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Optically isotropic microlens arrays using nanoencapsulated liquid crystals

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ABSTRACT

We propose an optically isotropic switchable microlens array (MLA) based on nanoencapsulated liquid crystals (LCs). In its initial state, the encapsulated LC layer has an refractive index intermediate to that of the LC and capsule shell polymer even if the LC molecules' structure has any alignment, because the nanocapsules are much smaller than the wavelengths of the incident visible light. Applying a voltage causes the LC molecules to align vertically within the LC capsules, changing their refractive index from that of the initial state. The MLA can be designed to have switching characteristics by means of index matching between the encapsulated LC layer and the polymer lens structure. The proposed switchable MLA shows high light efficiency and true optical isotropy.

KEYWORDS

Polarization independence; microlens array; nanocapsule; liquid crystals

1. Introduction

Liquid crystal devices (LCD) have been widely used in various photonic systems such as optical switches, data storage devices, and light modulators, in addition to their well-known use in flat panel displays. Among these uses, microlens arrays (MLAs) based on LCs play an important role in 2D/3D switchable displays and tunable photonic devices because of their tunable focusing properties [1–5]. However, in most LC MLAs, the intrinsic optical anisotropy of the LCs makes the optical characteristics of the resulting devices dependent upon the polarization of the incident light. Polarization dependency causes only half of the light to be involved in focusing, meaning that light efficiency cannot exceed 50%.

To overcome these problems, orthogonally aligned LC Fresnel lenses [4–6] and vertically aligned (VA) LCs [7] have been proposed to increase the light efficiency by exploiting their polarization-independent properties. However, such lenses require extremely precise alignment and/or complicated fabrication processes. In addition, upon switching of the electric field, MLAs based on LCs are switched from an optically isotropic state to an optically anisotropic, birefringent state. When LC molecules are aligned vertically, they have no birefringent property in the direction of the incident light. In this state, the LC layer shows optical isotropy. When an electric field is applied, however, the LC molecules lay down on the

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substrate. In this state, the LC layer assumes a planar alignment on the surface and the MLA will thus show polarization-dependent properties. To ensure optical isotropy in this state, some researchers have designed LC molecules that are aligned omnidirectionally within one lens. However, because the lenses are larger than the wavelengths of the incident light, such LC layers show birefringence and polarization-dependent properties, imposing a limit on light efficiency about the same as that for the simpler polarization-dependent lenses.

In our previous work, we proposed an optically isotropic MLA based on LCs, in which the refractive indices of the LC layers are controlled by Joule heating [8]. To increase the temperature, we used transparent electric-heating layers. Because that MLA is switched from homeotropic alignment to an isotropic state, it showed optical isotropy over the entire switch state. However, precise temperature control is difficult because the ambient temperature.

In this paper, we propose a truly optically isotropic MLA using nanoencapsulated LCs with radii much smaller than the wavelengths of the incident visible light. This MLA's focusing properties can be controlled by the application of an electric field. Because the alignment of the LC molecules switches from an isotropic to a homeotropic state, the MLA shows polarization-independent properties through its entire switching state.

2. Operation principle

Figure 1 shows the operating principle of the proposed MLA. In the initial state with no electric field, the director field of the LC molecules within the capsules is bipolar because the polymer encircling the LC droplets has a planar alignment property. However, because the size of the LC capsule is smaller than the wavelength of the incident visible light, the LC droplets show optical isotropy. This principle works with other alignments of LC molecules such as in toroidal, radial, and axial droplets. The LC within a capsule has a refractive index (n_a) intermediate to that of the extraordinary (n_e) and ordinary (n_o) refractive indices, which can be calculated as follows:

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

Further, the refractive index ($n_{capsule}$) of the nanoencapsulated LC is the average value of the refractive indices between the polymer (n_{pva}) and the averaged value of LCs (n_a). Because we designed the refractive index of the nanoencapsulated LC layer ($n_{capsule}$) to be greater than that of the lens structure polymer (n_p), the resulting lenses can focus incident light from any direction. When a strong electric field is applied, the director of LC molecules that have positive dielectric anisotropy follows the electric field direction, yielding homeotropic alignment. When the LC molecules are homeotropically aligned, the effective refractive index of the LC molecules is almost the same as the ordinary refractive index. As a result, the refractive index

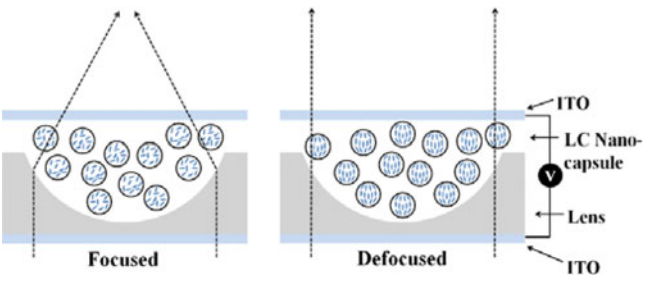


Figure 1. Operating principle for the proposed isotropic MLA.

of nanoencapsulated LCs under an electric field is smaller than ncapsule, and is almost the same as n_p. Thus, the incident light is defocused.

3. Experiments

We used a conventional coacervation method for LC nanoencapsulation [9]. A nematic host LC (HTW-106700, $n_e = 1.745$ and $n_o = 1.504$, Jiangsu Hecheng Display Technology Co.) was added to a mixture of nonionic polymer surfactants (polyethylene oxide–polypropylene oxide–polyethylene oxide block copolymers, Pluronic, BASF) and emulsifier (partially hydrolyzed polyvinyl alcohol, Aldrich) dissolved in aqueous solution, where the polymeric surfactant and emulsifier respectively played the important roles of reducing surface tension and forming a shell material around the LC droplet. The resulting immiscible mixture was homogenized at room temperature using a magnetic stirring system, resulting in the formation of oil-in-water (O/W) nanoemulsions. Then, the mixture was heated up to the cloud point (about 50°C) and kept at that temperature for several hours while being stirred, thereby allowing the PVA to become phase-separated around the nanoscale LC droplets and thus to form a thin polymeric shell surrounding each droplet. The resulting nanoscale LC droplets encircled with thin polymeric membranes in the nanoemulsions were chemically crosslinked by the addition of crosslinking agents (glutaraldehyde, Sigma-Aldrich) to ensure that they were sufficiently strong to withstand external forces.

To fabricate the surface relief structure, we used a microtransfer molding method. First, the master substrate was prepared with an array of convex surface structures using an electrohydrodynamic patterning method [10]. The convex structures were transferred to polydimethylsiloxane (PDMS, Sigma-Aldrich), yielding a concave structure (Fig. 2(a)). Then, a convex mold structure was fabricated to allow the preparation of a concave MLA. For this, we coated an aluminum layer of 20 nm thickness onto the concave MLA mold, and then transferred again with PDMS (Fig. 2(b)). To make lens structures, we stamped UV-curable polymer (NOA65, Norland) onto an indium tin oxide (ITO)-sputtered glass substrate with the PDMS mold (Fig. 2(c)). After UV exposure, we removed the PDMS mold, yielding a concave MLA polymer lens structure on the substrate. After the lens structure was formed, we coated it with the LC nanocapsule solution using a bar coating method (Fig. 2(d)). Next, we dried the solvent

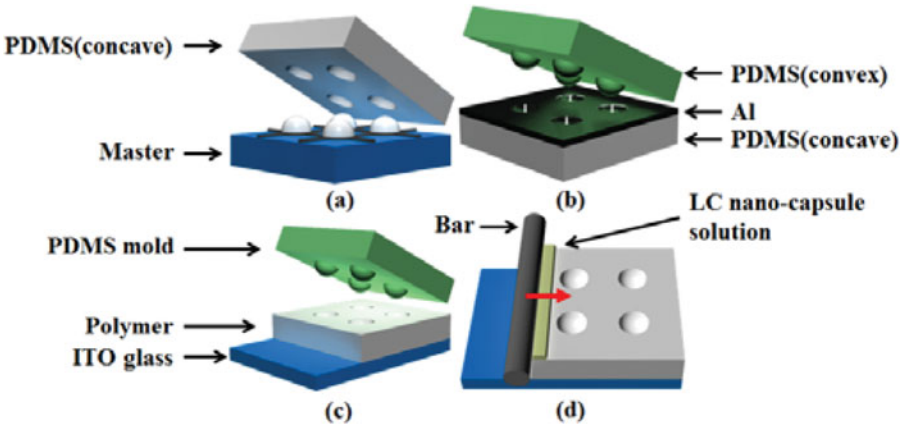
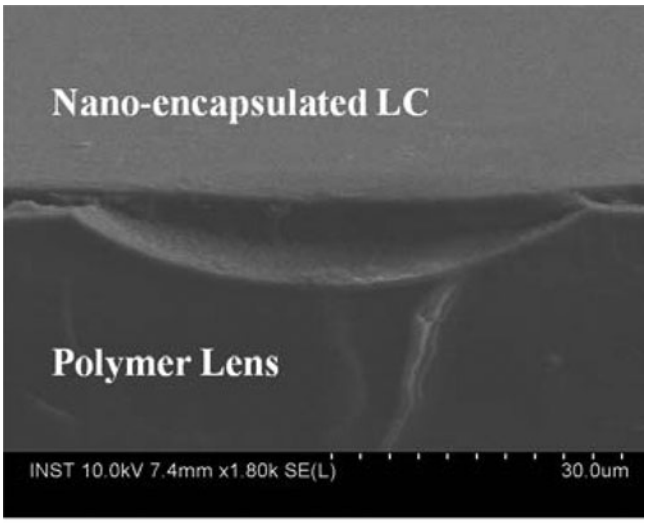


Figure 2. Schematic diagram of fabrication procedure. (a) Transferring master substrate to PDMS. (b) Transferring concave PDMS with aluminum layer to convex PDMS. (c) Stamping LCP lens structure on an ITO glass substrate with PDMS mold. (d) Bar coating LC nano-capsule solution on the LCP lens structure.

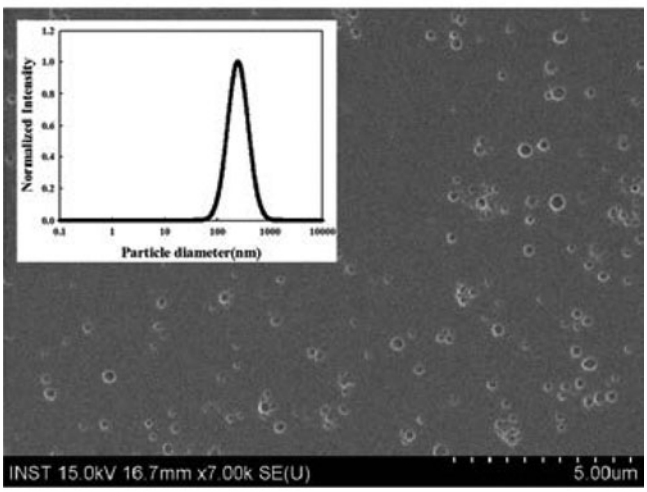
within the coated layer by heating at 65°C for 30 min on a hotplate. After that, the structure was covered with ITO glass as a top electrode.

4. Results and discussion

Figure 3(a) shows a cross-sectional SEM image of the fabricated MLA. The UV-curable polymer formed the lens structure, and the nanoencapsulated LC layer covered and flattened the surface. The measured depth and diameter of each microlens were 5.1 μm and 75 μm, respectively. From these, we calculated the radius of curvature of the lens (R) to be 91 μm by using a spherical model [11]. A surface SEM image showed that the LC capsules, which were visible



(a)



(b)

Figure 3. (a) Cross section SEM image of microlens structure. (b) SEM image of LC nanocapsules coated on the substrate. The inset graph is LC nanocapsule size distribution measured by dynamic light scattering method.

as circular holes, were randomly dispersed in the polymeric bonding matrix (Fig. 3b). The largest hole observed was estimated to be about 300 nm in diameter or less. The size distribution of the LC nanocapsules was measured by means of a dynamic light scattering method (DLS). The maximum peak intensity was observed at 245 nm, half the size of the shortest wavelength of visible light (Fig. 3b inset). This extremely small size of the LC nanocapsules and the random distribution of LC molecules inside each capsule made the capsules optically isotropic on average.

The MLAs could be optically modulated by applying an electric field to change the refractive indices of the LCs. Figure 4 shows microscopic images of focused beam patterns generated by the MLAs with and without an electric field. For measuring, we used a white light source. In the initial state, because the effective refractive index of the encapsulated LC layer ($n_{capsule} = 1.576$) with no electric field was larger than that of MLA polymer structure

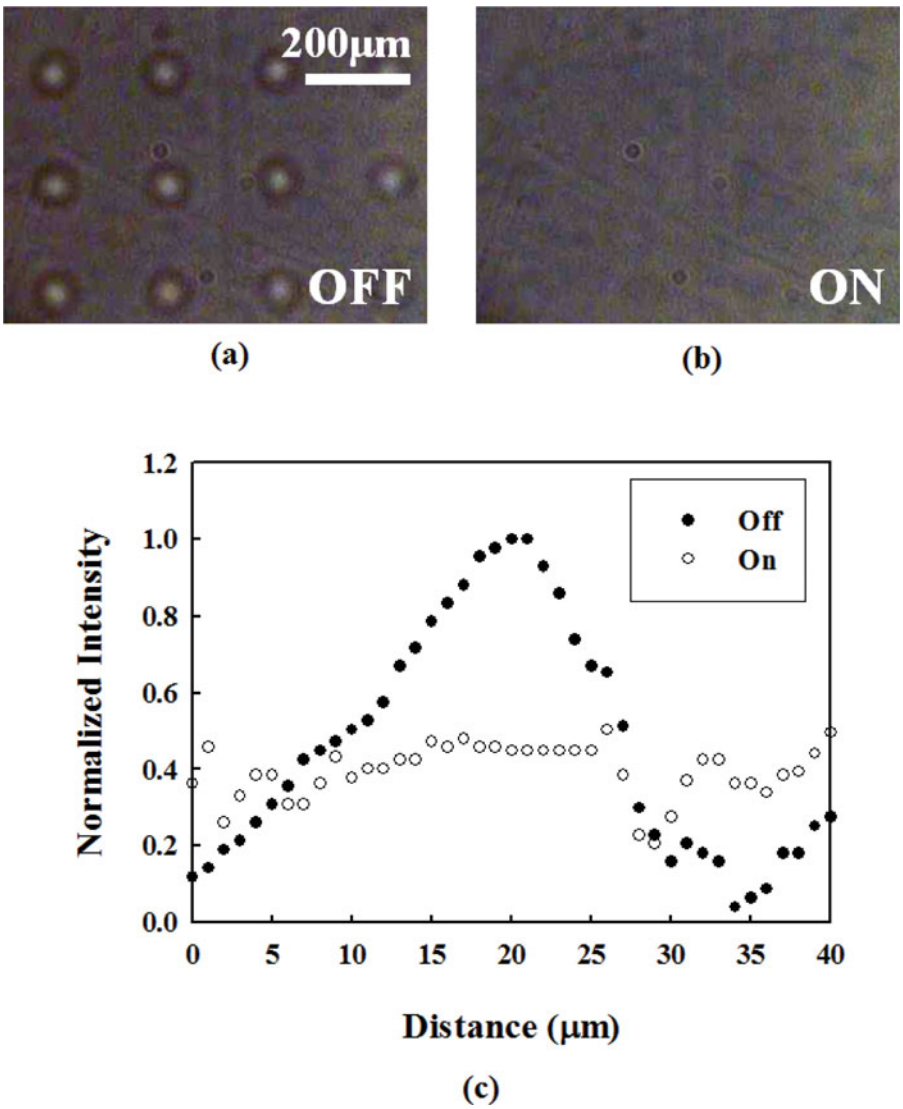


Figure 4. Microscopic images of (a) focused beam pattern without applied electric field, and (b) with applied electric field. (c) Spatial light intensity profiles.

($n_p = 1.524$), incident light passed through the MLA and was focused by the encapsulated LC layer (Fig. 4a). The focal length (f) of the microlens can be calculated from

$$f = \frac{R}{(n_{capsule} - n_p)}. \tag{2}$$

The calculated and measured focal lengths without an applied electric field were 1.7 mm and 1.5 mm, respectively. The discrepancy between these two focal lengths arose because of spherical aberration due to the spherical lens structure. If we made a hyperbolic lens structure, the aberration would be decreased. When an electric field is applied, the LC director reorients to become parallel to the direction of the electric field, corresponding to homeotropic alignment of the LC molecules. Because the effective refractive index of the encapsulated LCs is the same as the ordinary refractive index of the LCs ($n_o = 1.504$), the effective refractive index of encapsulated LC layer changes to 1.534. This is similar to the refractive index of the lens polymer (n_p), and thus incident light passing through MLA and encapsulated LC layer is defocused (Fig. 4b). Spatial light intensity profiles of the proposed MLAs at the focal plane ($f = 1.5\ mm$) were collected both with and without applied electric field; at the center of the microlens, the beam profile formed as a Gaussian function (Fig. 4c).

The focusing intensity of the proposed MLAs was independent of the polarization state of the incident light at the focal plane ($f = 1.08\ mm$) without an applied electric field (Fig. 5). The polarization direction of linearly polarized incident light was rotated counterclockwise from 0° to 360°; the rotation angle is represented as θ in the figure. The beam intensity at 0° was normalized, and other angle beam intensities were compared to the intensity at 0°. The beam intensities were almost the same for all rotation angles, showing that the proposed MLAs had polarization-independent characteristics. In addition, the focal length of the MLAs could be controlled continuously by the applied electric field.

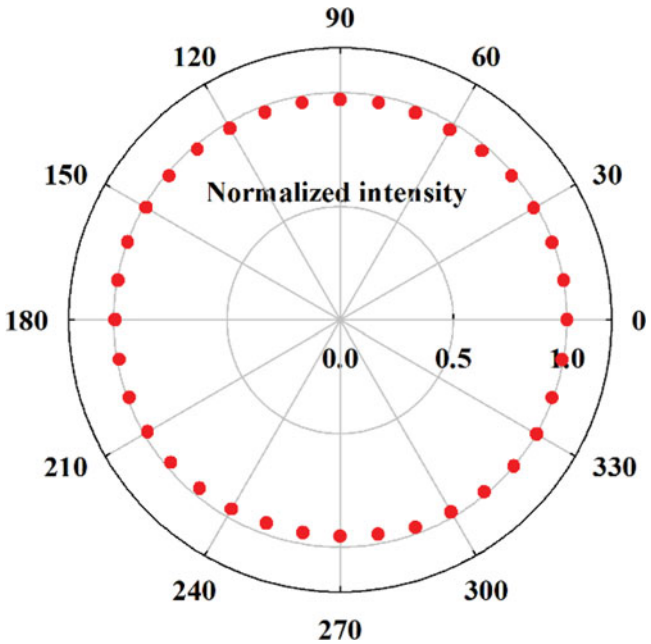


Figure 5. Normalized intensity of the proposed MLA at the focal point as a function of the polarization state of incident light.

5. Conclusions

In this work, we proposed an optically isotropic microlens array with tunable focal length, based on the use of nanoencapsulated LCs. Because the LC capsules are much smaller than the wavelengths of the incident visible light, the encapsulated LC layer is optically isotropic. In the initial state, the refractive index of the encapsulated LC layer is greater than that of the polymer lens structure, allowing the incident light to be focused. Under application of an electric field, the LC molecules become vertically aligned and the refractive index of the encapsulated LC layer becomes smaller than that of the polymer lens structure, and the incident light is defocused. For all LC states, because the encapsulated LC layer is optically anisotropic, the proposed MLA has truly polarization-independent characteristics over the entire switching state.

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