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Voltage-Controllable Liquid Crystals Lens

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***Abstract*—**This study investigates a voltage-controllable liquid crystals lens with a Fresnel zone electrode. When applying a proper voltage on the liquid crystal cell, a Fresnel-zone-distributed electric field is induced to direct liquid crystals aligned in a concentric structure. Owing to the concentrically aligned liquid crystals, a Fresnel lens is formed. We probe the Fresnel liquid crystal lens using a polarized incident beam with a wavelength of 632.8 nm, finding that the diffraction efficiency depends on the applying voltage. A remarkable diffraction efficiency of ~39.5 % is measured at the voltage of 0.9V. Additionally, a dual focus lens is fabricated by attaching a plane-convex lens to the Fresnel liquid crystals cell. The Fresnel LC lens and the dual focus lens may be applied for DVD/CD pick-up head, confocal microscopy system, or electrically-controlling optical systems.

***Keywords*—**Liquid Crystals Lens, Fresnel Lens, and Dual focus

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I. INTRODUCTION

LIQUID crystal (LC) devices support the external manipulation of optical beams via external electrical fields. The tunable ability on the basis of applying voltage attracts considerable attention. Particularly, the optical birefringence of liquid crystals is important to this optical modulation [1-5]. Fresnel zone plate reveals various potential applications in display, millimeter-wave devices and spectroscopic systems [6-8]. Applying liquid crystal materials as a matrix of Fresnel zone plate becomes interesting due to electrically-tunable function on the optical beam.

The diffractive lens of liquid crystals has been widely explored in recent years. Patel *et al.* and Wu *et al.* [9-11] propose a Fresnel liquid crystal lens, which possesses an electrically controllable diffraction property. Fuh *et al.* [12] developed a Fresnel lens based on dye-doped liquid crystals, and the lens exhibits polarization-independent properties and high efficiency. Guogiang *et al.* [13, 14] also fabricates a nematic liquid crystal with a switchable large-aperture. These devices exhibit tunable focusing length, and tunable phase modulation, and et al., however, a Fresnel LC lens with uncomplicated fabrication, high diffraction efficiency and a low driving voltage is demanded for practical applications.

This study fabricates a Fresnel lens of liquid crystals (LC), that the diffraction efficiency of the lens depends on the applying voltage. The lens forms owing to the concentric orientation of liquid crystals in the cell. With a probe of a polarized laser beam of 632.8 nm in wavelength, the lens reveals voltage-dependent diffraction efficiency. The maximum efficiency of 39.5 % occurs at the driving voltage of 0.9 V. We also fabricate a dual focus Fresnel lens by attaching a plane-convex lens to the LC cell. The results of our experimental investigation are presented and discussed.

II. THEORETICAL BACKGROUND

A Fresnel lens, known as a kinoform lens, consists of several segments of a small positive lens. The Fresnel zones of the Fresnel lens individually collect the optical beams and effectively diffract them to the focal point. Generally, the phase difference between the odd and even zones of the Fresnel pattern is π. For an ideal phase binary Fresnel zone plate, the first-order diffraction efficiency can be expressed as [15]

$$\eta_1 = \left[\sin\left(\frac{m\pi}{2}\right) / \left(\frac{m\pi}{2}\right) \right]^2 \tag{1}$$

where m denotes the diffraction order. Equation (1) shows the diffraction efficiency of the primary focus is theoretically 40.5 %. This fabricates a binary Fresnel LC lens as a phase Fresnel zone plate. We apply voltages to the Fresnel LC lens for controlling the phase difference between the odd and even zones. As the liquid crystal molecules are reoriented by the voltage, the diffraction efficiency becomes be able to be electrically modulated. The experimental investigation of the Fresnel LC lens is described in following sections.

III. EXPERIMENT

In this study, the Fresnel LC cell is assembled with two indium tin oxide (ITO) glass plates. An ITO Fresnel zone electrode is fabricated on one of the glass plates by lithography. Figure 1 (a) shows the Fresnel pattern of ITO electrode. The radius of the *m*th zone of a binary Fresnel pattern is $r_m = \sqrt{m} r_1$, where r_1 (=0.5 mm) denotes the radius of the innermost zone. The zone number is 100. The even zones of ITO coatings are constructed as a Fresnel zone electrode. According to the binary Fresnel zone pattern, the primary focal length (f~39.5 cm) can be estimated, where $f = r_1^2 / \lambda$ [15] and the wavelength of the incident beam λ is 632.8 nm. Figure 1 (b) illustrates the configuration of the Fresnel liquid crystal cell. The plate with

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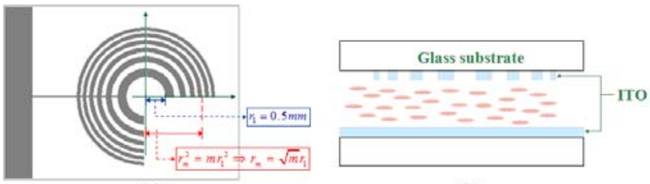
the ITO Fresnel electrode is set on top side and the ITO layers are on the inner faces of the LC cell. The cell gap is 38 μm. It has to be noted that both two ITO plates are spin-coated with a polyimide layer and then rubbed unidirectionaly for homogeneous orientation of LCs. The empty cell was injected into nematic LC E7 (E. Merck). The nematic phase of E7 ranges from T= $-10\,^{o}C$ to $60.5\,^{o}C$. The extraordinary and ordinary refractive indices (n_e and n_o) are 1.7354 and 1.5175, respectively (measured at a wavelength of λ=644 nm and a temperature of $T = 20\,^{o}C$.)



(a) (b)

Fig. 1 (a) Fresnel zone pattern of ITO electrode; radius (r_1) of innermost zone is 0.5 mm, (b) configuration of Fresnel liquid crystal cell

Figure 2 shows that the incident beam is focused by the Fresnel LC lens when applying a voltage on the cell. With a voltage, liquid crystal molecules E7 under the Fresnel zone electrode are reoriented due to the positive dielectric anisotropy. In the zone without an electric field, the LC molecules remained in homogeneously orientated state. Consequently, the concentric orientation of LCs is considered as a Fresnel phase lens to focus the incident beam. Herein, the Fresnel-distributed refraction index leads to a phase difference between adjacent Fresnel zones. The point A is the focus the lens. A leakage fringe field may be slightly reoriented the liquid crystals, but affects the Fresnel concentric orientation of LCs.

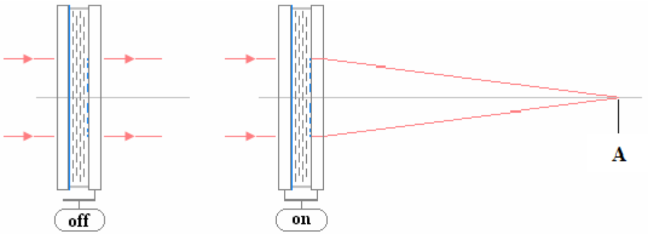


Fig. 2 The Fresnel LC lens focuses the incident beam by an applying voltage

Since the LC cell is a Fresnel phase lens, the diffraction depends on the phase difference between the odd and the even zones in the Fresnel pattern. When the LC molecules are homogeneously oriented in the cell, no phase difference occurs between the beam in the odd and the even zones. As increasing the driving voltage, a phase difference appears to affect the beam propagation. It has to be mentioned that the LCs layer dominates the phase difference. The phase difference cased by the Fresnel ITO pattern is negligible because of only 20nm-thickness of the ITO film.

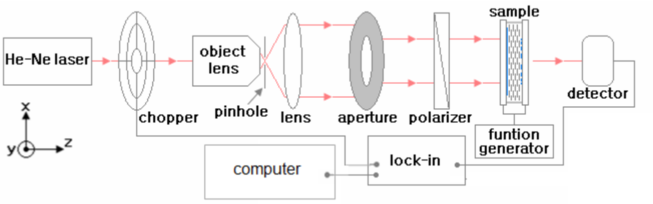


Fig. 3 Experimental setup for measuring diffraction efficiency of Fresnel LC lens

Figure 3 shows the experimental setup for measuring the diffraction efficiency of the Fresnel LC lens. The Fresnel LC lens is probed by an optical beam emerged from a He-Ne laser. The wavelength is 632.8 nm. The beam is expanded using a spatial filter, which included an objective and a pinhole. Then, a lens collimates light to normally incident into the Fresnel LC lens cell. A polarizer is adopted to control the beam polarization parallel to the x axis. The probe beam is eventually collected by an optical detector, placed at the focal point. Lock-in amplifier extracts the signal from the noise environment. In this study, the diffraction efficiency is defined as

$$\eta = \frac{p - p_o}{p_t} \qquad (2)$$

where p the optical intensity at the focal point of the Fresnel LC lens, p_t the intensity that passed through the Fresnel zone LC device when no driving voltage was applied, and p_o the residual optical intensity due to noise.

IV. RESULTS AND DISCUSSION

Figure 4 presents the diffraction efficiencies of Fresnel LC lenses with 100 electrode zones. It is found that the diffraction efficiency is an oscillatory function of driving voltage. The maximum efficiency of 39.5% occurs at the driving voltage of 0.9V. The remarkable high diffraction efficiency is referred to the numerous Fresnel zones, which effectively diffracting beam to the focus point. Theoretically, the phase Fresnel lens yields the maximum diffraction efficiency of 40.5 %. The measured diffraction efficiency is closed to the theoretical value.

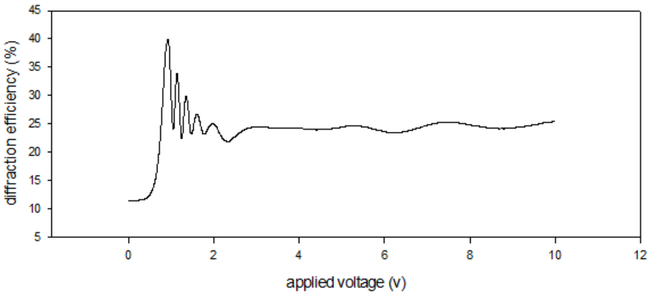


Fig. 4 Diffraction efficiencies of Fresnel LC lens with 100 Fresnel zones depends on applied voltage (frequency~1 kHz)

We also found that the diffraction efficiency at the focus depends linearly within the regime from 0.6 to 0.9 V. The diffraction efficiency dramatically increases from 14 to 39.5 %. The linear dependence of the diffraction efficiency within the narrow voltage regime of 0.3 V suggests a convenient modulation of the device operation.

Additionally, it is observed that the diffraction efficiency oscillates as increasing the applying voltage and the oscillation quenches when the voltage above 2.6 V. The thickness of 38 um of liquid crystal layer is considered the cause of the oscillation of diffraction efficiency. Since each evolution of 2π phase delay results in a period of oscillating diffraction efficiency, the thick LC layer can make a dramatic phase variation via a slight reorientation of LC molecules. When the applied voltage exceeded 2.6 V, the LC reorientation becomes stable and that leads to steady diffraction efficiency.

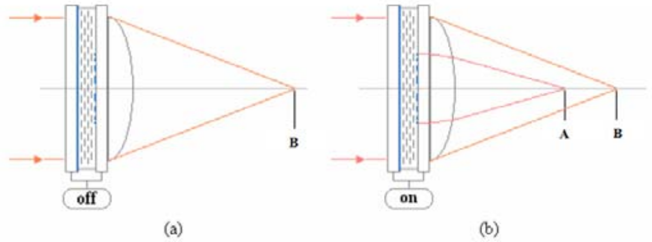


Fig. 5 Dual focus Fresnel LC lens (a) without and (b) with an applying voltage

This study also fabricates a dual focus lens by attaching a plane-convex lens to the Fresnel LC cell. Figure 5 shows the configuration of the dual focus system. The Fresnel LC cell is combined with a plane-convex lens, its focus length is 20 cm. Figure 5(a) illustrates that only one focus point B appears when no voltage applied to the dual focus lens. The attached plane-convex lens is responsible for the focusing of the incident beam. With the applying voltage, another focus (A) is observed due to both the primary Fresnel LC lens and the plane-convex lens.

Figure 6 illustrates the optical intensity of both two foci of the dual focus lens. The applied voltage is 0.9 (Fig. 6(a)) and 8.0 V (Fig. 6(b)). In Fig. 6(a), the optical intensity of focus A and B is 63.35 and 86.32 mV, respectively. It is noted that the cross section of the plane-convex lens is larger than that of the Fresnel LC lens. As a result, much more incident beam is collected by the plane-convex lens, i.e. leads to the higher intensity.

When increasing the voltage to 8.0 V, the intensity at the focus A decreases to 58.24 mV, but slight change at focus B. The decline of the diffraction efficiency from 39 to 24% is considered to be the cause of the decrease of the optical intensity at focus A. However, the optical intensity at focus B is slightly increased to 86.73V. The Fresnel LC lens, with an applying voltage of 8.0V, diffracts parts of incident beam to high-order focal positions and that possibly increases the optical intensity at focus B.

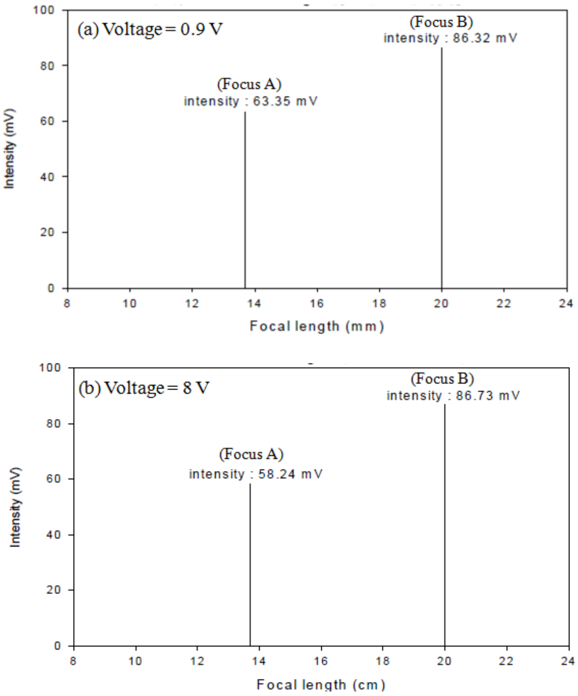


Fig. 6 Optical intensities at foci of LC lens, the applied votage is (a) 0.9 V and (b) 8.0V

In the study, the variance of phase difference between light paths in the odd and even zones determines the diffraction efficiency of both the Fresnel LC lens and the dual focus lens. The voltage-dependent phase difference of the lens leads to a possibility to be applied as electrically-controlling objectives for camera, tunable pick-up heads for DVD/CD, or other optical systems.

V. CONCLUSION

In summary, we have experimentally investigated the voltage-dependent diffraction efficiency of the Fresnel LC lens. The voltage-dependence of diffraction is inferred to the phase difference between odd and even zones of this Fresnel LC lens. With a low driving voltage of 0.9 V, the diffraction efficiency approaches even to~39.5%. Additionally, a dual focus lens is fabricated by attaching a plane-convex lens to the Fresnel LC cell. The Fresnel LC lens and the dual focus LC lens with tunable diffraction efficiency reveals high potential for optical devices required electrical controllability.

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REFERENCES

[1] S. Sato, “Liquid-crystal lens-cells with variable focal length,” Jpn. J. Appl. Phys. vol. 18, pp. 1679-1684, 1979.
[2] Nabeel A. Riza and Michael C. Dejule, “Three-terminal adaptive Nematic liquid-crystal lens device,” Opt. Lett. vol. 19, pp. 1013-1015, 1994.

[3] F. Naumov, M. Yu. Loktev, I. R. Guralnik, and G. Vdovin, “Liquid-crystal adaptive lenses with modal control,” Opt. Lett. vol. 23, pp. 992-994, 1998

[4] A. F. Naumov, G. D. Love, M. Yu. Loktev, and F. L. Vladimirov, “Control optimization of spherical modal liquid crystal lenses,” Opt. Express vol. 4, pp. 344-352, 1999.

[5] Wen-Chi Hung, Wood-Hi Cheng, Ming-Shan Tsai, Yi-Chung Juan, I-Min Jiang, and Pochi Yeh, “Surface Plasmon Enhanced Diffraction in Cholesteric Liquid Crystals”, Applied Physics Letter, vol. 90, 183115, 2007.

[6] F. Sobel, L. Wentworth, and J. C. Wiltse, “Quasi-optical surface waveguide and other components for 100- to 300-Ge region”, IRE Trans. Microw. Tech. vol. 9, pp. 512-518, 1961.

[7] C. H. Tsai, P. Lai, K. Lee, and C. K. Lee, “Fabrication of a large F-number lenticular plate and its use as small-angle flat-top diffuser in autostereoscopic display screens”, Proc. SPIE vol. 3957, pp.322-329 2000.

[8] N. Kitatura, S. Ogata, and Y. Mori, “Spectrometer employing a micro-Fresnel lens”, Opt. Eng. vol. 34, pp. 584-588, 1995.

[9] J. S. Patel and K. Rastani, “Electrically controlled polarization-independent liquid-crystal Fresnel lens arrays,” Opt. Lett. vol. 16, pp. 532-534, 1991.

[10] Yun-Hsing Fan, Hongwen Ren, and Shin-Tson Wu, “Switchable Fresnel lens using polymer-stabilized liquid crystals”, Optics Express, vol. 11, pp. 3080-3086, 2003.

[11] Hongwen Ren, Yun-Hsing Fan, and Shin-Tson Wu, “Tunable Fresnel lens using nanoscale polymer-dispersed liquid crystals,” Appl. Phys. Lett. vol. 83, pp. 1515-1517, 2003.

[12] Liang-Chen Lin, Hong-Chang Jau, Tsung-Hsien Lin, Andy. Y. G. Fuh*, 2007,“Highly efficient and polarization-independent Fresnel lens based on dye-doped liquid crystal”, Optics Express, vol. 15, pp. 2900-2906, 2007.

[13] Guoqiang Li, Pouria Valley, M. S. Giridhar, David L. Mathine, Gerald Meredith, Joshua N. Haddock, Bernard Kippelen, and N. Peyghambarian “Large-aperture switchable thin diffractive lens with interleaved electrode patterns”,Appl. Phys. Lett., vol. 89, 141120, 2006.

[14] Guoqiang Li, David L. Mathine, Pouria Valley, Pekka Äyräs, Joshua N. Haddock, M. S. Giridhar, Gregory Williby, Jim Schwiegerling, Gerald R. Meredith, Bernard Kippelen, Seppo Honkanen, and Nasser Peyghambarian, “Switchable electro-optic diffractive lens with high efficiency for ophthalmic applications”, Applied Physical Sciences, vol. 103, p. 6100, 2006.

[15] H. Dammann, “Blazed synthetic phase-only holograms,” Optik, vol. 31, pp. 95-104, 1970.