

Fast switching characteristics of a microlens array using the electroclinic effect of SmA* liquid crystals

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We present a microlens array characterized by the electroclinic effect of chiral smectic A (SmA*) liquid crystals, which show the very fast dynamic switching characteristics required in high-speed optical devices. In order to easily control the intensity at the focal length of the proposed dynamic microlens structure, we adopt a solid-type liquid crystal polymer with optical anisotropy, which can split the beam intensity into two directions, depending on the vectorial portion of the polarization state of the light. The proposed microlens shows a focal intensity tunable by controlling the polarization of light at the SmA* liquid crystal. The lens has a very fast switching time of about 24 μ s, which is several times faster than conventional microlens arrays with surface-stabilized ferroelectric liquid crystals. © 2009 Optical Society of America

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1. Introduction

With the rapid progress in information technology, there is a need for real-time reconfigurable optical elements such as beam-steering (e.g., diffractive gratings) and wavefront-shaping devices (e.g., a microlens array) to apply to data storage, optical interconnects, beam modulating, and image integration components in 3D displays [1–3]. In these devices, the electrically tunable focusing property is a key issue. A number of attempts, based on the electrically controllable optical anisotropy of liquid crystals

(LCs), have been made to construct real-time reconfigurable microlens arrays. The microlenses used in various approaches include a combination of a passive solid-state lens array and an LC modulator, a gradient refractive index profile type of LC induced from an axially symmetric electric field generated by spatially designed electrode patterns, and a 3D anisotropic phase-separation type of LC and polymer [4–7] that is switchable on command and has a variable field-dependent focal length. All of these have excellent characteristics. The switching time, however, is only of the order of 100 ms because of the intrinsic speed of nematic LCs. These speeds are not sufficiently fast to be applicable to optical communication or wavefront-shaping devices.

Recently, several attempts have been made to achieve fast switching microlens arrays using nano-sized polymer-dispersed LCs [8,9] and surface-stabilized ferroelectric LCs (SSFLCs) [10,11]. SSFLCs are attractive materials for use in display applications because of their fast (about 100 μ s) switching time and bistable nonlinear electro-optic effects. Although these methods lead to a fast switching device for optical applications, SSFLCs have been used in microlens systems only for binary optical modulation because of their hysteresis characteristics [12].

In this study, we demonstrate a dynamic LC microlens array based on the electroclinic effect [13] of chiral smectic A (SmA*) LCs. The microlenses can modulate continuous focal intensity at a speed of a few microseconds, which is 10 or 1000 times faster than microlenses using SSFLC or nematic LC, respectively.

2. Experimental Details

Schematic diagrams illustrating the operating principle of the proposed microlens array structure are shown in Fig. 1. The microlens array consists of a focusing unit, which modulates beam focusing, and a tuning unit, which controls the polarization of the incident beam. This separated structure enables the microlens array to vary the focal intensity depending on the incident polarization and has an advantage in LC alignment because of the flat surface boundary. The focusing unit is composed of a liquid crystalline polymer (LCP) layer stacked on a concave microlens structure made of UV curable polymer. The focusing unit can control the beam intensity of two paths, depending on the vectorial portion of the polarization state of the light incident from the polarization tuning unit, because of the birefringent characteristics of LCPs. When the polarization of the incident light is parallel to the alignment of the LCP directors, the

light is focused because the effective refractive index of LCP is greater than that of UV curable polymer. On the other hand, the light is defocused because the effective refractive index of LCP is less than that of UV curable polymer when the incident light polarization is orthogonal to the alignment of the LCP directors. As a polarization tuning unit, an LC layer is constructed to control the incident light polarization. For fast switching and continuous control of polarization, we used SmA* LC, which exhibits the electroclinic effect [14–17]. The electroclinic effect is an electric field-induced tilt θ of the average molecular director \mathbf{n} , which rotates in the plane perpendicular to the applied field \mathbf{E} , where θ is proportional to the magnitude of \mathbf{E} . Owing to the linearity of the tilt angle with respect to the applied electric field, the polarization of an incident beam with linear polarization can be changed by the modulation of an optical retardation induced from the magnitude of the electric field after passing through the LC layer. Consequently, we can control in a simple way the focusing properties in the microlens array with a combination of the focusing unit and the tuning unit.

To fabricate the focusing unit, we spin-coated UV curable polymer NOA61 (Norland) on an indium tin oxide (ITO) substrate. The UV curable polymer layer was irradiated by a UV ($\lambda = 365$ nm) light source for 10 s through a dot-type patterned photomask. The intensity modulation of UV light creates an anisotropic diffusion of uncured monomer from the UV blocked region to the UV exposed region [10]. The surface relief structure was formed with this polymerization and diffusion. A second UV light irradiation was performed for 5 min without the photomask to fully harden the shape of the surface relief structure. For LCP alignment, we spin-coated a homogeneous LC alignment layer of RN-1199A (Nissan Chemical) on the UV polymer and rubbed it in one direction.

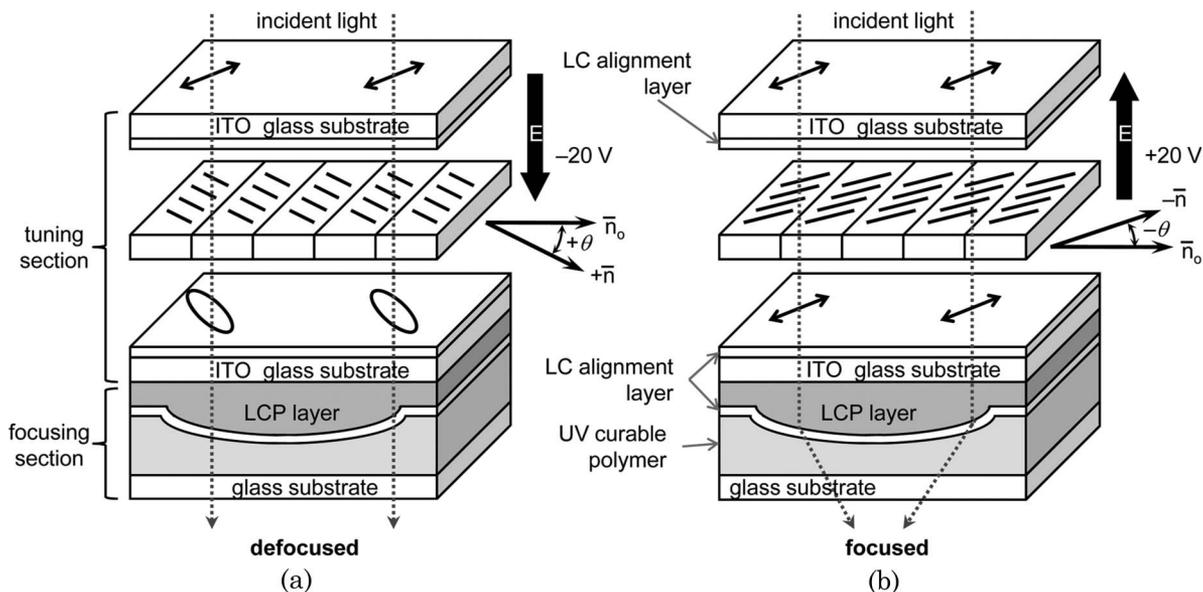


Fig. 1. Schematic diagrams of the proposed microlens array using electroclinic effect: (a) defocused state at the applied field of -20 V, (b) focused state at the applied field of $+20$ V.

Then we spin-coated LCP material (RMS03-001C, Merck) onto the LC alignment layer at under 1000 rev/min for 10s in the first step and 3000 rev/min for 20s in the second step. To fill the surface relief structure and obtain a flat boundary condition, the LCP layer coating process was repeated. The spin-coated layer was cured in a baking oven at 60°C for 5 min, followed by UV irradiation for 30 min. Under these conditions, we produced a concave microlens array in which the diameter and the inner depth of each microlens were 200 μm and 4 μm , respectively. The ordinary and extraordinary refractive indices of the LCP and the refractive index of UV curable polymer were 1.529, 1.684, and 1.56, respectively. Here, the effective radius of curvature in our LCP lens was estimated to be 2.5 mm, and thus the focal length was to be 20.2 mm when the incident light is linearly polarized along the axis of the LCP lens.

To fabricate the tuning unit of the microlens array using LCs, we prepared two substrates with RN-1199A rubbed on the ITO-coated glass. The cell gap was maintained by bead spacers of 2 μm . As an LC material, we used Felix-020 (Clariant), which shows the following phase sequence: (SmC*) 18°C (SmA*) 75°C (Ch) 103°C (I), where the symbols SmC*, SmA*, Ch, and I represent chiral smectic C, chiral smectic A, chiral nematic (or cholesteric), and isotropic phases, respectively. The extraordinary and the ordinary refractive indices of the LC material are 1.671 and 1.495, respectively. The LC material was filled into the assembled cell by capillary action at the isotropic phase (110°C) and cooled slowly (1°C/min) to room temperature.

3. Results and Discussion

The focusing property of the proposed structure depends on the alignment of the LCP and LC in the focusing and tuning units, respectively. Figure 2(a) shows the alignment textures of the focusing unit with the LCP layer under crossed polarizers. When the rubbing direction for the LCPs is not coincident with the optic axes of the polarizers, optically regular internal structures are formed, indicating a continuous variation of optical retardation due to the thickness variation of LCP layers from their center to their edges. In Fig. 2(a) on the right, one can obtain a uniformly dark state when the rubbing direction coincides with one of the crossed polarizers. This means that the LCPs are homogeneously well aligned on the surface relief structure. Figure 2(b) shows microscopic textures of the microlens array after it is assembled with the tuning unit under crossed polarizers without an applied voltage. From this figure, we confirmed a circular structure and dark state depending on the angle between the LC alignment direction and the crossed polarizers. This illustrates that the LC molecules of the control unit are uniformly aligned with the LCP layer.

In general, LCDs control optical transmittance by changing optical polarization of the incident light

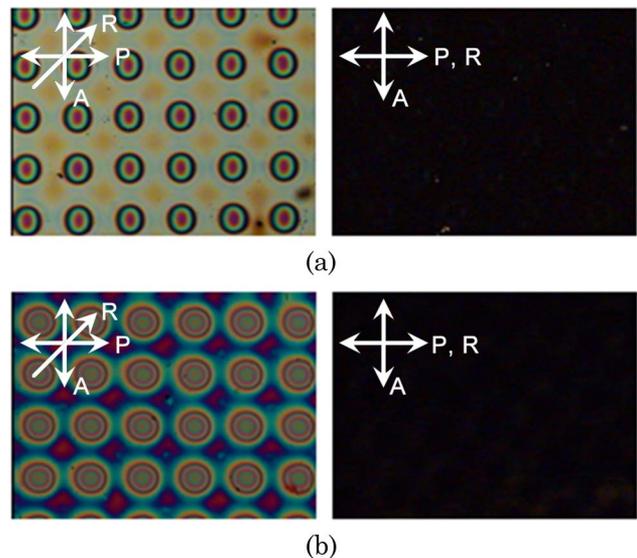


Fig. 2. (Color online) Texture images of (a) focusing section without an LC tuning section, (b) microlens array. R, A, and P represent the rubbing direction, the optic axis of the analyzer, and the optic axis of the polarizer, respectively.

due to the reorientation of LC molecules induced by the applied voltage. In our proposed microlens array, optical polarization can be controlled in the same manner. Figure 3 shows the induced tilt angle θ of smectic LC as a function of the applied electric field at several temperatures. The induced tilt angle was determined by using Eq. (24) of [14], where the peak-to-peak intensity modulation is directly related to the tilt angle induced under voltage switching. For temperature control, the LC cell was mounted in a Mettler hot stage (FP82HT, Toledo). In general, the induced tilt angle follows a linear dependence on the applied electric field at above the transition temperature T_c , but it exhibits the relationship of $E^{1/3}$ to the applied electric field (E) in the vicinity of the transition temperature T_c [18]. As shown in Fig. 3, the induced tilt angle at room temperature showed almost linear behavior up to 12° as the applied electric field increased up to 45 V. In our

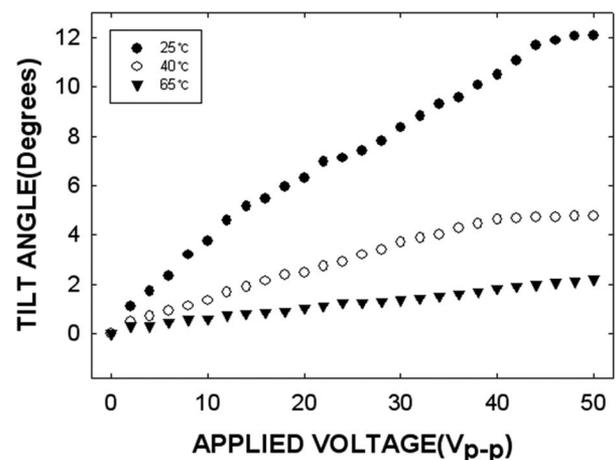


Fig. 3. Induced tilt angle θ as a function of applied voltage.

experiment, we tested a microlens array in the linear regime. The polarization of light incident on the LC layer can be changed from linear to elliptical depending on the molecular ordering of the LC (i.e., the induced tilt angle θ) because of the birefringence of LCs.

Optical modulation of the microlens array can be obtained by changing the molecular orientation of LCs in the tuning unit. Figure 4(a) shows images of the focused beam patterns generated by the microlens array at the applied voltages of -20 , 0 , and 20 V, respectively. With a negative electric field, the LC molecular axes are tilted parallel to the rubbing direction. If the polarization direction of incident light is misaligned by tilt angle θ with respect to the LC molecular axes, the linear polarization of the incident light is changed to elliptical polarization in the tuning unit owing to birefringence, except that its retardation is half of the wavelength. Then, the component perpendicular to the alignment directions of LCPs at the elliptically polarized light diverges. Here, focal length is not changed, but intensity is changed depending on the ellipticity of the incident polarization. As the applied electric field increases, the intensity of the focused beam increases progressively because of the increase of the tilt angle of the LC directors. This increase in tilt angle gradually changes the incident polarization and results in increasing the focusing intensity of the microlens array. When the applied electric field is above 0 V, the LC directors are rotated parallel to the incident light polarization. Then there is no change of polarization while transmitting the tuning and the focusing units, since the polarization of the transmitted

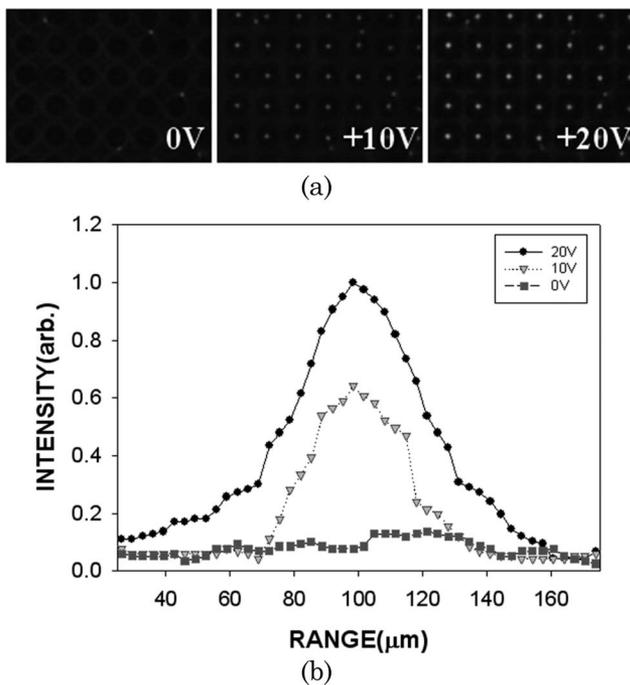


Fig. 4. (a) Images of the focused spot patterns. (b) Measured beam intensity profiles at the applied voltages of -20 , 0 , and 20 V, respectively.

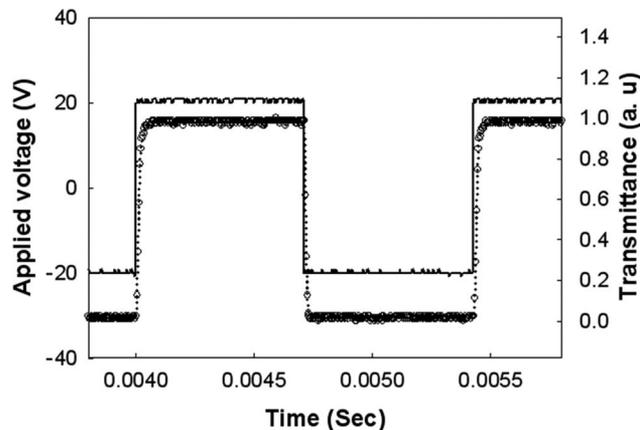


Fig. 5. Switching speed measured at the LC microlens array. The solid curve and the circles with the dotted curve represent applied voltage and light transmittance, respectively.

light is parallel to the LC director and the LCP alignment direction. In this case, the light is focused because of the difference in the effective refractive indices between the LCP layer and the UV curable polymer layer. We observed maximized intensity spots as the induced tilt angle became saturated above 20 V. The intensity profiles for these cases are shown in Fig. 4(b). The measured contrast ratio at focal length was $12:1$.

Figure 5 shows the switching characteristics of the microlens array when the alternative electric field of ± 20 V was applied to the array. The measured switching times of the microlens array are $24 \mu\text{m}$ in the ON state and $6 \mu\text{s}$ in the OFF state, which may be the faster switching time in dynamic LC microlens arrays.

4. Conclusion

In summary, we demonstrated a fast tunable LC microlens array using the electroclinic effect of chiral smectic A LCs. As the change of the tilt angle of the LC director in the smectic A phase is linearly induced by an electric field, the focusing beam intensity of the proposed microlens array is linearly tunable with the applied electric field. The switching time of the microlens array was found to be several tens of microseconds. We expect that this fast switching microlens array can be applied to real-time processing optical systems.

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