DOI: 10.1143/JJAP.51.072201

Low Voltage and High Transmittance Polymer-Stabilized Blue-Phase Liquid Crystal Device by Combined In-Plane and Oblique Electric Field along the Horizontal Direction

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Received November 25, 2011; accepted March 17, 2012; published online June 11, 2012

We propose a polymer-stabilized blue-phase liquid crystal (PS-BPLC) device with high transmittance and low driving voltage by designing the electrode structure. The electrodes are comprised with two interdigitated bottom pixel electrodes with opposite polarities and a top common electrode with 0 V, which is placed in the middle of the two bottom electrodes. Since these electrode structures could generate a strong horizontal electric field and induce a high Kerr effect, we could realize a lower driving voltage (30 V) and higher transmittance characteristics (20%) than those of conventional PS-BPLC cells with an in-plane switching electrode structure.

1. Introduction

Polymer-stabilized blue-phase liquid crystal (PS-BPLC) devices with an extended temperature range of blue phase (BP) are promising candidates for next-generation technology owing to their revolutionary display characteristics, such as fast response times in the sub-millisecond range, excellent dark level by an inherent optically isotropic phase, wide and symmetric viewing angle, and no need for initial LC alignment process.[1–5] However, despite several advantages, PS-BPLC devices have two major technical challenges, i.e., high operating voltage and low transmittance, which must be overcome before they can acheive widespread application. Several solutions have been proposed to overcome these problems. For example, a device which used a BPLC material with a large Kerr constant was developed and the operating voltage was lowered by optimizing the electrode structure with the electrode width and their interval in in-plane switching (IPS) mode.[6,7] Also, the technologies using the traditional IPS electrode structure with the partitioned wall-shaped electrode structure,[8] the protrusion electrode structure,[9] and the periodic corrugated electrode structure[10] have been studied. However, although these electrode structures can markedly decrease the operating voltage in PS-BPLC devices, they still have issues such as low transmittance characteristics and fabrication process difficulties.

In this paper, we propose a PS-BPLC display with high transmittance and low driving voltage by designing the electrode structure. The electrodes are composed of three parts: two interdigitated bottom pixel electrodes like a conventional IPS mode and a top common electrode, which is placed in the middle of the two bottom electrodes. When we apply voltage, the interdigitated pixel electrodes have the opposite polarity and the common electrodes keep 0 V. Through this electrode structure and driving method, our PS-BPLC cell could generate a strong horizontal electric field, which can penetrate deeply into the BPLC layer and induce the high Kerr effect. As a result, we could realize the low driving voltage and high transmittance characteristics in a PS-BPLC cell.

2. Cell Structure and Operating Principle of the Proposed Device

A PS-BPLC device is operated with the conventional IPS electrode structure. In the voltage off state, the symmetric cubic structures of PS-BPLC induced the optically isotropic state.[11] When the strong horizontal electric field with respect to the substrate is applied, the LC molecules with the symmetric cubic structure are oriented along the electric field by the Kerr effect.[12] In this case, the induced birefringence (Δn_i) by the electric field can be characterized as follows:[7]

$$\Delta n_i = \lambda K E^2 = (\Delta n)_0 \left(\frac{E}{E_s}\right)^2, \quad (1)$$

where λ, K, $(\Delta n)_0$, E, and E_s are the wavelength of the incident light, maximum birefringence, applied electric field, and the saturation electric field for LC orientation, respectively. While increasing the E, the Δn_i is increased gradually. When the E reaches E_s, Δn_i could be close to the maximum birefringence value $[(\Delta n)_0]$. The transmittance of the PS-BPLC device between the crossed polarizers could be expressed as[13]

$$T = \sin^2 2\Psi \sin^2 \left[\frac{\pi \sum_{i=0}^{d} d_i \Delta n_i(V)}{\lambda} \right], \quad (2)$$

where Ψ is the angle between the optic axis of LC molecules, which are oriented by the applied electric field, and the transmission axis of the polarizers. $d_i \Delta n_i$ is the phase retardation of the PS-BPLC layer. From this equation, maximum transmittance could be produced when the Ψ is 45° and $\sum_{i=0}^{d} d_i \Delta n_i(V)$ is $\lambda/2$.

The PS-BPLC cell with the conventional IPS electrode structure shows poor optical efficiency because the electric field is gradually weakened near the top substrate from the bottom pixel electrode in the horizontal direction in particular. Therefore, for high transmittance, high electric fields are needed. To overcome these problems, a strong horizontal electric field is essential for the higher transmittance.

We prepared two types of PS-BPLC cell: one with a conventional IPS electrode and the other with the proposed electrode structure. In a conventional IPS cell, the electrodes on the bottom glass substrate have 10 µm electrode widths and 15 µm electrode gaps for pixel and common electrodes formed by the photolithography process, and a bare glass substrate without indium–tin-oxide (ITO) electrodes was used as the top substrate. Then, the two substrates were assembled, sustaining a 12 µm cell gap. For the proposed PS-

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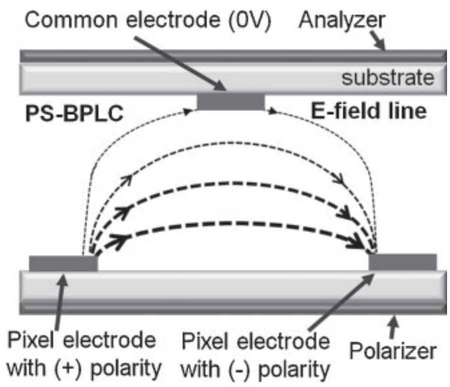
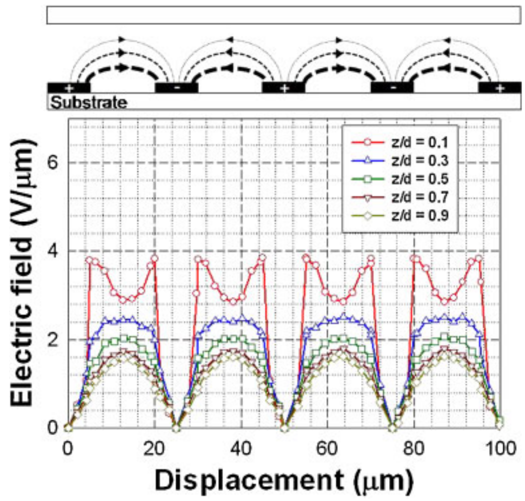


Fig. 1. Schematic diagram of the electrode structure for the proposed PS-BPLC cell.

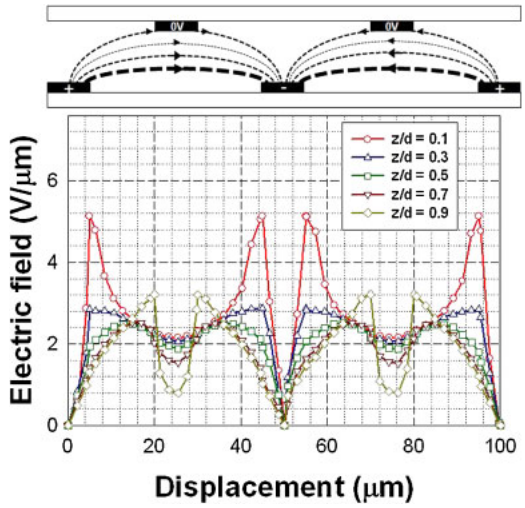
BPLC cell, the pixel electrodes on the bottom glass substrate were prepared, which have a 10 µm electrode width and 45 µm electrode gap, and the common electrodes were also prepared on the top glass substrate with a 10 µm electrode width and 45 µm electrode gap. When assembling the two substrates, the common electrodes were positioned at the center on each pixel electrode, as shown in Fig. 1, and the cell gap was sustained by 12 µm with glass spacers. From these electrode configurations, two cells could have same active area for direct comparison, e.g., driving voltage and transmittance characteristics. Then the LC mixture which was composed of reactive mesogen (RM; Merck RM257), monomer (Aldrich EHA), two types of chiral dopants (Merck R50 and R811), and photo initiator (Ciba Chem. Igracure651) with suitable molar ratio in the particular host nematic LCs was injected in both cells at isotropic phase (over 50 °C). The mixture before the polymerization has a phase transition sequence as follows: cholesteric (36.2 °C), blue phase (38.8 °C), and isotropic phase. We calculated the Kerr constant using the measured voltage–transmittance (V–T) characteristics of a BPLC cell. The transmittance characteristics depending on applied voltages were measured for a BPLC cell with an IPS electrode structure using a host LC material ($\Delta n \sim 0.17$). The cell gap (d), electrode width (w), and electrode gap (g) of the electrode structure were 12, 10, and 15 µm, respectively. After the LC filling process, we exposed UV light (intensity: $\sim$5.4 J/cm^2, $\lambda = 365$ nm) for polymerization of RM, which could stabilize the blue phase structure and widen the temperature range. The polymer-stabilized LC mixture could maintain blue phase until 56 °C. When we applied an electric field to the proposed PS-BPLC cell, the common electrode is remained at 0 V. Voltages with opposite polarities are applied to the pixel electrodes with interdigitated structure on the bottom substrate. We expect that the oblique electric field between the pixel and common electrodes could create a strong horizontal electric field and could penetrate deeply into the LC bulk region near the top substrate. From this configuration, the operating voltage will be reduced and high transmittance will be achieved.

3. Results and Discussion

First, we have analyzed the electric field distribution along the horizontal direction in a conventional IPS electrode structure and proposed electrode structure by using a



(a)



(b)

Fig. 2. (Color online) Electric field directions in electrode structure and two-dimensional electric field distribution according to the z/d, where z is the vertical position from the bottom substrate and d is the cell gap: (a) conventional and (b) proposed PS-BPLC cells.

simulation tool (Sanayi System Techwiz LCD), as shown in Fig. 2. The electric field distribution is calculated at five different positions between the bottom pixel electrode ($z/d = 0.1$) and the top common electrode ($z/d = 0.9$), where d is the cell gap and z is the position between the bottom and top substrates. In the calculation, the electrode structure was set up in the same manner as the experimental LC cells, as mentioned in the above section. The applied voltage was 70 V for both cells. In both cases, the electric field is decreased approaching the top substrate. Near the top substrate, however, the electric field of the proposed electrode structure is stronger than that of the conventional IPS structure (compared at $z/d = 0.9$). In particular, near the top electrode region (around the position at 25 and 75 µm in Fig. 2), the electric field strength of the proposed structure is much higher than that of the conventional IPS structure.

Using the electric field distribution, we can calculate the induced birefringence (Δn_i) and transmittance at each position using eqs. (1) and (2), as shown in Fig. 3. The

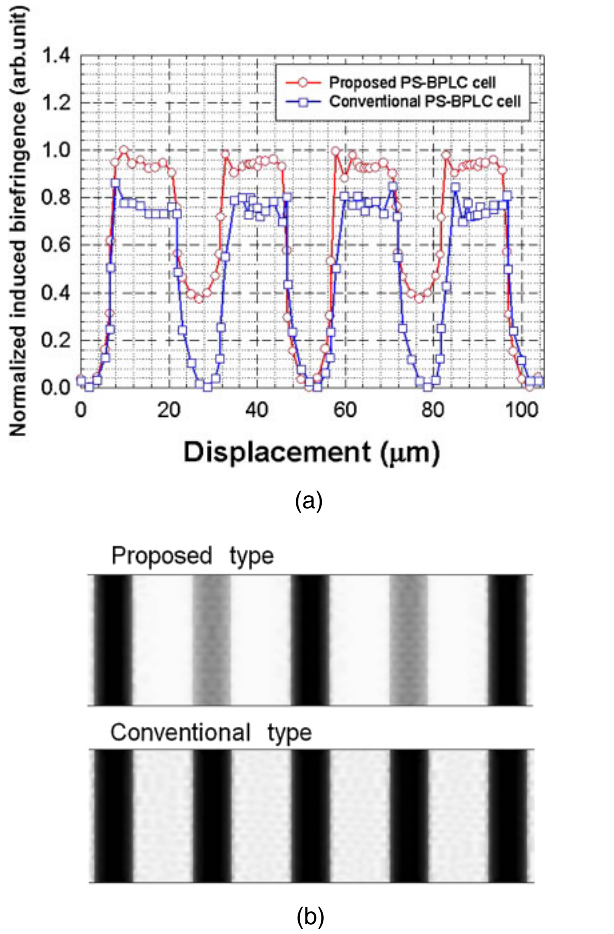


Fig. 3. (Color online) (a) Calculated induced birefringence by the electric field along the horizontal direction at 70 V and (b) transmittance images at the same voltage obtained by the simulation tool for conventional and proposed PS-BPLC cells.

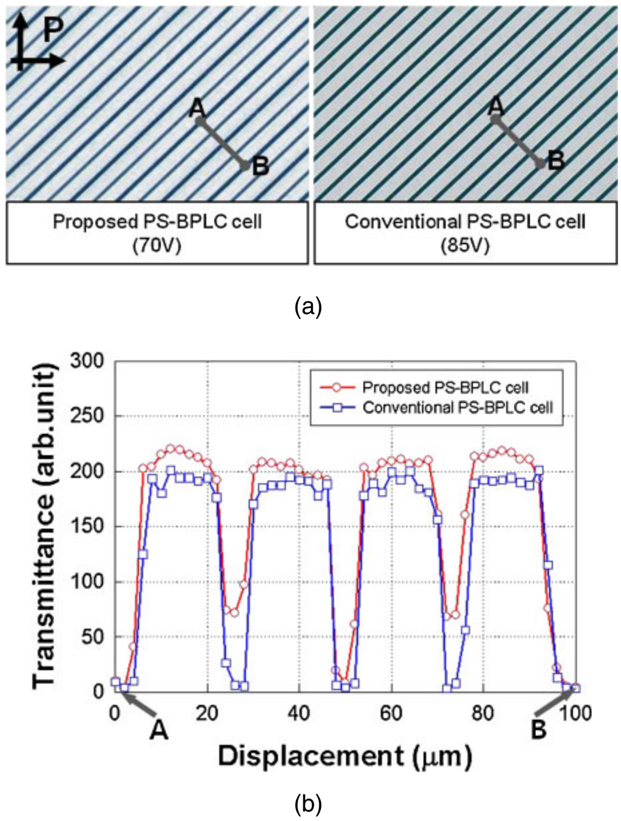


Fig. 4. (Color online) (a) Compared microscopic textures of the manufactured PS-BPLC devices with the different electrode structures and (b) transmittance plots obtained by image scanning.

induced birefringence of the proposed PS-BPLC cell shows high values at the active area, and this result could produce the high transmittance, as shown in Fig. 3(b). At the position of the bottom electrode regions, the transmittance between the conventional and proposed PS-BPLC cells shows the almost same value (around the position at 0, 50, and 100 μm in Fig. 3). However, near the top electrode region (around the position at 25 and 75 μm in Fig. 3), the proposed PS-BPLC cell shows higher transmittance than the conventional PS-BPLC cell owing to the high Δn_i. If we applied the electric field higher than the saturation voltage of the conventional PS-BPLC cell, the transmittance of the conventional PS-BPLC cell at the active area could reach that of our PS-BPLC cell. However, in this case, a higher electric field is needed, and the transmittance at the electrode region is still lower than that of our PS-BPLC cell. From these results, we could confirm that our PS-BPLC cell with the designed electrode structure acheives the good device characteristics, such as low driving voltage and a high transmittance.

To verify the simulated results, we fabricated the PS-BPLC cells. Figure 4(a) depicts the microscopic images under crossed polarizers for the conventional PS-BPLC cell with the IPS electrode structure and our PS-BPLC cell with the proposed three terminal electrode structures. The electrode is rotated by 45° with respect to the direction of polarizers. The applied voltages are 70 and 85 V for our PS-BPLC cell and the conventional PS-BPLC cell, respectively, which are the maximum transmittance voltages. Figure 4(b) shows the transmittance between A and B positions in Fig. 4(a) for two cells. The results are well matched with the simulation. The transmittance at the active area is enhanced by 13% compared with the conventional PS-BPLC cell. Moreover, the transmittance near the common electrode regions is remarkably improved even if the applied voltage is lower. These advanced optical characteristics are caused by the strong horizontal electric field near the bottom substrate and the oblique electric field, which is generated between the top common electrode and the bottom pixel electrode. Among them, the oblique electric field deeply penetrates the LC layer owing to their opposite polarity and could induce the high Kerr effect in a PS-BPLC cell.

Figure 5 shows the V–T characteristics of the conventional and proposed PS-BPLC cells using a He–Ne laser with $\lambda = 633$ nm. In the field off-state for both cells, there is no light leakage even though the cells are rotated between crossed polarizers. When the applied electric field is increased gradually, the transmittance is also increased until the induced retardation ($d_i \Delta n_i$) by the electric field reaches $\lambda/2$. As shown in Fig. 5, the maximum transmittance is acheived at 70 and 85 V for the proposed and conventional PS-BPLC cells, respectively. The Kerr constant of the BPLC material used in this work decreases from 12.6 to 8.0 nm/V^2 after polymer stabilization by UV irradiation. However, in a PS-BPLC cell with the proposed electrode structure, the reduced Kerr constant increases to 11.9 nm/V^2. The lower

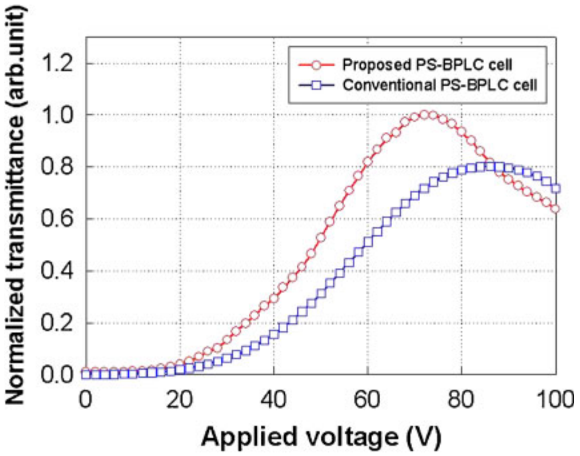


Fig. 5. (Color online) Normalized voltage–transmittance (V–T) characteristics of conventional and proposed PS-BPLC cells.

operation voltage is because the oblique electric field could penetrate into the LC layer and produce the high induced birefringence near the top common electrode regions. Actually, in our PS-BPLC cell, the voltage difference between the bottom electrodes is 140 V, because the cell needs voltage with opposite polarities. In the conventional PS-BPLC cell, it seems that only 85 V is needed. However, in a real LCD panel, the driving voltage swings from positive to negative voltages. If the DC voltage is applied, residual DC current is produced owing to the ions, free electrons and impurities in the LC cell, which are caused by the image sticking. Therefore, opposite polarities of the applied voltage are needed for DC free at frame by frame.[14] In our experiment, the conventional PS-BPLC cell needs 170 V, which is 30 V larger than the proposed PS-BPLC cell. For a low driving voltage, the V_{com} inversion methods which changes the voltage of the common and pixel electrodes frame by frame, was suggested.[15] By changing the applied voltage, the LC molecules have opposite polarities. However, this method brings about problems such as crosstalk and flicker. Our PS-BPLC cell shows a transmittance about 20% higher than that of the conventional PS-BPLC cell, as well as a low driving voltage, which well agrees with the simulation results, as shown in Fig. 5.

4. Conclusions

We proposed a PS-BPLC device operated by in-plane and oblique electric fields induced by the interdigitated bottom pixel and top common electrodes. The patterned common electrodes, keeping 0 V, are located in the top substrate and pixel electrodes on either side of the common electrode are swung to the same voltage, but the opposite polarities. Using the unique operating method on our electrode structure, we could acheive a lower operating voltage and transmittance of 20% higher than those of the conventional PS-BPLC cell with the IPS electrode owing to the enhanced horizontal electric field. We believe that our PS-BPLC device is excellent for high display performance.

Acknowledgments

This research was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST, No. 20110016968) and a grant from Samsung Electronics, LCD R&D Center.

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