Polarization-Selective Reflective Liquid Crystal Lens with Wavelength-Tunability

Hyunbae Park*, You-Jin Lee, Jae-Hoon Kim*** and Chang-Jae Yu*****
*Department of Electronic Engineering, Hanyang University, Seoul 133-791, Korea
** Department of Information Display Engineering, Hanyang University, Seoul 133-791, Korea

Abstract
We demonstrated a polarization-selective reflective lens with a wavelength-tunability based on a cholesteric liquid crystal (CLC). The reflective CLC lens in a plano-convex shape acts as a biconvex lens due to the Bragg reflection, and exhibits wavelength-tunability and polarization-selectivity like the conventional CLC cell.

Author Keywords
Liquid crystal lens; reflective lens; wavelength-tunability

1. Introduction
Switchable liquid crystal (LC) microlens arrays play an important role in various optical systems such as camera lens, smart glasses, optical information processing and three-dimensional display due to their focal length tunability [1-8]. Most switchable LC microlens arrays were demonstrated as transmissive lenses. Although the reflective lens based on LC on silicon was reported, 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 [9].

In this work, we demonstrated the polarization-selective reflective lens based on a cholesteric LC (CLC). The reflective LC lens was prepared by assembling a planar substrate and a concave substrate with planar alignment layer [9]. The plano-convex CLC lens acts as a biconvex lens with the same curvature due to the Bragg reflection of the CLC layer, and exhibits the wavelength-tunability originated from the temperature-dependent pitch variation of the CLC and the polarization-selectivity originated from the handedness of the CLC helix like the conventional CLC cell.

2. Operating Principle
Figure 1 shows the principle of the wavelength-tunable reflective lens of the CLC in the shape of a plano-convex lens. The wavelength-tunable 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. 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 Figure 1. The helical pitch of the CLC was sensitively affected by varying temperature. The helical pitch of the CLC is decreased with increasing temperature of CLC. Figure 1 shows that reflected and focused wavelength is blue shift with increasing temperature.

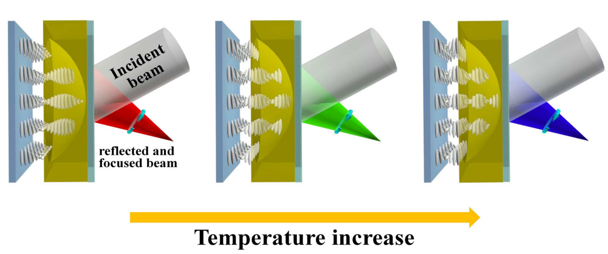

Figure 1 Operating principle of the wavelength-tunable reflective lens of the CLC.

3. Experiment
Figure 2 shows a schematic diagram of the fabrication process of the polarization-selective refractive CLC lens. 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 a substrate, covered with the PDMS mold, and irradiated by ultraviolet (UV) light. Finally the PDMS mold was gently peeled off. The alignment layer (Nissan RN1199) was spin-coated on the concave lens surface to promote a planar alignment. The other substrate without surface relief was also spin-coated with the RN1199. Both substrates were assembled after rubbing, and the CLC was injected by capillary action in the isotropic phase of the CLC. The CLC was prepared by nematic LC (E7, Merck) with chiral dopant (R-811, Merck). The chiral dopant was mixed with 30 wt% for nematic LC. From an image of the concave lens surface by field-emissive scanning electron microscope (FESEM; Hitachi S-4800), the depth and diameter of the lens are 3.7 μm and 49.5 μm, respectively.

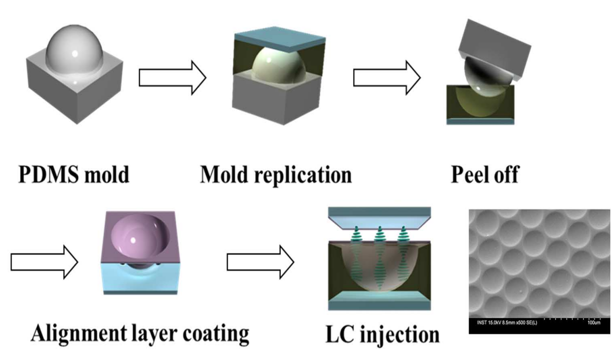

Figure 2. The schematic diagrams of cell fabrication and FESEM image.

 ISSN 0097-966X/16/4702-0696-$1.00

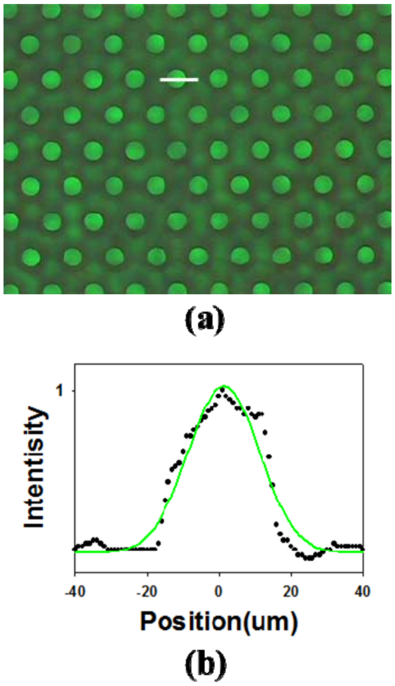

Figure 3. (a) Texture of ChLC lens and (b) intensity profile. The thin solid line is Gaussian fitting line.

4. Result and Discussion

The lens properties were observed by using polarized optical microscopy (POM; Nikon E600W POL). Figure 3 (a) shows the reflected texture of the CLC lens. Here, the average refractive index of the CLC layer is about 1.575 which is greater than that of NOA 65 (1.524), therefore light reflected by the CLC is focused. The intensity of the focused light was measured by pixel data and fitted with Gaussian curve which shows that CLC layer acts as a convex lens. It should be noted that the plano-convex CLC lens acts as a biconvex lens since the light traveling through the CLC layer is twice.

Figure 4 shows the images under right-handed circular polarizer and left-handed circular polarizer at different substrate temperature. Temperature was controlled by a microfurnace (FP900, Mettler Toledo). With increasing temperature of the substrate, the pitch of the CLC gradually decreases. Due to the handedness of chiral dopant only right-handed circularly polarized light is reflected and focused. On the other hand left-handed circularly polarized light is neither reflected nor focused.

We also investigated the lens properties of the reflective CLC lens with an object. Figure 5 shows the clear focusing images of the letters "HY" under various temperatures. We inserted the letters "HY" in front of a light source in the POM and observed the focusing images under the right-handed circular polarizer.

5. Conclusion

We proposed a polarization-selective reflective lens with the wavelength-tunability and the polarization-selectivity in a plano-convex CLC lens. The convex lens was fabricated by the replication of the PDMS mold by phtocurable polymer. The plano-convex CLC lens acted as a biconvex lens with the same curvature since the CLC layer worked as a wavelength-selective mirror depending on temperature. In addition, the reflective CLC lens was defocused by applying external voltage. Our polarization-selective reflective lens is expected to be applicable to implementation in various optical systems and devices.

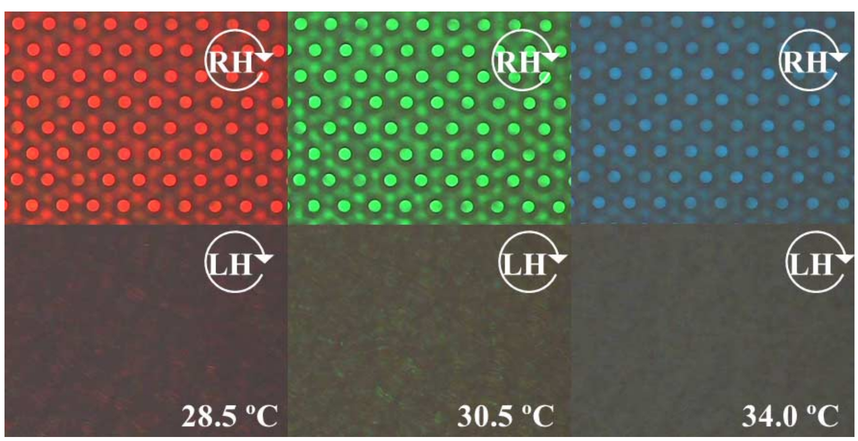

Figure 4. Reflection image under right- and left-handed circular polarizer.

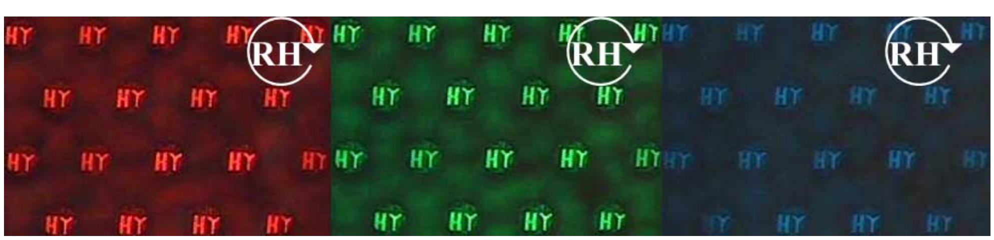

Figure 5. Images focused on the letter 'HY' under right handed circular polarizer.

6. Acknowledgements
This research was supported by the ICT R&D program of MSIP/IITP (10041416, The core technology development of light and space adaptable energy-saving I/O platform for future advertising service) and LG Display Co., Ltd.

7. References
[1] G. Li, D.L. Mathine, P. Valley, P. Ayras, J.N. Haddock, M.S. Giridhar, G. Williby, J. Schwiegerling, G.R. Meredith, B. Kippelen, S. Honkanen, N. Peyghambarian, "Switchable electro-optic diffractive lens with high efficiency for ophthalmic applications," Proc. Natl. Acad. Sci. U.S.A. 103(16), 6100–6104 (2006).

[2] D.M. Levi, S.A. Klein, I.N. Chen, "What is the signal in noise?" Vision Research 45, 1835-1846 (2005).

[3] S. Sato, "Liquid-crystal lens-cells with variable focal length", Jpn. J. Appl. Phys. 18, 1679 (1979).

[4] Y. Choi, J.-H. Park, J.-H. Kim, and S.-D. Lee, "Fabrication of a focal length variable microlens array based on a nematic liquid crystal" Opt. Mater. 21, 643 (2003).

[5] J.-H. Kim and S. Kumar, "Fabrication of electrically controllable microlens array using liquid crystals" J. Lightwave Technol. 23, 628 (2005).

[6] M. Ye, Y. Yokoyama, S. Sato, "Liquid crystal lens prepared utilizing patterned molecular orientations on cell walls" Appl. Phys. Lett. 89, 141112 (2006).

[7] Y. Choi, H.-R. Kim, K.-H. Lee, Y.-M. Lee, and J.-H. Kim, "A liquid crystalline polymer microlens array with tunable focal intensity by the polarization control of a liquid crystal layer" App. Phys. Lett. 91, 221113 (2007).

[8] N. A. Riza and M. C. DeJule, "Three-terminal adaptive nematic liquid-crystal lens device" Opt. Lett. 19, 1013 (1994).

[9] H. Ren, Y.-H. Fan, S. Gauza, and S.-T. Wu, "Tunable reflective lens array based on liquid crystal on silicon" Appl. Phys. Lett. 84, 4789 (2004).

[10] X. Wang, H. Dai, and K. Xu, "Tunable reflective lens array based on liquid crystal on silicon" Opt. Express 13, 352 (2005).

[11] J.-H. Lee, J.-H. Beak, Y. Kim, Y.-J. Lee, J.-H. Kim, and C.-J. Yu, "Switchable reflective lens based on cholesteric liquid crystal" Opt. Express 22, 9081 (2014).