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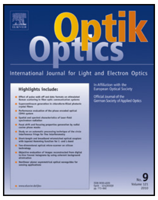

Tunable double annular shaped cylindrical vector beam generator

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ABSTRACT

Cylindrical vector beam has gained amounts of interest in recent years due to its unique focusing characteristic. In this paper, a novel optical setup based on axicons is proposed to convert linearly polarized beam into cylindrical vector beam directly. The radius of the output beam can be adjusted by changing the distance of axicons. We clarify the design philosophy in details and certify the feasibility of the proposed structure by using LightTools™ software. This work is important for micro-manipulation and microscope.

1. Introduction

In recent years, the cylindrical vector beam (CVB) such as radial polarization (RP) beam and azimuthal polarization (AP) beam has gained amounts of interests. The RP beam can be converted into sub-wavelength spot with a strong longitudinally polarized component at the focal plane, while AP beam becomes a ring shaped intensity distribution with a zero field on axis when focused by a high NA aplanatic lens [1–3]. These properties can be applied in many fields such as optical tweezers [4], high-resolution microscopy [5], micro-lithography [6], surface plasmon excitation [7], DNA sequencing, genes transplant, micro-machining [8,9]. Motivated by these amusing applications, a large amount methods of generating CVB have been investigated in the past two decades. Among these methods, these can be divided into two types. The one is called direct method and the other is indirect method. Direct method needs to insert a special optical element in resonator or customize a special laser. In fact, it is not convenient for commercial applications because the specific laser is required for end user. The indirect method utilizes a polarization converter outside the resonator with help of wave-front reconstruction engineering, and this method gains flexibility to generate CVB with arbitrary polarization. Until now, generating of novel and tunable CVB is an important issue.

The method utilizing two orthogonally polarized beams was reported, but it has strict requirement on the interferometric stability [10–12]. Another method based on liquid crystal spatial light modulators (SLM) was presented by Wang et.al. It can generate arbitrary CVB by choosing appropriate additional phase distribution, but the main limitation of this method lies in the pixel size of SLM, low diffraction efficiencies and the influence of holographic grating [13]. These factors become a hinder for generating high quality CVB. Hu and co-workers demonstrate a schematic setup of generating radially and azimuthally polarized beam simultaneously [14]. To best of our knowledge, the concept presented by Qi Hu was one of the most effective methods. Unfortunately, a birefringence material prism and several off-axis prisms are needed for his method. The off-axis aberration such as coma and astigmatism would deteriorate the wave-front of CVB when off-axis prism tilt at wavelength scale, and the radius of CVB might not be tunable easily.

This article contributes to provide a novel optical setup for generating a radius-tunable double annular shaped CVB based on axicons. The main components of the design are the concave axicon and the convex axicon with special designed films. Based on the transfer matrix method we derive the Jones matrix of the output beam. In addition, we deduce the mathematical expressions of annular radius. In order to analyze the feasibility, the proposed structure is simulated by LightTools. The simulation results indicate that our design is feasible.

2. Design principle and simulation

The schematic optical path for generating tunable double annular shaped CVB is depicted in Fig. 1. All optical elements shown in Fig. 1 are arranged coaxially and symmetrically. It can be seen that the collimated beam passes through a quarter wave plate, a concave axicon (Axicon1), an optical rotator, a convex axicon (Axicon2), a spiral phase plate (SPP) and two half wave plates (*W*2 and

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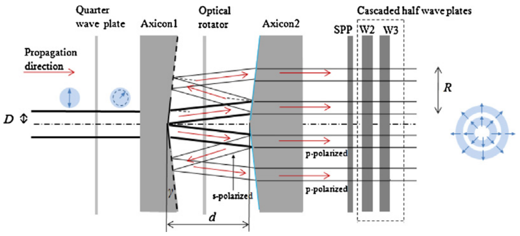

Fig. 1. The schematic for tunable cylindrical polarized vector double shaped beam.

*W*3), sequentially. The base angles of two axicons are matched to ensure that the output beam is parallel to the optical axis. In order to receive CVB, some coatings are designed on the surface of Axicon1 and Axicon2. The concave surface of Axicon1 is coated with anti-reflection film at the inner circle area with the diameter of the input beam, and high reflective film at the outer ring area. The convex surface of Axicon2 is coated with polarization beam splitting film (PBSF) reflecting *s* component and transmitting *p* component. In addition, the optical rotator consisted of cascaded half wave plates are used to rotate the polarized direction, and the angle between fast axes of the two wave plates is 22.5°.

An input linear polarized beam is converted into circular polarization by a quarter wave plate, followed by passing through Axicon1 and an optical rotator without changing polarization. When the beam incident on the convex surface of Axicon2, it splits into reflected *s* component and transmitted *p* component. After then, the *p* component will propagate through Axicon2, while the reflected *s* component returns to the concave surface of Axicon1. As shown in Fig. 1, the reflected *s* component beam will pass through the optical rotator twice. Its polarization direction will rotate 90° and become *p* component, which can transmit Axicon2. It can be seen that a double annular shaped beam is generated after Axicon2. In the following part, the output beam from Axicon2 will be proved as cylindrical polarization carrying vortex component. A SPP is used to remove vortex polarization component to get pure CVB. Two half wave plates (*W*2 and *W*3) are applied to turn the polarization of the output beam. As a result, a double annular shaped CVB with tunable polarization and beam diameter will be received.

In the following, we derive the Jones matrix of the output beam at the convex surface of Axicon2 by adopting transmission matrix method. As shown in Fig. 2, we define a coordinate system composed of the *s* component, *p* component and the propagation vector *k* (*s*, *p*, *k*). The *s*- and *p*-polarized vectors are perpendicular and parallel to the incident plane at the convex surface, respectively. Due to convex surface of Axicon2 is cone shaped, the incident plane is a rotational symmetry. Therefore, the defined coordinate system is rotated with the rotating meridional plane at the convex surface of Axicon2. A transmission matrix is chosen to convert the defined coordinate system into the laboratory coordinate system for presenting the output beam. The laboratory coordinate system (*x*, *y*, *k*) can be rotated into (*s*, *p*, *k*) coordinate system with the rotation angle of θ. The coordinate transformation matrix from the laboratory coordinate system to the defined coordinate system is written as

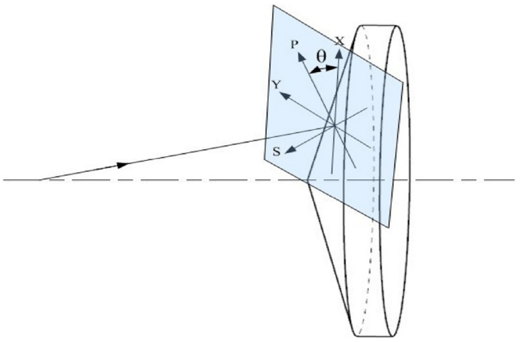

Fig. 2. Illustration of coordinates transformation.

$$\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{1}$$

while the reversed transformation matrix is

$$\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \tag{2}$$

The Jones matrix for the *s* and *p* component are expressed as

$$J_s = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \tag{3}$$

$$J_p = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \tag{4}$$

By considering Eqs. (1–4), the reflective *s* component and the refractive *p* component at the convex surface of Axicon2 can be expressed as

$$\begin{aligned} M_s &= \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} 1 \\ i \end{bmatrix} \\ &= \begin{bmatrix} \sin^2\theta - i\sin\theta\cos\theta \\ -\sin\theta\cos\theta + i\cos^2\theta \end{bmatrix} \\ &= \mathrm{i}e^{i\theta} \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} \end{aligned} \tag{5a}$$

$$\begin{aligned} M_p &= \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} 1 \\ i \end{bmatrix} \\ &= \begin{bmatrix} \sin^2\theta - i\sin\theta\cos\theta \\ -\sin\theta\cos\theta + i\cos^2\theta \end{bmatrix} \\ &= \mathrm{i}e^{i\theta} \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} \end{aligned} \tag{5b}$$

The reflecting component will pass through the optical rotator twice, so the polarization state can be calculated as

$$\begin{aligned} J_s &= \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \mathrm{i}e^{i\theta} \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix} \\ &= \mathrm{i}e^{i\theta} \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} \end{aligned} \tag{6}$$

It is obviously that the Eq. (5b) and Eq. (6) indicate the same polarization state. So far, we have demonstrated the polarization state of the outer ring and the inner ring, and the polarization state of output beam in our design is cylindrical polarization carrying on an exponential term called vortex phase. If an analyzer is inserted in front of the quarter wave plate, right hand circular polarization beam (RHCP) is generated by rotating the fast axes of analyzer. When the RHCP propagates through the proposed setup, a negative vortex is obtained. In other words, the beam generated from our appliance should be called cylindrical vector vortex beam. The vortex beam generates great research interest which has resulted in a new branch in modern optics due to the special focusing and propagating properties. But in this design, a pure radially polarization state is more preferred, so the vortex phase would be removed. Some methods are proposed to eliminate the vortex phase, but to our knowledge, spiral phase plate (SPP) is the best choice. As usual, SPP is used to generate vortex. It can also be used to compensate the vortex phase of the output beam by placing SPP in the rear of Axicon2. Cascade half wave plates (CHWP) are placed in the rear of