Polymer-Stabilized Blue-Phase Liquid-Crystal Fresnel Lens Cured by Patterned Light Using a Spatial Light Modulator †

Na Rong, Yan Li *, Yachao Yuan, Xiao Li, Pengcheng Zhou, Shuaijia Huang, Shuxin Liu, Jiangang Lu, and Yikai Su *
National Engineering Lab for TFT-LCD Materials and Technologies, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

Abstract
A novel fabrication method for polymer-stabilized blue-phase liquid-crystal Fresnel lens is proposed. Blue phase is stabilized by patterned light illumination directly obtained from a spatial light modulator. The lens diffraction efficiency can be continuously tuned. With full programmable capability, this method holds great potential in optical applications.

Author Keywords
Polymer-stabilized blue-phase liquid crystal; patterned light; spatial light modulator; Fresnel lens.

1. Introduction
Fresnel lenses are widely used in in the fields of optical communications, optical imaging and three-dimensional (3D) displays [1-3]. To control the diffraction efficiency and focal length, Fresnel lenses using liquid crystals have been developed [4-7]. However, for most devices, conventional nematic LC materials are employed, and several problems such as polarization dependency and slow response time remain to be overcome. Blue phase liquid crystal (BPLC), with several favorable characteristics such as fast response, quasi-optical isotropy and no requirement of alignment layers [8-10], is an attractive candidate for tunable Fresnel lenses. Lin et al. proposed a polarization-independent BPLC Fresnel lens [11], with an even-zone electrode formed on one of the substrates. However, patterned electrode structure involves sophisticated photolithography processes. Tan et al. presented a Fresnel type BPLC/polymer lens fabricated via holographic polymer template [12]. However, the method is complicated due to multi-step fabrication, and the temperature range of the BPLC Fresnel lenses is rather narrow without polymer stabilization.

In this paper, we demonstrate a novel method to fabricate polymer stabilized blue phase (PSBPLC) Fresnel lenses using a spatial light modulator (SLM). BPLC is directly stabilized by patterned light illumination generated from a SLM, forming a polymer concentration distribution pattern simultaneously. With a vertical electric field, alternating high and low refractive index distributions are obtained in right and dark regions due to different polymer concentrations and network strengths. Thus, focusing effect is observed and the Fresnel lens is switched on. The method features easy fabrication and programmable capability, and can achieve high spatial resolution at low cost.

2. Fabrication and operating principle
As depicted in Fig.1, an expanded laser beam (533 nm) illuminates the SLM (Hololoye), producing a binary Fresnel light pattern. A telescopic system (lenses L2 and L3) projects the miniﬁed light pattern to the sample [13], which is a visible-curable BPLC precursor [14]. After an appropriate exposure period, BPLC is stabilized by the non-uniform visible illumination, resulting in stronger polymer networks in bright regions and weaker networks in the dark regions as shown in Fig. 2. If a vertical external electric field is applied, smaller birefringence is induced in bright regions due to stronger polymer networks, and larger birefringence is induced in dark regions, creating alternating high and low refractive index distributions [15]. Thus, the Fresnel lens phase profile is obtained.

3. Experimental results
The BPLC precursor in this experiment is a mixture of nematic liquid crystal host HTG135200-100 (85.4 wt%, HCCH), chiral dopant R5011 (4.0 wt%, HCCH), monomer TMPTA (4.0 wt%, Aldrich), monomer RM257 (6.0%, HCCH), photoinitiator Rose Bengal (0.3 wt%, Aldrich), and coinitiator Nphenylglycine (0.3 wt%, Aldrich). Then the mixture was injected to an empty LC cell assembled with two ITO glass substrates (separated by a 20 μm spacer and coated with a polyimide alignment layer). The blue
phase is present between 68 ~61 °C during cooling. The precursor is cured at 63°C for 1.5 hour by the patterned laser illumination (532 nm) with an average intensity of 12.5mW/cm².

**Figure 3.** (a) Polarizing micrographs of the PSBPLC Fresnel lens at room temperature. (b) Light pattern loaded on the SLM

Fig.3 (a) shows morphologies of the BPLC lens observed using a polarizing optical microscopy (POM), which works in transmissive mode. One can see the Fresnel zones along with the characteristic platelet texture of blue phase. Bright zones are corresponding to denser polymer networks and dark zones corresponding to looser polymer networks. The innermost radius of our PSBPLC Fresnel lens is 110 μm. So the primary focal length is related to the innermost radius \( r_1 \) as
\[
 f = \frac{r_1^2}{\lambda} = 1.91 \text{ cm}
\]
(for \( \lambda = 633 \text{nm} \)), where \( r_1 \) is the innermost radius and \( \lambda \) is the wavelength of the probe beam [16].

**Figure 4.** Experimental setup for measuring the focusing properties of the lens.

Fig. 4 depicts the experimental setup for measuring focusing properties of the lens [11]. An expanded He-Ne laser (633 nm) beam serves as the probe beam. A polarizer is inserted to change the polarization direction of the beam. A CCD camera connected to a computer is placed behind the sample to record beam images. A sinusoidal wave of 1 kHz is applied to the cell. Fig. 5 (a) shows the corresponding diffraction efficiency of the PSBPLC Fresnel lens under different applied voltages. If the applied voltage is less than 31 \( V_{\text{rms}} \), the diffraction efficiency decreases to 0 from 0.93%. As the voltage varies from 31 \( V_{\text{rms}} \) to 140 \( V_{\text{rms}} \), the diffraction efficiency increases gradually, reaching 9.3% at 140 \( V_{\text{rms}} \). If the voltage is off, the small index mismatch occurs between the PSBPLCs in bright and dark regions, causing the weak diffraction effect, as shown in Fig. 5 (b). When a vertical external electric field is applied, alternating electric-field-induced refractive index distributions are obtained due to polymer network strength variation. At 31\( V_{\text{rms}} \) the refractive indices of the polymer chains and the BPLC match, thus no diffraction occurs, as shown in Fig. 5 (c). At 140 \( V_{\text{rms}} \), the focusing effect reaches the maximum, as shown in Fig. 5 (d). Therefore, the diffraction efficiency of our lens can be controlled continuously from 0 to 9.3%. Moreover, as the polarization direction is varied from 0° to 45° and 90°, the diffraction efficiency does not change much, thus, the Fresnel lens is polarization insensitive. The measured focal length is about 2 cm, which is close to the calculated value of 1.91 cm.

**Figure 5.** (a) Measured diffraction efficiency of the PSBPLC Fresnel lens as a function of applied voltage under 0°, 45°, 90° linearly polarized light. Recorded CCD images of the beam after passing through the Fresnel lens at (b) 0 \( V_{\text{rms}} \), (c) 31 \( V_{\text{rms}} \) and (d) 140 \( V_{\text{rms}} \). (\( T = 24 \text{ °C} \) and \( \lambda = 633 \text{ nm} \)).

**Figure 6.** Electro-optical response of the PSBPLC Fresnel lens.

Fig. 6 shows the measured response times of the PSBPLC Fresnel lens. The CCD in Fig. 4 is replaced by a photodetector. An imaging lens with a focal length of 50 mm is placed right before the photodetector to collect the light through the sample [17][12]. The response times of the lens between defocused (31 \( V_{\text{rms}} \)) to focused states (140 \( V_{\text{rms}} \)) are measured. The rise time is 700 μs and the decay time is 1.2 ms, respectively.
Figure. 7. (a) Binary light pattern loaded on the SLM. (b) Recorded CCD images of the beam after passing through the 2D microlens array at 31 Vrms and (c) 140 Vrms. (T=24 °C and λ= 633 nm)

We also prepared a two-dimensional PSBPLC microlens array, as shown in Fig. 7 (b) and (c). The measured focal length is 0.95 cm which is close to the calculated value of 1 cm.

4. Impact

We have demonstrated a Fresnel PSBPLC lens cured by patterned light directly generated from a spatial light modulator. Such an electrically tunable Fresnel lens is polarization insensitive and has fast response. This novel method offers a simple and programmable procedure that allows the realization of various electro-optical BPLC devices.

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6. References