Optically isotropic switchable microlens arrays based on liquid crystal

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Received 26 March 2014; revised 1 May 2014; accepted 5 May 2014; posted 5 May 2014 (Doc. ID 208952); published 4 June 2014

We present an optically isotropic switchable microlens array (MLA) based on liquid crystals (LCs) using the Joule heating electrode structure. The LC molecules were initially aligned vertically on the lens and electrode surfaces. By applying voltage to the transparent electrodes, the temperature of the LC layer could be changed. Above the clearing point temperature of LCs, the LC layer shows an averaged refractive index that differs from the nematic state refractive index. The MLA could have switching characteristics by index matching between the LC layer and polymer lens structure. The proposed switchable MLA shows high light efficiency with truly optically isotropic properties. © 2014 Optical Society of America

OCIS codes: (230.0230) Optical devices; (220.0220) Optical design and fabrication; (230.3720) Liquid-crystal devices.

http://dx.doi.org/10.1364/AO.53.003633

1. Introduction

Liquid crystal (LC) has been used for various optical devices as photonic systems such as optical switches and light modulators as well as flat-panel displays. Among this use, the microlens array (MLA) with a tunable focal length has found useful applications in 2D/3D switchable displays and in tunable photonic devices [1–5].

A variety of methods based on LCs have been suggested for switchable or tunable MLAs. One of these methods is based on the reorientation of nematic liquid crystal (NLC) molecules under an applied electric field. Because NLCs have a large optical birefringence, the optical path lengths can be controlled over a wide range by application of an electric field.

1559-128X/14/173633-04$15.00/0

However, in most MLAs that use LCs, the intrinsic uniaxial anisotropy of the LC results in polarization-dependent properties on the incident light. Since only half of the light is involved in focusing properties, the light efficiencies could not exceed 50%.

To overcome these problems, orthogonally aligned LC Fresnel lenses [4–6] or vertically aligned (VA) NLC [7] lenses have been proposed to eliminate polarization dependence. However, such lenses require an extremely precise alignment technique and/or complicated fabrication processes. In addition, the LC lenses are switched from an optically isotropic state to a birefringent state upon switching of the electric field. When LC molecules are aligned vertically, the LC molecules are optically isotropic in the direction of the incident light. At this stage, the LC layer shows optically isotropic property. When the electric field was applied, the LC molecules lay down to the substrate, so the LC layer has planar alignment on the surface. At this state, for optically isotropic property, they designed that LC molecules

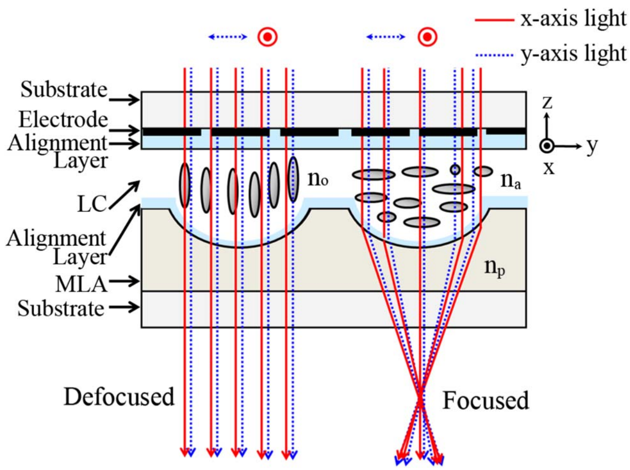


Fig. 1. Operating principle for the proposed MLA system.

are aligned omnidirectionally within one lens. However, since the lens size is larger than the wavelength of the incident light, the LC layer has birefringence. Therefore, the light efficiency is almost the same as for polarization-dependent lenses.

In this paper, we propose a truly optically isotropic MLA in which the refractive indices of the LC layers are controlled by Joule heating. To increase the temperature, we used transparent electric-heating layers. Because the proposed MLAs are switched from homeotropic alignment to an isotropic state, our MLAs show truly optically isotropic properties over the entire switch state.

2. Operation Principle

Figure 1 shows a schematic diagram for the proposed MLA system. In their initial state, the LC molecules are aligned vertically for substrates, and the LC layer has an ordinary refractive index. Because we matched ordinary refractive indices for the LC and polymer's layer, incident light is defocused.

In the nematic phase, LC molecules have a short-range order characterized by an order parameter, which is related to the angular distribution of the long axis of the molecules about the director. The order parameter of NLCs decreases with increasing temperature and goes to zero in the isotropic phase of the LC [8]. Since birefringence is a function of the order parameter, there is no optical anisotropy in the isotropic phase of LCs [9]. When an electric field is applied to the electric heating layers, the temperature of the LC layer is increased. Above the phase transition temperature from the nematic to isotopic phase, the LC layer has an averaged refractive index (n_a) of the extraordinary (n_e) and ordinary (n_o) refractive indices of the NLCs, which can be calculated as follows [10]:

$$n_a = (n_e + 2n_o)/3. \tag{1}$$

Because that refractive index of the LC layer is higher than that of the polymer for the lens structure, incident light from any direction is focused.

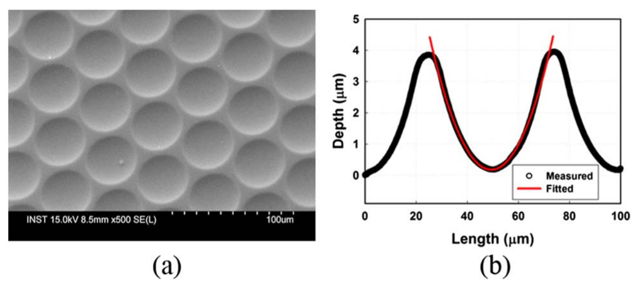
3. Experiments and Results

For the surface relief structure, we used the micro-transfer molding method. First, the master substrate was prepared with an array of concave-shaped surface structures made of glass. The diameter and pitch were 48 and 50 μm, respectively. Liquid poly-dimethylsiloxane (PDMS) was deposited to cover the master substrate glass. The PDMS structure produced by the patterned master structure can be effectively transferred to the covered bare glass substrate by heating under pressure. By peeling off the master substrate, the bottom substrate with convex-shaped PDMS structures was prepared. Since PDMS provides a very low interfacial free energy and good chemical stability, the master substrate can be easily detached without degradation of the microstructure on both substrates. We prepared another glass substrate coated with a UV-curable polymer (NOA65, Norland). The prepared PDMS mold was covered and pressed onto the UV-curable polymer substrate. After UV exposure, the PDMS substrate was detached, and, as a result, am MLA with the same structure as the master mold was obtained. Next the polymer was exposed to UV light for full polymerization.

To promote vertical alignment, we spin-coated the vertical-alignment material (AL60702, JSR) without a rubbing process. For the electric heating layer, indium-tin oxide (ITO) was patterned on the other glass substrate. The electrode has a line shape, and all are connected with one line. Since the created ITO layer has high resistivity, the layer could easily heat when we connected the electrode to the power supply.

Vertical-alignment material was also coated on the patterned electrode surface without a rubbing process. The cell thickness was maintained using glass spacers of 15 μm, which were filled with LC material (5CB, Merck) by capillary action at the isotropic phase temperature.

Figures 2(a) and 2(b) show an SEM image and surface profile of the fabricated MLA on the glass substrate, respectively. The MLA structures were hexagonal, which is good for high light efficiency. The measured depth and diameter of each microlens were 4 and 48 μm, respectively, as shown in Figs. 2(a) and 2(b). The transferred MLA structure was almost the same as the master concave-shaped structure. The calculated radius of curvature of the lens (R) using the spherical model was about 70.5 μm. Because



(a) (b)

Fig. 2. SEM image and surface profile of an MLA structure.

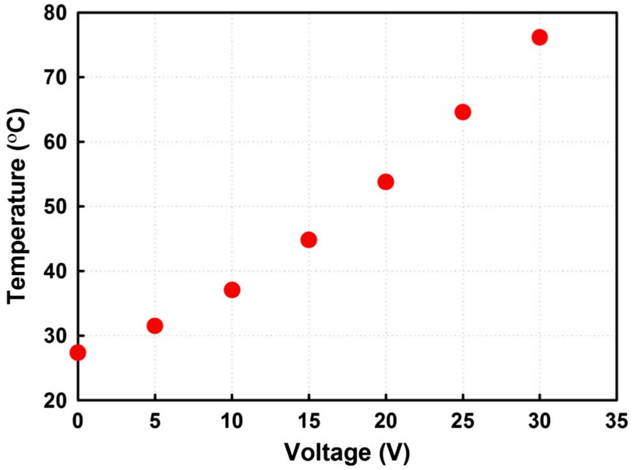


Fig. 3. Temperature characteristics as a function of applied voltage.

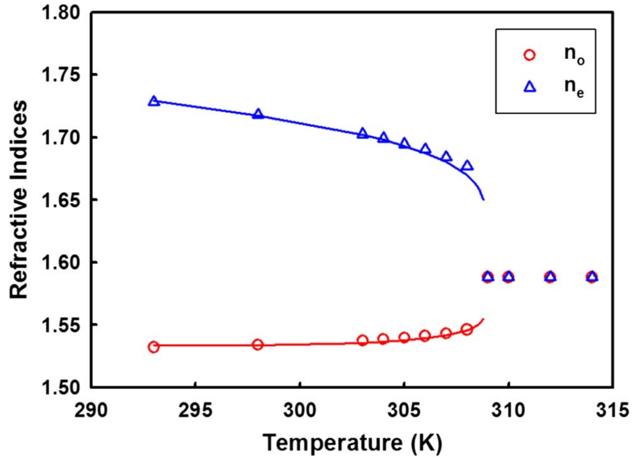


Fig. 4. Temperature-dependent refractive indices of 5CB LC at a wavelength of 589 nm. Triangles and circles represent experimental data, and solid lines were fit using the Wu model.

we used a spherical-shaped lens, the aberration could be generated. If we make the hyperbolic lens, the aberration could be decreased.

Figure 3 shows the experimental characteristics of temperature as a function of applied voltage. The temperature was controlled by the voltage and current of the power supply. Power consumption for heating the isotropic phase of 5CB was about 0.5 W for a 1 cm × 1 cm area. As the applied voltage was increase, the temperature was increased.

According to Wu's model [8,11], the temperature-dependent refractive indices of an LC can be described by

$$n_e \approx a - bT + (2/3)\Delta n(0)(1 - T/T_c)^{\beta}, \qquad (2)$$

$$n_0 \approx a - bT - (1/3)\Delta n(0)(1 - T/T_c)^{\beta}, \qquad (3)$$

where T_c and $\Delta n(0) = n_e(0) - n_o(0)$ are the clearing temperature and birefringence of the LC at $T = 0$ K, respectively, β is a material constant, and a and b are fitting parameters for the temperature-dependent refractive indices. The phase transition temperature from nematic to isotropic phase of 5CB was 36°C. The temperature-dependent refractive indices of the LC would be the same at the clearing temperature, i.e., the birefringence of the LC would be zero above the clearing temperature. Figure 4 shows the measured refractive indices with respect to temperature. The refractive indices were measured using Abbe refractometers. Open circles and triangles represent experimental refractive indices for 5CB. The lines in Fig. 4 were fit using the Wu model of Eqs. (2) and (3). When $a = 1.833$, $b = 7.98 \times 10^{-3}$ (K^{-1}), $\Delta n(0) = 0.3178$, and $\beta = 0.1644$, the experimental data for 5CB agree well with the Wu model.

Optical modulation of the MLAs could be obtained by changing the refractive indices of the LCs. Figures 5(a) and 5(b) show microscopic images of focused beam patterns generated by the MLAs at 28°C and 45°C, respectively. For measuring, we used the white light source. As mentioned in the above section, in the nematic state (28°C), incident light is unfocused because the effective refractive indices of the LCs ($n_o = 1.532$) and the UV-curable polymer ($n_p = 1.524$) were almost same. As a result, incident light passed through the MLAs and LC layers without a change of light status, and the light diverged, as shown in Fig. 5(a). In the isotropic state (45°C), the LC layer has an averaged refractive index ($n_a = 1.589$), which is larger than that of the polymer. As a result, the incident light was focused at the focal plane, as shown in Fig. 5(b). Figure 5(c) shows the spatial light intensity profile of the proposed MLAs at the focal plane, with changing temperature. At the center of the microlens, the beam profile is formed as a Gaussian function at 45°C.

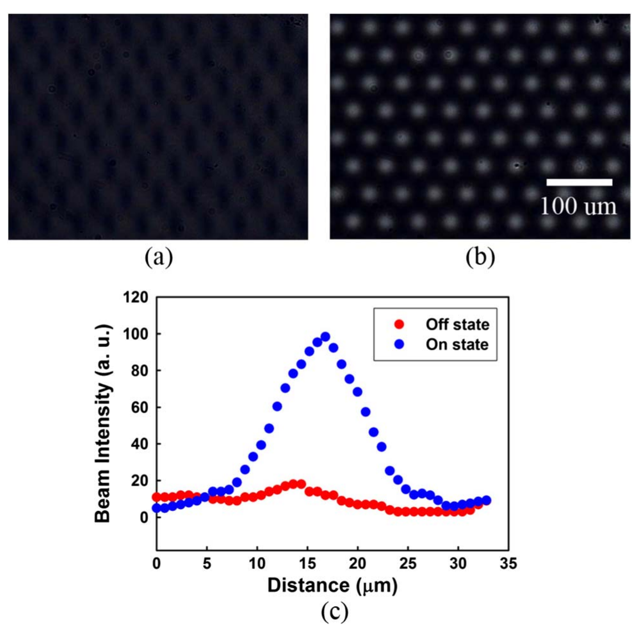


Fig. 5. Microscopic images of focused beam patterns at (a) 28°C and (b) 45°C. (c) Spatial light intensity profiles at the focal plane.

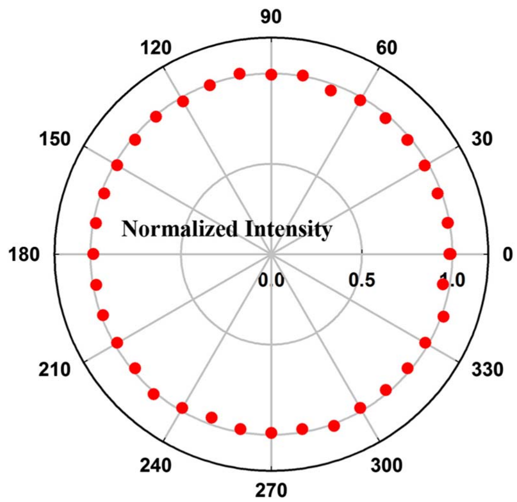


Fig. 6. Normalized beam intensity of the proposed MLA at the focal point as a function of the polarization state of incident light.

The focal length, f, of the microlens can be calculated from

$$f = R/(n_{\mathrm{lc}} - n_p), \tag{4}$$

where n_{lc} is the refractive index of the LCs, and n_p is the refractive index of the UV-curable polymer for the lens structure. At nematic phase temperatures, the focal length was almost infinite. At isotropic phase temperatures, the measured focal length of the MLA was 1.0 mm, which is in good agreement with the calculated value of 1.08 mm. Because we used a hexagonal array lens, light efficiency was high (about 78%).

Figure 6 shows the focusing intensity of the proposed MLAs, which is independent of the polarization state of the incident light at the focal plane ($f = 1.08$ mm), which is determined at 45°C. The linearly polarized incident light was rotated counterclockwise from 0° to 360° with the rotation angle represented by the angle θ. The beam intensity at 0° was normalized, and other intensities at the other angle of the polarizer were compared with the intensity at 0°. The beam intensities were almost the same for any angle, and it was found that our MLAs have polarization-independent characteristics. Additionally, the focal length of the microlens could be manipulated by temperature.

4. Conclusion

In this paper, we report on optically isotropic MLAs by controlling the refractive indices of LCs using temperature-control methods. The temperature was controlled by Joule heating with transparent electrodes. Since LC molecules were aligned vertically in the initial state, they only have a refractive index of LC for incident light. With the application of an electric field, the LC layer changed to the isotropic state with an averaged refractive index. With index matching between the LC layer and polymer, the MLA exhibited the switching characteristics. Because the proposed MLAs are switched from homeotropic alignment to an isotropic state, they show polarization-independent characteristics. As a result, our MLAs show truly optically isotropic properties over the entire switched state.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MEST) (2012R1A2A2A01046967) and by the Fundamental R&D Program for Core Technology of Materials funded by the Ministry of Knowledge Economy (10040035).

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