

Improvement in Switching Speed of Nematic Liquid Crystal Microlens Array with Polarization Independence

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The switching speed of a polarization-independent microlens array fabricated with a nematic liquid crystal (NLC) in the configuration of a plano-convex lens is improved by the reactive mesogen (RM) mixed in an alignment layer. Due to the NLC rotating directions predetermined by the polymerized RM, the direct switching from a vertical alignment to a spiral one is obtained without going through a metastable splay state, which gives rise to slow response in the vertically aligned NLC microlens with polarization independence. © 2010 The Japan Society of Applied Physics

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Switchable microlens arrays based on liquid crystals (LCs) play an important role in various optical systems for optical communications and three dimensional display systems because of their reconfigurable focal length.^{1–9)} However, in most LC optical devices, the intrinsic optical anisotropy of the LC results in the polarization dependence on the incident light. Thus, the orthogonally aligned LC Fresnel lenses^{10–12)} or the vertically aligned (VA) nematic LC (NLC) lenses¹³⁾ have been proposed for eliminating the polarization dependence. Although these approaches lead to no polarization dependence, they require an extremely precise alignment technique and/or complicated fabrication processes except for the VA NLC microlens. However, the switching speed of the VA NLC lenses with a nonflat surface is inevitably slow due to a two-step transition from an initial vertical state to a metastable splay one and to a final spiral configuration. To improve the switching speed, smectic LC lenses have been proposed, but they showed the polarization-sensitive feature and unstable alignment.^{9,14,15)}

Recently, the remarkable improvement of response time in VA NLC displays has been proposed using the surface-controlling technique with a mixed alignment layer with reactive mesogen (RM).^{16,17)} Here, the RMs polymerized under a certain voltage predetermined the switching directions of the NLC molecules even on a nonrubbed alignment layer when the external voltage was applied to operate the NLC displays. The predetermination of the switching directions in the VA NLC displays eliminated the defects during the electrooptical switching and thus gave rise to a fast response.

In this work, we demonstrate the improvement of the switching speed of the NLC microlens array with polarization independence using the surface-controlled RM mixed in a VA layer. The mixed VA layer is coated on a lens surface prepared by the anisotropic diffusion of the photocurable polymer through a photomask to produce the polarization insensitivity of the NLC lens. On the surface, the RMs polymerized under a certain applied voltage memorize the directions of the NLC molecules showing the stable spiral configuration at the applied voltage. In such situation, the NLC molecules directly switch from the initial vertical state to the final spiral one without going through the metastable splay state and thus the switching speed is improved. As a

result, the polarization-insensitive NLC microlens array with fast response is obtained through the surface control by the polymerized RMs.

The NLC microlens array with polarization independence was fabricated by the anisotropic diffusion of the photocurable polymer (Norland NOA60) by an amplitude photomask with a periodic circular pattern.^{13,18,19)} The photocurable polymer was spin-coated on an indium–tin–oxide (ITO) glass and irradiated by ultraviolet (UV) light (Osram mercury lamp) passing through the photomask where the pitch and diameter of the circular patterns were 200 and 100 μm, respectively. The microlens surface with a maximum depth of 4 μm was covered with the vertical alignment layer (JSR AL1H659) mixed with the RM (BASF RM257) in 5 wt. % to promote a vertical alignment and memorize the NLC directors on the surface. The mixed alignment layer was prebaked at 100 °C for 10 min and postbaked at 180 °C for 1 h. The NLC (Merck) with negative dielectric anisotropy ($\Delta\epsilon = -3.9$) was dropped and covered with a flat ITO glass coated with the mixed vertical alignment layer. The thickness of the assembled substrates was maintained by the use of 3 μm glass spacers outside of the microlens patterns. The ordinary and extraordinary refractive indices of NLC, and the refractive index of NOA60 are 1.50, 1.67, and 1.56, respectively.

The time-resolved switching behaviors of the NLC microlens arrays were characterized using a polarizing microscope (Nikon E600W POL) with a frame-grabbing system (Samsung SDC-450) and an arbitrary function generator (Stanford Research System DS345). The electro-optical properties such as the response time and the polarization insensitivity were measured using a He–Ne laser (632.8 nm), a digitized oscilloscope (Tektronix TDS745D), and a photodetector. The polymerized RMs were observed using a field-emissive scanning electron microscope (FESEM; Hitachi S-4800) after detaching the sandwiched cell and washing off the NLC with hexane for 10 min.

Figures 1(a) and 1(b) show the operating principles of the conventional and the proposed microlenses in the VA configuration, respectively. In the conventional microlens, LC molecules are aligned vertically at the lens surface due to the VA layer at the initial state. When a certain voltage was applied, the LC molecules with negative dielectric anisotropy fell to the surface toward the center of the lens because of the distorted electric field and surface morphology, and

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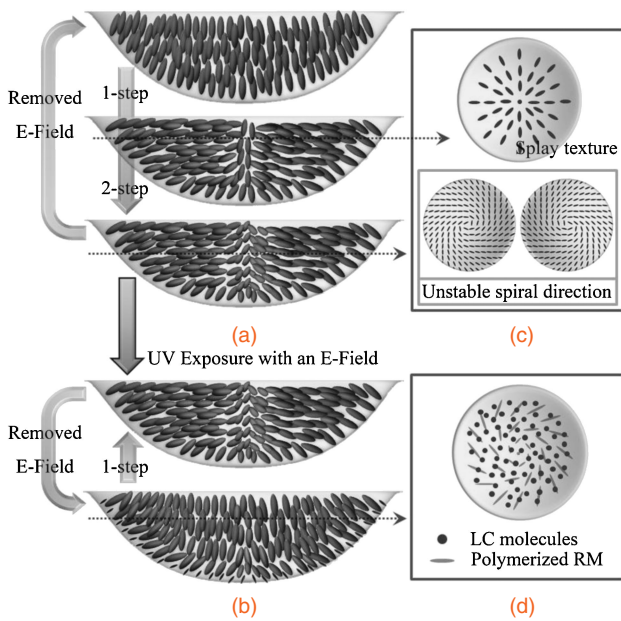


Fig. 1. Operating principle of the (a) conventional and (b) proposed microlenses in a VA configuration for switching. (c) Schematic diagrams of NLC molecules for a metastable splay texture and spiral textures with different directions. (d) Configuration of the LC molecules and the polymerized RMs on the lens surface at the initial state in the proposed NLC microlens.

form a splay texture as shown in Fig. 1(c). The splay texture is a metastable state and thus becomes spiral one to minimize the deformation energy. Because of this two-step reorientation process from vertical to splay, and finally, spiral texture, the conventional microlens array shows slow switching characteristics. In addition, the spiral direction is not determined for each microlens and always changed even at the same position for switching.

In our microlens array, on the other hand, the RM molecules on the alignment layer followed the stable NLC directors (spiral textures) due to the liquid crystalline feature of the RMs, and they were polymerized with UV irradiation. Therefore, the spiral directions were fixed on the alignment surface with the polymerized RMs along the LC director

determined by the applied field as shown in Fig. 1(d). The LC molecules directly fall to the alignment surface from vertical alignment to spiral texture without going through the metastable splay state during device switching due to the predetermined azimuthal direction with the polymerized RMs on every microlens surface.

Figure 2 shows the time-resolved microscopic textures of the conventional and the proposed microlens arrays under an applied voltage of 10 V (square wave, peak-to-peak value, 1 kHz) under crossed polarizers. In the absence of the applied voltage, the LC molecules are vertically aligned and thus the incident light passes through the sample without focusing because the effective refractive index of the LC is the ordinary refractive index of the NLC ($n_o = 1.50$), which is smaller than that of the UV-curable polymer with lens structure ($n_p = 1.56$). As a result, the dark state was obtained under crossed polarizers. When the voltage is applied, the LC molecules with negative dielectric anisotropy are reoriented into forming the spiral structure. In such case, the effective refractive index in the LC ($n_e = 1.67$) exceeds that of the UV polymer, n_p , and thus the incident light is focused. In the conventional microlens array as shown in Fig. 2(a), when the voltage is applied, the LC molecules are rotated perpendicular to the electric field direction forming the splay structure with defects within the lens structures. However, the LC directors are reoriented to reduce the elastic deformation energy and finally minimized through the formation of the spiral structure. Therefore, the two-step reorientation motions to reach the stable state (spiral structure) result in very slow response characteristics. In addition, the spiral direction at the same position is not even fixed at each driving frame (i.e., the spiral directions are changed) as represented by dashed circles in Fig. 2(a).

As shown in Fig. 2(b), in our proposed microlens array with the RM mixed alignment layer, the LC molecule directly formed the spiral structure (stable state) without going through the splay configuration (metastable state). The spiral structures are stable and always have the same rotation sense when an electric field switching occurs due to the azimuthal preference by the polymerized RMs on the alignment surface. As a result, switching speeds were remarkably improved. Figures 2(c) and 2(d) show the

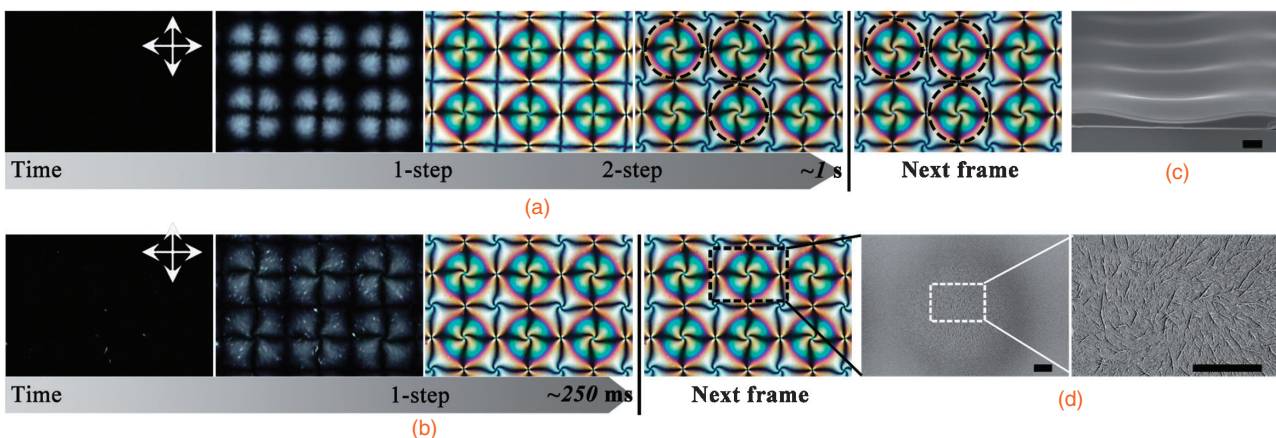


Fig. 2. Time-resolved textures under an applied voltage (10V) under crossed polarizers of the (a) conventional and (b) proposed microlens arrays. The FESEM images of (c) the conventional lens surface and (d) the polymerized RMs on the lens surface. The dashed circles represent the change in the spiral directions at each driving frame. The scale bars in the FESEM images are 20µm.

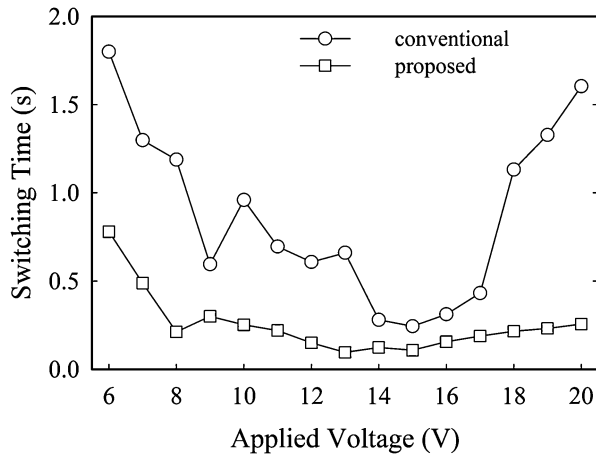


Fig. 3. Comparison of the measured switching speeds between the conventional and proposed microlens arrays as function of applied voltage.

FESEM images of the conventional microlens array and the polymerized RM on the lens surface, respectively. In the conventional NLC microlens array fabricated with the pure vertical alignment layer, no significant surface structure was observed in Fig. 2(c). However, as shown in a magnified FESEM image in Fig. 2(d), the filaments of the polymerized RMs have a spiral configuration, the same as in the polarizing microscopy images. The polymerized RMs determine the falling direction of the NLC molecules under the applied voltage and thus the LC molecules are switched under 1-step reorientation process with fast a response time.

Figure 3 shows the measured switching time of the conventional and the proposed microlenses as a function of applied voltage. In our NLC microlens, the switching time is remarkably faster than that of the conventional one over the entire applied voltage range since the polymerized RMs directly produce the spiral structure of LC molecules under the applied field without passing through the metastable structure (splay state).

Figure 4 shows the focusing intensity of the proposed microlens possessing the centrosymmetry irrespective of the polarization state of the incident light at a focal plane ($f = 10$ mm), which is determined at 20 V. The open circles, filled triangles, and open squares represent the measured beam intensities at the voltages of 0, 10, and 20 V, respectively. A linearly polarized incident beam was rotated counterclockwise from 0 to 360° and the rotation angle was represented by the angle θ . The beam intensities are almost the same for any angle, and it is found that our microlens array has the polarization independence, which is well preserved under any applied voltage. Also, the focal length of the microlens could be changed by the applied voltage.

We demonstrated the improved switching speed of the polarization-independent NLC microlens array by memorizing the NLC molecules on a lens surface with the RMs. The omnidirectional feature of the NLC lens was obtained through the vertical alignment in the absence of an applied voltage and the spiral structure in the presence of an applied voltage, similarly to the conventional VA NLC lenses. To improve the switching speed, the mixture of the vertical alignment material and RMs was used on the lens surface. The RMs polymerized with UV exposure under an applied

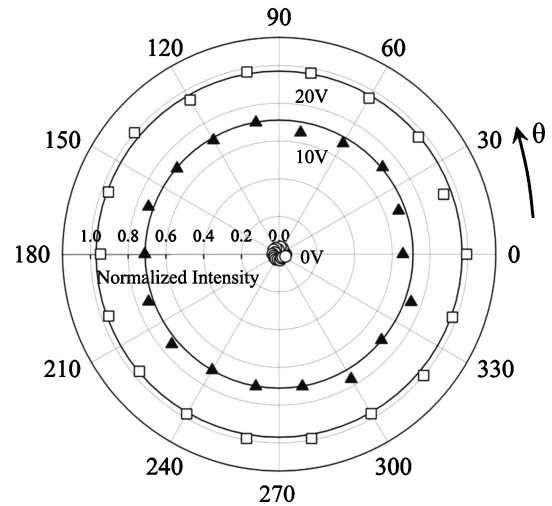


Fig. 4. Polar plot of the centrosymmetrical focusing intensities as a function of the polarization state of the incident light for various applied voltages.

voltage memorized the stable spiral configuration of the NLC molecules and thus the NLC molecules directly switched from vertical alignment to spiral one without going through a metastable splay state, which gives rise to a slow response in the conventional VA NLC lenses with the polarization insensitivity.

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