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Fast Switching Characteristics of Surface-Relief Microlens Array Based on a Ferroelectric Liquid Crystal

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We demonstrated a fast switching microlens array that is composed of a ferroelectric liquid crystal (FLC) and a UV curable polymer. The electrically controlled microlens array was fabricated by preparing the FLC layer on one of two substrates in a sandwiched cell which has a pre-processed surface-relief structure of the UV curable polymer. Using the FLC as an active layer to modulate the refractive index, fast switching characteristics together with good focusing properties were obtained. The response time was found to be a few hundred microseconds. Moreover, the well-defined surface-relief structure of the UV curable polymer on one of the substrates allows for easy and inexpensive fabrication of the microlens array. The optical devices with such microlens array would be suitable for future optical communication components.

Keywords Ferroelectric liquid crystal; microlens array; UV curable polymer

Introduction

Recent advances in optoelectronic technologies require more functional photonic devices with high performances. A microlens array is currently one of the most promising devices for its versatile usage such as a photonic switching component in optical communication systems and an essential device for future three-dimensional displays [1–4]. It has been previously reported that a nematic liquid crystal (NLC) can be used as an active layer to have tunable refractive index for a microlens array [5]. Although the NLC-based microlens array has some useful characteristics such as good focusing properties and relatively wide variations of the focal length, the slow response resulting from the intrinsic nature of the collective molecular rotation of the NLC limits fast photonic applications. Thus, a new material capable of fast switching should be needed for the active layer to be suitable for fast switching devices.

In this work, we demonstrate a fast switching microlens array using a ferroelectric liquid crystal (FLC) layer as an active layer on the pre-processed surface-relief structure of a UV curable polymer. In this configuration, a direct coupling of the spontaneous polarization of the FLC leads to fast switching characteristics of the microlens array device. Moreover, the well-defined surface-relief structure of the UV curable polymer allows for good focusing characteristics and easy fabrication of the microlens array.

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Device Configuration of a Switchable FLC Microlens Array

Our refractive-type FLC microlens array is produced on a periodic array of surface-relief structures that behaves as micro concave lenses with fixed curvature as shown in Fig. 1. The FLC material, capable of fast switching, was inserted into a sandwiched cell whose inner surfaces were treated with an aligning polymer for planar alignment. In fact, the FLC filled in the concave cavities provides electrically focusing properties in the uniform background. We now describe qualitatively the operation principle of the FLC microlens array shown in Fig. 1. Considering that the bottom substrate with the surface-relief structures of the UV polymer is electrically grounded, the microlens can be switched from one state (focused) to the other (defocused) above a certain electric field in the bipolar driving scheme. Under a negative unipolar pulse, the electric field direction is upward. This case is defined as the "field up" state and the other case as the "field down" state as shown in Fig. 1. If the incident light polarized along the molecular director in Fig. 1(a) passes through the FLC microlens, it experiences the extraordinary refractive index of the FLC layer. The incident light will be focused after passing the FLC microlens due to the difference in the refractive indices of the UV polymer and the FLC layer. As the refractive index difference becomes large, the focal length of the FLC microlens becomes short. As shown in Fig. 1(b), the focusing effect disappears in the "field down" state and the defocused state is obtained. Moreover, the focal length of the FLC microlens can be controlled by the amount of the molecular

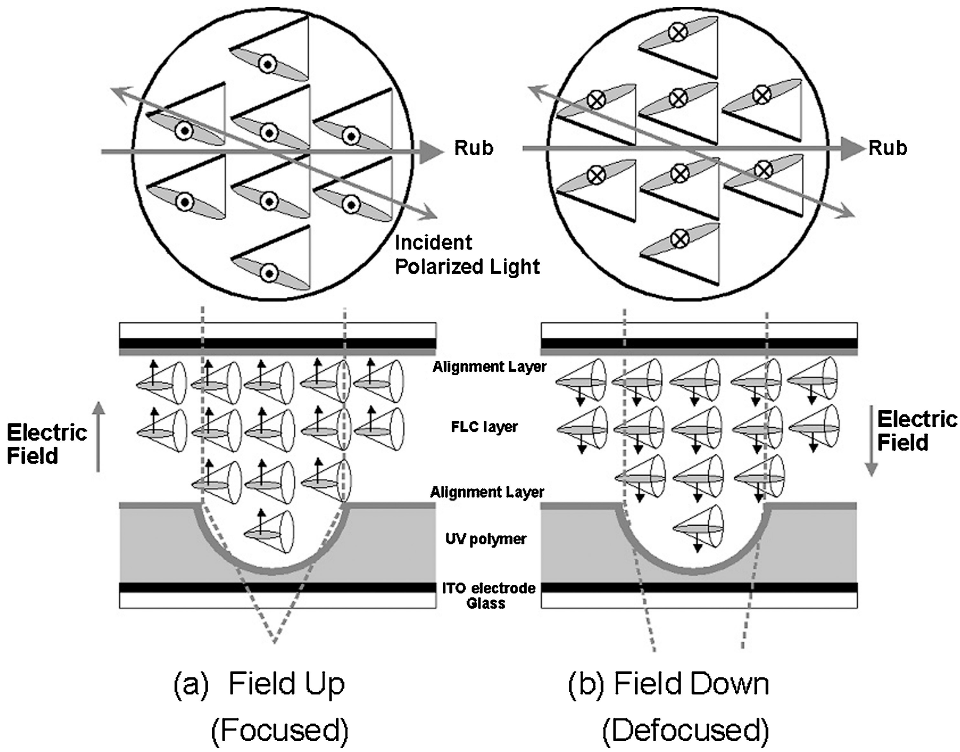

FIGURE 1 Device configuration of the FLC microlens: (a) the "field up" state represents a focused state and (b) the "field down" state represents a defocused state. The upper and lower diagrams represent the top view and the side view of the FLC microlens, respectively. Dots and crosses in the molecules denote the directions of dipole moments. Small arrows in the side view of the FLC microlens denote the directions of dipole moments.

rotation by means of the electric field. This provides the degree of the tuning capability of the FLC microlense device with fast response.

Experimental Methods

For fabricating the FLC cell with a microlens array, a periodic array of the surface-relief structures of the UV curable polymer was prepared on the top of the indium-tin-oxide (ITO) coated glass substrates. The UV curable polymer layer was first spin coated on the ITO glass substrate and the spatially modulated UV light was then irradiated onto the polymer layer through a photomask with an array of periodic holes. A commercial UV curable polymer, NOA 65 of Norland Co. was used. The refractive index of the UV polymer is 1.524. During the UV exposure, the diffusion of monomers in the polymer layer creates the surface-relief structures of the microlens array as reported previously [6, 7]. The thickness of the UV polymer film was about 4 μm at the spinning rate of 4000 rpm for 30 seconds. The depth and the radius of the concave surface-relief structure were found to be about 9 μm and 200 μm, respectively.

The aligning agent of AL1051, commercially available from Japan Synthetic Rubber Co., was coated onto two glass substrates of the sample cell. The aligning polymer was rubbed unidirectionally to promote planar alignment. The FLC sample cell was assembled in a way such that two rubbing directions defined on the substrates are antiparallel. The FLC material of Felix 15-100 of Clariant Co. (crystal $\rightarrow$ the smectic C* phase at $-12°$C, the smectic C* phase $\rightarrow$ the smectic A phase at 72°C) was injected into the sandwiched cell in the isotropic state above the clearing temperature of 86°C. The cell gap from the edge of the surface-relief structure was maintained with glass spacers of 10 μm thick. The cone angle θ of the FLC is 20° at room temperature. The extraordinary and the ordinary refractive indices of Felix 15-100 are 1.664 and 1.490, respectively.

Results and Discussion

Microscopic textures of the FLC microlens array were first examined to confirm the applicability of the bipolar driving scheme for focusing and defocusing the incident light in the presence of an external electric field E. As shown in Fig. 2, the "field up" state becomes dark at $E = 5$ V/μm above a certain saturation field when the rubbing direction makes the angle of 20° to one of the crossed polarizers. In this case, the angle between the rubbing direction and the polarizer is exactly same as the cone angle θ of the FLC, meaning that the molecular director coincides with the polarizer. In the "field down" state, however, the molecular director makes $2\theta = 40°$ to the polarizer so that the "field down" state becomes leaky.

In the light of the above concept, we now discuss the focusing properties of the FLC microlens device in the presence of a switching electric field. A simple optical setup for measuring the focused image of the input through the FLC microlens device is illustrated in Fig. 3. A He-Ne laser with the wavelength of 543.5 μm was used as a light source. An image plate with Arabian number 2 was used as an input to observe the focusing effect of the FLC microlens under the electric field $E = 5$ V/μm. In two switching configurations, I and II, the focusing characteristics of our FLC microlens device were shown in Fig. 4. The "field up" state and the "field down" state are interchangeable when the polarization of the incident light rotates oppositely by $\theta = 20°$ with respect to the rubbing direction. Two configurations, I and II, correspond to $\theta = -20°$ and $\theta = +20°$, respectively. As discussed above, the focusing effect arises mainly from the refractive index

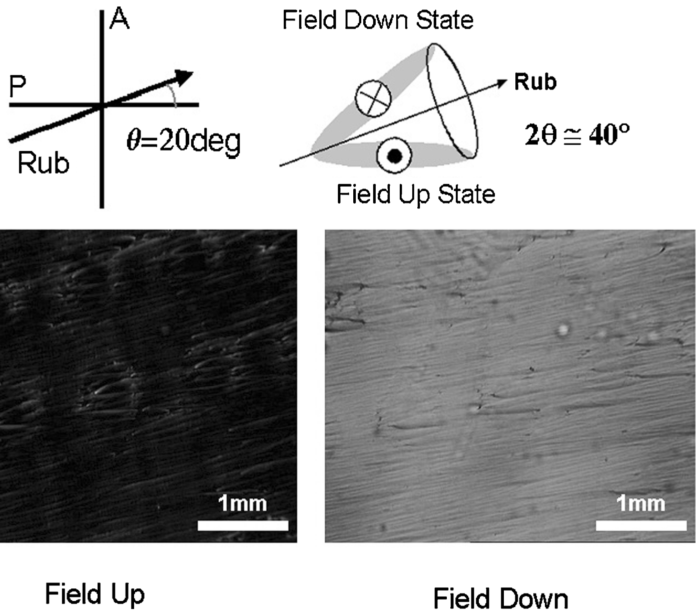

FIGURE 2 Microscopic textures under crossed polarizers corresponding to the "field up" and the "field down" states at $E = 5$ V/μm. The polarization of the incident light was rotated by $\theta = -20°$ with respect to the rubbing direction. The molecular director in the "field up" state coincides with the polarizer.

difference between the UV polymer and the FLC when the incident polarization coincides with the molecular director in the presence of the electric field. Note that the focusing and defocusing characteristics in Fig. 4(a) were obtained in the device geometry of Fig. 1. Depending on the configuration of the rubbing direction, the electric field direction, and the polarization state of the incident light, different focusing and defocusing effects can be produced.

In Fig. 5, the switching characteristics of our FLC microlens device were shown as a function of the electric field when the "field up" state was switched into the "field down" state and vice versa. Two response times $\tau_{\pm}$ follow a form of $(E - E_s)^{-1}$ where E_s is a certain bias field related to the surface field. This is a typical behavior of the ferroelectric

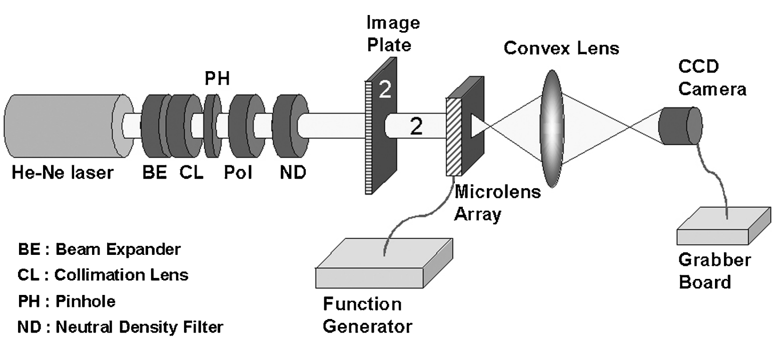

FIGURE 3 An optical setup for measuring the focused image of the input through the FLC microlens device. The grabbed image was analyzed with a computer processing system. A He-Ne laser with the wavelength of 543.5 μm was used as a light source.

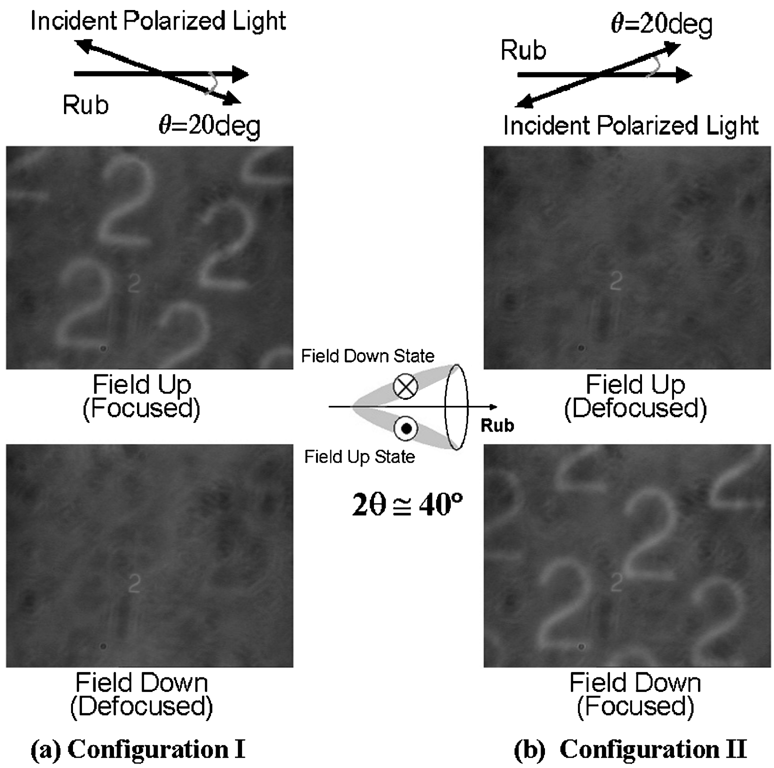

FIGURE 4 The focusing characteristics of the FLC microlens array device at $E = 5$ V/μm. The "field up" state and the "field down" state are interchangeable when the polarization of the incident light rotates oppositely by $\theta = 20^\circ$ with respect to the rubbing direction.

switching in the FLC system. One point is that $E_s \approx 0$ for τ_+ and $E_s \approx 3$ V/μm for τ_-. The response time of the FLC microlens was found to be a few hundred microseconds. At a relatively high field of $E_s = 10$ V/μm, the response time $\tau_+ \approx 170$ μsec and $\tau_- \approx 140$ μsec.

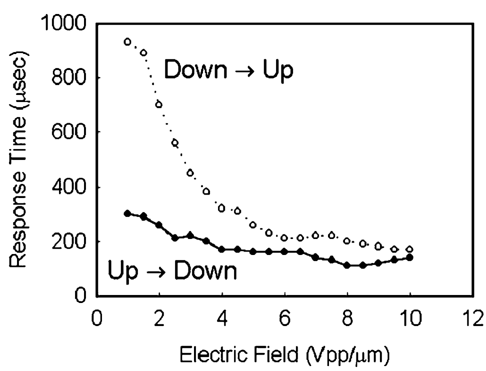

FIGURE 5 The response time of the FLC microlens array device as a function of the electric field. Open circles and filled circles correspond to the switching from the "field down" to the "field up" state and that from the "field up" to the "field down" state, respectively.

Concluding Remarks

We demonstrated a fast switching FLC microlens device fabricated on an array of the surface-relief structures of the UV curable polymer. The focusing and defocusing effects were well controlled by the application of an external electric field. The switching time of the FLC microlens device was found to be a few hundred microseconds. The surface-relief structures of the UV curable polymer allows for inexpensive and easy fabrication of the FLC microlens array. The FLC microlens array device presented here would be suitable for future photonic switching systems and 3-dimensional displays.

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