Display Technology Letters

Low Voltage Blue-Phase LCDs With Double-Penetrating Fringe Fields

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***Abstract*—A blue-phase liquid crystal display (BP-LCD) with an in-plane switching (IPS) electrode and etched substrate for generating double-penetrating fringe fields is proposed. An etching depth of 1–2 μm helps to lower the operating voltage by $\sim$30%. This etched IPS BP-LCD also exhibits a wider viewing angle than the conventional one because of the created multi-domain structures in the etched areas. Physical mechanisms responsible for the observed phenomena are discussed.**

***Index Terms*—Blue phase, fast response time, Kerr effect.**

I. Introduction

BLUE-PHASE liquid crystal display (BP-LCD) based on the Kerr effect [1]–[10] is emerging as next-generation display technology due to its submillisecond gray-to-gray response time [11], alignment-layer-free process, and cell gap insensitivity [8] when an in-plane switching (IPS) electrode is used. Especially, the fast response time not only reduces motion blurs but also enables color sequential displays using RGB LEDs. The elimination of color filters triples the optical efficiency and resolution density. However, some urgent technical issues, such as low operating voltage, suppressed hysteresis, and long term stability, etc., remain to be addressed before this promising technology can be implemented.

Recently, some approaches have been developed to lower the operating voltage, such as protruded electrodes [8], corrugated electrodes [9], and wall-shaped electrodes [10]. These methods can reduce the driving voltage from over 50 V (conventional IPS) to below 10 V, however, their fabrication process is comparably complicated.

In this paper, we propose a new IPS structure with an etched substrate to generate double-penetrating fringe fields. The electro-optical properties of such an IPS cell under different electrode configurations and substrate etching depth are investigated. With 1–2 μm etching depth, the operating voltage is reduced by $\sim$30%. Moreover, the viewing angle is widened because of the generated multi-domains. Physical mechanisms responsible for the observed phenomena are discussed.

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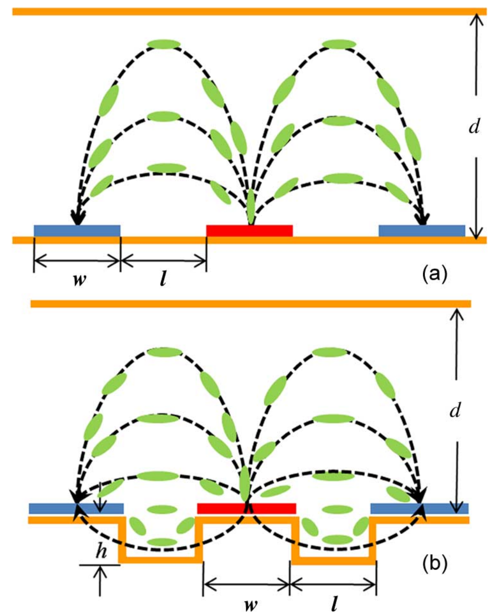

Fig. 1. (a) BP-LCD with conventional IPS structure. (b) BP-LCD with double-penetrating fringe fields.

II. Device Physics and Structure

Kerr effect is a type of quadratic electro-optic effect caused by an electric-field-induced ordering of polar molecules in an optically isotropic medium. The local director reorientation within the unit lattice of the cubic blue phase structure shows a submillisecond response time. At null voltage state, the BPLC medium appears optically isotropic; it becomes anisotropic when an electric field is applied. The induced birefringence (Δn) is related to the electric field (E) as [1]:

$$\Delta n = \lambda K E^2 \tag{1}$$

where λ is the wavelength and K is the Kerr constant. However, the induced birefringence cannot exceed the maximum birefringence of the host LC composite [6], [12].

Fig. 1(a) depicts a traditional planar IPS cell employed in BP LCDs; here w is the electrode width, l is the spacing between the electrodes, and d is the cell gap. The horizontal fringe fields generated from IPS electrodes cause phase retardation to the incident light. The cell is placed between two crossed linear polarizers. For an IPS-5,10 ($w = 5$ μm and $l = 10$ μm) structure, the driving voltage is $\sim$ 50 V_{rms} even the Kerr constant is as large as $K = 10$ nm/V^2, which is a great burden to amorphous silicon TFT technology [13]. In BPLC, when an electric field is applied, optical anisotropy is induced with its effective optic axis oriented along the electric field vector. From previous

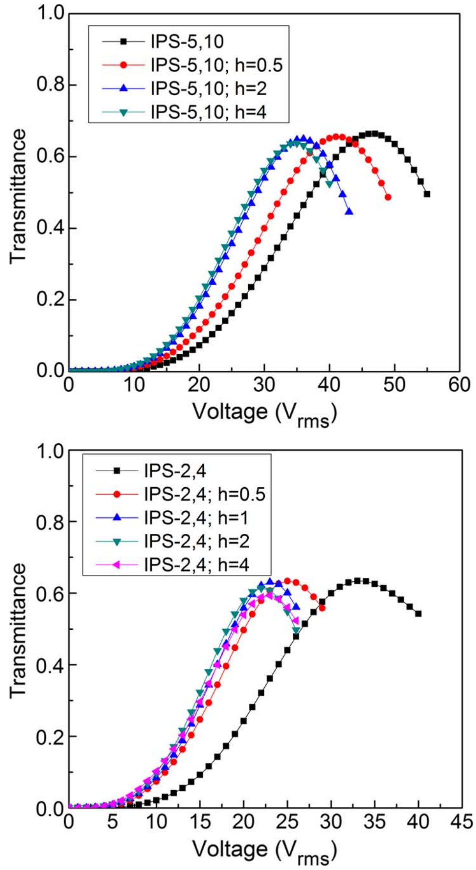

Fig. 2. Simulated VT curves of the BP cell with etched (a) IPS-5,10 substrate and (b) IPS-2,4 substrate. $\lambda = 550$ nm; h (in μm) is the etching depth.

studies [8], only the horizontal field component contributes to the transmittance of the IPS cell. To enhance the transmittance and lower the driving voltage, it is essential to generate a strong and deep-penetrating fringe field.

Fig. 1(b) shows the proposed device structure with an etched bottom substrate. The glass substrate between the electrodes is etched with a depth h. In this design, the fringe fields penetrate into both sides of the substrate. As a result, the BPLC molecules filled in the etched part of the substrate also contribute to phase retardation so that the driving voltage will be lowered.

III. Simulation Results and Discussion

To evaluate the performance of the proposed structure, we calculate the voltage-dependent transmittance (VT) curves under two different electrode dimensions. The simulation method is the same as that described in [7]. The Kerr constant is $K = 12.68$ nm/V^2 ($\lambda = 550$ nm) and the refractive index of the host LC is 1.5. The dielectric anisotropy is assumed to remain unchanged under different voltages. The transmittance is normalized to that of two parallel polarizers (34.83%).

Fig. 2(a) shows the simulated VT curves ($\lambda = 550$ nm) for IPS-5,10 ($w = 5$ μm, $l = 10$ μm, and $d = 10$ μm). From previous studies [8], the operating voltage and transmittance are insensitive to the cell gap, as long as $d > 3$ μm. The line with the black squares is the planar IPS structure without etching; others are with a certain etching depth (h) on the substrate. The voltage at the peak transmittance ($\mathrm{V_p}$) for the planar IPS-5,10 is ~ 47 $\mathrm{V_{rms}}$. As the etching depth increases, $\mathrm{V_p}$ decreases. When

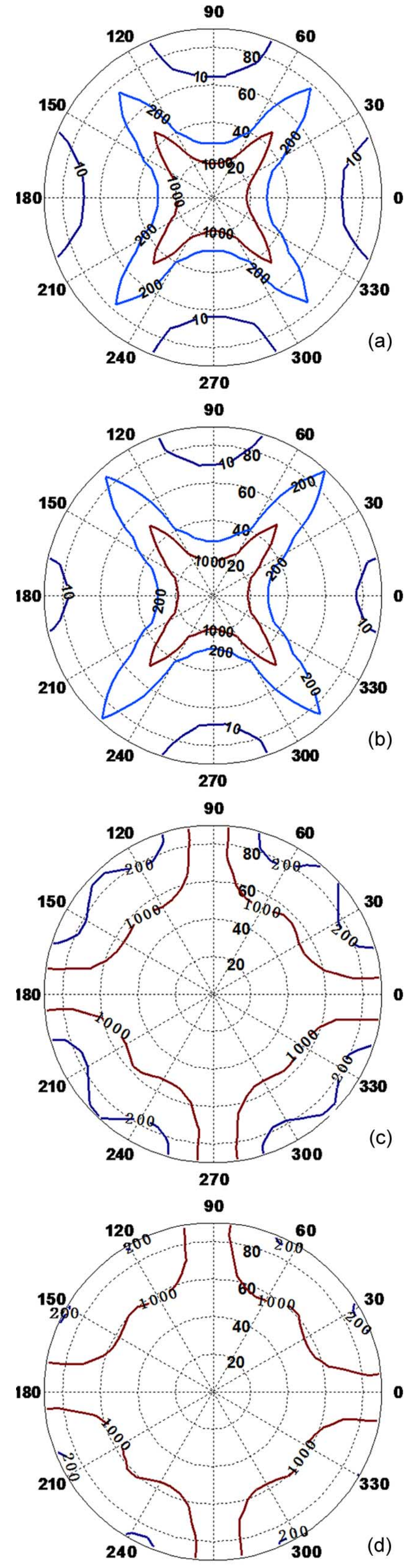

Fig. 3. Isocontrast plots of BPLC in: (a), (c) traditional IPS, without any compensation film and (b), (d) etched IPS substrate, with a biaxial film.

the etching depth exceeds $\sim$ 2 μm, $\mathrm{V_p}$ drops by $\sim$26% and saturates at $\sim$ 35 $\mathrm{V_{rms}}$. The peak transmittance of the etched structure stays almost the same as that of planar IPS.

Similarly, Fig. 2(b) shows the simulated VT curves at $\lambda =$ 550 nm for IPS-2,4 ($w = 2\ \mu$m, $l = 4\ \mu$m, and $d = 10\ \mu$m). The line with black squares represents the planar IPS structure without etching; others are with a certain etching depth (h) on the bottom substrate. The operating voltage of the planar IPS-2,4 is $\mathrm{V_p} \sim 33\ \mathrm{V_{rms}}$. As the etching depth increases to $h = 0.5\ \mu$m, $\mathrm{V_p}$ decreases to $\sim$ 25 $\mathrm{V_{rms}}$. As h continues to increase to 1 μm and beyond, $\mathrm{V_p}$ saturates at $\sim$ 23 $\mathrm{V_{rms}}$, which means the on-state voltage is lowered by $\sim$30.3%. Such a small etching depth can be easily achieved by the wet etching process.

The larger electrode spacing in IPS-5,10 [see Fig. 2(a)] than IPS-2,4 [see Fig. 2(b)] results in a weaker electric field intensity so that its driving voltage is higher. However, according to the typical Poisson problem in the form of $\nabla^2\Phi = 0$, the penetrating depth of the electric fields into the LC medium strongly depends on the dimension $(w + l)$ [7]. As a result, IPS-2,4 has a shallower electric field penetration depth than IPS-5,10 so that its maximum transmittance is $\sim$5% lower. It is also because of this shallower electric field, in the etched IPS-2,4 cell only those LCs near the surface (above and below) can be activated. This explains why in Fig. 2(a) (IPS-5,10) the etching depth saturates at $\sim$ 2 μm, while it is only $\sim$ 1 μm in Fig. 2(b) (IPS-2,4).

At $V = 0$, the BPLC index ellipsoid is like a sphere and appears to be optically isotropic. Therefore, it has a very good dark state. The only light leakage would arise from the oblique incidence that the two crossed polarizers appear to be no longer perpendicular to each other [14]. In a voltage-on state, the BPLCs are reoriented by the electric fields as shown in Fig. 1. We chose IPS-2,4 as an example for viewing angle comparison. The etching depth is set at 1 μm. Fig. 3(a) and Fig. 3(c) are the isocontrast plots of traditional IPS structure without and with a biaxial compensation film. Similarly, Fig. 3(b) and Fig. 3(d) are the corresponding isocontrast plots for BP LCDs with etched IPS substrate. The biaxial film applied in Fig. 3(c) and Fig. 3(d) has following parameters: $N_z = 0.5$ and $R_0 = (n_x - n_y) \cdot d = \lambda/2$ [14]. For both device configurations, the viewing angle is wide and symmetric. The viewing angle for the etched structure is somewhat wider than that of planar IPS cell. This is due to the additional symmetric domains formed in the etched areas.

IV. Conclusion

We proposed an etched IPS structure for lowering the operating voltage of BP-LCDs. From simulations, the operating voltage is reduced by $\sim$30% in the IPS-2,4 structure, if the etching depth is $\sim$ 1 μm. The etching process is simpler than making protruded electrodes, although the latter is more effectively in voltage reduction. Moreover, the etched structure improves the viewing angle because of the generated symmetric domains in the etched areas.

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