

Fast Bistable Microlens Arrays Based on a Birefringent Layer and Ferroelectric Liquid Crystals

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We fabricated a fast bistable ferroelectric liquid crystal (FLC) microlens array by combining a focusing unit with a tuning unit. The focusing unit with birefringent liquid crystalline polymer focuses the incident light depending on the polarization. The tuning unit with ferroelectric liquid crystal controls the polarization state of the incident light. The resultant microlens array shows fast switching time of the order of 10 μ s and bistable characteristics which are not possible with nematic liquid crystal microlens arrays. [DOI: 10.1143/JJAP.47.6343]

KEYWORDS: microlens, ferroelectric liquid crystal, liquid crystalline polymer

1. Introduction

A number of attempts have been made to fabricate liquid-crystal (LC)-based real-time reconfigurable microlens arrays^{1–10} to perform real-time optical interconnection in optical computing and photonic switching circuits. With the advancements in computing and communications technology, there is a growing and critical need for fast switchable microlens arrays. Most of methods employed in previous studies, however, are used nematic LCs which have switching time of the order of 100 ms.

Recently, several attempts have been made to achieve a fast-switching microlens array using ferroelectric LCs (FLCs)^{11,12} which are attractive materials for use in display applications as well as integrated optical non-display applications because of their fast (order of 10 μ s) switching time and bistable non-linear electro-optic effects.¹³ With these techniques, however, it is not easy to realize defect free alignment of FLC due to the non-flat boundary conditions or the unpolymerized monomers. Moreover, the fabrication processes are quite complicated and limit development of their applications.

In this paper we suggest a fast-tunable and bistable FLC microlens array with a good focusing characteristic even with simple fabrication process. In the proposed structure, the beam focusing and the electrical tuning of polarization state are performed separately at the prepared focusing unit with birefringent LC polymer (LCP) layer and polarization control unit with FLC, respectively. The FLC microlens array can be controlled at a speed of a few tens microseconds with its bistable properties.

2. Experimental Procedure

The FLC microlens array adopts a new lens structure consisting of a focusing unit and a tuning unit as shown in Fig. 1. The focusing unit is composed by the stacked layer of LCP on the concave microlens structure of the UV curable polymer. The focusing unit focuses the incident light depending on the polarization direction due to the birefringence of LCPs. When the incident light polarization is parallel to the alignment of LCP directors, the light is focused due to the larger refractive index of LCP than that of

the UV curable polymer. On the other hand, the light is diverged owing to the smaller refractive index of LCP than that of the UV curable polymer when the incident light polarization is orthogonal to the alignment of LCP directors. As the tuning unit, we used FLC to control the polarization of incident light with a fast switching time and bistability. Depending on the direction of applied electric field, optical polarization can be controlled due to the reorientation of FLC molecules. As a result, we can control the focusing properties of the microlens array by combining the focusing unit with the tuning unit.

In order to fabricate the focusing unit of the microlens array, the UV curable polymer (NOA60) from Norland was spin-coated on the top of the indium tin oxide (ITO) glass substrates at the rate of 1000 rpm for 10 s and followed by the rate of 4000 rpm for 30 s. The UV curable polymer was exposed to UV light of $\lambda = 365$ nm through a patterned photo mask. The surface relief structures on the UV polymer layer were obtained by the anisotropic diffusion of monomers due to the UV intensity modulation. The refractive index of polymerized UV polymer was 1.56. For the alignment of LCP molecules, polyimide RN-1199 from Nissan Chemical was spin-coated on the concave microlens array substrate and rubbed with a velvet cloth. The LCP RMS03-001 from Merck was spin-coated on the concave microlens array at the rate of 3000 rpm for 30 s and cured by UV exposure. The ordinary and extraordinary refractive indices of the LCP were 1.529 and 1.684, respectively. The widths of LCP and UV-P layer were 6 and 14 μ m, and the diameter and inner depth of each microlens were 200 and 4 μ m, respectively.

The tuning unit of the FLC microlens array was constructed as a thin layer of LCs with smectic C* phase which is sandwiched between the microlens array substrate and an ITO-coated substrate with alignment layer. The cell gap was maintained 3 μ m using glass spacers. The FLC Felix 016-100 from Clariant was introduced on the flat focusing section at isotropic phase (>98 °C) by dropping and then slowly cooled (0.1 °C/min) to room temperature.

3. Results and Discussion

The focusing property of the proposed structure is depending on the alignment of LCP layers in the focusing unit. Figure 2 shows the microscopic images of the focusing

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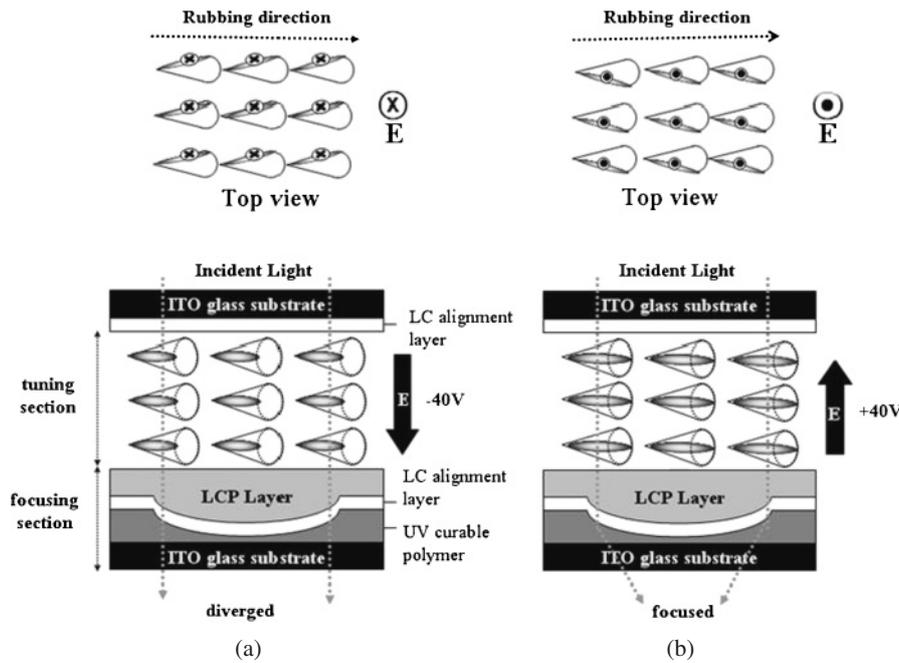


Fig. 1. Schematic diagrams of the proposed FLC microlens array with two bistable states: (a) a diverged state at the applied field of $-40V$ (b) a focused state at the applied field of $+40V$. The upper and lower diagrams illustrate top view of the FLC directors and cross-section view of the microlens array.

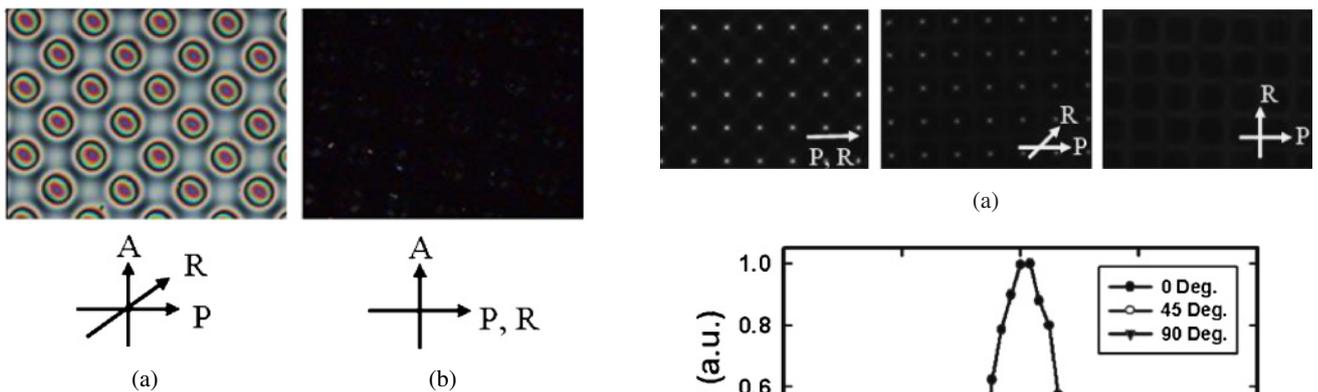


Fig. 2. (Color online) Texture images of a microlens array under a polarizing microscope without applied voltage. R, A, and P represent rubbing direction, analyzer, and polarizer, respectively.

unit under crossed polarizers. By rotating the microlens array cell, a set of concentric circular structures are observed on microlens array when the rubbing direction is misaligned with the crossed polarizers. A uniformly dark state is obtained when we align the rubbing direction with one of the crossed polarizers. From the results, we found that the LCP layer is well aligned along the rubbing direction on UV polymer. To verify the polarization dependency of the focusing unit, we observed focused beam images and measured beam intensity profiles depending on the polarization of the incident light as shown in Figs. 3(a) and 3(b), respectively. When the rubbing direction is parallel to the incident polarization, maximum intensity of light is observed due to the anisotropy of refractive indices of LCP. As rotating the angle of incident linear polarized light, the intensity of the focused light is gradually decreased and disappeared when the polarization of incident light is perpendicular to the rubbing direction of LCPs. Figure 3(b)

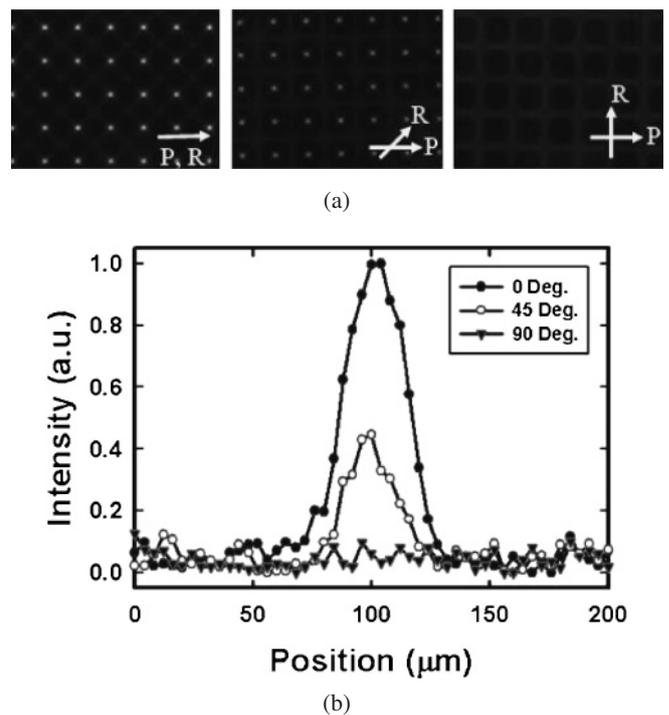


Fig. 3. Polarization-dependent characteristics of a microlens array without applied voltage: (a) focused-beam images and (b) beam intensity profiles, corresponding the angles between rubbing direction and polarizer are 0, 45, and 90° respectively.

shows the intensity profile of focused beam of Fig. 2(a) at the focal plane. The maximum intensity corresponding to 45° is approximately half of that corresponding to 0° which is well matched with theoretical calculation. The natural focal length, f , of a microlens can be calculated from $f = R/(n_{lcp} - n_p)$; where R is the radius of curvature of the UV polymer's surface, n_{lcp} is the extraordinary refractive

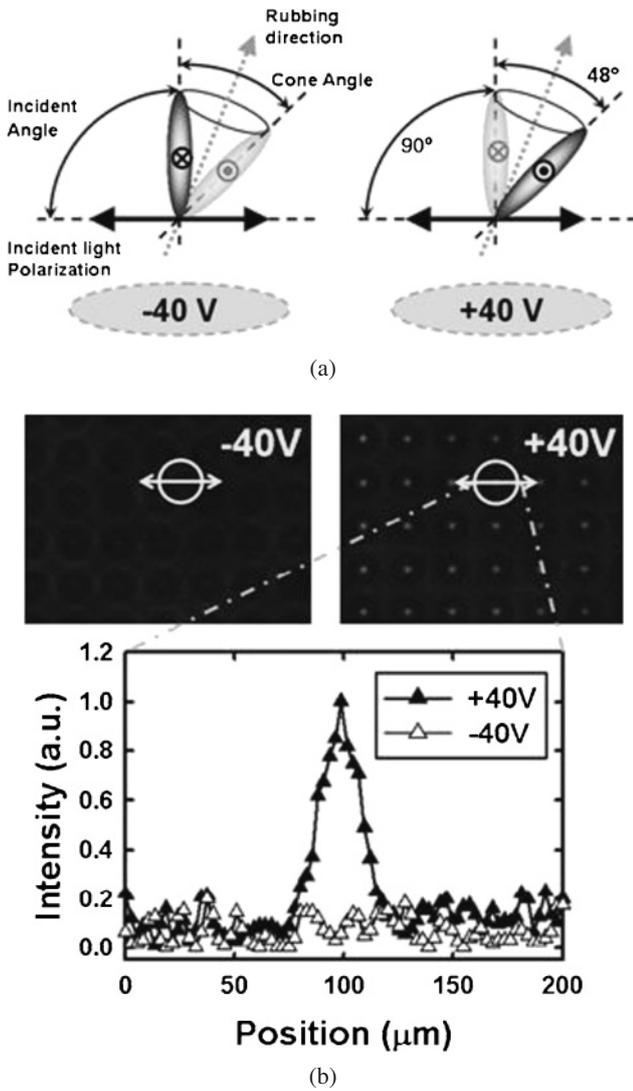


Fig. 4. Focusing properties of a microlens array: (a) FLC molecular orientation status and (b) diverged and focused beam images with their beam intensity profiles at the applied voltage of ± 40 V, respectively.

index of LCP, and n_p is the refractive index of UV polymer. The measured focal length of the focusing unit was 9.5 ± 0.2 mm which is nearly matched with the calculated value of 10.1 mm.

Optical polarization is controlled by changing the molecular orientation of FLCs depending on the direction of applied electric field in the tuning unit. Figure 4(a) shows the schematic diagram of the molecular orientation when we applied ± 40 V. With -40 V, FLC molecules are aligned in one side of the cone angle of FLCs due to the direct coupling of electric field and dipole moment of FLC molecules. If we set the FLC molecular axes is perpendicular to the incident polarization, then the optical polarization is not changed when passing through the FLC layer. When we applied $+40$ V, the molecular axes of FLCs are reoriented at the other side of cone angle of FLCs. In our case, the cone angle is about 48° which is depending on the material, temperature, and applied voltage. The reorientation of FLC molecules perturbs the linear polarization of incident light due to the birefringence of FLC molecules. As we mentioned before, the lens properties of focusing unit depends on the polarization of the incident light to the focusing unit.

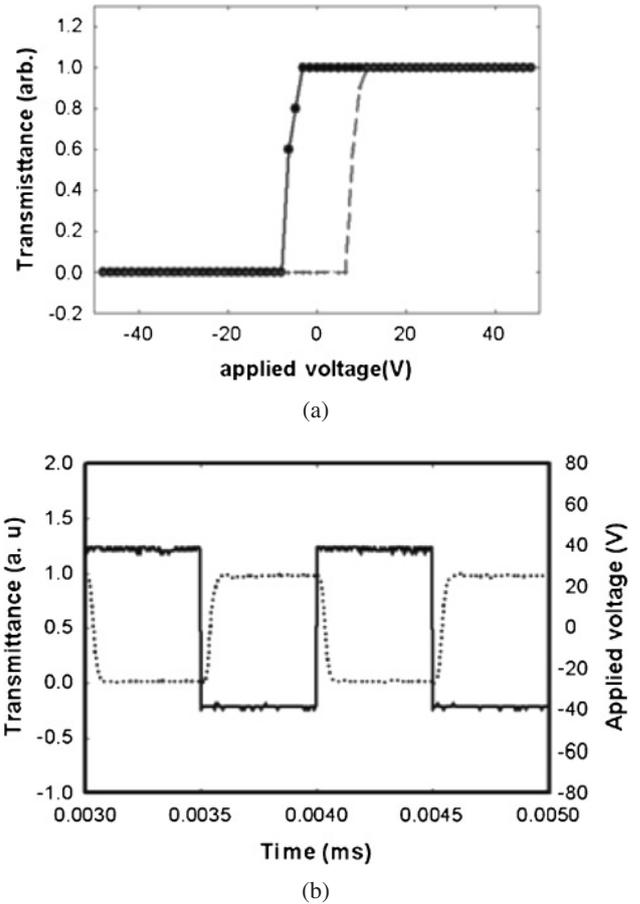


Fig. 5. (a) Light transmittance as a function of applied voltage, showing bistable characteristics of a FLC microlens array. (b) Transmission vs time curve for a FLC microlens array. The solid and the dotted line represent applied voltage and light transmittance, respectively.

Therefore, we can fabricate dynamic lens array by combining the focusing and the tuning unit. Figure 4(b) shows the focusing properties of the assembled microlens array. With ± 40 V, the focused spots are clearly observed and disappeared, respectively. The intensity profiles for these cases are also illustrated in Fig. 4(b). The contrast ratio between the maximized and the minimized intensity is 8 : 1 which is 4 times larger than that of our previous FLC lens which is fabricated by the anisotropic phase separation.¹¹⁾ The result may come from the enhancement of FLC molecular alignment due to the flat boundary conditions of FLCs on top and bottom surface and no impurities such as uncured monomer. Note that, in this structure, the electric field distortion between the center and the edge of a single microlens is small enough to obtain an uniform director profile of LCs on the whole microlens area. This is essential since we do not want to induce a spatial modulation of the optical phase at the LC layer unlike the other approaches of LC based active lenses.

Figure 5 shows the optical properties of the assemble microlens array mainly due to the properties FLC materials. Figure 5(a) shows the bistable characteristics of the microlens array which were examined by measuring the focused beam intensity of the microlens array with continuously changing the applied voltage between ± 50 V. We can observe two stable states at zero voltage due to the bistability

of surface stabilized FLC structure.¹²⁾ Due to the spontaneous polarisation of FLCs, FLCs show hysteresis in response to an applied switching voltage. If the hysteresis is sufficiently broad and the transition from one state to the other is sufficiently steep, then the FLC remains in its prior state when the applied field is removed. Figure 5(b) shows the switching characteristics of the microlens array when the alternative electric field of ± 40 V is applied to the microlens array. The times to turn the lenses ON and OFF are 74 and 68 μ s, respectively. In our previous studies,¹¹⁾ the switching time of nematic microlenses was measured to be the order of 100 ms. Evidently, and as expected, the switching time of proposed FLC microlens array is about 1000 times faster than that of the NLC microlens arrays. We believe that our proposed microlens array will be a key component in optical communication technologies in near future.

4. Conclusions

In conclusion we demonstrated a fast-tunable and bistable FLC microlens array by combining of the polarization-dependent focusing unit using birefringent LCP layer and the tuning unit for polarization control using FLC. By separation of functions we can enhance the optical properties of microlens array with simple fabrication method. The

switching time is found to be three orders of magnitude faster than for similar devices built using nematic liquid crystals. Furthermore, the FLCs exhibit the memory effect.

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