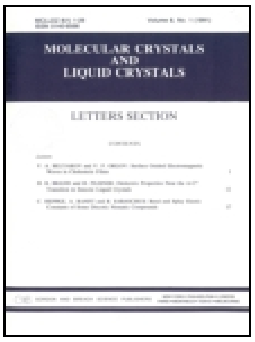

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Switchable Aperture of Liquid Crystal Lens Array Fabricated with a Hole-Array Patterned Metal Foil Spacer

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A liquid crystal lens array (LCLA) with switchable dual apertures via a middle layer of hole-array patterned metal foil in the cell is demonstrated. The behaviour of electro-optical capabilities in fabricated LC lens arrays is directly relative to the ways of applying voltages, especially for switchable lens apertures. The hole-array patterned metal foil was fabricated via a laser drilling process, which was responsible for some functions including conductive electrode, controllable spacer, and cell substrate.

Keywords liquid crystals; lens array; metal foil

1. Introduction

In the past decades, the studies on liquid crystal lenses attracted numerous researchers' attention and proposed many application fields including photonic devices, displays [1–7], and three dimensional (3D) imaging systems [8–10]. For the purpose of 3D imaging applications, a way called integral imaging (InIm) system is very potential to be commercialized as autostereoscopic displays because of its unique characteristics [11]. The conventional lens arrays play an important role in InIm system, which are responsible two major processes of pickup and reconstruction. By contrast, LC lens arrays (LCLAs) are capable of lens ON/OFF to achieve the purpose of 2D/3D imaging switch in InIm system, and tunable focuses to enhance performance of image viewing depth. In order to achieve full parallax 3D images in InIm system, polarization-independent LCLAs are necessary instead of polarization-dependent ones. We propose that a structure of LCLA is composed of a middle metal foil with hole-array sandwiched between two ITO glass substrates to form

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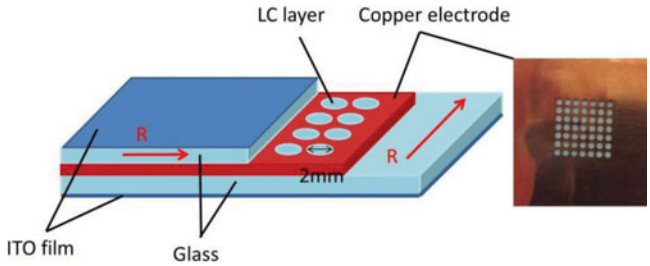

Figure 1. Scheme of a proposed LCLA. The cell is composed of a hole-array patterned metal foil sandwiched between two ITO glass substrates with rubbed PI films. The conductive ITO films on both glass substrates are located at outsides of the whole cell. The LCs is only filled in the volume of hole-array patterned areas. Two symbols of arrow-R mean rubbing directions on glass substrates for LC alignments.

two LC lens combination as a whole. If two LC lenses are individually fabricated with homogeneous cells and composited each other with orthogonal rubbing directions, the whole LC lens will be polarization-independent.

In this paper, we demonstrate a proposed structure of LCLAs with only LCs filled in volume of hole-array of metal foil (i.e., no LC layers exist between ITO glass substrates and metal foil) to investigate its electro-optical performance. Experimental results and discussions are illustrated as follows.

2. Processes of LCLA Fabrication

The proposed LCLA is mainly composed of one hole-array patterned metal foil (type C1020, 50 μm thickness), two ITO glass substrates (0.55 mm thickness for each one), and liquid crystals. The hole-array patterned metal foil was progressed via a high power laser drilling. The conductive surfaces of two ITO glass substrates were located at the outsides of LC cells. Liquid crystals (E7, purchased from Merck, with birefringence of $n_e = 1.7$ and $n_o = 1.5$) was only filled in volume of hole-array of patterned metal foil (2 mm in diameter for each unit). Figure 1 shows the scheme of proposed structure of LCLA in this study. In order to align LCs in the cells, two glass substrates with polyimide (PI) films were mechanically rubbed and assembly with orthogonal rubbing directions.

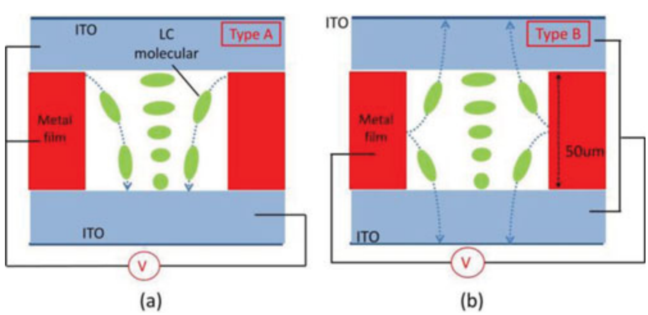

Figure 2. Cross-section view of predictive LC molecular distributions in a lens unit of LCLA with respect to the applying voltage ways. (a) Type A, (b) Type B.

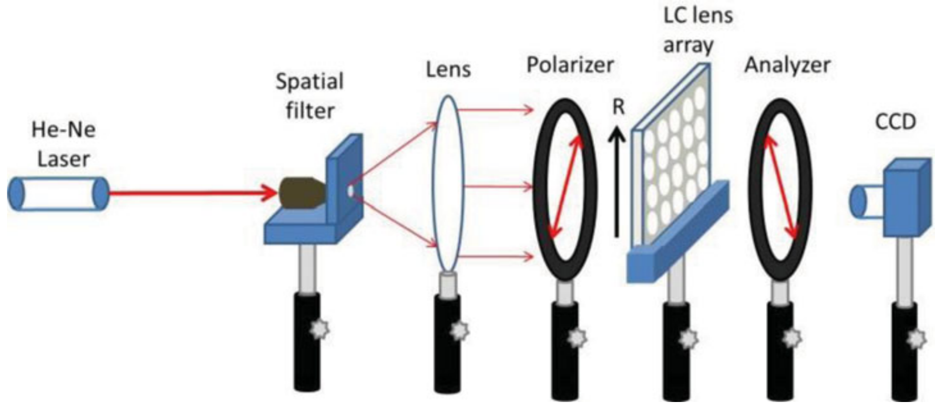

Figure 3. Experimental setup used to measure optical performance of the fabricated LCLAs.

Figure 2 shows a cross-section view of predictive LC molecular distributions occur in a lens unit of LCLA when individually applying voltages with Type A or Type B methods. When applying voltages with Type A method in the cell, one terminal of AC power supply is connected with one ITO glass substrate and metal foil and the other terminal of AC power supply is connected the other ITO glass substrate. Therefore, a non-uniform electric field is generated in the LC layer as shown in Fig. 2(a). The directors of LCs are re-orientated to align along the electric field to generate a gradient distribution of refractive indices with capabilities of lens functions as shown in Fig. 2(a). By contrast, applying voltages with Type B method is that two terminals of AC power supply are individually connected with both ITO glass substrates and metal foil so that a predictive LC molecular distribution is shown in Fig. 2(b).

3. Optical Performance of Fabricated LCLAs

Figure 3 shows the experimental setup used to observe and measure the optical performance of fabricated LCLAs. A light beam of He-Ne laser ($\lambda = 632.8$ nm) passing through a

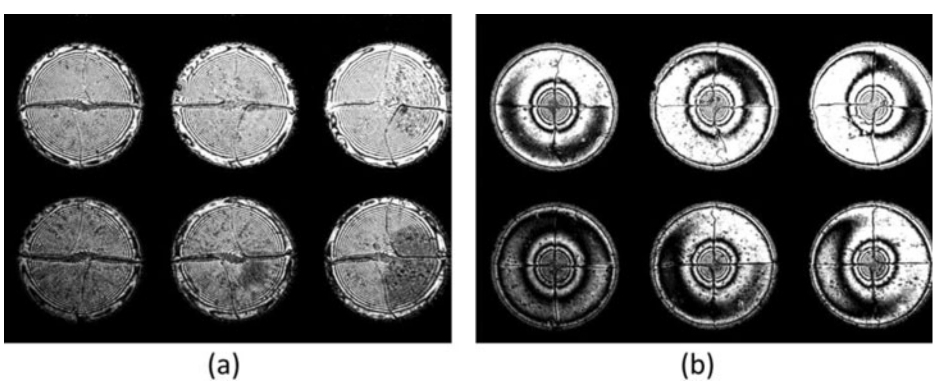

Figure 4. Observations of interference patterns occurred in a fabricated LCLA when applying voltages with Type A and Type B, respectively. (a) At the applied voltages of 40 V_{rms} in Type A; (b) At applied voltages of 180 V_{rms} in Type B.

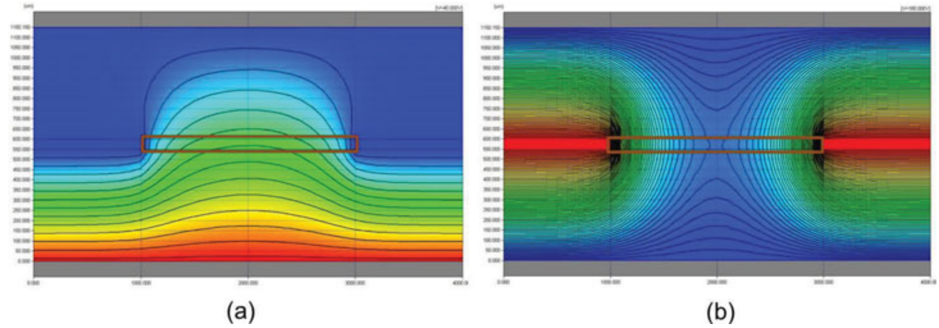

Figure 5. Comparisons of equal electric potential contours via simulation studies with respect to the applying voltage ways of Type A and Type B. (a) At applied voltages of 40 V_{rms} in Type A; (b) At applied voltages of 180 V_{rms} in Type B. The brown rectangles in two charts indicate the volume filled with LCs.

spatial filter and a lens became a circularly expanded and collimated beam with dimension of 35 mm in diameter. For the purpose of optical observations of interference patterns, the LCLA was placed at the position with a laser beam passing through and between a pair of crossed polarizers. Simultaneously, optical interference patterns in LCLAs were recorded via a CCD camera (DVC Company, 1500M-00-CL) when applying voltages with various ways.

Using the same experimental setup without the analyzer, the tunable focuses of LCLAs were also measured with respect to variously applied voltages. Figure 4 shows the interference patterns occurred in same LCLA when individually applying voltages of 40 V_{rms} in Type A and 180 V_{rms} in Type B. Obviously, it shows that the interference patterns are fully distributed in the circular area with a diameter of 2 mm in the former experimental conditions. By contrast, the interference patterns are only distributed in a smaller circular area with a diameter of 1 mm in the latter conditions.

According to electric field characteristics appeared in a lens unit via software simulation (LCD master, Shintech), the contours of equal electrical potential are very different and sensitive to the ways of applying voltages as shown in Fig. 5. In Fig. 5(a), it shows that

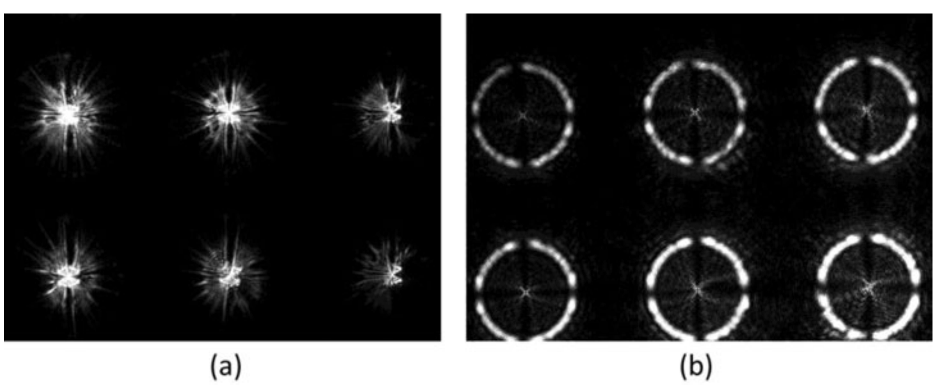

Figure 6. As same as experimental conditions in Fig. 4, optical focuses were observed and compared in the same LCLA.

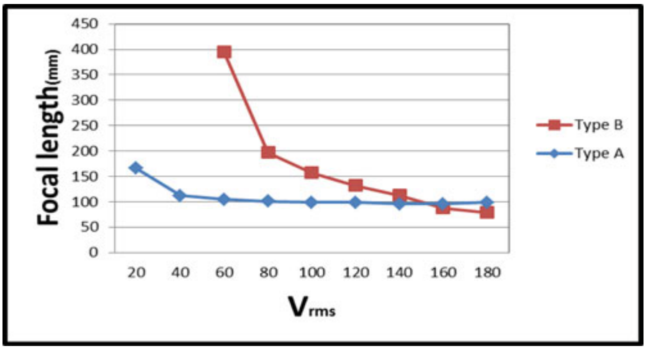

Figure 7. According to Eq. (1), tunable focuses in the fabricated LCLA with respect to the applying voltage ways of Type A and Type B are shown.

contours of equal electric potential occur in a lens unit of the proposed LCLA when applying voltages with Type A. Obviously, the gradient of electric potential is smoothly varied in LC volume so that interference patterns occur and fully occupy a whole patterned area. The optical behaviour of lens functions is very similar to LC lens with hole-patterned electrodes. By contrast, the contours of equal electrical potential with applied voltages in Type B are smoothly varied only in central area of LC volume so that interference patterns occur in a smaller area as shown in Fig. 5(b). In addition, Fig. 6shows focuses in LCLA with respect to individual applying voltage methods.

Usually, a focal length of LC lenses can be roughly evaluated with the following Eq. (1).

$$f = \frac{r^2}{2\lambda N}. \tag{1}$$

In Eq. (1), the r means the radius of circular area where interference patterns occur. The λ is wavelength of incident laser beam and N is total pairs of concentric black-white circles in lens area. In a fabricated LCLA, the tunable focal lengths with respect to the applied voltages are shown in Fig. 7. When applying voltages in Type A, a minimum focal length is close to 96 mm at applied voltages of 140 V_{rms}. When applying voltages in Type B, a minimum focal length is close to 79 mm at applied voltages of 180 V_{rms}. The tunable range of focuses are 166∼96 mm and 395∼79 mm with respect to the applying voltage ways of Type A and Type B, respectively.

4. Conclusions

By means of a hole-patterned array of metal foil, we have demonstrated a proposed LCLA with switchable dual apertures in lens units when applying voltages with two various ways. In addition, tunable focuses in lens units are obvious, which focal lengths are in the ranges of 166∼96 mm and 395∼79 mm with respect to the applying way of Type A and Type B, respectively. However, it is not convenient to operate the fabricated LCLAs with higher voltages. This issue is mainly occurred due to the usage of conductive ITO films located at the outsides of LC cells. If the inside ITO conductive films in the cells are used and simultaneously avoid possible short issues between ITO films and the metal foil, we believe the operation voltages will be obviously decreased.

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