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Critical Field for a Hysteresis-Free BPLC Device

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***Abstract*—A correlation between the peak electric field and hysteresis of a polymer-stabilized blue-phase liquid crystal (BPLC) is found experimentally. If the peak electric field is below ~ 5 V/μm, hysteresis is negligible. Based on this guideline, we propose elliptical protrusion electrodes to reduce peak electric field which in turn eliminates hysteresis while keeping a high transmittance. Such a hysteresis-free BPLC device is highly desirable for display and photonic applications.**

***Index Terms*—Blue phase liquid crystal (BPLC), hysteresis, Kerr effect.**

I. Introduction

POLYMER-STABILIZED blue-phase liquid crystal (BPLC) composite [1]–[5] is emerging as next-generation display and photonic devices because of its fast gray-to-gray response time [6], no need for surface alignment layer, optically isotropic dark state, and cell gap insensitivity if an in-plane switching (IPS) electrode is employed [7]. However, high operating voltage and hysteresis still hinder its widespread applications [8], [9]. Several approaches have been proposed to lower the operating voltage, such as protrusion electrode [10], [11], wall-shaped electrode [12], corrugated electrode [13], and developing large Kerr constant (K) BPLC materials [8], [14]. Hysteresis is a common phenomenon in polymer-stabilized LCs [15] including BPLCs [9]. Detailed mechanisms depend on the polymer concentration and composition [16], and UV curing conditions. Hysteresis affects the accuracy of gray-scale control and should be eliminated [17]. There is an urgent need to develop hysteresis-free BPLC devices.

In this paper, we correlate the hysteresis of a polymer- stabilized BPLC with the peak electric field of different IPS electrode dimensions. If the peak electric field is below a critical field (~ 5 V/μm), hysteresis is negligible. Based on this guideline, we propose elliptical protrusion electrodes with reduced peak electric field to achieve hysteresis-free BPLC devices.

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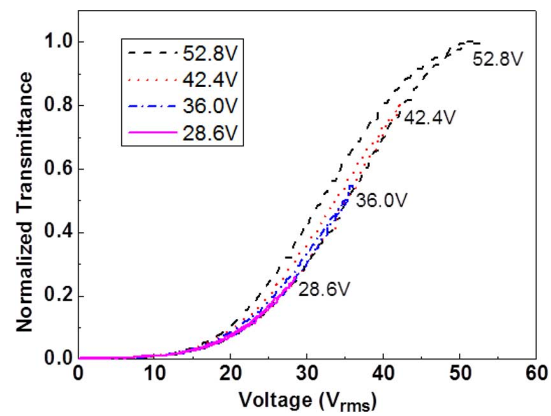

Fig. 1. Measured hysteresis of the 10-10 IPS cell. $\lambda = 633$ nm.

TABLE I
MEASURED $V_{\rm on}$ AND HYSTERESIS, AND CALCULATED $E_{\rm p}$ OF IPS TEST CELLS AT 25 °C

IPS Cell	V_{on} (V)	Hysteresis	E_p at V_{on} (V/μm)
10-10	56.7	6.4%	9.65
5-5	50.7	10.1%	17.53
2-4	40.0	10.0%	16.95

II. Experiment and Discussion

In experiment, we prepared three BPLC samples with following IPS electrode width (w) and gap (l): 10-10, 5-5, and 2-4 (unit: μm). The BPLC material (JC-BP01M) has a Kerr constant of $\sim$ 13.7 nm/V^2 at $\lambda = 633$ nm [14]. The IPS 10–10 device exhibits a fast response time ($\sim$1 ms), high contrast ratio ($\sim$1000:1), and hysteresis $\sim$6%. The peak transmittance depends on the individual electrode width and gap, and is in the 60%–80% range [18]. We measured the VT curves for two cycles of ascending and descending voltage scans at 25 °C. The transmittance was normalized to that when the BPLC cell was in an isotropic state and the two polarizers are in parallel position. Hysteresis is defined as the voltage difference at half-maximum transmittance between voltage-up and -down scans. Table I lists the measured $V_{\rm on}$ and hysteresis of the three IPS BPLC cells. From Table I, $V_{\rm on}$ varies according to the $w-l$ ratio. At a given voltage, a smaller electrode gap results in a stronger electric field and thus the on-state voltage is lower.

To evaluate the electric field effects on hysteresis, we simulated the electric field distribution at V_{on} of each cell and found that the peak electric field (E_p) is located near the edge of the electrodes. Results are also included in Table I. Although the 10-10 IPS cell has the highest on-state voltage ($V_{\rm on} \sim 56.7$ V

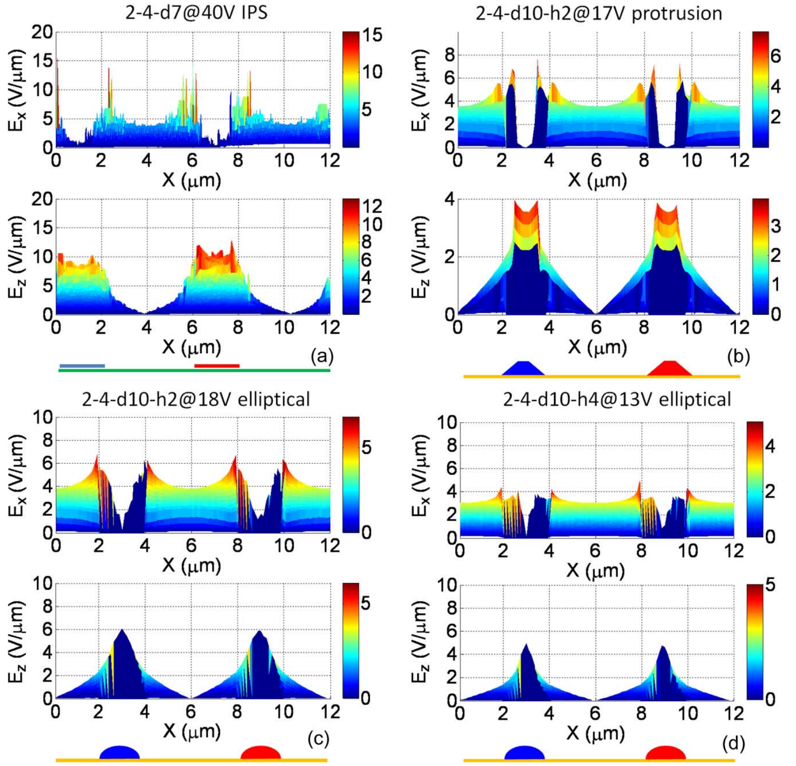

Fig. 2. Simulated horizontal (E_{x}) and vertical (E_z) electric field distribution for the specified device configurations: (a) planar IPS electrode with width $w = 2\ \mu$m and gap $l = 4\ \mu$m. Cell gap $d = 7\ \mu$m and $\mathrm{V} = 40\ V_{\mathrm{rms}}$; (b) trapezoid protrusion electrode with $w = 2\ \mu$m, $l = 4\ \mu$m, and height $h = 4\ \mu$m. Cell gap $d = 10\ \mu$m and $V = 17\ \mathrm{V}_{\mathrm{rms}}$; (c) elliptical protrusion electrode with $w = 2\ \mu$m, $l = 4\ \mu$m, and $h = 2\ \mu$m. Cell gap $d = 10\ \mu$m and $V = 18\ V_{\mathrm{rms}}$; and (d) elliptical protrusion electrode with $w = 2\ \mu$m, $l = 4\ \mu$m, and $h = 4\ \mu$m. Cell gap $d = 10\ \mu$m and $V = 13\ V_{\mathrm{rms}}$.

at 25°C), its E_p is the lowest among the three compared because of its large electrode gap. The E_p of the 5-5 and 2-4 IPS cells is almost twice as large as that of the 10-10 cell. From Table I, the measured hysteresis is strongly correlated to the electric field strength. The stronger the peak electric field, the larger the hysteresis.

To further investigate the correlation between electric field and hysteresis, we did another experiment using the same BPLC material with a 10-10 IPS cell. We measured the voltage- dependent transmittance (VT) curves at room temperature (~ 23 °C) with a He–Ne laser ($\lambda = 633$ nm). An rms voltage of 100 Hz was used to drive the cell. For the full transmittance cycle, we ascended the voltage to the peak transmittance and then descended the voltage. It is known that Kerr constant decreases as the temperature increases [19]. Therefore, at 23 °C the on-state voltage occurs at $V_{\mathrm{on}} = 52.8$ V. A hysteresis of $\sim$6.5% is found. We then drove the cell to the 80%, 55%, and 25% of the peak transmittance with the corresponding voltage of 42.4, 36.0, and 28.6 V, respectively. Results are plotted in Fig. 1. We notice that the hysteresis is vanished if the applied voltage is limited to 28.6 V. According to the electric field distribution calculation, the peak electric field is $E_p \sim 4.9$ V$/\mu$m, which is the critical electric field for achieving hysteresis-free operation with our polymer-stabilized BPLC (JC-BP01M). This critical field could vary depending on the polymers employed and their concentrations.

Once we have determined the critical field, in the following section, we will modify our device structure, e.g., changing the protrusion shape and depth, so that the peak electric field is kept below critical field for eliminating hysteresis. Meanwhile, we will maximize the transmittance and contrast ratio.

III. Hysteresis-Free Structure Design

Three types of electro-optic effects in a BPLC could occur as the electric field increases: local director reorientation within the double twist cylinders, lattice distortion (electrostriction effect) and eventually phase transition [20]. Local reorientation of the BPLC directors in the double twist cylinders is responsible for the submillisecond response time. However, the induced lattice distortion and phase transition by the increased electric field not only have slow response time but also cause hysteresis and ultimately irreversible structural damage. To eliminate hysteresis, the induced lattice distortion and phase transition should be avoided. That means, we should operate the device below the critical field so that the electrostriction effect will not take place. For our BPLC sample, the critical field for hysteresis-free operation is ~ 5 V$/\mu$m.

Based on this simple guideline from the above analysis, we design the electrode and calculate the electric field distribution with intention to reduce the peak electric field to be less than ~ 5 V$/\mu$m. For the 2-4 IPS cell, the measured V_{on} is 40 V, the peak total electric field E_p is 16.95 V$/\mu$m. The calculated horizontal (E_x) and vertical (E_z) electric field distribution is depicted in Fig. 2(a). When an electric field is applied, macroscopically, the blue phase LC index ellipsoid elongates along the direction of the electric field for the material with positive dielectric anisotropy. That is, the anisotropy appears with the optical axis along the field direction. The electric field has

TABLE II
SIMULATED ELECTRIC FIELD DISTRIBUTION FOR THE SPECIFIED CELL CONFIGURATIONS

Cell	V_{on} (V)	$E_{x\,max}$ (V/μm)	$E_{z\,max}$ (V/μm)	E_p (V/μm)
2-4 IPS (d=7μm)	40	15.53	12.91	16.95
2-4 trapezoid (d=10μm, h=2μm)	17	7.68	3.97	8.65
2-4 elliptical (d=10μm, h=2μm)	18	6.84	6.09	6.85
2-4 elliptical (d=10μm, h=4μm)	13	5.08	5.00	5.08

two components: E_x and E_z, but only the horizontal component contributes to the overall transmittance. We can see from Fig. 2(a) that vertical fields are strong on top of the common or pixel electrodes because electric fields are perpendicular to the electrodes, while the horizontal component (E_x) is strong in the gap area between the electrodes. The total electric field at each point is calculated as $E = \sqrt{E_x^2 + E_z^2}$. Through the calculation, the peak values for E_x, E_z and E may not be at exactly the same point, as shown in Fig. 2, but they are all around the edges of the electrodes and are strongly related to the shape of the electrodes. If we use the 2-4 trapezoid structure with protrusion height of 2μm in Fig. 2(b), $V_{\rm on}$ is decreased to 17 V and the electric field at the edge of the electrode is substantially reduced as compared to the planar IPS structure, while the field in the gap area is still large. However, due to the sharp taper angle of the protrusion, the field is still strong, especially at the edge of the electrodes. To further decrease the peak electric field, we changed the trapezoid protrusion to elliptical shape, and the sharp taper angle is now smooth. From Table II, the peak electric field is reduced from 8.65 V$/\mu$m for the trapezoid protrusion to 6.85 V$/\mu$m for the elliptical protrusion. If the height of the elliptical shape electrode is increased to 4 μm, the peak field is further reduced to 5 V$/\mu$m. As depicted in Fig. 2, with such a low peak electric field the device would be free from hysteresis.

IV. CONCLUSION

We have explored the physical mechanism for hysteresis and found that hysteresis effect is directly related to the electric field strength generated from the electrodes. Through experiment, we also found that the critical electric field for hysteresis-free operation is $\sim$ 5 V$/\mu$m. To reach this goal, we proposed an elliptical protrusion electrode structure for BPLC devices. In comparison to the planar IPS electrode structure, the protruded elliptical electrode exhibits a 3$\times$ lower on-state voltage. Compared with trapezoid electrode, the elliptical shape is more realistic to the actual fabrication profile. Moreover, its peak electric field is weaker which is favorable for hysteresis-free device operation. The established guidelines are useful for optimizing BPLC devices in order to eliminate hysteresis while keeping high contrast ratio and maximum transmittance.

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