Planar Polymeric Liquid Crystal Lens for 2-D/3-D Image Switching in Auto-Stereoscopic Display

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ABSTRACT

We propose a planar polymeric liquid crystal lens with a low cell-gap (~4.6 μm) for a 2D/3D switchable auto-stereoscopic display. This lens allows fast 2D/3D switching and low voltage due to a low cell gap. We verified the electro-optical characteristics of the proposed LC lens by fabricating each layer.

1. Introduction

In general, current 3D display devices need 2D/3D switchable optical elements because the 3D display device must also handle 2D display images on the same panel when the device accepts 2D-type data. Furthermore, visual fatigue becomes serious when we watch 3D images for a long time. Therefore, key technologies of the current 3D displays contain the optical design of the 2D/3D switchable optical elements and optimization. In particular, the active Lenticular lens type using liquid crystal (LC) molecules is currently the most representative technology because this type can easily perform the 2D/3D switching mode as well as show high luminance property in 3D mode than the other techniques [1,2]. Therefore, it is preferred for 2D/3D switchable display application. However, the proposed 2D/3D switchable lens devices in previous paper require a high cell gap (> 40 μm) to control a good focal length because of the small birefringence of the LC material [3-5]. Its problems cause high operating voltage (~several dozens of volts) and slow switching time (~over 1 second) for 2D/3D switching.

In this paper, we propose a planar polymeric LC (PPLC) lens, which has the merits of a low cell gap (~4.6 μm) for 2D/3D switchable autostereoscopic displays. The proposed lens consists of two LC layers: The top layer is a photo-polymerized LC lens layer with a non-uniform refractive index with parabolic curve distribution for ray focusing, and the bottom layer is a $\lambda/2$ vertical alignment (VA) LC switching layer, which is a 2D/3D image mode. The optimized refractive index of the LC lens layer was simply realized by polymerizing the LC molecules using a reactive mesogen (RM). As a result, we confirm that the proposed device can perform fast 2D/3D switching and low voltage due to the low cell gap of the LC switching layer. We verify the electro-optical characteristics of the proposed LC lens by fabricating each layer.

2. Electro-optical principle of the proposed 2D/3D switchable PPLC lens

The LC layer is birefringence media with an extra-ordinary (n_e) and an ordinary (n_o) refractive index. These refractive indices of LCs have high dependence on the polarization light. As illustrated in Fig. 1, there are two perpendicular polarizations P_a and P_b. When the linear polarization P_a is transmitted to LC directors in Fig 1(a), the refractive index are not affected regardless of the polar angle θ of LC directors, and only n_o is obtained. However, the incident polarization P_b in Fig. 1(b) feel the n_{eff} of the LC directors depending on the polar angle θ. And the n_{eff} can be calculated as follows [6]:

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

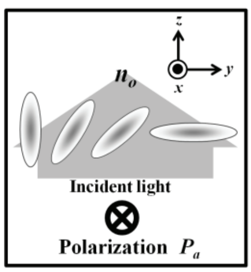

Fig. 1(a)

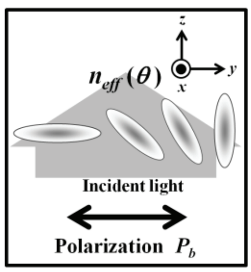

Fig. 1(b)

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Fig. 1. The polarization dependence of refractive index of LC on the polar angle: (a) polarization P_a and (b) polarization P_b

Based on the electro-optical properties mentioned above, we proposed a 2D/3D switchable PPLC lens. Figure 2 illustrates the proposed PPLC lens structure. The PPLC lens consists of two layers: The first layer is the LC lens layer [7,8], which is the LC layer photo-polymerized by an ultraviolet (UV) process; and the second layer is for 2D/3D switching for which we used a $\lambda/2$ VA mode because it allows a low cell-gap structure for the 2D/3D switching with a simple structure. In the LC lens layer, the parabolic distributed refractive indices of the LC molecules can be formed by exposing the UV light to the mixture of a reactive mesogen (RM) and an LC material that have non-uniform distribution of LC director orientation by an applied electric field. Thus, we obtain a photo-polymerized LC director profile with the desired refractive indices.

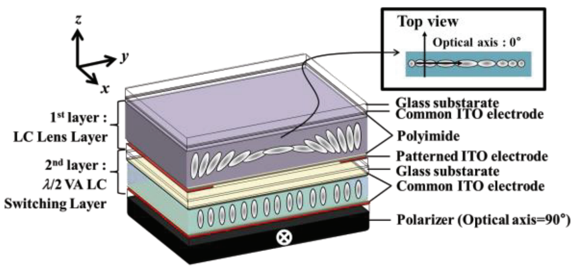

Fig. 2. The proposed 2D/3D switchable PPLC lens structure

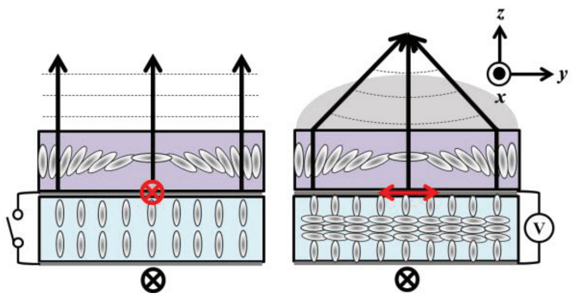

Fig. 3(a) Fig. 3(b)

Fig. 3. The electro-optical principle of the 2D/3D switching mode of the proposed PPLC lens cell: (a) the 2D mode and (b) the 3D mode

Figures 3 demonstrates the principle of the 2D/3D switching mode in the proposed lens. In the 2D 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 by input polarized light. Therefore, light that passes throught the LC lens layer is not affected by the LC lens layer in the 2D mode. On the other hand, the LC directors lie down with 45° of optical axis by applying the voltage in the 3D mode as shown in Fig. 3(b). In this case, the $\lambda/2$ 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_{eff} 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).

3. Experiments and discussions

In order to verify the proposed LC lens for 2D/3D switching, we fabricated two modules: the 2D/3D switching LC layer and the lens layer. As we mentioned before, the 2D/3D 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 needs the photo-polymerization process in order to align the parabolic LC molecules distribution at the voltage cut off state.

The intial LC lens layer in Fig. 2 is in a homogeneous state in two induim-tin-oxide (ITO) glass substrates coated with anti-parallel rubbed polyimide (PI). 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, Δn=0.2276, n_o=1.5219, n_e=1.7495, $\Delta\varepsilon$=6.6), a reactive mesogen (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 hr to homogenize the mixture. Then, we applied the appropriate voltage to the mixture of the material in order 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 minutes at 100°C to photo-polymerize the mixture.

Figure 4 shows the microscopic snapsots 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 due to the amplitude of the applied voltage. Compared to

Figs. 4 (a) and (b), the region *Wa* in Figs. 4 (c) and (d) takes place in the cell at high voltage. We can confirm that the region *Wa* implies a big change of the LC director orientation because of the high applied voltage. As a result, 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 3D image.

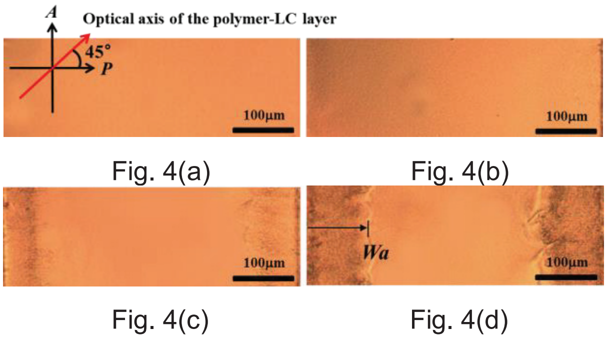

Fig. 4. The microscopic image of the fabricated LC lens layer at the applied voltage state of (a) 0 V, (b) 40 V, (c) 100 V, and (d) 160 V, repectively.

Figure 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 represents 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 under applied 140 volt.

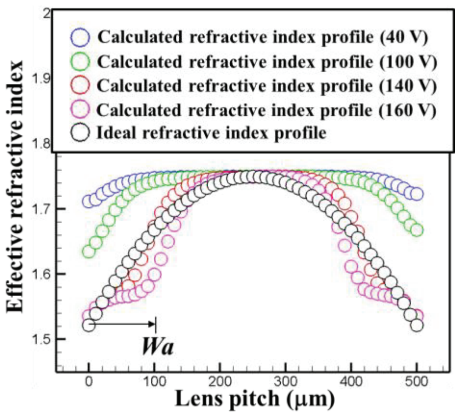

Fig. 5. Calculated effective refractive index profile of the LC lens layer in 3D mode.

The focal length of the proposed PPLC lens as a function of the applied voltage in the 3D mode can be calculated by using the simple equation below [9],

$$f = \frac{W^2}{8 \times \Delta n \times T} = \frac{D \times W}{R}, \ \Delta n = n_c - n_b \qquad (2)$$

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 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 and measurment, the focal length could be easily calculated by using Eq. (2) based on the calculated n_{eff} values.

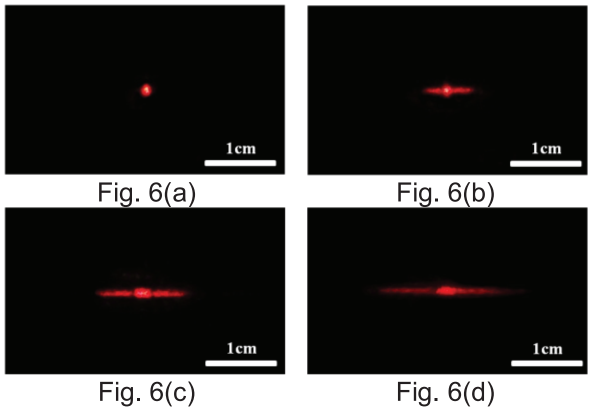

Fig. 6. The measured refracted light width at the observing distance (=30 cm) of the proposed PPLC lens (a) at 0 V, (b) at 40 V (~ 0.8 cm), (c) 100 V (~ 1.3 cm), and (d) 130 V (~ 2 cm).

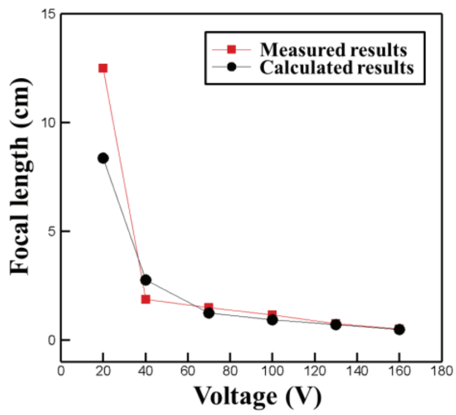

Fig. 7. The comparison of the focal length of the calculation and measurement in the proposed PPLC lens.

Figure 6 shows experimental photographs of the refracted light (He-Ne laser, λ=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 cm to 2 cm by changing the applied voltage from 40 V to 130 V. A comparison of the calculated focal length of the LC lens and the measured focal length is summarized 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 2D/3D switchable optical lens with a desirable focal length.

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

4. Conclusion

In summary, we proposed a 2D/3D switchable PPLC lens for autostereoscopic displays. The proposed LC lens consists of a 2D/3D switching LC layer with a λ/2 VA mode and a LC lens layer. The proposed lens allows fast 2D/3D switching and low voltage because of the low cell gap in the LC switching layer. We also used a simple photo-polymerization 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 3D mode was compared with the calculated focal length.

5. Acknowledgement

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6. References

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