Electrically switchable optical vortex generated by a computer-generated hologram recorded in polymer-dispersed liquid crystals

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Abstract: A computer-generated hologram designed to generate an optical vortex was recorded in a cell filled with polymer-dispersed liquid crystal material under a collimated Ar^+ laser beam operating at 514.5 nm. Owing to the photopolymerization-induced phase separation between the polymer and the liquid crystal, an index modulation was formed between the polymer-rich and liquid crystal-rich regions. A good optical vortex beam with high fidelity was reconstructed using a collimated He–Ne laser beam. The diffraction efficiency is estimated to be about 13%–17%. With a suitable voltage applied, the reconstructed optical vortex beam can be switched owing to the index change between the polymer and the liquid crystal.

OCIS codes: (050.1970) Diffractive optics; (090.1760) Computer holography; (230.3720) Liquid-crystal devices; (160.5470) Polymers.

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1. Introduction

Considerable attention has been paid to the optical vortex (OV) owing to its specialty and that it is widely used in many fields such as optical trapping [1, 2], rotational frequency shift [3, 4], and optical manipulation for microelectromechanical systems (MEMS) [5]. The OV has been described as a topological point defect (also known as a dislocation) on a wavefront and is manifested as a null within a light beam, because the phase at the defect point is indeterminate. There are several methods to generate an OV, such as computer-generated holograms [6], mode-converters [7], phase masks [8], and spiral phase plates [9].

A computer-generated hologram (CGH) is widely known as a useful tool for wavefront manipulations and optical information processing, which enables the creation of very sophisticated optics without any limits as to what the final diffraction pattern may look like. Many different kinds of materials were used to record CGHs, *e.g.*, Fe-doped $LiNbO_3$ single crystals [10], $BaTiO_3$ crystals [11], and bacteriorhodopsin [12]. Recently, we showed an electrically switchable CGH recorded in a cell filled with polymer-dispersed liquid crystal (PDLC) material [13]. PDLC material has been investigated extensively for displays [14, 15], switchable gratings [16, 17], photonic crystals [18 - 20], lasers [21 - 23], and microlenses [24]. A vitally important method used to construct PDLC devices is a photopolymerization-induced phase separation (PIPS) by either UV or visible lasers, depending on the materials used. In this paper, we report an OV generated by a PDLC CGH. The unique characteristic of such an OV is that it is electrically switchable and has fast response time, which is desired for adaptive optical devices.

2. Experiment

In our experiment, the materials and their respective weight ratios (wt%) used to record the CGH were: for the monomer, trimethylolpropane triacrylate (TMPTA), 53.9 wt%; for the cross-linking monomer, N-vinylpyrrolidinone (NVP), 7.0 wt%; for the surfactant, octanoic acid (OA), 7.4 wt%; for the coinitiator, N-phenylglycine (NPG), 0.8 wt%; for the photoinitiator, rose bengal (RB), 0.6 w% (all above from Aldrich); and for the LC, E7 (Merck), 30.3 wt%. The LC E7 that was used has an ordinary refractive index of $n_o = 1.521$ and a birefringence of $\Delta n = 0.225$. The prepolymer and LC were mechanically blended in dark conditions according to the appropriate weight ratio at 65°C (higher than the clearing point of the LC E7) to form a homogeneous mixture. The LC cell was fabricated using two pieces of indium-tin-oxide-(ITO) coated glass with the thickness of 1.1 mm. The cell gap used

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was 8 μm. The voltage was applied on the cell between the two ITO electrodes to observe the electrical tuning of the diffraction pattern.

A monochromatic beam propagating in the *z*-direction and containing a single vortex transversely centered at the origin (r = 0) can be expressed by the scalar envelope function

$$u(r,\theta,z) = A_m(r,z)\exp(im\theta)\exp[i\Phi_m(r,z)], \tag{1}$$

where (r,θ,z) is cylindrical and coordinates with the optical axis aligned along the *z*-axis, $\exp(im\theta)$ is the characteristic expression of the optical vortex, m is a signed integer called the topological charge, Φ_m is the phase, $k = 2\pi/\lambda$ is the wave number, and λ is the wavelength.

To construct a CGH of an OV, we first calculated numerically the interferogram of two waves: a planar reference wave and an object wave containing the desired optical vortex [25]. Once the interferograms were numerically calculated, they could be transferred to a transparency by a laser printer. In our experiments, three binary transparency masks with three different topological charges were fabricated with an effective area of 1×1 cm^2 and a resolution of 25 μm, as shown in Fig. 1. The pattern contains almost parallel lines with a fork-like bifurcation at the vortex core. The black and white regions represent phase values of 0 and π, respectively.

To record the CGH pattern, first the prepolymer/LC mixture filled a LC cell by capillary action. Then the photomask was clipped onto the cell and subjected to a collimated Ar^+ laser (514.5 nm) beam. Phase separation was carried out by PIPS. Finally, the morphologies similar to the mask were formed inside the cell. The intensity impinged on the mask after collimation was about 12 mW/cm^2. The optimal exposure time was 2 min in our experiment, judged from the fading of the RB color.

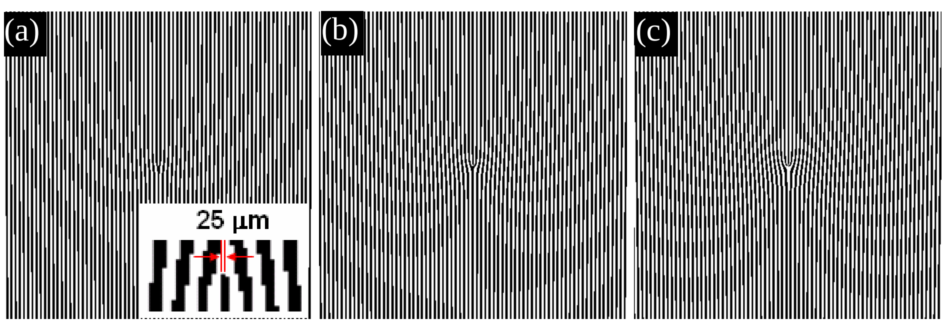

Fig. 1. Binary transparency masks fabricated with the topological charge of (a) m = 1, (b) m = 2, and (c) m = 3, respectively. Inset in (a) shows the resolution in the magnified image of (a).

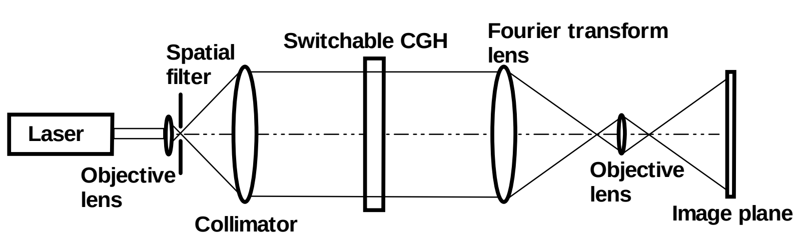

Fig. 2. Optical setup to reconstruct the image from PDLC OVs.

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Figure 2 shows the optical setup for OV reconstruction from the PDLC cell. The linear polarized light beam (the polarization direction is parallel to the fork pattern on the PDLC cell) from a green He–Ne laser operating at 543 nm with an output power of 4 mW is first incident on a spatial filter system consisting of an objective lens and a pinhole. The expanded beam is then collimated and falls on the PDLC cell. A Fourier transform lens is used to produce the Fraunhofer diffraction pattern of the hologram in its focal plane. Because the image is too small to observe, a second objective lens with a 5× magnification is used to magnify the image.

3. Results and discussion

Figure 3 shows the central morphologies of CGH masks on transparency and PDLC CGHs after phase separation under an optical microscope for (a) and (b) where m = 1, (c) and (d) where m = 2, and (e) and (f) where m = 3, respectively. It can be seen that a good phase separation between the polymer and the LC happened inside the cell, where the brighter and darker areas were the polymer-rich and LC-rich regions, respectively. In our configuration, the refractive index of the polymer, n_p, is set to be equal to the ordinary refractive index of the LC, n_o. Without voltage applied, the LC molecules are randomly distributed, and an effective refractive index larger than that of the polymer is present in the bright regions. As a result, there is an index difference between the LC-rich and polymer-rich regions. Upon applying voltage, the LC director aligns along the direction of the electric field. If the indices of the LC and polymer are matched, the composite film becomes a homogeneous medium and thus the phase difference disappears.

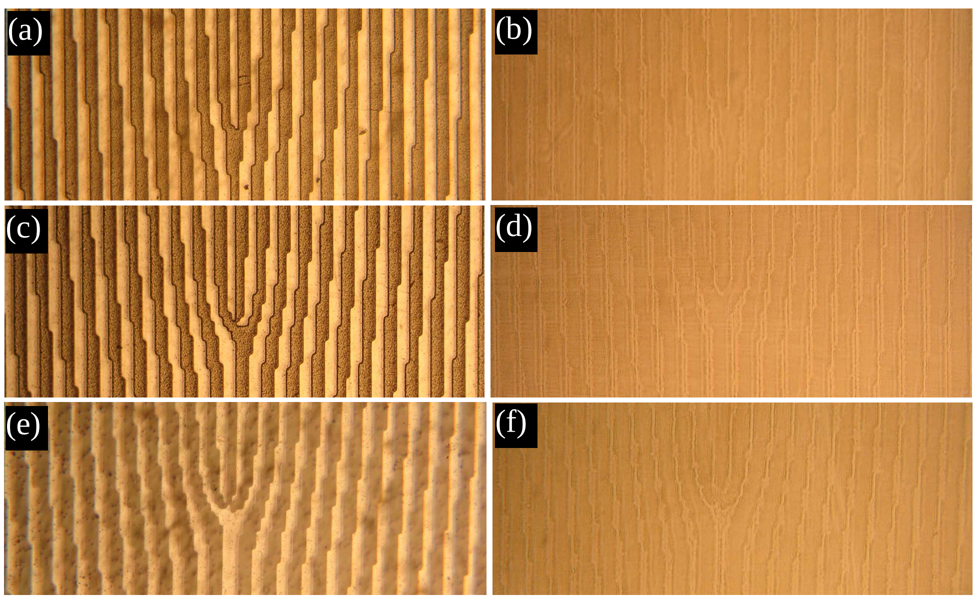

Fig. 3. Central optical microscopic images of CGH masks and PDLC CGH for (a) and (b) where m = 1, (c) and (d) where m = 2, and (e) and (f) where m = 3, respectively.

Figures 4(a), 4(b), and 4(c) show the photographs of the reconstructed OVs taken with a digital camera without voltage applied for m = 1, 2, and 3, respectively. It can be seen clearly that a dark hole centered at the middle of the diffracted beam shows a general sign of a doughnut beam [26]. The diffraction efficiency was measured by a power meter at the wavelength of 543 nm. Here, the diffraction efficiency was defined as the intensity ratio of the first-order diffraction to the sum of the zeroth-order and first-order beams (the higher orders were too weak to be measured). The measured efficiency was about 13%–17% for the

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samples with different charges. It is very important to increase the diffraction efficiency for the far-reaching application of the OV. One way to achieve high diffraction efficiency is to make the phase difference ($\Delta\delta$) between the adjacent LC-rich and polymer-rich regions closer to π. The relative phase difference $\Delta\delta$ can be written as

$$\Delta\delta = 2\pi(n_{eff} - n_p)d/\lambda\,, \tag{2}$$

where d is the cell gap, λ is the wavelength, and n_{eff} and n_p are the LC effective refractive index and polymer refractive index, respectively. The phase difference $\Delta\delta$ was estimated to be 0.8π in this experiment [12], which is slightly smaller than π. The other way to increase the diffraction efficiency is to achieve a thick volume Bragg-type hologram, where nearly all of the incoming light possibly may be diffracted into the first-order. The binary amplitude CGH mask can be converted into a thick volume phase Bragg hologram in the PDLC, according to the method reported in Ref. [25] where a 4f system was used to produce the CGH mask image as the object beam, which interferes with a reference beam to form the Bragg hologram.

With voltage applied, the reconstructed optical vortex was checked. Figures 5(a) and 5(b) show the reconstructed images of the m = 3 sample with an applied voltage of V = 0 and 70 V_{rms}, respectively. From Fig. 5, we can see that the reconstructed OVs become blurred and even disappear for the higher order diffractions, which is owing to the refractive index change in the LC region.

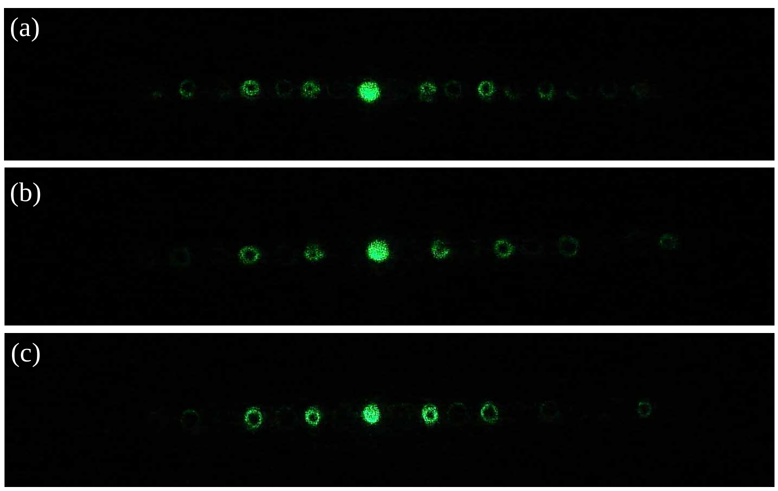

Fig. 4. Photographs of the reconstructed OV without voltage applied for (a) m = 1, (b) m = 2, and (c) m = 3, respectively.

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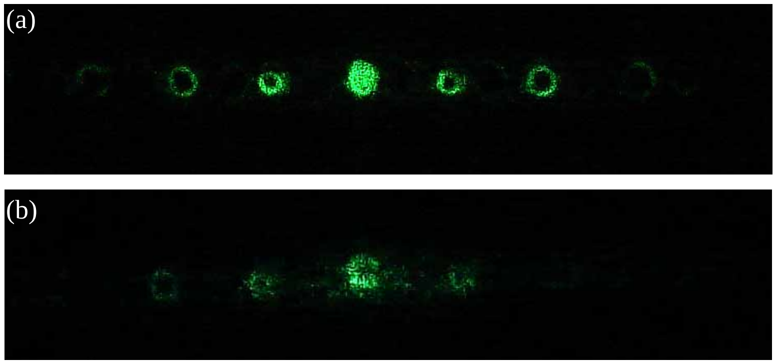

Fig. 5. Photographs of the reconstructed OV at (a) V = 0, and (b) V = 70 V_{rms}, respectively.

4. Conclusion

In conclusion, we showed an OV generated by a phase-type PDLC CGH. This kind of OV generation demonstrates easy fabrication, compactness, light weight, and low cost. Due to the change of the refractive index difference between the polymer-rich and LC-rich regions induced by an electric field, the reconstructed OV is electrically switchable. Our results show promising applications of PDLC materials in generating switchable OVs.

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