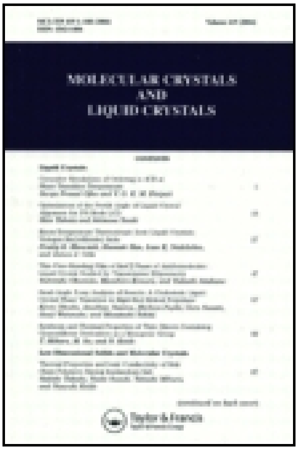

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Electrically Controlled Diffraction Efficiency of Liquid Crystal Fresnel Lens with Polarization-Independence

Dong-Woo Kim [a], Sin-Doo Lee [a] & Chang-Jae Yu [b]

[a] School of Electrical Engineering, Seoul National University, Kwanak, Seoul, Korea

[b] Department of Materials Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA

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Dong-Woo Kim
Sin-Doo Lee
School of Electrical Engineering, Seoul National University, Kwanak, Seoul, Korea

Chang-Jae Yu
Department of Materials Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA

We demonstrated an electrically controllable Fresnel lens with polarization-independence based on a liquid crystal. The polarization-independence of the Fresnel lens was obtained in an orthogonally aligned hybrid configuration between two adjacent zones. The Fresnel lens was fabricated using a single-masking process of the ultraviolet exposure for the photo-alignment of the LC. The polarization-independence and the electrical tunability of the Fresnel lens were analyzed at the different polarization states of an incident light as a function of the applied voltage.

Keywords: diffraction efficiency; Fresnel lens; liquid crystal; polarization-independence

INTRODUCTION

The Fresnel lenses performing various intensity modulation of an incident light play an important role in many optical technologies such as optical interconnection, optical information processing, and three-dimensional display system [1–3]. In general, the Fresnel lenses, fabricated by electron-beam writing [4] or thin film deposition [5], inevitably have several problems such as static diffraction efficiency and complicated fabrication techniques. Recently, dynamic Fresnel

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Address correspondence to Prof. Sin-Doo Lee, School of Electrical Engineering #032, Seoul National University, Kwanak P.O. Box 34, Seoul 151-600, Korea. E-mail: sidlee@plaza.snu.ac.kr

lenses based on liquid crystal (LC) [6–9] have been reported to achieve controllable diffraction efficiency. However, the intrinsic uniaxial anisotropic property of the LC molecules induces polarization-dependent diffraction efficiency for an incident light. In order to eliminate this polarization-dependence, several fabrication methods [8,9] have been proposed such as orthogonal cascading of two Fresnel lenses and orthogonal aligning of the LC molecules in neighboring zones. However, such fabrication methods required well-defined aligning technique, multi-rubbing process, and elaborate photolithographic technique.

In this work, we present a simple method of fabricating a polarization-independent liquid crystal Fresnel lens in a binary phase type [10]. The orthogonally aligned hybrid configuration between two adjacent zones was produced using a single-masking process of the ultraviolet (UV) exposure for the photo-alignment of the LC. The photopolymer used in this study has a property of homogeneously aligning the LC molecules depending on a linearly polarized ultraviolet (LPUV) light [11]. Note that the LPUV aligning capability of the photopolymer allows for essentially a single-masking process. This orthogonally aligned hybrid configuration of the LC molecules leads directly to the polarization-independent property of the Frensel lens irrespective of the polarization state of the incident light.

DESIGN OF FRESNEL LENS

The basic structure of our LC Fresnel lens is described in Figure 1(a). The LC molecules are aligned in an orthogonally aligned hybrid configuration with alternating zones. In this binary phase type of the LC Fresnel lens, the diffraction efficiency is electrically controllable and it has the maximum at the relative phase shift of π. It is known that in a binary phase type Fresnel lens, the radius R_m of the mth zone is determined by $R_m^2 = mR_1^2$ where R_1 is the radius of the innermost zone. The focal length f of the Fresnel lens is related to the innermost radius R_1 as $f = R_1^2/\lambda$ where λ is the wavelength of the input light.

The polarization state of the incident light propagating along the z axis can be decomposed into two orthogonal polarization components of $\cos\psi\,\hat{x}$ and $\sin\psi\,\hat{y}$ where ψ represents the input polarization direction with respect to the x axis. As shown in Figure 1(b) and 1(c), the relative phase shift $\Delta\phi$ of the x-polarized (or the y-polarized) light is different because of an orthogonally alternating hybrid configuration. In the case of the x component, the incident light passing through odd zones experiences the phase retardation of $2\pi n_{\text{eff}}\,d/\lambda$ where n_{eff} and d denote the effective refractive index controlled by applied voltage and the cell thickness, respectively. The phase retardation through even zones remains to

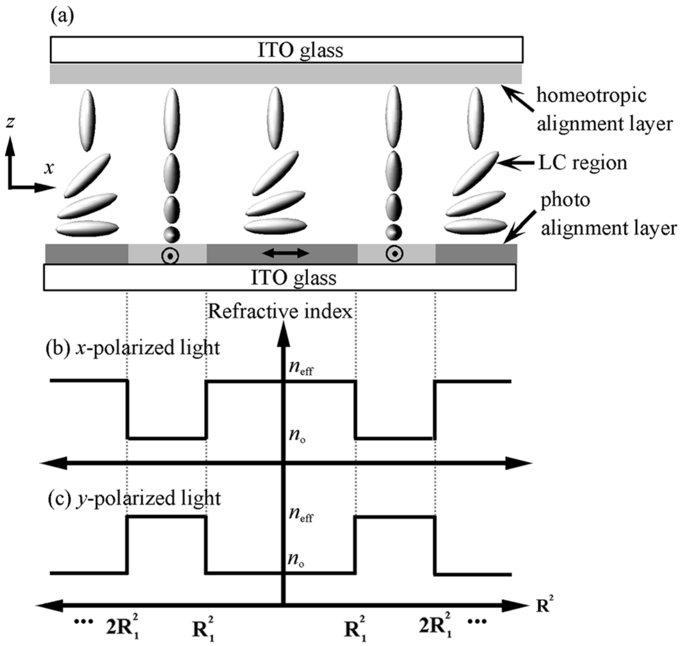

FIGURE 1 (a) Schematic diagram of our LC Fresnel lens in an orthogonally aligned hybrid configuration in a binary phase type. The refractive index profiles of (b) the x-polarized incident light and (c) the y-polarized incident light.

be $2\pi n_o d/\lambda$ where n_o is the ordinary refractive index of the LC. As a result, the relative phase shift between the odd and even zones is given by $\Delta\phi = 2\pi(n_{\text{eff}} - n_o)d/\lambda$, which is electrically controllable. Similarly, the phase retardation of the y component of the incident light is determined $2\pi n_o d/\lambda$ and $2\pi n_{\text{eff}} d/\lambda$ at odd and even zones, respectively.

In our case, the transmittance function of the x and y components in the Fresnel diffraction equation [12] is defined by

$$
\begin{aligned}
t_x(R^2) &= \cos\psi \cdot \sum_{m=0}^{M/2}\left[\operatorname{rect}\left(\frac{R^2 - 2mR_1^2 - \frac{R_1^2}{2}}{R_1^2}\right)\cdot \exp(j\Delta\phi)\right.\\
&\qquad\left. + \operatorname{rect}\left(\frac{R^2 - 2mR_1^2 - \frac{3R_1^2}{2}}{R_1^2}\right)\right],\\
t_y(R^2) &= \sin\psi \cdot \sum_{m=0}^{M/2}\left[\operatorname{rect}\left(\frac{R^2 - 2mR_1^2 - \frac{R_1^2}{2}}{R_1^2}\right)\right.\\
&\qquad\left. + \operatorname{rect}\left(\frac{R^2 - 2mR_1^2 - \frac{3R_1^2}{2}}{R_1^2}\right)\cdot \exp(j\Delta\phi)\right],
\end{aligned}
\tag{1}
$$

where rect(x) is 1 for $|x| \leq 1/2$, and 0 otherwise. Here, M and $\Delta\phi$ represent the number of the zones and the relative phase shift, respectively. Using the transmittance function of Eq. (1), the nth Fourier component of each polarization state, x_n or y_n, is given by

$$x_n = \frac{1}{2}\exp\left(-\frac{j\Delta\phi n}{2}\right)[-1 + \exp(-j\Delta\phi n)]\mathrm{sinc}\left(\frac{n}{2}\right) \cdot \cos\psi,$$
$$y_n = \frac{1}{2}\exp\left(-\frac{j\Delta\phi n}{2}\right)[1 - \exp(-j\Delta\phi n)]\mathrm{sinc}\left(\frac{n}{2}\right) \cdot \sin\psi, \tag{2}$$

where $\mathrm{sinc}(x) = \sin(\pi x)/\pi x$. Then, the diffraction efficiency in the focal plane, at $\Delta\phi = \pi$ and $n = -1$, can be obtained from Eq. (2) as

$$\eta = x_n \cdot x_n^* + y_n \cdot y_n^* = 0.41. \tag{3}$$

It is clear that the diffraction efficiency in Eq. (3) is constant irrespective of the polarization state of the incident light. The outcoming polarization state in the focal plane can be obtained by Fourier transformation of the odd and even zones polarization states [13] and is always symmetrical respective to the x axis for any polarization state of the incident light.

EXPERIMENTS

Our LC Fresnel lens in a binary phase type was fabricated using a single-masking process. In order to obtain the orthogonally alternating hybrid alignment in neighboring zones, the photopolymer of LGC-M2 (LG Cable Ltd., Korea) was spin-coated on one of two substrates for homogeneous alignment and the polyimide of JALS-203 (Japan Synthetic Rubber Co.) on the other for the homeotropic alignment. The LGC-M2 produces the homogeneous alignment of the LC molecules under the LPUV exposure along a certain direction which can be repeatedly defined according to the polarization direction of the last UV exposure [11]. Such aligning capability of the photopolymer permits to align the LC molecules orthogonally in neighboring zones. The whole region of the photopolymer layer was first illuminated with the LPUV to produce the homogeneous alignment of the LC molecules along the y direction. A subsequent LPUV exposure through a zone plate-type amplitude photomask was carried out to align the LC molecules perpendicular to the initial alignment direction (the y direction). Finally through a two-step UV exposure, an orthogonal alignment in neighboring zones was then produced. Such binary-type substrate and the homeotropic substrate were assembled to produce our LC Fresnel lens. The LC material used in this study was MLC-6082 of

Merck. The dielectric anisotropy $\Delta\varepsilon = 10.0$, the ordinary refractive index $n_o = 1.4935$, and the extraordinary refractive index $n_e = 1.6414$. The cell gap was maintained using glass spacers of 7.5 μm thick. Note that the focal length of the binary phase type Fresnel lens is governed by the physical dimensions of transparent odd zones and opaque even zones in the photomask. The photomask used in this work has a focal length of 30 cm at the wavelength of 543.5 nm and consists of 80 zones in the aperture size of 7.2 mm. The radius R_1 of the innermost zone is 403.8 μm.

RESULTS AND DISCUSSION

We measured the diffraction efficiency of our Fresnel lens as a function of the applied voltage in the focal plane. In this experiment a He–Ne laser of the wavelength of $\lambda = 543.5$ nm was used as a light source. The diffraction efficiency is plotted as a function of the applied voltage in Figure 2. In the case of no applied voltage, the cell thickness $d = 4.1$ μm is needed to have $\Delta\phi = \pi$. For our LC cell with $d = 7.5$ μm, the relative phase shift of $\Delta\phi = \pi$ occurs at 1 V. The maximum diffraction efficiency was measured as about 0.35, which is somewhat smaller than the theoretical value of 0.41. This discrepancy between experimental results and theoretical results comes from the smooth boundaries between alternating zones due to the fluidity and the continuum elasticity of the LC. Such boundary effect was reflected in a

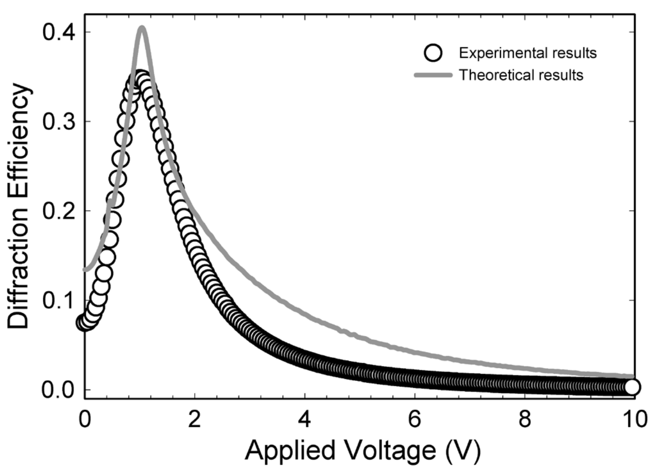

FIGURE 2 Dynamic diffraction efficiency of our LC Fresnel lens as a function of the applied voltage for an incident light polarized along the x axis.

linearly graded phase model [14] instead of using stepwise phase profiles as shown in Figure 1(b) and 1(c). At 10 V, the LC molecules become oriented perpendicular to the substrate plane and thus the effective refractive index n_{eff} approaches n_{o}. Therefore, the relative phase shift disappears. Thus, the diffraction efficiency of our Fresnel lens reduces asymptotically to zero as shown in Figure 2.

Figure 3 shows the dynamic focusing and polarization-independent properties. The images of a laser beam at 0 V, 1 V, and 10 V were captured at different polarization state of incident light by a charge-coupled device (CCD) camera in the focal plane. As the applied voltage increases from 0 V to 10 V, the relative phase shift approach zero and thus the focused laser beam becomes a Gaussian beam. In the focal plane, the spherical aberration of our lens is negligible but a certain degree of the chromatic aberration exists because the focal length is determined by $f = R_1^2/\lambda$ [15]. The focusing and defocusing times were about 35.4 ms for the voltage from 10 V to 1 V, and 10.5 ms from 1 V to 10 V, respectively.

In order to see the centro-symmetric polarization-independent property, the diffraction efficiency was measured at various incident polarization and applied voltage as shown in Figure 4. Open squares, circles, and triangles represent the diffraction efficiencies at the voltages of 0 V, 1 V, and 10 V, respectively. A linearly polarized incident beam was rotated counterclockwise from 0° to 360° with respect to the x axis. The magnitude of the diffraction efficiency is given by the

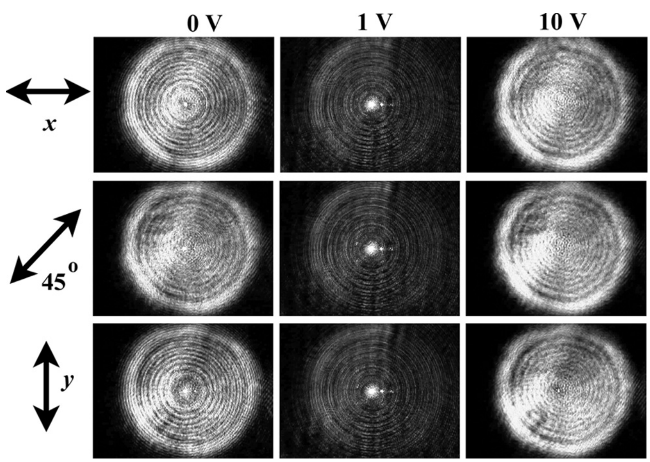

FIGURE 3 The CCD images of focusing and defocusing for the x, $+45^\circ$, and the y polarized light at various applied voltages.

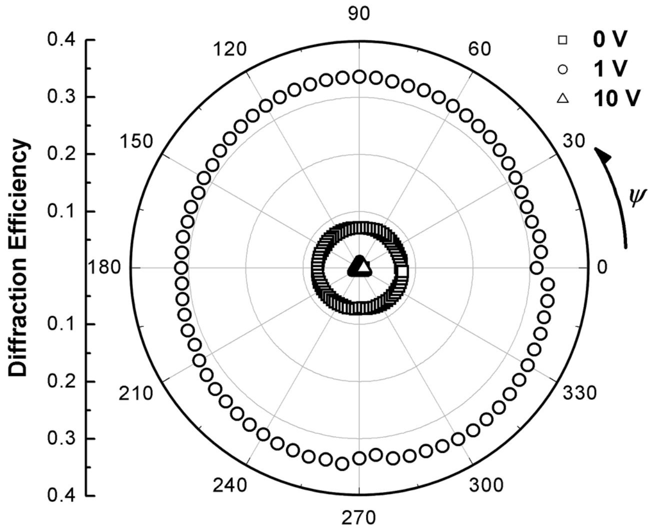

FIGURE 4 The polar plot of the centro-symmetrical diffraction efficiencies as a function of the polarization state of the incident light for various applied voltages.

radius of the circle and the polarization direction of the incident beam is denoted by the angle ψ. It was found that our LC Fresnel lens has the polarization independence which is well preserved under any applied voltage.

CONCLUSION

We presented a simple method of fabricating binary phase type polarization-independent LC Fresnel lens through a single-masking process. The single-masking technique presented here would be a powerful tool of fabricating LC-based optical devices that need orthogonally alternating hybrid zones such as the polarization-independent LC Fresnel lens. The centro-symmetrical diffraction efficiency together with the electrical tunability of our LC Fresnel lens is applicable for a variety of optical systems.

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