

Electrically switchable Fresnel lens using a polymer-separated composite film

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Abstract: A Fresnel lens with electrically-tunable diffraction efficiency while possessing high image quality is demonstrated using a phase-separated composite film (PSCOF). The light scattering-free PSCOF is obtained by anisotropic phase separation between liquid crystal and polymer. Such a lens can be operated below 12 volts and its switching time is reasonably fast (~10 ms). The maximum diffraction efficiency reaches ~35% for a linearly polarized light, which is close to the theoretical limit of 41%.

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OCIS codes: (160.3710) Liquid crystals; (050.1970) Diffractive optics; (160.5470) Polymers

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1. Introduction

Fresnel lenses have found important applications in photonics, optical imaging, long distance optical communication, and space navigation [1-5]. In some applications, such as maskless lithography [6], projection displays [7], and variable optical attenuators using a zone plate modulator, it is highly desirable to continuously control the diffraction efficiency of the Fresnel lens. This tuning ability would eliminate the need for a spatial light modulator and mechanical light shutter. A binary-phase Fresnel zone plate can be fabricated using different materials such as SiO₂ (glass) or Si₃N₄ by lithographic, etching, ion milling, or thin-film deposition techniques [8-12]. However, the diffraction efficiency of such a Fresnel zone plate is not tunable once it is fabricated.

The electrically switchable Fresnel lenses have been reported using a nematic liquid crystal [LC] [13-15], polymer-dispersed liquid crystal (PDLC) [16], polymer network liquid crystal (PNLC) [17], and ring-shaped 180° ferroelectric domains [18]. The nematic LC Fresnel lens could be fabricated by using patterned electrodes [13] or directly etching Fresnel structures onto a quartz substrate [15]. The desired phase shift is obtained by different orientation angle or different thickness of the LC layers between odd and even zones. Both patterned electrode structure and etched Fresnel substrate involve sophisticated photolithography processes. To overcome the polarization dependence, a Fresnel lens having two neighboring zones with orthogonal LC directors has been considered [14]. However, such a special rubbing requirement makes this device relatively difficult to fabricate. On the other hand, the polymer/LC composites can be fabricated by a single UV curing process while using a uniform continuous electrode. The major shortcoming of PDLC and PNLC devices is their light scattering behavior which significantly degrades the resolving power of the lens. Nanoscale PDLC [16] is scattering-free, polarization-independent, and fast-response, however, the required operating voltage is very high (> 100 V_{rms}) and the phase change is too small.

In this paper, we demonstrate a scattering-free, electrically-switchable Fresnel zone plate using a polymer-separated composite film (PSCOF). In a PSCOF, the LC and polymer layers are completely phase separated [19]. This is different from the polymer-stabilized systems where the polymer networks are entangled with LCs so that light scattering would occur unless the LC domains are controlled to be smaller than the light wavelength [20]. Small LC domain sizes lead to an undesirable high operating voltage (~7 V/μm). The demonstrated PSCOF Fresnel lens exhibits three major advantages: low operating voltage (~12 V_{rms}), reasonably fast switching time (~30 ms), and high resolution (>57 line pairs per mm). The diffraction efficiency of the lens is tunable from 0 to 35% for a linearly polarized light.

2. Device fabrication

Figure 1 shows the schematic drawing of the fabrication method. The key element is a chromium oxide photomask imbedded with Fresnel zone patterns. The innermost zone has radius $r_1 = 0.5$ mm and the n^{th} zone has radius r_n which satisfies $r_n^2 = nr_1^2$; n is the zone number. Our zone plate consists of 80 concentric rings within 1cm diameter. In a binary phase Fresnel lens, the focal length f is related to the innermost zone radius r_1 as $f = r_1 / \lambda$, where λ is the wavelength of the incident beam. The primary focal length of our lens is $f \sim 50$ cm for $\lambda =$

633 nm. Fresnel zone lens normally has multiple foci due to the higher-order Fourier components. The foci are at f , $f/3$, $f/5$,... Most of the incident light is diffracted into the primary focus. The diffraction efficiency (η_n) of these foci is $\eta_n = \sin^2(n/2)$, $n = \pm 1, \pm 3, \pm 5, \dots$. The theoretical maximum diffraction efficiency of the primary focus is 41% [9].

To fabricate PSCOF zone plate, we mixed 70% UV curable prepolymer NOA 65 (Norland) with 30% nematic LC E48 (Merck, $\Delta n = 0.231$). The E48/NOA65 mixture was injected to a homogeneous cell comprising of ITO (indium-tin-oxide)-coated glass substrates. The inner surfaces of the ITO-glass substrates were coated with thin polyimide layers and rubbed in anti-parallel directions. The pretilt angle is $\sim 3^\circ$ and cell gap is $d \sim 16 \mu\text{m}$. During exposure, the cell was in proximity contact with the photomask. Phase separation was carried out at a temperature of around 100°C . The UV (peak intensity at $\lambda \sim 365 \text{ nm}$) light with intensity $I \sim 20 \text{ mW/cm}^2$ was used to cure the cell from the photomask side for 15 minutes.

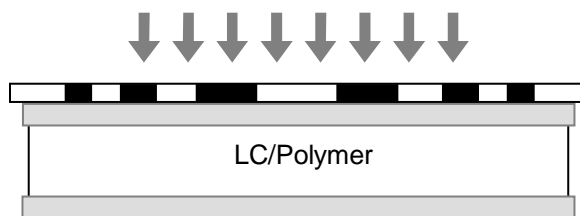


Fig. 1. Schematic representation of the fabrication process of the PSCOF Fresnel lens.

As shown in Figure 1, the odd zones are transparent and even zones are opaque. Thus, polymerization process would first take place in the odd zones resulting in a surface-relief structure corresponding to the photomask pattern [21]. The phase separation mechanism of the PSCOF is somewhat different from that of a uniform-sized PDLC. When the LC/prepolymer mixture is exposed by a UV light, there is an intensity gradient in the direction normal to the sample. When the curing temperature is above the clearing point, the photo-polymerization takes place preferentially at the interface of the sample near the UV source, i.e., high intensity region. The consumption of monomers in the region lowers their chemical potential. This pushes the monomers to diffuse from low to high UV intensity region. On the contrary, the LC molecules diffuse from high to low intensity direction to balance the chemical potential. In the phase separation process, LC droplet formation is inhibited. As a result, the interface near the UV light source forms a thin polymer layer while the interface away from the light source forms a thin LC layer. Therefore, under suitable cure conditions the PSCOF can be easily obtained with very little LC retained in the polymer film. Similar to the anisotropic phase separation happened in the odd zones, polymerizations could still proceed in the even zones. The even zones have a lower polymer concentration and, as a result, the LC layer is thicker and the threshold voltage is lower. A PSCOF replicating the photomask zone plate configuration is thus formed.

3. Operation principle

The PNLC and PDLC devices are usually translucent in one of the voltage-on or -off states due to light scattering. However, the PSCOF Fresnel lens we prepared is highly transparent in both voltage-on and -off states. Figure 2 shows the schematic diagram of the PSCOF Fresnel zone plate structure. After the UV-induced polymerization process, the LC layer is formed and completely separated from the polymer layer. The cured polymer layer adheres to the inner side of the top glass substrate where the UV light enters from. Since the polymerization starts from the UV irradiation area, the transparent zones beneath the photomask would have a thicker polymer layer. The thicker dielectric polymer layer reduces the voltage drop across the LC layer. Therefore, the odd zones with a thicker polymer layer would require a higher voltage to reorient the LC directors. In the low voltage regime, the LC directors in the even

zones are reoriented first while the LC directors in the odd zones remain in the original alignment owing to their higher threshold voltage. A binary-phase Fresnel lens is thus formed.

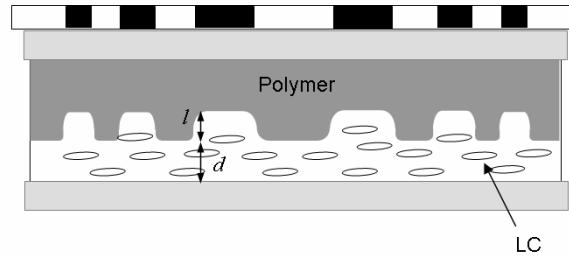


Fig. 2. Cross-sectional view of the PSCOF Fresnel lens.

In the beginning, both ITO-glass substrates have rubbed polyimide layers. After UV-induced phase separation the inner side of the top substrate is covered with a thin polymer layer, as shown in Fig. 2. It is not clear whether this thin polymer layer replicates the alignment capability of the top polyimide alignment layer. A fairly good homogeneous LC alignment is still obtained. Figure 3 shows a microscope photo of the PSCOF Fresnel lens sample observed under crossed polarizers, where the rubbing direction of the LC cell is parallel to the transmission axis of the polarizer. Small light leakage is observed between two neighboring zones because the polymer layer is not sharp enough between two zones, as depicted in Fig. 2. There, the LC directors maybe disturbed by the polymer walls causing light leakage through the crossed polarizers. The rest of the observed region is dark indicating that a relatively good homogenous alignment is achieved along the rubbing direction of the substrate.



Fig. 3. Microscope images of the PSCOF Fresnel lens cell at $V = 0$. The sample is sandwiched between crossed polarizers.

If the polarization of the incident light is parallel to the rubbing direction of the cell, the phase difference between the neighboring zones is $\Delta\delta = \frac{2\pi}{\lambda} [n_{eff,even}(l+d) - (n_{eff,odd} \cdot d + n_p \cdot l)]$, where $\Delta\delta$ is the phase difference of the effective refractive indices in the adjacent zones, d and $(l+d)$ represent the LC layer thickness of the odd and even zones, respectively, as shown in Fig. 2. After polymerization, the polymer layer thickness varies spatially resulted from the different UV intensities in the even and odd zones. The thickness difference of the polymer layers between the odd and even zones is l . In principle, we could determine l by analyzing the scanning electron microscope photos or measuring the threshold voltage difference between the odd and even zones. However, in this paper we did not attempt to measure l , rather, we focus on demonstrating the Fresnel lens properties.

In the above equation, $n_{eff,even}$ and $n_{eff,odd}$ is the effective LC refractive index for the even and odd zones, respectively, n_p is the polymer refractive index, and λ is the incident light wavelength. The phase retardation is different between even and odd zones in the

voltage-off state because the light propagates through different thickness of polymer and LC layer. When the applied voltage exceeds a threshold, the LC directors are reoriented which, in turn, causes the effective extraordinary index to change. Therefore, the induced phase shift is electrically tunable. This phase change corresponds to the color change when observed from an optical microscope through crossed polarizers. Under this visual inspection, the rubbing direction of the LC cell was oriented at 45° with respect to the optical axis of the linear polarizer. The optical micrographs of the PSCOF Fresnel lens were taken at different voltages. Results are shown in Fig. 4.

Figures 4(a-d) show a portion of the LC zone plate at $V = 0, 4, 6,$ and $16 V_{\text{rms}}$, respectively. At $V = 0$, the sample presents the Fresnel zone structure, because the odd and even zones exhibit different phases. The color shift of each odd or even zone is due to the non-uniformity of the cell gap. As the voltage exceeds a threshold ($\sim 2.3 V_{\text{rms}}$), the LC directors in even zones start to be reoriented first, as shown in Figures 4(b-d). The color change of the odd and even zones originates from the refractive index change. In the higher voltage regime ($\sim 16 V_{\text{rms}}$), the bulk LC directors are reoriented nearly perpendicular to the substrates, thus the zone structure is gradually erased.

A drawback of the PSCOF Fresnel lens is that it is polarization sensitive. For the light polarization perpendicular to the rubbing direction, it encounters the ordinary refractive index n_o of the LC layer and is not focused. To overcome the polarization dependence, stacking two orthogonal homogeneous PSCOF zone plates could be considered.

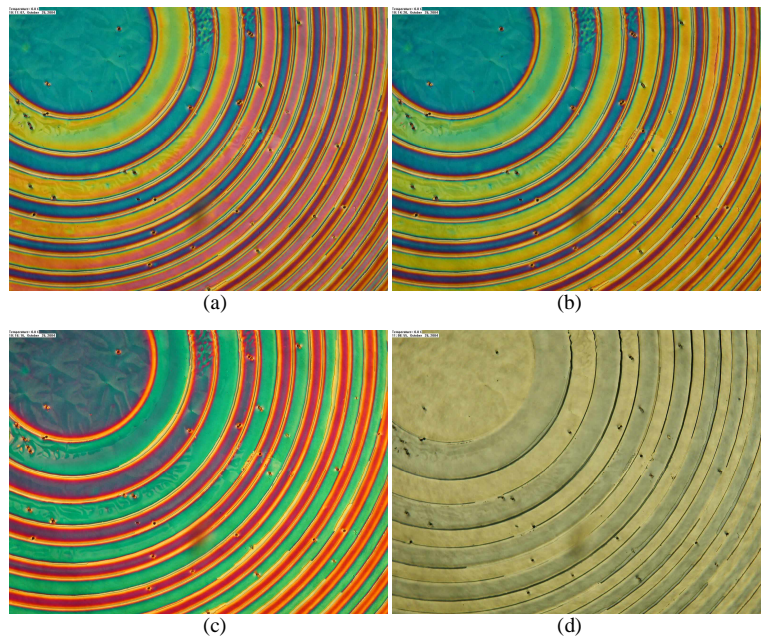


Fig. 4. Microscope images of the PSCOF Fresnel lens at (a) $V = 0$, (b) $4 V_{\text{rms}}$, (c) $6 V_{\text{rms}}$, and (d) $16 V_{\text{rms}}$. The LC cell is sandwiched between two crossed polarizers.

3. Experimental setup

Figure 5 shows the experimental setup for studying the focusing properties of the PSCOF Fresnel zone plate. The output beam of the He-Ne laser was magnified by two convex lenses with 50 mm and 250 mm focal lengths. A pinhole with 30 μm diameter was placed at the focal point of the first lens serving as a spatial filter. The beam diameter was expanded to ~ 1 cm just to cover the aperture of the zone patterns. A sheet polarizer was used with its optical axis parallel to the cell rubbing direction. Light focusing properties of the cell was measured

using a CCD camera (SBIG Model ST-2000XM) connected to a computer. The CCD camera was set at a distance of 50 cm from the PSCOF Fresnel lens.

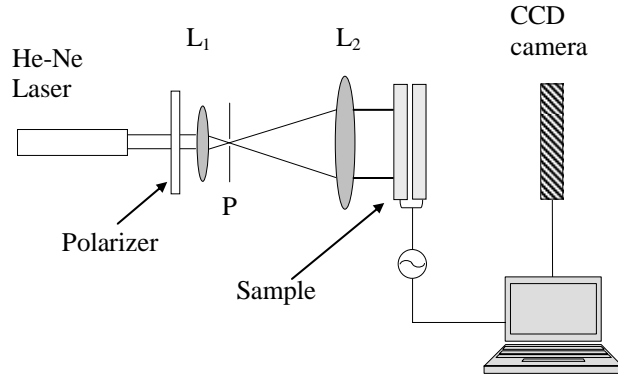


Fig. 5. The experimental setup for studying the focusing properties of the PSCOF Fresnel lens. Focal length $L_1 = 50$ mm, and $L_2 = 250$ mm, and pinhole diameter $P = 30$ μm.

3. Results and discussions

Figure 6 plots the measured diffraction efficiency as a function of the applied voltage. When the applied voltage exceeds a threshold, the LC directors begin to be reoriented. Since the threshold voltage in the odd and even zones is different, the resultant LC tilt angles are different when a uniform electric field is applied. The phase difference between the odd and even zones changes while the LC reorientation angle changes. The maximum diffraction efficiency is ~35% at $V = 5$ V_{rms} which is close to the 41% diffraction efficiency of the photomask alone. The slightly lower diffraction efficiency could be due to the defects of the polymer network near the zone edges, as explained above. From Fig. 6, the minimum diffraction efficiency occurs at ~12 V_{rms}. As the voltage continues to increase ($V > 22$ V_{rms}), all the bulk LC directors are reoriented nearly perpendicular to the substrates. Therefore, the diffraction efficiency is gradually decreased.

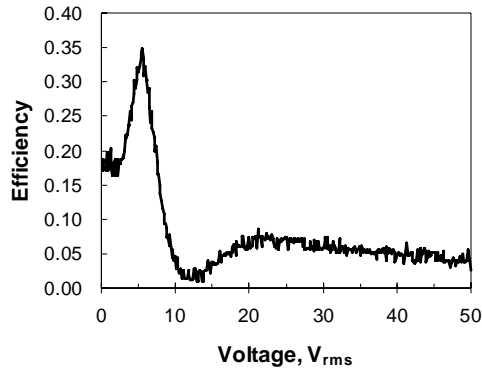


Fig. 6. The voltage-dependent diffraction efficiency of the PSCOF Fresnel lens. The diameter of the Fresnel zone plate is 1 cm and the focal length is 50 cm.

Figure 7 plots the measured 3D laser intensity profiles of the outgoing beam using a digital CCD camera at $V = 5$ and 12 V_{rms}. At $V = 5$ V_{rms}, the maximum diffraction efficiency occurs and the peak intensity is obtained. At $V = 12$ V_{rms}, the minimum efficiency is achieved and the focusing behavior is almost completely suppressed. The rise and decay time of the PSCOF Fresnel lens were measured by switching the applied voltages between 5 and 12 V_{rms}.

and results are 9.0 and 34.5 ms, respectively. Increasing the monomer concentration or reducing the cell gap would lead to a thinner LC layer and, consequently, a faster response time. However, the respective tradeoff is the increased voltage and decreased phase change.

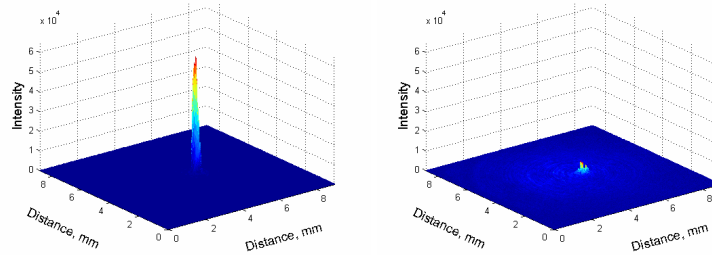


Fig. 7. Beam intensity profile measured by the CCD camera at (a) $V = 5 V_{\text{rms}}$ and (b) $12 V_{\text{rms}}$. The diameter of the Fresnel zone plate is 1 cm and the focal length is 50 cm.

We used an Air Force resolution chart to evaluate the imaging quality of the PSCOF Fresnel lens. Figure 8 (the left photo) shows the image quality of our sample. A lens testing system OS100 from Thorlab was used. The testing system includes a white light source and a collimator. A resolution chart (OSR1) was placed in front of the collimator. Our PSCOF Fresnel lens was set behind the collimator. A CCD camera was located at ~ 55 cm from the sample. When the maximum efficiency is achieved at $5 V_{\text{rms}}$, a clear image is obtained. Under such a circumstance, our Fresnel lens is able to resolve beyond the smallest chart (T6) of group 5, which indicates that the lens resolution is better than 57 line pairs per mm. At the minimum efficiency (at $V \sim 12 V_{\text{rms}}$), the image is washed out, as shown in the right photo of Fig. 8.

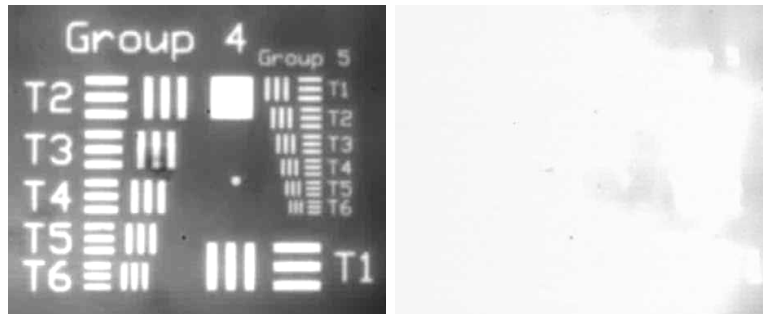


Fig. 8. Image properties of the PSCOF Fresnel lens recorded by a CCD camera at (a) $5 V_{\text{rms}}$ and (b) $12 V_{\text{rms}}$.

4. Conclusion

A switchable Fresnel zone plate lens is demonstrated using a phase-separated composite film. The fabrication process is relatively simple. Since the LC and polymer are separated completely to become two layers. The sample has no light scattering and a relatively low operating voltage. This feature is different from other conventional LC/polymer composites. The diffraction properties of the PSCOF Fresnel lens are also investigated. The diffraction efficiency can be controlled continuously by a uniform electric field. A 35% diffraction efficiency was achieved at $V = 5 V_{\text{rms}}$ for a linear polarized light. The rise time and decay time were measured to be 9.0 and 34.5 ms.

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