Hysteresis Effects in Blue-Phase Liquid Crystals

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Abstract—Hysteresis effects of two blue-phase (BP) liquid crystals BP-I and BP-II, and polymer-stabilized BP-I and BP-II are investigated. BP-I exhibits a relatively slow response time and a large hysteresis. After polymer stabilization, its operating voltage is increased slightly, but its response time is dramatically reduced and hysteresis narrowed. In contrast, BP-II exhibits almost no hysteresis and submillisecond response time, but after polymer stabilization its hysteresis is amplified.

Index Terms—Blue phase liquid crystal (BPLC), hysteresis effect, color sequential display.

I. INTRODUCTION

POLYMER-STABILIZED blue-phase liquid crystal (PS-BPLC) [1]–[6] holds potential to become next-generation display technology because of its submillisecond gray-to-gray response time [7], alignment-layer-free process, optically isotropic dark state, and cell gap insensitivity. Basically, BPLC is a highly chiral liquid crystal system possessed crystal like unit cell structure. From both Landau theory and defect theory [8], the lattice structure of a BPLC system can be classified into three types, i.e., body-centered cubic (BP-I), simple cubic (BP-II), and isotropic phase with identical symmetry (BP-III) [9]. Previously, the temperature range for a BPLC system is limited to few degrees [10]. But after polymerization, the stable temperature range for a BPLC system can be extended over 60 deg [1]. However, some important practical issues, such as operating voltage, hysteresis, residual birefringence, and long term stability remain to be addressed before its widespread applications can take off. Hysteresis is a commonly observed phenomenon in chiral [11] and polymer network systems [12]. Thermal hysteresis in a BPLC system that is due to different heating and cooling processes has been reported [13]. However, for display applications the Kerr effect-induced birefringence in a PS-BPLC system is even more complicated because it involves voltage-induced hysteresis, which will affect the accuracy of grayscale controls.

In this paper, we investigate the hysteresis effects in BP-I, BP-II, and polymer-stabilized BP-I and BP-II LC composites. Prior to polymerization, BP-I exhibits a fairly large hysteresis, but BP-II is free from hysteresis. After polymerization, the hysteresis of BP-I is slightly reduced but, on the contrary, the hysteresis of BP-II is amplified noticeably.
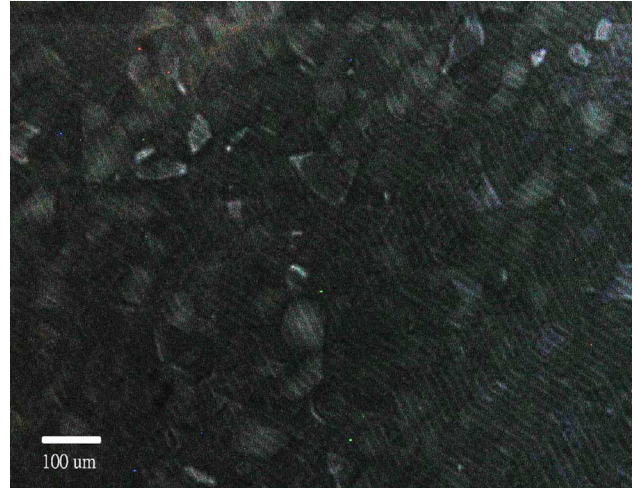
Fig. 1. Microscope photo at BP-I showing shadow-like platelets. Polarizers are crossed.

II. EXPERIMENT

To prepare BP LC samples, we used a high birefringence ($\Delta n \sim 0.27$) nematic mixture BL-038 and doped with 25 wt% chiral agents CB15 and R-1011 (both from Merck). This mixture was sandwiched between two glass substrates. The top glass substrate was a plain glass, and the bottom glass substrate was coated with zigzag ITO (indium tin oxide) electrodes, in the in-plane switching (IPS) geometry. The cell parameters are as follows: electrode width is 5 μm, electrode spacing is 10 μm, cell gap is $\sim$13 μm, and tilt angle between the zigzag electrodes is 152°. Ideally, we prefer to use simple IPS strip electrodes. The zigzag electrodes will affect the maximum transmittance, but will not affect the hysteresis effects we report here.

III. RESULT AND DISCUSSION

A. Blue-Phase Mixtures

For a full-color transmissive display, the reflection band of the BPLC mixture should be shifted outside the visible region. Fig. 1 shows a microscope photo of BP-I observed under crossed polarizers. The photo was post processed by enhancing the brightness and contrast in order to reveal the detailed structures. In BP-I, the classical shadow-like platelets are observed; their average size is $\sim$50 μm. As the temperature increases, BP-II appears and the shadow-like platelets are vanished resulting in a very good dark state.

To measure the electro-optical properties of our BPLC systems, we used a He–Ne laser ($\lambda = 632.8$ nm) as light source. The BPLC cell was placed between two crossed polarizers. In an IPS cell, the electric field-induced birefringence is in lateral direction. We rotated the cell in azimuthal direction to maximize the transmittance in a voltage-on state. A root-mean- square
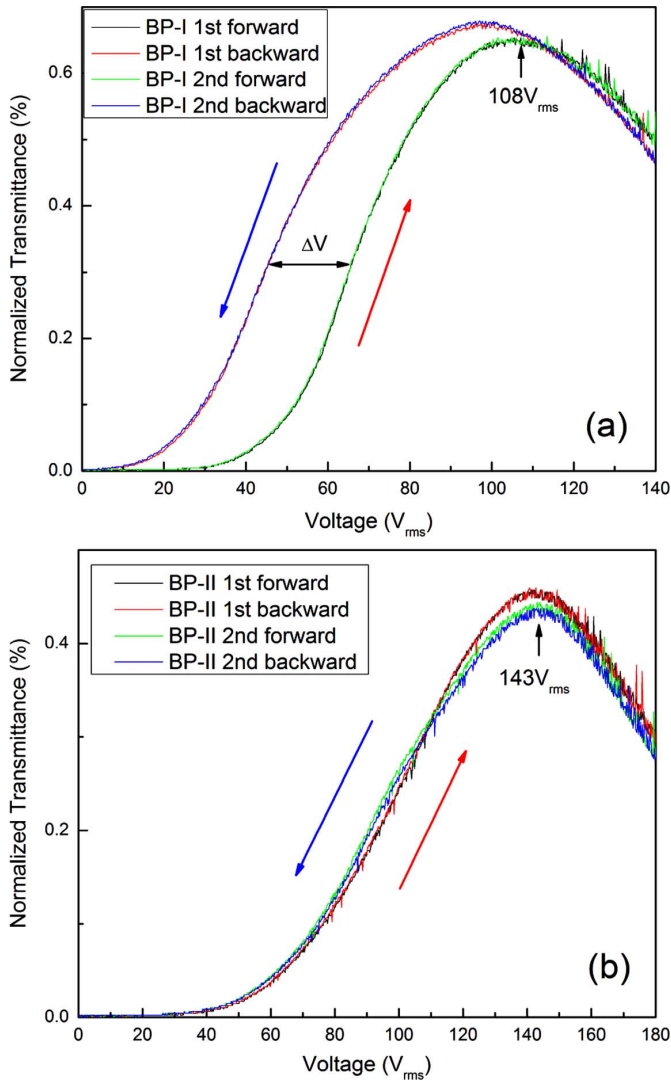
Fig. 2. Measured VT curves of the IPS cell at (a) BP-I, and (b) BP-II states. In each curve, two ascending and descending cycles are shown. $\lambda = 633$ nm.

Fig. 3. Measured response times in (a) BP-I and (b) BP-II states.

voltage with 1 kHz square waves was used to drive the IPS cell. Fig. 2(a) and (b) shows the measured voltage-dependent transmittance (VT) curves in BP-I (39 °C) and BP-II (40 °C), respectively. The voltage ramping rate was 100 ms per step. The transmittance was normalized to that when the BPLC cell was in an isotropic state and the two polarizers are in parallel position. In the BP-I state, as the voltage increases the transmittance increases gradually and reaches a peak (~64%) at $V_p \sim 108.2$ V_{rms}. While the voltage is descending from 150 V_{rms} the transmittance decreases but along a different route, as Fig. 2(a) shows. Although the hysteresis loop is quite noticeable, the ascending and descending curves are repeatable over many cycles. The hysteresis defined by the voltage difference at half-maximum transmittance between forward and backward directions is $\Delta V \sim 20$ V_{rms}. The ratio of $\Delta V/V_p$ is ~18.5%. For display applications, this ratio should be smaller than 5%.

Fig. 2(b) depicts the measured VT curves in a BP-II state. Similarly, the transmittance rises as the voltage increases, and V_p occurs at 143 V_{rms} with maximum transmittance ~44%. In the backward route, the VT curve overlaps reasonably well with the forward one. This measurement was repeated several
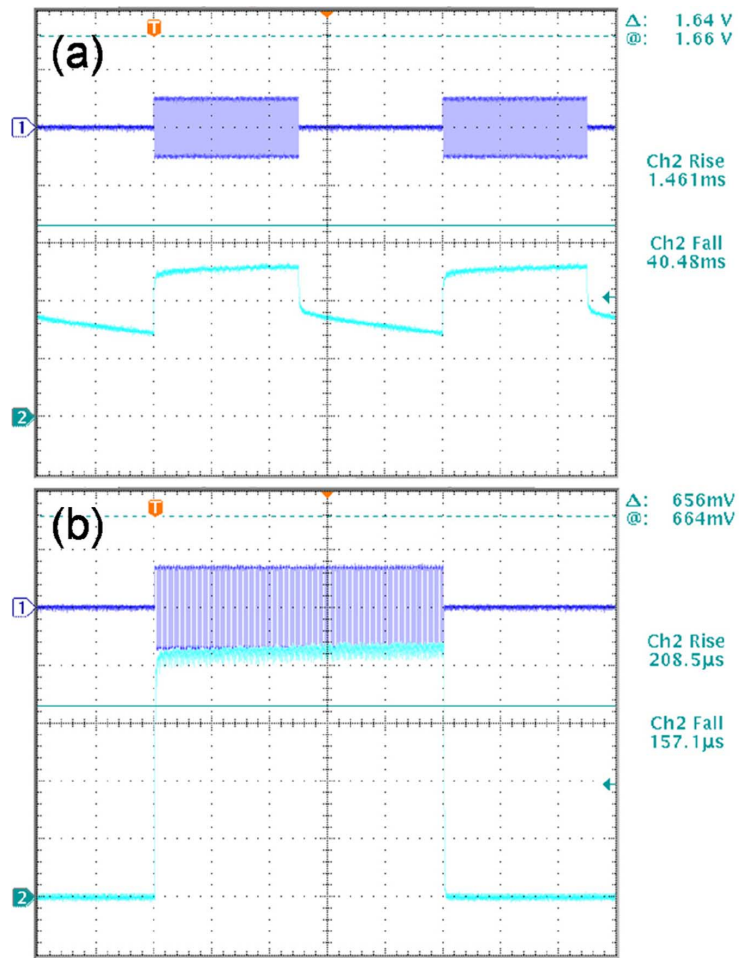
times and very little hysteresis observed. By comparing the VT curves of BP-I [see Fig. 2(a)] and BP-II [see Fig. 2(b)], we find that BP-I exhibits a higher transmittance and lower operating voltage, but its hysteresis is much larger.

The response time of the IPS cell was recorded, as shown in Fig. 3(a) and (b), for BP-I and BP-II, respectively. The upper traces show the driving voltage pulses: 100-ms on and 100-ms off. In both BP-I and BP-II experiments, the IPS cell was driven from $V = 0$ to their individual V_p states.

As Fig. 3(a) shows, both rise time and decay time of BP-I are in millisecond range, but not symmetrical. Two relaxation processes are clearly observed. Our experimental results agree with those described by Coles and Gleeson [14], [15], in which local molecular reorientations and restoration of BP-I structure are present. The latter has a much slower response time than the former. Because BP-I has a more compact (body-centered) structure, it takes a longer time for the disturbed (by the electric field) platelets to restore to their original arrangement, as noticed in Fig. 3(a). The structural restoration process in BP-I also affects the recorded VT curves. As Fig. 2(a) shows, the transmittance is higher in the voltage descending process than that of ascending. The mechanisms are explained as follows. As the voltage increases, the compact BP-I structure prevents the LCs from unwinding, so that the induced birefringence is smaller which leads to a lower transmittance. On the other hand, this

compact packing also hinders the formation of BP-I structure during the voltage descending process, which in turn leads to a higher transmittance when compared at the same voltage. As a result, the hysteresis loop is originated.

When the mixture was heated to BP-II, the response time is dramatically reduced to submillisecond level as Fig. 3(b) shows, and a good dark state is restored. It is known that BP-II has a looser structure (simple cubic) than BP-I [9], therefore, the restoration of BP-II structure does not influence the electro-optical performance of a BPLC cell too much. Instead, local molecular reorientation is the primary mechanism responsible for the submillisecond response time.

B. Polymer-Stabilized Blue Phase Mixtures

To stabilize the blue phases over a wide temperature range, the BPLC mixture was further doped with reactive monomer RM257 (Merck Inc.) and EHA (Aldrich) acrylic ester by 25% of the total weight to form a polymer precursor. After UV curing, the system could be stabilized in either BP-I or BP-II. Figs. 4 and 5 depict the measured electro-optical properties of polymer-stabilized BP-I and BP-II, respectively. The IPS cell used here has the same structure as that used for characterizing BP-I and BP-II mixtures.

Fig. 4(a) depicts the temperature effect on the VT curves of polymer-stabilized BP-I from 20 °C to 50 °C. The normalized maximum transmittance is ∼34%. A higher transmittance could be obtained if a simple strip-electrode IPS cell was employed. The solid lines represent the VT curves for the ascending voltage under four different specified temperatures; while the square dots stand for the descending voltages. From Fig. 4(a), three important features are found as the temperature increases: 1) the peak voltage (V_p) increases because of the reduced Kerr constant, 2) the hysteresis is suppressed, and 3) the dark state gets better, especially when the temperature exceeds 40 °C.

Fig. 4(b) reveals more details about the VT curves measured at 45 °C. Two cycles are presented here: the solid lines and square dots represent the voltage-up and -down scans, respectively. These VT curves are quite repeatable. However, the hysteresis is still fairly large: $\Delta V \sim 15.3\ V_{rms}$, which corresponds to 12.2% of the peak voltage $(V_p \sim 125.4\ V_{rms})$. Fig. 4(c) shows the measured response time at 45 °C. In a PS-BPLC system, the polymer networks not only stabilize the BP structure for extending its temperature range [1], but also suppress the deformation of BP lattice structure during voltage operation. As a result, the response time is reduced from millisecond to submillisecond, and hysteresis is also suppressed as compared to the pure BP-I system (ΔV is decreased from ∼20 to 15.3 V). However, the formation of polymer networks enhances the anchoring energy so that its peak voltage is increased by ∼15% (from $108 V_{rms}$ to $125\ V_{rms}$).

As mentioned above, blue-phase LC system possesses two other phases: BP-II and BP-III. Usually, BP-III requires a quite high voltage $(V_{on} > 200\ V)$ and is not included in this study. To obtain polymer-stabilized BP-II, we prepared another sample under the same polymer stabilization process but cured at a higher temperature. We measured the VT curves of this sample between 20 °C and 50 °C and results are shown in Fig. 5(a). Similar to polymer-stabilized BP-I, as the temperature increases the peak voltage also increases. The normalized
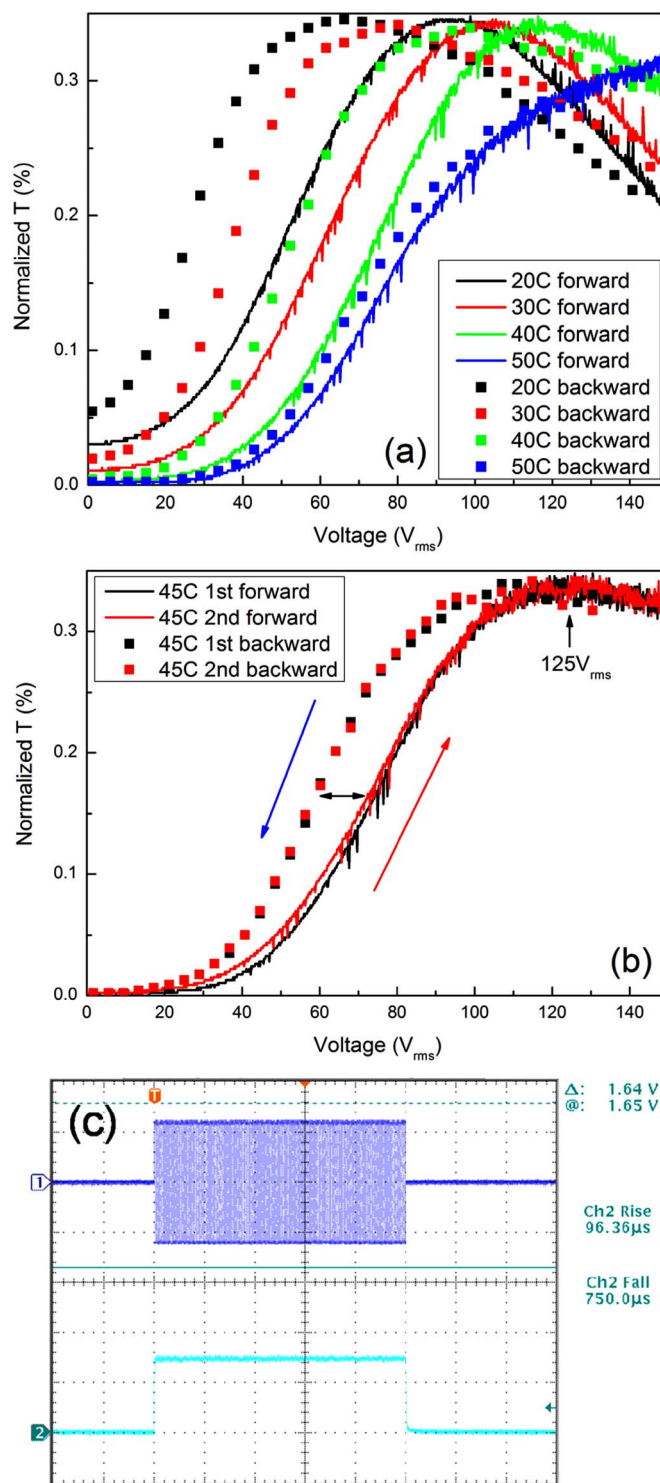

Fig. 4. Electro-optical characteristics of the PS-BPLC cell cured at BP-I. (a) Measured VT curves from 20 °C to 50 °C, (b) detailed VT curve measurements at 45 °C, and (c) measured response time at 45 °C. $\lambda = 633$ nm.

maximum transmittance is about the same $(\sim 34\%)$ as that stabilized at BP-I.

By comparing the results shown in Figs. 4(a) and 5(a), we find that polymer-stabilized BP-II exhibits a better dark state, but its peak voltage is higher at each corresponding temperature. Fig. 5(b) shows detailed VT curves at 45 °C for two repeated scans. In comparison to the corresponding polymer-stabilized BP-I system presented in Fig. 4(b), the polymer-stabilized BP-II
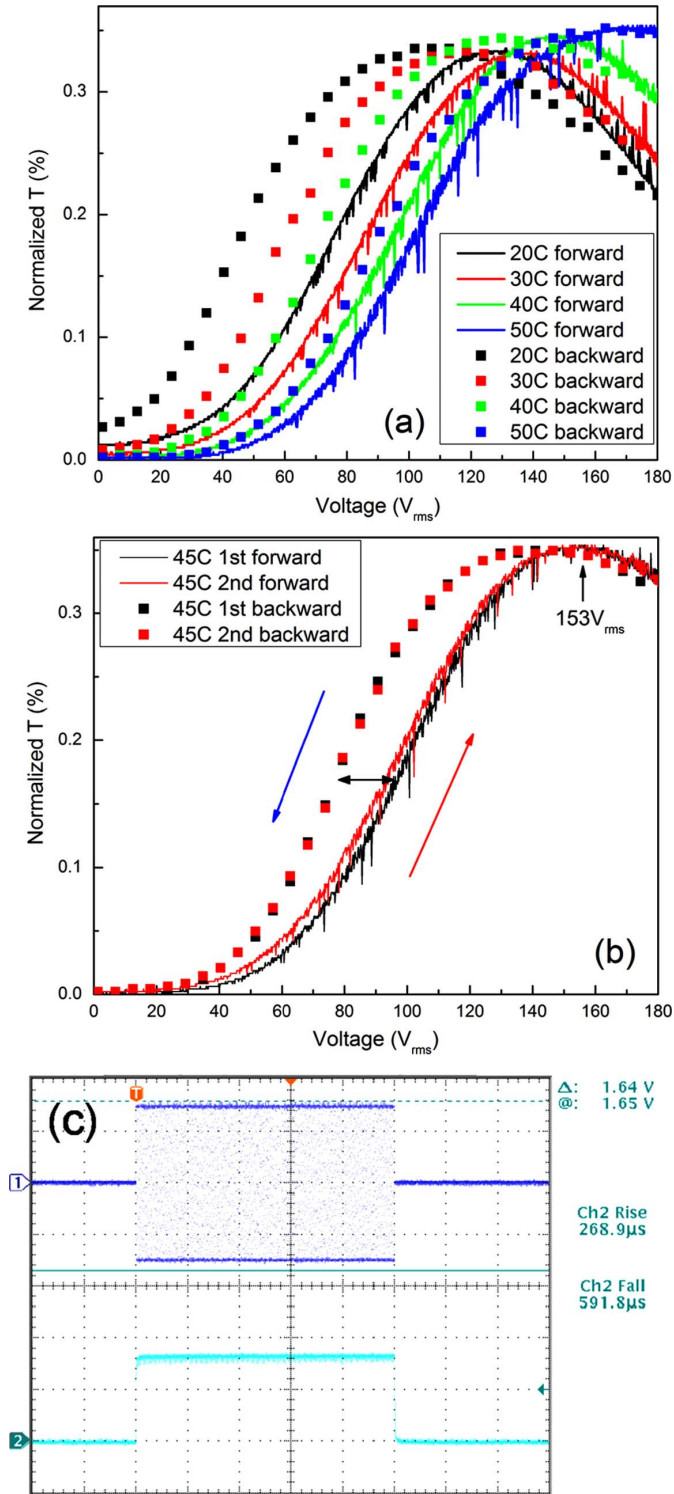
Fig. 5. Electro-optical characteristics of polymer-stabilized BP-II: (a) Measured VT curves from 20 °C to 50 °C. (b) Detailed VT curves measured at 45 °C. (c) Measured response time at 45 °C. $\lambda = 633$ nm.

TABLE I
SUMMARY OF THE OPERATING VOLTAGES AND HYSTERESIS IN BP-I, BP-II AND POLYMER-STABILIZED BP-I AND BP-II SYSTEMS

	Peak voltage (V_p)	Down (T50,V_{rms})	Up (T50, V_{rms})	Hysteresis (%) ($\Delta V/V_p$)
Pure BP				
BP-I	108.2	46.0	66.0	18.5
BP-II	143.1	96.5	96.5	~0
Polymer-stabilized BP-I				
40°C	116.2	51.6	73.1	18.6
45°C	125.4	59.5	74.8	12.2
Polymer-stabilized BP-II				
40°C	147.4	70.3	92.1	14.8
45°C	153.2	79.1	97.1	11.8

increased dramatically after the formation of polymer networks. The pure BP-II shows almost no hysteresis, but polymer-stabilized BP-II shows a fairly large hysteresis.

To summarize our experimental findings between different molecular systems, Table I compares the measured results of pure BPLC and two PS-BPLC systems. The big surprise is that the initially hysteresis-free BP-II system becomes hysteresis haunted after the introduction of polymer stabilization.

As for BP-I, before polymerization the peak voltage is $V_p \sim 108.2$ V_{rms} and hysteresis $\Delta V = 20$ V_{rms}. After polymer stabilization, V_p is increased to $125.4 V_{rms}$ and $\Delta V \sim 15$ V_{rms} when operated at 45 °C. The calculated hysteresis is suppressed from 18.5% to 12.2%. As for BP-II, after polymerization V_p is increased from $143.1 V_{rms}$ to 153.2 V_{rms}, but ΔV is widened from nearly zero to 18 V_{rms}. In comparison to polymer-stabilized BP-I and BP-II systems, the latter exhibits a higher peak voltage, but its hysteresis is narrower and dark state is better. From above comparisons, the BP system evolves from LC to LC/polymer composite after polymerization. In addition to the original characteristics inherent from LC system itself, polymer networks also make a great influence to the formed composite. Several other factors will also affect the electro-optical properties of the system, such as polymer density [16], [17], interaction between polymer network and liquid crystal molecules, and the formation of the polymer networks [18], [19].

Based on our studies, the following approaches could be considered for minimizing hysteresis: 1) Operating the polymer stabilized BP cells at an elevated temperature; 2) Increasing the amount of monomers to form robust polymer networks at defect regions. However, a tradeoff is in the increased operating voltage; and 3) improved curing method for making polymer networks distributed more uniformly throughout the BPLC medium.

IV. CONCLUSION

We have investigated the operating voltage, hysteresis and response time in two BPLC phases (BP-I and BP-II) before and after polymer stabilization. BP-I exhibits a slow response time and a large hysteresis. After polymer stabilization, its operating voltage is increased by ~15%, but its response time is improved dramatically and hysteresis reduced. In contrast, BP-II exhibits a negligible hysteresis and submillisecond response time, but after polymer stabilization its hysteresis is widened. Methods for suppressing hysteresis are in urgent need in order to accelerate the emergence of blue-phase LCDs.

has a higher peak voltage (153.2 V_{rms}) and the hysteresis remains at ~11.8%. Fig. 5(c) shows the measured response time at 45 °C, which is also in the submillisecond level. The higher V_p for PS BP-II than PS BP-I is expected because BP-II has a higher operating voltage than BP-I. However, by comparing Fig. 5(b) with Fig. 2(b), we find that the hysteresis of PS BP-II is

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