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Wall-shaped electrodes for reducing the operation voltage of polymer-stabilized blue phase liquid crystal displays

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Abstract
Polymer-stabilized blue phase liquid crystal displays based on the Kerr effect are emerging due to their submillisecond response time, wide view and simple fabrication process. However, the conventional in-plane switching device exhibits a relatively high operating voltage because the electric fields are restricted in the vicinity of the electrode surface. To overcome this technical barrier, we propose a partitioned wall-shaped electrode configuration so that the induced birefringence is uniform between electrodes throughout the entire cell gap. Consequently, the operating voltage is reduced by $\sim 2.8\times$ with two transistors. The responsible physical mechanisms are explained.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Thin film transistor-based liquid crystal displays (TFT-LCDs) have been commonly used in cell phones, notebook computers, desktop monitors and large screen televisions. The image quality of LCDs has been improved to a comparable level as that of emissive displays due to the advances of wide-view technologies, such as in-plane switching (IPS) [1], fringe-field switching (FFS) [2] and multi-domain vertical alignment (MVA) [3]. However, the response time of present LCDs is about 5 ms which leads to noticeable motion picture image blurs.

Recently polymer-stabilized blue phase (BP) LCDs which utilize the transition from an optically isotropic nano-structured liquid crystal (LC) state to an anisotropic state are emerging because of their submillisecond response time and simple fabrication process [4–10]. Fast response time is particularly attractive because it enables colour sequential displays without using colour filters. As a result, the display brightness and resolution are tripled [11]. However, the operating voltage of a BP LCD is too high (>100 V) which cannot be addressed by conventional amorphous TFTs. Reasons for the observed high operating voltage are as follows: (1) the Kerr constant of the employed LC mixture is fairly small (in the order of 1 nm V^{-2}) [7–9] and (2) the strong in-plane electric fields generated by the interdigitated electrodes are mainly confined near the electrode surface [10]. Thus, the induced birefringence only appears in a very thin layer (<3 μm) above the electrodes. To overcome the high voltage problem, in this paper, we propose to use partitioned wall-shaped electrodes and to drive the device with two TFTs.

2. Switching principle of the device based on the Kerr effect

In the voltage-off state, the BP LC mixture is optically isotropic so that it appears black under crossed polarizers. In the presence of an electric field (E), the induced LC birefringence is determined by

$$\Delta n_{\mathrm{induced}} = \lambda K E^2, \quad (1)$$

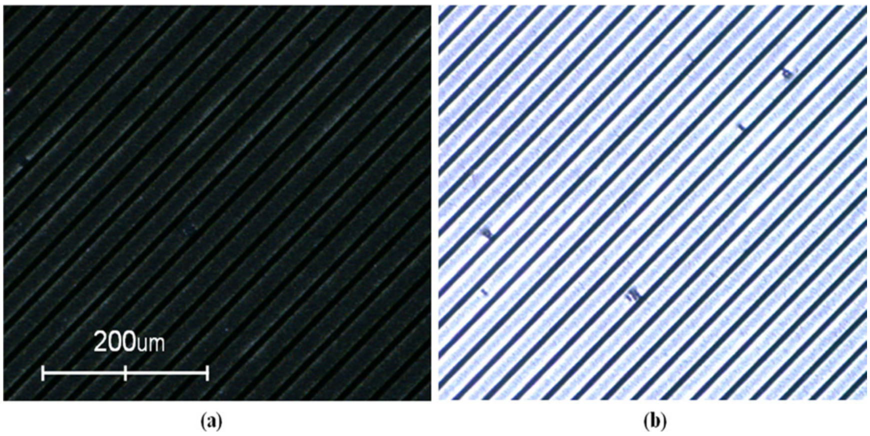

Figure 1. Microphotographs of polymer-stabilized BP using a polarizing optical microscope: (*a*) dark state and (*b*) white state.

where $\Delta n_{\text{induced}}$ is the induced birefringence, λ is the wavelength of the incident light and K is the Kerr constant of the mixture [5]. The normalized transmittance T of the device between crossed polarizers is related to the phase retardation as the following:

$$T = \sin^2 2\psi \sin^2(\pi d \Delta n_{\text{induced}}(V)/\lambda), \qquad (2)$$

where ψ is the angle between the transmission axis of the polarizer and the LC director and d is the LC layer thickness with an induced birefringence. Generally speaking, the induced birefringence is not uniform throughout the LC medium because the electric fields are not uniform. In order to maximize transmittance, ψ should be equal to 45° and $d\Delta n_{\text{induced}}$ should be $\lambda/2$.

3. Experimental and calculated results and discussion

In the experiment, we fabricated a polymer-stabilized BP cell driven by in-plane electric fields generated from interdigital electrodes. The LC cell has the following parameters: electrode width $w \sim 10\,\mu$m, electrode gap $l \sim 20\,\mu$m, electrode height $\sim 0.3\,\mu$m, the Kerr constant of the LC material employed is $K \sim 0.7$ nm V^{-2} and LC layer thickness $\sim 10\,\mu$m. The polymer-stabilized BP LC shows a clear dark state, as shown in figure 1(*a*) and the transmittance starts to appear at 100 V$_{\text{rms}}$. However, the transmittance is not fully saturated even at 200 V$_{\text{rms}}$, as shown in figure 1(*b*). This implies that the transmittance in the middle of electrode gaps is still not saturated. Therefore, in order to lower the operating voltage the following approaches should be taken: (1) reducing the electrode gap because E is roughly proportional to $1/l$, (2) modifying the electrode structure and (3) using a LC with a larger Kerr constant.

To better understand why the device shows such a high operating voltage, we have analysed the electric field distribution inside the cell. In the conventional structure, when the voltage is applied an in-plane field (E_y) is generated between pixel and common electrodes. However, the thickness of electrode is less than 1 μm so that it is expected that the field intensity decreases along the z-direction from electrodes surface. Consequently, the induced birefringence is dependent on the vertical position, as shown in figure 2(*a*). The effective vertical penetrating layer is roughly proportional to the electrode dimension ($w + l$, w is the electrode width and l is the electrode gap) [9, 10], as the potential distribution from this configuration is a Poisson problem. Therefore, to reduce driving voltage a more effective way for guiding the electric fields into the LC bulk region is critical.

Here, we propose to use wall-shaped electrodes for generating strong in-plane electric fields throughout the LC layer thickness. Unlike conventional LCDs, the polymer-stabilized BP devices do not require any alignment layer or surface treatment; they appear optically isotropic in the dark state. Therefore, the height and shape of the electrodes will not degrade the dark state of the BP LCD devices. Figure 2(*b*) shows the ideal partitioned wall-shaped electrodes. With this structure, the electric field intensity E_y remains the same irrespective of vertical position of the LC layer. As a result, the required operating voltage would be reduced significantly. To fabricate such wall-shaped electrodes, we could coat a layer of organic resin with a height larger than 3 μm, etch off the unwanted areas and then deposit electrodes on the sides [12], as illustrated in figure 2(*b*). The vertical wall with high height can also be formed using screening printing process [13] or inkjet printing process [14].

In addition to using wall-shaped electrodes, we also propose a new driving method to effectively reduce the driving voltage by another factor of two. In a conventional LCD, the LC cell should be always driven by ac voltage to eliminate image sticking. The voltage of common electrode is fixed at a certain voltage and the signal voltage onto the pixel electrode swings from 0 to 2× of the LC operation voltage V_{on} with the use of one transistor in the dot inversion driving scheme. For example, with 10 V output capability of the existing driver IC, potential of common electrode is always fixed at 5 V and the potential of pixel electrode changes from 0 to 10 V to supply the voltage onto the LC cell between 5 V and +5 V. Thus the maximum possible voltage that can be applied to LC cell (at 5 V) is reduced to half of the TFT driver capability (at 10 V). Although most of current LCDs use only one transistor to switch one pixel, recently two transistors are adopted in one pixel to realize eight domains in MVA devices [15] by applying

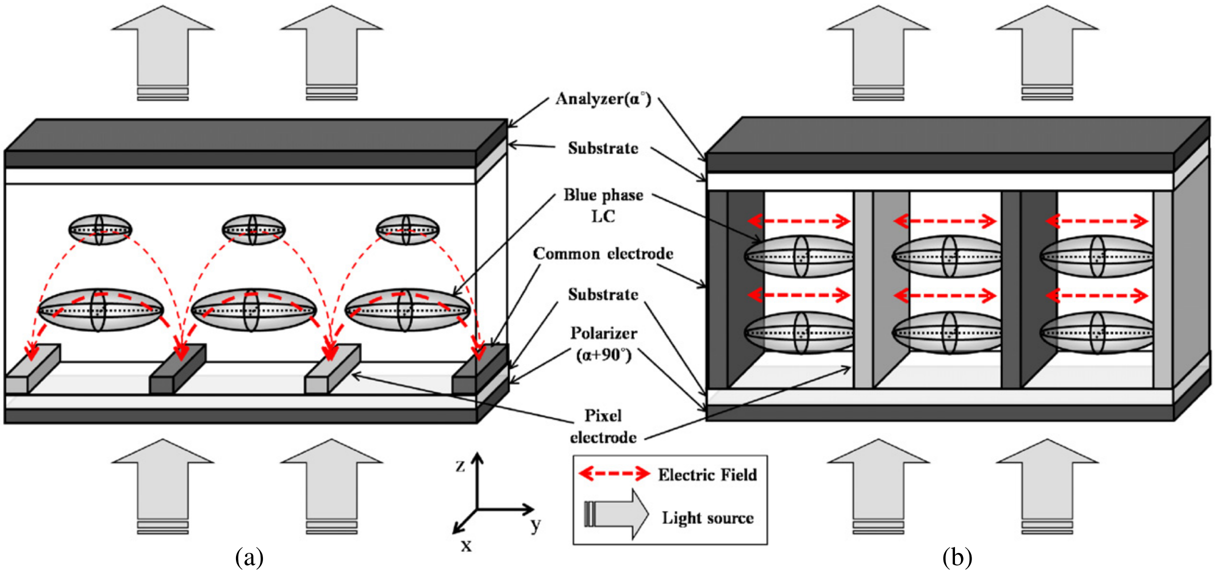

Figure 2. Schematic cell structure of (*a*) conventional device with interdigital electrode structure and (*b*) proposed device with partition wall-shaped electrodes.

different voltages on two sub-4-domains. Two TFT driving is also utilized in FFS device to lower the operating voltage [16]. The concept of two transistors can also be applied to this device so that polarity of pixel and common electrode can be separately controlled by two transistors. Strictly speaking, here the common electrode is no longer a common one for all pixels; rather, it is a second pixel electrode that is controlled by a separate TFT in each single pixel. With this approach, potential of pixel and common (or second pixel) electrodes can be controlled separately to utilize the maximum possible driving capability of the IC driver. For example, when the potential of pixel electrode is 10 V (0 V), the corresponding voltage on the common electrode (or second pixel) can be 0 V (10 V) to generate +10 V (10 V).

Next, we calculated the in-plane electric field intensity in both structures at three different positions: near electrode surface, middle and top of LC layer as shown in figure 3, by applying a same voltage of 10 V. For the purpose of simulations, we assume the electrode width $w = 5\,\mu$m and electrode gap $l = 10\,\mu$m and the cell gap between top and bottom substrate is $10\,\mu$m. In a conventional IPS device the electrode height is $\sim$40 nm, but in our proposed structure we assume it is the same as the electrode gap, i.e. $10\,\mu$m. The applied voltage is 10 V. As indicated in figure 3, in the conventional structure the maximum field intensity decreases along the z-direction from electrode surface. In contrast, in the new structure the field intensity is uniform irrespective of the z-direction because of the partitioned wall-shaped electrodes.

Once the field distribution is obtained, we calculated the voltage dependent transmittance for each device structure. To do so, we employed three-dimensional commercial simulation software Techwiz (Sanayi, Korea). We have developed a numerical solver to characterize the electro-optical properties of polymer-stabilized BPLC cell. Our modelling approach is based on the calculation of the induced birefringence by the Kerr effect of BPLC. It consists of three steps: (1) to calculate the electric field distribution in the BPLC media by solving the Laplace equation. We treat BPLC as an electrically isotropic material with an effective dielectric constant ($\varepsilon_{\rm BP} = \varepsilon_\perp + \frac{1}{3}\Delta\varepsilon$) in the E-field calculation because of its macroscopic structural symmetry. (2) To calculate the induced birefringence and its optic axis from the electric field distribution obtained in step one and (3) to calculate the transmittance by the conventional extended Jones matrix technique. Similar approach has been reported by Ge *et al* [9, 10].

In our model, we also restrict the induced birefringence to have a maximum value. The induced birefringence ($\Delta n_{\rm i}$) in the BPLC system can be expressed by the applied E-field ($\vec{E}$) shown in equation (1). Besides, since polymer-stabilized BPLC is a combination of nano-structured host LCs with nematic-like short-range ordering and polymer network, we assumed that the induced birefringence ($\Delta n_{\rm i}$) cannot exceed the birefringence of the host LC ($\Delta n_{\rm h}$). Therefore, we set an upper constraint as follows:

$$\Delta n_{\rm i} = \Delta n_{\rm h}, \qquad \text{when } \left|\vec{E}\right| > \sqrt{\frac{\Delta n_{\rm h}}{\lambda K}}. \tag{3}$$

The Kerr constant of the BPLC is assumed to be 7 nm V^{-2}. Figure 4 shows the voltage dependent transmittance of three device configurations: (I) the conventional IPS device, (II) proposed device using partitioned wall-shaped electrodes with one TFT and (III) the proposed device with 2 TFTs. The transmittance of device-I is slightly higher than that of other two because the LC directors above the electrodes also make a small contribution. As shown in figure 4, the voltage corresponding to peak transmittance of device-I, -II and -III occurs at 148, 106 and 53 $V_{\rm rms}$, respectively. It deserves a special mention that our proposed device-III lowers the operating voltage by $\sim$2.8$\times$, as compared with a normal IPS structure. However, 53 V is still too high to drive using a normal driver IC in LCDs. To further reduce operating voltage, the following options can be considered: (1) to reduce the

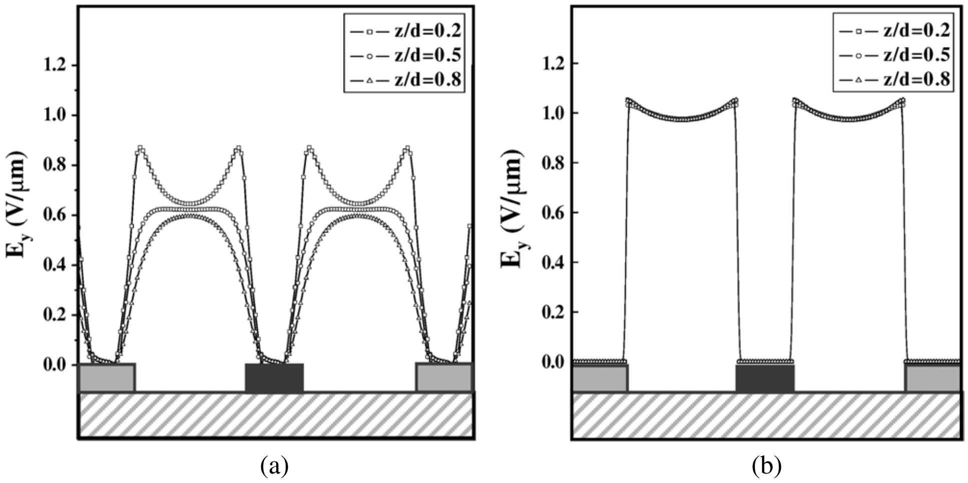

Figure 3. Electric field according to the z/d, where z is perpendicular direction and d is cell gap. (*a*) Conventional horizontal electric field induced device and (*b*) Proposed device using partition-wall shaped electrodes.

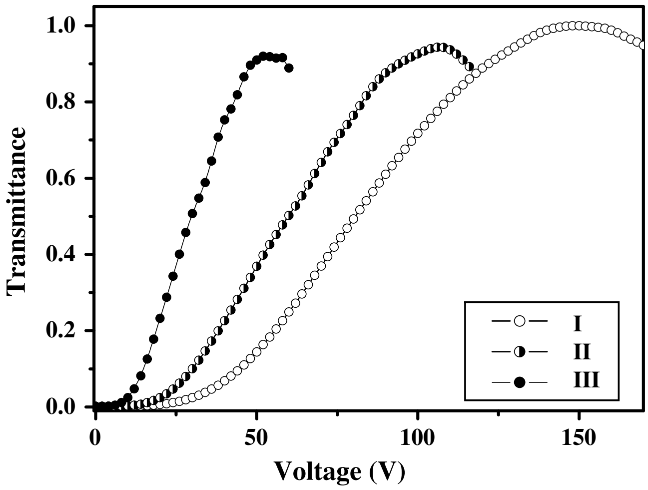

Figure 4. Voltage dependant-transmittance curves in a conventional (I) and proposed (II) IPS devices and two transistors with proposed IPS device (III).

electrode distance in the proposed wall-shaped electrodes and (2) to employ a LC mixture with a larger Kerr constant. As the Kerr constant increases by 100×, the operating voltage would decrease by ∼10× [9, 10]. When shrinking the electrode spacing, the number of electrodes increases at a given pixel size. Thus, the transmittance will decrease accordingly because the horizontal fields above the electrodes are too weak to effectively reorient the LC directors. Therefore, the latter approach, i.e. using a larger Kerr constant material, is preferred from the viewpoint of preserving a high optical efficiency.

4. Summary

In conclusion, our proposed device structure with partitioned wall-shaped electrodes and two transistors offers an effective way for reducing the operating voltage by ∼2.8× in comparison with the conventional IPS structure. To further lower the operating voltage to 15 V so that a conventional driver IC can be used for driving BP LCDs, we could reduce the electrode gap and develop LC mixtures whose Kerr constant is larger than 10 nm V^{-2}.

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