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Fabrication of Electrically Controllable Microlens Array using a Birefringent Bilayer

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Electrically switchable microlens array is demonstrated using a stacking system of UV curable polymer, liquid crystalline polymer (LCP) and liquid crystal (LC) layers. The birefringent LCP provides the incident beam focusing ability of polymer microlens structure as well as the LC aligning property. By engaging external voltage to the device, we can obtain fine dynamic characteristics of the focus switching from the polarization tuning ability of twisted nematic LC layer on the flat boundary condition and the light focusing role of polymer microlens structure, separately. The measured focal characteristics are well matched to the calculated ones and arrayed focused spots are easily switched by applying external voltage. This active microlens array is expected to play a critical role in the various photonic systems such as optical switches, beam modulators and 3-D imaging units.

Keywords: liquid crystal; liquid crystalline polymer; microlens array; twisted nematic LC

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INTRODUCTION

Recently, the electro-optic effect together with large optical anisotropy of a LC has been successfully utilized for developing information displays and photonic components. For optical applications, several types of the LC microlens arrays have been investigated to explore the possibility of using them as optical switches, wave front detectors, and image integrators in 3-dimensional displays. Many of existing LC microlens has gradient refractive-index (GRIN) profile of LC produced by a designed electric field pattern or a surface relief structure to obtain and control the focusing properties [1–9]. However in most conventional approaches, the dynamic focusing properties were not satisfactory for real-time optical system, which originated in the non-uniform tilt of the LC's reorientation during the driving from the curved surface. Even in the flat boundary, various problems like complicated fabrication from the patterning process of the electrode should be solved for the practical application.

In this article, we demonstrate an electrically switchable microlens array which is composed of a highly birefringent polymer microlens structure and a LC layer for polarization control of an incident light. The polarization state of incident polarized light is controlled by an electric field at the LC layer and then the light focused passing through the next refractive type polymer microlens. Fine dynamic focusing properties of LC microlens can be achieved in this device since the refraction effect for light focusing and the ability of the active device from the polarization control are obtained from the polymer microlens structure and the twisted nematic (TN) LC layer on the flat boundary, separately. Moreover, LC molecular aligning ability of a liquid crystalline polymer (LCP) supports the simple fabrication without additional LC aligning treatment.

PRINCIPLE OF DEVICE OPERATION

Our concept for electrically switchable microlens device is based on the separate operations of the light focusing role and the control of incident polarization. Fundamentally, the polymer microlens structure takes the focusing role of device with highly birefringent feature, and the TN LC layer controls the polarization state of light with an applied voltage. Therefore, in first we made the polymer microlens on the conventional ITO (indium tin oxide) glass substrate as depicted in Figure 1. Then through use of this polymer microlens as a bottom substrate, we realized a typical TN LC cell with another ITO glass substrate which can act as an active microlens array. Note that the

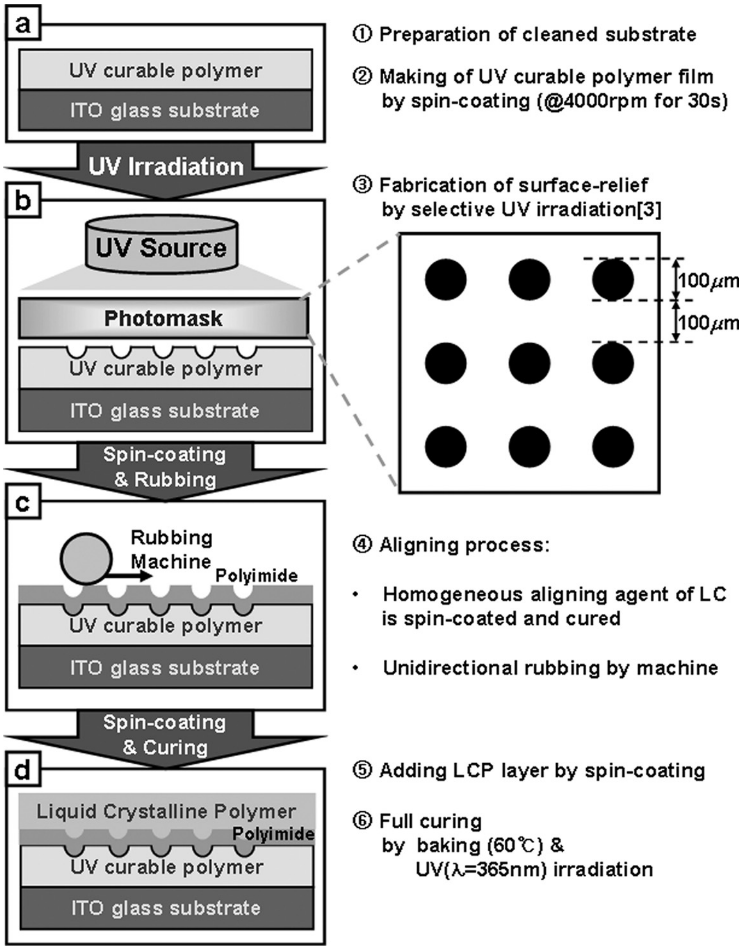

FIGURE 1 Schematic illustration for the fabrication of a bottom polymer microlens structure. (a) Preparation of UV curable polymer layer (b) Fabrication of the surface relief construct of UV curable polymer with a single photomask and a simple UV irradiation process (c) Treatment of LC alignment layer. (d) Formation of LCP layer.

well-ordered structure of LCP from the chain ordering effect has the ability for homogeneous LC alignment by itself. As shown in Figures 1(a) and (b), a concave microlens array with a UV curable polymer was prepared by controlling curing process and a patterned UV irradiation at first. On the concave UV curable polymer relief, a homogeneous LC aligning agent (in this case, a polyimide was used) was spin-coated with a unidirectional rubbing treatment (Fig. 1(c)). When a LCP was cast on this concave microlens structure and cured by UV irradiation, a highly birefringent LCP film was produced due to the chain ordering of LCP induced by the rubbed polyimide (Fig. 1(d)). Due to the refractive index difference of LCP and UV curable polymer, this double polymer layer can act as the convex or concave microlens depending on the polarization state of the incident light. This focusing control possibility of polymer microlens is originated from the birefringent characteristic of LCP. If the polarization direction of incident light is parallel to the LCP molecular aligning direction (i.e., rubbing direction of polyimide in the Fig. 1(c)), the input beam converges after passing through the polymer microlens structure and this results in the focused state (beam converging) of the device. In the orthogonal case (i.e., perpendicularly incident case), the input beam diverges and results in the de-focused state of the device. In our driving scheme, we set our device to work as a convex lens initially because in general the beam focusing function has many applications in the field of optics. To control the focusing properties, a TN LC layer was promoted on the flat-polymer microlens surface.

As an example, when the direction of incident polarization is parallel to the rubbing of top substrate, the input beam is focused by passing through the device without an applied voltage as explained previously. When the external field is engaged, the LC layer became an optically isotropic medium with a homeotropic alignment. In this case, the polarization state of incident light doesn't change after passing the LC layer and the beam diverges due to the concave lens effect of the polymer microlens structure. Therefore, we can obtain the de-focused state of incident light.

In addition, at the initial driving condition (0 V), the polarization direction of linearly polarized incident light can be continuously controlled from the extraordinary axis of the LCP to the ordinary axis by changing the input beam direction. Therefore we can also tune the relative intensity of focused spots by rotating the incident polarization direction (linearly polarized) from the highly converged state to the fully diverged state. The detailed studies for the focusing characteristics under various polarization states and engaged voltages are remained to be explored.

EXPERIMENTS

Our electrically controllable microlens array with LCP and LC layer was fabricated by using two-sandwiched ITO glass substrates. One of the substrates had a polymer microlens structure consist of UV curable polymer and reactive mesogen (LCP) as described previously. The concave relief structure of the UV curable polymer was obtained by the selective UV irradiation through a photomask based on the diffusion effect of the monomer [2–4,10,11]. The spin-coating process for LCP was made twice to flatten the curved surface of UV curable polymer and LCP was cured by UV ($\lambda = 365\,\text{nm}$) irradiation. Through this, a well-ordered LCP layer was produced on the concave relief of UV curable polymer to realize the highly birefringent polymer microlens structure. Note that the diameter of single microlens was 200 μm and the height of relief (concave structure) was 4 μm. A total thickness of LCP and UV curable polymer layer was about 20 μm.

A commercial homogeneous alignment layer of RN-1199 (Nissan Chemical), a LCP of RMS03–001 (Merck), UV curable polymer NOA60 (Norland), and a nematic LC of MLC-6080 (Merck) with positive dielectric anisotropy were used in this study. The dielectric anisotropy of LC, the ordinary and extraordinary refractive indices of LCP, the cured refractive index of the NOA60 are $\Delta\varepsilon = 7.2$, $n_{\text{o\_LCP}} = 1.529$, $n_{\text{e\_LCP}} = 1.684$, and $n_{\text{UVpolymer}} = 1.56$, respectively. The cell thickness was maintained using glass spacers of 4 μm thick to satisfy the wave-guiding condition (i.e., Mauguin condition [12]). To achieve the stable spacing through whole sample, the LC was inserted by dropping method.

Microscopic textures of the LC microlens were acquired with a polarizing optical microscope (Nikon, ECLIPSE E600) under the crossed polarizers. All the focal images were captured by the CCD and a computer-controlled image grabbing system at the focal plane of microlens.

RESULTS AND DISCUSSION

First, we examined the microscopic textures to assure the TN mode driving on the arrayed microlens structure. In Figure 2, the driving characteristics of our sample were presented by the proofs of microscopic textures. The initially white image (0 V) and completely dark image (20 V) of the sample provided the realization of stable TN structure. The diameter of single LC microlens and the distance between lenses were 200 μm each. Note that the suggested microlens array showed a threshold driving characteristic with 5 V threshold voltage.

Figure 3 shows the focusing properties of our LC microlens under the applied voltages of 0 V and 20 V. Initially focused beam spots were disappeared as increasing an applied voltage when the polarization direction of incident light is parallel to the rubbing direction of the top substrate. Note that due to the threshold driving feature of LCs,

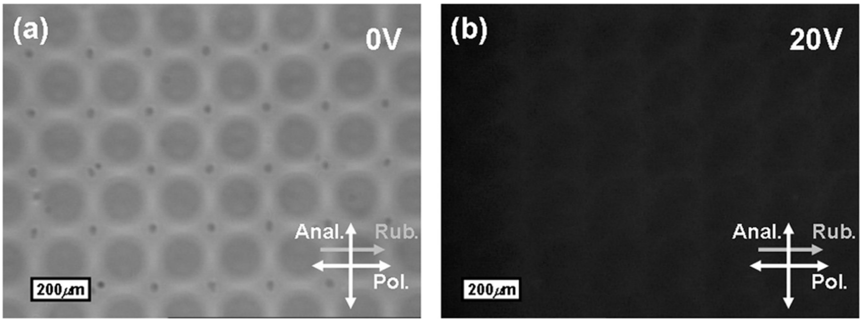

FIGURE 2 Microscopic texture images of the device under crossed polarizing microscope at 0 V and 10 V applications.

no particular focal characteristic change was monitored before the 5 V application. After engaging full voltage (20 V in our experiment), the arrayed focus was completely disappeared as shown in the figure. This voltage controlled focal switching ability was obtained by controlling the incident polarization state of light with the TN LC layer and is expected to be highly applicable for various real optical systems with the small voltage applications.

The measured static focal length was 11.4 ± 0.5 mm. In a simple model [13], the focal length of microlens, f, is simply given by $R/(n_{e\_LCP} - n_{UVP})$, where n_{e_LCP} is the extraordinary refractive index

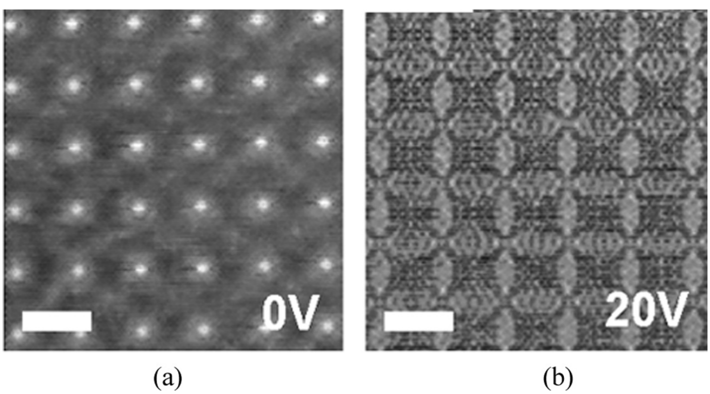

FIGURE 3 Dynamic focus switching characteristics of our microlens array. No external voltage was applied in (a) and 20 V was applied in (b). Note that the polarization of incident light is parallel to the rubbing direction of the top substrate. The white scale bars in the figures represent 200 μm.

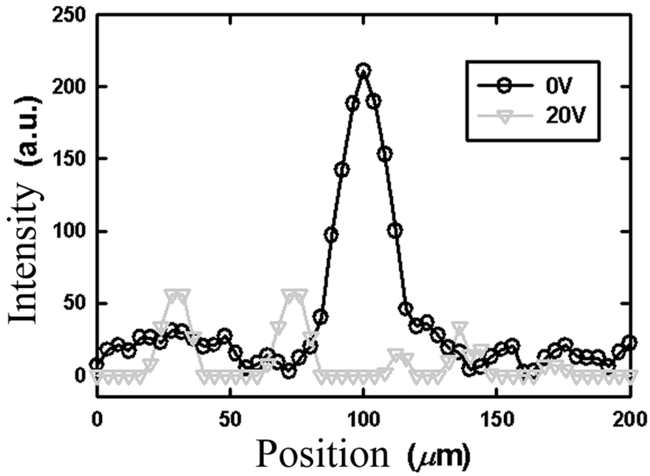

FIGURE 4 The intensity profiles of focusing spot at the focal plane under applied voltages of 0 V and 20 V. The focal intensity is presented in arbitrary units and the center of microlens locates at the position of 100 μm.

of the LCP, n_{UVP} is the refractive index of cured NOA 60 and R is the curvature of the concave relief structure. From the spherical fitting process of the surface profile of relief structure, R was 1252 μm in our experiment, and the resultant theoretical value of the focal length is calculated to be 10.1 mm. This is almost consistent with the above measured result. Note that the calculation is carried out in case of 633 nm laser light source which we used in experiment. Some aberration can be occurred when the white light is used.

The beam profile analysis as switching the device is illustrated in the Figure 4. The focused beam intensity was diminished dramatically as engaging an applied field. Note that due to the interference, squared far-field pattern were observed (Fig. 3(b)) and the side robes were monitored (Fig. 4(b)). However, this can be considered as a noise signal. The FWHM (Full Width at Half Maximum) of intensity at 0 V was measured as 30 μm.

CONCLUSION

We have demonstrated the electrically switchable microlens array by using LCP, UV curable polymer and twisted LC layer. The fine focusing properties of device were obtained from the control of applied voltage. Due to the separate operation of tuning and focusing at twisted LC layer and polymer microlens layer, suggested device can show the stable and good focal switching characteristics within a simple fabrication. The measured response time of the device was about 94 ms and it can be reduced by the optimization of device parameters. With the high performances of microlens, this device is expected to be useful for various optical applications like optical communications and 3-D imaging devices.

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