Polarizer-Free Liquid Crystal Lenses with Positive and Negative Focal Length

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ABSTRACT

Liquid crystal lenses with the hole-patterned electrodes are widely applied for imaging applications due to the simple structure and ease of fabrication. A polarizer-free and disclination-free LC lens with positive and negative focus length is demonstrated by using four hybrid-aligned nematic LC layers with hole-patterned electrodes and dual-frequency LC materials.

1.Introdution

The LC lenses with switchable positive and negative optical power are suitable for many applications, such as myopia or presbyopia glasses and augmented reality head-mounted displays. In order to have the positive or negative optical power controllability for an LC lens, approaches like the two-voltage driving method [1,2] and dual-frequency liquid crystal (DFLC) cell with high pretilt angle [3,4] are utilized. Disclination lines are often appeared in the hole-patterned electrode LC lenses and they are produced due to the opposite rotations of LCs on two sides of an LC lens along the rubbing direction. Several methods, such as polymer stabilization [5], in-plane electrode field [6], inserting an insulating film [7], high pretilt angle [8], and hybrid-aligned nemtic (HAN) LC mode [9], have been successfully demonstrated for preventing the LC lens from the disclination lines. The requirement of using the polarized light for conventional LC lenses reduces their transmittance. To obtain the polarizer-free LC lenses, several approaches, such as the structure of a residual-type LC phase modulator [10], two cavity structure [11] and multi LC layers have been investigated. In this paper, we present a four-layer DFLC lens with the properties of controllable positive/negative optical power, disclination-free, polarizer-free by combing the above-mentioned advantages of multi LC layers, HAN mode and DFLC.

2. DFLC lens structures

A one-layer hole-patterned electrode LC lens with DFLC material (HEF951800-100, n_o=1.496 and n_e=1.718, Hecheng Display) is schematically shown in Fig. 1(a). The inner surface of the lower substrate is coated with an indium tin oxide (ITO) film as one transparent electrode. The outer surface of the upper substrate is coated with an aluminum (Al) film with a hole of 4.5 mm in diameter acting as the second electrode. The cell is filled with the DFLC, which has the positive dielectric anisotropic $\Delta\varepsilon$ for the driving frequency small than the crossover frequency (20 kHz), and negative $\Delta\varepsilon$ for driving frequency higher than the crossover frequency. The dielectric anisotropic $\Delta\varepsilon$= 2.1 at driving frequency 1 kHz, and $\Delta\varepsilon$= -1.6 at driving frequency 50 kHz. The most distinctive feature of our approach is the application of HAN DFLC cell, the upper substrate is the homeotropic alignment and the lower substrate is the homogeneous alignment with rubbing direction y. In this alignment mode, the DFLC lens can have an optical power from negative to positive by applying different driving frequency, 1 kHz and 50 kHz frequencies working as the positive and negative lenses, respectively.

The DFLCs tend to be aligned parallel to an electric field with a driving frequency of 1 kHz as shown in Fig. 2(a). The effective refractive index of the center area is larger than the edge area, and the effective refractive index decreases as the radius increases. The proposed DFLC lens functions as a positive lens due to a convex phase profile caused by the inhomogeneous electric field inside the LC cell. The DFLCs tend to be aligned perpendicular to an electric field with a driving frequency of 50 kHz as shown in Fig. 2(b). The effective refractive index of the center area is smaller than the edge area, and the effective refractive index increases as the radius increases. The proposed DFLC lens functions as a negative lens due to a concave phase profile caused by the inhomogeneous electric field inside the LC cell.

We utilize the two-layer LC structures using opposite pretilt angles as shown in Fig. 3(a) for compensating the asymmetric phase retardation. Finally, the four-layer LC structure is applied in this work to obtain a low aberration DFLC lens as shown in Fig. 3(b). Furthermore, two pairs of LC layers with orthogonal optical axes makes the four-layer DFLC lens becoming a polarizer-free device. Therefore, the proposed DFLC lens can increase two times of optical efficiency than the conventional one-layer DFLC structure. It is noted that the cell gap of two-layer and four-layer structures shown in Fig. 3 is designed as one half of the one for the one-layer structure shown in Fig. 1.

3. Experimental result

Disclination lines are usually observed in the hole-patterned electrode LC lenses. However, the LC lens using HAN mode can effectively reduce the disclination lines due to the high pretilt angle [12]. The disclination-free feature is clearly observed by studying the interference patterns shown in Fig. 4, where the DFLC lens is placed between two crossed polarizers and the rubbing direction (y-direction) of the DFLC lens is 45° with respective to the transmission axis of the polarizers.

The interference patterns of the two-layer and four-layer LC structures are shown in Fig. 5 for comparison, where the driving voltage is 150 V. These interference patterns have better circular symmetry than the one-layer structure shown in Fig. 4. The property of off-center position is corrected by using the multi-layer LC structure. It can also reduce the aberration of LC lens.

The optical power of multi-layer DFLC lenses as a function of the applied voltage is shown in Fig. 6. The absolute value of optical power of DFLC lens increases with applying voltage. The absolute value of optical power can reach 1.1 D and -1.25 D at 150 V for the driving frequency operated at 1 kHz and 50 kHz, respectively.

The phase retardation distribution is conventionally applied to analyze the quality of LC lens, and the results of as-prepared multi-layer DFLC lenses are shown in Fig. 7, where the driving voltage is 150 V and the fitted quadratic curves are shown in solid lines. The fitting lines of x and y-direction are not overlapped to each other for one-layer DFLC lens as shown in Fig. 7(a), indicating the asymmetry distribution of phase retardation in x-y plane and the generation of tilt and coma aberration. This issue can be overcome by using the four-layer DFLCs lens as shown in Fig. 7(b), where the four-layer DFLCs lens behaves similar to an ideal thin lens. The root mean squares (RMS) is defined as the difference between the measured data and the fitted quadratic curve. In Fig. 7(a), the RMS for the one-layer DFLC lens positive lens is 0.25λ and 1.36λ in x-direction and y-direction, respectively, and for negative lens is 1.00λ and 0.9λ in x-direction and y-direction, respectively. In Fig. 7(b), the RMS for the four-layer DFLC lens positive lens is 0.09λ and 0.07λ in x-direction and y-direction, and for negative lens is 0.17λ and 0.18λ in x-direction and y-direction, respectively. The properties of RMS in four-layer structure is better than one-layer structure, that means the four-layer structure is more similar to an ideal thin lens.

The image performance by using as-prepared four-layer DFLC lens is demonstrated in Fig. 8. The DFLC lens was attached on the camera. Two pieces of objective papers with “A” letter are placed 400 cm and 40 cm for the left and right sides in front of the DFLC lens, respectively. At 0 V, the camera cannot focus any “A” letter. The location of the focal plane is somewhere between 40 and 400 cm. As shown in Fig. 8, the images of the right side and left side of object “A” are becoming clear by increasing the driving voltage with the frequencies of 1 kHz and 50 kHz, respectively. It indicates the focal plane of the proposed imaging system can be electrically controlled from 400 to 40 cm using the properties of positive and negative optical power.

4. CONCLUSION

We have demonstrated a polarizer-free and disclination-free by using four-layer HAN mode DFLC lens with the hole-patterned electrode. The optical power can be adjusted from positive (1.1D) to negative (-1.25D) by applying different frequency. The properties of disclination-free, polarizer-free and low aberration of LC lens are obtained based on the proposed scheme.

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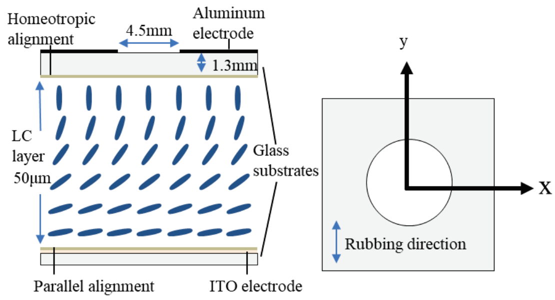
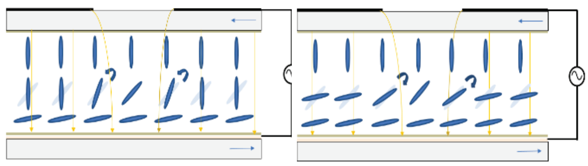


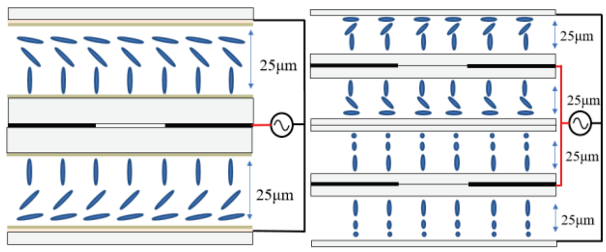
(a) (b)

Fig. 1 Schematic demonstration of the HAN DFLC lens with one-layer structure (a) Side view (b) Top view.



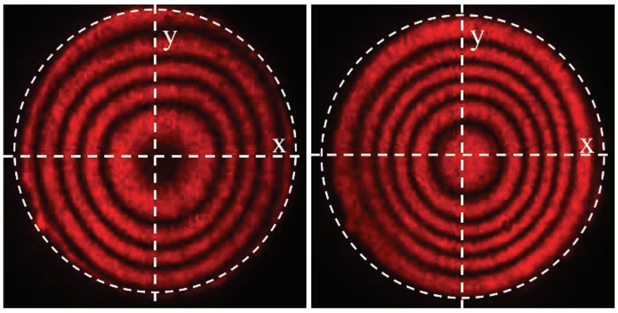
(a) (b)

Fig. 2 Working principle of the HAN DFLC lens (a) positive lens at 1kHz (b) negative lens at 50 kHz.



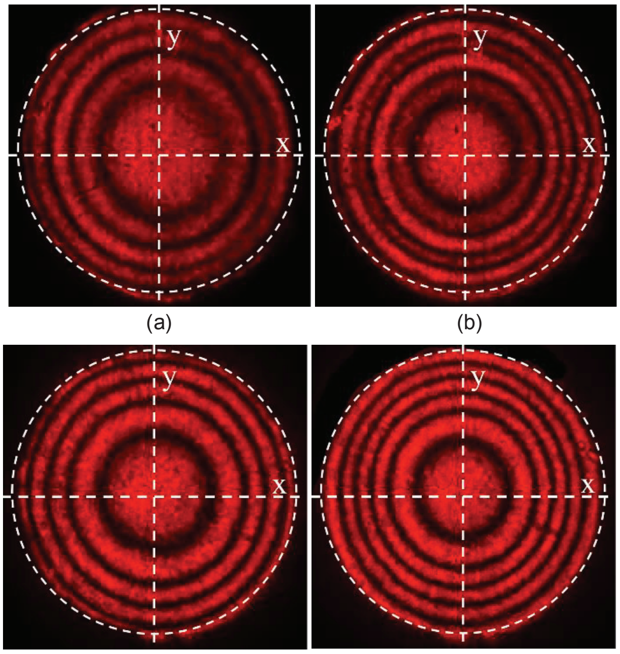
(a) (b)

Fig. 3 Schematic demonstration of the DFLC lens (a) two-layer structure (b) four-layer structure.



(a) (b)

Fig. 4 The interference patterns of disclination-free HAN mode LC lens with one LC layer (a) positive lens with optical power 1.1D (b) negative lens with optical power -1.25D.



(c) (d)

Fig. 5 Interference patterns of multi-layer LC lenses. (a) two-layer structure with optical power 1.1 D (b) two-layer structure with optical power -1.25D (c) four-layer structure with optical power 1.1 D (b) four-layer structure with optical power -1.25 D.

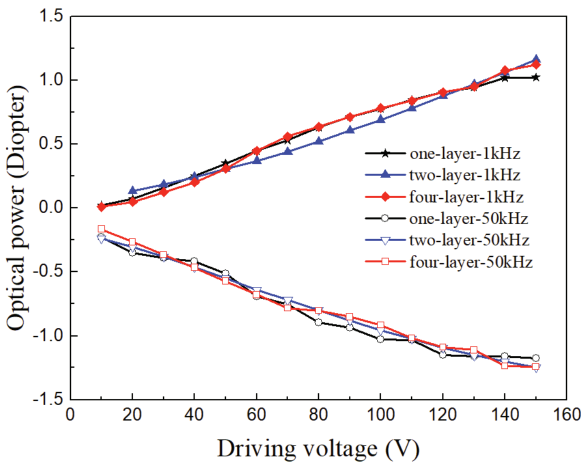
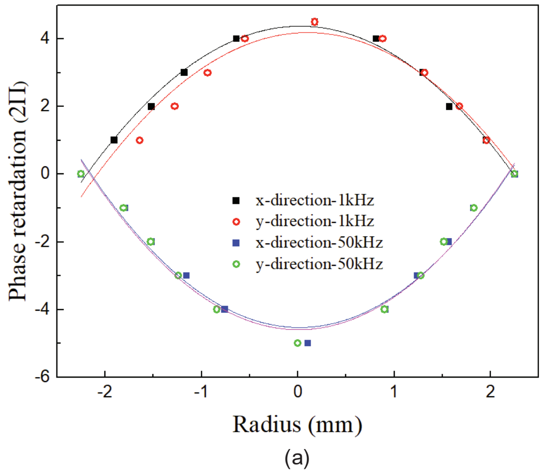


Fig. 6 Optical power of the DFLC lens as a function of applied voltage.



(b)

Fig. 7 Phase retardation of DFLC lens operated at 150 V (a) one-layer structure (b) four-layer structure.

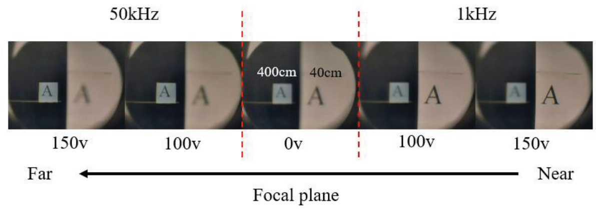


Fig. 8 Image performance of the four-layer DFLC lens.

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