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Generation of arbitrary vector beams with liquid crystal polarization converters and vector-photoaligned q-plates

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Arbitrary vector beams (VBs) are realized by the designed polarization converters and corresponding vector-photoaligned q-plates. The polarization converter is a specific twisted nematic cell with one substrate homogeneously aligned and the other space-variantly aligned. By combining a polarization-sensitive alignment agent with a dynamic micro-lithography system, various categories of liquid crystal polarization converters are demonstrated. Besides, traditional radially/azimuthally polarized light, high-order and multi-ringed VBs, and a VB array with different orders are generated. The obtained converters are further utilized as polarization masks to implement vector-photoaligning. The technique facilitates both the volume duplication of these converters and the generation of another promising optical element, the q-plate, which is suitable for the generation of VBs for coherent lasers. The combination of proposed polarization converters and correspondingly fabricated q-plates would drastically enhance the capability of polarization control and may bring more possibilities for the design of photonic devices. © *2015 AIP Publishing LLC*.
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Vector beams (VBs), featured by spatially variant polarization states, have gained considerable interest in a variety of fields during the past few decades.[1] Compared to homogeneously polarized beams, VBs possess a high degree of polarization symmetry, which can give rise to unique high-numerical-aperture focusing properties.[2] Particularly, a specific VB with radial polarization can be focused into a tighter spot with a strong and localized longitudinal electric field component, enabling high-resolution imaging[3] and optical manipulation[4] of particles. When the radially polarized beams are incident onto axially symmetric metal/dielectric structures, surface plasmons are excited with high efficiency, and optimal plasmonic focusing is obtained due to the exact match of polarization.[5] In addition, VBs have great potentials in a number of applications including laser processing,[6] nonlinear optics,[7] and terahertz technology.[8]

The technique for arbitrary and high-quality VB generation is crucial for all the applications listed above. The current strategies can be classified into active or passive types.[1] Typically, active ones are accomplished by polarization mode selection via laser intracavity devices.[9] The passive ones, which convert homogeneously polarized beams into desired VBs, are more popular. The conversion can be achieved through various approaches. One approach employs spatially variant phase retarders based on waveplates,[10] dielectric subwavelength gratings,[11] and metasurfaces.[12] These components work only for specific wavelength or suffer from low efficiency, and only low-order VBs are demonstrated. A second method uses the interference of two orthogonally polarized beams from computer-generated holograms.[13] This strategy is suitable for arbitrary VB generation, but the setups are complex and costly, while the efficiency is quite low. Another method relies on spatially variant polarization converters realized via twisted nematic (TN) liquid crystals (LCs) where the molecular orientation is induced by electric-field,[14] circular rubbing,[15,16] cylindrical cavity confinement,[17] and photoaligning.[18] These elements have the advantages of simple configuration, convenient use, low cost, and high conversion efficiency. The polarization-guiding effect of the TN LC is achromatic at the Mauguin condition, which makes the components broadband-capable.[16] Unfortunately, the design and fabrication of these devices is still restricted to simple VBs for incoherent light. If this limitation could be overcome, the capability for VBs generation would be drastically enhanced and would give rise to more possibilities for the design of photonic devices.

In this work, LC polarization converters and corresponding vector-photoaligned q-plates suitable for arbitrary VB generation are proposed and demonstrated. The converters are special TN cells characterized by one uniformly aligned substrate and a second, opposing substrate which has space-variant alignment states. A dynamic micro-lithography system is utilized to photoalign a polarization-sensitive agent deposited on the substrates. By this means, various polarization converters have been fabricated. In addition to traditional radially/azimuthally polarized light, high-order and multi-ringed VBs, and even VB arrays with different orders are generated. Moreover, this converter is demonstrated as a polarization mask to implement photoaligning to obtain a q-plate,[19] which can convert circularly and linearly polarized laser beams into optical vortices and VBs, respectively.

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The polarization distribution φ of a VB can be described as[16]

$$\varphi(\theta, r) = P \times \theta + \varphi_0, \tag{1}$$

where θ is the azimuthal angle, r is the polar radius, P is the polarization order (the number of polarization rotations per round trip), and φ_0 is the initial polarization direction for $\theta = 0$. As mentioned previously, such VBs could be realized via certain TN LC cells. For a TN cell with a twist angle Φ, the polarization guiding effect is valid for $\Phi \ll 2\pi\Delta nd/\lambda$ (Mauguin condition),[20] where Δn is the birefringence of the LC, d is the cell gap, and λ is the wavelength of the incident light. At this condition, the linearly polarized incident light, with polarization either parallel or perpendicular to the LC director on the front substrate, will be rotated by Φ. The output polarization obtained will be determined by the local director orientation on the rear substrate. Therefore, by designing the LC orientations on the rear substrate according to Eq. (1), and keeping a uniform alignment on the front substrate, corresponding VBs may be converted.

The designed space-variant LC orientations are carried out through photopatterning via dynamic micro-lithography.[21] The excellent image output capability of the technique allows arbitrary LC orientations to be generated easily. A polarization-sensitive and rewritable sulphonic azo-dye SD1 (Dai-Nippon Ink and Chemicals Inc., Japan) is used as the alignment agent. The SD1 molecules tend to reorient their absorption oscillators perpendicular to the ultraviolet (UV) light polarization and further guide the LC directors. The designed space-variant orientations are recorded in SD1 by a multi-step partly overlapping exposure process.[22] In brief, the objective LC orientations are calculated according to Eq. (1). The φ modulo π is considered due to the reciprocity of the LC director. Each 0 to π region is equally divided into eighteen sub-regions and endowed with a uniform angle. The adjacent five sub-regions are exposed simultaneously, and subsequent exposure shifts one sub-region while the polarizer rotates $\pi/18$ synchronously. After completing one full rotation, every sub-region on this substrate will have been exposed with a dose of $\sim$5 J/cm^2, which writes the desired LC director orientations into the SD1 layer. A second SD1-coated substrate is uniformly aligned using a linearly polarized UV light. Afterwards, the two substrates are assembled using 12 μm Mylar spacers and then sealed with epoxy glue to form the cell. Filling the cell with LC E7 yields the desired polarization converters.

Figure 1 shows the typical cases of $P = 1$, $\varphi_0 = 0$, $\pi/4$, and $\pi/2$ for VBs with radial, vortex, and azimuthal polarizations, which are pictorially illustrated on the top. These polarization converters are observed under a crossed-polarized optical microscope, and captured micrographs are presented in the middle. Here, the Mauguin condition is satisfied for the entire visible range, resulting in the gray-scale appearance of the micrographs.[16] In the observation, the polarization of incident light is parallel to the LC orientation at the uniformly aligned front substrate. In this case, the output polarization follows the local LC director distribution on the rear substrate, thus designed VBs are generated. Some fanlike extinction patterns are observed. The dark and bright regions correspond to the output polarization perpendicular and parallel to the analyzer axis, respectively. The brightness gradually changes between these two extreme cases and forms the fanlike images due to the cylindrical symmetric polarization distribution. The obtained results are consistent with the theoretical simulations calculated from the Jones matrix formulism.[20] Owing to the minimization of elastic twist energy, $\Phi \leq \pi/2$, and areas of reversed twist occur in the same cell. As shown in micrographs, disclination lines occur where the reversed twisted molecular orientations join each other.[16]

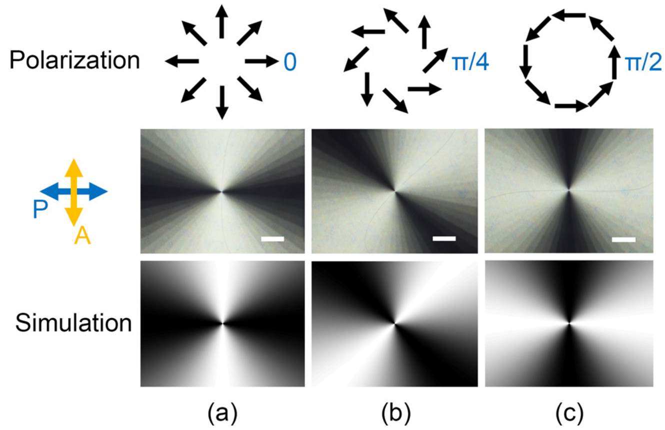

FIG. 1. The schematic polarization distributions (top), experimental (middle), and simulated (bottom) intensity distributions of VBs with $P = 1$, and (a) $\varphi_0 = 0$, (b) $\varphi_0 = \pi/4$, and (c) $\varphi_0 = \pi/2$. All scale bars indicate 200 μm. P: polarizer and A: analyzer.

To further explore the capability of VB generation, more complicated polarization converters have been fabricated. A high-order one with $P = 8$ and $\varphi_0 = 0$ is exhibited in Fig. 2(a), which shows a greater multiplicity of alternating bright/dark states. Even for such a large P, the generated VB is an excellent match to the simulation, and the quality is significantly improved with respect to the previously employed cascading method.[16] In Fig. 2(b), the four different converters with $P = 1$, 2, 3, and 4 shown were fabricated simultaneously to form an array. Unlike the converter array with single P confined by the cylindrical cavity array,[17] here arbitrary and multiple polarization orders P are achievable. Moreover, a polarization converter with $P = 1$ and $\varphi_0 = 0$, $\pi/2$, 0, and $\pi/2$ from center to edge is demonstrated. As

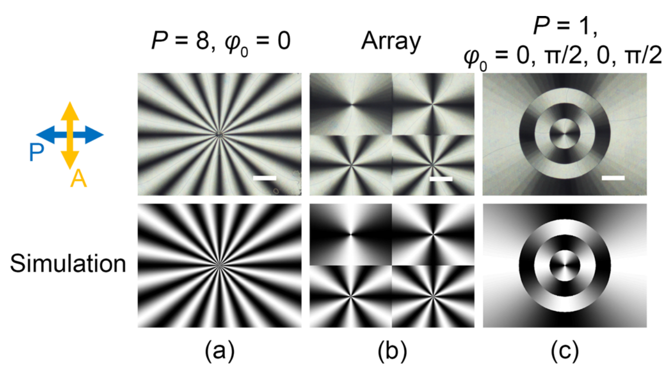

FIG. 2. The experimental and simulated intensity distributions of VBs with (a) $P = 8$ and $\varphi_0 = 0$, (b) array with $P = 1$, 2, 3, and 4, $\varphi_0 = 0$, and (c) $P = 1$ and $\varphi_0 = 0$, $\pi/2$, 0, and $\pi/2$. All scale bars indicate 200 μm. P: polarizer and A: analyzer.

shown in Fig. 2(c), the generated VB is multi-ringed and exhibits alternate radial and azimuthal polarizations. As expected, disclination lines consistent with P are observed in all micrographs. The VB generation is not limited to the cases shown above. Thanks to the excellent flexibility of LC orientation design and pronounced image output capability of the photopatterning technique, the VB with arbitrary polarization distribution is realizable.

The obtained converters can themselves be used directly as polarization masks to implement photoalignment, by a process we define as vector-photoaligning. The experimental setup is very simple and is shown schematically in Fig. 3(a). UV light with polarization perpendicular to the LC orientation of the uniformly aligned front substrate illuminates the sample through the converter. The sample could be either an SD1-coated substrate or an empty cell. In addition to the volume duplication of polarization converters, another promising element (the q-plate)[19,23] could also be fabricated. A converter with $P = 1$ and $\varphi_0 = 0$ was used to fabricate a q-plate with $q = 1$. The obtained q-plate and resultant optical vortex are presented in Figs. 3(b) and 3(c), respectively. Though a simple example is given here, the vector-photoaligning technique is completely applicable to the fabrication of more complicated q-plates.

The obtained polarization converters are suitable for broadband incoherent beam conversions, which are verified by their high-quality micrographs and the vector-photoaligned q-plate. Although for coherent beams the disclination lines will result in polarization conflict[24] and destroy the VBs, q-plates could satisfactorily solve this problem.[25] The q-plates will convert circularly polarized light into an optical vortex (topological charge $m = 2q$) and convert linearly polarized light into a vector beam (polarization order $P = 2q$). For the example of $q = 1$, when we fix the polarization of incident laser beam and rotate the analyzer after the q-plate, the generated VB patterns ($P = 2$) are captured by a CCD as shown in Fig. 3(d). As expected, the light patterns rotate along with the analyzer synchronously, verifying the polarization characteristics of generated VBs for coherent beams. At present, only simple q-plates have been reported. As a result, the generated VBs via this element are quite limited. Herein, thanks to the excellent flexibility on the fabrication of polarization converters, much more complex q-plates can be obtained via the vector-photoaligning process using the polarization converters as polarization masks. Through this method, theoretically arbitrary VBs can be realized for coherent beams. An example of bi-ringed VBs with $P = 3$, $\varphi_0 = 0$ and π generated by a q-plate with $q = 1.5$, $\varphi_0 = 0$ and $\pi/2$, which is vector-photoaligned by an LC polarization converter with $P = 1.5$, $\varphi_0 = 0$ and $\pi/2$, is shown in Fig. 3(e). The improvement on the capability for polarization control is expected to have a significant impact on advancing corresponding applications. The realization of multi-P converter arrays makes it possible to process multiple beams simultaneously,[26] and the multi-ringed VBs might possess specific focusing properties.[27]

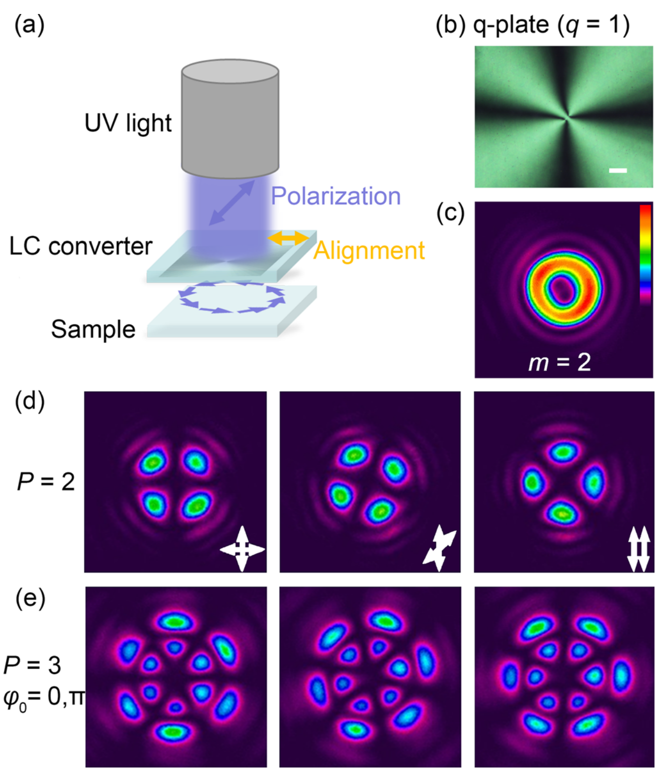

FIG. 3. (a) Experimental setup for the vector-photoaligning, (b) micrograph of an obtained q-plate with $q = 1$, (c) resultant optical vortex captured by a CCD with topological charge $m = 2$ when circularly polarized light is incident, (d) and (e) the generated VB patterns ($P = 2$ and $P = 3$, $\varphi_0 = 0$ and π) of q-plates with $q = 1$ and $q = 1.5$, $\varphi_0 = 0$ and $\pi/2$, respectively, when rotating analyzer with fixed incident linear polarization. The scale bar indicates 200 μm and the color bar indicates the relative optical intensity.

In summary, we proposed a design for LC polarization converter and corresponding vector-photoaligned q-plate that permits the convenient generation of arbitrary VBs. A technique suitable to realize the design was developed via the combination of a polarization-sensitive alignment agent and a dynamic micro-lithography system. By this means, various LC polarization converters were demonstrated, and resultant radially/azimuthally polarized light, high-order and multi-ringed VBs, and VB arrays with different orders were generated. The obtained converters were further used as polarization masks to implement vector-photoaligning. It makes the volume duplication of the converters and the fabrication of q-plates practical. The capability to fabricate more complex q-plates facilitates the arbitrary generation of VBs as well. The proposed polarization converters and correspondingly fabricated q-plates in this work satisfy a fundamental requirement for polarization control and may pave a practical path towards applications like focus engineering, high-resolution imaging, and nanoparticle manipulations.

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