Polarization Dependent Switchable Micro-lenticular Lens Arrays using Optically Isotropic Liquid Crystals

Srinivas Pagidi, Ramesh Manda, Junhyuk Lee, Sung Guk Lee, Seong Min Song, and Seung Hee Lee*

Applied Materials Institute for BIN Convergence, Department of BIN Convergence Technology and Department of Polymer-Nano Science and Technology, Chonbuk National University, Jeonju, Jeonbuk 561-756, Republic of Korea

Abstract

We propose polarization-dependent micro-lenticular lens arrays (MLAs) based on optical phase modulation by reorientation of nano-sized LC droplets of the optically isotropic liquid crystals (OILC). On applying gradient in-plane field, the gradient refractive index is generated between the electrodes, giving rise to the MLAs with the focal length of 22 μm at 50 V_{rms} and switching time of few ms. The OILC can also be applied to switchable microlens. The proposed device has a potential to be applicable to 2D/3D switchable optical lens.

Author Keywords

Micro-lenticular arrays; optically isotropic liquid crystal; 3D image; polarization-dependent

1. Introduction

Since a few decades, adoptive lenticular lenses using liquid crystals (LCs) achieved much popularity in developing in various applications such as displays, imaging, biometrics, and beam steering. The 2-dimensional (2D) and 3-dimensional (3D) switchable displays utilizing LC parallax barriers [1,2] or lenticular lens arrays [3,4] are more indeed in achieving the 3D visual effects without the need of the 3D glasses. The lenticular lenses are particularly of interest in this area owing to less sacrifice of brightness. However, in the conventional LC modes using for lenticular lenses required a higher cell gap for achieving periodic phase modulation, which leads to a few inevitable internal aberrations causing poor performances including slow response time and high sensitivity to incident polarization. In addition, the conventional LC modes cannot resist the external pressure and show a distortion in the LC orientation so that the image becomes blurred when the externally applied force is stronger.

To overcome the aforementioned drawbacks, a binary composite of LC and pre-polymer for optically isotropic liquid crystal (OILC) phase has been introduced. The OILC phase achieved from nano-phase separated LC exhibits a high transparency and very fast response time which is essential requirement for developing the switchable lenticular lenses. Additionally, the OILC also retains a great advantage of easy processing and, remarkably resistance to external mechanical forces that is feasible for emerging technologies such as bendable and flexible devices [5-7]. Besides, for eliminating the feeble light scattering, smaller size LC droplets than the wavelength of visible light is highly desirable. Most recently, the feeble light scattering was eliminated by utilizing the twisted LC behavior inside the droplet [8] and various pre-polymers [9]. In addition, we also achieved reduced driving voltages by incorporating conductive materials into the OILC system [10]. Considering these advantages, few photonic devices includes polarization independent tunable microlens [11-13] and diffraction gratings [14,15] were developed. When compared to the conventional LC modes, the OILC is the potential candidate for developing the 2D/3D display and photonic devices.

In this paper, we propose a switchable micro-lenticular lens arrays (MLAs) utilizing phase modulation of OILCs. Under the applied field, the nano-sized LC droplets reorient in a parallel direction to the field. Consequently, the optical path follows the gradient refractive index and results in the proposed MLAs. Besides, the focused arrays are changed with the incident polarization. As a proof, a 3D image was realized when the polarized image of the 2D panel's arrays experiences the difference in the gradient refractive index of the micro-lenticular device.

2. Mechanism of the micro-lenticular lens arrays

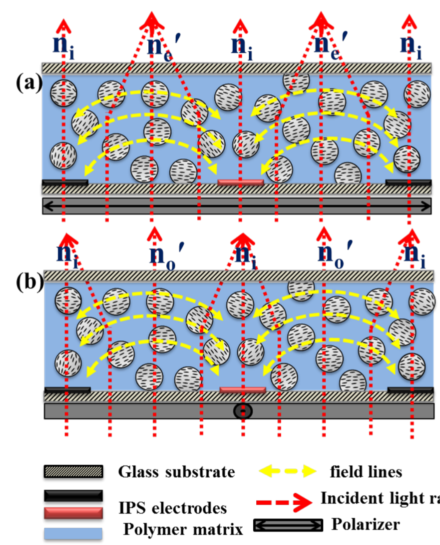

Figure 1. Schematic mechanism of the micro-lenticular lens arrays using OILCs. Position of focused beam changes with the polarization direction of an incident beam with respect to the electrode direction.

Figure 1 shows the schematic mechanism of the proposed polarization-dependent switching micro-lenticular lens utilizing the OILC phase. An OILC phase is optically isotropic which has a refractive index of n_i whose value is between polymer refractive index n_p and average n_{ave} of LC and does not contribute to any optical change, at field-off state. However, on the field-on state, the LC directors in nano-sized droplets tend to reorient along the field direction and thus allowed it to form the graded refractive index enforced by the induced birefringence.

ISSN 0097-996X/19/4801-0489-$1.00 © 2019 SID

Therefore, the incident light propagating through the medium experiences optical phase change between electrodes ($n_e'(n_o')$) and above the electrodes (n_i), when the incident polarization is perpendicular (parallel) to the electrode direction. Consequently, the effective optical phase modulation occurs with the direction of incident polarization considered as a polarization-dependent micro-lenticular lens effect of the IPS device.

In OILC, when the electric field is applied, the LC directors in nano-sized droplets aligne parallel to the applied field between electrodes so that the birefringence is induced. This phenomenon can be explained by Kerr effect or molecular orientations [14,16,17]. In addition, the incident light experiences the $n_e'(E)$ along the field direction, and $n_o'(E)$ perpendicular to the field direction, and $n_i = v_p n_p + v_{LC} n_{ave}$ where v_p and v_{LC} are filling factor in the composite. The optical phase difference between electrode gaps and above electrodes when the polarized direction of an incident light is perpendicular to the electrodes can be expressed as [15],

$$\Delta\varphi = \frac{2\pi}{\lambda}\left|\int_0^d n_e'(E)\,dz - n_i d\right|, \tag{1}$$

where d is the cell gap, λ is the wavelength of the incident light. Comparing the magnitude of each refractive indices qualitatively, it follows $n_e' > n_i > n_o'$ and in addition, n_e' and n_o' change along vertical and horizontal position of LC layer between electrodes, giving rise to graded index. As a result, when the field is applied, $\Delta\varphi$ along horizontal position and graded index between electrodes exist, giving rise to the micro-lenticular array.

3. Experimental procedure

The OILC composite was prepared by utilizing the positive high dielectric anisotropy nematic liquid crystal mixture MLC2053 ($\Delta\varepsilon = 42.6$, $\Delta n = 0.235$, and $T_{NI} = 86^{\circ}$C, from Merck Advanced Technology, Korea) and commercial monomer NOA-65 (Norland Optical Adhesive, $n_p = 1.5122$ at 20ºC and 589 nm). The prepared OILC sample consists of 42.5% of LC and 57.5% of NOA-65. A small amount of the photoinitiator (Irgacure-907) was added to the mixture to initiate the radical polymerization upon the UV exposure. The prepared mixture was injected into the in-plane switching (IPS) (w x l = 4 x 4 μm) cell by a capillary action at 90ºC, followed by UV irradiation 140mW/cm^2 for 5 mins. The cell gap was fixed to 10 μm. The polarizing optical microscope (POM) (Nikon, ECLIPSE E600, Japan) attached with CCD camera (Nikon, DXM 1200), was used to observe its polarization-dependent micro-lenticular arrays. The response time was measured as a function of the applied voltage by using a lab-made set-up consisted of photo-detector, a function generator (Agilent 33521A) and oscilloscope (Tektronix DPO 2024B).

4. Results and Discussion

Figure 2 depicts the POM images of the proposed micro-lenticular device with crossed polarizers and just one polarizer on the bottom of the cell. The device showed an efficient dark state between the crossed polarizers, in field-off state. Also, there is no change in the optical intensity while the sample's plane is rotated on its axis. This shows that the LC droplets are smaller in size as compared with the wavelength of incident light, which results in the optically isotropic phase. On the other hand, on the field-on state, the LC directors in nano-sized LC droplets reorient parallel direction to the field only between electrodes and hence, the bright and dark fringe patterns are observed, as depicted in Figure 2 (b).

To observe micro-lenticular arrays, the analyzer is removed, and the polarization of incident light is kept parallel and perpendicular to the electrode direction. Consequently, the focused MLAs are obtained and the measured focal length of the proposed micro-lenticular device is 22 μm at 50 V_{rms}. Besides, the position of focused beam arrays changes depending on the polarized direction of an incident, that is, when it is perpendicular to the electrode direction, $n_e' > n_i$ so the light is focused between electrodes whereas when it is parallel to the electrode direction, $n_o' < n_i$ so the light is focused above electrodes as depicted in Figure 2(c) and 2(d). The change in the optical path could strongly emphasize the device working as a polarization dependent micro-lenticular lens.

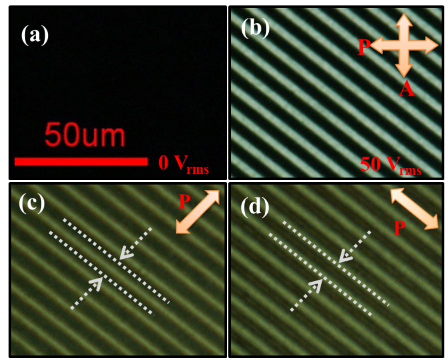

Figure 2. POM images (a) V = 0, (b) 50 V_{rms}, under crossed polarizers. (c and d) focused beam position in micro-lenticular arrays changes with polarized direction of an incident light with respect to IPS electrodes.

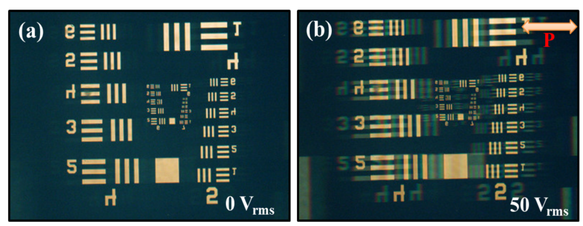

Figure 3. Optical images of the USAF-1951 resolution target observed through IPS device (a) V = 0 V_{rms} and (b) V = 50 V_{rms}.

Furthermore, the device is placed on the USAF-1951 target and the light transmission of the polarization is kept perpendicular to the electrode direction. When no field is applied the resolution target is clearly visible, whereas, in field-on state, the image of the resolution target is deviated in a perpendicular direction to electrodes, as shown in Figure 3. The obtained image looks triple in the transverse electrode direction showing a micro-lenticular lens effect. A similar kind of results was reported with PVD/DBP [18] and PNLC [19] lenses.

Figure 4 depicts the schematic array diagram of the 2D/3D switchable display prepared by assembling the micro-lenticular device placed on the 2D flat panel display (FPD). Each microlens formed across the electrodes of the micro-lenticular device covers two pixels of the FPD, i.e. left pixel and right pixel. In field-off state, the 2D static and moving images are very clear and there is no deviation in the image was realized while we observe through the device in all possible directions. However, when the electric field is applied across the electrodes, the optical phase change occurs by the effective refractive index change to n_e', which is originated from the molecular orientation inside the nano-sized LC droplets. Therefore, the right pixel and left pixel arrays encounter the gradient refractive index and hence deviated towards the left eye and right eye, while the incident polarization positioned perpendicular to the electrode direction. By combining the spatially diverged images, the resultant 3D image of the 2D panel could be realized without any special glass. In our case, the lens pitch is very short, so it can be applied to very high-resolution short pitch display or should adjust the lens pitch according to the resolution of the display. Figure 5 (a) and 5(b) shows such feasibility when the device is applied to conventional FPD with twisted nematic LCD.

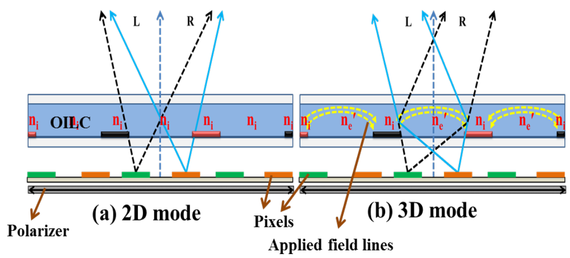

Figure 4. Schematic array diagram of the switchable 2D/3D display with a micro-lenticular device (a) V = 0 and (b) V = 50 V_{rms}. The polarized light is in the perpendicular direction to the IPS electrode.

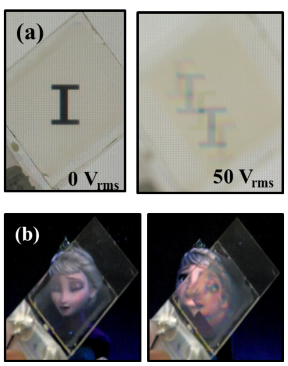

Figure 5. Photographic 2D at V = 0 V_{rms} and 3D at V = 50 V_{rms}, (a) static image on the top row, (b) moving image on the bottom row of the 2D panel.

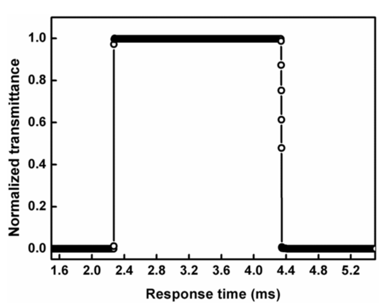

Figure 6. Response time behavior at an applied voltage 60 V_{rms}.

The response time was measured as a function of time by applying constant square wave voltage of 60 V_{rms} at 1 kHz. The rise and decay times are defined as the transmittance increased from (10% to 90%) and decreased from (90% to 10%), respectively. Obtained rise and decay response times for the micro-lenticular device is 0.99 ms & 2.8 ms, respectively, as depicted in Figure 6. This shows the responses time is faster as compared to the conventional LCD modes because the nano-sized LC droplets experience stronger anchoring force owing to an increased effective surface area of the LC to anchoring with polymer walls [7,12]. The fast response time of the device is feasible to head mounted or head up displays.

Finally, the LC extracted morphology of the polymer network was studied by using the FE-SEM, as depicted in Figure 7(a). The image reveals that the LC droplets are uniformly distributed all over the polymer matrix and each droplet is isolated by a thicker polymer wall. The average droplet size of the composite is 160 nm. Figure 7(b) photographic image shows the optical transmittance of the proposed device, in which the background text image "*ID Lab*" is clearly visible through the empty cell as compared to the OILC cell, owing to the feeble light scattering [8]. The higher transparency of the device can be easily achieved with different materials and approaches [8,9].

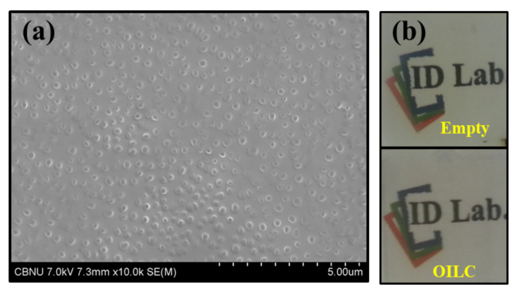

Figure 7. (a) Surface morphology of the polymer matrix (b) the macroscopic images of an empty IPS cell and the OILC cell which informs high transparency of OILC cell.

5. Impact

We proposed fast switchable polarization-dependent MLAs using optically isotropic liquid crystals. The gradient refractive index by the reorientation of the LCs in nano-sized droplets makes MLAs realize with the focal length of 22 µm. Interestingly, a 3D image was found to be realized when the device is placed above the 2D panel. The proposed micro-lenticular device has a potential candidate for the switchable 2D/3D flexible device applications

6. Acknowledgments

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2016R1A6A3A11930056 and 2016R1D1A1B01007189).

7. References

[1] J. Flack, J. Harrold, G. J. Woodgate, "A prototype 3D mobile phone equipped with a next-generation autostereoscopic display," In Stereoscopic Displays and Virtual Reality Systems v.6490, p.64900M (2007).

[2] N. S. Holliman, N. A. Dodgson, G. E. Favalora, L. Pockett,

"Three-dimensional displays: a review and applications analysis," IEEE transactions on Broadcasting **57(2)**, 362 (2011).

[3] M. P. Krijn, S. T. de Zwart, D. K. de Boer, O. H. Willemsen, M. Sluijter, "2D/3D displays based on switchable lenticulars," Journal of the Society for Information **16(8)**, 847–855 (2008).

[4] H. Ren, S. Xu, Y. Liu, S. T. Wu, "Switchable-focus using a polymeric lenticular microlens array and a polarization rotator," Optics Express **21(7)**, 7916–7925 (2013).

[5] 5. N. H. Park, S. C. Noh, P. Nayek, M. H. Lee, M. S. Kim, L. C. Chien, J. H. Lee, B. K. Kim, S. H. Lee, "Optically isotropic liquid crystal mixtures and their application to high-performance liquid crystal devices," Liquid Crystals **42(4)**, 530-6 (2015)

[6] B. Kim, H. G. Kim, G. Y. Shim, J. S. Park, K. I. Joo, D. J. Lee, J. H. Lee, J. H. Baek, B. K. Kim, Y. Choi, H. R. Kim, "Fast-switching optically isotropic liquid crystal nano-droplets with improved depolarization and Kerr effect by doping high k nanoparticles" Applied Optics **57(2)**, 119-129 (2018).

[7] S. J. Shin, N. H. Cho, Y. J. Lim, P. Nayek, S. H. Lee, S. H. Hong, H. J. Lee, S. T. Shin, "Optically isotropic liquid crystal mixture showing high contrast ratio and fast response time," IMID Digest 139–140 (2011).

[8] S. Pagidi, R. Manda, Y. J. Lim, S. M. Song, H. Yoo, J. H. Woo, Y. H. Lin, S. H. Lee, "Helical pitch-dependent electro-optics of optically high transparent nano-phase separated liquid crystal," Optics Express **26(21)**, 27368-80 (2018).

[9] Y. J. Lim, J. H. Yoon, H. Yoo, S. M. Song, R. Manda, S. Pagidi, M. H. Lee, J. M. Myoung, S. H. Lee, "Fast switchable field-induced optical birefringence in highly transparent polymer-liquid crystal composite," Optical Materials Express **8(12)**, 3698-707 (2018).

[10] S. Pagidi, R. Manda, S. S. Bhattacharyya, K. J. Cho, T. H. Kim, Y. J. Lim, S. H. Lee, "Superior electro-optics of nano-phase encapsulated liquid crystals utilizing functionalized carbon nanotubes," Journal of Composite Part B **164**, 675-682 (2019).

[11] Y. H. Lin, H. S. Chen, H. C. Lin, Y. S. Tsou, H. K. Hsu, W. Y. Li, "Polarizer-free and fast response microlens arrays using polymer-stabilized blue phase liquid crystals," Applied Physics Letters **96(11)**, 113505 (2010).

[12] J. H. Yu, H. S. Chen, P. J. Chen, K. H. Song, S. C. Noh, J. M. Lee, H. Ren, Y. H. Lin, S. H. Lee, "Electrically tunable microlens arrays based on polarization-independent optical phase of nano liquid crystal droplets dispersed in polymer matrix," Optics Express **23(13)**, 17337–17344 (2015).

[13] H. Ren, Y. H. Fan, Y. H. Lin, S. T. Wu, "Tunable-focus microlens arrays using nanosized polymer-dispersed liquid crystal droplets", Optics Communications **247(1-3)**, 101-106 (2005).

[14] R. Manda, S. Pagidi, S. S. Bhattacharyya, C. H. Park, Y. J. Lim, J. S. Gwag, S. H. Lee, "Fast response and transparent optically isotropic liquid crystal diffraction grating," Optics Express **25(20)**, 24033–24043 (2017)

[15] J. Yan, Y. Li, S. T. Wu, "High-efficiency and fast-response tunable phase grating using a blue phase liquid crystal," Optics Letters **36(8)**, 1404–1406 (2011).

[16] J. Kerr, "A new relation between electricity and light: Dielectrified media birefringent," Journal of Science **50(332)**, 337-348 (1875).

[17] J. Yan, H. C. Cheng, S. Gauza, Y. Li, M. Jiao, L. Rao, S. T. Wu, "Extended Kerr effect of polymer stabilized blue-phase liquid crystals," Applied Physics Letters **96(7)**, 071105 (2010).

[18] M. Xu, B. Jin, R. He, H. Ren, "Adaptive lenticular microlens arrays based pn voltage-induced waves at the surface of polyvinyl chloride/dibutyl phthalate gels", Optics Express **24(8)**, 8142 (2016).

[19] X. Wang, H. Ren, Q. Wang, "Polymer network liquid crystal lenticular microlens array with no surface treatment", Journal of Display Technology **12(8)**, 773-778 (2016).