Electrically switchable liquid crystal Fresnel lens using UV-modified alignment film

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Abstract: A simple method to make a switchable liquid crystal (LC) Fresnel lens with high diffraction efficiency and a low driving voltage was proposed based on the photo-induced surface modification of the vertical alignment layer. UV illumination alters the pretilt angle of alignment layers, a Fresnel zone-distribution hybrid alignment in the homeotropic LC cell can be straightforwardly achieved through UV exposure, yielding a concentric structure of the Fresnel phase LC lens. A remarkable diffraction efficiency of ~31.4%, close to the measured diffraction efficiency of the used Fresnel-zone-plate mask of 32%, was detected using a linearly polarized incident beam.

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1. Introduction

Electrically modulated diffraction efficiency of the Fresnel lens has recently attracted considerable research attention in some applications, such as spectrometer [1], projection displays [2], long distance optical communication [3], and variable optical data storage system [4] using a zone plate modulator. The superior electro-optic property and low operating voltage of the liquid crystal (LC) make it a very good candidate for electrically switchable lens devices. Recent research has also extended the conventional Fresnel device by combining the Fresnel zone plate and LC material to make the optical properties electrically tunable [5–14]. With the application of an electric field, the phase difference between the odd and even zones is induced by reorienting the LC molecules. Thus, the diffraction efficiency of a Fresnel lens can be electrically modulated.

The electrically switchable LC Fresnel lenses have been demonstrated using electron-beam lithography [9], polymer-dispersed liquid crystals (PDLC) [10], polymer-stabilized liquid crystals (PSLC) [11], and dye-doped nematic liquid crystals (DDLC) [12,13]. Among these methods, the fabrication of PDLC or PSLC Fresnel lens is quite simple; however, PSLC Fresnel lens [11] has low diffraction efficiency due to the defects of the polymer network at the zone edges. Meanwhile, Fresnel lenses based on PDLC [10] with the diffraction efficiency close to the theoretical limit require a very high operating voltage (approximately 12 $V_{rms}/\mu m$), yet the phase change is very small. The generated DDLC Fresnel lens, which is fabricated by photo-induced dye-adsorption, requires a high power laser (~24 mW/cm^2) to pump azo-dyes to align LC directors.

In this paper, we demonstrated an electrically switchable, highly efficient Fresnel lens based on hybrid aligned liquid crystal (HALC) by using a single-sided photo-alignment technique. It is well documented that UV exposure extensively modifies the physical and chemical properties of the polymer materials [15]. The surface tension of polymeric polyimide (PI) alignment film is increased by increasing the amount of UV irradiation. UV illumination is thus an effective tool for surface modification of the alignment layers to achieve the desired LC alignment. UV exposure of a homeotropic alignment film through a Fresnel-zone-plate mask yields an alignment layer with binary zone structures to obtain the alternating hybrid-aligned LC configuration. A Fresnel zone-distributed alignment was thus formed in the vertical LC cell, yielding a concentric structure of LCs as a Fresnel phase lens. This fabrication method is relatively inexpensive, simple, and exceptionally promising. In addition, the proposed lens device can be operated at less than 8 volts, with a remarkable diffraction efficiency of approximately 31.4% and fast response time. Such a device works well for a linearly polarized light

2. Fabrication method

The technique of a UV-induced surface modification of the polyimide alignment film was applied to fabricate a switchable LC Fresnel lens. Based on the UV-induced changes in the pretilt angle of the vertically aligned PI films, a binary LC Fresnel lens can be easily achieved, as shown in the fabrication process of Fig. 1. The critical element for making the Fresnel zone plate is the photomask with a circular pattern, which has opaque odd zones and transparent even zones. In this work, the radius r_1 of the innermost zone designed is 0.4 mm and the radius of the n^{th} zone (r_n) is given by $r_n^2 = nr_1^2$, where n is the zone number. Our Fresnel zone plate consists of 100 zones in approximately a 1 cm aperture.

According to the Fresnel diffraction theory [13], the focusing diffraction efficiency of the proposed Fresnel lens can be deduced as

$$\eta_m = \left[\frac{\sin\left[\frac{\pi}{\lambda}\left(\Delta_{even} - \Delta_{odd}\right)\right]}{\frac{m\pi}{2}} \right]^2 \tag{1}$$

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where m represents the diffraction order, Δ_{odd} and Δ_{even} are the optical paths through the odd zones and the even zones of the Fresnel pattern, respectively. When the phase difference of the proposed LC Fresnel lens between the odd zones and the even zones, $\frac{2\pi}{\lambda}(\Delta_{even}-\Delta_{odd})$, is designed to be π, the theoretical maximum first order (m = ± 1) diffraction efficiency η_1 can be obtained.

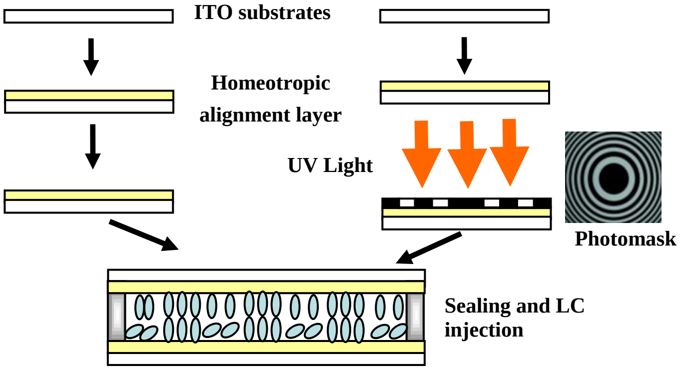

Fig. 1. The process flow of the hybrid aligned liquid crystal Fresnel lens

To fabricate the LC Fresnel lens device with hybrid alignment in the even zones, the buffed polyimide AL60101 (JSR) films, serving as LC vertical alignment layers, were first spin-coated on the two ITO substrates and then pre-baked at 100°C on the hot plate; finally, they were baked in a thermal oven for one hour. Subsequently, a UV light (intensity: 34.1 $\mathrm{mW/cm^2}$) illuminated only the homeotropic alignment film of the bottom substrate through a Fresnel-zone-plate mask. After finishing UV illumination, the homeotropic alignment film became horizontally aligned. The top and bottom substrates were then assembled into a cell such that the rubbing directions at the glass plates were anti-parallel, with a cell gap of 9.3 μm maintained by spacers. The positive LC (E7, n_e = 1.7371 and n_o = 1.5183 at wavelength λ = 632.8 nm; Merck) was injected into the empty cells using the capillary effect. The UV illumination-modified PI film made the LC molecules hybrid aligned in the selective even zones of a homeotropic LC cell, thereby readily obtaining a tunable LC Fresnel lens.

For characterizing the focusing properties of the LC Fresnel zone plate, the image quality, 3D spot intensity profiles, and voltage-dependent diffraction efficiency were measured. Figure 2 shows the experimental setup. The output beam of the He-Ne laser was magnified to approximately 1 cm just to cover the aperture of the zone patterns with an expander. A polarizer was used, with its optical axis parallel to the cell-rubbing direction. The cell's light-focusing properties were measured using a CCD camera and detector, which were set at ~25 cm from the Fresnel lens.

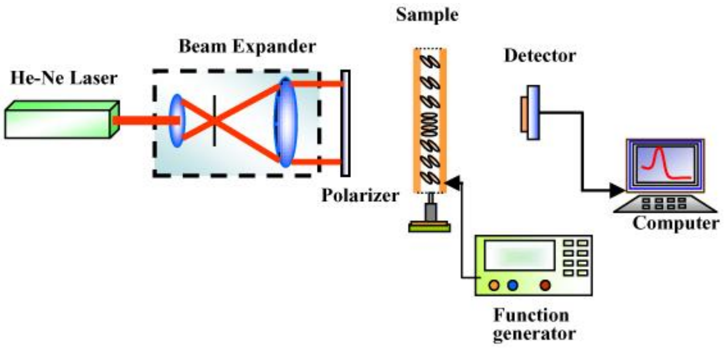

Fig. 2. The experimental setup for studying the focusing properties of the LC Fresnel lens

3. Experimental results and discussion

3.1 UV-induced changes in the polyimide (PI) alignment layer

The exposure of PI alignment film to UV irradiation can lead to extensive physical and chemical modification of PI layers; the interaction between LC and PI alignment films is also altered. To obtain the optimum UV exposing condition, UV light-induced changes in the surface tension and pretilt angle of PI alignment films for different UV exposure times were studied, in which the pretilt angle of the UV-modified PI layer was measured using the modified crystal rotation method [16]. Both the surface tension and pretilt angle were expected to be modified by UV illumination, as shown in Fig. 3. The pretilt angle of the rubbed PI layer was observed to continuously decrease with increasing UV illumination time. However, the pretilt angle decreased strongly, correlating to the surface tension increases with UV-exposed time, as reported elsewhere [15]. According to the experimental results, the effect of UV-modified pretilt angle of PI alignment layers was utilized to achieve Fresnel lens with hybrid alignment in this work.

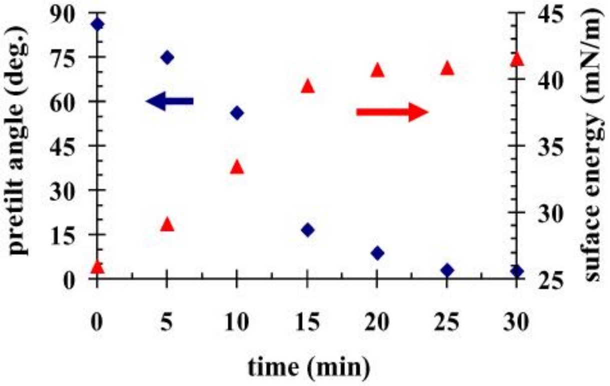

Fig. 3. The relationship between pretilt angle and surface energy versus UV illumination time

3.2 Characteristics of LC Fresnel lens

Figures 4(a-c) show a portion of the LC zone plate at V=0, 1.0, 2.0, and 7.0 V_{rms}, respectively, in which the rubbing direction of the LC cell was oriented at 45° relative to the transmission axis of the linear polarizer. At V=0, the orientation of LC molecules on the even and odd zones are hybrid and vertically aligned, respectively. As the applied voltage exceeds the threshold voltage, the color in the even zones changes as shown in Figs. 4(b-d). The color transforms result from the voltage-induced refractive index change. Although the applied voltage is beyond 7 V_{rms}, the bulk of LC directors are oriented nearly perpendicular to the substrates; therefore, the zone structure was gradually erased.

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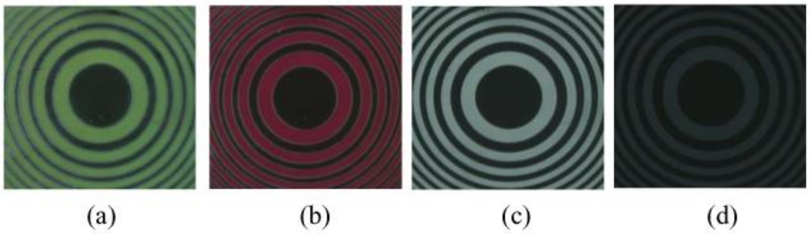
(a) (b) (c) (d)

Fig. 4. Polarizing microscope photographs of the Fresnel lens cell at (a) V=0, (b) 1.0 V_{rms}, (c) 2.0 V_{rms}, and (d) 7.0 V_{rms}. The LC cell is sandwiched between crossed polarizers.

Owing to the different LC molecule alignment between odd and even zones, the focusing behavior of the LC lens occurs. Figure 5 shows the focusing properties of the HALC Fresnel lens displayed from the CCD camera. As the sample is absent, no focusing effect occurs, as shown in Fig. 5(a). Once the LC Fresnel lens was presented and the voltage was 0V, a clear but smaller light spot is observed, as shown in Fig. 5(b), although some circular noises exist due to diffraction. Then at V=1.1 V_{rms}, the focusing effect is strengthened, as shown in Fig. 5(c). However, when the voltage progressively increased from 1.1V to 10V, the focusing ability of LC lens gradually degrades, as shown in Fig. 5(d). Based on these experimental results, the sample definitely behaves like a switchable lens.

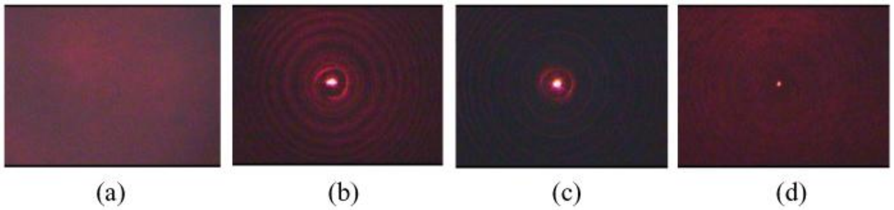
(a) (b) (c) (d)

Fig. 5. The observed laser beam images (a) without LC sample and with sample at the applied voltage (b) V=0, (c) V = 1.1 V_{rms}, (d) V = 10 V_{rms}, respectively.

The 3D profiles of the outgoing beams were also measured using a digital CCD camera. When the hybrid-aligned LC Fresnel zone plate is in position, a sharp focus occurs at the primary focal point (~25 cm), as shown in Fig. 6. In the voltage-off state, a slight focusing effect of the LC cell is observed. As the driving voltage increases, the peak intensity gradually increases, approaching the maximum at V_{rms} = 1.1 V. However, as the applied voltage continues to increase, the peak intensity gradually decreases.

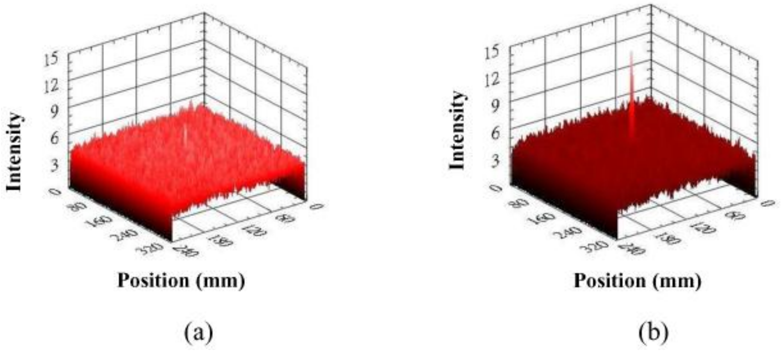

Fig. 6. Beam intensity profiles measured by the CCD camera under different conditions: (a) with sample at V=0 and (b) V=1.1 V_{rms}.

To evaluate the voltage-dependent image quality of the HALC Fresnel lens, a black piece of cardboard with a transparent letter *V* was placed in front of the LC sample. The CCD camera was set up at approximately 30 cm behind the sample. Figures 7(a)–7(c) present the projected images of the *V* pattern on the screen of the Fresnel LC lens under applied voltages of 0, 1.1, and 10 V, respectively. At V=0, the *V* images at the original and bigger sizes were recorded by CCD, as shown in Fig. 7(a). Small *V* image is the original *V* pattern of the cardboard directly mapped on the screen. The bigger *V* image and a bright point appeared at the center of the projected image reveal the property of the Fresnel lens associated with the diffraction mechanism. As the applied voltage increased to 1.1 V_{rms}, the intensity of the bigger *V* was obviously enhanced while the intensity of *V* at the original size became weaker. As previously noted [14], the proportion of transmitted light that was diffracted to the focal point was high herein; some of the transmitted light was diffracted to high-order focal positions, as shown in Fig. 7(b). Subsequently, as the applied voltage was increased to 10V, the difference of LC reorientation between odd zone and even zone nearly vanished. As a result, the diffraction effect is not obvious, as demonstrated in Fig. 7(c).

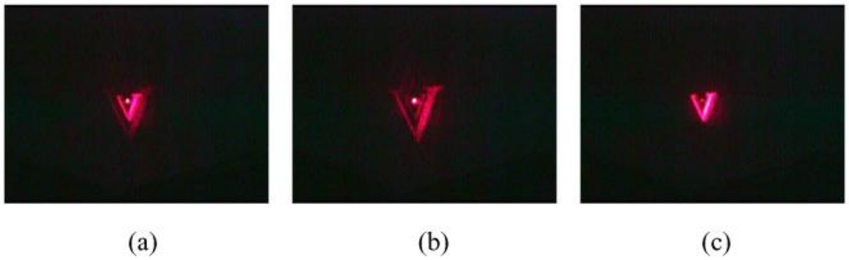
(a) (b) (c)

Fig. 7. Diffracted *V* patterns of the Fresnel LC lens when voltages are applied at (a) 0, (b) 1.1, and (c) 10 V_{rms}. The CCD camera was 30 cm away from the sample.

The first order diffraction efficiency of a LC Fresnel lens is determined by the phase difference $\delta = \frac{2\pi}{\lambda}(n_{even} - n_{odd})d$ between the adjacent zones. Here d is the cell gap, n_{even} and n_{odd} are the refractive index of the LC layer in even and odd zones, respectively. The maximum efficiency is realized when $\delta = \pi$. Figure 8 shows the measured diffraction efficiency as a function of the applied voltage. The experimental results imply that the initial δ at V=0 is slightly larger than π and the diffraction efficiency is η~7%. When an external voltage beyond the critical value of approximately 0.5 V_{rms} was applied, the LC directors in the even rings began to realign in the direction of the electric field while the LC directors in the odd rings remained fundamentally unchanged. The phase difference δ gradually reduced and approached π, so that the diffraction efficiency progressively increased to the maximum at V =1.1 V_{rms}. The greatest diffraction efficiency is 31.4%, which is very close to the diffraction efficiency of 32% for the photo mask alone and not so far off the theoretical maximum. Since the reflection at two interfaces of glass-air occurred, the reflectance was measured by using a glass substrate as a test sample and was determined as ~12%. The diffraction loss is mainly induced by the reflection at two interfaces of glass-air. When the voltage continues to increase, the phase difference between the even and odd rings slowly decreases below π, so that the diffraction efficiency continuously declines and finally decreases to zero as all the bulk LC directors are reoriented nearly perpendicular to the substrates. Furthermore, due to the hybrid alignment configuration, the HALC Fresnel lens has fast response time. The rise time and fall time measured between 0 and 7 V_{rms} were 2.6 ms and 189 ms, respectively.

Based on the experimental results, the diffraction efficiency of this Fresnel HA-LC lens is sensitive to the applied voltage. The proposed HALC Fresnel lens affords potential advantages of high diffraction efficiency, low operating voltage, and fast response time. As no additional photo-resist processing is necessary in this work, the UV-modified PI film technique is positively and simply implemented to realize the switchable HALC Fresnel lens. Therefore the proposed Fresnel lens has potential for real applications. For an example, it can be used in the beam steering, beam deflector, three-dimensional (3D) display, wave front shaping, and imaging systems. Since UV light can decrease the pretilt angle of PI alignment layer. As the lens device is UV exposed for the second time, the stability of the prepared LC Fresnel lens must be concerned. Fortunately, for the practical application, the UV light passes the polarizer and ITO glass substrate before reaches the PI alignment layers. The transmittance of UV passing through the glass substrate and polarizer was measured and determined as 0.67% and ~0.01%, respectively. Accordingly, the performance of HALC Fresnel lens is stable under ambient condition.

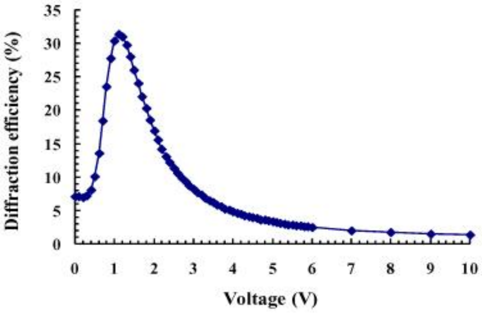

Fig. 8. The voltage-dependent diffraction efficiency of the LC Fresnel lens

4. Conclusions

This work successfully demonstrated a novel, simple, and low-cost approach for fabricating an electrically switchable HALC binary phase Fresnel lens based on UV-induced surface modification of the alignment film. This proposed method is very promising and powerful because only a single-masking process is required to bring the modification of the PI pretilt angle. The focusing behavior of the LC Fresnel lens with high diffraction efficiency can be electrically tunable while the required operating voltage remains below 8V_{rms} with fast response time.

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