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For the fabrication of protrusions in multi-domain vertical alignment liquid crystal displays (MVA-LCDs), a series of complicated and expensive photolithographic processes has to be gone through for the wide viewing angles. In this research, we proposed and demonstrated a new manufacturing approach of the protrusion utilising ink-jet printing technology. Parallel lines were ink-jet printed on the substrates and solidified by a subsequent baking process, and then used as the protrusions of MVA-LCDs. The geometric dimensions of the protrusion patterns were optimised by the comparison of experimental observations and computer simulation results. The MVA-LCD cell was fabricated by arranging the protrusion lines forming right angles between the top and the bottom lines, which resulted in cross-line protrusions. Due to the square-shaped geometric arrangement of the protrusions, the vertically aligned LCs formed the symmetric four-domains in the MVA-LCD cell. With the help of a surface polymer-stabilisation technique, the response time of the LC molecules under the electric field was significantly improved. Therefore, we can conclude that, without sacrificing the viewing angle and response time of MVA-LCD, the printing technique for the formation of the protrusions can give us a new fabrication opportunity with low cost in contrast to the conventional photolithography process.

Keywords: Liquid Crystal; Multi-domain Vertical Alignment; Ink-jet printing

1. Introduction

With the commercialisation of active matrix organic light emitting displays (AM-OLED), liquid crystal displays (LCDs) demonstrate much higher image qualities and faster response times compared with the conventional displays. The performance of LCDs is mainly determined by the liquid crystal modes, such as multi-domain vertical alignment (MVA) using either protrusion [1] or patterned vertical alignment (PVA) [2–4], or fine patterned electrodes combined with a polymer stabilisation technique [5, 6], in-plane switching (IPS) [7], and fringe-field switching (FFS) [8–14] modes. Among these LCD modes, the VA mode exhibits the highest contrast ratio in the normal direction and this mode does not need the rubbing process. In spite of these advantages of the VA mode, this mode requires the complicated and expensive photolithography process for the fabrication of the protrusions, which can make multi-domain LC alignments, as shown in Figure 1(a). The multi-domain LC alignment by protrusions in the VA mode makes the view-angle wide, which is the weakest point of the VA mode, especially compared with the IPS mode.

In this research, we proposed and demonstrated a new manufacturing approach for the fabrication of protrusions, which can be applied in the VA mode. By utilising an ink-jet printing technology, parallel protrusion lines were printed on the substrates and solidified by a subsequent baking process as shown in Figure 1(b), and then applied for the fabrication of the MVA LCD cells. The geometric dimensions of the protrusion patterns were optimised by the comparison of experimental observations and computer simulation results. The MVA-LCD cell was fabricated by arranging the protrusion lines forming right angles between the top and the bottom ones, which resulted in cross-line protrusions. Due to the square-shaped geometric arrangement of the protrusions, the vertically aligned LCs formed the symmetric four-domains in the MVA-LCD cell. Although LC directors tilt downward in multi-directions, the tilting directions and angles in each domain are not stable enough, especially at a fast switching time.

To solve this problem, we adopted a surface polymer stabilisation (PS) technology [15–20]. With the help of the surface PS technique, the response time of the MVA-LCD was significantly improved because the LC tilting directions and angles in each domain were stabilised. From this research, we realised that without sacrificing the viewing angle and response time of MVA-LCD, the printing technique (Figure 1(b)) for the formation of the protrusions can give us a new fabrication opportunity with a low cost in contrast to the conventional photolithography process (Figure 1(a)).

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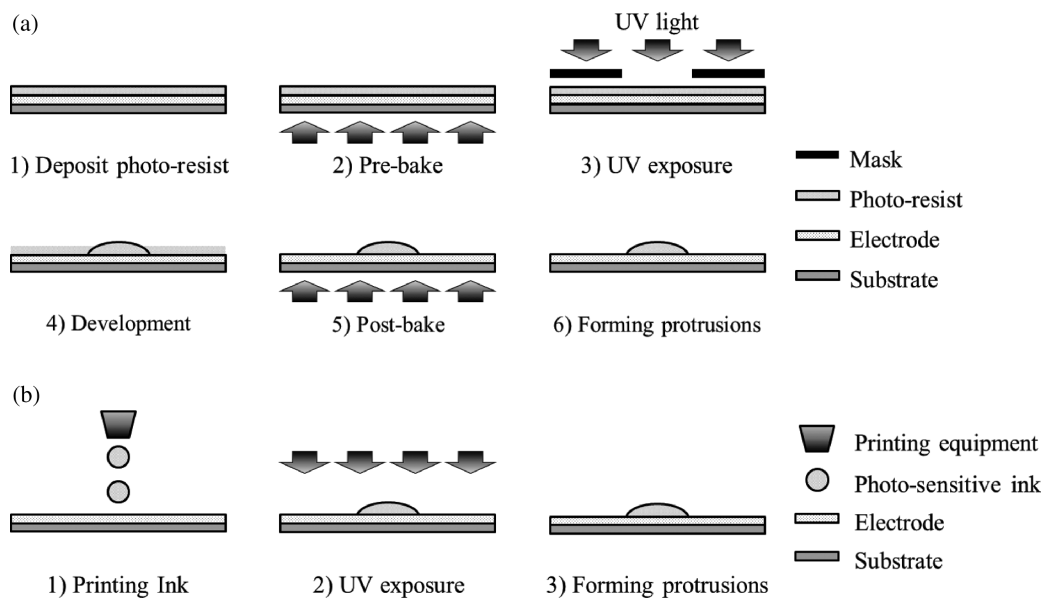

Figure 1. Comparison of processes for forming protrusions in the MVA mode: (a) a conventional photolithographic process, and (b) proposed ink-printing process.

2. Formation of protrusions and cell fabrication

Since the protrusion geometry can change the optical property of the MVA-LC cell, the geometric dimensions of the protrusion patterns should be optimised first by computer simulations before the fabrication of a real MVA-LCD cell. The results will be compared with the experimental results later in this paper. The linear protrusion parallel lines are schematically illustrated in Figure 2.

The contact angle (θ) represented in Figure 2 can be defined as:

$$\theta = \tan^{-1}\frac{2h}{w} \tag{1}$$

where w and h are the width and height of a protrusion, respectively. As w becomes narrower, h gets higher so that θ increases. Therefore, a surface pre-tilt angle of LC near to the protrusion surface will increase with the values of θ. When based on the computer simulated results of the surface pre-tilt angle of LC near to the protrusion surface and the LC director distributions in each domain of the MVA LCD, the geometric dimensions of the protrusion patterns, such as w, l, h and θ (Figure 2), were optimised. Since the experimentally obtained data were sensitive to the fabrication and working conditions, such as process temperature, humidity, viscosity of ink and polarity of indium−tin oxide (ITO) substrate, it is critical to optimise the geometric dimensions of the protrusion patterns by the comparison of the calculated data with the experimental ones. In addition, we can grasp the LC molecular behaviours in detail, especially near the protrusion surface with respect to the electric field and response time, which is very much limited in the real experimental observations.

By utilising the ink-jet printing technique, the optimised protrusion lines were fabricated and their morphologies were investigated by optical microscopy (Figure 3(a) and 3(b), *Nikon ECLIPSE E600 POL, Japan*) and three-dimensional (3D) nanoview microscopy (Figure 3(c) and 3(d), *Nano View E1000,* Korea). The material used for the ink-jet process was photosensitive acrylate type (PMA-1100P-002, LIXON COAT of Chisso, Japan).

As shown in Figure 3(a) and 3(b), the uniform protrusion lines were successfully fabricated using an ink-jet printing technique (*Fuji film Dimatix, Japan*) in the

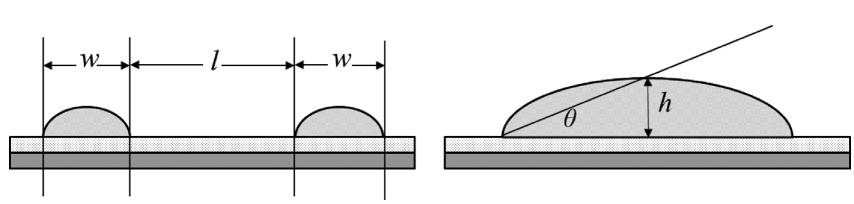

Figure 2. A schematic diagram of a protrusion.

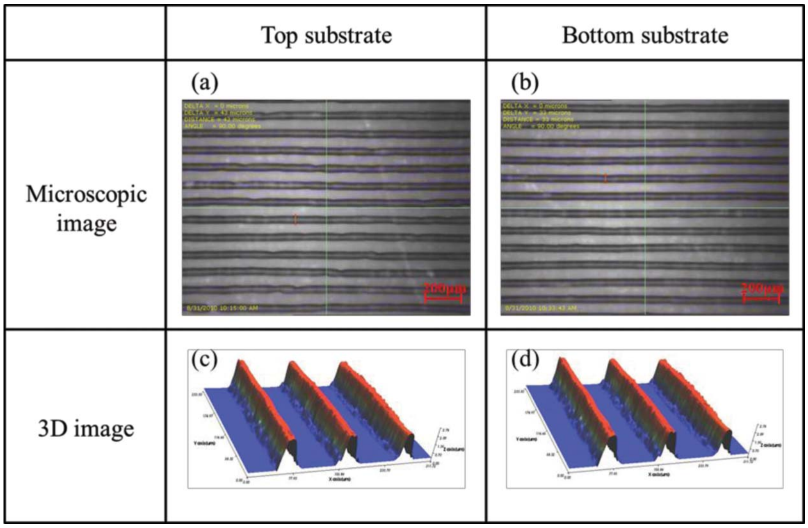

Figure 3. Optical microscope images of a protrusion formed on (a) top and (b) bottom substrates and (b) three dimensional (3D) images of a protrusion on (c) top and (d) bottom substrates.

range of the experimental deviations. The width (w) and height (h) of the protrusion is 36 μm ± 4 μm and 1.90 μm ± 0.2 μm, respectively, and the length range (l) between two protrusions is 64 μm ± 2 μm. The optimised contact angle (θ) of the printed protrusion is calculated in the range between 2.7 and 3.5°. This result indicates that the vertically aligned LC on the surface of protrusion can be tilted between 86.5° and 87.3° due to the existence of protrusions. The tilted LC director near to the surface of protrusion can induce the bulk LC reorientation under the electric field.

The vertical alignment was coated on the top of the protrusion-printed substrates and the MVA-LCD cell was fabricated by arranging the protrusion lines forming right angles between the top and the bottom ones, which resulted in cross-line protrusions. The detail MVA-LCD fabrication procedures are schematically illustrated in Figure 4.

With the help of a plastic ball spacer and sealant, two substrates were assembled and the cell gap was maintained at 4.54 μm. The nematic LC mixture with photo-reactive LC monomer RM257 and

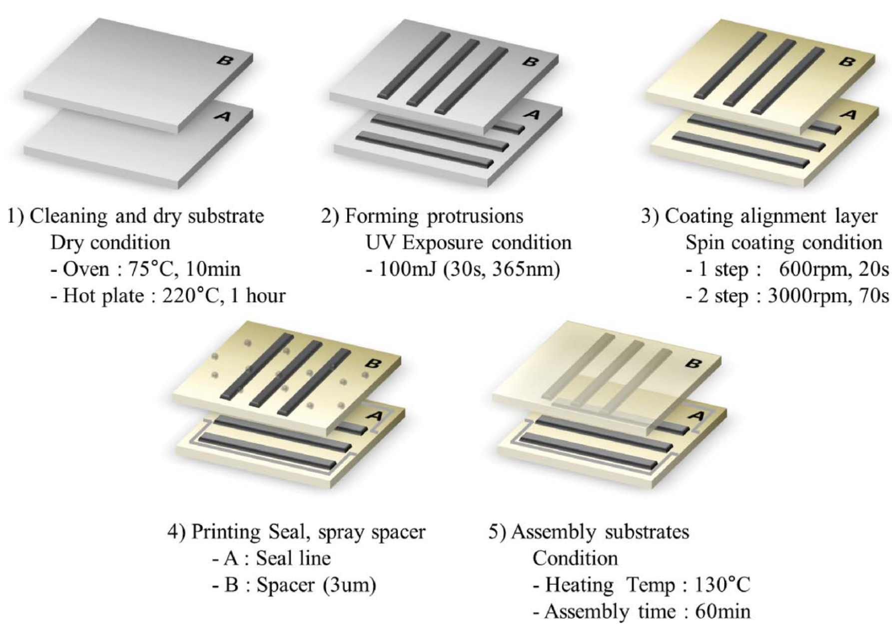

Figure 4. A schematic diagram of the cell fabrication process.

photo-initiator in a ratio of 99.9/0.1/0.001 wt% was filled into the cell. The birefringence (Δn) of the LC is 0.077 at 550 nm, 20°C and its dielectric anisotropy is −4. In order to analyse the voltage-dependent LC reorientation, we observed the LC textures by polarising optical microscope (POM) images depending on the electric field.

3. Results and discussion

Transmittance in the MVA-LCD can be estimated by the equation, $\sin^2 2\Psi \sin^2 \delta/2$, where Ψ represents the angle between the transmittance axes of crossed polarisers and the optical axis of LC and δ means the phase difference generated by LC layer. In the conventional LC device, Ψ becomes 45° with the patterned protrusion and the subsequent PS process. Therefore, when the pre-tilt angle is larger in the normal MVA cell, the rising response time becomes faster. However, the high pre-tilt angle makes the light leakage worse and decreases the contrast ratio due to the increased δ.

The fabricated cell was experimentally observed using POM and the results are shown in Figure 5(a) and 5(b), exhibiting excellent dark states.

To understand the LC orientation, 3D computer simulations were performed utilising the commercially available software (*Sanayi System TechWiz, Korea*). Although LCs near to the protrusion surface will have a certain surface-tilting angle of about 88°, LCs in the bulk show perfect vertical alignment, as indicated in Figure 5(c). One of the possible reasons for a good dark state even above the protrusions can be found from the fact that the transmittance axes of crossed polarisers are parallel to the patterned direction of the protrusions. Since Ψ is 0° in the proposed device, a relatively larger pre-tilt angle is acceptable for the dark state above the protrusions.

When the electric field much larger than when the Freedericksz transition voltage is applied to the device, the uniform transmittance with the crossed-shaped Schlieren texture is observed (Figure 5(d) and 5(e)). This crossed-shaped Schlieren texture indicates that the vertically aligned LC directors reorients to the multiple directions due to the combined effects of the surface anchoring force of the protrusions and the electrical field orientation force. This result is well matched with the computer simulated one as shown in Figure 5(f).

In order to investigate the response time of the proposed device, the time-resolved textures were observed according to the various electric voltages: the mid-grey (Figure 6(a)) and the full white states (Figure 6(b)).

Because the collisions between LC directors are generated, the response time of the device is relatively slow in both cases. This phenomenon can be understood by the fact that the azimuthal tilting directions of LCs are not well defined when a voltage larger than the Freedericksz transition is applied, as shown in Figure 6. This explanation can be supported by the time-resolved LC texture observation, which is emphasised by the dotted line box in Figure 6.

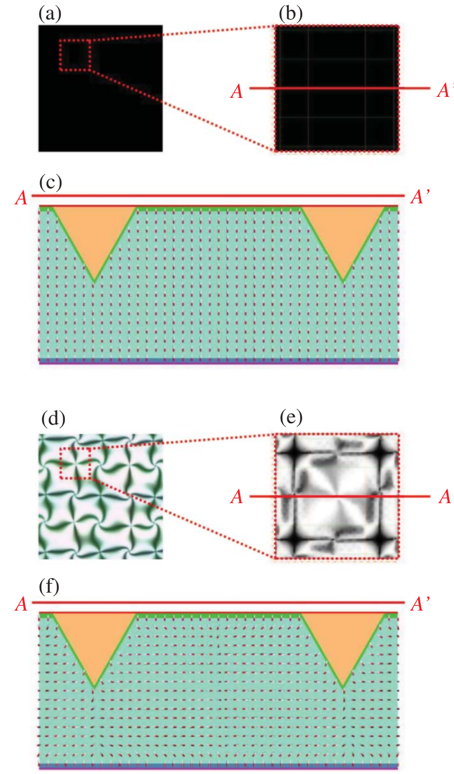

Figure 5. POM images of a dark state (a) and its magnified image with 200 X (b) (the white lines indicate the position of protrusions). (c) Simulation results of the LC orientation in a dark state along cross-sectional line A−A'. POM images of a white state (d) and its magnified image with 200 X (e). (f) Simulation results of LC orientation in a white state along cross-sectional line A−A'.

To improve the response time and to stabilise the LC tilting angles and directions of the proposed device, PS technology was introduced. The PS processes are schematically described in Figure 7.

Here, the LC with negative dielectric anisotropy and UV curable reactive mesogen (RM) are mixed and the LC mixture are filled into the LC cell. In the off state, most of the LC molecules are aligned vertically to the substrates but LCs around the protrusions are tilted, as illustrated in Figure 7(a). The LC molecular arrangements in the on state are also represented in Figure 7(b). When we apply a voltage larger than the Freedericksz transition voltage to the cell, the LCs and the RM monomers reorient with a small tilting angle in response to the electric field. Under the electric field, UV is exposed to the cell as shown in Figure 7(c).

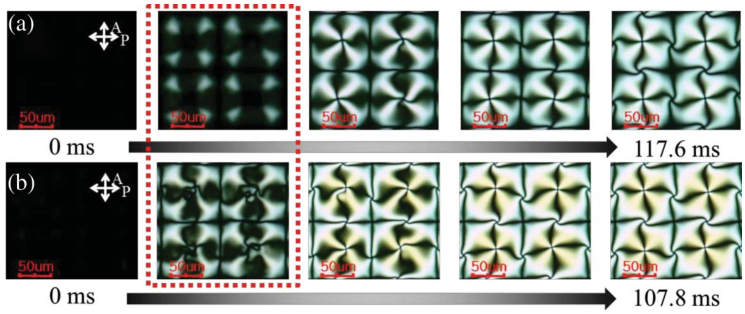

Figure 6. Time-resolved LC textures in rising time before UV exposure at two different voltages: (a) mid-grey and (b) full white state.

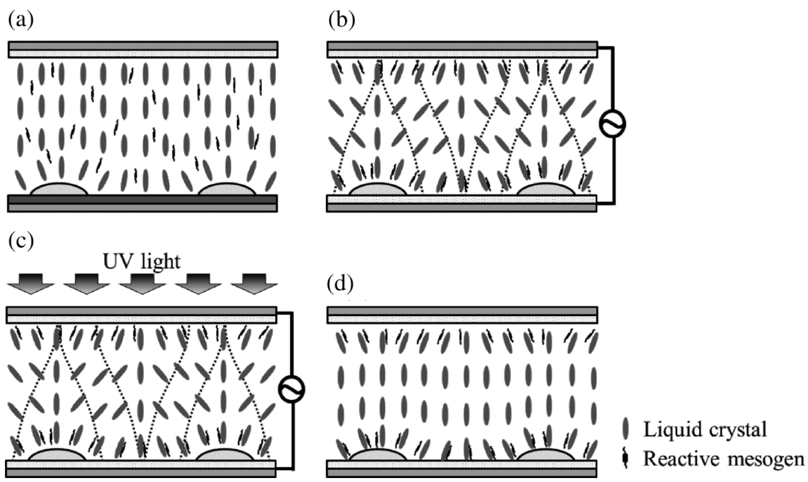

Figure 7. A schematic diagram of the polymer stabilisation process. (a) LC and RM is vertically aligned, (b) voltage is applied to the cell to induce surface tilt angle from vertical alignment, (c) UV is exposed to polymerise RM on the polymer surfaces of both substrates, (d) slight surface tilt angles from vertical alignment are generated on polymer surfaces of both substrates although the applied voltage is released.

As a result, the LC molecules on the plane surface as well as the protrusion surfaces are fixed with a defined azimuthal pre-tilt angle, even without the electric field, as illustrated in Figure 7(d).

To confirm the existence of the surface pre-tilt angle, the dark state of the proposed device was investigated after the PS process. The POM results, according to the rotation angle of crossed polariser with maximum intensity of input light source, are shown in Figure 8.

As expected, light leakage increases by rotating from 0° to 45°. Note that light leakage increases not only near to the protrusions but also in whole LC areas. The results clearly indicate that the pre-tilt angle is formed not only on both sides of the protrusions but also in the region far away from the protrusions. The defined pre-tilt angle far away for the protrusions should be due to the PS. Therefore, when the rotating angle is 45°, the maximum light leakage occurs. Since the LC tilt direction in the proposed LC cell is parallel to the crossed polariser direction, light leakage can be minimised.

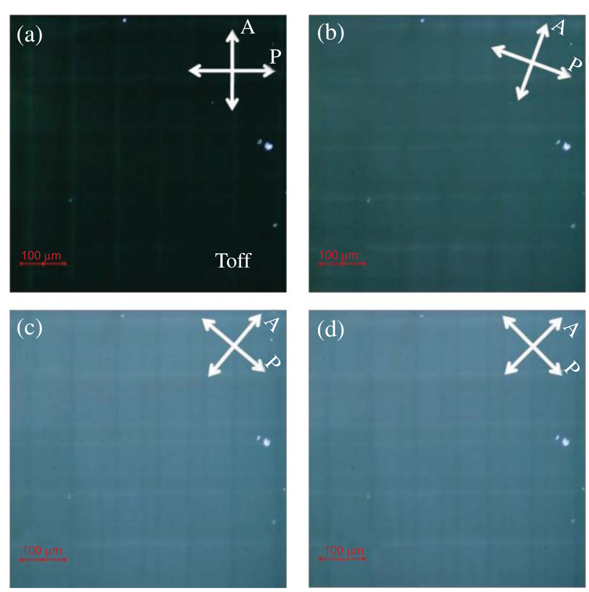

Figure 8. POM images of light leakage of the proposed cell in voltage-off state while rotating the cell under crossed polarizers: (a) 0°, (b) 20°, (c) 40° and (d) 45°.

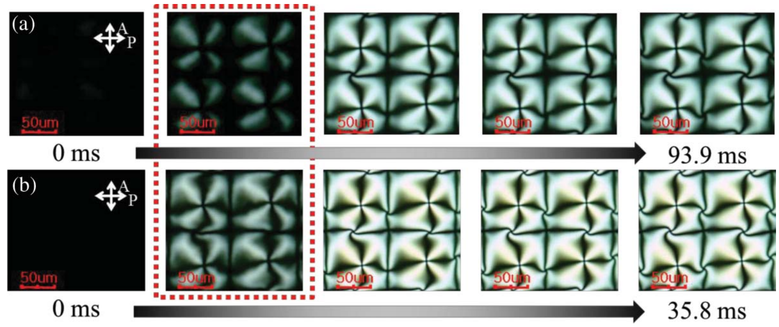

Figure 9. Time-resolved LC textures in increasing time after UV exposure at two different voltages: (a) mid-grey and (b) full white state.

The response time of the proposed device after the PS process was also studied when the voltages for mid-grey and white state were applied. From this experiment, obtained a possible answer to the question: whether LC directors are stabilised or not? As shown in the time-resolved textures of Figure 9, the rising response time before the UV irradiation is slow even at the applied voltage for the white state.

The result could be due to the LC collisions LCs, as explained in Figure 6(b). As clearly indicated in Figure 9, when the voltages for the mid-grey and white states are applied, all the time-resolved textures show defined textures, implying that the rising time is improved after applying the PS technology. As a result, the rising time becomes faster by 8.3% for mid-grey and 66.8% for white state, respectively. The result indicates that the LC molecules on the whole surface area have a defined pre-tilt angle by PS techniques using the UV curable reactive mesogen.

The voltage-dependent transmittance curves (Figure 10) were obtained before and after the UV curing process to confirm the generation of the pre-tilt angle in the bulk LC region, which is far away from the printed protrusions.

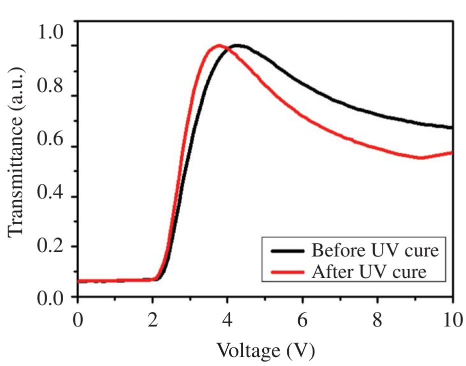

Figure 10. Comparison of voltage-dependent transmittance curves before and after UV exposure.

As shown in Figure 10, the $V-T$ curve after UV curing is shifted to the left. This means that the PS induces the pre-tilt angle on the whole surfaces, which results in the operation (from 4.3 V to 3.8 V) and the threshold voltage decreases. With the help of the PS technique, the response time of the LC molecules under the electric field was significantly improved without sacrificing the viewing angle.

4. Summary

Through the combination of ink-jet printing and surface polymer-stabilisation techniques, a photolithographic free multi-domain VA mode with a fast response time and a high contrast ratio was successfully designed and demonstrated. The geometric dimensions of the protrusion liner patterns were optimised by the comparison of experimental observations and computer simulation results. Since the protrusions forming the multi-domain were fabricated by using ink-jet printing technology, the proposed LC device can be fabricated at a lower cost without sacrificing the high performance of the VA LC mode, compared with the conventional, complicated and expensive photolithographic patterning technology.

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