High Transmittance Blue-phase LCD with a Floating Electrode

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Abstract

A high transmittance polymer-stabilized blue-phase liquid crystal display with floating electrodes in conjunction with protruded electrodes is proposed. The floating electrodes help to confine the electric field and reduce the dead zone areas. As a result, the peak transmittance over 90% is achieved.

Author Keywords

blue phase display; floating electrode; protrusion electrode

1. Introduction

Polymer-stabilized blue phase liquid crystal (BPLC) has potential to become next-generation display technology [1, 2]. Both in-plane switching (IPS) [3] and vertical field switching (VFS) [4] have been developed for driving the BPLC cell. Each approach has its own merits and demerits. For example, VFS mode offers high transmittance, low voltage, compressed hysteresis, and submillisecond response time, but its viewing angle problem remains to be widened, although some promising progress has been demonstrated recently [5]. On the other hand, large Kerr constant BPLC materials [6, 7] in conjunction with protrusion IPS electrodes [3, 8] have been adopted to reduce operation voltage, but the peak transmittance is ~70% because of the dead zones on top of the electrodes. The corrugated electrode approach [9] offers low voltage and high transmittance, but its fabrication process is rather sophisticated.

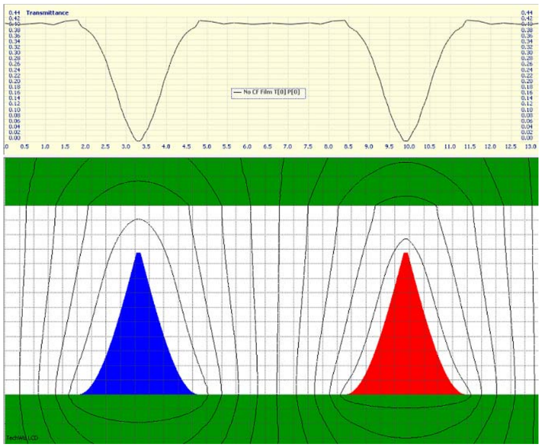
In this paper, we propose to use floating electrodes on the top substrate in conjunction with bottom protrusion IPS electrodes to improve the peak transmittance to over 90%. The cell gap and floating electrode dimension are optimized to maximize the peak transmittance.

2. Device structure and operation principles

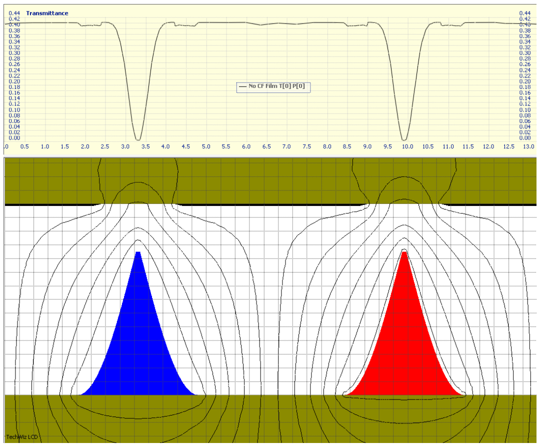
In an IPS-based BPLCD, including double penetrating fringing field mode [10] and enhanced protrusion mode [11], the lateral electric field between electrodes determines the field-induced birefringence, and so as the transmittance. However, on top of each electrode, the electric field is primarily in vertical direction. Therefore, the incident light does not experience enough phase retardation, and will be blocked by the crossed analyzer. This low-transmittance region is usually referred to as “dead zone”. To suppress dead zones, double sided IPS electrode design has been proposed, in which electrodes are fabricated not only on bottom substrate but also on top substrate [12]. Top electrodes generate lateral electric field to remove the dead zones of bottom electrodes, and vise versa. Therefore, the dead zone areas of bottom electrodes and top electrodes are complemented. A major tradeoff of this design is that it requires two TFTs (thin film transistors), which not only reduces the pixel’s aperture ratio but also increases the complexity in pixel registration.

Although the “two-TFT design” is complicated, the idea of reducing dead zones by fabricating electrodes on top substrate is still valuable. The challenge is how to let these top electrodes generate tunable lateral electric field without a second TFT. To overcome this problem, here we propose a floating electrode approach. These floating electrodes are not connected to any fixed voltage signal; its potential is solely determined by the surrounding electric field. As a result, each floating electrode serves as an equal-potential conductor, which affects the nearby electric field distribution. Thus, when the bottom electrodes are driven by a voltage, the potential of top electrode will be changed accordingly, even although it is not directly driven by a TFT. Lateral fields are generated between floating electrodes and bottom electrodes. These lateral fields help to reduce the dead zone areas and improve the overall transmittance of the BPLC cell.

Figure 1 depicts the device structure, equal-potential lines, and corresponding transmittance of a protrusion IPS without (a) and with (b) floating electrodes. To simulate the device performance, we used TechWiz simulation program. In Figs. 1(a) and 1(b), red and blue shapes represent protrusion electrodes on the bottom substrate. In Fig. 1(b), the floating electrodes are drawn as black lines on the top substrate. As Fig. 1(a) shows, dead zone appears on top of each protrusion electrode.



(a)



(b)

Figure 1. Simulated equal potential lines of protrusion IPS without (a) and with (b) floating electrodes.

As Fig. 1(b) shows, the floating electrodes affect the electric field distribution. In our simulation, all protrusion electrodes are equally separated, each protrusion is symmetric in shape, and floating electrode is placed in equal distance from two neighboring protrusions. In this case, the potential of floating electrode is the median of potentials on two protrusions. Thus, in the local regions between protrusions and floating electrodes, the electric field is strengthened, which increases the induced birefringence of BPLC. Therefore, even though the effective cell gap on top of protrusion is smaller, the transmittance is still improved. This is why we observe narrower dead zones and higher overall transmittance in Fig. 1(b).

In Fig. 1, the protrusion electrodes have reverse-sine side wall, which is also a result of optimization. Yoon, et al. has investigated how the side wall shape of protrusion electrode affects the peak transmittance of a BPLC cell [8]. As described in Ref. 8, steep sidewall, such as the top of reverse-sine protrusion electrode, bears a higher transmittance than trapezoid or elliptical protrusion, because it generates a stronger lateral electric field. Therefore, we also use this protrusion design in conjunction with floating electrode.

A tradeoff of floating electrode is the increased operating voltage. It is known that the electric field near an ideal conductor surface tends to be normal to the surface. This phenomenon is also shown in Fig. 1(b): the equal-potential lines below floating electrodes are bent towards horizontal direction, which means the vertical component of electric field dominates near floating electrode surface. This vertical field reduces the phase retardation in protrusion gap area, and decreases the overall transmittance. So floating electrode will increase the driving voltage, as discussed in the following section.

3. Simulation result and discussion

To simulate the electric field-induced birefringence of the polymer-stabilized BPLC composite, we use the following extended Kerr model [13]:

$$\Delta n = \Delta n_{sat}\left(1-\exp\left[-\left(\frac{E}{E_S}\right)^2\right]\right), \qquad (1)$$

where Δn_{sat} stands for the saturated induced birefringence and E_s represents the saturation field. Table 1 lists the physical properties of the BPLC we prepared in our labs.

Table 1. Physical properties of the BPLC material we formulated.

λ	650nm	550nm	450nm
Δn_{sat}	0.141	0.154	0.169
E_s	4.15V/μm		

The protrusion electrode dimension and cell gap are also critical parameters. Considering the practical manufacturability, we have chosen following parameters for our simulation, as listed in Table 2.

Table 2. Protrusion IPS structure parameters

Cell gap	4μm
Protrusion electrode width	3μm
Protrusion electrode height	3μm
Protrusion sidewall shape	Reversed sine

3.1 Electrode dimension effect

We first investigate how the gap (G) between protrusion electrodes and the width (W) of floating electrode affect the transmittance. Figure 2 shows the simulated voltage-dependent transmittance (VT) curves at λ= 550nm. In Fig. 2, all the black lines represent the VT curves with G=2.4μm, blue lines for G= 3.6μm, and red lines for G= 4.8μm. Solid lines are protrusion IPS without floating electrode. Dotted-and-dashed lines are for W=3.6μm, and finally dotted lines for W= 4.8μm.

From Fig. 2, we find that when G=3.6μm and W=4.8μm, the peak transmittance reaches 90%, which is ~15% higher than the case without floating electrode. But the peak voltage increases from ~19V to ~23V.

If G is reduced to 2.4μm, a lower driving voltage is achieved. In this case, W=3.6μm is an optimal choice, which provides ~85% peak transmittance. On the other hand, if G is increased to 4.8μm, the peak transmittance of protrusion IPS electrode without floating is already quite high (~80%), so floating electrode does not help too much. With W=4.8μm, the peak transmittance rises to ~87%, but the driving voltage also increases to 27V.

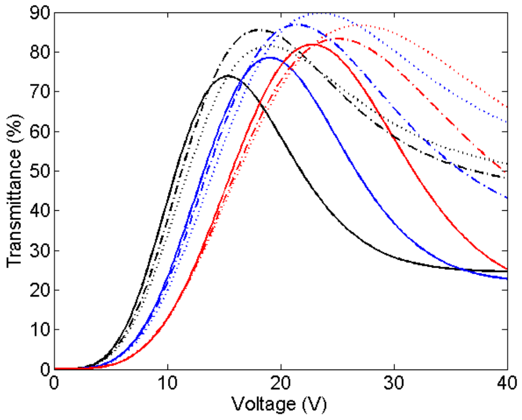


Figure 2. Simulated VT curves of different electrode configurations. λ=550 nm.

3.2 Cell gap effect

Another important parameter is cell gap. Fig. 3 shows the VT curves vs. cell gap. Here protrusion electrode gap is fixed as G =3.6μm, and W=4.8μm.

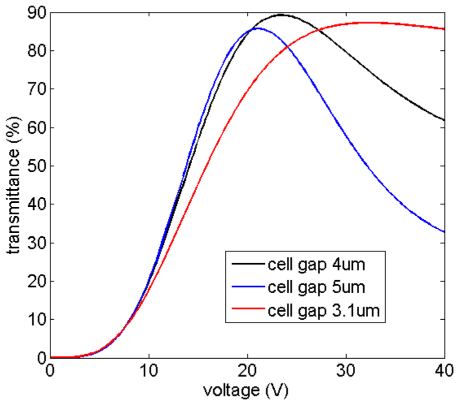


Figure 3. VT curves with different cell gaps.

From Fig. 3, we find that 4μm is the optimal cell gap (black line). This is due to the fact that the transmittance is improved by strengthening electric field near the protrusion top. So when the cell gap increases from 4μm to 5μm (blue line), the separation between floating and protrusion is enlarged. The voltage between floating electrode and protrusion does not change, so the electric field and the induced birefringence near protrusion top are smaller for a thicker cell gap. As a result, the peak transmittance is lowered. If, on the other hand, the cell gap is reduced to 3.1μm (red line), it is difficult for the incident light to accumulate π phase retardation in such a thin cell. So the peak transmittance is lower, and driving voltage is higher.

3.3 Misalignment problem

It is easy to notice that floating electrode has to be fabricated on the top substrate, and misalignment between top and bottom substrates will affect the function of floating electrode. Here, we simulate the VT curves of three configurations. Results are shown in Fig. 4. The black line stands for perfect alignment, the blue line means 1μm lateral misalignment between two substrates, and the red line shows the case with 2μm misalignment. The electrode dimensions of these three configurations are the same as in previous section, and cell gaps are all 4μm. The simulated wavelength is 550 nm.

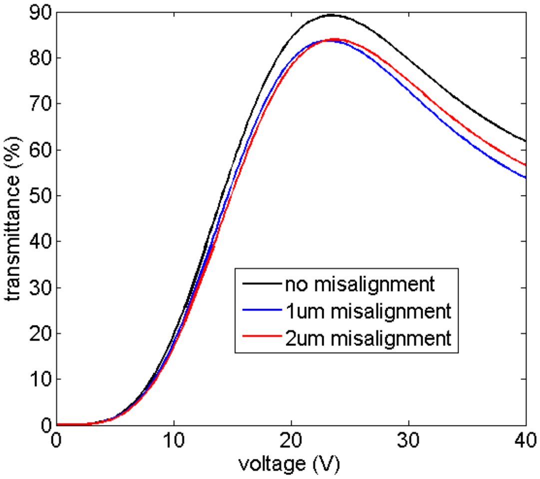


Figure 4. VT curves of different misalignment

From Fig. 4 we see that when there is 1μm and 2μm misalignment, the peak transmittance decreases to ~84%, which is still higher than the peak transmittance of protrusion IPS without floating electrode. The peak voltages of misaligned cases, on the other hand, are almost unchanged.

4. Conclusion

With the help of floating electrode, the overall transmittance of our BPLC cells is increased to 90%. This makes protruded IPS mode more competitive to VFS-based BPLC displays. It still keeps all the advantages of protruded IPS modes, such as wide view, simple phase compensation scheme, and no need for a directional backlight. However, the major challenges are the fabrication of protruded electrodes, and the increased driving voltage.

5. Acknowledgements

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6. References

[1] H. Kikuchi, M. Yokota, Y. Hiskado, H. Yang, and T. Kajiyama, “Polymer-stabilized liquid crystal blue phases,” *Nat. Mater.* **1**, 64–68 (2002).

[2] Z. Ge, S. Gauza, M. Jiao, H. Xianyu, and S.T. Wu, “Electro-optics of polymer-stabilized blue phase liquid crystal displays,” *Appl. Phys. Lett.* **94**, 101104 (2009).

[3] L. Rao, Z. Ge, S. T. Wu, and S. H. Lee, “Low voltage blue-phase liquid crystal displays,” *Appl. Phys. Lett.* **95**, 231101 (2009).

[4] H. C. Cheng, J. Yan, T. Ishinabe, and S. T. Wu, “Vertical field switching for blue-phase liquid crystal devices,” *Appl. Phys. Lett.* **98**, 261102 (2011).

[5] H. C. Cheng, J. Yan, T. Ishinabe, C. H. Lin, K. H. Liu, and S. T. Wu, “Wide-view vertical field switching blue-phase LCD,” J. Display Technol. **8**, 627-633 (2012).

[6] L. Rao, J. Yan, S. T. Wu, S. Yamamoto, and Y. Haseba, “A large Kerr constant polymer-stabilized blue phase liquid crystal,” Appl. Phys. Lett. **98**, 081109 (2011).

[7] M. Wittek, N. Tanaka, D. Wilkes, M. Bremer, D. Pauluth, M. K. Memmer, J. Canisius, A. Yeh, R. Yan, and K. Skjonnemand, “New Materials for Polymer-Stabilized Blue Phase,” SID Int. Symp. Digest Tech. Papers, **43**, 25-28 (2012).

[8] S. Yoon, M. Kim, M. S. Kim, B. G. Kang, M. K. Kim, A. K. Srivastava, S. H. Lee, Z. Ge, L. Rao, S. Gauza, and S. T. Wu, “Optimisation of electrode structure to improve the electro-optic characteristics of liquid crystal display based on the Kerr effect,” *Liq. Cryst.* **37**, 201-208 (2010).

[9] M. Jiao, Y. Li, and S. T. Wu, “Low voltage and high transmittance blue-phase liquid crystal displays with corrugated electrodes,” *Appl. Phys. Lett.* **96**, 011102 (2010).

[10] L. Rao, H. C. Cheng, and S. T. Wu, “Low voltage blue-phase LCDs with double-penetrating fringe fields,” J. Display Technol. **6**, 287-289 (2010).

[11] Y. Li, and S. T. Wu, “Transmissive and transflective blue-phase LCDs with enhanced protrusion electrodes,” J. Display Technol. **7**, 359-361 (2011).

[12] Y. Chen, Y. Sun, and G. Yang, “Low voltage and high transmittance blue phase LCDs with double-side in-plane switching electrodes,” Liq. Cryst. **38**, 555-559 (2011).

[13] J. Yan, H. C. Cheng, S. Gauza, Y. Li, M. Jiao, L. Rao, and S. T. Wu, “Extended Kerr effect in polymer-stabilized blue-phase liquid crystals,” *Appl. Phys. Lett.* **96**, 071105 (2010).