Switchable reflective lens based on cholesteric liquid crystal

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Abstract: We demonstrated a switchable reflective lens based on choleteric liquid crystal (CLC) with a plano-convex shape. The plano-convex CLC lens was fabricated by assembling a planar substrate and a concave substrate. The reflective CLC lens exhibits wavelength selectivity and handedness sensitivity like the conventional CLC cell. The plano-convex CLC lens acts as a biconvex lens with the same curvature due to the Bragg reflection of the CLC layer. In addition, the reflective CLC lens was defocused by applying external voltage.

OCIS codes: (230.3720) Liquid-crystal devices; (220.3630) Lenses

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1. Introduction

Switchable microlens arrays based on liquid crystals (LCs) play an important role in various optical systems such as optical communications, optical information processing systems, and three-dimensional display systems since their focal length is reconfigurable [1–8]. LC microlens arrays have been fabricated by introducing surface modulations [1–5] and/or electric field modulations [6–8] to produce variation of the effective refractive index. All the switchable LC microlens arrays were demonstrated as transmissive lenses. Although the reflective lens is useful in reflective block optics for packaging an optical computing system [9], a switchable reflective LC lens has yet to be reported except for a tunable reflective lens based on LC on silicon (LCoS) [10]. In the LCoS-based reflective lens, the lens properties were obtained by precisely controlling the electric field for individual pixels, and thus the lens performance is limited by the resolution of the LCoS [10].

In this work, we demonstrate a switchable reflective lens based on choleteric liquid crystal (CLC). The reflective CLC lens was fabricated by assembling the planar substrate and the concave polymer substrate and filling the CLC into the sandwiched substrates. As a result, a plano-convex lens was obtained for the CLC with a larger refractive index than the polymer layer. Here, the concave polymer surface was replicated from the convex master. The plano-convex CLC lens acted as a biconvex lens with the same curvature since the CLC layer worked as a wavelength-selective mirror. The wavelength and handedness of the reflective focused beam coincided with the helical pitch and sense of the CLC, respectively. Also, by applying an external voltage, the reflective CLC lens was defocused. Our switchable reflective lens is expected to be applicable for packaging optical systems [9].

2. Operating principle

Figure 1 shows the operating principle of the switchable reflective lens of the CLC in the shape of a plano-convex lens. The switchable reflective lens is fabricated with a surface relief structure and a planar texture of the CLC. In the planar texture of the CLC, an incident light is reflected to a circularly polarized light whose wavelength and handedness coincide with the helical pitch and the chirality of the CLC, respectively [11]. The incident light into the CLC layer from the lens surface is refracted at the interface between the lens surface and the CLC and reflected from the planar texture of the CLC with wavelength selectivity. Finally, the reflected light is refracted again at the interface between the CLC and the lens surface. Also, the reflected and focused beam shows the same handedness of the circular polarization as the chirality of the CLC, as shown in Fig. 1(a). It should be noted that the reflected color corresponding to the helical pitch of the CLC can be controlled by the concentration of the chiral agent and/or the temperature of the system.

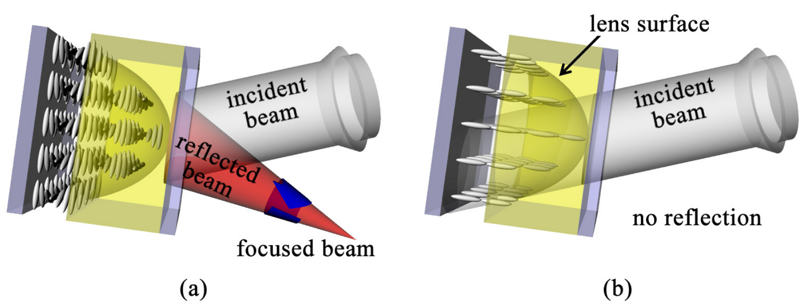

Fig. 1. Operating principle of the switchable reflective lens of the CLC. (a) reflected beam with circular polarization coinciding with the helix of the CLC is focused in the planar alignment of the CLC. (b) No reflection occurs at the homeotropic alignment under an applied voltage.

When an electric field is applied to the CLC cell, the planar texture of the CLC with positive dielectric anisotropy is changed into a homeotropic alignment as shown in Fig. 1(b). In such a situation, the incident light passes through the CLC layer without wavelength-selective reflection. In particular, if the ordinary refractive index of the CLC coincides with the refractive index of the surface relief, the incident light passes the CLC lens devices without focusing, as shown in Fig. 1(b). As a result, a switchable reflective lens uses the plano-convex lens configuration based on the CLC.

3. Experiments

Figure 2 shows a schematic diagram of the fabrication process of the switchable refractive lens based on the CLC. First, the concave lens surface was prepared by replication with a photocurable polymer (Norland NOA 65) from a polydimethysiloxane (PDMS) mold in the shape of a convex lens. The photocurable polymer was spin-coated on an indium-tin-oxide (ITO) glass and covered with the PDMS mold. The photocurable polymer was irradiated by ultraviolet (UV) light (Osram mercury lamp), and the PDMS mold was gently peeled off. The alignment layer (Nissan RN1199) was spin-coated on the ITO substrate with the concave lens surface to promote a planar alignment. The alignment layer was prebaked at 100 °C for 10 min and postbaked at 180 °C for 1 h. The other ITO substrate without surface relief was also spin-coated with the RN1199. Both substrates coated with the alignment layer were assembled after rubbing, and the CLC with positive dielectric anisotropy ($\Delta\varepsilon = 4.4$) was injected by capillary action in the isotropic phase of the CLC. The CLC was prepared by nematic LC (MLC-6422, Merck) with chiral dopant (R-811, Merck). The chiral dopant was mixed with 20 wt% for nematic LC, and the chiral pitch of the prepared CLC mixture was 485 nm. The ordinary and extraordinary refractive indices of the CLC and the refractive index of the NOA 65 were 1.509, 1.707, 1.524, respectively.

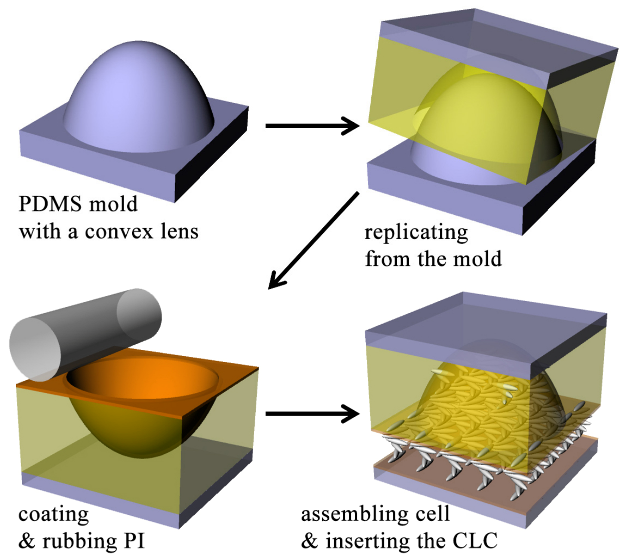

Fig. 2. Schematic diagram of the fabrication process of the reflective CLC lens.

The lens properties were characterized using a polarizing optical microscope (POM; Nikon E600W POL) with frame-grabbing (Samsung SDC-450). The lens surface of the assembled cell was faced to the incident light for observation of the reflective lens properties. All observations were carried out at room temperature. The morphology of the polymer lens surface was observed using a field-emissive scanning electron microscope (FESEM; Hitachi S-4800).

4. Results and discussion

Figure 3(a) shows a FESEM image of the polymer layer (concave) replicated from the PDMS mold (convex). The period and the maximum depth of the concave microlens array (replica) were measured to be 49.5 μm and 3.7 μm, respectively. The reflective CLC lens was observed with the POM under the reflective mode, as shown in Fig. 3(b). A uniform reflection color was observed around the center of the concave polymer lens, which represents the uniform planar texture of the CLC due to the small variation of the helical axes. The near edges of the lens and the variations of the color and reflectance originating from the large variation of the helical axes were observed. Such variation resulted from spatially steep variation of the normal direction to the substrate near the edges of the CLC lens. The wavelength selectivity

#207145 - $15.00 USD Received 25 Feb 2014; revised 31 Mar 2014; accepted 31 Mar 2014; published 7 Apr 2014

of the reflective CLC lens was investigated with the reflective spectra of the CLC lens and the conventional CLC cell, as shown in Fig. 3(c). For measuring, we used the circularly polarized light for an incident beam. The spectrum of the reflective CLC lens almost coincided with the intrinsic spectrum of the planar-aligned CLC cell except for the reflection intensity. A subtle change in the reflective spectrum of the CLC lens is expected to have originated from variation of the helical axes on the concave surface.

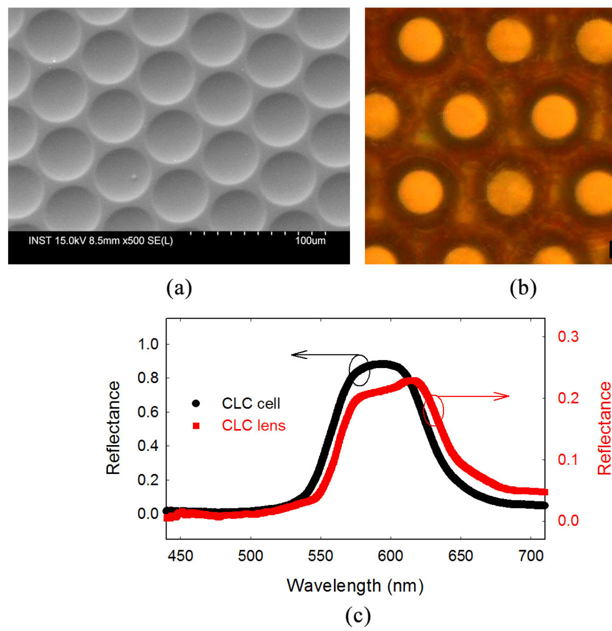

Fig. 3. (a) FESEM image of the replicated polymer substrate with the shape of a concave lens, (b) POM image of the reflective CLC lens, and (c) the reflective spectra of the CLC lens (red squares) and the conventional CLC cell (black circles).

Figure 4 shows the reflective images of the CLC lens array at the focal plane for various situations. In the planar texture of the CLC under no applied voltage, the average refractive index of the CLC layer (~1.575) is greater than that of NOA 65 (1.524), and thus the CLC lens acts as a convex lens, as shown in Fig. 4(a). The inset presents the intensity profile and the Gaussian curve fit corresponding to the white line in Fig. 4(a). The incident light experiences refractions twice during the incidence and reflection at the interface between the polymer lens surface and the CLC layer since the CLC layer acts as a wavelength-selective mirror. As a result, the reflective CLC lens works as a biconvex lens.

When the voltage was applied across the two ITO substrates, the CLC molecules with positive dielectric anisotropy rotated vertically to the substrates. In such a configuration, the effective index of refraction in the CLC layer was reduced to the ordinary refractive index of the CLC (1.509) and is similar or less than that of the lens surface. As a result, the reflected light is defocused, as shown in Fig. 4(b). The applied voltage for homeotropic alignment is so high (160 V) because of the thick polymer layer for lens structure. If we make an electrode layer on the polymer structure, the applied voltage could be reduced as conventional CLC cells.

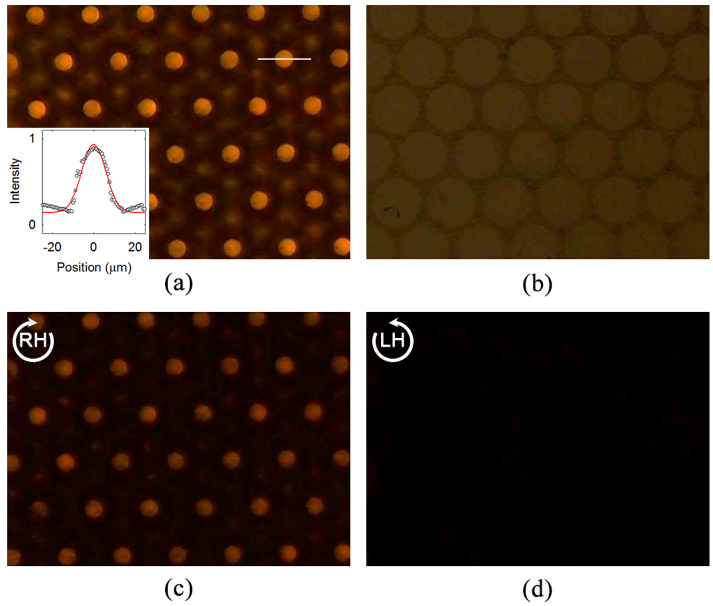

Fig. 4. The microscopic reflection images of the reflective CLC lens array at a focal plane under (a) no applied voltage (planar alignment) and (b) applied voltage (homeotropic alignment). The inset presents an intensity profile and a Gaussian curve fit corresponding to the white line in Fig. 4(a). In the planar alignment (no applied voltage), the microscopic reflection images under (c) the right- and (d) the left-handed circular polarizers.

The handedness of the reflected light was confirmed by introducing a circular polarizer in front of the image sensor. Figure 4(c) and 4(d) shows the focused reflection images under the right- and left-handed circular polarizers, respectively. Under the right-handed circular polarizer coinciding with a helical sense of the CLC, focused spots were observed, as shown in Fig. 4(c). Note that the intensity of the reflectance was reduced due to the intensity loss of the inserted circular polarizer. On the other hand, no reflection was observed under the left-handed circular polarizer, as shown in Fig. 4(d). As a result, the reflective CLC lens shows a switchable focusing effect with handedness sensitivity.

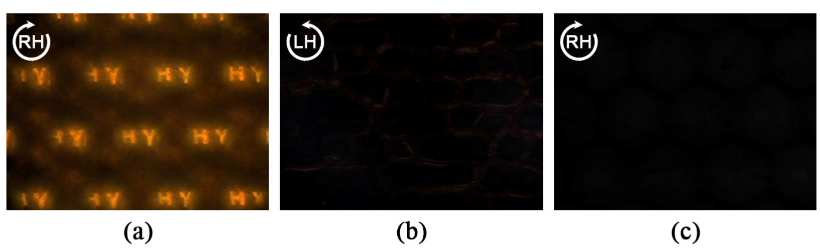

Fig. 5. The focusing images of the letters “HY” in the reflective switchable CLC lens under (a) right- and (b) left-handed circular polarizers in the planar alignment (no applied voltage), and (c) the right-handed circular polarizer in a homeotropic alignment.

We also investigated the lens properties of the reflective CLC lens with an object. Figure 5 shows the focusing images of the letters “HY” under various situations. We inserted the letters “HY” in front of a light source in the POM and observed the focusing images. In principle, a real image in a lens system is inverted. As shown in Fig. 5(a), erect images were observed under a right-handed circular polarizer in our lens system. This originates from the beam splitter for a reflection mode in the POM. In the same optical system, the image of “HY” disappeared replacing the right-handed circular polarizer with the left-handed one in

#207145 - $15.00 USD Received 25 Feb 2014; revised 31 Mar 2014; accepted 31 Mar 2014; published 7 Apr 2014

front of the image sensor, as shown in Fig. 5(b). Also, no image was observed even under the right-handed circular polarizer in the presence of an applied voltage since CLC molecules with positive dielectric anisotropy were homeotropically rotated, as shown in Fig. 5(c).

5. Conclusions

In summary, we demonstrated a switchable and reflective lens based on a plano-convex CLC lens. A sandwiched cell filled with CLC was fabricated by assembling a planar substrate and a concave polymer substrate. The reflective CLC lens exhibited wavelength selectivity and handedness sensitivity similar to a conventional CLC cell. The plano-convex CLC lens acted as a biconvex lens with the same curvature since the CLC layer worked as a wavelength-selective mirror. In addition, the reflective CLC lens was defocused by applying external voltage. Our switchable reflective lens is expected to be applicable to implementation in various optical systems and devices such as optical computing systems.

Acknowledgments

This work is supported by a National Research Foundation of Korea (NRF) grant (No. 20110016968) funded by the Ministry of Education, Science, and Technology of the Korean government (MEST).