

Polarizer-free liquid crystal display with electrically switchable microlens array

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Abstract: We propose a polarizer-free liquid crystal display (LCD) with an electrically switchable microlens array. The incident lights are controlled to focused or defocused states by index matching of the lens polymer and LC layer. By adopting two light-blocking masks that have a circular stop pattern and the complementary open pattern, the LCD was able to realize the entire gray scale. Additionally, to achieve fast response time characteristics, we introduce polymerized RMs within the alignment layers.

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1. Introduction

Liquid crystal displays (LCDs) have been most widely used for applications such as digital cameras, mobile phones, monitors, and television sets due to their high image performance with low power consumption. Various kinds of LC modes have been studied, such as twist nematic (TN), in-plane switching (IPS), fringe-field switching (FFS), and patterned vertical alignment (PVA) [1–5]. Because they use the optical anisotropic properties of LCs, some kinds of optical components are mandatory, such as polarizers and optical compensation films. However, these optical components limit the display performance, especially the transmittance characteristics, and increase the cost.

To eliminate the polarizers in LCDs, some LC modes have been suggested, such as polymer-dispersed (PD) LCDs, cholesteric LCDs, and dye-doped guest-host LCDs [6–10]. PDLCDs make use of the light scattering properties near the polymer droplet boundaries. However, the polymer structures require very high driving voltages of more than 50 V. For the cholesteric LC mode, due to the phase transition properties among planar, finger print, and vertical states, the LCDs show hysteresis characteristics during applied voltage. In addition, the dark state in those LCD modes was not good since it was obtained from scattering or absorption of light. In our previous work, we presented an LCD with a single polarizer based on MLA [11]. In this case, we could fabricate a low-cost LCD, but transmittance was still low, and the display had the polarization dependence property.

In this work, we propose a polarizer-free LCD using an electrically switchable LC microlens array (MLA) with light-blocking masks. The vertically aligned LC molecules are switched with applied voltage, which changes the refractive index of the LC layer. From index matching between the polymer lens and the LC layer, the MLA can focus or defocus the incident light. By adopting two light-blocking masks that consist of a circular stop mask and its complementary open mask, gray scales and black and dark states of the device can be realized, depending on the focusing state of the MLA with the LC layer.

2. Operating principle

Figure 1 shows the operating principle of the polarizer-free LCD mode with the switchable MLA. The pixels consist of a surface relief structure made of UV-curable polymer on the circular light stop mask (the first black matrix [BM]), the complementary open mask (the second BM), and the LC layer. In the absence of an applied voltage, the incident beam is defocused, because the LC molecules are vertically aligned, and the effective refractive index of the LC layer is slightly smaller than that of the polymer. Therefore, the defocused beam is completely blocked by the circular stop mask and its complementary open mask, because the optical axis of the microlens coincides with both masks' centers, as shown on the left side of Fig. 1.

When the electric field is applied to the cell, the LC molecules with negative dielectric anisotropy fall down to the substrate; they do so in a spiral configuration, due to the spherical shape of the microlens. This can be confirmed through the microscopic texture seen under crossed polarizers, as shown in the inset box of Fig. 1. In this case, since the effective refractive index of the LC layer is higher than that of the polymer, the incident light is focused. The focused beam passes through the open hole at the second BM even though the light is partially blocked by the circular stop mask (the first BM), as shown on the right side of Fig. 1. Because the incident light near the optical axis of the microlens simply passes through the microlens and polymer layer without refraction, the circular light-stop mask is essential for achieving the real black, state even if this decreases the transmittance characteristics.

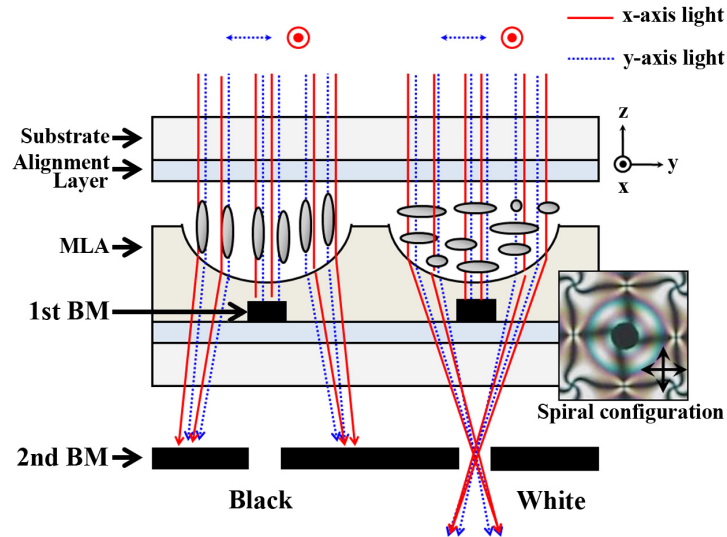


Fig. 1. The operating principle of the polarizer-free LCD with switchable microlens array. At initial state, the unfocused lights are blocked by the two BM masks. Under the electric field, the lights are focused and pass through the open holes of the 2nd BM layer.

3. Experiments

Figure 2 shows the schematic diagram of the fabrication process. The first BM layer was patterned on the cleaned ITO glass with aluminum (Al) using the conventional lift-off photolithographic method. The diameter and pitch of the circular stop mask are $50\ \mu\text{m}$ and $200\ \mu\text{m}$, respectively. On the first BM layer, the UV-curable polymer (NOA60, Norland) was spin-coated to form the microlens surface. Here, the refractive index of the polymerized NOA60 is 1.56. Because we used a self-masking method to fabricate the MLA, the UV light was exposed on the side opposite from the polymer-coated surface. The patterned circular stop mask blocked the UV light from reaching the UV polymer layer. The spatial modulation of the UV light intensity produced modulation of the monomer density, and thus the UV-curable monomers were diffused from the blocked regions to the unblocked regions to maintain the relative density of the monomers [12,13]. Then the polymer-coated side was irradiated by UV light for full polymerization. As a result, the optical axis of the fabricated MLA could be exactly matched to the center of the circle patterns. The complementary open mask was fabricated using the same photolithography method. The diameter and pitch of the open mask were $40\ \mu\text{m}$ and $200\ \mu\text{m}$, respectively. To promote the vertical alignment and establish the falling direction of the LC molecules, we spin coated the mixture of vertical alignment material (AL60702, JSR) and reactive mesogen (RM257, Merck) with less than 5 wt% on the MLA surface as a bottom substrate and an ITO surface as a top substrate [14,15]. The two substrates were assembled and the cell thickness was maintained using glass spacers of $3.0\ \mu\text{m}$ and filling with negative dielectric anisotropic LC material (MAT-08-192, $\Delta\epsilon = -3.8$ and $\Delta n = 0.17$, E. Merck). Their extraordinary and ordinary refractive indices were 1.67 and 1.50, respectively. At the initial state, the LC molecules were aligned vertically, and the RM monomers were distributed randomly in the alignment layer. When a voltage was applied larger than the threshold voltage, the LC molecules fell down oriented perpendicularly to the electric field with a spiral configuration along the microlens surface. In this state, UV light was exposed onto the LC cell for polymerization of the RMs. The operation principle of the polarizer-free LCD was characterized using a polarizing microscope (E600W POL, Nikon) with a frame-grabbing system (SDC-450, Samsung). The electro-optic characteristics were

measured using a He-Ne laser (633 nm), a digitized oscilloscope (TDS745D, Tektronix), and a photo-detector (PDA55 from THORLABS).

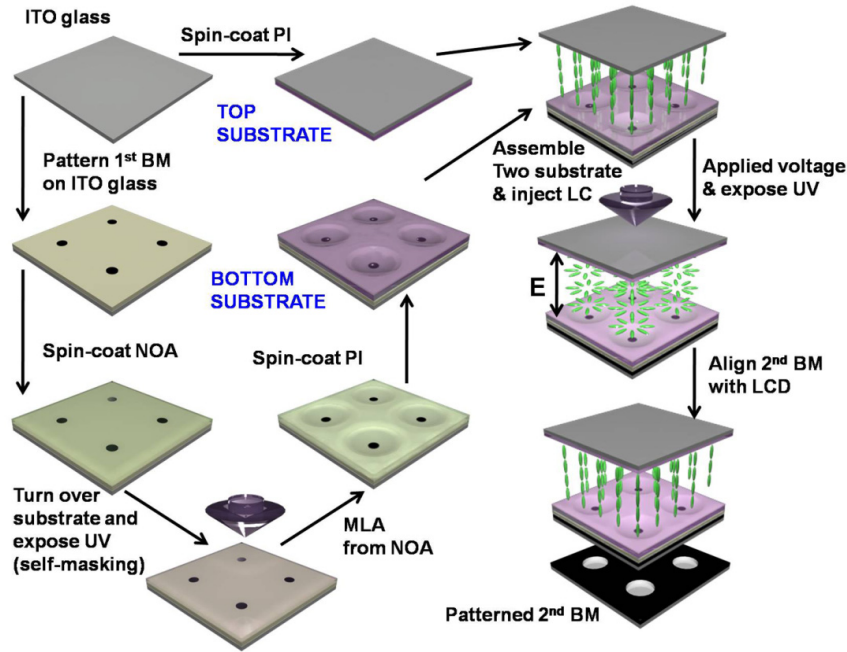


Fig. 2. Schematic diagram of fabrication process.

4. Results and discussion

Figures 3(a) and 3(b) show the cross-sectional SEM image and the surface profile of the fabricated MLA on the first BM layer, respectively. The microlens is formed exactly on the circular stop layer, and the measured depth and diameter of each microlens were 10 μm and 200 μm , respectively, as shown in Figs. 3(a) and 3(b). The calculated radius of curvature (R) of the lens using the spherical model was about 340 μm , and that resultant focal length determined the position of the complementary open mask.

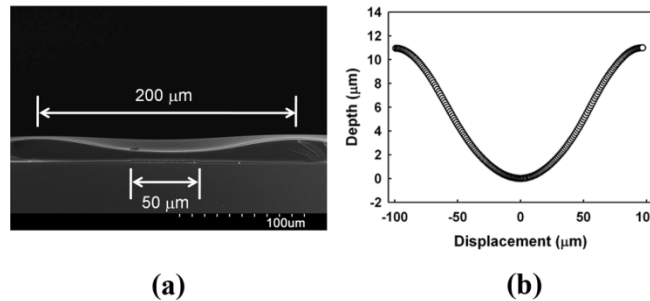


Fig. 3. Cross-sectional SEM image and surface profile of microlens.

Figure 4(a) shows the microscopic images of the LC cell with only the first BM layer under crossed polarizers, depending on the applied voltage. In the absence of the applied voltage, the LC molecules are vertically aligned, and thus the incident light passes through the cell without phase changing. As a result, the dark state was obtained. When voltages are applied, the LC molecules with negative dielectric anisotropy are reoriented into forming the spiral structure, and the bright states are shown as the effective retardation of the LC layer.

The black circles in the centers of the images represent the first circular stop-mask arrays. Figure 4(b) shows the microscopic images without polarizer depending on the applied voltage with only the first BM layers at the focal plane (~3 mm). When the applied voltage is zero, the incident light passes through the cell without focusing, because the effective refractive index of the LC is the ordinary refractive index of the LC (1.50), which is smaller than that of the UV polymer with a lens structure (1.56). So the black state could be obtained at the lens area. When the voltage is applied, the LC molecules fall down the microlens surface, focusing the incident light because the effective refractive index of the LC (1.67) is larger than that of the polymer. As a result, the bright state could be obtained, depending on the strength of applied voltage. To understand the polarization-independent characteristics, we took microscopic texture with a single polarizer placed on the front of the cell by the incident light. The transmittance increased with increasing applied voltage, but the texture was the same, irrespective of the optical direction of the polarizers, as shown in Figs. 4(c) and 4(d).

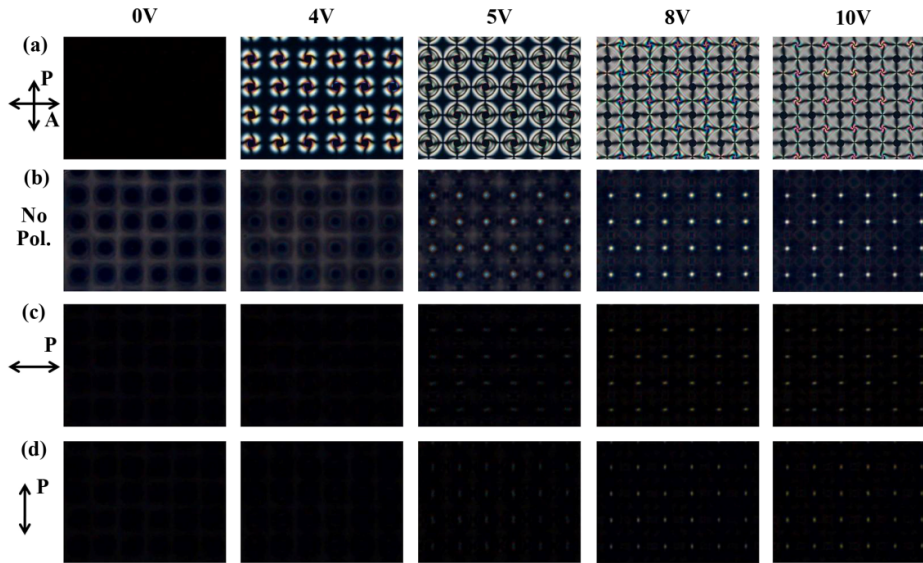


Fig. 4. The microscopic textures of (a) the liquid crystal layer under crossed polarizers, and (b) LCD without polarizer at the focal plane (~3 mm), depending on the applied voltages. (c) and (d) show the microscopic images with different directions of the single polarizer. The proposed LCD shows polarization-independent characteristics. .

Figure 5(a) shows the spatial light intensity profile of the polarizer-free LCD at the focal plane with only the first BM layer, for changing applied voltage. At the center of the microlens, the beam profile is formed as a Gaussian function at 10 V, and as a result, the white state is revealed in spite of the light-blocking layer because the light is tightly focused. At the edge of the microlens, there is some light leakage. However, this light is blocked when the second blocking layer is adopted. Figure 5(b) shows the transmittance characteristics measured with a He-Ne laser. The electro-optic switching characteristics are similar to those of the conventional VA mode. The operating voltage is somewhat high, due to the cell gap of the LC layer based on MLA. The light efficiency of our sample was measured to be 16%. Light efficiency is somewhat low due to the aperture ratio of the two BM layers and MLA. If we optimize the circle size of the first BM layer and adjust the open circle of the second BM layer, we can increase the light efficiency. The 1-inch polarizer free LCD is fabricated and their textures are shown at inset boxes of Fig. 5(b). In the absence of an applied voltage (0V), they show the dark images. As increasing the voltage, the part of “HYU” logo which has not electrode remains dark state, and the other part shows the bright state.

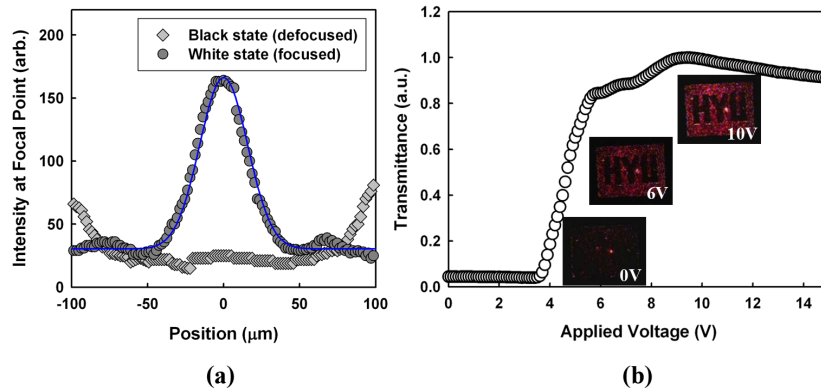


Fig. 5. (a) The spatial light intensity profile of the polarizer-free LCD at the focal plane with only the first BM layer at focused/defocused state and (b) electro-optic characteristics of polarizer-free LCD and corresponding textures.

The switching speed of LC molecules on the relief structure such as the lens surface is very slow, because the effective electric field on the LC layer is different at every position, even though the same voltage is applied. And there is another reason that the LC molecules have a two-step switching process. When the electric field is applied to the vertical-alignment LC layer, the LC molecules with negative dielectric anisotropy fall down to the lens surface unidirectionally with splay structure, and then they reorient into the spiral configuration for a stable state [16]. Thus, if we predetermine the rotating direction of the LC molecules, they will fall directly down to the surface, and as a result, the response time characteristics will be improved. In our previous work, we reported the method to establish the reorientation direction of the LC molecules with applied voltage using directionally polymerized reactive mesogen in an alignment layer [14,15]. Additionally, we reported that a fast-switching MLA structure was achieved by adopting this method [16]. Based on these results, we can improve the response time characteristics for polarizer-free LCD. The measured response time with/without the RM system was 85 msec and 1.2 sec, respectively, at 10 V.

5. Conclusions

In summary, we propose the polarizer-free LCD using switchable MLA with two light-blocking masks. The incident lights are defocused in the absence of an electric field, because the refractive index of vertically aligned LC molecules is smaller than that of the lens polymer. The defocused light is blocked by the two blocking masks. When we apply an electric field, the LC molecules fall down to the lens surface. In this case, since the effective refractive index of LC molecules with spiral structure becomes larger than that of the lens polymer, the incident light is focused and passes through the second open mask, placed at the focal plane. As a result, we were able to realize the entire gray scale by controlling the electric field. Additionally, by adopting the polymerized RMs within the alignment layer, we improved the response time characteristics.

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