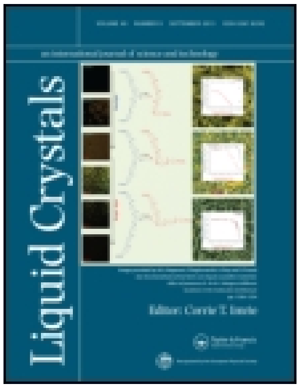

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Surface polymer-stabilised in-plane field driven vertical alignment liquid crystal device

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In-plane field driven vertical alignment device using a liquid crystal with positive dielectric anisotropy has been studied. In the device, the distance between inter-digital electrodes needs to be increased to achieve higher transmittance; however, such a design results in an increase in operating voltage and slower response time. In this work, we use polymer stabilisation technique, which generates surface tilt angle other than 90°, to improve upon these drawbacks. As a result, the proposed device shows lower operating voltage and faster response time while keeping transmittance at the same level, compared to those prior to polymer stabilisation.

Keywords: vertical alignment; in-plane field; positive dielectric anisotropy; polymer stabilisation

1. Introduction

Recently, liquid crystal displays (LCDs) play very important roles in the information age for interfacing between human beings and machines. Image qualities of the present LCDs in viewing angle and response time are greatly improved with the adoption of several liquid crystal (LC) modes such as in-plane switching (IPS),[1] fringe-field switching (FFS),[2–6] and multi-domain type of vertical alignment (VA).[7–9] At present, majority of the large-sized LCD-TVs (over 50 inches) with pixel size over few hundred micrometres adopt VA mode. The advantages of the VA mode over FFS and IPS modes include no rubbing process for device fabrication and a very high contrast at normal direction, mainly attributed to the initial vertical alignment of LCs. However, they have some drawbacks such that the image quality at off-normal axis is less satisfactory than other competitors, an operating voltage is rather high and improvement of response time is limited. These impediments are mainly originated from the use of vertically aligned LCs with a negative dielectric anisotropy, since the LCs with negative dielectric anisotropy, in general, have much higher rotational viscosity as well as lower dielectric anisotropy.

In order to overcome the intrinsic drawbacks of conventional VA mode, polymer-stabilised VA modes [10–15] and photo-aligned VA modes [16] have been developed recently. However, all the above-mentioned VA modes are still utilising LCs with negative dielectric anisotropy. The decaying response time of the VA device is proportional to $d^2\gamma/K_3$, where d, γ and K_3 are the cell gap, rotational viscosity and bend elastic constant of the LC, respectively. In general, K_3 is largest among all three splay, twist (K_2) and bend elastic constants, so the VA mode has an advantage in decaying response time, compared to those of IPS- and FFS-modes where the twist deformation is predominant under electric field. However, this advantage of VA mode over other two modes diminishes because the γ value of VA devices is much higher than IPS and FFS modes due to the use of LCs with a negative dielectric anisotropy. In this respect, if the VA device that utilises LCs with positive dielectric anisotropy can be developed, it would have great advantage in response time and also in operating voltage.

In 1997, Lee *et al*. proposed in-plane field driven VA device named VA-IPS,[17,18] in which vertically aligned LC with positive dielectric anisotropy experiences bend deformation along the in-plane field. Unfortunately, this device has some disadvantages, such as high operating voltage and low transmittance when compared with other multi-domain VA modes with negative dielectric anisotropy LCs. To improve upon these problems, a modified structure to lower the operating voltage has been suggested later,[19,20] but the modified structure also exhibits a low transmittance with relatively high operating voltage. Consequently, to increase the transmittance of the VA-IPS mode, an electrode structure with a narrow electrode width and long inter-electrode distance is required. However, this design can cause slow response time and high operating voltage when the

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inter-electrode distance is too long. In this paper, we propose the polymer-stabilised VA-IPS device utilising positive dielectric anisotropy LCs, which exhibits lower operating voltage and faster response time than those in conventional VA-IPS device with no stabilised director pretilt.

2. Switching principle of the VA-IPS device

In general, the normalised transmittance (T/T_0) for a uniaxial LC cell under crossed polarisers can be defined as follows:

$$T/T_0 = \sin^2 2\psi(V)\sin^2(\pi d\Delta n_{\mathrm{eff}}(V)/\lambda) \quad (1)$$

where ψ is a voltage (V)-dependent azimuthal angle between the crossed polarisers and the LC director, d is a cell gap, Δn_{eff} is voltage-dependent effective birefringence of the LC layer and λ is the wavelength of an incident light. To achieve maximum transmittance at normal direction, ψ should be 45° and $d\Delta n_{\mathrm{eff}}$ should be $\lambda/2$.

Figure 1 shows the schematic illustration of the operating principle of the proposed VA-IPS mode for off and on states. The signal and common electrodes exist only on the bottom substrate in an interdigitated form with electrode width (w) and distance (l) between electrodes. However, the top substrate is a glass plate without conductive layer. Initially, LC molecules are vertically aligned in the off state so that ψ = 0° and Δn_{eff} = 0, and the device appears black. When a voltage is applied, the vertically aligned LC molecules tilt downward along the in-plane field direction while making ψ = 45°, so that the light transmittance is observed and, in addition, the LC director forms two domains in the on state spontaneously. In the device, LC directors above the electrodes remain almost vertically aligned in the on state, so that the transmittance is not induced in these areas. On the other hand, the threshold voltage V_{th} of the device can be defined as follows:

$$V_{\mathrm{th}} = \pi\frac{l}{d}\sqrt{\frac{k_3}{\Delta\varepsilon}} \quad (2)$$

where $\Delta\varepsilon$ and K_3 are dielectric anisotropy and bend elastic constant of the LC, respectively. As can be clearly understood from Equation 2 and discussion earlier, small l is favoured for a low operating voltage. However, the smaller l, more the number of interdigitated electrodes present at a given pixel size, subsequently resulting in a decreased overall transmittance. Therefore, keeping l in an appropriate distance is very important for achieving high transmittance and proper operating voltage. In addition, the existence of a dual domain concept of surface pretilt of the director, rather than a perfect vertical alignment, towards the central area between electrodes will allow the LC molecules to reorient more easily in a harmonised fashion.

In this case, the predetermined director tilt facilitates faster rising response and lower operating voltage, compared to those in the vertically aligned VA-IPS cell without a director pretilt.

3. Experimental

Figure 2 shows the schematic illustration of a fabrication process of the proposed polymer-stabilised VA-IPS mode. The LC- and UV-curable reactive mesogens (RMs) are initially mixed in a weight ratio of 99.9:0.1, and the mixture is loaded into the cell using a capillary action. Figure 2(a) shows a homogeneously mixed state of the LC and RM molecules in the electro-optic cell before photo-induced polymerisation of the RMs. When a voltage larger than the V_{th} is applied to the cell, the LC directors are tilted and realigned along the in-plane electric field, as shown in Figure 2(b). When LC directors are in a stable state with a specific tilt orientation at the surface, UV light is exposed to the cell to initiate polymerisation of the RMs and subsequent diffusion of the polymer aggregates to the surfaces, as illustrated in Figure 2(c). Upon removal of the applied electric field, the LC

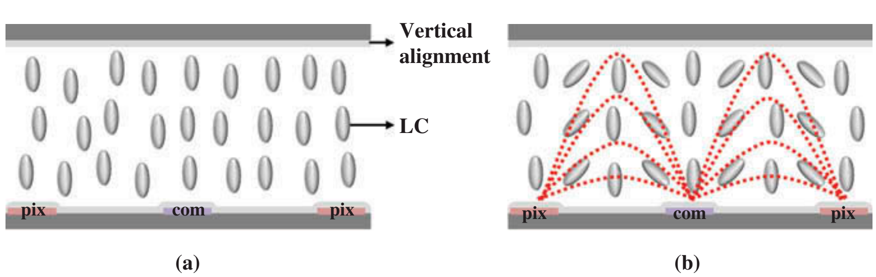

Figure 1. (colour online) Schematic illustration of the operating principle of VA-IPS mode for (a) Off and (b) On states. The red dotted lines represent the direction of applied electric field.

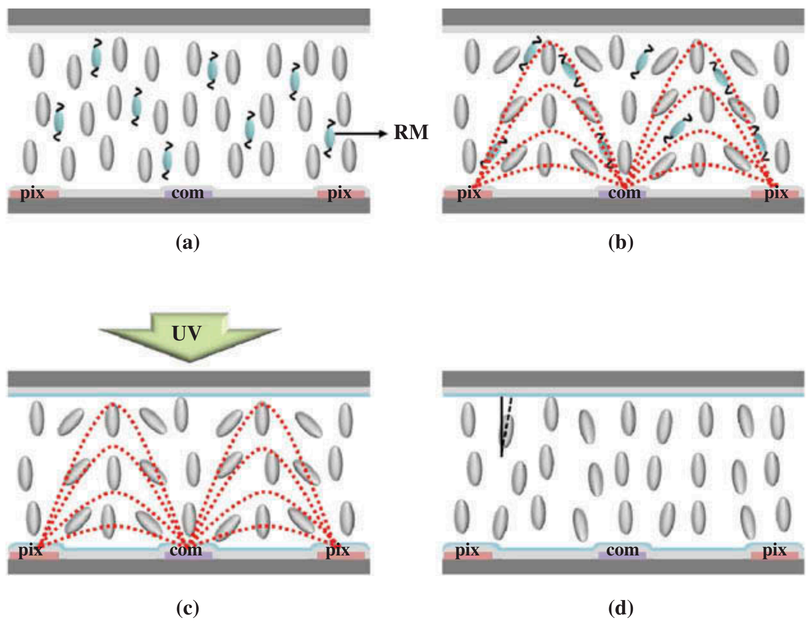

Figure 2. (colour online) Schematic representation of a fabrication process for the proposed PS-VA-IPS mode: (a) The homogeneous mixture of host LC and RM molecules confined in the cell before photo-polymerisation of RMs, (b) reoriented LC directors along the in-plane electric field at above threshold ($V > V_{th}$), (c) deposition of polymer aggregates to the surfaces under applied electric field and UV-light exposure and (d) near vertical alignment of the LC director with a small predetermined tilt at the surfaces after removal of the applied field.

director relaxes back to near vertical state with a slight tilt coined by the polymerised RMs at both surfaces (Figure 2(d)).

For the cell fabrication, the LC mixture with positive dielectric anisotropy ($\Delta\varepsilon$ = 8.9) and birefringence (Δn = 0.1 at 589.3 nm and 20°C) is used. The RM used in the study is RM 257 (Merck, Darmstadt, Germany). For the IPS substrate, two different electrode structures have been used: Case 1 (w = 3 μm, l = 7 μm) and Case 2 (w = 3 μm, l = 15 μm). The cell gap is maintained at 3.46 and 3.39 μm for Case 1 and Case 2, respectively.

During the UV curing process, it is important to choose the appropriate applied voltage for polymer stabilisation in order to achieve surface tilt angle of 88° ~ 89° at the area between electrodes. For this purpose, we have applied the voltage where the cell transmittance is 90% of the maximal value. The intensity of UV light is 35 mW/cm^2 and irradiation time is for 48 minutes. The polarised optical images have been taken by using Nikon ECLIPSE E600 (Nikon, Japan) equipped with Nikon DXM 1200 digital camera. The electro-optical properties are characterised by the LCMS-200 (Sesim photonics technology, Korea).

4. Results and discussion

As explained in the switching principle of the device, formation of director pretilt at surfaces via polymer stabilisation process would improve electro-optic characteristics of the device, such as response time, transmittance and the operating voltage. Figure 3 shows voltage-dependent images of polarising optical microscopy (POM) before and after UV stabilisation for Cases 1 and 2. For a detailed comparison, the POM images before and after UV stabilisation have been recorded at the same voltage. As seen in Figure 3, both cells exhibit the same level of dark state at normal direction, indicating that although the surfaces retain predetermined director pretilt for the stabilised cell, the resulting retardation due to the director tilt is negligible. With the increasing applied voltage, the transmittance first occurs near the electrodes and gradually extends to inter-electrode areas at higher voltage. Although it is not easily perceived by the first sight, careful observations of the POM images show that the polymer-stabilised cells exhibit slightly higher transmittance at the same applied voltage.

In general, the cell shows different tone of white colour according to the value of phase retardation in the VA mode. If the phase retardation is smaller than the optimum value in the VA mode, a bluish-white colour appears. On the other hand, the yellowish-white colour appears when the retardation value is larger than the optimum phase retardation. In this experimental result, it exhibits bluish-white colour near its maximum brightness, T_{80} ~ T_{100} in Figure 3, before UV cure and yellowish-white colour after UV

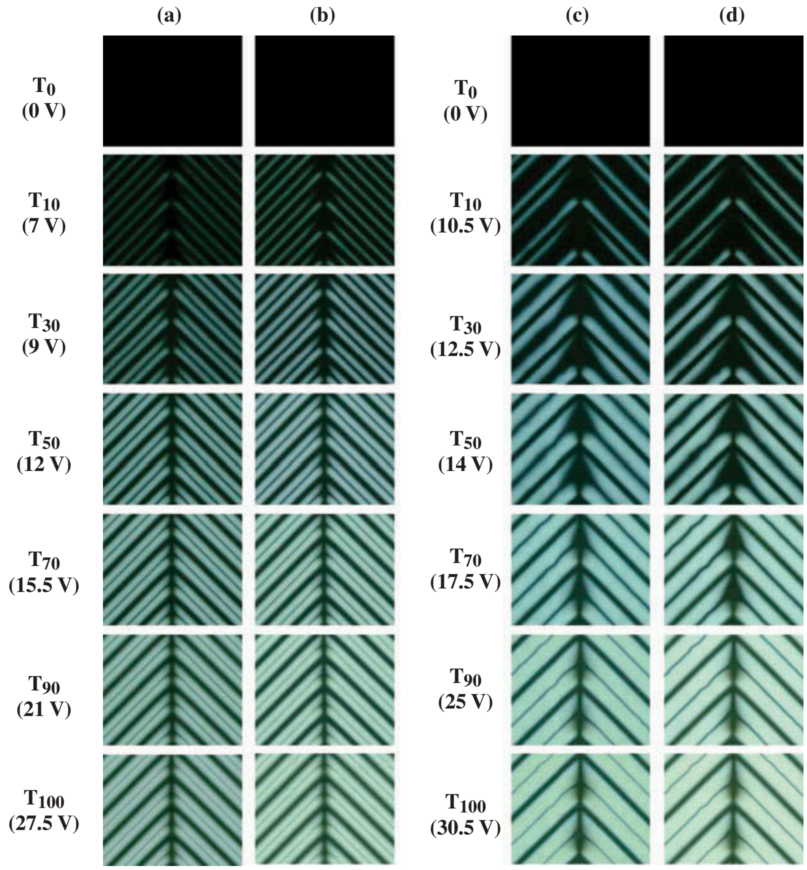

Figure 3. (colour online) Polarised optical microscope images for Case 1 and Case 2 before and after UV curing: (a)/(c) and (b)/(d) present transmittance variations as a function of applied voltage before and after the polymer stabilisation, respectively.

stabilisation. The colour shift in the on state indicates that the effective phase retardation at the same applied voltage is larger after UV stabilisation due to the existence of a director pretilt at the surfaces. Especially for Case 2, the yellowish-white tone of transmittance has been observed at lower voltage for the stabilised sample. It is also corroborative to the voltage–transmittance curves in Figure 4.

Figure 4 shows the comparison of voltage-dependent transmittance (V–T) curves of the proposed PS-VA-IPS cells before and after polymer stabilisation for Cases 1 and 2. After the polymer stabilisation, V–T curve is shifted to the left, such that the threshold and operating voltages become lower. It indicates that the LC molecules respond more easily to the electric field due to the predetermined director pretilt at the surfaces. In addition, the transmittance becomes higher after the stabilisation at the same voltage, suggesting that the LC molecules start responding at lower voltage also due to the existence of surface pretilt.

The transmittance curves show a tendency to be continuously increasing, as shown in Figure 4. This is arguably associated with the *l* value of patterned electrodes and thickness of the LC layer. For both cases, however, it is evident that the polymer-stabilised cells perform better both in transmittance and driving voltage, primarily benefitted from the

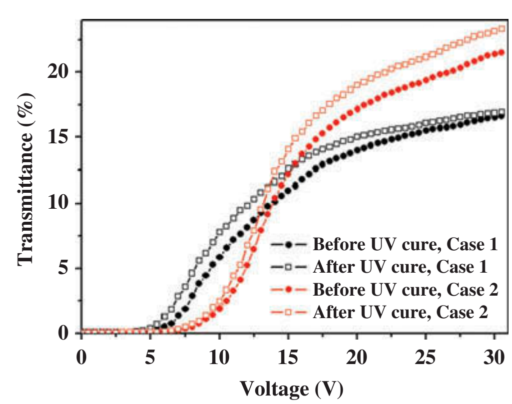

Figure 4. (colour online) Voltage-dependent transmittance curves before and after polymer stabilisation for Case 1 and Case 2.

director pretilt formed by the polymer stabilisation at the surfaces. Therefore, we believe that further optimisation of *l* and *d* values, together with polymer content and physical parameters of the LC host such as Δn, $\Delta\varepsilon$ and γ values, can accommodate much improved performance for the PS-VA-IPS device.

Figure 5 shows grey-to-grey response times of the proposed PS-VA-IPS cells before and after polymer stabilisation for different dimensions of the patterned electrodes. The rising time and decaying time have been defined as a turn-on time from zero-voltage transmittance to each grey-level transmittance and turn-off time from the grey-level transmittance to zero-voltage transmittance, respectively.

As shown in Figure 5(a), the grey-to-grey rising response becomes faster after the polymer stabilisation through the whole grey levels for both Cases 1 and 2. On the other hand, the decaying response shown in Figure 5(b) becomes slightly sluggish for both cases except for the T_{10} grey level. The observed response behaviours of the PS-IPS-VA mode before and after pretilt stabilisation are somewhat distinct from the previously reported PS-IPS mode with an initial planar alignment and predominant twist deformation of LCs at voltage-on state.[21] In our case, more stabilisation effects on the rising response are evident. For the latter case, however, stronger stabilisation effects have been reported for the decaying response time owing to reduced cell gap effect due to an additional polymer layer. It should also be noted that the overall response characteristics of the PS-VA-IPS mode are similar to the conventional PS-VA mode. In the case of PS-VA mode, the pretilt stabilisation shows substantial impacts on the rising response, with little effect on the decaying time.[11] The similarities are probably due to the same initial homeotropic alignment and predominant bend deformation for both cases, although the direction of applied electric field is completely different. As discussed earlier and seen in Figure 5(a), the main drawback of the VA-IPS mode is a slow rising response at low grey levels. Although this intrinsic shortcoming is improved by the polymer stabilisation process, there is still a large room to make a progress. Nevertheless, the decaying response times in most grey levels are less than 3 milliseconds. Considering the cell gap larger than 3.3 μm, it is a very fast response that is intrinsically attributed to a low value of γ/K_3 with the use of positive dielectric anisotropy LCs.

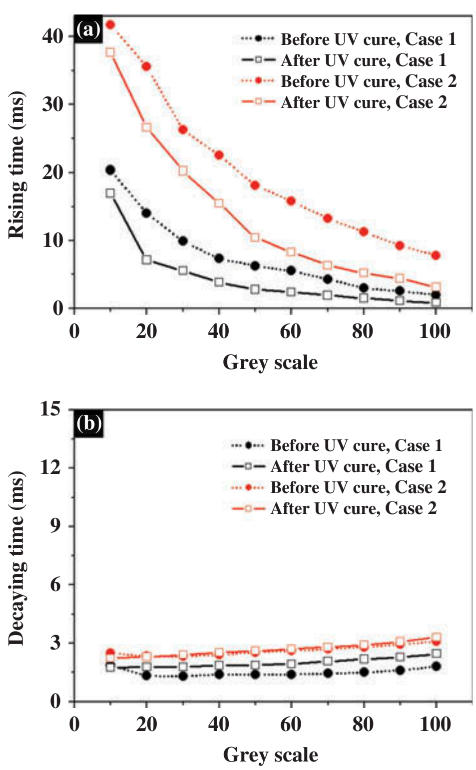

Figure 5. (colour online) The effects of polymer stabilisation on the grey-to-grey response times for both rising and decaying responses of Case 1 (red symbols) and Case 2 (black symbols): the filled circles are for the cells prior to stabilisation and the empty squares are for the cells after polymer stabilisation.

5. Summary

We report the effects of polymer stabilisation for the proposed VA-IPS mode. The PS-VA-IPS mode shows an improved performance, such as enhanced brightness, fast response time and low driving voltage, which will potentially overcome long-standing problems of the conventional VA-IPS mode. With the proposed approach, more flexibility in selecting the optimum length (*l*) is given, which can solve the low transmittance problem of the device while keeping the fast response time characteristics. Although it shows preliminary advances, the proposed concept of polymer stabilisation together with intrinsic advantages of the VA-IPS mode may suggest a success in large-sized LCD market. We believe that further optimisation of *l* and *d* values, together with polymer content and physical parameters of the LC host such as Δn, $\Delta\varepsilon$ and γ values, can accommodate much improved performance for the PS-VA-IPS device.

Acknowledgements

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