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Single Polarizer Liquid Crystal Display Mode with Fast Response

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We propose a single polarizer liquid crystal display (LCD) with a fast response that was designed using a polarization-dependent microlens array fabricated by the planarization of a curved lens surface with a liquid crystalline polymer. The single polarizer LCD is operated by the polarization-dependent focusing properties of a microlens consisting of a circular stop-mask and complementary open mask. Fast response can be obtained by the planarized lens surface because distortions associated with applied electric fields and LC alignments observed in conventional curved lenses are eliminated.

Keywords Liquid crystalline polymer; microlens array; polarization-dependent microlens; single-polarizer LCD mode

1. Introduction

Liquid crystal displays (LCDs) such as twisted nematic (TN), patterned vertical alignment, and in-plane switching (IPS) modes use optical anisotropy of LCs under crossed polarizers [1–4]. Various optical components, such as polarizers and optical compensating films, are mandatory for satisfactory LCD device performance. We previously reported a single polarizer LCD mode fabricated with an LC microlens array (MLA) that was controlled by the refractive index consisting of two complementary light-blocking layers (LBLs) [5]. A circular stop-mask and complementary open-mask, coinciding with the optical axis of the LC microlens, were successively placed in front of each microlens in order to control the optical paths of the incident light. However, single polarizer LCDs are characterized by slow response due to the complicated switching behaviors of LC molecules that are affected by distortions caused by applied electric fields and LC alignment in curved lens surfaces.

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In this paper, we propose an improved single polarizer LCD mode design with fast response. In this design, a polarization-controlled MLA is fabricated by the planarization of a curved lens surface from a single polarizer LCD mode as previously presented [5] with a well-ordered liquid crystalline polymer (LCP) [6]. Under an applied voltage, the MLAs were controlled by the effective refractive index of the LC layer in our previous single polarizer LCD mode, whereas they were controlled by the polarization state entering them in this improved LCD mode. The planarized lens surface acts as an alignment layer for the LC. Additionally, it acts as a polarization-dependent MLA controlling the electro-optic (EO) transmittance according to focusing properties in complementary LBL configurations. In these MLA structures, the LC layer changes the polarization state entering the polarization-dependent MLA, according to applied voltage, and governs the response time of the single polarizer LCD. As a result, fast response is obtained by the planarized lens surface. This is facilitated by eliminating the distortions associated with the applied electric field and the LC alignment that are typical of conventional curved lens surfaces [7].

2. Operating Principles

Figure 1 is a schematic diagram and illustrates the operating principle of the proposed fast response single polarizer LC mode; this consists of a polarization-switching part in the TN configuration and a polarization-dependent focusing component with two complementary LBLs having circular array patterns. The polarization-dependent focusing component, shaped as a plano-convex MLA, is obtained by the planarization of a plano-concave lens surface with a homogeneously aligned LCP. When the extraordinary refractive index of the LCP is larger than the refractive index of the UV curable polymer forming the plano-concave lens, the incident light parallel to the LCP alignment is focused by the plano-convex LCP lens. As shown in Figure 1(a), the focal plane corresponds to the position of the second LBL,

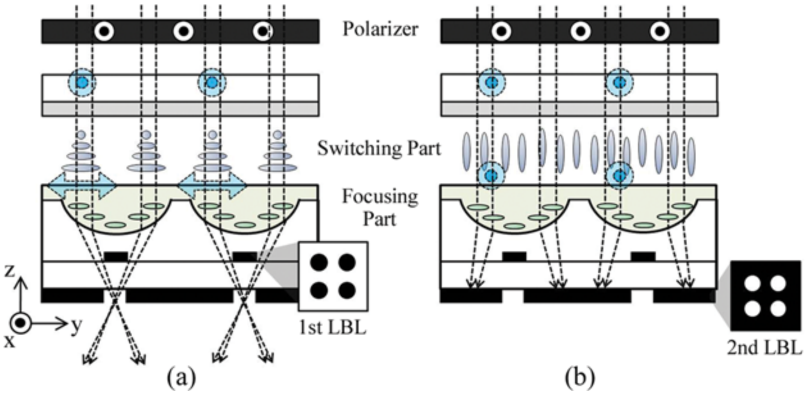

Figure 1. Schematic diagram and operating principles of the proposed single polarizer LC mode with fast response consisting of a polarization-dependent MLA planarized with the aligned LCP, and two complementary LBLs having circular array patterns: (a) bright state at no applied voltage, and (b) dark state at a specific applied voltage. (Figure appears in color online.)

which is a circular open mask. Thus, the incident light is transmitted except at the center of the lens, which is blocked by the first LBL, a circular stop-mask. Alternately, the incident light perpendicular to the LCP's alignment is defocused by the LCP lens and is blocked by both LBLs. This is a result of the ordinary refractive index of the LCP being slightly smaller than the refractive index of the UV curable polymer, as shown in Figure 1(b).

In the proposed fabrication, the TN mode was used for polarization-switching. Note that no additional alignment layer for the TN configuration is required because the LCP acts as the alignment layer on the lens-formed substrate. To form a TN structure, the alignment of the other substrate, without the MLA, is perpendicular to that of the LCP. In the absence of an electric field, the linearly polarized incident light passing through a polarizer rotates along the TN configuration, focuses at the MLA, and finally, transmits the second LBL. In the presence of an electric field, LC molecules with positive dielectric anisotropy are switched to be vertical to the substrates. In this situation, no change in the polarization state and no focus at the MLA occur. As a result, the incident light is blocked in both of the LBLs and a dark state is obtained.

3. Experiments

A self-masking method was used to fabricate the polarization-dependent MLA with two complementary LBLs; the first LBL acts as an amplitude mask to form a lens surface, as well as a beam-blocking mask [5]. First, the circular stop-mask array (the first LBL) was patterned with aluminum (Al) using a conventional photolithography process. The diameter and pitch of the circular stop-mask array are 50 and 200 μm, respectively. A UV curable polymer (NOA60, Norland) was coated on the patterned substrate and irradiated by UV light on the opposite side from the coated surface. In such situations, the spatial modulation of the UV intensity by the stop-mask array produces modulation of the monomer density. Thus, the UV curable monomers are diffused from the blocked regions to the unblocked regions and maintain a relative density of monomers [8,9]. As a result, the fabricated MLA exactly matches the circular stop-mask array. Here, the refractive index of the polymerized NOA60 is 1.56. Next, the planar alignment layer of RN1199 (Nissan) was spin-coated onto the MLA and rubbed uni-directionally in order to obtain uniform alignment of the LCP (RMS03-001C, Merck). After coating the LCP, UV light was exposed in a nitrogen atmosphere for 5 min to polymerize the aligned LCP, finally obtaining a polarization-dependent MLA with a plano-convex shape. The extraordinary and ordinary refractive indices of the employed LCP are 1.684 and 1.525, respectively. For the complementary open-mask array (the second LBL), the same photolithography process was adopted as for the circular stop-mask. The diameter of the open-mask array is 40 μm. To form the TN configuration, the other substrate without the MLA was assembled orthogonally to the aligning direction of the LCP, after spin-coating and rubbing the RN1199. A nematic LC ($\Delta n = 0.104$, $\Delta\varepsilon = +5.5$) was injected into the sandwiched cell by a capillary action at the isotropic phase. A cell gap is maintained using 4.5 μm glass spacers.

The operation principle of the improved single polarizer LCD was characterized using a polarizing microscope (E600 W POL, Nikon) with a frame-grabbing system (SDC-450, Samsung). The electro-optic characteristics, such as the switching time and transmittance, were measured using a He-Ne laser (633 nm), a digitized oscilloscope (TDS745D, Tektronix), and a photo-detector (PDA55 from THORLABS). The polarization-dependent MLA was observed using a field emissive scanning electron microscope (FESEM) (S-4800, Hitachi). All of the measurements were performed at room temperature.

4. Results and Discussion

Microscopic textures under crossed polarizers and a cross-sectional FESEM image of the polarization-dependent LCP lens are shown in Figure 2. The uni-directionally aligned LCP is similar to the planar aligned LC layer, with the dark state obtained under crossed polarizers when the alignment direction of the LCP is parallel to that of one of the crossed polarizers, as shown in Figure 2(a). Therefore, the LCP lens does not focus. However, a bright state was obtained when its alignment direction was rotated by ±45° with respect to the cross polarizers. Uniform interference patterns corresponding to the MLA were observed, as shown in Figure 2(b). Here, the black circles in the centers of the circular interference patterns represent the first stop-mask arrays. Therefore, the focusing properties of an LCP lens depend on the incident polarization, unlike the focusing properties governed by the electrically controlled refractive index of the previous single polarizer LCD mode [5]. Figure 2(c)

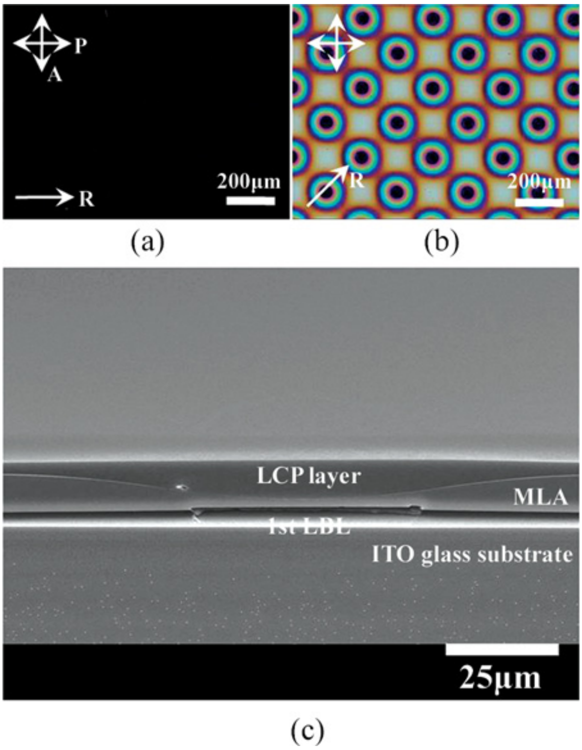

Figure 2. Microscopic textures at an angle of (a) 0°, and (b) 45°, with respect to a single polarizer under crossed polarizers, and (c) cross-sectional FESEM image of the polarization-dependent LCP MLA. (Figure appears in color online.)

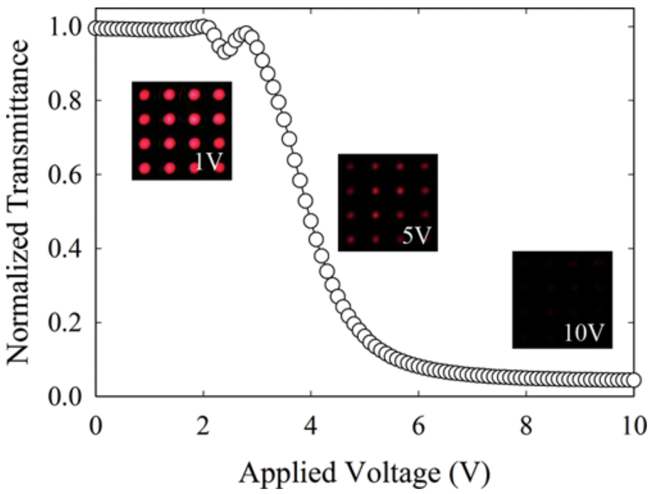

Figure 3. EO transmittance and corresponding microscopic images of the improved single polarizer LCD. (Figure appears in color online.)

shows a cross-sectional FESEM image of the plano-convex LCP lens, prepared by the planarization of the plano-concave MLA formed by the UV curable polymer.

Figure 3 shows the EO transmittance and corresponding microscopic images of the improved single polarizer LCD, measured with an He-Ne laser. The EO switching characteristics are similar to that of the TN LC mode, except for the shift of the threshold voltage to a higher voltage due to effective voltage reduction by the planarized LCP lens and UV curable MLA. Below the threshold voltage, the polarization state of the incident light is guided along the TN configuration, and is finally rotated by 90°. As a result, the focused beam passes through the circular open-mask (the second LBL) at a focal plane and thus a bright state is obtained. By increasing

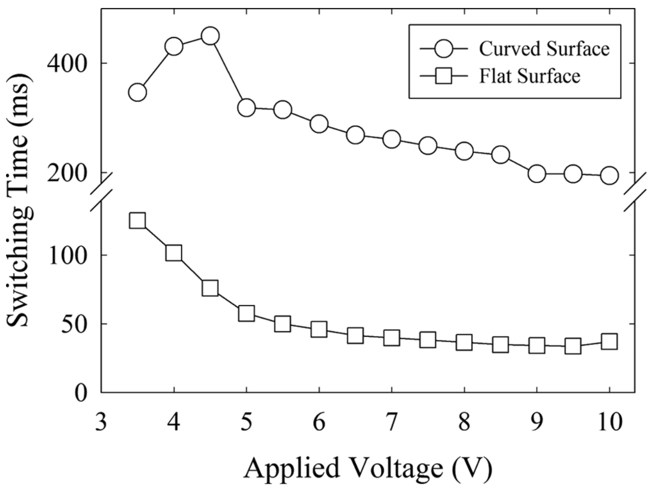

Figure 4. Dynamic responses of the improved single polarizer LCD and the previous single polarizer LCD.

the voltage above the threshold voltage, the LC molecules gradually rotate perpendicular to the substrates, thus reducing the rotation of the polarization. The defocused beams are blocked by both LBLs, as shown in Figure 3. Here, an optical bounce of the transmittance, in the vicinity of 2 V, primarily originates from the subtle distortion of the electric field. This is a result of a dielectric mismatch between the LCP and the UV curable polymer.

The dynamic responses of the improved single polarizer LCD with the planarized LCP and the previous single polarizer LCD with the curved lens surface, presented in Reference [5], are shown in Figure 4. In the curved lens, the distortion of the electric field and the non-uniformity of the alignment on the curved lens surface produced a slow switching behavior of approximately 200 ms under an applied voltage, as shown in Figure 4 (open circles). In contrast, with the planarized LCP lens, the response time was 5 times faster than that in the previous single polarizer LCD; it was approximately 40 ms without any advanced driving scheme such as dynamic capacitance compensation [10].

5. Conclusions

We have reported an improved single polarizer LCD with fast response. It is based on polarization-dependent MLAs by the planarization of a curved lens surface with a uni-directionally aligned LCP. The focusing properties of the MLAs were not governed by the effective refractive index of the LC layer; rather, they were governed by the polarization state entering them from the LC layer. The planarized lens surface acting as the flat alignment layer for the LC layer, served to eliminate the distortions from an applied electric field and the LC alignment observed in a conventional curved lens surface. Therefore, fast response were obtained in the planarized MLA structure in order to process a dynamic image at a video rate.

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