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Switchable polarisation-independent blue phase liquid crystal Fresnel lens based on phase-separated composite films

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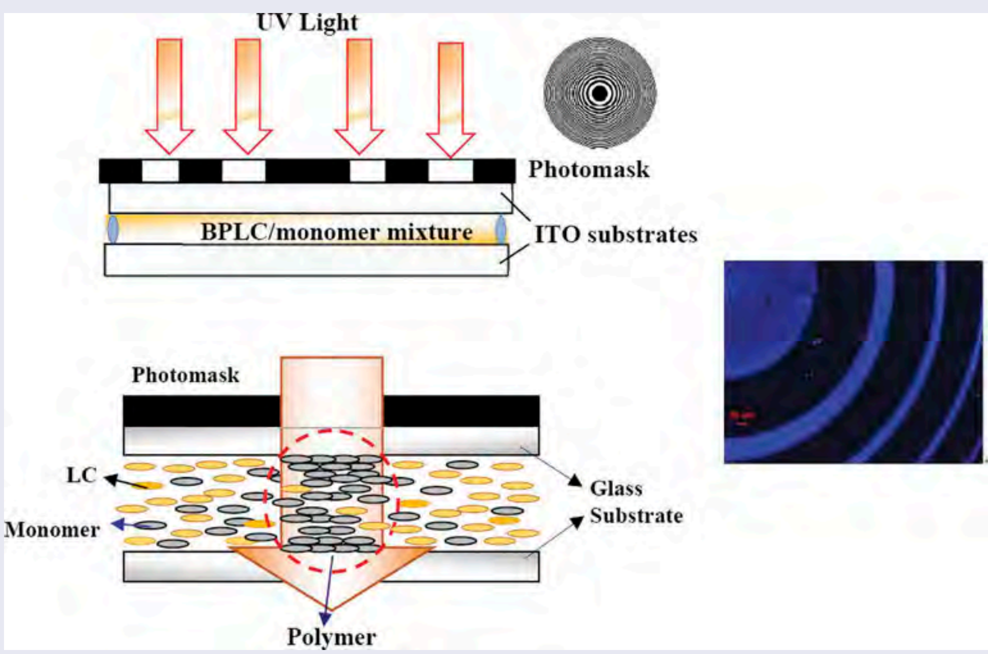
ABSTRACT
A simple method for fabricating a polarisation independent blue-phase liquid crystal Fresnel lens (BPLCFL) is demonstrated by utilising the photo-polymerisation-induced phase separation. The BPLC/polymer binary Fresnel zones is obtained well by periodic UV illumination with phase separation of the BPLC molecules and UV-curable pre-polymer mixture. The diffraction efficiency can be controlled when applying a uniform electric field which modulates the phase difference between even and odd Fresnel zones. Experimental results show that the maximum diffraction efficiency reaches 24.3%, which is close to the measured diffraction efficiency of the used Fresnel zone-plate mask of 25%. We also characterise the tunable lens performance at different applied voltages.



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Blue phase liquid crystal; Fresnel lens; photo polymerisation-induced phase separation; diffraction

1. Introduction

Fresnel lenses have been widely implemented for long distance optical communication, millimetre-wave devices, optical interconnection, optical information processing, variable optical data storage system, three-dimensional display systems and space navigation [1–5]. Due to the electrically controllable orientation and the refractive index of liquid crystal (LC) molecules, switchable liquid crystal Fresnel lens (LCFL) without mechanical moving parts has attracted considerable research attention. The unique properties of LCs, such as field-induced reorientation and low operating voltage, make LC a very good candidate for electrically switchable lens devices. Significant efforts have been made into making such electrically switchable LCFs [6–12] by using polymer-dispersed liquid crystals [6], polymer-stabilised liquid crystals [7], dye-doped nematic liquid crystals [8], polymer-separated

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composite film [9], hybrid aligned liquid crystals [10] and so on. However, because of the intrinsic uniaxial anisotropy of LCs, the focusing properties of the LC Fresnel lens depend strongly on the polarisation state of the incident light. As a result, numerous methods have been demonstrated to eliminate the polarisation-dependency of LCFL device [11–13], such as the orthogonal alignment of LC molecules in adjacent zones [11], surface-mode switching of 90° twisted-nematic LCs [12] and circularly symmetric hybrid-aligned liquid-crystal film [13]. While these devices are polarisation-independent, they necessitate particular alignment processes such as a multi-rubbing, circular rubbing or masking photolithographic process, limiting the range of practical applications of such an LC Fresnel lens.

Recently, blue-phase liquid crystal (BPLC) materials have received intense interest due to its several attractive features including fast response time, alignment-free fabrication and optical isotropy at voltage off state. Therefore, BPLC serves as a good candidate for polarisation-independent switchable lens with potentially fast response time and easy processing. Recently, some groups have explored its potential for Fresnel lenses [14–18]. By using patterned electrodes, Lin et al. [14] demonstrated a high-efficiency BP Fresnel lens; however, the fringing field effect in this method results in a non-uniform distortion on the polymer network around the boundaries of the electrode. Tan et al. [15] showed that using holographic exposure technique, one can eliminate the need for a photomask; however, delicate fabrication processes of washing out LCs in the cell and refilling BPLC mixture must be performed.

In this work, an alternative method is proposed for fabricating an electrically switchable BPLC Fresnel lens (BPLCFL) based on phase-separated composite film (PSCOF) where the BPLC and polymer are separated completely to form binary zones. In this case, a photomask is exploited to define the even and odd Fresnel zones, and a BPLC/polymer binary Fresnel zone lens is effectively generated by using photo-polymerisation-induced phase separation (PIPS) technique [19,20]. The phase difference between the neighbouring zones can be changed electrically, so that the diffraction efficiency of the proposed BPLCFL is continuously tunable through an external electric field. The diffraction intensity increases as the uniformly applied electrical field induces the phase difference in the hybrid PSBP. Besides, the field-induced focusing properties of the proposed BPLCFL is independent of polarisation state of the incident light. Comparing with other methods, this PSCOF-based BPLCFL is fabricated easily by only one-step exposure process and is thus suitable for practical applications.

2. Experimental

2.1. Fabrication of BPLCFL

The PIPS technique was applied to fabricate a switchable BPLCFL. Based on the spatially modulated ultraviolet (UV) light intensity by using a photomask, a binary BPLCFL can be easily achieved, as shown in the fabrication process in Figure 1. The critical element used here is the chromium oxide photomask, which is used for defining the Fresnel zone pattern. The innermost zone has a radius of $r_1 = 0.5$ mm and the n^{th} zone has radius r_n which satisfies $r_n{}^2 = nr_1{}^2$, with n indicating the zone number. Our zone plate consists of 80 concentric rings approximately within 1-cm diameter.

To form an electrically controllable BPLCFL with uniform binary layers of the BPLC and polymer, phase-separated composite film is carried out by exposing the LC cell to UV light. Upon UV exposure, the monomer concentration reduced in the unmasked area due to the UV-induced polymerisation, this concentration change led to diffusion and further aggregation of polymer which gradually expelled LC to the masked area. As a result, polymer walls were formed in the even zones, and the BPLC was formed in the odd zones to form an electro-optically-responding BPLCFL as shown in Figure 1(b). It is well known that two processes of spatially non-uniform polymerisation and diffusion of small molecules play important roles in

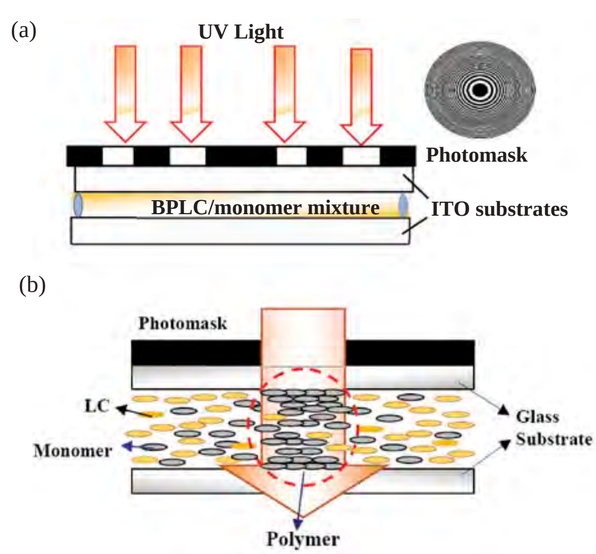

Figure 1. (colour online) Schematic demonstration of (a) the fabrication process of BPLC Fresnel lens by (b) the photo-polymerisation-induced phase separation of the LC/polymer.

determining a specific PSCOF polymer structure during phase separation. The variations in UV irradiation intensity critically influence these two processes and can impact the resultant PSCOF bilayer structure. To achieve complete phase separation of BPLC and polymer, a low-intensity exposure is absolutely required to ensure sufficient diffusion.

To fabricate a BPLC Fresnel zone plate based on PSCOF structure, we prepared a BPLC precursor comprising of 44 wt% HTG135200-100 (a positive-dielectric-anisotropy ($\Delta\varepsilon > 0$) nematic liquid crystal (HCCH, China), 6 wt% a high twisting power and photo-stable chiral dopant R-5011 (HCCH), and 50 wt% photo-curable monomers [(30% RM257 (Merck) and 20% TMPTA (Sigma Aldrich)]. The concentration of monomer is chosen to be 50% since in a typical Fresnel zone plate the even and odd zones have the same area. The physical properties of the nematic host are as follows: $\Delta n = 0.205$ at $\lambda = 632.8$ nm, $\Delta\varepsilon = 85$ at 1 kHz and 21°C, and the clearing temperature is 90°C. The BPLC/monomers mixture was filled into an empty cell with indium-tin-oxide-coated glass substrates by means of capillary flow. The cell was heated to a temperature above the isotropic phase of the LC/monomer mixture during the infiltration in order to avoid separation caused by the viscosity difference between the LC and monomer. The cell gap was measured to be d = 11.5 μm. Subsequently, the cell was illuminated by a uniform UV light with a central wavelength of 365 nm through the photo-mask in isotropic phase. During UV-light (Loctite model 98016) exposure, the photomask was in proximity contact with the LC cell. Since the odd zones were blocked by the photo-mask while even zones were transparent, polymerisation process would first take place in the even zones resulting in the formation of PSCOFs corresponding to the photomask pattern.

Since the residual monomers left in the masked region will hinder the reorientation and thus degrade the electro-optical response of LC molecules, sufficient exposure must be applied. After the PIPS process, the sample was cooled down to room temperature and then re-illuminated by uniform UV light with higher intensity without the photo-mask for 30 minutes to photo-polymerise the remaining monomers. Then the polymer stabilised BPLC layer was formed in the odd rings and was completely separated from the polymer layer defined in the even rings. A binary-phase BPLCFL was thus successfully formed. With the BPLC, the refractive index distribution of the Fresnel lens can be tuned by the electric field which induces the birefringence of BPLC according to the extended Kerr model [21].

In the absence of an external electric field, the BPLC in the odd zones is nearly optically isotropic with an index n_i. When external electric field applies, the director of LC molecules tends to align parallel to electric field direction, thus the BPLCs will be optically anisotropic following the Kerr effect. Based on the extended Kerr model [21], the induced birefringence in a BPLC $\Delta n(E)$ can be described by

$$\Delta n_{\text{ind}}(E) = \Delta n_{\text{s}}\left[1 - \exp(-(\frac{E}{E_{\text{s}}})^2\right], \tag{1}$$

where Δn_s stands for the saturated induced birefringence and E_s is the saturation electric field. The induced ordinary index $n_o(E)$ and extraordinary refractive index $n_e(E)$ can be represented as

$$n_o(E) = n_i - \Delta n_{\text{ind}}(E)/3, \tag{2a}$$

$$n_e(E) = n_i + 2\Delta n_{\text{ind}}(E)/3. \tag{2b}$$

However, the electrically induced birefringence in more rigid polymer layer is much smaller in the even zones. As a result, the phase difference between the odd zones and the even zones can be practically controlled by the Kerr effect of BPLCs under a uniform vertical electric field. For normally incident light, both s and p waves experience the same index $n_o(E)$, so that the Fresnel lens functions independently of the polarisation state and the phase difference between odd and even regions could be expressed as $\Gamma(E) = \frac{2\pi}{\lambda}[n_o(E) - n_p]d$, which varies with the strength of external electric field. Here d is the cell gap and n_p is the refractive index of polymer layer.

2.2. Voltage-dependent focusing properties of BPLCFL

Figure 2 shows the experimental set-up for characterising the focusing properties of the BPLC Fresnel zone plate. The voltage-dependent diffraction efficiency and image quality were also measured through this set-up. A He–Ne laser (632.8 nm) was used as a probing light source and was filtered and collimated. The output beam of the laser was expanded by a beam expander and a diaphragm was used to adjust the aperture area such that the collimated laser beam filled the entire zone plate of the Fresnel lens. The voltage-dependent diffraction efficiency and spatial profile at primary focal point were measured by a photo-diode detector (New Focus Model 2031) and a charge-coupled device (CCD) camera placed at the primary focal point (~50 cm) after the BPLCFL, respectively. Due to the higher-order Fourier components, Fresnel zone lens typically has multiple foci, e.g., at f, f/3, f/5..., but

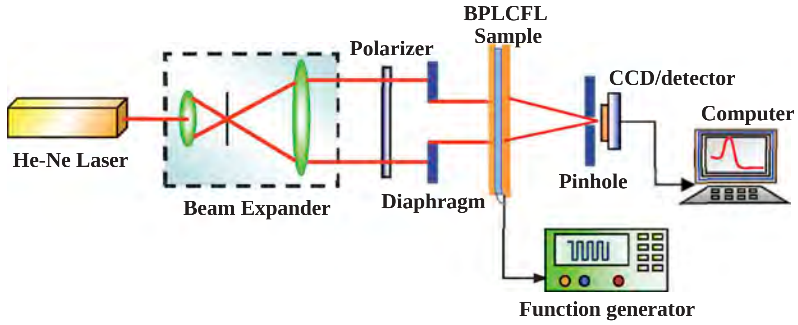

Figure 2. (colour online) Experimental set-up for measuring the focusing properties of the BPLCFL. A CCD/detector is set at the focus point of the BPLCFL to measure the focusing profile/diffraction efficiency.

most power of incident light is diffracted to the primary focus. The optical diffraction efficiency (η_n) of these foci can be described by $\mathrm{sinc}^2(n/2) = [\sin(n\pi/2)/(n\pi/2)]^2$, $n = \pm 1, \pm 3, \pm 5 \ldots$. Hence, a small pinhole was placed in front of the photo-diode to block light with higher-order focal points.

3. Results and discussion

Figure 3 shows the optical microscopic photograph of BPLCFL formed with PIPS process at different UV curing intensities. The PSCOF-based Fresnel zone structure was observed under crossed polarisation microscope. We found the phase separation of BPLC and polymer cannot be successfully achieved when the UV curing intensity is higher than 1 mW/cm^2 as shown in Figures 3(b,c). To efficiently achieve a good phase separation between BPLC and UV-curable monomer, the UV intensity irradiated on the cell should be as weak as possible. The UV light intensity of 0.5 mW/cm^2 at $\lambda \sim 365$ nm is suitable for realising good PSCOF-based Fresnel lens structure.

Figure 4 demonstrates the optical microscopic photograph of a portion of Fresnel BPLC zone plate at V = 0, 80, 120, and 180 V_{rms} with frequency of 1 kHz, respectively. In the absence of electric field, the sample exhibits BPLC/polymer composite Fresnel zone structure. The odd and even zones show different colours. When the applied voltage exceeded a threshold voltage (30 V_{rms}), the appearance in the odd zones (with BPLC) changed as shown in Figures 4(b–d). The appearances in the even zones were kept unchanged, indicating there is no BPLC in that region. The change in appearance is due to the electric-field-induced lattice distortion, which is known as the electrostriction effect [22]. When external voltage was applied, the electric field-induced Kerr effect resulted in the change in refractive index of PS-BPLC in the odd region, while the refractive index of the polymer region was kept unchanged, and thus the phase difference between these two regions changed and the diffraction efficiency changed gradually with increased electric field.

To measure the primary focal length, a photodiode detector was placed at near the focal point (50 cm), and then its relative position with respect to the Fresnel lens was adjusted until a sharp focal point was achieved. At this point, the distance between the Fresnel lens and the photodiode detector equals to the primary focal length. Given the PSCOFs between odd and even zones, which makes the effective refractive indices slightly different between adjacent zones, the focusing effect of the BPLCFL occurs. Figure 5 plots the measured first-order diffraction efficiency as

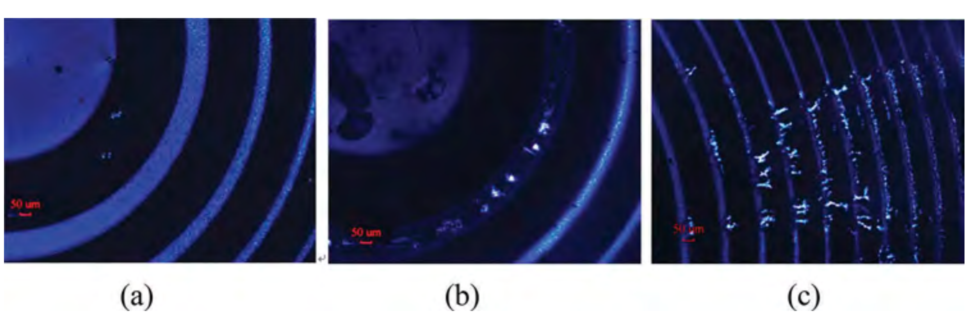

Figure 3. (colour online) The microscopic images of PSCOF Fresnel structure constructed under UV intensities of (a) 0.5 mW/cm^2 and (b, c) 1 mW/cm^2.

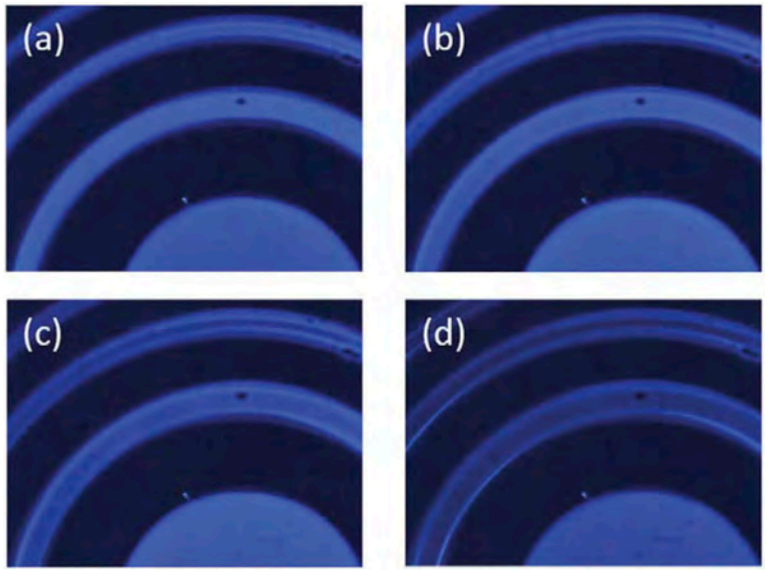

Figure 4. Microscope images of the BPLC cell at (a) V = 0, (b) 80 V_{rms}, (c) 120 V_{rms}, and (d) 180 V_{rms}. The LC cell was placed between crossed polarisers.

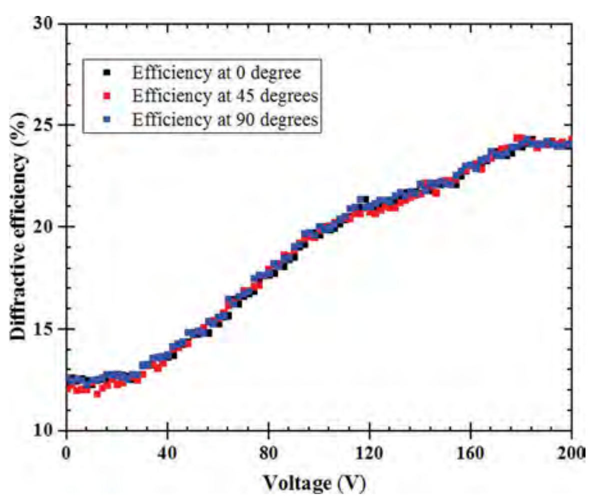

Figure 5. The voltage-dependent diffraction efficiency of the Fresnel lens at different voltage and polarisation angles with respect to X-axis.

a function of the applied voltage under different polarisation angle of the incident linearly polarised laser beam at room temperature. The diffraction efficiency is defined as the ratio of the diffracted light intensity at the primary focal point to the total light intensity passing through the sample. The experimental results show that the initial diffraction efficiency at V = 0 is 12.3%. This is due to the slight difference of effective refractive indices between the odd and even zones. For some applications, such an initial state is undesirable, and this can be avoided if an optimum cell gap or a BPLC material with refractive index matching the polymer zones at voltage off state is carefully chosen. When an external voltage beyond the critical value of approximately 80 V_{rms} was applied, the LC directors in the odd rings began to realign in the direction of the electric field, and the effective refractive index is then induced according to Kerr effect; on the other hand, the polymer in the odd rings remained basically unchanged. As the voltage increases, the phase difference between the two neighbouring zones increases, and so does the optical diffraction efficiency. When the voltage increases to 180 V_{rms}, the diffraction efficiency reaches the maximum value of ~24.3%. The measured value is very close to the measured diffraction efficiency of the used Fresnel-zone-plate mask (~25.6%). The slightly lower diffraction efficiency might be a result of weak light scattering occurred at the zone edges. The transmittance fluctuates slightly because of interference of multiple beams between two glass substrates. Through proper control of the polymerisation time and temperature, an optimised phase separation should be achievable with lower operation voltage and improved performance.

Due to the high driving voltage, hysteresis may occur. Some possible methods to reduce hysteresis at high voltage including better selection of polymer composition and alternative curing method are discussed in [23,24]. It can be also seen that the diffraction efficiency does not change with the polarisation angle, confirming that the BPLC Fresnel lens is independent of the incident light polarisation. Based on these experimental results, the sample can be used as a switchable lens. In addition, chromatism always causes great quality degradation of the diffraction imaging system. The chromatic

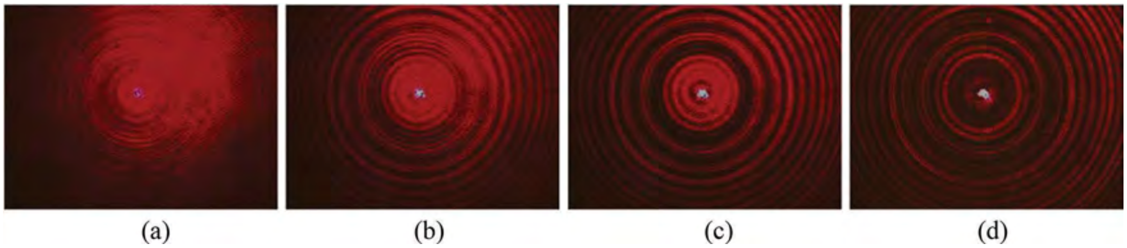

Figure 6. Imaging and focusing properties of the BPLC Fresnel lens recorded by a CCD camera at (a) 0 V, (b) 70 V_{rms}, (c) 140 V_{rms} and (d) 180 V_{rms}.

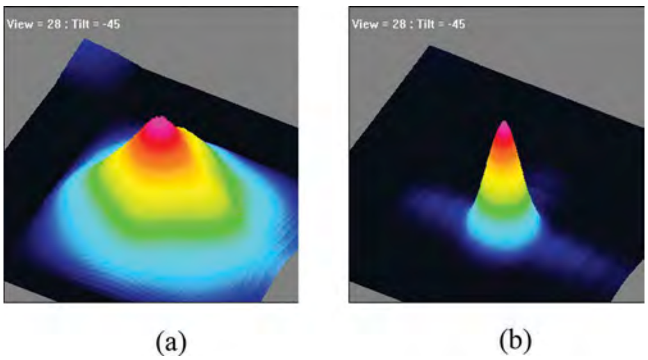

Figure 7. Spot intensity profiles measured by the CCD camera under applying voltages. (a) V = 0, and (b) V = 180 V_{rms}.

dispersion of the proposed BPLC Fresnel lens is caused by its nature more significant comparing to a typical biconvex lens. This is a result of exploiting phase modulation instead of refraction. Although this is largely forgiven for laser applications, the compensation methods to overcome chromatism for light source with wider band should be critically exploited such as the previous works [25,26].

Figure 6 shows the focusing properties of the BPLCFL captured by a digital CCD camera. When the sample was present with no voltage applied, the LC lens slightly focused light to the centre as seen in Figure 6(a), which was due to the refractive index mismatch between LC-rich and isotropic polymer domain layers. Diffraction rings were observed due to higher diffraction orders. As the applied voltage increased, the BPLC lens achieved higher efficiency as shown in Figure 6(b–d). The surrounding area became darker, indicating more light focusing to the centre. In addition, the optical diffraction efficiency was almost steady at the applied voltages beyond 180 V_{rms}.

Figures 7(a–b) show the measured three-dimensional intensity distribution at the primary focal point of BPLC Fresnel lens with different voltages. A weak focusing effect was observed at zero-voltage state and the peak intensity is obtained at 180 V_{rms}.

Moreover, to illustrate the imaging and focusing qualities of the LC Fresnel lens, a piece of black cardboard with a transparent letter U was placed in front of the LC sample as an object. Figure 8 shows the recorded images as the CCD camera is located in front of, at or behind the focal point (near 45, 50 and 55 cm, respectively) from the LC lens which operated at V = 180 V_{rms}. As the CCD camera was put at a distance of 45 cm from the LC Fresnel zone plate (5 cm in front of the focal plane), two images were observed simultaneously as shown in Figure 8(a). The bigger 'U' image represents the projected images of the U pattern without being diffracted, and smaller 'U' image corresponds to the first focus order. As the CCD was just in focal point position (at 50 cm), the observed first order focus 'U' image was focused to a bright spot as shown in Figure 8(b). When the

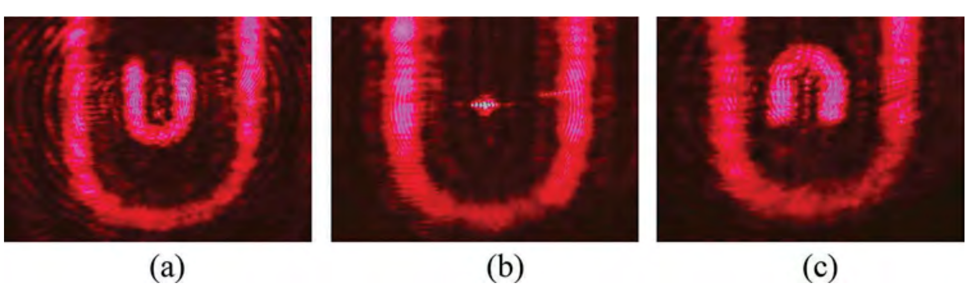

Figure 8. Image properties of the BPLC Fresnel lens recorded by a CCD camera placed (a) 5 cm before the focal point, (b) at the focal point and (c) 5 cm after focal point.

distance of CCD from the LC Fresnel lens was adjusted to 55 cm, the smaller 'U' image is reversed as illustrated in Figure 8(c). Therefore, proper focusing and imaging can be performed with the proposed polymer/BPLC composite Fresnel zone plate.

4. Conclusion

We have demonstrated an electrically switchable polarisation-independent binary-phase Fresnel lens using the photo-polymerisation-induced phase separation technique. This proposed method is simple for fabricating BPLC-based optical devices because only one photo-mask exposure is required to realise the binary phase-separated composite films. The focusing behaviour of the BPLCFL with high diffraction efficiency can be controlled continuously by a uniform electric field. With the merit of simple fabrication, polarisation-independency and continuous modulation, we believe the proposed BPLC Fresnel lens has wide potential applications.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

[1] Kitaura N, Ogata S, Mori Y. Spectrometer employing a micro-Fresnel lens. Opt Eng. 1995;34:584–588. DOI:10.1117/12.188608.

[2] Jahns J, Walker SJ. Two-dimensional array of diffractive microlenses fabricated by thin film deposition. Appl Opt. 1990;29:931–936. DOI:10.1364/AO.29.000931.

[3] Rastani K, Marrakchi A, Habiby SF, et al. Binary phase Fresnel lenses for generation of two-dimensional beam arrays. Appl Opt. 1991;30:1347–1354. DOI:10.1364/AO.30.001347.

[4] Mingtao L, Wang J, Zhuang L, et al. Fabrication of circular optical structures with a 20 nm minimum feature size using nanoimprint lithography. Appl Phys Lett. 2000;76:673–675. DOI:10.1063/1.125896.

[5] Canning J, Sommer K, Huntington S, et al. Silica-based fiber Fresnel lens. Opt Commun. 2001;199:375–381. DOI:10.1016/S0030-4018(01)01591-7.

[6] Ren H, Fan YH, Wu ST. Tunable Fresnel lens using nanoscale polymer-dispersed liquid crystals. Appl Phys Lett. 2003;83:1515–1517. DOI:10.1063/1.1604943.

[7] Fan Y-H, Ren H, Wu S-T. Switchable Fresnel lens using polymer-stabilized liquid crystals. Opt Express. 2003;11:3080–3086. DOI:10.1364/OE.11.003080.

[8] Lin LC, Cheng KT, Liu CK, et al. Fresnel lenses based on dye-doped liquid crystals. Proc SPIE. 2008;6911:69110I–1.

[9] Fan Y-H, Ren H, Wu S-T. Electrically switchable Fresnel lens using a polymer-separated composite film. Opt Express. 2005;13:4141–4147. DOI:10.1364/OPEX.13.004141.

[10] Jeng SC, Hwang SJ, Horng J-S, et al. Electrically switchable liquid crystal Fresnel lens using UV-modified alignment film. Opt Express. 2010;18:26325–26331. DOI:10.1364/OE.18.026325.

[11] Kim D-W, Lee S-D, Yu C-J. Electrically controlled diffraction efficiency of liquid crystal fresnel lens with polarization-independence. Mol Cryst Liq Cryst. 2007;476:133–140. DOI:10.1080/15421400701685977.

[12] Lin C-H, Huang H-Y, Wang J-Y. Polarization-independent liquid-crystal fresnel lenses based on surface-mode switching of 90° twisted-nematic liquid crystals. IEEE Photon Technol Lett. 2010;22:137–139. DOI:10.1109/LPT.2009.2036738.

[13] Hwang S-J, Chen T-A, Lin K-R, et al. Ultraviolet light treated polyimide alignment layers for polarization-independent liquid crystal Fresnel lenses. App Phys B Lasers Optics. 2012;107:151–155. DOI:10.1007/s00340-012-4885-0.

[14] Lin C-H, Wang -Y-Y, Hsieh C-W. Polarization-independent and high-diffraction-efficiency Fresnel lenses based on blue phase liquid crystals. Opt Lett. 2011;36:502–504. DOI:10.1364/OL.36.000502.

[15] Tan J, Song Y, Zhu JL, et al. Blue phase LC/polymer Fresnel lens fabricated by holographics. J Display Technol. 2014;10:157–161. DOI:10.1109/JDT.2013.2291068.

[16] Lin YH, Chen HS, Lin HC, et al. Polarizer-free and fast response microlens arrays using polymer-stabilized blue phase liquid crystals. Appl Phys Lett. 2010;96:113505-113505-3. DOI:10.1063/1.3360860.

[17] Lee CT, Li Y, Lin HY, et al. Design of polarization-insensitive multi-electrode GRIN lens with a blue-phase liquid crystal. Opt Express. 2011;19:17402–17407. DOI:10.1364/OE.19.017402.

[18] Li Y, Wu ST. Polarization independent adaptive microlens with a blue-phase liquid crystal. Opt Express. 2011;19:8045–8050. DOI:10.1364/OE.19.008045.

[19] Hwang SJ. Characterisation of polymer wall formation in nematic liquid crystal devices. Liq Cryst. 2008;35:365–371. DOI:10.1080/02678290701877536.

[20] Baek J-I, Shin J-H, Oh M-C, et al. Pixel-isolation walls of liquid crystal display formed by fluorinated UV-curable polymers. Appl Phys Lett. 2006;88:161104–3. DOI:10.1063/1.2195902.

[21] Yan J, Cheng HC, Gauza S, et al. Extended Kerr effect of polymer-stabilized blue-phase liquid crystals. Appl Phys Lett. 2010;96:071105. DOI:10.1063/1.3318288.

[22] Ge Z, Gauza S, Jiao M, et al. Electro-optics of polymer-stabilized blue phase liquid crystal displays. Appl Phys Lett. 2009;94:101104. DOI:10.1063/1.3097355.

[23] Lee YH, Gou F, Peng F, et al. Hysteresis-free and sub-millisecond-response polymer network liquid crystal. Opt Express. 2016;24:14793–14800. DOI:10.1364/OE.24.014793.

[24] Liu Y, Xu S, Xu D, et al. A hysteresis-free polymer-stabilized blue phase liquid crystal. Liq Cryst. 2014;41:1339–1344. DOI:10.1080/02678292.2014.920055.

[25] Sharp TE, Wisoff PJ. Analysis of lens and zone plate combinations for achromatic focusing of ultrashort laser pulses. Appl Opt. 1992;31:2765–2769. DOI:10.1364/AO.31.002765.

[26] Li Y, Li X, Pu M, et al. Achromatic flat optical components via compensation between structure and material dispersions. Sci Rep. 2016;6:19885–1. DOI:10.1038/srep19885.