A liquid crystalline polymer microlens array with tunable focal intensity by the polarization control of a liquid crystal layer

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We propose a focal intensity tunable microlens array by using a birefringent liquid crystalline polymer for lensing action. Due to the difference of effective refractive indices, it acts as a positive or negative microlens with respect to the polarization state. As we control the incident polarization by adding a liquid crystal layer, the focal intensity can be tuned by an applied voltage. Twisted nematic and bistable ferroelectric liquid crystal modes were applied to demonstrate the possibility of various driving features such as a continuously tunable focal intensity or fast switching with memory effect. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2813638]

Dynamic lenses play an important role in various optical systems such as optical interconnections, electro-optic components in adaptive optics (e.g., wave front detectors), focusing devices in high-density data storage, and image integration components in three-dimensional displays.[1] In these devices, an electrically controllable focusing property is a key requirement. Furthermore, if we can reduce the dimension of the lens up to the microscale with an array structure, the range of application can be greatly expanded. A number of attempts have been made to construct liquid crystal (LC) based dynamic lens using LC's large anisotropy by a combination of a passive solid lens structure and a LC modulator, by a spatial phase modulation for a Fresnel lens, or by generation of a gradient refractive index (GRIN) profiles of LC produced with an axially symmetric electric field.[2–11] However, in cases of GRIN profile, it usually requires a high driving voltage and complex fabrication which is hard to implement on microsized arrays and has a long focal length due to the limited modulation of the electric field gradient. In the case of LCs on a passive lens structure, it produces poor focal properties due to the light scattering from the nonuniform LC behavior on the nonflat geometry.

In this letter, we propose a dynamic microlens array (MLA) by using the birefringent liquid crystalline polymer (LCP) microlens and adding a LC layer for controlling the polarization state electrically. We used a LCP to provide a polarization sensitive focusing property as well as a flat boundary to increase the quality of the focal image by eliminating the non-uniform LC behavior. The focal intensity in our MLA is switched by an applied voltage with various driving properties (e.g., continuous variation of focal intensity, fast switching with memory effect) at the static focal plane while other approaches usually support the voltage-controlled focal length. These unique focusing features are highly applicable for increasing the amount of data to be transferred in optical communications and opening a new range of interconnection applications.[10,11] Moreover, a short focal length (less than 1 cm) for compactness of the device is achievable by designing the curvature and the materials in the LCP microlens, which is hard to obtain with conventional approaches.

Figure 1 shows a schematic diagram of the proposed device and the operational principle. In our microlens, the focusing and the electrical tuning of polarization are performed at the LCP microlens and the polarization control unit, respectively. The LCP MLA was prepared by spin coating a thin LCP layer on a planoconcave microlens structure of UV curable polymer (UV-P) with a unidirectional rubbing process for ordering LCPs, as shown in Fig. 1(a). Due to the birefringence of LCPs, it converges or diverges the incident

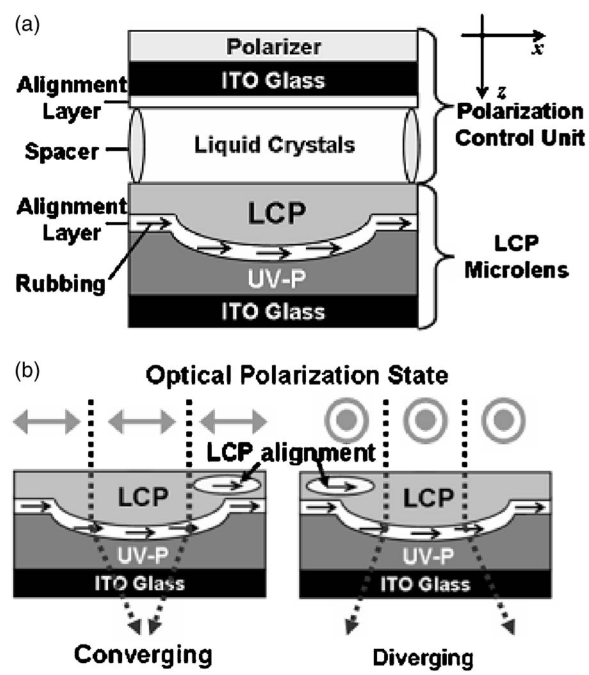

FIG. 1. (a) Schematic illustration of device configuration. (b) Polarization sensitive operations of the LCP microlens.

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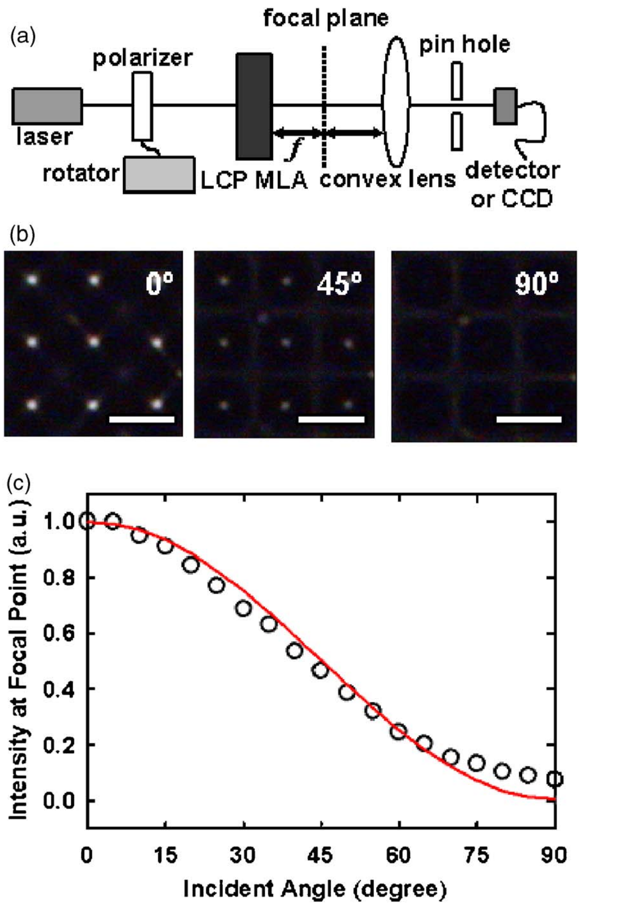

FIG. 2. (Color online) Characteristics of the LCP MLA. (a) Experimental setup for measuring a focal property. (b) Charge coupled device captured images of the LCP MLA at the focal plane. The incident angles with respect to the x axis are denoted. Scale bar is 200 μm. (c) Intensity of one spot at the focal plane as a function of the azimuthal angle of the incident linearly polarized light.

light [see Fig. 1(b)] by the difference of effective refractive indices between surrounding materials depending on the polarization state.[2–4,7] When the incident polarization is parallel to the alignment of the LCPs (x axis), the light completely converges (i.e., negative lens) because the effective refractive index of the LCP layer is larger than the UV-P. In the case of perpendicular incidence (i.e., the incident angle θ with respect to the x axis is 90°), the light fully diverges (i.e., positive lens) due to the smaller effective refractive index of the LCPs compared to the UV-P. In cases of $0° < \theta < 90°$, both effects simultaneously occur and the intensity at the focal point is reduced with respect to the incident angle. Using simple wave optics,[12] the focused intensity I of a single spot at the same aperture in the focal plane can be expressed as

$$I = I_0\left[\cos^2\theta + \sin^2\theta\left(\frac{n_e - n_{\mathrm{UV}}}{n_e - n_o}\right)^2\right], \tag{1}$$

where I_0 is the initial intensity, and n_e, n_o, and n_{UV} are the extraordinary and ordinary refractive indices of the LCP and the refractive index of the cured UV-P, respectively. Note that the focal length of our device is predetermined by designing the LCP microlens due to the fixed structure of cured LCPs.

If we combine an appropriate polarization control layer, a dynamic MLA can be achieved. Since LC exhibits large optical anisotropy and it is possible to make various configurations to modulate the polarization state, we used LCs as the polarization control unit. A twisted nematic[13] (TN) LC and a bistable ferroelectric LC (FLC) (Ref. 14) structure were integrated on the LCP MLA because these two modes exhibit very different polarization tuning abilities which result in unique driving characteristics of each device.

A commercial polyimide, RN-1199 (Nissan Chemical) for alignment layer, RMS03-001 (Merck) for LCP, and NOA60 (Norland) for UV-P were used in this experiment. n_o and n_e of the LCP and the cured refractive index of NOA60 were 1.529, 1.684, and 1.56, respectively. For the fabrication of the planoconcave microlens structure, we spin coated UV-P on indium-tin oxide glass and cured it with a predesigned photomask. By controlling the irradiated UV dosage, various morphologies and curvatures can be obtained from the spatial diffusion of the monomer.[3,4] This fabrication is effective to obtain the MLA with a simple process. The diameter and depth of each microlens were measured at 200 and 4 μm, respectively. Fitting the spherical model, the curvature (R) of the single microlens was 1252 μm, which was used to evaluate the theoretical focal length.

We first examine the characteristics of the LCP MLA. The experimental setup is shown in Fig. 2(a). We used the highly refractive convex lens to magnify the images. The focused intensities of each microlenses are simultaneously reduced by approximately half in the case of $\theta=45°$ and almost disappeared in the case of $\theta=90°$, as shown in Fig. 2(b). The experimentally measured focal intensity of a single spot (circle) was gradually reduced and well matched to the theoretical calculation (line) from Eq. (1) as shown in Fig. 2(c). In a simple lens model,[12] the focal length f can be calculated as

$$f = R/(n_e - n_{\mathrm{UV}}). \tag{2}$$

The measured static focal length of the focusing unit was 9.5 ± 0.2 mm and nearly matched the calculated value of 10.1 mm. Note that this focal length can be reduced by increasing the curvature R or optimizing the materials used for the LCP microlens.

We now describe the experimental results for the dynamic MLA combined with LCs. To examine the performance of TN-type microlens, a nematic LC MLC-6080 (Merck) with positive dielectric anisotropy was used and the cell gap was maintained with 4 μm thick spacers. The initial polarization is set to be parallel to the y axis and under no applied voltage it rotates 90° after passing the LC layer. Thus, the light was focused initially and then it defocused as we increased the voltage due to the waveguiding effect of the TN LC mode.[13] The corresponding polarization states which enter the LCP MLA are schematically shown in Fig. 3(a). The transmittance was measured using a He–Ne laser (633 nm) and the spot size was 1 mm which covers five microlenses. The threshold voltage was about 4.5 V and the transmittance was saturated at 10 V. The switching characteristics of our TN device are the same as those of conventional TN structures because of the flat boundary. Note that a slightly high threshold voltage can be reduced by using a conducting film on the LCP MLA.

Figure 3(b) shows the switching characteristics of our TN device. The maximum focal intensity at 0 V is gradually reduced when we increased the applied voltage to 10 V. Note that the amount of reduction in focal intensity can be estimated by the transmittance reduction in Fig. 3(a). It was

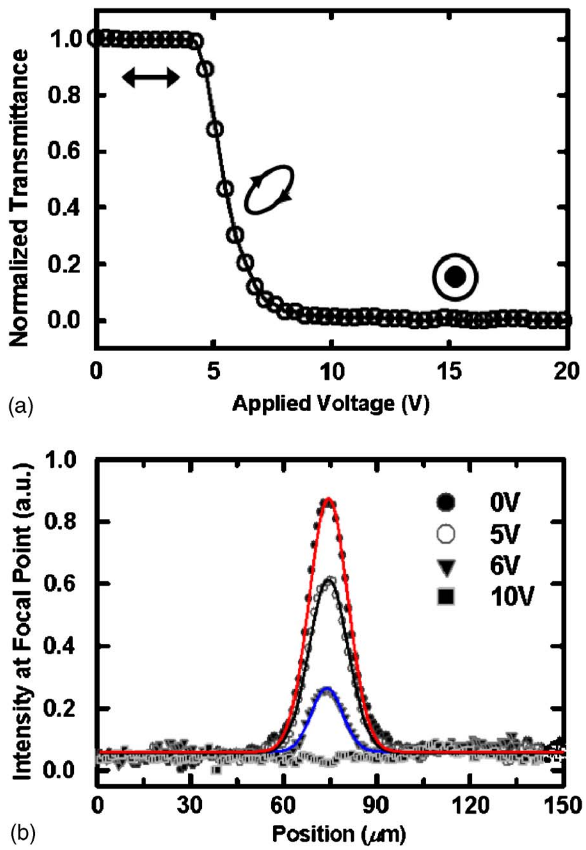

FIG. 3. (Color online) (a) Transmittance of the TN device under crossed polarizers as a function of an applied voltage. Inserted figures represent the corresponding polarization states after passing the TN LC layer. (b) The intensity profiles of the single spot at the focal plane. Symbols denote the experimental data and lines are the fitted results for Gaussian function.

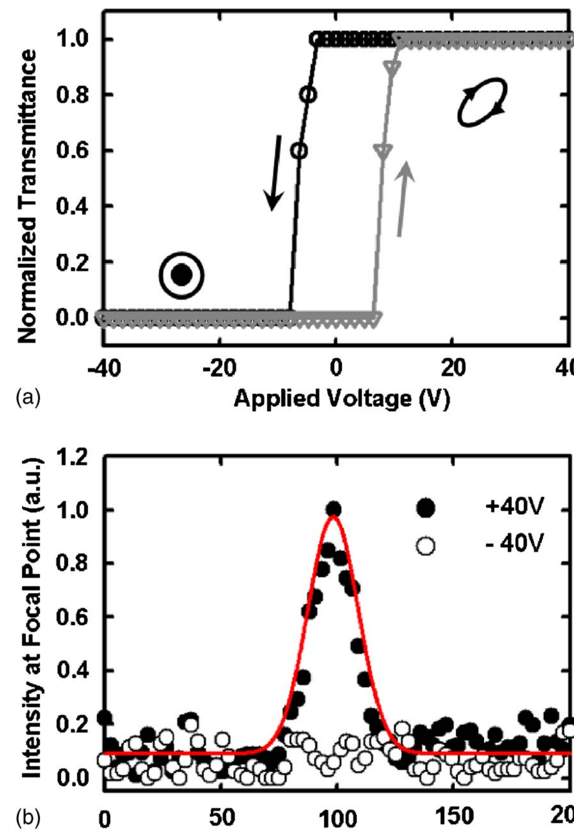

FIG. 4. (Color online) (a) Transmittance of the FLC device under crossed polarizers as a function of an applied voltage. Inserted figures are the polarization states entering the LCP MLA. (b) The intensity profiles of the FLC device. Symbols denote the experimental data and line is the Gaussian fit.

well matched in our experiment. The measured focal length is 10.0 ± 0.5 mm and almost identical to that of the LCP MLA. The response time was measured at about 94 ms.

Although good tuning characteristics can be obtained with a TN structure, some systems such as optical communications need a faster response. Thus, we applied a commercial FLC Felix 016-100 (Clariant), which exhibits a smectic C phase at a wide temperature range ($-20 \sim 72$ °C) for fast switching applications. In bistable FLC mode, two stable states exist with respect to the spontaneous polarization of the molecule and the polarity of the applied field with the hysteresis, as shown in Fig. 4(a).[14] If we set the initial polarization and one stable state of FLC parallel to the y axis and x axis, respectively, the polarization state entering the LCP MLA can be defined as depicted in the figure. Thus, the focal intensity can be switched by changing the polarity of an applied field. The proposed optical configuration exhibits a high contrast ratio of the focused image. Note that this can be easily changed by rotating θ. The cell gap was 3 μm and the cone angle of the FLC was measured as 48°.

In Fig. 4(b), the focused spot at a positive voltage (+40 V) totally disappears with a negative voltage (−40 V). The contrast ratio of focal intensity was measured at about 10:1. The switching time was measured at 37 μs, which is 1000 times faster than that of the TN case.

In summary, we have proposed an electrically switchable MLA by controlling optical polarization with LCs and using birefringent LCP. Due to the use of LCP and the separate operation of focusing and polarization control, the focal intensity can be tuned with various driving features showing fine image quality from the flat boundary. The proposed concept is simple and powerful to fabricate the dynamic MLA in diverse systems such as optical communication and microwave electronics.

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