Tunable Liquid Crystal Lenses and Their Applications

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Liquid crystal (LC) lens with transparent multiple ring electrodes and circular electrode inside is proposed for controlling spherical and conical lens-like optical phase retardations. Almost circular interference fringes can be smoothly tuned by adjusting the voltage applied across each patterned-electrode and the common flat electrode. The spherical and conical lens-like properties can be obtained, and the focal lengths at an optical axis can also be estimated by a ray tracing calculation resulting from the experimental phase retardation distribution.

Keywords: Liquid crystal, LC lens, Highly-resistive film, Ring electrodes, Phase retardation

1. Introduction

Liquid crystals (LCs) have electro-optical properties of a large birefringence and dielectric anisotropy. The LCs have been widely used in small-sized high resolution and brightness flat displays such as smart phones, digital cameras, and head mounted displays, and in large-sized lightweight displays such as direct-view TVs. The LCs have also been used in optical devices such as laser beam steering prisms and tunable focus lenses. An LC lens with an electrically tunable focal length was first reported using a lens-shaped LC layer [1]. There are various LC lenses with different structures such as a plano-convex cylindrical LC lens [2], an LC microlens array [3,4], an LC lens with a thin-film-resistor network [5], a polymer-stabilized or polymer composition LC lenses [6,7], an LC lens with any size [8], an LC diffractive lens [9], an LC lens with a hidden dielectric structure [10], an Fresnel LC lens [11], an LC lens having an additional floating electrode [12,13] and an LC lens with a photo-aligned dual frequency [14].

The lens property from a negative lens property to positive lens property (from a positive lens property to negative lens property) was demonstrated. The lens power of the LC lenses can be controlled with no mechanical movements by using an LC cell with a circularly hole-patterned electrode and circular electrode [15]. The improved LC lens with a wide variable range of lens power and the parabolic distribution of the phase profile is implemented using circularly patterned highly resistive transparent films with different diameters and sheet resistances [16]. The spherical refractive-index distribution can be obtained in the hole-patterned electrode when the circularly hole-patterned electrode of the LC lens is divided into several parts and the different voltages are applied to the divided electrodes. The beam-steering property in addition to the beam-focusing property can be obtained [17-20].

When three-dimensional (3D) objects are observed by using a camera system, the focused and defocused images can be obtained in same area. It is remarkable that the effect of focused and defocused images depends on the magnification of the video lens since a depth of field is inversely proportional to the aperture of the lens. There are several methods for estimating depth properties of an object [21-23].

In this work, a tunable focus LC lens with multiple ring-electrodes and circular electrode inside is proposed for controlling spherical and conical optical-phase retardation by applying the voltages across the upper patterned electrodes and lower common electrode. When the rays parallel to an optical axis are incident on the lens, the
focal length at the optical axis are obtained by a ray tracing calculation from the phase retardation of the lens. The spot size along the optical axis is also estimated by the ray tracing results.

2. Structure of an LC lens

Figures 1(a) and (b) show top and side views of an LC lens with the ring-electrodes and highly resistive film. The top substrate is coated with a transparent indium tin oxide film, where the ring electrodes with same widths of 2.8 mm in addition to a central circular-electrode of 2.0 mm in diameter, separated by a slit of about 0.1 mm. These circular-electrode and ring electrodes are fabricated by using a photolithographic process. The diameter of the outermost ring electrode is about 33 mm. A photo polymer film as an insulation is uniformly coated on the surfaces of circular-electrode and ring electrodes. The thickness of the polymer film is about 5 μm. The surface of the polymer film is coated with a zinc oxide thin film as a highly resistive film by a radio frequency sputtering deposition. The sheet resistance of the highly resistive film is controlled to be approximately 100 MΩ/sq. The surfaces of the highly resistive films on the top substrate and the transparent common electrode on the bottom substrate are coated with a parallel alignment polyimide material (AL1254, JSR Co.) by using a spin coater. The substrates are baked at the temperature of 180 ºC for 1 hour and then the surfaces of the polyimide film are rubbed in one direction by a rubbing machine. Two substrates are overlapped at anti-parallel rubbing directions. The cell gap is controlled by using polymer ball spacers of 60 μm in diameter. The LC material with Δn = 0.298 at 0.589 μm is injected into the empty cell. The AC voltages are applied across the circular and ring electrodes #1 ~ #7 on the upper substrate and the common electrode on the lower substrate.

3. Results and discussion

Figures 2(a) and (b) show interference fringe images of the LC lens observed under crossed polarizers at a wavelength of 0.55 μm. The rubbing direction in the LC lens is 45 degrees with respect to the polarization directions of both polarizers. When the voltages of \( V_1 = 0.8 \) V, \( V_2 = 1.0 \) V, \( V_3 = 1.1 \) V, \( V_4 = 1.4 \) V, \( V_5 = 1.6 \) V, \( V_6 = 3.5 \) V and \( V_7 = 3.5 \) V are applied across the top and bottom electrodes of the LC lens, the almost circular interference fringe images can be obtained as shown in Fig. 2(a). It seems that the spacing between two neighbor dark and / or interference fringes to decrease gradually. On the other hand, the circular interference fringes are also circular and the almost constant spacing can be seen between dark fringes as shown in Fig.2(b) when the voltages of \( V_1 = 0.9 \) V, \( V_2 = 1.1 \) V, 

![Fig. 1. Schematic diagram of an LC lens with ring electrodes and a circular electrode inside. (a) Top view and (b) Side view.](image)

![Fig. 2. Interference fringe images.](image)
$V_3=1.3\,V$, $V_4=1.7\,V$, $V_5=1.8\,V$, $V_6=3.5\,V$ and $V_7=3.5\,V$ are applied.

Figures 3(a) and (b) show the distributions of optical phase retardation obtained by counting the interference fringes along $y$-axis as shown in Figs. 2 since the neighbor interference fringe is $2\pi$. As shown in Fig. 3(a), the phase retardation can be obtained when the voltages of $V_1 \sim V_7 = 0.8\,V$, $1.0\,V$, $1.1\,V$, $1.4\,V$, $1.6\,V$, $3.5\,V$, $3.5\,V$ are applied. The solid line as shown in the Fig. 3(a) is a regression curve resulting from the quadratic equation of the measured phase retardation. The lens power can be estimated by calculating the parabolic regression curve of phase retardation. The focal length is 2.2 m and the lens power is 0.45 diopter. The rms (root mean square) difference between measured values and regression curve is 0.6. The conical distribution of phase retardation; that is the almost linear distribution of phase retardation along $y$-axis can also be obtained by arranging the applied voltages of $V_1 \sim V_7 = 0.9\,V$, $1.1\,V$, $1.3\,V$, $1.7\,V$, $1.8\,V$, $3.5\,V$, $3.5\,V$ as shown in Fig. 3(b). Two regression lines can be obtained by fitting the measured values. The rms difference between measured values and regression curve is about 0.5. The phase retardation near the center circular electrode seems to be a parabolic (quadric) curve.

The light parallel to an optical axis of symmetry through the center of the LC lens passes through the LC lens and then the focal length at the optical axis can be obtained by calculating the ray tracing from the phase retardation. Figures 4(a) and (b) show the focal length profiles when same voltages as shown in Figs. 2 are applied across the patterned electrodes and common electrode of the LC lens, where a radius indicates the position of light from the optical axis incident on the LC lens. As shown in Fig. 4(a) of the LC lens with the spherical lens profile, the focal length is about 2 m in the radius of 4 mm. The variation of focal length seems to increase as increasing the radius since the phase retardation deviates gradually from the quadric regression curve. As increasing the radius of the light, focal length becomes longer monotonically from 0 mm to about 7 mm in radius as shown in Fig. 4(b). The focal length also increases sharply from 7 mm to 8 mm in the radius.

Figure 5 shows the spot size property along the position of the optical axis determined by calculating the ray tracing from the experimental results of phase retardation. The spot size is gradually smaller and the value becomes $\phi=3.5\,mm$ at the position of 3.0 m and then the value increases monotonically as shown in Fig. 5(a) when the LC lens has the spherical lens-like profile. It is seen that the increase in the diameter
of a beam spot due to the deterioration of a wavefront aberration such as a spherical aberration. The spot size of the LC lens with the conical lens-like profile also decreases and the value becomes $\phi_{10.7}$ mm at the position of 5.6 m as shown in Fig. 5(b). The spherical aberration of the conical lens-like profile is larger than that of the spherical lens-like profile by arranging the voltages across the patterned electrode and common electrode.

The electrically tunable LC lens with function of the spherical and conical lens-like profiles can be applicable to an imaging lens system for effectively correcting wavefront aberration, a Bessel beam applications and a laser beam machining apparatus for beam shapers.

4. Conclusion

The tunable LC lens with ring electrodes and circular electrode inside has been developed. The spherical and conical lens-like optical phase retardation can be continuously controlled by arranging the voltages applied across the ring and central circular electrodes and common electrode. Both the focal length and beam spot size can be estimated by calculating the ray tracing from the experimental phase retardation distribution.

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