Low Cell Gap Polymeric Liquid Crystal Lens for 2-D/3-D Switchable Auto-Stereoscopic Display

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***Abstract*— We propose a planar polymeric liquid crystal (LC) lens with a low cell gap (∼4.6 μm) for a 2-D/3-D switchable auto-stereoscopic display. The proposed lens consists of two LC layers, one is a photopolymerized LC lens layer with a non-uniform refractive index with parabolic curve distribution, and the other is a half-wave LC switching layer of the vertical alignment type, which performs the 2-D/3-D image switching. The optimized refractive index of the LC lens layer was simply realized by polymerizing the LC molecules using a reactive mesogen. The proposed LC lens allow fast 2-D/3-D switching with low voltage and a simple fabrication process because of a low cell gap of the switching layer. We verified the electro-optical characteristics of the proposed LC lens by fabricating each layer after optimizing the cell structure. The measured focal length as a function of the applied voltage in the 3-D mode was compared with the calculated focal length and we confirmed that the measured results agreed with the calculated results.**

***Index Terms*— 2-D/3-D switching mode, effective refractive index, focal length, low cell gap, planar polymeric liquid crystal (PPLC) lens.**

I. Introduction

THE current technology of 2-D flat panel displays can show the excellent display image quality in terms of resolution, contrast ratio, gamma curve, and viewing angle characteristics [1]–[4]. Nevertheless, many viewers still desire more natural and realistic images with their visual experience. Unfortunately, 2-D display devices have a fundamental limitation, they cannot express image depth. Thus, many researchers are studying the key technologies of 3-D displays to achieve more realistic images.

In general, current 3-D display devices have 2-D/3-D switchable optical elements because the 3-D display device must also handle 2-D display images on the same panel when the device accepts 2-D-type data. Furthermore, visual fatigue becomes serious when we watch 3-D images for a long time. Therefore, key technologies of the current displays contain the optical design of the 2-D/3-D switchable optical elements and optimization.

The main techniques for 2-D/3-D image switching in auto-stereoscopic displays can be classified by two types: 1) an active barrier type and 2) an active lenticular lens type [5]–[7]. The barrier type controls the transmittance from the barrier pattern using liquid crystal (LC) directors. This technique has an easy fabrication process and relatively low 3-D crosstalk. The barrier type, however, has a serious problem with light luminance because of the barrier [5]. On the other hand, the active lenticular lens type has a 2-D/3-D switching mode without any loss of luminance because the 3-D image is achieved using only the effective refractive index (n_{eff}) of LC directors [6], [7]. Therefore, the active lenticular type display is preferred for applications in auto-stereoscopic 2-D/3-D switchable displays.

In previous papers [8]–[13], several techniques for the 2-D/3-D switchable lens with an active lenticular type display have been proposed. Philips [8] proposed a geometric parabolic LC lens using a phase separation method. This method, however, requires a high cell gap (>60 μm) in the LC layer because of the small birefringence of the LC material. In addition, light loss in the 2-D mode can occur because of a refractive index mismatch between the LC layer and the polymer layer [9]. The company LG display used a multielectrode method for modulating the refractive index of the LC layer to focus the rays [10], [11]. That method also requires a high cell gap (>45 μm) of the LC layer for an acceptable focal length. Therefore, we can predict these LC lens structure may show high voltage (∼several dozens of volts) and slow response time (∼over 1 s) for 2-D/3-D switching because of the high cell gap. AUO's lens [12] uses two optical layers that consist of a 2-D/3-D switching layer by a TN LC cell and a ray focusing layer. This method also requires a high cell gap in the TN LCD because light efficiency is proportional to the satisfaction of the Mauguin condition. Furthermore, light loss in the ray focusing layer can also occur in a 2-D mode because of a refractive index mismatch [13].

Current 2-D/3-D switching display devices require a low cell gap lens structure for fast 2-D/3-D switching and low driving voltage. Furthermore, in general, a high cell gap of over ∼10 μm is not suitable because the current display process widely uses the column space process. To satisfy

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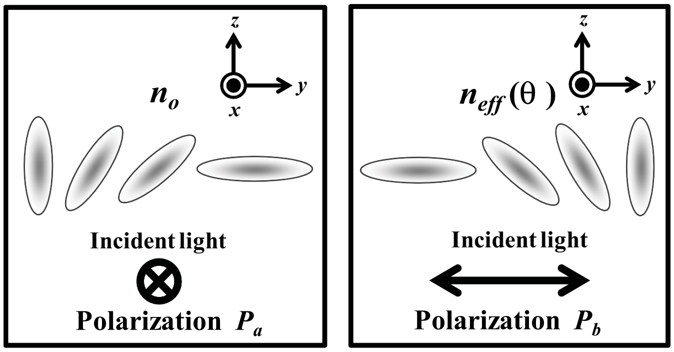


(a) (b)

Fig. 1. Polarization dependence of refractive indexes of the LC directors on the polar angle θ. (a) Polarization P_a in x-axis. (b) Polarization P_b in y-axis.

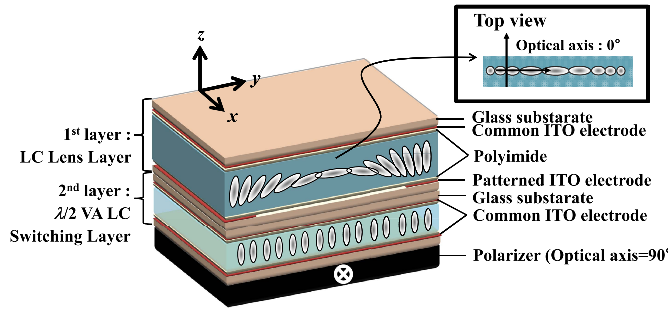
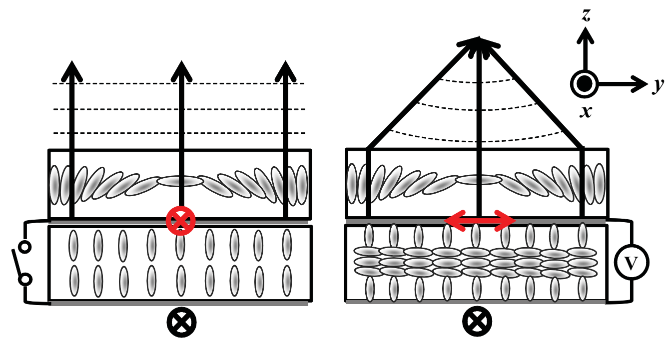


Fig. 2. Schematic diagram of the proposed 2-D/3-D switchable PPLC lens structure.



(a) (b)

Fig. 3. Electro-optical principle of the 2-D/3-D switching image mode of the proposed PPLC lens device in (a) 2-D mode and (b) 3-D mode.

these requirements, we propose a planar polymeric LC (PPLC) lens, which has the merits of a low cell gap (~4.6 μm) and a simple fabrication process, for 2-D/3-D switchable auto-stereoscopic displays. The proposed lens consists of two LC layers: 1) the top layer is a photopolymerized LC lens layer with a nonuniform refractive index with parabolic curve distribution for ray focusing and 2) the bottom layer is a half-wave (λ/2) vertical alignment (VA) LC switching layer, which is a 2-D/3-D image mode. The optimized refractive index of the LC lens layer was simply realized by polymerizing the LC molecules using a reactive mesogen (RM). The proposed LC lens allow fast 2-D/3-D switching and low voltage because of the low cell gap of the LC switching layer. Futhermore, the low cell gap procell of the 2-D/3-D switching layer is more suitable for LC application because the current display process uses a column space method that can cover the low cell gap process. We verify the electro-optical characteristics of the proposed LC lens by fabricating each layer.

II. Electro-Optical Principle of the Proposed PPLC Lens in Auto-Stereoscopic 2-D/3-D Switchable Display

In general, the 2-D/3-D switchable lens control the light path of the polarized light because the display panels, including the LCD and the organic light-emitting diode, use polarizers on the upper side of the panel. Fig. 1 shows the two perpendicular polarizations states P_a and P_b on the output polarizer of the display panel. In this case, the effective refractive index n_{eff} of the LC layer in the LC lens can be simply described as follows [14], [15]:

$$n_{\text{eff}}(\theta) = \frac{n_e n_o}{(n_o^2 \sin^2\theta + n_e^2 \cos^2\theta)^{1/2}} \tag{1}$$

where, n_o and n_e are the ordinary refractive index and extraordinary refractive index of the LC layer. θ is the incident polar angle.

With the electro-optical characteristics mentioned above, we designed a 2-D/3-D switchable PPLC lens. Fig. 2 shows the proposed PPLC lens structure. The PPLC lens consists of two LC layers: 1) the top layer is the LC lens layer [16]–[18], which is the LC layer photopolymerized by an ultraviolet (UV) process and 2) the bottom LC layer is for 2-D/3-D switching for which we used a λ/2 VA mode because it allows a low cell-gap structure for the 2-D/3-D switching with a simple structure. In the LC lens layer, the parabolic distributed refractive indexes of the LC molecules can be formed by exposing the UV light to the mixture of a RM and an LC material that have nonuniform distribution of LC director orientation by an applied electric field. Thus, we obtain a photopolymerized LC director profile with the desired refractive indexes.

Fig. 3 shows the principle of the 2-D/3-D switching mode in the proposed lens. In the 2-D mode as shown in Fig. 3(a), the LC director is in a homogeneous state because we applied a VA LC mode, so that the effective refractive index of the switching LC layer is n_o. In this state, the refractive index of the switching layer can be exactly the same as the upper LC lens layer. Therefore, light that passes throught the LC lens layer is not affected by the LC lens layer in the 2-D mode. On the other hand, the LC directors lie down with 45° of optical axis by applying the voltage in the 3-D mode as shown in Fig. 3(b). In this case, the λ/2 retardation of the LC layer rotates the polarization of light 90° from the initial state. Therefore, the 90° rotated polarized light feels the effective refractive index $n_{\text{eff}}(\theta)$ in (1) when passing through the LC lens layer. Finally, the light passing through the LC lens layer is refracted by the parabolic refractive index distribution in the LC lens layer as shown in Fig. 3(b).

III. Experiments and Discussions

To verify the proposed LC lens for 2-D/3-D switching, we fabricated two modules, the 2-D/3-D switching LC layer and

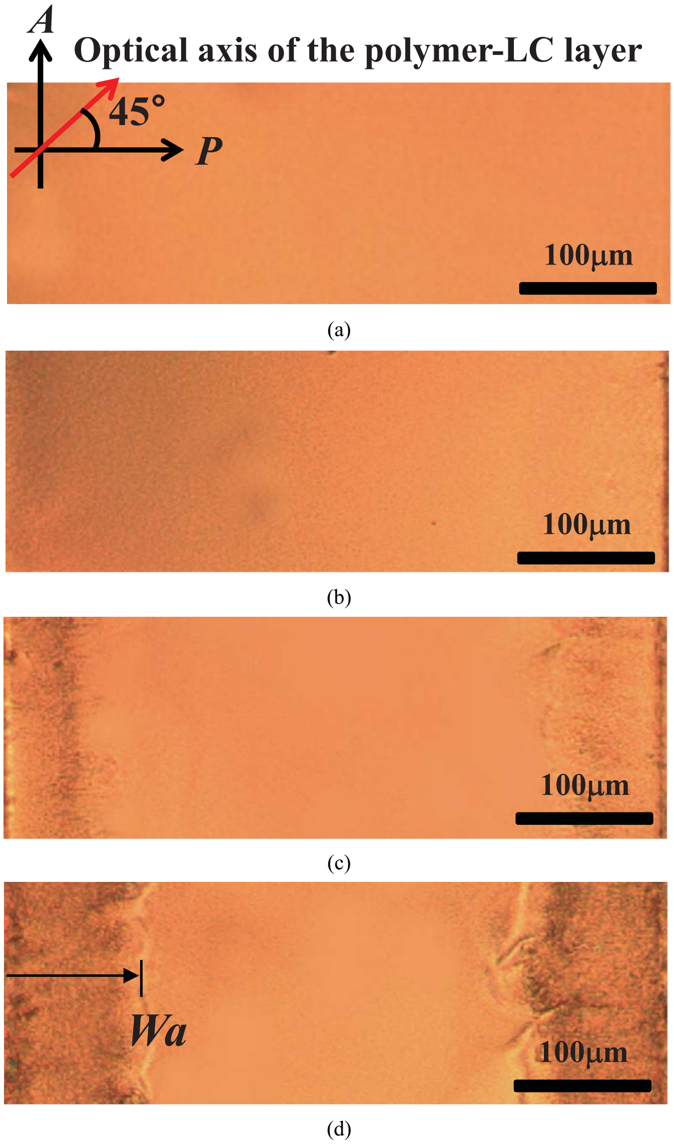


Fig. 4. Microscopic image of the fabricated LC lens layer at the applied voltage state of (a) 0, (b) 40, (c) 100, and (d) 160 V, respectively. This image observed when the LC lens layer was rotated to 45° from the polarizer P.

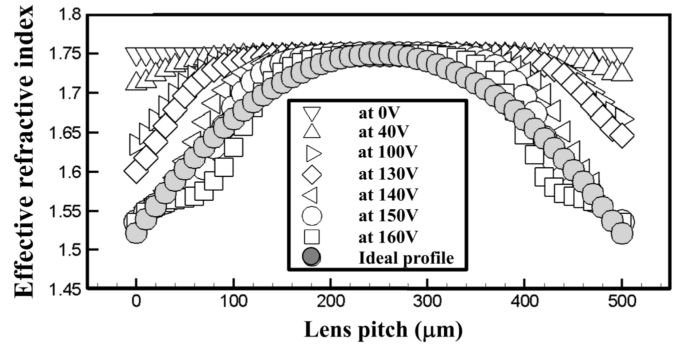


Fig. 5. Calculated effective refractive index profile of the LC lens layer in the 3-D mode as a function of the applied voltage.

the lens layer. As we mentioned before, the 2-D/3-D switching LC layer was simply realized by applying the $\lambda/2$ VA mode as shown in Fig. 3. On the other hand, the LC lens layer for light focusing needs the photopolymerization process to align the parabolic LC molecules distribution at the voltage cutoff state.

The intial LC lens layer in Fig. 2 is in a homogeneous state in two induim tin oxide (ITO) glass substrates coated with antiparallel rubbed polyimide. The bottom ITO substrate was etched for a patterned electrode structure with a lens pitch (W) of 500 μm to provide an inhomogeneous electric field to the LC lens layer, and the top substrate has a common electrode. The thickness of the LC layer is 30 μm.

To fabricate the LC lens layer, we first filled a mixture of a LC (Merck, MAT-10-566, $\Delta n = 0.2276$, $n_o = 1.5219$, $n_e = 1.7495$, and $\Delta\varepsilon = 6.6$), a RM (Merck, RM257), and a photoinitiator (Ciba, Irgacure 651) with a ratio of 20:79:1 wt% into two ITO glass substrates. This mixture was stirred at 100 °C for 24 h to homogenize the mixture before injecting it into the two glass substrates. Then, we applied the appropriate voltage to the mixture of the material to stabilize the RM257 with the designated inhomogeneous distribution. The stabilization of the RM257 was completed by exposing it to UV light during the RM and the LC molecules were oriented along the applied voltage. In these experiments, we exposed the mixture to the UV light (~1.5 mW/cm^2) for 2.5 min at 100 °C to photopolymerize the mixture.

Fig. 4 shows the microscopic image of the stabilized LC lens layer as a function of the applied voltage at the crossed polarizer (A and P). The optical axis of the LC lens layer was rotated to 45° from the transmission axis of the polarizer in a microscope. In Fig. 4, we can simply observe the different stabilized images of the cell because of the amplitude of the applied voltage. Compared with Fig. 4(a) and (b), the clear stabilized region *Wa* in Fig. 4(c) and (d) takes place in the cell at high voltage. We can confirm that the clear region *Wa* implies a big change of the LC director orientation because of the high applied voltage. Therefore, we assume the refractive index profile for light focusing can be controlled by applying the appropriate voltage to the LC mixture, so that we can control the focal length for the optimized 3-D image.

Fig. 5 shows the calculated effective refractive index of the LC lens layer as a function of the voltage. The calculation is performed by the commercial LC software TechWiz LCD provided by the Sanayi System Co. in Korea. In Fig. 5, the circle symbol shows the ideal refractive index profile of the LC director, which provides the focal length of 0.45 cm. In the calculated results, the appropriate voltage that provides a similar focal length with the ideal refractive index distribution can be found in the range between 140 and 150 V.

The focal length of the proposed PPLC lens as a function of the applied voltage in the 3-D mode can be calculated using [19]

$$f = \frac{W^2}{8 \times \Delta n \times T}, \quad \Delta n = n_c - n_b \tag{2}$$

$$f = \frac{D \times W}{R} \tag{3}$$

where *W, T, D*, and *R* represent the lens pitch, thickness of the LC lens layer, observing distance, and refracted light width at the observing distance, respectively. Δn is the difference

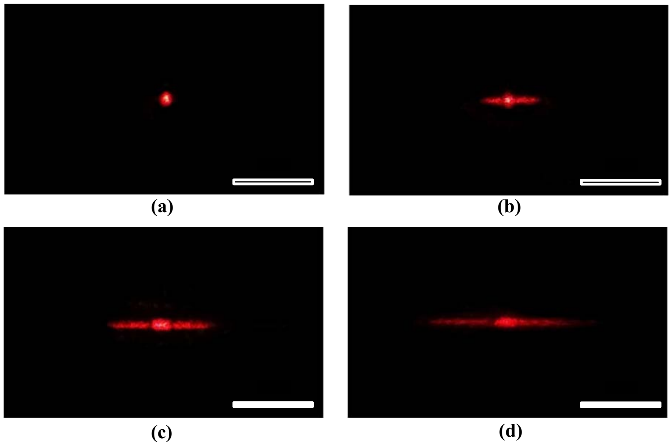


Fig. 6. Measured refracted light width at the observing distance (= 30 cm) of the proposed PPLC lens as a function of the applied voltage at (a) 0 V, (b) 40 V (~0.8 cm), (c) 100 V (~1.3 cm), and (d) 130 V (~2 cm).

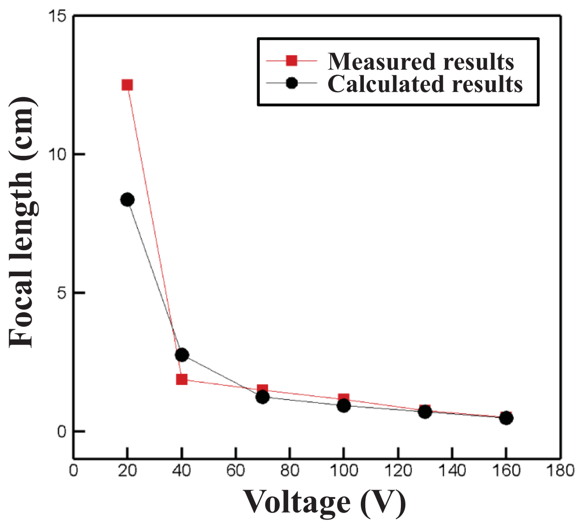


Fig. 7. Comparison of the focal length of the calculation and measurement in the proposed PPLC lens.

between the refractive index of center (n_c) and boundary (n_b). We fixed the observing distance and lens pitch at 30 cm and 500 μm, respectively.

In a simulation, the focal length could be easily calculated using (2) based on the calculated $n_{\rm eff}$ values of Fig. 5. Further, in the case of fabricated PPLC lens cell, we can measure the focal length of the cell using (3).

Fig. 6 shows experimental photographs of the refracted light (He–Ne laser, $\lambda = 630$ nm) at the observing distance. In Fig. 6, we can observe that the refracted angle of the light passing through the LC lens can be increased as we increase the amplitude of the stabilization voltage. The measured refracted light width R was varied from 0.8 to 2 cm by changing the applied voltage from 40 to 130 V. A comparison of the calculated focal length of the LC lens and the measured focal length is shown in Fig. 7. The measured focal length of the LC lens agrees with the calculated result and we can confirm the proposed LC structure is a 2-D/3-D switchable optical lens with a desirable focal length.

For the 2-D/3-D switching LC layer, as we mentioned above, we applied a VA LC mode ($\Delta n = 0.2276$, $n_o = 1.4792$, $n_e = 1.5622$, and $\Delta\varepsilon = -3.8$). Cell gap of the switching LC cell is 4.6 μm. In this experiment, we applied 5 V to the cell and measured under 20 ms for 2-D/3-D switching.

IV. Conclusion

In summary, we proposed a 2-D/3-D switchable PPLC lens for auto-stereoscopic displays. The proposed LC lens consist of a 2-D/3-D switching LC layer with a $\lambda/2$ VA mode and a LC lens layer. The proposed lens allow fast 2-D/3-D switching and low voltage because of the low cell gap in the LC switching layer. We also used a simple photopolymerization process for the light focusing LC layer. We verified the electro-optical characteristics of the proposed LC lens by fabricating each layer. The measured focal length as a function of the applied voltage in the 3-D mode was compared with the calculated focal length. We believe that the technology presented here will further upgrade 2-D/3-D switching technology in auto-stereoscopic displays and can be applied to various applications such as 3-D mobile, 3-D TVs, and 3-D monitors.

References

[1] R. Lu, S.-T. Wu, and S. H. Lee, "Reducing the color shift of a multidomain vertical alignment liquid crystal display using dual threshold voltage," *Appl. Phys. Lett.*, vol. 92, no. 5, pp. 051114-1–051114-3, 2008.

[2] M. Oh-e, and K. Kondo, "Electro-optical characteristics and switching behavior of the in-plane switching mode," *Appl. Phys. Lett.*, vol. 67, no. 26, pp. 3895–3897, 1995.

[3] S. H. Lee, S. L. Lee, and H. Y. Kim, "Electro-optic characteristics and switching principle of a nematic liquid crystal cell controlled by fringe-field switching," *Appl. Phys. Lett.*, vol. 73, no. 20, pp. 2881–2883, 1998.

[4] B.-J. Mun, T. Y. Jin, G.-D. Lee, Y. J. Lim, and S. H. Lee, "Optical approach to improve the γ curve in a vertical-alignment liquid-crystal cell," *Opt. Lett.*, vol. 38, no. 5, pp. 799–801, 2013.

[5] R.-Y. Tsai, C.-H. Tsai, K. Lee, C.-L. Wu, L.-C. Lin, K.-C. Huang, W.-L. Hsu, C.-S. Wu, C.-F. Lu, J.-C. Yang, and Y.-C. Chen, "Challenge of 3D LCD displays," *Proc. SPIE*, vol. 7329, pp. 732903-1–732903-8, Apr. 2009.

[6] G. Woodgate and J. Harrold, "Efficiency analysis for multi-view spatially multiplexed autostereoscopic 2-D/3-D displays," *J. Soc. Inf. Display*, vol. 15, no. 11, pp. 873–881, 2007.

[7] K. W. Chien and H. P. D. Shieh, "Time-multiplexed three-dimensional displays based on directional backlights with fast-switching liquid-crystal displays," *Appl. Opt.*, vol. 45, no. 13, pp. 106–3110, 2006.

[8] M. C. M. Krijn, S. de Zwart, D. G. de Boer, O. Willemsen, and M. Sluijter, "2-D/3-D displays based on switchable lenticulars," *J. Soc. Inf. Display*, vol. 16, no. 8, pp. 847–855, 2008.

[9] M. G. H. Hiddink, S. T. de Zwart, O. H. Willemsen, and T. Dekker, "Locally switchable 3D displays," in *SID Symp. Dig. Tech. Papers*, vol. 37. 2006, pp. 1142–1145.

[10] H. K. Hong, S. M. Jung, B. J. Lee, and H. H. Shin, "Electric-field-driven LC lens for 3-D/2-D autostereoscopic display," *J. Soc. Inf. Display*, vol. 17, no. 5, pp. 399–406, 2009.

[11] H. K. Hong, "Analysis of the performance of the electric-field-driven liquid crystal lens (ELC lens) for light of various incident angles," *Liquid Cryst.*, vol. 38, no. 9, pp. 689–696, 2011.

[12] G. Woodgate and J. Harrold, "LP-1: Late-News Poster: High efficiency reconfigurable 2D/3D autostereoscopic display," in *SID Symp. Dig. Tech. Papers*, vol. 34. 2003, pp. 394–397.

[13] J. Harrold and G. Woodgate, "Autostereoscopic display technology for mobile 3DTV applications," *Proc. SPIE*, vol. 6491, pp. 64900K-1–64900K-12, Jan. 2007.

[14] R. A. M. Hikmet, T. van Bommel, and T. C. Kraan, "Study of light distribution through liquid crystal (LC) lens arrays," *J. Appl. Phys.*, vol. 103, no. 1, pp. 013111-1–013111-8, 2008.

[15] T. C. Kraan, T. van Bommel, and R. A. M. Hikmet, "Modeling liquid-crystal gradient-index lenses," *J. Opt. Soc. Amer. A*, vol. 24, no. 11, pp. 3467–3477, 2007.

[16] H.-C. Lin and Y.-H. Lin, “An electrically tunable focusing liquid crystal lens with a built-in planar polymeric lens,” *Appl. Phys. Lett.*, vol. 98, no. 8, pp. 083503-1–083503-3, 2011.
[17] H.-C. Lin and Y.-H. Lin, “An electrically tunable-focusing liquid crystal lens with a low voltage and simple electrodes,” *Opt. Exp.*, vol. 20, no. 3, pp. 2045–2052, 2012.
[18] H. Ren, Y.-H. Lin, and S.-T. Wu, “Flat polymeric microlens array,” *Opt. Commun.*, vol. 261, no. 2, pp. 296–299, 2006.
[19] J. W. Goodman, *Introduction to Fourier Optics*. New York, NY, USA: McGraw-Hill, 1968.

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