-millisecond level, but increases slightly with high electric field due to the lowered anchoring energy of the polymer network. Therefore, the response time of PS-BPLCs will not degrade with the low electric fields during polymerization.

In conclusion, applying electric fields during polymerization can enhance the electro-optic properties of PS-BPLCs. The electric field induces a uniform blue phase liquid crystal monodomain, thus improves the contrast ratio of PS-BPLC. With an optimized electric field, the contrast ratio and the Kerr constant of PS-BPLC can be improved by 4.1 times and 15%, respectively, and hysteresis can be decreased by 10%, while the response time and residual birefringence will not suffer from degradation. The PS-BPLCs with uniform monodomain and enhanced electro-optic properties show more benefits for applications for color sequential displays, phase modulators, and photonic devices.

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