Airy beams generated by a binary phase element made of polymer-dispersed liquid crystals

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Abstract: Using polymer-dispersed liquid crystals (PDLCs), an electrically switchable binary phase pattern was fabricated to generate Airy beams through a programmable lithographic system. The right main lobe of the reconstructed Airy beam experienced 1.3 mm transverse deflection within 24 cm propagation distance. With a suitable voltage applied, the binary PDLC pattern can be erased due to the index match between polymers and liquid crystals. This versatile approach can be also used to generate other special beams with electrically tunable capability.

OCIS codes: (050.1970) Diffractive optics; (050.5080) Phase shift; (160.2100) Electro-optical materials; (230.3720) Liquid-crystal devices.

References and links

1. K. Dholakia, P. Reece, and M. Gu, "Optical micromanipulation," Chem. Soc. Rev. **37**(1), 42–55 (2007).
2. V. Garcés-Chávez, D. McGloin, H. Melville, W. Sibbett, and K. Dholakia, "Simultaneous micromanipulation in multiple planes using a self-reconstructing light beam," Nature **419**(6903), 145–147 (2002).
3. Z. Ding, H. Ren, Y. Zhao, J. S. Nelson, and Z. Chen, "High-resolution optical coherence tomography over a large depth range with an axicon lens," Opt. Lett. **27**(4), 243–245 (2002).
4. J. Durnin, "Exact solutions for nondiffracting beams. I. The scalar theory," J. Opt. Soc. Am. A **4**(4), 651 (1987).
5. J. Durnin, J. J. Miceli, Jr., and J. H. Eberly, "Diffraction-free beams," Phys. Rev. Lett. **58**(15), 1499–1501 (1987).
6. D. G. Hall, "Vector-beam solutions of Maxwell's wave equation," Opt. Lett. **21**(1), 9 (1996).
7. U. T. Schwarz, M. A. Bandres, and J. C. Gutiérrez-Vega, "Observation of Ince-Gaussian modes in stable resonators," Opt. Lett. **29**(16), 1870–1872 (2004).
8. J. C. Gutierrez-Vega and M. A. Bandres, "Ince-Gaussian beams in a quadratic-index medium," J. Opt. Soc. Am. A **22**, 306 (2005).
9. J. C. Gutiérrez-Vega, M. D. Iturbe-Castillo, and S. Chávez-Cerda, "Alternative formulation for invariant optical fields: Mathieu beams," Opt. Lett. **25**(20), 1493–1495 (2000).
10. M. V. Berry and N. L. Balazs, "Nonspreading wave packets," Am. J. Phys. **47**(3), 264 (1979).
11. G. A. Siviloglou, and D. N. Christodoulides, "Accelerating finite energy Airy beams," Opt. Lett. **32**(8), 979–981 (2007).
12. G. A. Siviloglou, J. Broky, A. Dogariu, and D. N. Christodoulides, "Observation of accelerating Airy beams," Phys. Rev. Lett. **99**(21), 213901 (2007).
13. J. Broky, G. A. Siviloglou, A. Dogariu, and D. N. Christodoulides, "Self-healing properties of optical Airy beams," Opt. Express **16**(17), 12880–12891 (2008).
14. G. A. Siviloglou, J. Broky, A. Dogariu, and D. N. Christodoulides, "Ballistic dynamics of Airy beams," Opt. Lett. **33**(3), 207–209 (2008).
15. M. A. Bandres, and J. C. Gutiérrez-Vega, "Airy-Gauss beams and their transformation by paraxial optical systems," Opt. Express **15**(25), 16719–16728 (2007).
16. H. I. Sztul, and R. R. Alfano, "The Poynting vector and angular momentum of Airy beams," Opt. Express **16**(13), 9411–9416 (2008).
17. P. Saari, "Laterally accelerating airy pulses," Opt. Express **16**(14), 10303–10308 (2008).
18. P. Saari, "Airy pulse-A new member of family of localized waves," Laser Phys. **19**(4), 725–729 (2009).
19. J. Baumgartl, M. Mazilu, and K. Dholakia, "Optically mediated particle clearing using Airy wavepackets," Nat. Photonics **2**(11), 675–678 (2008).
20. J. Baumgartl, G. M. Hannappel, D. J. Stevenson, D. Day, M. Gu, and K. Dholakia, "Optical redistribution of microparticles and cells between microwells," Lab Chip **9**(10), 1334 (2009).

#114389 - $15.00 USD Received 23 Jul 2009; revised 2 Oct 2009; accepted 2 Oct 2009; published 12 Oct 2009

21. P. Polynkin, M. Kolesik, J. V. Moloney, G. A. Siviloglou, and D. N. Christodoulides, "Curved plasma channel generation using ultraintense Airy beams," Science **324**(5924), 229–232 (2009).
22. T. Ellenbogen, N. Voloch-Bloch, A. Ganany-Padowicz, and A. Arie, "Nonlinear generation and manipulation of Airy beams," Nat. Photonics **3**(7), 395–398 (2009).
23. H. W. Ren, Y.-H. Fan, and S.-T. Wu, "Tunable Fresnel lens using nanoscale polymer-dispersed liquid crystals," Appl. Phys. Lett. **83**(8), 1515 (2003).
24. H. W. Ren, Y.-H. Lin, Y.-H. Fan, and S.-T. Wu, "Polarization-independent phase modulation using a polymer-dispersed liquid crystals," Appl. Phys. Lett. **86**(14), 141110 (2005).
25. Y. J. Liu, X. W. Sun, P. Shum, and X. J. Yin, "Tunable fly's-eye lens made of patterned polymer-dispersed liquid crystal," Opt. Express **14**(12), 5634–5640 (2006).
26. Y. J. Liu, and X. W. Sun, "Electrically tunable three-dimensional holographic photonic crystal made of polymer-dispersed liquid crystals using a single prism," Jpn. J. Appl. Phys. **46**(No. 10A), 6634–6638 (2007).
27. Y. J. Liu, and X. W. Sun, "Electrically switchable computer-generated hologram recorded in polymer-dispersed liquid crystals," Appl. Phys. Lett. **90**(19), 191118 (2007).
28. Y. J. Liu, X. W. Sun, Q. Wang, and D. Luo, "Electrically switchable optical vortex generated by a computer-generated hologram recorded in polymer-dispersed liquid crystals," Opt. Express **15**(25), 16645–16650 (2007).
29. Y. J. Liu, H. T. Dai, X. W. Sun, and T. J. Huang, "Electrically switchable phase-type fractal zone plates and fractal photon sieves," Opt. Express **17**(15), 12418–12423 (2009).
30. T. Shimobaba, Y. Sato, J. Miura, M. Takenouchi, and T. Ito, "Real-time digital holographic microscopy using the graphic processing unit," Opt. Express **16**(16), 11776–11781 (2008).
31. The GWO library, *http://sourceforge.net/projects/thegwolibrary/*.
32. Q. Wang, X. W. Sun, and X. J. Yin, "Equidistant fringe phase shift measurement by use of a trough integration method," Opt. Eng. **47**(11), 115601 (2008).

1. Introduction

Diffraction-free beams play an important role in a wide range of applications including optical micromanipulation [1,2], super-resolution microscopy and optical coherence tomography etc [3]. Examples of diffraction-free waves are Bessel beams [4,5], Laguerre-Gauss beams [6], Ince-Gauss beams [7,8], and Mathieu beams [9], which have been studied extensively. Most of them are solutions of the paraxial propagation of scalar optical fields in different planar geometries. Among these diffraction-free beams, Airy beam, which was analyzed by Balazs *et al.* [10] in 1979 with the context of quantum mechanics, has recaptured attentions recently since Siviloglou *et al.* [11] first introduced finite energy Airy beams with "transverse acceleration" property [12–16]. To date, Airy type beams have been extended from continuous wave to pulse [17,18] and various applications have also been developed, such as particles manipulation [19,20], generation of curved Plasmon channel [21].

All the aforementioned Airy beams are generated either by a continuous phase modulation, which realized by phase-only liquid crystal spatial light modulator (SLM) [12,19,20], continuous transparent phase mask [21], or asymmetric nonlinear photonic crystals [22]. Sometimes, these methods are limited by either rather high cost or complicated fabrication. In certain applications, such as x-ray Airy beam or surface two-dimensional (2D) optics, it is difficult to fabricate a mask with continuous phase modulation. To address this issue, binary or multilevel patterns would be a proper alternative. And it becomes necessary to characterize the properties of Airy beam generated from a binary phase pattern.

In this paper, we analyze the propagation properties of Airy beam generated from a binary phase-type polymer-dispersed liquid crystal (PDLC) sample, which was formed by transferring a computer-generated binary pattern into a cell filled with LC/prepolymer mixture through a programmable lithographic system based on a digital micromirror device (DMD). PDLC material has been extensively investigated for electro-optical applications [23–29], and could be a good candidate to generate special beams with low cost, easy fabrication, and compact configuration; moreover, it is electrically tunable. The simulation and experiment results show that the "transverse acceleration" property of the Airy beam generated from a binary phase pattern is still preserved within a propagation distance except a "twin" lobe appeared.

2. Mask design

The ideal Airy beam can be expressed as below [12]:

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$$\phi(\xi,s)=Ai(s-(\xi/2)^2)\exp(i(s\xi/2)-i(\xi^3/12)), \quad (1)$$

where i is the imaginary unit, φ is the electric field envelope, $s = x/x_0$ represents the dimensionless transverse coordinate, where x_0 is an arbitrary transverse scale, and $\xi = z/kx_0^2$ is the normalized propagation distance, with $k = 2\pi n/\lambda_0$, where λ_0 is the wavelength of incident light in vacuum, Ai(·) denotes the Airy function. According to Eq. (1), such Airy wave packets are propagation-invariant with an additional constant "transverse acceleration" [12]. The parabolic trajectory is the result of acceleration. The transverse shift of the main lobe of the Airy beam, which can be calculated by

$$x_d \cong \lambda_0^2 z^2 / \left(16\pi^2 x_0^3\right) \quad (2)$$

The finite-energy Airy beam can be optically reconstructed by the Fourier transform function Ai(s)exp(as), which is a Gaussian beam modulated with a cubic phase. Figure 1(a) shows the 2D continuous cubic phase pattern. The phase in our designed pattern varies from −20π to + 20π within 3.2mm, which has been wrapped between 0 and 2π. The binary pattern was designed by setting the value of phase delay [Fig. 1(a)] between 0 and π as minimum gray level 0, π and 2π as maximum gray level 255 [Fig. 1(b)]. Figure 1(c) and (d) show the reconstructed image from gray pattern and binary pattern using angular spectrum method in GWO library [30,31], respectively.

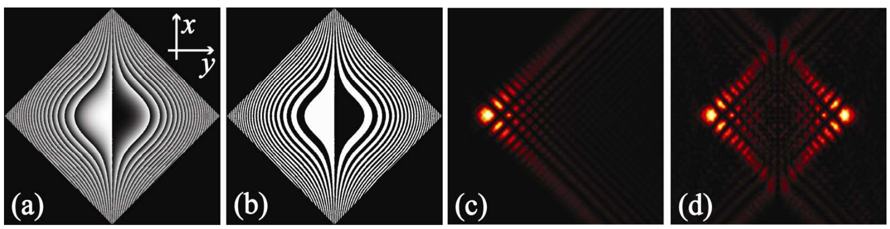

Fig. 1. The gray (a) and binary (b) patterns to generate the Airy beam, and the reconstructed diffraction patterns (c) and (d) by numerical simulation, respectively.

3. Experimental setup and results

The experimental configuration of programmable lithography system is shown in Fig. 2(a). A collimated laser beam (532 nm) impinges onto the surface of a DMD chip (1024 × 768 pixels with a pitch of 10.8 μm), which is controlled via a VGA port of computer. The modulated beam carrying a binary cubic pattern was recorded in the PDLC through an imaging system composed of a convex lens (f = 15 cm) and an objective lens (5 ×). The optical configuration to reconstruct the Airy beam from PDLC is depicted by Fig. 2(b). The syrup of LC/prepolymer mixture consisted of 54.53 wt% monomer, trimethylolpropane triacrylate (TMPTA); 9.06 wt% cross-linking monomer, *N*-vinylpyrrolidone (NVP); 0.79 wt% photoinitiator, rose bengal (RB); 0.98 wt% coinitiator, *N*-phenylglycine (NPG); 7.87 wt% surfactant, octanoic acid (OA); and 26.8 wt% LC E7. The ordinary index, n_o, and extraordinary index, n_e, of LC are 1.521 and 1.746 respectively at room temperature. The mixture was injected into a LC cell by capillary action. The cell gap was controlled to be 10 μm. During exposure, the binary cubic pattern displayed on the DMD chip was recorded inside the PDLC cell with a scale factor of ~1. The optimized exposure intensity and time were 0.7 mW/cm2 and 10 min respectively [27].

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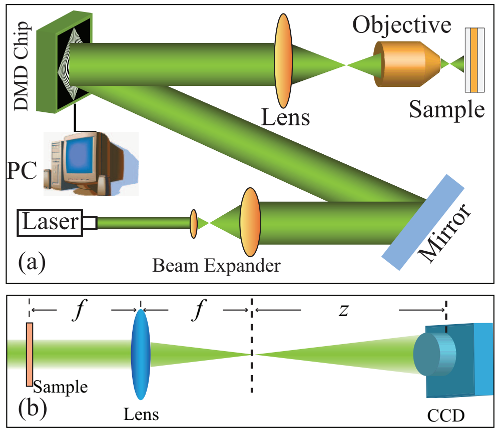

Fig. 2. The schematic of DMD programmable lithography system (a), and the reconstruction setup (b).

The PDLC sample with binary patterns was investigated under an optical microscopy first. Figures 3(a) and 3(b) show the typical morphologies of the PDLC pattern under an optical microscope with and without crossed polarizers. A clear binary pattern was observed with the bright areas and the dark areas corresponding to LC-rich and polymer-rich regions, respectively. The light passing through LC-rich and polymer-rich regions will experience different phase modulation. The size of binary pattern was about 3.2 mm × 3.2 mm measured from Fig. 3(a). The phase difference between dark and bright region from Fig. 3(b) was about 0.3 π estimated by the method described in Ref. 27 and 32.

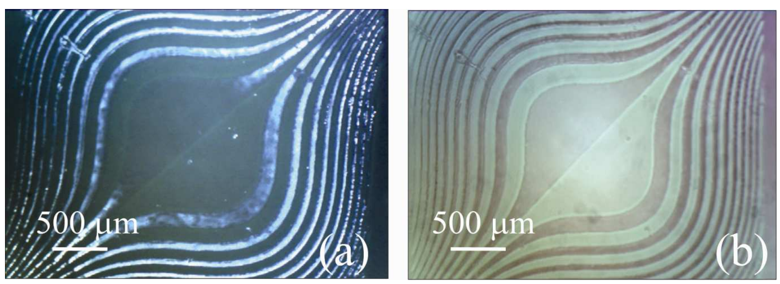

Fig. 3. Optical microscopy images of the PDLC pattern with (a) and without (b) crossed polarizers.

A simulation was performed to describe the propagation of the Airy beam generated by the binary pattern utilizing the numerical method introduced before [30,31]. The simulated configuration was set according to the practical experimental setup, with a Fourier transform lens (f = 20 cm) and 0.3π phase difference between LC-rich region and polymer-rich region of PDLC sample. Figure 4(a) shows the simulation results. We also experimentally recorded the dynamic propagation of the reconstructed Airy beam using a well aligned charge-coupled-device (CCD) camera, which was placed behind the Fourier frequency plane of a spherical lens (f = 20 cm) [Fig. 2(b)]. The result was shown in Fig. 4(b). In our experiment, a collimated He-Ne laser beam with a diameter of ~1 cm was used to cover the effective working area of the PDLC pattern. Due to the intrinsic property of a binary element, a "twin" lobe appeared in the reconstructed image from the PDLC pattern. Because of overlap, these two lobes could not been distinguished clearly until after 21cm distance propagation. The experiment and simulation results were in agreement and showed the preserved "transverse acceleration" property of the Airy beam for a binary phase pattern.

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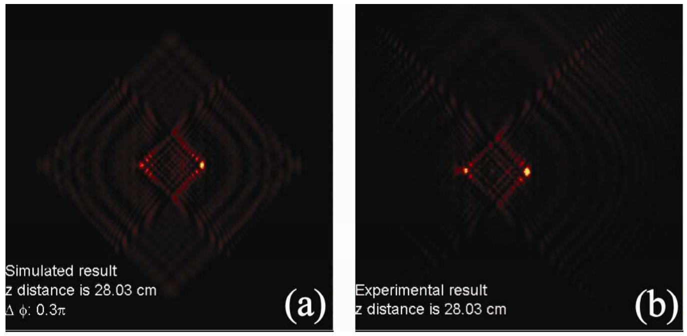

Fig. 4. The propagation of Airy beam generated by binary phase mask (a) simulated by GWO library (Media 1) and (b) the experimental results (Media 2).

The transverse shift of main lobe of the reconstructed Airy beam can be calculated from sequentially recorded CCD images at various propagation distances via digital imaging processing method. Figure 5 shows the transverse trajectory of the local intensity maxima of the generated Airy beam as a function of propagation distance. In our experiment, the deflection of right main lobe increased from 0.44 mm to 1.74 mm in the transverse direction within a 24 cm propagation distance from 24.03 cm to 48.03 cm. The absolutely transverse shift was 1.3 mm within 24 cm longitude distance. This value was larger than the reported result in Ref [12]. because of the smaller focal length of Fourier transform utilized in our experiment. Circles in Fig. 5(a) mark the experimental trace of main lobe of Airy beam. The red solid curve in Fig. 5(a) shows the simulated trajectory of the main lobe of Airy beam generated from the binary pattern based on beam propagation simulation. The blue dashed curve is the simulated trajectory of the Airy beam obtained from a continuous phase mask. Figure 5(b) shows the 3D slice demonstration of simulated results. The simulated results coincide with experimental results well according to Fig. 5. Therefore, a binary phase pattern can be used to not just generate an Airy beam but keep it unique properties as well in a close approximation to a continuous phase pattern.

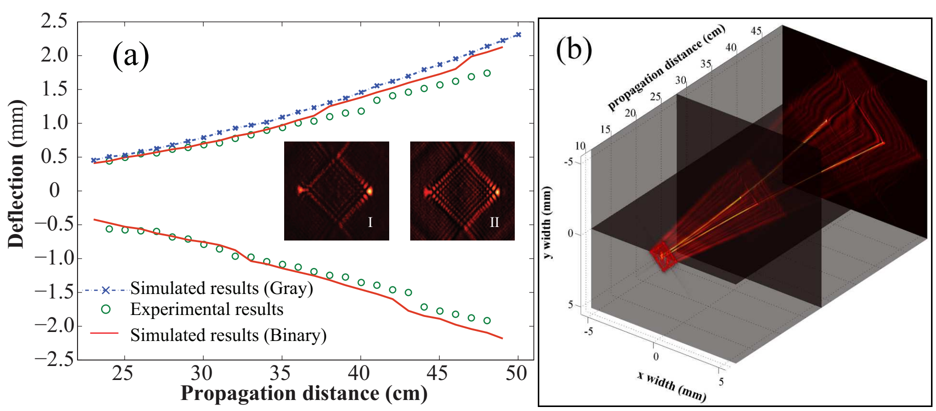

Fig. 5. (a)Transverse acceleration of the reconstructed Airy beam as a function of beam propagation distance. Circles mark experimental data while the red solid line represents a numerical simulating result. The dashed blue line is the simulated trace of Airy beam generated from continuous phase pattern. The insets are the intensity profiles of reconstructed the Airy beam from PDLC sample recorded by a CCD at distance of (I) 33.03 cm and the corresponding simulation result (II). (b) 3D slice demonstration of simulated results.

As predicted, the 2D Airy beam will experience a transverse shift in both x and y directions when it propagates along z direction. However, in our experiments, the binary pattern was placed by rotating a $45°$ angle compared with the pattern described in Ref [12]. As a result, there was no shift along the y direction but a shift ($\sqrt{2}x_d$) along x direction under the

#114389 - $15.00 USD Received 23 Jul 2009; revised 2 Oct 2009; accepted 2 Oct 2009; published 12 Oct 2009

frame of laboratory coordinate system. Transverse scale x_0 of 77.57 μm was achieved through data fitting.

Usually, PDLC devices are electrically tunable due to the index match between LC-rich and polymer-rich regions. In our experiment, electro-optical measurement was also carried out by applying a square waveform voltage with a frequency of 1 KHz on the sample from a function generator. When the applied voltage exceeded a threshold (2 V/μm), the LC molecules started to reorient toward electric filed direction and the phase difference between LC-rich and polymer-rich regions was decreased. As a result, the reconstructed image became more and more ambiguous with the increasing of applied voltage. Finally, the reconstructed pattern disappeared when the switching field was larger than 11 V/μm. There was no visible position shift for the main lobe of Airy beam during the electrical tuning.

4. Conclusion

In conclusion, Airy beams have been reconstructed using a binary phase-type PDLC pattern. Though the overlap of "twins" lobes has a side effect at the beginning of propagation, the acceleration property is preserved well along a relative distance. In our experiment, PDLC pattern was proved to produce high-quality Airy beams as a binary phase element. To fabricate the PDLC element, a designed binary pattern was transcribed into the PDLC sample by a programmable lithographic system based on a DMD chip. The PDLC device was flat and electrically switchable, and potentially useful in some adaptive applications. This approach can be also extended to generate the other different special beams including Mathieu beam, Ince beam, parabolic beam, hypergeomitric beam, etc.

Acknowledgements

The author would like to thank Professor T. Shimobaba for his kind help on the using GWO library. Partially financial support from a Poland – Singapore collaborative project sponsored by Agency for Science, Technology and Research of Singapore (No. 062 120 0016) is gratefully acknowledged.