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Fast Switchable and Bistable Microlens Array Using Ferroelectric Liquid Crystals

Jae-Hoon KIM* and Satyendra KUMAR[1]

Division of Electrical and Computer Engineering, Hanyang University, Seoul 133-791, Korea
[1]*Department of Physics, Kent State University, Kent, Ohio 44242, USA*

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Fast-switching ferroelectric liquid crystal microlens arrays have been fabricated using the anisotropic phase separation of liquid crystal from its solution in an ultra violet-curable prepolymer. The microlenses can be electrically controlled to modulate the transmitted light and change their focal length within a few microseconds, i.e., ~1000 times faster than nematic liquid-crystal-based microlenses. These microlenses also exhibit the memory effect. [DOI: 10.1143/JJAP.43.7050]

KEYWORDS: microlens, ferroelectric liquid crystal, polymer and liquid crystal composite, anisotropic phase separation

1. Introduction

A number of attempts have been made to fabricate liquid-crystal (LC)-based real-time reconfigurable microlens arrays[1,2] to perform real-time optical interconnection in optical computing and photonic switching circuits. The technology required to realize such *active* microlenses is fundamentally different from that used in *passive* devices fabricated using surface-relief structures.[3–5] The methods employed in previous studies to fabricate electrically controllable microlens arrays include (i) a combination of a passive solid-state lens array and a LC modulator[6] and (ii) a gradient refractive index (GRIN) profile of LC produced with an axially symmetric electric field generated by a specially designed electrode pattern for each microlens.[1,2)]

Recently, a new type of switchable microlens array using nematic LC (NLC) has been fabricated using the phase-separation method.[7] The microlenses in these arrays are switchable on command and have variable focal length which depends on the applied field. The switching time, however, is of the order of 100 ms due to the intrinsic speed of nematic LC. These speeds are not sufficiently fast to be applicable for optical communication or wavefront shaping devices.

In this paper, we report on the construction of a switchable microlens array which uses ferroelectric LC (FLC). The microlenses can be switched *bistably* at a speed of a few microseconds, i.e., nearly 1000 times faster than microlenses incorporating NLC.

2. Experimental

The materials used in this study are commercial FLC Felix 15-100 from Clariant and photocurable prepolymer NOA65 from Norland. The ordinary (n_o) and extraordinary (n_e) refractive indices of FLC Felix 15-100 at room temperature are 1.490 and 1.664, respectively, at 590 nm. The refractive index of cured NOA 65 (n_p) is 1.524 and lies in the middle of the FLC refractive indices. To align the FLC, cells are fabricated using a substrate coated with rubbed films of Nylon 6 (N6). The N6 film was unidirectionally rubbed after drying to achieve a homogeneous LC alignment. The cell spacing is controlled with the use of glass spacers of 3 μm diameter. A solution of the LC and prepolymer with a weight ratio of 60 : 40, respectively, is introduced into the cell by capillary action at a temperature higher than the clearing point of the FLC. The cells are exposed to UV light of $\lambda = 350$ nm to initiate polymerization. The source of UV light is a Xenon lamp operated at 300 W.

3. Results and Discussion

As reported[8] previously, when a cell filled with a mixture of LC and prepolymer is exposed to normally incident UV light, an intensity gradient in the z-direction perpendicular to the cell is produced due to UV absorption by the mixture. The intensity gradient causes anisotropic phase separation[9,10] along the z-direction. The use of a suitable mask during the exposure produces additional intensity gradients in the xy-plane of the cell. Monomers in the high-intensity region near the UV source undergo polymerization first and those in the low-intensity region diffuse to the high-intensity region to maintain their relative concentration, and join the polymerization reaction.[11] The LC molecules are immiscible and are expelled from the polymerized volume. Therefore, the phase separation is anisotropic in three-dimensions. One can use photomasks of different shapes to fabricate a variety of complex microstructures of pure LC of various shapes, sizes, and director orientations.

In the experiments reported here, we use a surface-relief array of hemispheres as a photomask, as shown in Fig. 1.

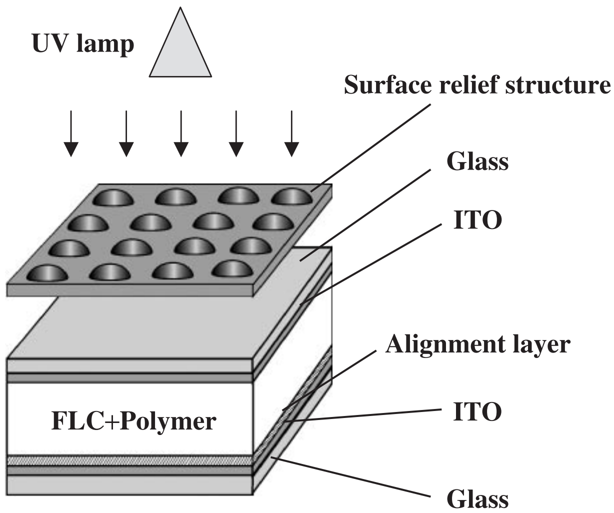


Fig. 1. Schematic diagrams of fabrication setup of nematic LC microlens array. The surface relief array of hemisphere is fabricated using UV-curable polymer.

*E-mail address: jhoon@hanyang.ac.kr

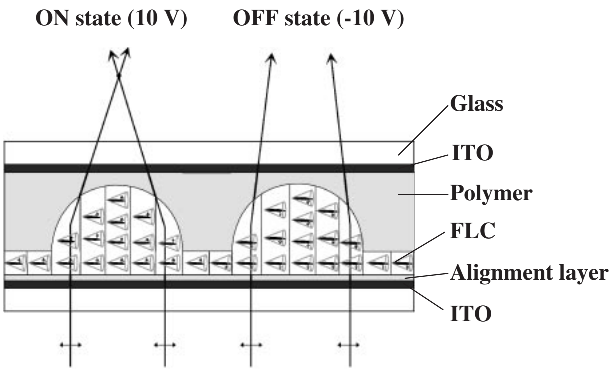
The surface-relief structure is placed on one of the glass substrates without a N6 alignment layer. The cell with the LC+prepolymer mixture is irradiated with UV light for 10 min. A second exposure is performed without the relief array for five min to fully harden the polymer. During this second exposure, the LC molecules which remained in the polymer network after the first UV exposure are expelled from the polymerized volume. Because of the thickness-dependent absorption, a UV intensity gradient is created across the circular areas which in turn causes anisotropic phase separation resulting in the highest LC concentration being in the middle of the circular areas. Upon the completion of polymerization, an array of three-dimensional planoconvex lenses is obtained, as shown in Fig. 2(a), which act as microlenses.

In a simple model, the focal length of a microlens, f, is easily obtained from

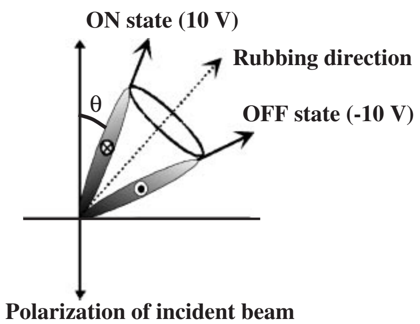
$$f = \frac{R}{(n_{\mathrm{lc}} - n_{\mathrm{p}})}, \tag{3.1}$$

where n_{lc} is the effective refractive index of the LC layer and R is the radius of curvature of the lens surface. In FLC, the directors are tilted in the smectic plane by the direct coupling of dipole moments and the electric field. Figure 2(b) shows the molecular orientation as viewed along a direction normal to the cell. The effective value of n_{lc} can be given as

$$n_{\mathrm{lc}} = \frac{n_{\mathrm{e}} n_{\mathrm{o}}}{\sqrt{n_{\mathrm{e}} \sin^2\theta + n_{\mathrm{o}} \cos^2\theta}}, \tag{3.2}$$



(a)



(b)

Fig. 2. Schematic diagrams of (a) light propagation through FLC microlens structure and (b) orientation of FLC molecules in two states in the x–y plane as viewed along the direction normal to the cell.

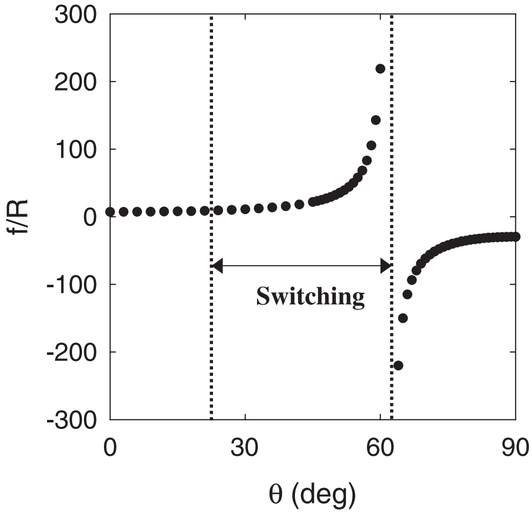
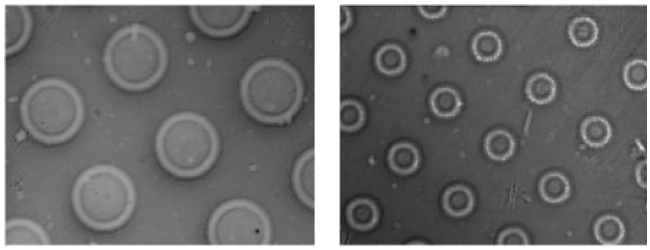


Fig. 3. Calculated focal length as a function of smectic tilt angle θ using eqs. (1) and (2) (see text). The tips of the arrows indicate the two stable operating states shown in Fig. 2(b).



(a) (b)

Fig. 4. Microscopy image of two microlens arrays, with lens diameters of (a) 355 μm and (b) 225 μm, as viewed through a polarizing microscope without any applied voltage.

where θ is the angle between the polarization of the incident light and the azimuthal orientation of molecules. Figure 3 shows the calculated focal length as a function of θ. We found that the focal length diverges at $\theta = 62°$. Since the tilt angle of the FLC is measured as 20° at room temperature, the best switching characteristics of the lens are obtained between 22° and 62°, as shown in Fig. 2(b). In our experiment, however, the focal length diverges at $\theta = 65°$ because the LC medium is dispersive.

Figure 4 shows a polarizing microscopy image of microlenses with different diameters [(a) 355 and (b)225 μm] after UV exposure without an applied field. The diameters are controlled by using different diameters of hemispheres in the surface-relief structures. Clearly, very regular internal structures are formed in the shadow of the hemispheres indicating a continuous variation of the optical pathlength from their center to edge. The circular rings are surrounded by relatively uniform regions. One can achieve a uniformly dark state outside the circular regions by rotating the cell between crossed polarizers. We note that the size of FLC microlenses is dependent on the diameter of the hemispheres in the surface-relief structure, the UV intensity and the distance between the photomask and the LC cell.

The focal length of these microlenses is experimentally measured by mounting the cell on a micrometer-motion

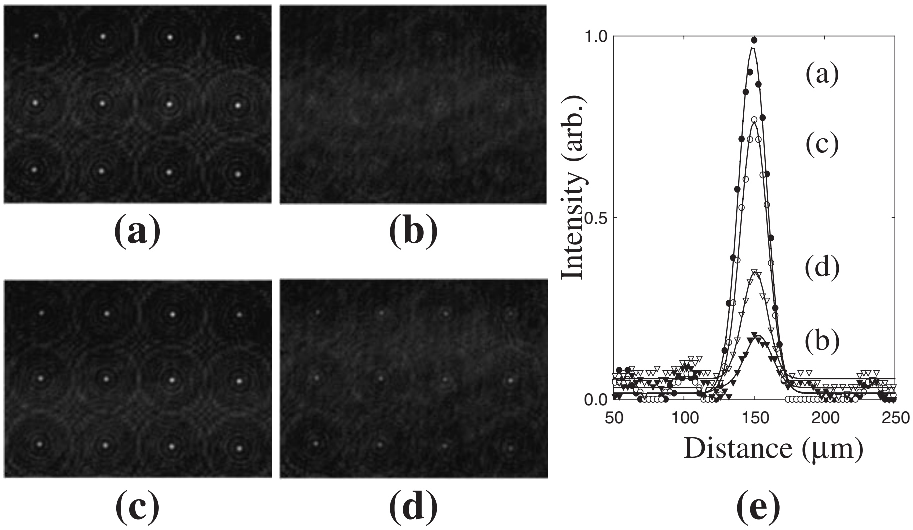


Fig. 5. Focusing characteristics of microlens for laser beam passing through lens 355 μm in diameter. (a) and (b) are beam images at 11 mm with +10 and −10 V, respectively. Panels (c) and (d) show the images of the beam when the applied voltage is changed from +10 to 0 V and −10 to 0 V, respectively. (e) Profiles of transmitted light beam in (a) and (d).

translation stage. The lenses are illuminated with a collimated beam of a He–Ne laser (632.8 nm) through a polarizer. The light passing through the lens is collected by an imaging lens and detected with a charge-coupled device (CCD) camera. To measure the focal length, we first focus the imaging lens on a microlen surface and then move the lens array toward or away from the imaging lens to determine the focal point.

Figure 5 shows the focusing properties of the laser beam propagating through a lens with a diameter of 335 μm. Figures 5(a) and 5(b) show the images of the beam with a potential difference of 10 and −10 V, respectively, applied across the lens. With 10 V, the focal length is determined to be 11 mm and 7.5 mm for the two lenses with diameters of 355 μm and 225 μm, respectively. In this case, the director of the FLC is oriented at 25°, and the incident beam experiences an effective refractive index (n_{lc}) of 1.628. Therefore, the beam is focused. When we apply −10 V, the director of the LC is reoriented at 65°. At this angle the focal length diverges as shown in Fig. 3. Therefore, the beam is defocused. Figures 5(c) and 5(d) show the images of the beam when the applied voltage is changed from ±10 V to 0 V. The intensity profiles for these situations are shown in Fig. 5(e). Although the intensities are slightly changed in Figs. 5(c) and 5(d) with respect to Figs. 5(a) and 5(b), respectively, the observations clearly demonstrate the memory effect of these FLC microlenses. The extinction ratio of the two beams is approximately 1 : 2. The slight changes in the intensities are due to the remaining polymer in the FLC layers. If we reduce the polymer content, it is possible to obtain high-extinction bistable microlenses. It should be noted that the bistability also depends on the thickness of the cell. With a thicker cell (>5 μm), we found that the beam intensity varied continuously.

In Fig. 6, we present the switching characteristics of a focused laser beam. The required durations for switching the lenses ON and OFF are 150 μs and 88 μs, respectively. In one of our previous studies,[7] the switching time of nematic microlenses was measured to be of the order of 100 ms.

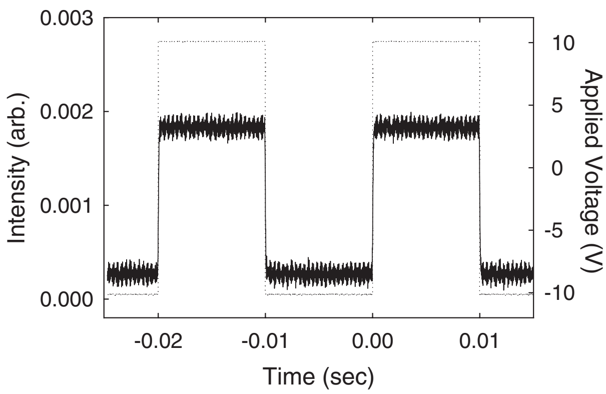


Fig. 6. Transmission vs time curve for FLC microlens. ON and OFF times are 150 and 88 μs, respectively.

Evidently, and as expected, the switching times of the FLC microlenses are approximately 1000 times faster than those of the NLC microlenses. We consider that these devices will find applications in optical communications technology in the near future.

4. Conclusions

To summarize, two-dimensional FLC microlens arrays have been fabricated using the method of three-dimensional anisotropic phase separation of FLC from its solution in a UV-curable prepolymer. The switching time was found to be three orders of magnitude faster than for similar devices fabricated using nematic liquid crystals. Fruthermore, the FLC microlenses exhibit the memory effect.

Acknowledgements

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