Finite Airy Beam Based on Polymer-stabilized Blue Phase Liquid Crystal

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Abstract— Polymer-stabilized blue phase liquid crystal was used to generate polarization-independent finite energy Airy beam. The intensity of output Airy beam was unchanged while rotating the linear polarization direction of illumination laser. This device also exhibited advantages of simplified fabrication process, and fast opto-electro response time.

1. TECHNICAL SUMMARY

1.1. Objective and Background

Blue phases (BPs) are special phase between the isotropic and chiral nematic phase of liquid crystal. The applications of BPs are limited due to its narrow temperature of around 2 K, which can be improved by adding a small concentration of polymer to form polymer-stabilized blue phase liquid crystal (PS-BPLC) [1]. Because of its intrinsic features, e.g., sub-micro second response time, PS-BPLC is thought to be a good choice for next generation display [2–5]. The blue phase liquid crystal is useful for fabricating tunable polarization-independent photonic devices, due to the Kerr effect-induced birefringence under external electric field [6, 7].

Airy beam is a kind of beam with acceleration and non-diffraction during propagation [8, 9]. It has been widely used in optical manipulation, plasma channel generation and optical vortex generation [10–12]. Different kinds of ways have been used to generate finite Airy beam, such as spatial light modulator, phase mask [11], or liquid crystal/polymer [13, 14]. However, in all of mentioned ways, polarized light source is required for phase difference generation, thus a great part of energy is wasted before it meets the Airy beam generator. Therefore, photonic device with non-polarization incident light is highly desirable. In this letter, a PS-BPLC Airy beam cell with binary-phase is demonstrated in vertical filed driven (VFD) mode. It has advantages of polarization independence, electrically tunable property, wide working temperature range, fast response time, and easy fabrication.

The finite energy Airy beams is generated through multiplying an exponential aperture function by the Airy function, and in initial condition we have [8]:

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

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

When $a \ll 1$, the finite energy Airy beams will closely resemble the Airy functions and could be expressed by [9]:

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

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.

2. RESULTS

A two-dimensional (2D) binary-phase pattern of Airy wave packet with cubic phase modulation was generated from a continuous phase pattern, varying from $-11.5\pi \sim 11.5\pi$ in 0.43 cm, by choosing the phase value delay between $0 \sim \pi$ as 0 and $\pi \sim 2\pi$ as π, respectively. An indium-tin-oxide (ITO)-coated glass substrate was recorded the phase pattern through a photomask by photolithographic method. A cell was formed by assemble the patterned ITO glass with another blank ITO glass. The cell gap was $d = 8\,\mu$m controlled by spacers. Here, no rubbing process was needed. The cross section of cell and enlarged electrode pattern are shown in Figure 1. The optical property of PS-BPLC depends on external electric field. The PS-BPLC is optically isotropic without electric field. The refractive index of PS-BPLC could be approximated to $n_i = (2n_e + n_o)/3$. When electric field applies, the LC director tends to be parallel to the electric field. Due to Kerr effect, the PS-BPLC is optically anisotropic. The index ellipsoid thus becomes ellipsoidal, with its optic axis (n_z) parallel to the electric field, as shown in Figure 1.

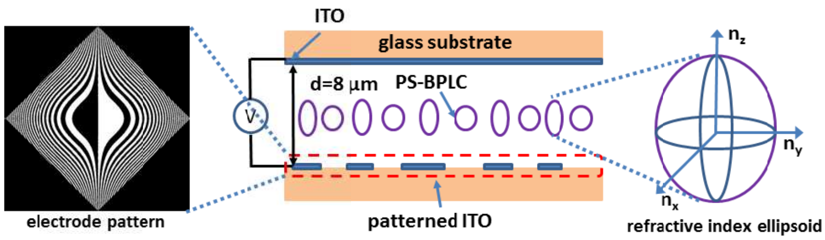

Figure 1: PS-BPLC in glass cell with patterned ITO and refractive index ellipsoid change of PS-BPLC under applied electric field.

The induced ordinary refractive index of BPLC $n_o(E)$ varies with the strength of electric field. Therefore, the phase difference between regions with and without electrode is expressed by: $\Gamma = \frac{2\pi}{\lambda}[n_o(E) - n_i]d$, where λ is the wavelength.

The LC/monomer mixture consists of 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 heated up to an isotropic phase of liquid crystal and filled into the cell. Then, the sample was cooled down at a rate of 0.1°C/min. The blue phase showed within range of 39.4°C to 32.0°C. To generate the finite Airy beam, an expanded and collimated He-Ne laser beam (633 nm) was used to illuminate the PS-BPLC cell. A neutral density (ND) filter was used to adjust intensity of laser. Two polarizer and one quarter wave plate were used to control and monitor the polarization status of light. The polarization of light from the first polarizer was set to have angle 45° to the fast and slow axis of quarter-wave plate to generate circular polarized light, the second polarizer was used to control the polarization of output light. A spherical lens, with focal length of $f = 20$ cm, was located after the sample at distance of focal length for Fourier transform. The Fourier transform or Airy beam was obtained behind the lens and collected by a screen behind. Without external voltage, the phase difference Γ 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, thus changed the phase difference between those two regions. Figures 2(a)–2(c) show the PS-BPLC image obtained by optical microscopy at different voltages of 10, 35, and 45 V, respectively.

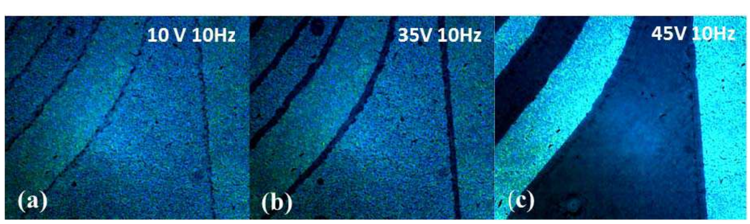

Figure 2: Image of PS-BPLC cell at different voltages, (a) 10 V, (b) 36 V, (c) 45 V, the frequency is 10 Hz.

The images of simulated and actually generated finite Airy beam are shown in Figures 3(a)–3(b) respectively. The generated finite Airy beam was consisted with the simulated one. It is noticed that, the changing input polarization of light didn't influence the output finite Airy beam profile, which meant that this kind of photonic devices, based on PS-PBLC, had no specially requirement on the polarization of input light, thus polarization independent. The PS-BPLC cell had a fast opto-electro response time. The PS-BPLC sample was measured to have rise time of $\tau_{rise} = 526$ μs and decay time of $\tau_{decay} = 678$ μs, respectively, where the rise and decay times were defined as 10%–90% transmittance change of main lope of generated Airy beam.

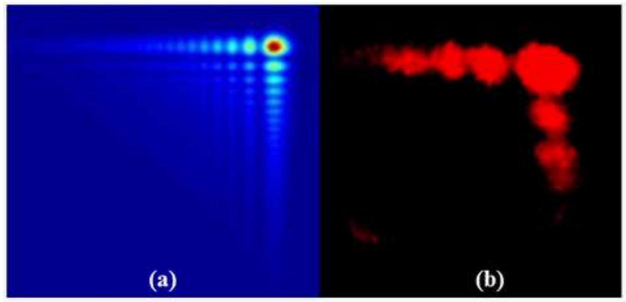

Figure 3: (a) Simulated and (b) experimentally generated finite Airy beam.

3. IMPACT

In summary, we demonstrated a PS-BPLC based finite Airy beam. The PS-BPLC Airy beam cell has simplified fabrication process, wide working temperature range, polarization independence, electrically tunable property, and fast opto-electro response time. The intrinsic features of PS-BPLCs also make it useful for application in other tunable binary-phase diffractive optical elements and photonic devices.

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