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Integrated and reconfigurable optical paths based on stacking optical functional films

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Abstract: A strategy for integrated and reconfigurable optical paths based on stacking optical functional films is proposed. It is demonstrated by stacking two liquid crystal polymer *q*-plates and one quarter-wave plate for vector vortex beams generation. The topological charge and polarization order of generated vector vortex beams can be controlled independently by stacking and reordering different optical films with repeated adhesive ability. It supplies a low-cost, light-weight and versatile technique for reducing the volume of free-space optical system and has a great potential in optical researches and applications.

OCIS codes: (160.3710) Liquid crystals; (230.3720) Liquid-crystal devices; (050.4865) Optical vortices; (310.4165) Multilayer design.

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1. Introduction

Optical path is composed of a set of elements to achieve certain functions, such as imaging, optical measurement and manipulation of wavefront. It is the fundamental requirement for both researches and applications of optics and photonics. The components for conventional free-space optical path could be reconfigured freely, however, they are usually heavy and bulky. Integrated optics [1,2] is compact, but it suffers from poor reconfigurability because their configurations are determined once fabricated. If one can combine their superiorities and avoid respective shortcomings, it will supply a powerful way for virtual/augmented reality display [3,4], optical communications [5] and computing [6].

A possible strategy is to replace the free-space optical elements with functional thin films and stacking them to realize the desired optical paths. It keeps the freedom of selecting and assembling of optical elements, while the overall volume and weight are drastically reduced. Liquid crystal polymer (LCP) [7,8] is a promising candidate for realizing such optical films. Thanks to M. Schadt *et al*'s great efforts [9], photoalignment can control the optical axis of LCP precursor conveniently, making the optical wavefront manipulation, the fundamental

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function for most passive optical elements possible. After UV polymerization, molecular orientation can be maintained with robust thermal and photochemical stability. LCP brings new features such as self-standing, repeated adhesive ability and flexibility [10]. LCP functional film can possess such function as gratings, lenses, prisms, beam splitters and mode converters via specific designs [11–13]. Through overlaying different functional LCP films, a cascaded free-space optical path can be produced. In previous work, the feasibility of stacking numerous LCP films with arbitrary LCP director orientations in space was demonstrated [14], and complex optical functions such as beam steering [15–17] and polarization controlling [18,19] were presented. If one can take the advantage of repeated adhesive ability of separate LCP films, integrated and reconfigurable optical paths can be realized by stacking and reordering different optical functional films.

In this work, LCP films with both homogeneous and spatially variant optical axes are fabricated. Then they are stacked together to generate vector vortex beams (VVBs), which is featured by the cylindrically variant polarization and spiral wavefront [20–22]. By changing and rearranging the separate films, the polarization order and topological charge of generated VVBs are controlled independently. Besides the complex mode conversion, other optical functions could also be demonstrated via this compact and reconfigurable strategy.

2. Results and discussions

Two q-plates and a quarter-wave plate (QWP) are required for generating VVBs [23]. Q-plate is a half-wave plate with specific optical axis orientation [24]: $\alpha(\mathrm{r},\varphi)=q\varphi+\alpha_0$, where r is the radius, q is the topological charge of the q-plate, φ is the azimuthal angle, and α_0 is the initial angle when $\varphi=0$. The q-plate can convert circularly polarized light into an optical vortex (topological charge $m = 2q$) and convert linearly polarized light into a vector beam (polarization order $P = 2q$). Here, the first q-plate (α_1, q_1) is used to generate optical vortex, the QWP is utilized to convert circular polarization to linear polarization, and the second q-plate (α_2, q_2) is applied to generate vector beams. The principle can be described as following. Jones matrix for each q-plate is:

$$\mathrm{M}_q=\begin{pmatrix}\cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & -\cos 2\alpha\end{pmatrix}. \tag{1}$$

Jones matrix for a QWP with its fast axis direction (θ) is:

$$\mathrm{M}_{QWP}=\mathrm{R}(-\theta)\cdot\begin{pmatrix}1 & 0 \\ 0 & i\end{pmatrix}\cdot\mathrm{R}(\theta), \tag{2}$$

where $\mathrm{R}(\pm\theta)$ is the rotation matrix. For a left circular incident polarization $\mathrm{E}_{in}=E_0[1,i]^T$, the output beam can be described as:

$$\mathrm{E}_{out}=\mathrm{M}_{q_2}\cdot\mathrm{M}_{QWP}\cdot\mathrm{M}_{q_1}\cdot\mathrm{E}_{in}. \tag{3}$$

When $\alpha_{01}=\alpha_{02}=0$ and $\theta=-45^\circ$, $\mathbf{E}_{out}$ can be simplified as:

$$\mathrm{E}_{out}=E_0\cdot e^{i2q_1\varphi}\cdot\begin{bmatrix}\cos 2q_2\varphi \\ \sin 2q_2\varphi\end{bmatrix} \tag{4}$$

It can be seen that the generated beam possesses a phase factor $\exp(i2q_1\varphi)$, corresponding to a spiral wavefront with $m = 2q_1$. Meanwhile, a polarization factor $[\cos 2q_2\varphi, \sin 2q_2\varphi]^T$ indicates a cylindrically variant polarization with $P = 2q_2$. And thus a VVB can be generated.

Moreover, the topological charge and polarization order of resultant VVB are decoupled and can be modulated by selecting different q-plates separately.

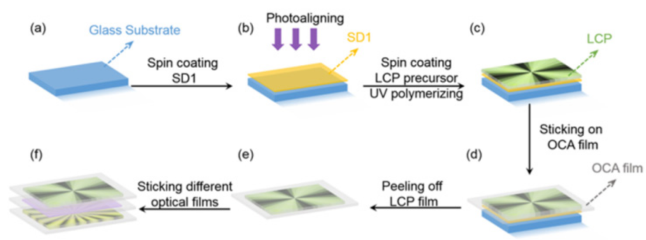

Fig. 1. Schematic illustration of fabrication procedure for LCP q-plate and assembling of different optical films.

By means of photoalignment [25–27], the above optical functional films could be easily fabricated in high quality. In this work, photoalignment is carried out on a dynamic micro-lithography system, which can output arbitrary light patterns with precise polarization control [28]. The fabrication procedure for LCP q-plate and assembling of different optical films are schematically illustrated in Fig. 1. At first, the photoalignment agent sulfonic azo-dye SD1 (synthesized by DIC, Japan) is spin coated onto a glass substrate, and heated at 100 °C for 10 min to remove excess solvent. Subsequently, the alignment layer is photopatterned via a multi-step, partly overlapping exposure as reported in our previous works [29,30]. After photoaligning, the LCP precursor (UCL017, DIC, Japan, 23%wt LCP dissolved in methylbenzene) is spin coated onto the alignment layer. The thickness of LCP layer is optimized to be ~1.6 μm to satisfy the half-wave condition at 633 nm. Heating over 80 °C is needed for residual solvent evaporation. The polymerization of LCP is performed under an LED (365 nm, 13 mW/cm^2, 2 min). An optically clear adhesive film (OCA, 8173D, 3M, USA) is attached on the top of LCP to remove the film from the glass substrate. Thus, a self-standing flexible functional LCP film (here q-plate for instance) is realized. Finally, we assemble one q-plate, one QWP and the other q-plate subsequently to form the optical path for VVB conversion.

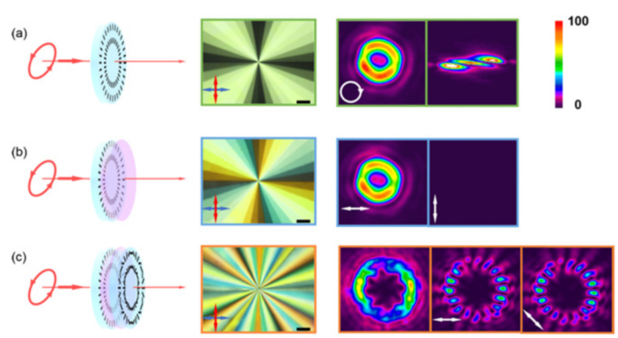

Fig. 2. Schemes, micrographs and output beam patterns of: (a) first q-plate, (b) after stacking a LCP QWP, (c) overlaying all desired films. The short black lines in blue plate indicate the LC director distribution in the q-plate and pink plate indicates QWP. Red and blue arrows represent the direction of polarizer and analyzer of microscope, respectively. White arrows show the direction of analyzer before CCD. The scale bars and color bar indicate 200 μm and relative optical intensity, respectively.

As an example, q-plates with $q_1 = 1$, $q_2 = 4$ and $\alpha_{01} = \alpha_{02} = 0$ are chosen to demonstrate our design. Left circularly polarized Gaussian beam (633 nm) is used as the incident light. The first q-plate is characterized and corresponding results are presented in Fig. 2(a). The micrograph depicts the inhomogeneous LC orientation that is translated to variation in

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intensity under the polarizing optical microscope. The output beam is captured by a CCD and possesses a doughnut-like profile corresponding to the phase singularity of the optical vortex. To verify its topological charge, a cylindrical lens is employed to implement astigmatic transformation [31] and the converted pattern is also presented. Two dark stripes can be clearly observed, suggesting an optical vortex with m = 2. The polarization of generated optical vortex is reversed to right circular polarization. Subsequently, a LCP QWP with its fast axis orientated at −45° with respect to x axis is stacked to the first q-plate to convert the output beam into linear polarization. A polarizer is employed to check the polarization state, as shown in Fig. 2(b), revealing a horizontal linearly polarized optical vortex. After passing through the second stacked q-plate, the VVB is generated and analyzed by different polarization direction, as shown in Fig. 2(c). Sixteen lobes are observed and rotate with the analyzer, which is consistent with the properties of vector beam with polarization order $P = 2q_2 = 8$.

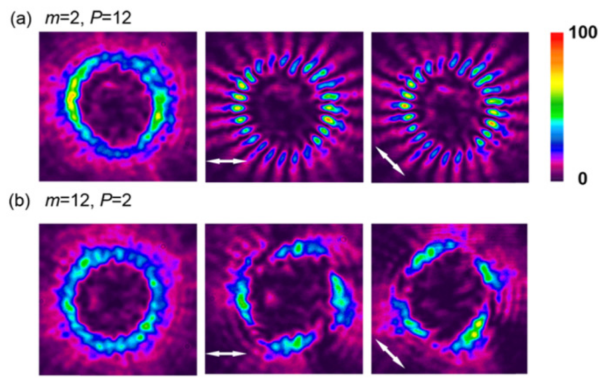

Fig. 3. Output beam patterns of VVBs with: (a) m = 2, P = 12 and m = 12, P = 2, respectively. White arrows indicate the direction of analyzer and color bar reveals the relative optical intensity.

Taking the advantage of repeated adhesive ability of separate LCP films, integrated and reconfigurable optical paths can be realized by stacking and reordering different optical functional films. The polarization order and topological charge of generated VVBs can be tuned separately by changing and rearranging the films. For example, VVBs with m = 2, P = 12 and m = 12, P = 2 are shown in Figs. 3(a) and 3(b), which are obtained by reordering the two LCP q-plates with q = 1 and 6 in our integrated thin-film device. They all exhibit good performances and match well with theoretical expectations.

3. Conclusion

In summary, we demonstrate a compact and reconfigurable strategy to generate VVBs based on stacking LCP films with both homogeneous and spatially variant optical axes. By changing and rearranging the separate films, the polarization order and topological charge of generated VVBs are controlled independently. Moreover, other complex optical field, such as Airy beam [32], Airy-vortex beam [33,34] and beam array [35,36], could also be realized. Besides, the flexibility of LCP films makes their covering on other optical elements with curved surfaces possible. This low-cost, light-weight versatile technique dramatically reduces the volume of optical system and has great potentials in optical communications, virtual/augmented reality display and optical computing.

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