Polarization controllable Fresnel lens using dye-doped liquid crystals

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Abstract: A scattering-free, polarization controllable Fresnel zone plate lens is demonstrated using a photo-induced alignment of the dye-doped liquid crystal film. This photo-aligned liquid crystal zone plate provides orthogonal polarization states for odd and even zones. The different focus orders can be separated because of their different polarization states. The fabrication process is relatively simple and the operation voltage is less than $5 \, V_{rms}$.

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References and links

1. E. Marom, E. Ben-Eliezer, L. P. Yaroslavsky, and Z. Zalevsky, "Two methods for increasing the depth of focus of imaging systems," Proc. SPIE **5227**, 8-15 (2004).
2. M. Makowski, G. Mikula, M. Sypek, A. Kolodziejczyk, and C. Prokopowicz, "Diffractive elements with extended depth of focus," Proc. SPIE **5484**, 475-481 (2004).
3. S. C. Kim, S. E. Lee, and E. S. Kim, "Optical implementation of real-time incoherent 3D imaging and display system using modified triangular interferometer," Proc. SPIE **5443**, 250-256 (2004).
4. X. Ren, S. Liu, and X. Zhang, "Fabrication of off-axis holographic Fresnel lens used as multiplexer/demultiplexer in optical communications," Proc. SPIE **5456**, 391-398 (2004).
5. J. T. Early and R. Hyde, "Twenty-meter space telescope based on diffractive Fresnel lens," Proc. SPIE **5166**, 148-156 (2004).
6. R. Menon, E. E. Moon, M. K. Mondol, F. J. Castaño, and H. I. Smith, "Scanning-spatial-phase alignment for zone-plate-array lithography," J. Vac. Sci. Technol. B **22**, 3382-3385 (2004).
7. C. H. Tsai, P. Lai, K. Lee, and C. K. Lee, "Fabrication of a large F-number lenticular plate and its use as a small-angle flat-top diffuser in autostereoscopic display screens," Proc. SPIE **3957**, 322-329 (2000).
8. N. Kitaura, S. Ogata, and Y. Mori, "Spectrometer employing a micro-Fresnel lens," Opt. Eng. **34**, 584-588 (1995).
9. J. Jahns and S. J. Walker, "Two-dimensional array of diffractive microlenses fabricated by thin film deposition," Appl. Opt. **29**, 931-936 (1990).
10. K. Rastani, A. Marrakchi, S. F. Habiby, W. M. Hubbard, H. Gilchrist, and R. E. Nahory, "Binary phase Fresnel lenses for generation of two-dimensional beam arrays," Appl. Opt. **30**, 1347-1354 (1991).
11. L. Mingtao, J. Wang, L. Zhuang, and S. Y. Chou, "Fabrication of circular optical structures with a 20 nm minimum feature size using nanoimprint lithography," Appl. Phys. Lett. **76**, 673-675 (2000).
12. J. Canning, K. Sommer, S. Huntington, and A. Carter, "Silica-based fiber Fresnel lens," Opt. Commun. **199**, 375-381 (2001).
13. A. Y.-G. Fuh, C. C. Liao, K. C. Hsu, C. L. Lu, and C.-Y. Tsai, "Dynamic studies of holographic gratings in dye-doped liquid-crystal films," Opt. Lett. **26**, 1767-1769 (2001).
    http://www.opticsinfobase.org/abstract.cfm?URI=ol-26-22-1767
14. C. R. Lee, T. S. Mo, K. T. Cheng, T. L. Fu, and A.Y. G. Fuh, "Electrically switchable and thermally erasable biphotonic holographic gratings in dye-doped liquid crystal films," Appl. Phys. Lett. **83**, 24-26 (2003).
15. C. R. Lee, T. L. Fu, K. T. Cheng, T. S. Mo, and A. Y. -G. Fuh, "Surface-assisted photoalignment in dye-doped liquid-crystal films," Phys. Rev. E **69**, 031704 (2004).
16. A. Y. G. Fuh, C. R. Lee, and T. S. Mo, "Polarization holographic grating based on azo-dye-doped polymer-ball-type polymer-dispersed liquid crystals," J. Opt. Soc. Am. B **19**, 2590-2594 (2002).
    http://www.opticsinfobase.org/abstract.cfm?URI=josab-19-11-2590
17. G. Williams, N. J. Powell, A. Purvis and M. G. Clark, "Electrically controllable liquid crystal Fresnel lens," Proc. SPIE **1168**, 352-357 (1989).

18. J. S. Patel and K. Rastani, "Electrically controlled polarization-independent liquid-crystal Fresnel lens arrays," Opt. Lett. **16**, 532-534 (1991).
19. M. Ferstl and A. Frisch, "Static and dynamic Fresnel zone lenses for optical interconnections," J. Mod. Opt. **43**, 1451-1462 (1996).
20. H. Ren, Y. H. Fan, and S. T. Wu, "Tunable Fresnel lens using nanoscale polymer-dispersed liquid crystals," Appl. Phys. Lett. **83**, 1515-1517 (2003).
21. Y. H. Fan, H. Ren and S. T. Wu, "Switchable Fresnel lens using polymer-stabilized liquid crystals," Opt. Express **11**, 3080-3086 (2003).
   http://www.opticsinfobase.org/abstract.cfm?URI=oe-11-23-3080
22. R. S. Cudney, L. A. Ríos, H. M. Escamilla, "Electrically controlled Fresnel zone plates made from ring-shaped 180° domains," Opt. Express **12**, 5783-5788 (2004).
   http://www.opticsinfobase.org/abstract.cfm?URI=oe-12-23-5783
23. T. Sasaki, H. Ono, N. Kawatsuki and M. Kuwabara, "Liquid crystal phase gratings using photoregulated photocrosslinkable polymer liquid crystals" Appl. Phys. Lett. **87**, 161112 (2005).

1. Introduction

Fresnel lens has been used extensively in photonics, optical imaging, long distance optical communication, and space navigation [1-5]. A Fresnel zone plate can be fabricated using different materials such as SiO_2 (glass) or Si_3N_4 by lithographic, etching, ion milling, or thin-film deposition techniques [8-12]. In some applications, such as maskless lithography [6], projection displays [7], and variable optical attenuators, however, continuously controlling the diffraction efficiency of the Fresnel lens is highly desirable in order to eliminate the need of a spatial light modulator or mechanical light shutter. To fabricate the switchable Fresnel lens, a material with electrically controllable physical properties is needed.

Liquid crystal (LC) is a good candidate for making tunable photonic devices, such as tunable lens, grating, prism, and Fresnel lens because of its high birefringence and low operating voltage. In the LC based Fresnel lens, the desired phase difference between the odd and even zones is obtained by either different orientation angles or different thicknesses of the LC layers. Various methods have been developed for fabricating electrically switchable LC Fresnel lenses [17-19], e.g., patterned electrodes [17], directly etching Fresnel structures onto a quartz substrate [19], polymer-dispersed liquid crystal (PDLC) [20], polymer network liquid crystal (PNLC) [21], and ring-shaped 180° ferroelectric domains [22]. For the patterned electrode structure and etched Fresnel substrate, high resolution and sophisticated photolithography processes are commonly involved. By contrast, the fabrication processes of polymer/LC composites are quite simple. But light scattering is often present in the PNLC and PDLC systems, which significantly degrades the resolving power of the lens. Nanoscale PDLC [20] is scattering-free, polarization-independent, and fast-response, but the required operating voltage is very high (> 100 V_{rms}) and the phase change is too small.

In this paper, we develop a simple photoalignment method for fabricating a Fresnel zone plate in a dye-doped LC film and demonstrate its applications for a scattering-free, polarization-controllable Fresnel lens. Compared to other methods, our fabrication processes are quite simple. In addition, the Fresnel lens based on the photoaligned dye-doped LC exhibits three attractive features: 1) scattering free, 2) very low operating voltage (~5 V_{rms}), and 3) the zero and first focus orders can be separated by rotating the analyzer by 90°. The diffraction efficiency of the lens can be tuned by the applied voltage.

2. Device fabrication

Figure 1 shows the schematic drawing of the device 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 nth 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 $f = r_1^2 / \lambda$, where λ is the wavelength of the incident beam. The primary focal length of our lens is f~50 cm for λ = 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 $\eta_n = \sin c^2(n/2)$, n = ±1, ±3, ± 5,… The theoretical maximum diffraction efficiency of the primary focus is 41% [9].
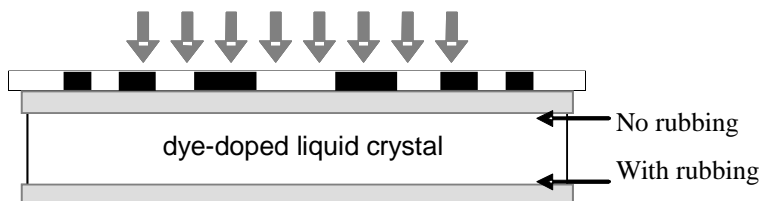

Fig. 1. Schematic representation of the fabrication process of the dye-doped LC Fresnel lens

The LC and azo dye used in the present experiment are E7 (Merck) and Methyl Red (MR, purchased from Aldrich), respectively. The mixing ratio of MR:E7 is 1:99 wt%. Two indium-tin-oxide (ITO)-coated glass slides were used to fabricate an empty cell with 10 μm gap. The bottom glass slide was coated with a thin polyvinyl alcohol film (PVA) and gently buffed with a nylon cloth; but the top slide did not have PVA film. The dye-doped LC mixture was stirred thoroughly and then injected into the empty cell in the isotropic phase. The strong anchoring energy induced by the rubbed surface can extend its alignment capability throughout the entire cell. As a result, a homogeneous LC layer was formed. The conoscopy experiment confirmed such a molecular alignment.

To reorient the LC molecules on the untreated surface to a desired direction, in principle, we can simply illuminate the dye-doped LC with a linearly polarized light whose wavelength is around the azo dye's absorption peak. Under the excitation of the linearly polarized light, the azo dyes in the LC sample undergo trans–cis isomerization, followed by molecular reorientation, diffusion and finally adsorption onto the ITO surface. As a result, the long axes of the azo-dyes are aligned along the untreated substrate of the LC cell but perpendicular to the polarization of the pump light. The adsorbed dyes then force the LC molecules on the untreated surface to reorient along the direction of the azo-dyes' long axes [13-16]. In the meantime, the LC molecules on the untreated surface are affected by the extended anchoring force from the rubbed surface. In this case, the competition between the anchoring force established by the adsorbed dyes and the extended anchoring force from the rubbed surface exists. The LC molecules on the unrubbed surface can only be aligned along the direction of the azo-dyes' director when the former force overcomes the latter one. This can be achieved by irradiating the dye-doped LC sample with the linearly polarized light for long enough (~15 minutes) and sufficiently high intensity, because long enough photo-illumination on the sample can induce enough amount of adsorbed dyes to generate adequate anchoring force for overcoming the extended anchoring energy from the rubbed substrate. To make a ~90° TN LC film, we can simply use the pump light with polarization parallel to the rubbing direction of the rubbed substrate to illuminate the dye-doped LC sample.

In our experiment, a linearly polarized laser light (λ=532 nm) from a diode-pump solid state laser was used to irradiate the dye-doped LC sample because the 532 nm laser is within the absorption band of the Methyl Red. The intensity was set at 50 mW/cm^2. The linearly polarized green laser with polarization parallel to the rubbing direction of the bottom substrate was used to illuminate the dye-doped LC sample through a photomask with Fresnel zone patterns, as Fig. 1 shows. The odd zones are transparent and even zones are opaque. After 15 minutes of illumination, the Fresnel zone patterns with alternating TN and homogenous structures for the odd and even zones, respectively, are obtained, as Fig. 2 shows.
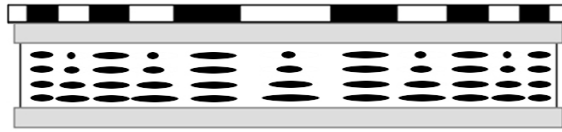
Fig. 2. Schematic diagram of the corresponding LC arrangement of the photo-aligned dye-doped LC Fresnel lens. The top layer is a patterned photomask.

For a 90° TN cell, if the Mauguin's condition ($\Delta nd \gg \lambda$) is satisfied the polarization of the incident light will be rotated by ~90° after traversing through the cell. Our sample has satisfied the Mauguin's condition. Therefore, the polarization of the light is rotated ~90° after passing through the odd zones, while for the homogenous LC, if the polarization of the incident light is parallel to the rubbing direction, the LC cell does not change the incident light polarization. Thus, under the crossed-polarizer optical microscope, the black and white Fresnel zone patterns which correspond to the even and odd zones, respectively, can be observed by placing the dye-doped LC sample with the homogeneous part parallel to polarizer's absorption axis, as Fig. 3(a) shows. The reverse is true if the microscope is under the parallel-polarizer condition as Fig. 3(b) shows.
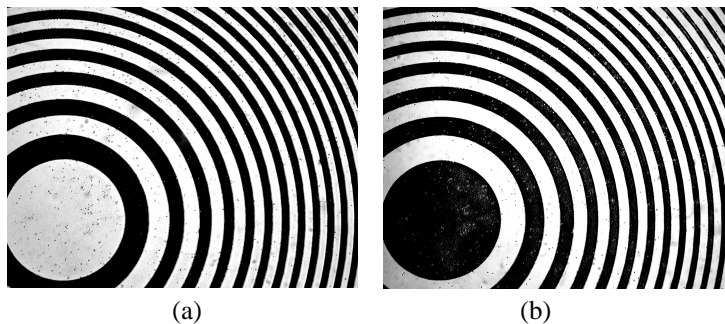

(a)   (b)

Fig. 3. Microscope images of the photo-aligned dye-doped LC Fresnel lens cell with (a) crossed polarizers, and (b) parallel polarizers.

3. Experimental setup

Figure 4 shows the experimental setup for studying the focusing properties of the photo-aligned dye-doped LC Fresnel zone plate. The output beam of the He-Ne laser was expanded to ~1 cm by lens 1 and lens 2 to cover the aperture of the zone patterns. A polarizer with its optic axis parallel to the cell's rubbing direction was placed behind the laser to select the desired linear polarization. Light focusing properties of the cell were measured using a CCD camera (SBIG Model ST-2000XM) connected to a computer, and an analyzer was used to verify the image polarization. The CCD camera was set at a distance of 50 cm from the LC Fresnel lens.
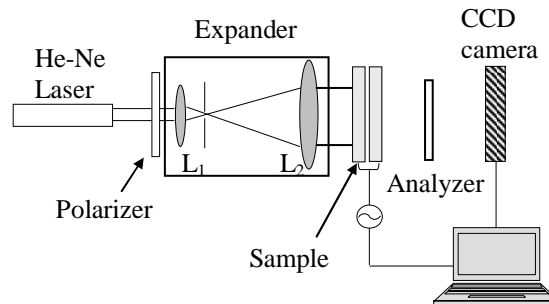

Fig. 4. The experimental setup for studying the focusing properties of the dye-doped LC Fresnel lens. Focal length L_1= 50 mm, and L_2= 250 mm, and pinhole diameter P= 30 µm.

4. Results and discussions

Figure 5 shows the focusing property of the dye-doped LC Fresnel lens captured by a digital camera. When the sample is present, the LC lens possesses the focusing effect, as shown in Fig. 5(a). This can be explained as follows. The polarization of the incident light through the even zones is not changed since the even zones are composed of homogenous LC and the polarization direction of the incident light is parallel to the LC's directors, while the polarization of the incident light passing through the odd zones will be rotated by ~90° because the odd zones are composed of ~90° TN LC. As a result, orthogonal polarization is induced between the odd and even zones. Since the polarizations of the output light from the odd and even zones are orthogonal, the final polarization of the combined diffracted light by the odd and even zones is rotated and the rotation angle is 45°. According to the diffraction character of the polarization grating, the polarization states of the 0th and 1st diffraction orders are orthogonal to each other [23]. In our case, the 0th and 1st diffraction orders correspond to the zero and first focus orders, respectively. Therefore, only the first focus order can pass through the analyzer if the analyzer is placed at an angle $\alpha = 45°$, and only the zero order focus appears when the analyzer is set at $\alpha = -45°$, as shown in Figs. 5(b) and 5(c), respectively. Here, α is the angle between the analyzer and the probing beam's polarization. These phenomena clearly indicate that the photo-aligned dye-doped LC film can switch the focus order of a Fresnel lens.
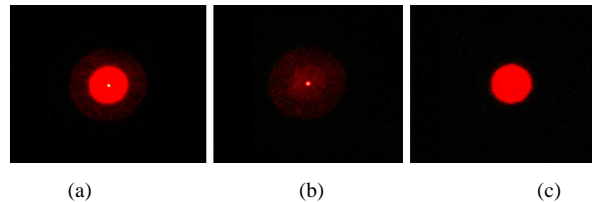

(a) (b) (c)

Fig. 5. The observed laser beam images: (a) Without analyzer, (b) With analyzer, $\alpha = 45°$, (c) With analyzer, $\alpha = -45°$.

To evaluate the image quality of the dye-doped LC Fresnel lens, a transparent alphabet L was placed between lens L_2 and sample. The CCD camera was set at 25 cm behind the sample. Figure 6(a) shows the photos taken without the analyzer. Two focus order images were observed at the same time. The smaller and bigger "L" images represent the first and zero focus orders, respectively. Once the LC Fresnel lens is in position, a clear but smaller image is observed, although some circular noises exist due to diffraction. When α is equal to 45°, only the first focus order (smaller "L") passes through the analyzer. When $\alpha = -45°$, the first focus order vanishes and only the zero focus order (larger "L") appears.
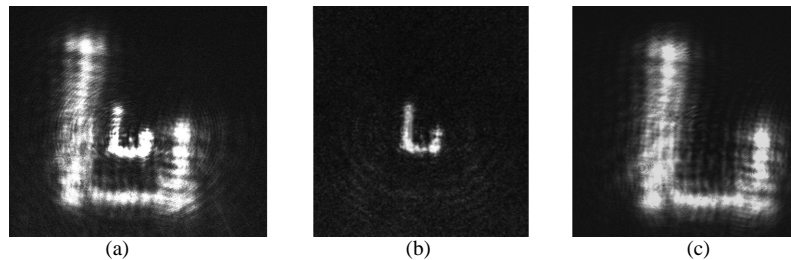

(a) (b) (c)

Fig. 6. Imaging and focusing properties of the photo-aligned dye-doped LC Fresnel lens recorded by a CCD camera. (a) Without analyzer, (b) With analyzer, $\alpha = 45°$, (c) With analyzer, $\alpha = -45°$.

Figure 7 shows the measured first order focus diffraction efficiency as a function of the applied voltage. The first order diffraction efficiency of a Fresnel lens is determined by the relative phase difference ($\Delta\delta$) between the adjacent zones $\Delta\delta = 2\pi d(n_{even} - n_{odd})/\lambda$, where d is the cell gap, n_{even} and n_{odd} are the effective LC refractive index in the even and odd zones, respectively. When the applied voltage exceeds a threshold, the LC directors begin to be reoriented. Since the structure in the odd (TN) and even zones (homogeneous) is different, the resultant LC tilt and azimuth angles are different when a uniform electric field is applied. The phase difference between the odd and even zones changes as the LC reorientation angle changes. As the voltage exceeds a threshold (~1 V_{rms}), the LC directors are reoriented by the electric field. The local minimum shown in Fig. 7 occurs when $\Delta\delta$ approaches 1.5π. The maximum efficiency reaches ~31% when $\Delta\delta$ reaches π. Beyond 2 V_{rms}, both n_{even} and n_{odd} are reduced and $\Delta\delta$ drops to below π. From this point on, the diffraction efficiency declines gradually. As the voltage continues to increase, all the bulk LC directors are reoriented nearly perpendicular to the substrates. Therefore, the diffraction efficiency is gradually decreased to zero. The response time of the photo-aligned dye-doped LC Fresnel lens was measured to be ~30 ms.
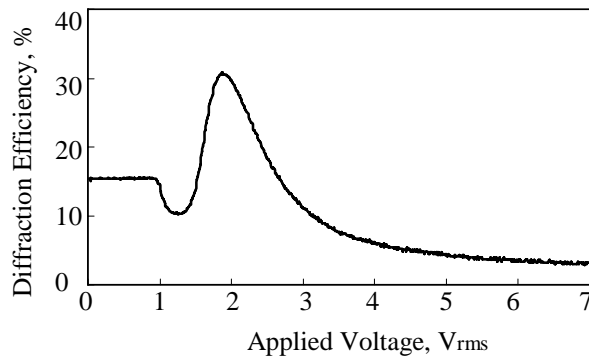

Fig. 7. The voltage-dependent diffraction efficiency of the dye-doped LC Fresnel lens. The diameter of the Fresnel zone plate is 1 cm and the focal length is 50 cm.

5. Conclusion

A focus order switchable Fresnel zone plate lens is demonstrated using a photo-aligned dye doped liquid crystal film. The fabrication process is relatively simple, since the odd and even zones consist of TN and homogeneous LC structures, respectively. The different focus orders can be separated by an analyzer. The sample is scattering free and exhibits a relatively low operating voltage. This feature is different from other conventional LC/polymer composites. The diffraction properties of the photo-aligned dye-doped LC Fresnel lens are also investigated. The diffraction efficiency can be controlled continuously by a uniform electric field. A 31% diffraction efficiency was achieved at V = 2 V_{rms} for a linearly polarized light. The response time was measured to be ~30 ms.