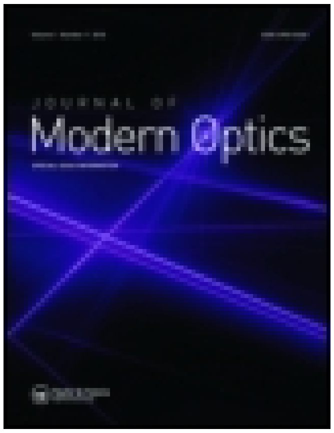

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In general, the super in-plane switching (S-IPS) liquid crystal (LC) mode is widely used for LCD applications because of its wide-viewing properties. However, it can also diminish the aperture ratio in active areas due to the zigzag pattern. In this paper, we proposed an IPS LC mode that has wide-viewing properties even if the stripe-patterned electrodes, which can provide a high transmittance property, are applied using the double-exposed UV alignment method to the upper/lower domain of the active area. The initial alignment direction of the upper/lower domain was optimized with simple experiments and we achieved both the superior dark level in the initial mode and wide-viewing properties in the applied voltage mode. As a result, we obtained an increased aperture ratio of about 10% and a higher optical transmittance of 15% compared to the conventional S-IPS LC cell because of the high aperture ratio without any optical loss of the initial dark state and viewing angle property.

Keywords: in-plane switching liquid crystal; UV alignment method, multi-domain transmittance; wide-viewing angle

1. Introduction

Current liquid crystal (LC) technologies for various applications are required to provide superior electro-optical performances, including wide viewing angle, fast response time, and high contrast ratio. In addition, many kinds of LC modes, such as twisted nematic mode (TN) [1,2], vertical alignment mode (VA) [3–6], in-plane switching mode (IPS) [7–9], and fringe-field switching mode [10–12] have been developed in order to enhance the display image quality of LC cells. Of all the LC modes, the IPS mode shows a wider off-axis viewing angle due to the horizontal optical reorientation of the LC molecules. The stripe-patterned electrodes in the IPS cell, in particular, can provide the high aperture ratio in a pixel so that the highest level of brightness can be achieved. In spite of its superior optical performances, the conventional IPS mode shows the color shift for some practical viewing points due to the single domain structure. To overcome these optical problems, the super IPS (S-IPS) mode [7,13], which contains the zigzag patterned electrodes for multi-domain effect in a pixel, has been proposed to enhance the wide-viewing angle and the color shift performance. However, zigzagged electrodes in the S-IPS cell reduce the aperture ratio in a single pixel and also generate several disclinations around the edge of the electrodes and boundary of the multi-domain located in the middle area of the cell. Therefore, these drawbacks induce poor brightness to the extent that the optical transmittance of the S-IPS mode is somewhat lower than that of the conventional IPS mode.

In this paper, we propose an IPS mode with the stripe-patterned electrode structure with multi-domain effect using the double-exposed UV alignment method to the upper/lower domain of the active area. The proposed IPS LC cell can show the high aperture ratio because of the stripe-patterned electrode, so that the transmittance is higher than that of the conventional S-IPS LC cell. By inspecting the difference between the UV exposure angles in the upper/lower area that can guarantee a sufficient multi-domain effect, we calculate and measure the light leakage in the dark state. As a result, the variation of the initial dark state due to the different UV angles in the upper/lower area can be almost ignored and we confirmed that the proposed LC cell can provide an excellent multi-domain effect and high transmittance simultaneously.

2. Cell structure and the optimized electro-optical principle of the proposed IPS liquid crystal cell.

Figure 1 shows the cross-sectional view of the cell structure. Basically, the top substrate had no indium tin oxide (ITO) electrode layer. On the bottom substrate, we used the stripe-patterned electrode that consists of the pixel

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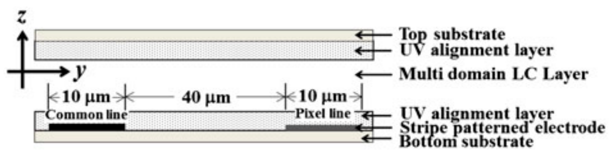

Figure 1. The cross-sectional view of the cell structure in the proposed IPS mode. (The colour version of this figure is included in the online version of the journal.)

line and common line to improve the aperture ratio of the cell. The electrode width of both the common and the pixel line is 10 μm and the distance between two electrodes is designed to be 40 μm, respectively. In this structure, an aperture ratio of a proposed IPS LC cell could be increased by more than 10% compared to that of the conventional S-IPS LC cell.

Figure 2(*a*) and (*b*) illustrate the switching principle of the LC molecules for each domain in the proposed IPS cell. In this mode, the initial LC molecules are set at the angle $\pm\alpha$ from the transmission axis of input polarizer *P* on the upper/lower domain area as shown in Figure 2(*a*). In the applied voltage mode from the stripe-patterned electrodes, the LC molecules placed on the upper/lower domain area could be reoriented at ±45° angles, which is the maximum effective retardation angle for the horizontal switching LC mode, so that multi-domain effect in bright state could be realized in Figure 2(*b*). However, the initial UV angle of the upper/lower domain α can induce light leakages in the dark mode because the transmittance obviously depends on the optical axis of the LC director. Therefore, we should decide the appropriate value of the angle α to guarantee both an excellent dark state and a sufficient multi-domain effect. Firstly, we calculated the optical transmittance as a function of the angle α as shown in the following equation [14,15]:

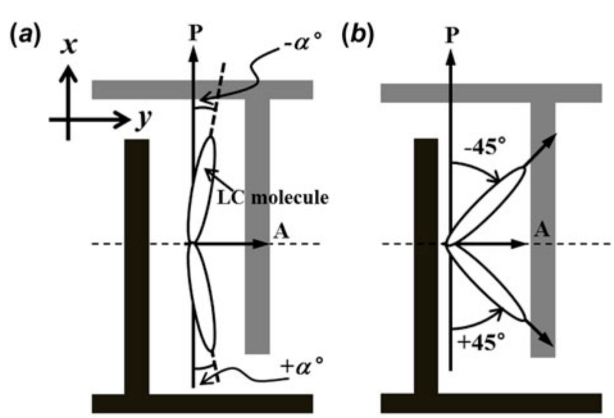

Figure 2. The orientation of the LC molecules for the upper/lower domain area of the proposed IPS cell (*a*) in a dark state and (*b*) a bright state.

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

where d is the cell thickness, Δn_{eff} is the effective birefringence of the LC layer, and λ is the wavelength of the incident light. Equation (1) confirms that the optical light leakage in the dark state occurs less than 0.1% compared to the case that the polarization axis of the polarizer is coincident to the optical axis of the LC director if α is 0.5°. Therefore, if we induce the multi-domain effect within 0.5° of angle α, we can achieve a high aperture ratio and high transmittance with less than 0.1% loss of the dark state. In the experiment, we found that ±0.4° of the angle α does not induce the multi-domain effect of the proposed LC cell in the bright mode, and that the minimum angle can provide the multi-domain effect in the bright mode is ±0.5°.

3. Experiments and discussions

To precisely demonstrate the electro-optical performance of the proposed LC mode, we fabricated a unit cell based on the cell structure mentioned in Figure 1. Figure 3 shows the schematic diagram of the simple fabrication process of the proposed IPS LC cell. Initially, we prepared a top substrate and a bottom substrate with a patterned ITO electrode by means of a lithography process, as shown in Figure 3(*a*). Next, the UV alignment material (PIA-PA57-08X, JNC Co.) was spin-coated on two prepared substrates at the rate of 1100 rpm for 15 s, and then 4000 rpm for 45 s. Covered alignment layers were then hard baked at 230 °C for 1 h 30 min for the polyimidization, as shown in Figure 3(*b*). To set the LC molecules to ±0.5° angle for the upper/lower domain of an active area, we performed the double-exposed UV alignment method on the domain for both top and bottom substrates, in Figure 3(*c*) and (*d*). In this process, a linearly polarized UV light (365 nm) was exposed for 2 h with 21 mW/cm^2. While exposing the UV light to the upper/lower domain, we used the black mask which can prevent opposite domain area from the UV light as shown in Figure 3(*c*) and (*d*) so that LC alignment of each domain could be successfully performed without any optical loss. To achieve the superior multi-domain effect, exact matching for alignment direction of the top and bottom substrate is important when assembling two substrates. For this reason, we applied the alignment key, which can indicate the position between the upper and lower domain area, on top and bottom substrate. Therefore, we could exactly match the alignment direction of multi-domain for two substrates by using the alignment keys after double-exposing the UV light. Finally, the LC (MLC-7037, $\Delta\varepsilon = 5$, and $\Delta n = 0.1144$, Merck) was injected into the cell with 3 μm gap, followed by the annealing of the fabricated cell at 100 °C to enhance the LC ordering.

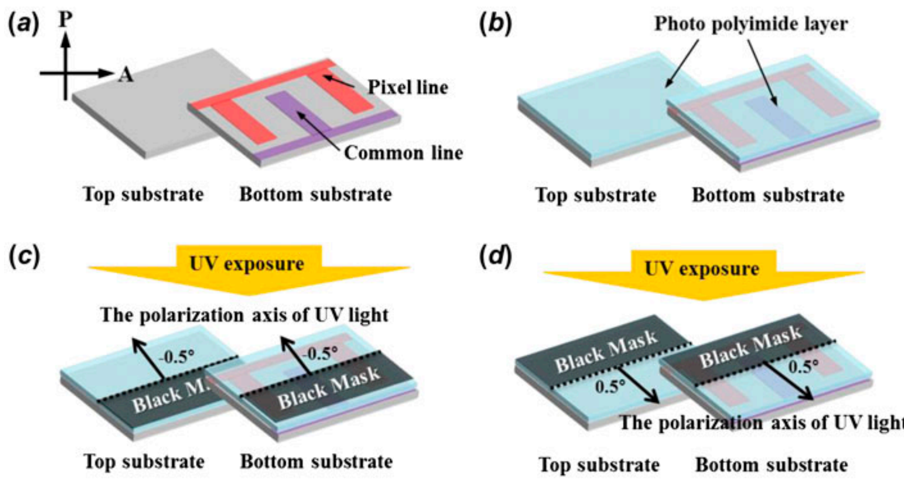

Figure 3. The schematic diagram of the fabrication process of the proposed IPS LC cell: (*a*) the preparation of the top substrate and bottom substrate with stripe-patterned ITO electrode, (*b*) the spin-coating of UV alignment materials, (*c*) the exposed UV alignment in the upper domain area, and (*d*) the exposed UV alignment in the lower domain area. (The colour version of this figure is included in the online version of the journal.)

Figure 4 shows the optical microscopic images of an IPS cell under crossed polarizers *A* and *P*. Here, the red line represents the direction of the stripe-patterned electrodes and the two dotted lines represent the optical axis O_1 and O_2 of the upper/lower domain area. To observe the light leakage in the dark mode, the electrode direction of the cell is set at 0°, which is the same as the transmission axis of the input polarizer *P* in Figure 4(*a*). Because of the optimal UV alignment angle of ±0.5°, the proposed IPS cell can show the superior dark level without any light leakage in the initial state. Furthermore, we could demonstrate the multi-domain effect in the middle voltage state at 15 V after rotating the cell to an angle of ±20°, as shown in Figure 4(*b*) and (*c*), because the optical axis of each domain area that deviates from the polarization axis can optically lead to two different effective retardations. At the rotation angle of 20° in Figure 4(*b*), the optical axis of the upper/lower domain area is 0° and 45°, respectively. From this, we observed that the upper/lower domain area has a bright state and a slight dark state. Inversely, the optical axes at a 20° rotation angle are located at around 45° and 0° from the polarization axis for each domain, so that the slight dark state in the upper domain area and the bright state in the lower domain area could be shown in Figure 4(*c*). As results, we confirmed that the double-exposed UV alignment method applied to the proposed LC cell successfully provided the multi-domain effect on the stripe-patterned electrodes.

Figure 5 shows the photographs of calculated (Fig. 5(*a*)) and measured (Fig. 5(*b*)) optical intensity at crossed polarizers, depending on the strength of the

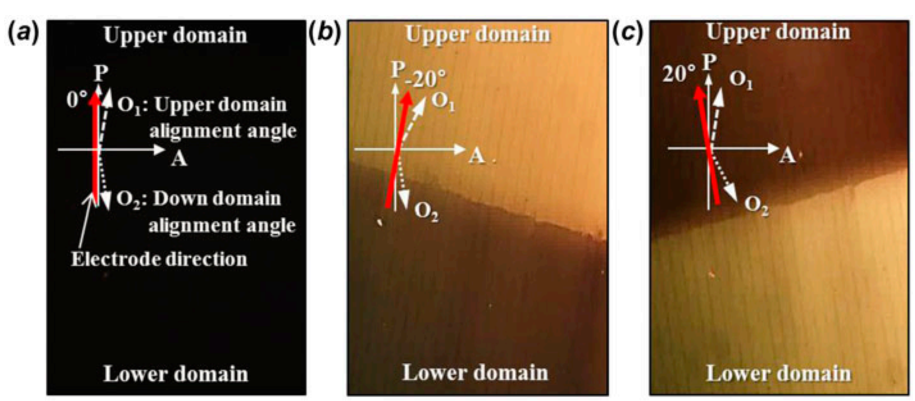

Figure 4. Optical microscopic images of the fabricated IPS cell under crossed polarizers when the direction of electrodes is set to (*a*) 0°, (*b*) –20°, and (*c*) +20° from the polarizer *P*. (The colour version of this figure is included in the online version of the journal.)

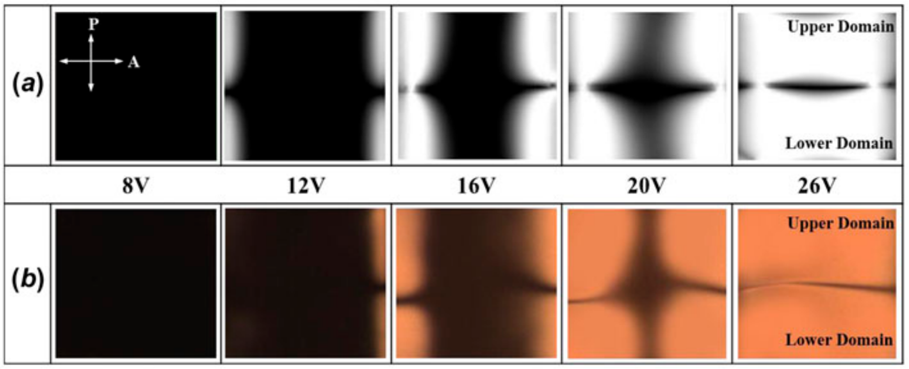

Figure 5. The photographs of the optical intensity for (*a*) calculation and (*b*) experiment of the proposed cell under crossed polarizer, depending on the strength of the applied voltage. (The colour version of this figure is included in the online version of the journal.)

applied voltage. In the calculation, we used the commercial LC software Techwiz LCD provided by the Sanayi System Co. in South Korea. When the voltages are increased, the LC molecules in the upper/lower domain were reoriented along the electric field between electrodes. In its 26 V state, a proposed cell shows the maximum transmittance for each domain. In this state, however, the disclination line at the multi-domain boundary appears due to a defect of the LC molecules in this area. Although this can induce a loss of light in bright mode, we verified that optical transmittance of a proposed IPS cell is still superior to that of the conventional S-IPS mode by calculating the transmittance in IPS modes. Figure 6 shows a comparison for the calculated voltage–transmittance (V-T) curve of a basic IPS cell, a conventional S-IPS cell, and a proposed IPS cell. As a result, optical transmittance in the proposed cell almost agreed with that of the basic IPS mode in spite of the disclination line in the cell and the fact that the optical transmittance was 15% higher than in the conventional S-IPS mode. Therefore, we can expect both a high transmittance and an excellent viewing angle compared to the conventional S-IPS LC cell.

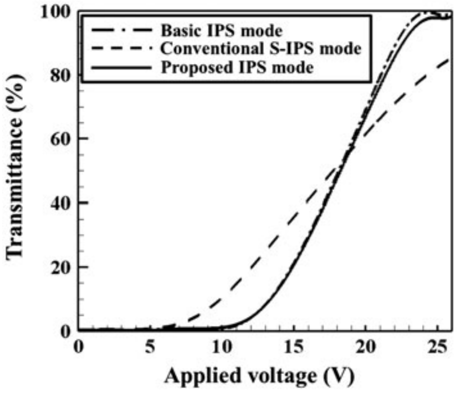

Figure 6. Comparison for the calculated voltage–transmittance (V-T) curve of a basic IPS mode, a conventional S-IPS mode, and a proposed IPS mode.

4. Conclusion

In conclusion, we proposed the IPS mode with a stripe electrode structure that can show multi-domain effect using the double-exposed UV alignment method to the upper/lower domain of the active area. The proposed cell improved the aperture ratio because the stripe-patterned electrodes provided a higher transmittance than the conventional S-IPS cell. We optimized the initial UV exposure angles for the upper/lower domain area within 0.5° of the angle α, which scarcely affected the dark state. This result provided a high aperture ratio in addition to excellent dark state at the initial mode and wide-viewing properties in applied voltage. Our calculations confirmed that the light transmittance of the proposed IPS LC cell was more than 15% better than the conventional S-IPS mode without any optical loss of the dark level and viewing angle properties.

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