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P20 Microlens array using ferroelectric liquid crystals

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We fabricated fast switchable microlens array using anisotropic phase separation from a mixture of ferroelectric liquid crystals (FLCs) and ultra-violet curable prepolymer. The microlens can be switched in microseconds order,which is 1000 times faster than that of conventional microlens using nematic liquid crystals, by applying electric field. And each microlens shows bistability.

I. Introduction

Various attempts have been made to construct real-time reconfigurable microlens array using liquid crystals (LCs), which perform real-time optical interconnection in optical computing and photonic switching circuit[1,2]. The technology required to realize such active microlens is fundamentally different from those of the passive elements using surface relief structures[3~5]. Methods used in previous studies to build electrically controllable microlens array include (i) a combination of passive solid state lens array and a LC modulator[6] and (ii) gradient refractive index (GRI) profile of liquid crystal (LC) produced with axially symmetric electric field generated by specially designed electrode patterns [1,2].

Recently, a new type of switchable microlens array with nematic LC (NLC) is fabricated using phase separation method[7]. The microlens is switchable demanding on command and has variable focal length depending on applied field. The switching time, however, is the order of 100 ms due to the intrinsic properties of nematic LC.

Therefore, it is highly required fast switching microlens for future application in optical communication.

In this paper, we report a switchable microlens array using ferroelectric liquid crystal (FLC) for the first time. The microlens can be switched 1000 times faster than that of micorlens using NLCs, and shows bistable behavior.

II. 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 the Felix 15-100 at room temperature are 1.490 and 1.664, respectively, at 590 nm. And the refractive index of the cured NOA 65 (n_p) is 1.524. To align the LC, cells are made using substrates coated with rubbed films of Nylon 6 (N6). The N6 film was unidirectionally rubbed after drying to achieve homogeneous LC alignment and induce anisotropic phase separation. Cell spacing is controlled with the use of glass spacers of 3 μm diameter. A solution of the LC and prepolymer, in the weight ratio of 60:40, is introduced in to the cell by capillary action in the isotropic phase. 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 of electrical power.

In the simplest case, 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's absorption by the mixture. The intensity gradient causes anisotropic phase separation along the z-direction. The use of a suitable mask during UV exposure produces additional intensity gradients in the (xy-) plane of the cell. Monomers in high intensity region near the UV source, undergo polymerization first and the monomers in low intensity region diffuse to the high intensity region, to maintain their relative concentration, and join the polymerization reaction. The LC molecules are immiscible in and are expelled from the polymer. Therefore, the phase separation is anisotropic in 3-dimmension. Depending on the shape of photomask, we can fabricate complex microstructures of pure LC of various shape, size, and director orientation.

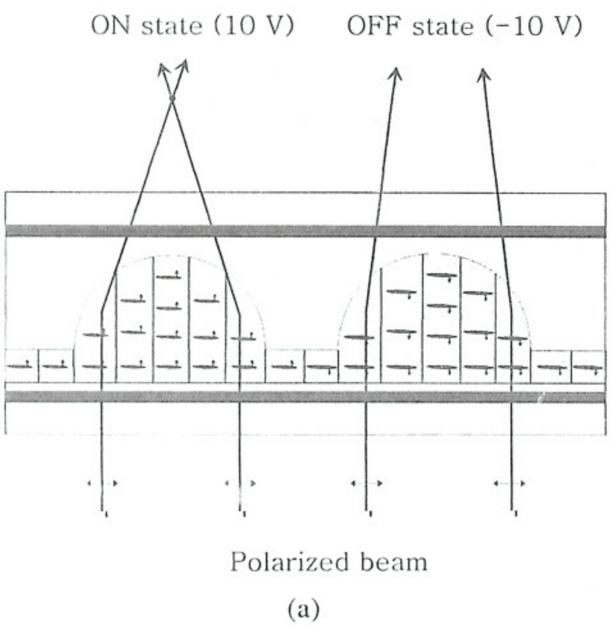
In this experiment, we used a surface relief array of hemispheres as a photomask. The surface relief structure is placed on one of glass substrates without the PVA alignment layer. The cell with the LC+prepolymer mixture is irradiated with UV light for 10 minutes. A second exposure is performed without the relief array for five minutes to fully harden the polymer. During this process, the LC molecules which remain in polymer network after first UV exposure are expelled from the polymerized volume. Because of the thickness dependent absorption, UV intensity gradient is created across the circular areas which in turn causes anisotropic phase separation resulting in the highest LC concentration in the middle of the shadow. Upon the completion of polymerization, an array of 3-dimensional plano-convex structures is obtained as shown in Fig. 1(a), which act as microlenses.

III. Results and Discussion

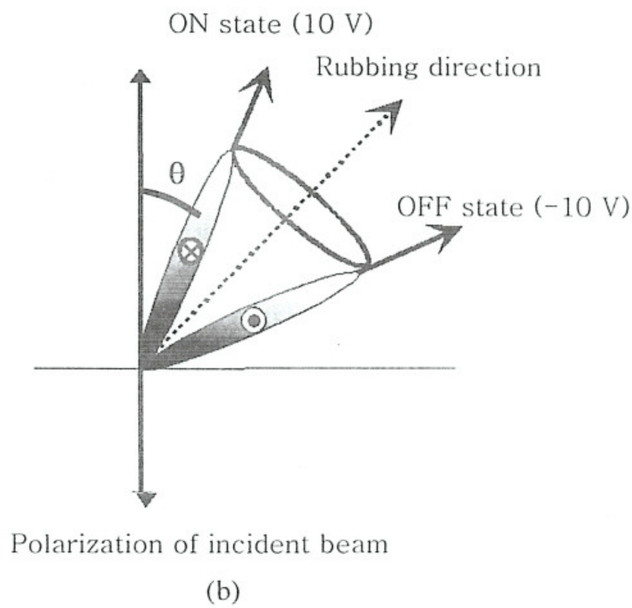
In a simple model, the focal length of microlens, *f*, is easily obtained from

$$f = \frac{R}{n_{lc} - n_p}$$

where n_{lc} is the effective refractive index of LC layer and *R* is the radius of curvature of the lens's surface. In FLCs, the directors are tilted in plane by direct coupling of dipole moment and electric field as shown in Fig. 1(b). The effective value of n_{lc} can be given as



(a)



(b)

Fig. 1. Schematic diagrams of (a) microlens structure and (b) two operating states of a FLC microlens array.

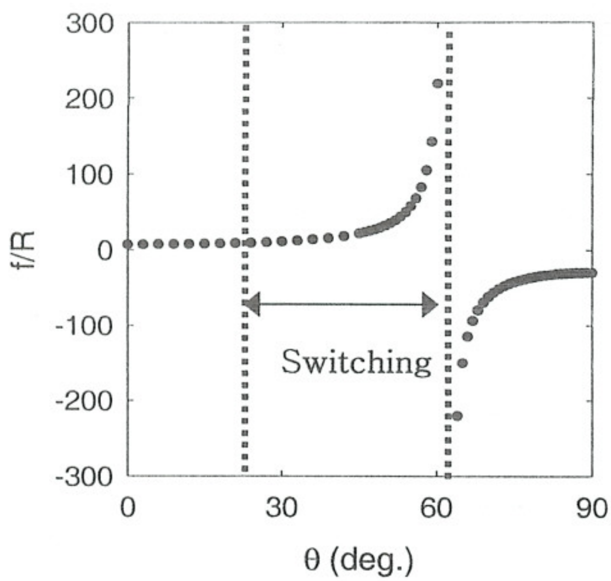
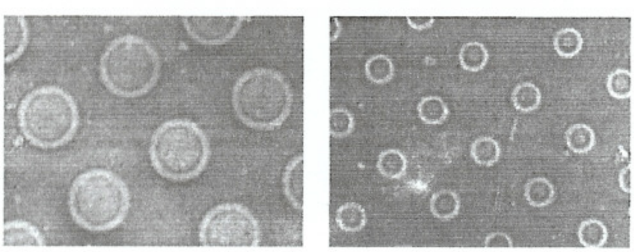


Fig. 2. Calculated focal length as a function of θ using Eqs. (1) and (2). The arrow indicates the two operating states in Fig. 1(b).

$$n_{lc} = \frac{n_e n_o}{\sqrt{n_e \sin^2\theta + n_o \cos^2\theta}}$$

where θ is the angle between the polarization of the incident light and the direction of molecules. Fig. 2 shows the calculated focal length as a function of θ. We found that the focal length diverges at θ=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. 1(b). In experiment, however, the focal length diverges at θ=65° due to



(a) (b)

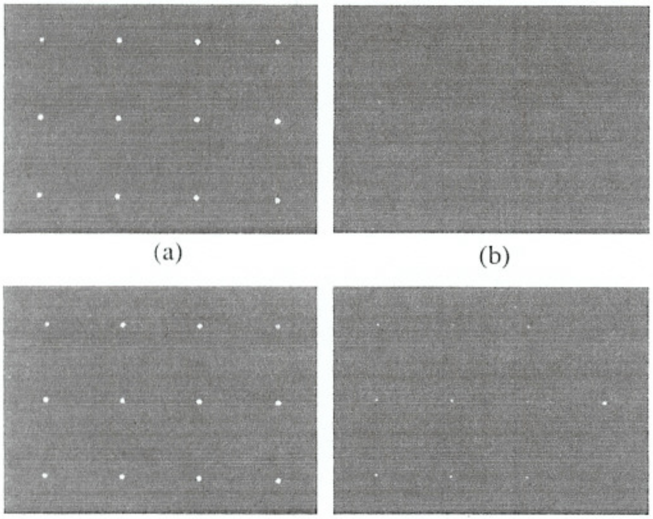
Fig. 3. Microscopic textures of microlens arrays under a polarizing microscope with no voltage applied: (a) 355 μm and (b) 225 μm in diameter.

the dispersion of refractive index.

Fig 3 shows polarizing microscope textures of the microlens with different diameters [(a) 355 and (b)225 μm] after UV exposure without an applied field. Clearly, very regular internal structures are formed under the surface-relief hemisphere indicating a continuous variation of the optical pathlength from the center to the edge. The circular rings are surrounded by relatively uniform regions. One can get uniformly dark state outside the circular regions by rotating the cell between crossed polarizers. We note that the size of FLC microlens is depending on the diameter of hemisphere, UV intensity and/or the distance between the photomask and LC cell.

The focal length of these microlenses is determined by mounting the cell on a micro-meter motion translation stage. The cell is mounted on a micrometer motion translation stage illuminated with a collimated He-Ne laser beam (632.8 nm) through polarizer. Light passing through the lens is collected by an imaging lens and detected by a CCD camera. To measure the focal length, we first focus the imaging lens on the microlen's surface and then we move the lens array toward and away from the imaging lens to find the focal point. Fig. 4 shows the focusing properties of the laser beam through the lens with a diameter of 335 μm. Fig. 4(a) and (b) shows the images of the beam with -10 and 10 V, respectively. With 10 V, the focal length is measured as 11 mm and 7.5 mm for the lens with diameter of 355 and 225 μm, respectively. In this case, the director of the FLC located at 25°, and the incident beam sees effective refractive index n_{lc} of 1.628. Therefore, the beam is focused. When we apply -10 V, the directors of the LC are located at 65°. At this angle the focal length diverges as shown in Fig. 2. Therefore, the focusing spots are diminished. Fig. 4

(c) and (d) are the images of the beam when we change the applied voltage from ± 10 V to 0 V, respectively. Though the maximum intensities are slightly changed in (c) and (d) with respect to (a)



(c) (d)

Fig. 4. Focusing properties of the laser beam through the lens of 3555 μm in diameter. (a) and (b) are beam images at 11 mm with ±10 V, respectively. (c) and (d) are beam images when the applied voltages are changed from ±10 V to 0 V, respectively.

and (b), respectively, it clearly shows the bistability of the microlens. The extinction ratio of the two beams are about 1:2. The slight change is due to the remaining polymer in the FLC layers. If we reduce

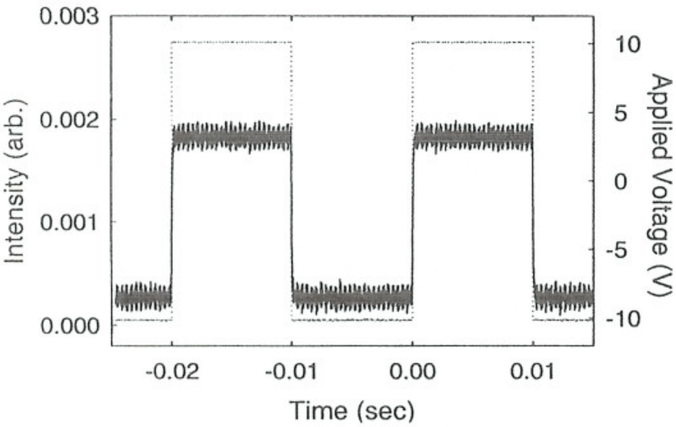


Fig. 5. Switching behavior of FLC microlens. On and off times are 150 and 88 μs, respectively.

the polymer contents in the layer, it is possible to obtain more extinct bistable microlens. Within our first hand knowledge, it is the first time to fabricate bistable microlens array. It is note that the bistability is also depending on the thickness of the cell. With thicker cell (> 5 μm), we found that the beam intensity is varying continuously.

In Fig. 5, we present the switching behavior of focused beam. The on and off times are 150 μs and 88 μs, respectively. In our previous study, the switching time of microlens using NLCs is the order of 100 ms. Therefore, the switching time of FLC microlens is about 1000 times faster than NLC microlens. It could be very important factor for future optical communication application..

IV. Concluding Remarks

In conclusion, we propose and demonstrate a two-dimensional FLC microlens array using 3-dimensional anisotropic phase separation from a composite of an UV curable polymer and FLCs. The switching time is 1000 times faster than that of nematic liquid crystals and the focusing property shows bistable manner..

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