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Luo, D.; Dai, Haitao; Sun, Xiaowei

2013

Luo, D., Dai, H., & Sun, X. W. (2013). Polarization-independent electrically tunable/switchable airy beam based on polymer-stabilized blue phase liquid crystal. Optics express, 21(25), 31318-31323.

https://hdl.handle.net/10356/97063

https://doi.org/10.1364/OE.21.031318

Polarization-independent electrically tunable/switchable Airy beam based on polymer-stabilized blue phase liquid crystal

D. Luo,[1,*] H. T. Dai,[2] and X. W. Sun[1,3,4]

[1] *Department of Electrical & Electronic Engineering, South University of Science and Technology of China, Tangchang Road 1088, Shenzhen, Guangdong 518055, China*
[2] *Department of Applied Physics, College of Science, Tianjin University, Tianjin 300072, China*
[3] *School of Electrical and Electronic Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 639798, Singapore*
[4] *sun.xw@sustc.edu.cn*
[*] *luo.d@sustc.edu.cn*

Abstract: Because of their non-diffraction and freely acceleration during propagation, finite energy Airy beams are interesting for application such as optical manipulation, plasma channel generation and optical vortex generation. Especially interesting are tunable/switchable Airy beams, in which the Airy beam tuning by electric field, temperature or optical intensity can be realized. Here we experimentally demonstrate polarization-independent, electrically tunable/switchable Airy beam based on polymer-stabilized blue phase liquid crystals with wide working temperature range and fast response time through a structure called vertical field driven mode.

OCIS codes: (230.3720) Liquid-crystal devices; (050.1970) Diffractive optics.

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1. Introduction

Blue phases (BPs) are distinct mesophases which exist between the isotropic and chiral nematic phase of liquid crystals. Normally, BPs only appear within a narrow temperature range (typically less than 2K), which limits its applications. Blue phases became not popular until the research works carried by Kikuchi et al in 2002 [1]. They reported that the temperature range of BPs can be largely extended to more than 60K by adding a small concentration of polymer into blue phase liquid crystals (BPLCs), called polymer-stabilized blue phase liquid crystal (PS-BPLC). PS-BPLC [2, 3] has attracted people's interesting in field of liquid crystal display [4, 5], due to its excellent intrinsic features such as fast response time, no requirement for alignment layer, and isotropic dark state. The Kerr effect-induced birefringence appears along the electric field if the BPLC employed has a positive dielectric anisotropy ($\Delta\varepsilon>0$) [6], which makes the blue phase liquid crystal also be a good choice for tunable/switchable polarization-independent optical and photonic devices [7–11].

Airy beam is a kind of diffraction-free beam with acceleration during propagation [12, 13], which finds its applications widely in such as optical manipulation, plasma channel generation and optical vortex generation [14–16]. Methods of fabrication Airy bema vary from using spatial light modulator [13], and continuous phase mask [15], which possesses high cost, complicated fabrication process with narrow fabrication tolerance and non-tunability, to binary-phase based liquid crystal or polymer dispersed liquid crystal cell, which could provide low cost way for tunable/switchable Airy beam's generation [17, 18]. However, in all above methods, properly selected linear polarized incident light is necessary because the phase difference is directly dependent on the relationship between the polarization of incident light and the alignment of liquid crystal molecules in devices, thus a part of light energy is filtered or wasted before it illuminates the Airy beam photonic device. The requirement for the direction of linear incident polarization complicates the optical setup system as well. Therefore, tunable Airy beam device with non-polarization incident light source is highly desirable. In this letter, we demonstrate a PS-BPLC based polarization independent Airy beam in vertical filed driven (VFD) mode. This approach has advantages of simplified fabrication procedure, polarization independence, electrically tunable/switchable property, wide working temperature range, and fast response time. All these features have made PS-BPLCs attractive for potential application in other types of polarization independent photonic devices with less complex optical production system.

2. Experiments

The finite energy Airy beams is generated through multiplying an exponential aperture function by the Airy function, and in initial condition we have [12]:

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$$\phi(s, \xi = 0) = Ai(s)\exp(as), \tag{1}$$

where ϕ represents the electric field envelope, $s = x/x_0$ is a dimensionless transverse coordinate, x_0 is an arbitrary transverse scale, $\xi = z / kx_0^2$ is the normalized propagation distance, k is the wavenumber of the optical wave, and a is a positive parameter.

When a<<1, the finite energy Airy beams will closely resemble the Airy functions and could be expressed by [13]:

$$\begin{aligned}\phi(\xi, s) = Ai[s - (\xi/2)^2 + ia\xi]\exp[as - (a\xi^2/2) \\ - i(\xi^3/12) + i(a^2\xi/2) + i(s\xi/2)].\end{aligned} \tag{2}$$

The Fourier transform of finite energy Airy beam, $\Phi_0(k) \propto \exp(-ak^2)\exp(ik^3/3)$, which can be treated as a Gaussian function modulated by a cubic phase. For two-dimensional (2D) case, we have $\Phi_0(k_x, k_y) \propto \exp[-a(k_x^2 + k_y^2)]\exp[i(k_x^3 + k_y^3)/3]$, where k_x and k_y are Fourier spectrum coordinates. The generated finite Airy beam is a quasi-diffraction-free beam. The examples of 2D ideal and finite Airy beams (a = 0.1) is shown in Figs. 1(a) and 1(b) respectively, where $x_0 = y_0 = 100$ μm, and $z = 0$ cm. The tail of Airy beam main lope will be truncated when the exponential aperture function added on the Airy beam.

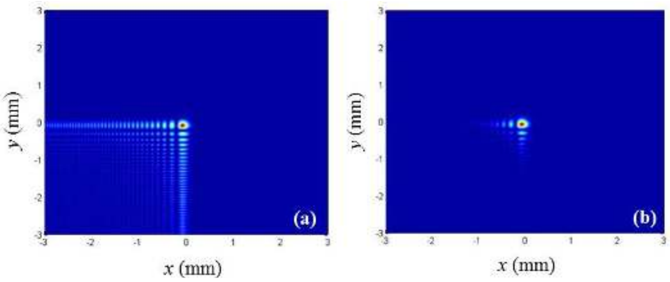

Fig. 1. (a) 2D ideal Airy beam and (b) 2D finite Airy beam with a = 0.1.

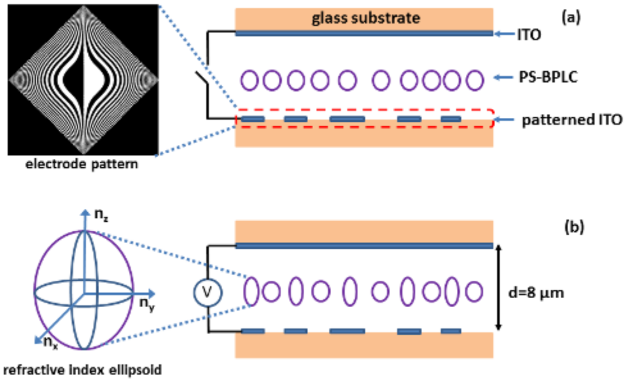

Fig. 2. (a) Schematic drawings of the PS-BPLC in glass cell with 2D binary-phase of Airy wave packet with cubic phase modulation patterned ITO. (b) Refractive index ellipsoid of PS-BPLC under applied electric field. The cell gap is d = 8μm.

A two-dimensional (2D) binary-phase pattern of Airy wave packet (a = 0.1) with cubic phase modulation was generated from a continuous phase pattern, varying from −11.5π ~11.5 π in 0.43 cm, by selecting the phase value delay between 0~π as 0 and π~2π as π, respectively. An indium-tin-oxide (ITO)-coated glass substrate was used to record the phase pattern through a photomask by photolithographic method. A cell was formed by assembling the patterned ITO glass with another blank ITO glass. The cell gap was $d = 8$ μm which was controlled by spacers. Here, no rubbing process was needed, which simplified the fabrication procedure comparing to traditional liquid crystal based photonic devices. The schematic of cell cross section and enlarged electrode pattern recorded is shown in Fig. 2(a).

Generally, the optical property of PS-BPLC depends on external electric field. When there is no external electric field, as shown in Fig. 2(a), the PS-BPLCs are optically isotropic in both regions with and without electrode. The refractive index of PS-BPLCs could be approximated to $n_i = (2n_e + n_o)/3$. When external electric field applies, as shown in Fig. 2(b), in the region with electrode, the director of liquid crystal molecules tends to align parallel to electric field direction, thus the PS-BPLCs will be optically anisotropic due to the Kerr effect. The index ellipsoid also becomes ellipsoidal, with optical axis (n_z) parallel to the vertical electric field. Meanwhile, the PS-BPLCs in region without electrode will keep unchanged. The induced ordinary refractive index of PS-BPLCs $n_o(E)$, which is polarization independent for normally incident light, varies with the strength of external electric field. In this case, the phase difference between regions with and without electrode could be expressed by:

$$\Gamma = \frac{2\pi}{\lambda}\left[n_o\left(E\right) - n_i\right]d, \tag{3}$$

where λ is the wavelength.

The PS-BPLCs were prepared by mixing 59.55 wt% nematic LC host MLC-2142 (Merck), 30.18 wt% chiral dopants (22.49 wt% CB15 and 7.69 wt% R-1011, Beijing Ba Yi Space), 9.27 wt% monomers (5.72 wt% RM257, Merck, and 3.55 wt% TMPTA, Sigma-Aldrich), and 1 wt% photoinitiator Darocur 1173 (Sigma-Aldrich). The mixture was firstly heated up to an isotropic phase and then filled into the ITO glass cell with pattern. Then, the cell sample was cooled down at rate of 0.1 °C/min. The blue phase appeared at temperature from 39.4 °C to 32.0 °C. Afterwards, a UV light with wavelength of 365 nm and intensity of 20 mW/cm^2, was used to irradiate the sample for 3 hours at temperature of 37 °C. After UV curing, the polymer-stabilized BPLC composite showed an extended blue phase temperature range from 41 °C to 25.5 °C, while cooling down at rate of 0.1 °C/min. The images of PS-BPLC cell under polarized optical microscope (POM) at temperatures of 33 °C and 39 °C are shown in Figs. 3(a) and 3(b), respectively. The PS-BPLCs showed different colors when temperature changed, it was because of the pitch lengths change and refractive index change with the temperature [19]. Apparently, the green and blue colors dominated at 33 °C and 39 °C, which corresponded to a longer and shorter pitch length of PS-BPLC respectively. In Fig. 3, the multiple colors within one image correspond to different crystal planes formed in blue phase [3].

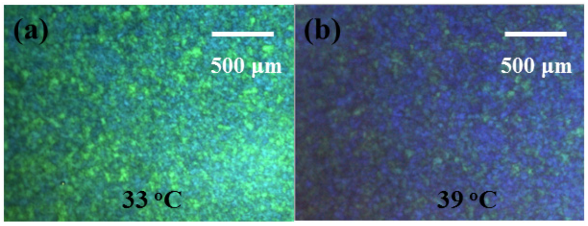

Fig. 3. Images of PS-BPLC cell under optical microscope with cross polarizers under temperature of (a) 33 °C and (b) 39 °C.

3. Results and discussion

The optical setup of Airy beam generation is shown in Fig. 4. An expanded and collimated He-Ne laser beam with wavelength of 633 nm was used to illuminate the PS-BPLC cell. A neutral density (ND) filter was placed behind the He-Ne laser for intensity adjustment. A quarter wave plate and two polarizers were used here for polarization adjustment. The

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polarization of light from the first polarizer was set to have 45° angle with the fast axis of quarter-wave plate for generating circular polarized light, the second polarizer was used to control the direction of linear polarized light passing through it, which was also the incident light for PS-BPLC cell. A spherical lens, with focal length of $f = 20$ cm, was located after the PS-BPLC sample at distance of focal length to perform Fourier transform. The Fourier transform or Airy beam was obtained behind the lens, at the distance of focal length or the position of $z = 0$. A screen was placed to receive the image. It is noticed that the quarter-wave plate and polarizers were used just for polarization controlling and testing purpose. They can be removed in real application as the PS-BPLC based Airy beam can be produced regardless of the direction of linear polarization incident light source.

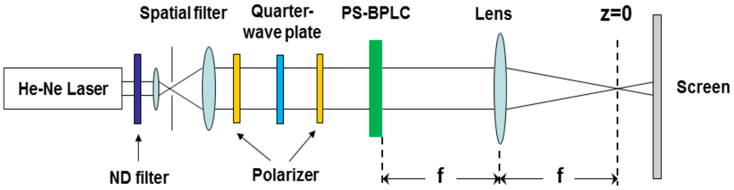

Fig. 4. Optical setup of Airy beam generation.

When there was no external voltage applied, the phase difference Γ between region with and without electrode was zero. When external voltage applied, the electric field induced Kerr effect started to change the refractive index of PS-BPLC in the region with electrode, while the refractive index of PS-BPLC in the region without electrode was keeping unchanged, thus the phase difference between these two regions changed. As a result, the phase difference started to change from zero to π with gradually increased electric field. Figures 5(a)–5(d) shows the optical microscopic photograph of PS-BPLC cell under increased voltage from 35 to 120 V_{rms}, respectively. The color change of PS-BPLC in region with electrode was due to the electric-field-induced lattice distortion electrostriction [20]. In contrast, the color of PS-BPLC in region without electrode was stable with slightly shift due to a weak fringing field [7].

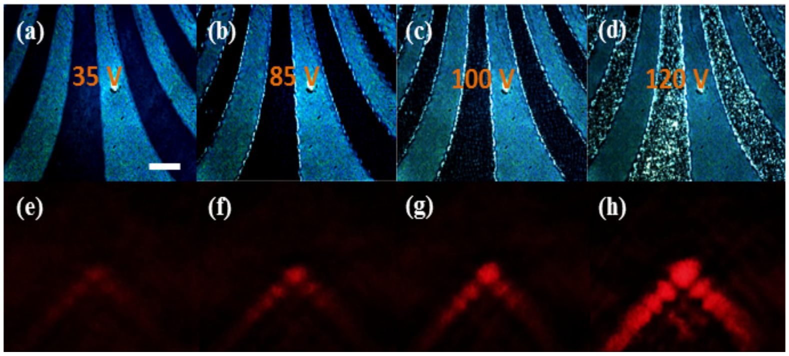

Fig. 5. Image of PS-BPLC cell at different voltages (a) 35 V, (b) 85 V, (c) 100 V, and (d) 120 V. Corresponding Airy beams captured by CCD are shown in (e)-(f), respectively. Scale bar: 500 μm.

The images of generated Airy beam based on PS-BPLC cell are shown at different voltages in Figs. 5(e)–5(h) respectively. The obtained image showed a very weak Airy beam while no voltage presented, which was due to the slight phase different between the glass with and without electrodes. In contrast, the generated finite energy Airy beam was becoming brighter and clearer while increasing voltage, which indicated an increased phase difference Γ from zero to π. When external voltage reached 120 V_{rms}, the best and brightest Airy beam was achieved, which indicated that the phase difference Γ was equal to π. When further increased

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voltage, the obtained Airy beam became worse, which indicated the phase difference increased larger and deviated from the phase match condition of π. In other words, this cell could be easily switched between on/off status by adding voltage on or switching voltage off. It was noticed that the hysteresis effect became significant in high operation voltage [21], which would affect accuracy of controlling photonic devices based on PS-BPLC. Possible methods of minimizing hysteresis effect had been discussed in Ref. 21 in detail. To reduce the operation voltage of BPLC photonic devices, blue phase materials with large Kerr constant could be used [22, 23].

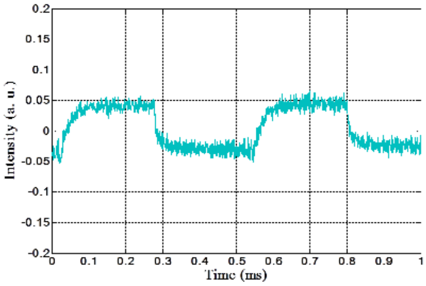

Fig. 6. Response time of the PS-BPLC Airy beam sample with rise time τ_{rise} = 526 μs and decay time τ_{decay} = 678 μs.

It was worth to mention that, all generated Airy beams kept their intensity constantly when we rotated the second polarizer to generate linear polarized light source with equally intensity but different polarization directions, which confirmed a polarization-independent property of our PS-BPLC based Airy beam. It meant that for this kind of photonic device, based on PS-PBLC, no specific requirement on the polarization of incident light if it was linearly polarized.

Beside the advantage of polarization-independent property, the PS-BPLC cell also exhibited a fast opto-electro response time, which was in the order of sub millisecond. The measured response time of the PS-BPLC Airy beam sample was rise time τ_{rise} = 526 μs and decay time τ_{decay} = 678 μs respectively, as shown in Fig. 6. The rise and decay times were defined as 10%-90% transmittance change of main lope of generated Airy beam.

4. Conclusion

In summary, this work demonstrated a PS-BPLC Airy beam cell based on vertical filed driven mode. The PS-BPLCs powered Airy beam cell with excellent characteristics including simplified fabrication procedure, wide working temperature range, polarization independence, electrically tunability/switchability, and fast opto-electro response time. Those intrinsic features of PS-BPLCs provided a new way for Airy beam generation regardless the linear polarization direction of incident light source, which makes it useful for potential applications even in other tunable diffractive optical elements and photonic devices.

Acknowledgments

This work is supported by National Research Foundation (NRF-CRP-6-2010-02 and NRF-RF-2009-09), National Natural Science Foundation of China (NSFC) (Project Nos. 61006037, 61177014, 61076015, 61177061, and 11204208), and Tianjin Natural Science foundation (Project Nos. 11JCZDJC21900 and 11JCYDJC25800).

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