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Generating electrically tunable optical vortices by a liquid crystal cell with patterned electrode

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An electrically tunable optical vortex was generated in an antiparallel liquid crystal cell, where one electrode was patterned by a photomask, which is achieved by transferring a computer-generated hologram onto a transparency with a resolution of about 25 μm. When a voltage was applied on the cell, an index modulation was induced due to the realignment of liquid crystal molecules, and then an optical vortex beam was produced. The diffraction efficiency measured was about 27.5%. The device also showed a reasonably fast response time. © *2008 American Institute of Physics*.

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Optical elements containing an angular phase pattern can create an optical vortex (OV) beam,[1] which has been generated by a variety of approaches, such as computer-generated holograms (CGHs),[2] mode-converters,[3] phase masks,[4] and spiral phase plates.[5] OV has been described as a topological point defect (also known as a dislocation) on the wavefront and is manifested as a "null" within a light beam because the phase at the defect point is indeterminate. OV has been paid considerable attention due to its speciality and applications in many fields, such as optical trapping,[6,7] rotational frequency shift,[8,9] and optical manipulation.[10]

CGH is widely known as a useful tool for wave front 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 crystal,[11] $BaTiO_3$ crystal,[12] bacteriorhodopsin,[13] and polymer-dispersed liquid crystals.[14,15] In this paper, we report an OV generated in an antiparallel liquid crystal cell. The unique characteristics of such kind of OV are that it is electrically switchable and it has a reasonably fast response time, which is desired for adaptive optical devices with no moving parts. The ability to adjust in a rapid time scale would add to the possibility of a dynamic manipulation of particles in complex guides and traps.

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 the cylindrical coordinates with the optical axis aligned along the z-axis, $\exp(im\theta)$ is the characteristic expression of the OV, m is a signed integer called the topological charge, and Φ_m is the phase.

To construct the CGH of an OV, we first calculated numerically the interferogram of two waves: a planar reference wave and an object wave containing the desired OV.[16] For simplicity, we choose the object wave to be a point vortex of unit charge on an infinite background field of amplitude C_{obj},

$$E_{\text{obj}} = C_{\text{obj}}\exp(im\theta), \tag{2}$$

and a reference wave of amplitude C_{ref}, whose wave vector lies in the (x,z) plane, subtending the optical axis z at the angle φ, can be expressed as

$$E_{\text{ref}} = C_{\text{ref}}\exp(-i2\pi x/\Lambda), \tag{3}$$

where $\Lambda=\lambda/\sin\varphi$ is the spatial period of the plane wave in the transverse plane. The interferogram is given by the intensity of the interfering waves,

$$I_{z=0}(x,\theta) = |E_{\text{obj}} + E_{\text{ref}}|^2_{z=0} = 2C^2[1+\cos(2\pi x/\Lambda + m\theta)], \tag{4}$$

where we set $C_{\text{ref}}=C_{\text{obj}}=C$ to achieve a unity contrast.

For a blazed grating, the efficiency can be made almost perfect as with a suitable choice of grating period and blazed angle, almost all of the beam can be sent in the desired direction of the principal diffraction maximum. The transmittance function of a blazed phase hologram can be written as[17]

$$T(x) = \exp[ip\text{Mod}(x,\Lambda)], \tag{5}$$

where p is the amplitude of phase modulation and $\text{Mod}(a,b)=a-b\text{Int}(a/b)$. If $p\Lambda/2=\pi$ is satisfied, the blazed grating diffracts all the light into one order, enhancing the diffraction efficiency accordingly. Neglecting the constant term in Eq. (4), the blazed interference patterns can be written as

$$I(x,\theta) = \text{Mod}(2\pi x/\Lambda + m\theta, 2\pi). \tag{6}$$

The resulting blazed interferogram for $m=2$, depicted in Fig. 1, resembles a sinusoidal intensity diffraction grating. The pattern contains almost parallel lines with a bifurcation at the vortex core. Once the interferogram was numerically calculated, it was transferred to a transparency by a laser printer. In our experiment, a binary transparency mask with the topological charge of $m=2$ was fabricated with an effective area of 1×1 cm^2 and a resolution of 25 μm. The black and white regions represent phase values of 0 and π,

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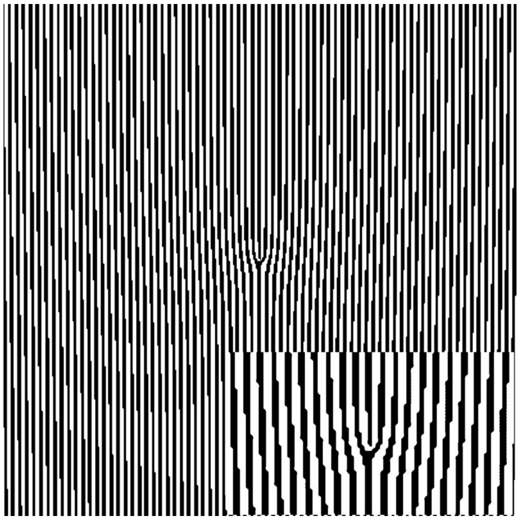

FIG. 1. Binary transparency mask fabricated with the topological charge of $m=2$. The inset shows the magnified central part of the image.

respectively. For the reconstruction, the detailed experimental setup can be found elsewhere.[14] In this experiment, an objective lens with 5× magnifications was used to magnify the image.

The liquid crystal used was E7 from Merck with an ordinary refractive index of $n_0=1.521$, and birefringence of $\Delta n=0.225$. The liquid crystal cell was prepared by antiparallel rubbing. The pretilt angle was about 3–5°. The LC molecules were aligned in anti-parallel directions. The cell gap was about 2 μm.

With a voltage applied, the reconstructed OV was examined. Figure 2 shows the reconstructed images of the $m=2$ sample with an applied voltage of $V=0$ (a), $V=3.6$ V (b), $V=4.8$ V (c), and $V=6.2$ V (d). From Fig. 2, we can see that at $V=0$ there is no reconstructed OV. At a threshold voltage of $V=3.6$ V, the LC molecules start to realign along the electric field direction, and a smaller index modulation is formed, resulting in weaker OVs (±1st order) [Fig. 2(b)]. When the voltage is further increased, a larger index modulation is formed, and then the higher order diffracted OVs appear [Figs. 2(c) and 2(d)]. Due to the blazed effect, the diffracted orders at the left are slightly higher in intensity than those at the right; meanwhile, another set of diffracted orders appears, which is clearly shown in Fig. 2(d). It is worth mentioning that the blazed angle was set at an arbitrary value in the design. Therefore, the efficiency is still low in the direction of the principal diffraction maximum. With the careful design of the grating period and blazed angle, the efficiency can reach the theoretical value of 100%. Figure 3(a) and 3(b) show the two- and three-dimensional intensity profiles of the first order diffraction measured by a change coupled device profiler, respectively, which are similar to the observation in Ref. 18.

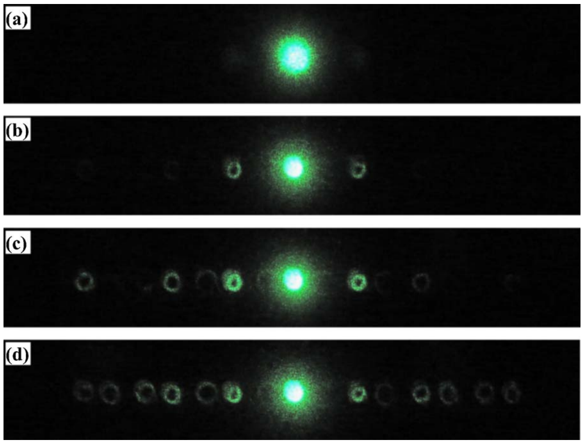

FIG. 2. (Color online) The reconstructed images of the sample for $m=2$ with an applied voltage of $V=0$ (a), $V=3.6$ V (b), $V=4.8$ V (c), and $V=6.2$ V (d).

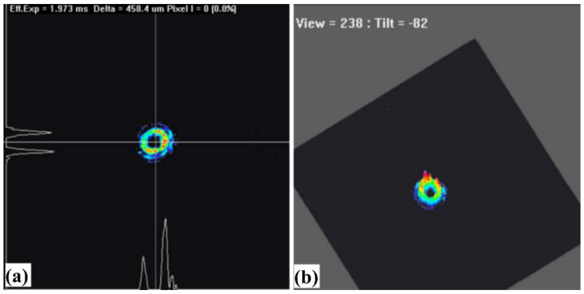

FIG. 3. (Color online) Two-dimensional (a) and three-dimensional (b) intensity profiles of the first order diffraction.

Figure 4 shows the transmission and the first order diffraction curves as a function of applied voltages. The threshold is 3.6 V_{rms}. At the voltage of 6.2 V_{rms}, the first order diffraction reaches its maximum, indicating that the phase difference is very close to π at this voltage. The relative phase difference $\Delta\delta$ can be written as $\Delta\delta=2\pi(n_1-n_2)d/\lambda$, where d is the cell gap, λ is the wavelength, n_1 and n_2 are the LC refractive indices in the regions with indium tin oxide (ITO) patterns and without ITO patterns, respectively. The maximum phase difference $\Delta\delta$ was estimated to be 1.7π in this experiment. The highest first order diffraction efficiency measured is about 27.5%. With the voltage further increased, the efficiency decreases again because the phase difference is larger than π.

Figure 5 shows the measured electro-optical response time when the sample was driven by a square wave of 5.6 V_{rms} with a frequency of 5 Hz. From Fig. 5, the rising time (10–90% intensity changed) and the falling time (90–10% intensity changed) are about 9.7 and 6.5 ms, respectively.

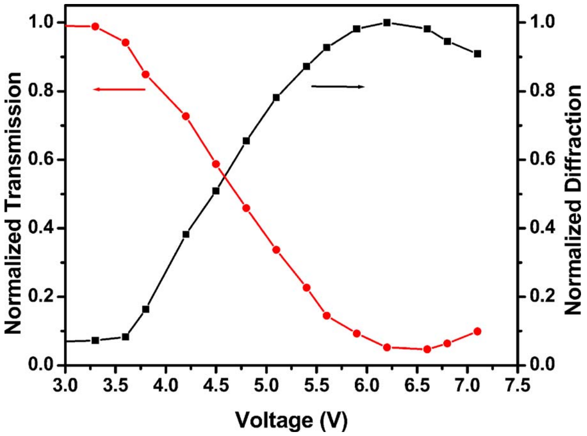

FIG. 4. (Color online) The transmission and the first order diffraction curves as a function of applied voltages.

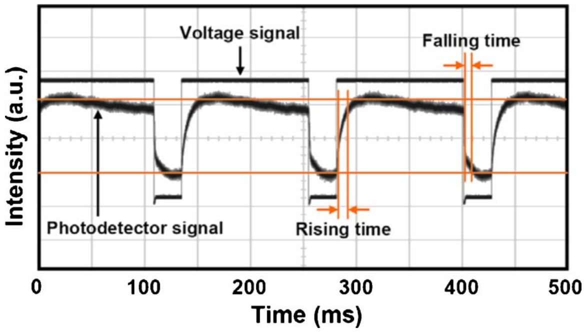

FIG. 5. (Color online) Measured electro-optical response time.

In conclusion, we demonstrated an OV generation in a LC cell. This kind of OV generation shows easy fabrication process, compactness, light weight, and low cost. Due to the change of the refractive index difference induced by an electric field, the reconstructed OV is electrically tunable. The highest first order diffraction efficiency measured was about 27%. It showed a reasonably fast response time. This kind of OV is promising for adaptive optical devices with no moving parts.

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