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Focus shaping effect of annular cylindrical vector beam generated by novel polarized convertor

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ABSTRACT

Based on the diffractive vector theory, the focusing properties of annular cylindrical vector beams generated by the novel polarized convertor are investigated. By the combination of the vortex phase plate $e^{im\varphi}$ and the phase variety parameter $\cos\varphi + ih\sin\varphi$ which exists naturally in the CV beams, the intensity pattern at the focus can be tailored. Flattop spot and light intensity with pure transverse and longitudinal component are formed in the focal region. More interestingly, tunable dark focal spot is also achieved. By changing h, the light intensity in the center of spot can be changed at will while the outer ring of spot remains the same. This works are important for microscope imaging and optical lithography, particle manipulation, electric acceleration etc.

1. Introduction

Cylindrical vector (CV) beam has drawn great interest in recent years, owing to its unique properties in high numerical aperture (NA) optical system, which has potential applications in many areas, such as confocal microscope [1], particle manipulation [2–6], photolithography [7]. As for confocal microscope, sharp focal spot is urgent needed for superresolution. Symmetrical focal spot smaller than that of linearly polarized light is proved by employing CV beams [8]. However, the size of focal spot is determined by axis field which is diminished owing to the index of refraction (IR) mismatch between the objective coupling medium with low IR and the sample with high IR [9,10]. In our previous works, multi focal spots with major light intensity of transverse component are obtained by focusing composite vector beams [11]. However, focal spots mentioned above are not so small to break the diffractive limit. To the best of our knowledge, ultrasmall focal spot was reported by wavefront phase coding couple with amplify modulation [12]. However, it is not an economical way to form small focal spot by wasting much light energy.

In the field of particle manipulation, the focal spots with major light intensity of longitudinal component are of great value. The reason is that the trapping stability is determined by two forces, one is optical gradient force which is proportional to the gradient of the square of the electric field (energy density) and is responsible to pull the particles toward the center of the focus; the other is scattering force which is tend to push the particle out of the trap. Due to the stronger longitudinal component provided by radially polarized light, it is easier to trap particles than that of linearly polarized light [2]. However, the light intensity of transverse component which increases the scatting force cannot be ignored by focusing radially polarized light [13]. Focal spot with pure longitudinal component is still worth achieving. On the other hand, focal spot with low light intensity surrounded by high light intensity, namely dark focal spot, is an effective tool for trapping the particle with low refractive index [3]. Generally, such focal spot can be obtained by focusing azimuthally polarized light [13]. To enhance the efficiency of trapping particle, multi dark focal spots are needed. However, most works are concentrated in multi focal spots along z axis [5,6]. Although multi dark focal spots in transverse plane can be formed by hyperbolic cosine Gaussian beams [14], it is not tunable to control the spots continually.

In this letter, we intend to solve the above problems. First, flexible polarized convertor is designed. Second, focal properties of CV beams generated by above convertor are theoretically investigated. In Section 2, we present the principle of polarized convertor and mathematical expression of CV beams. Section 3 shows the simulation results and discussions. The conclusions are summarized in Section 4.

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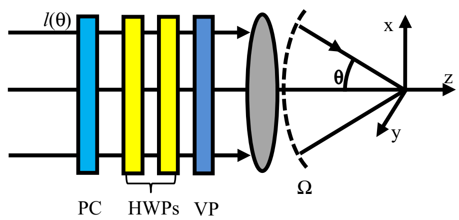

Fig. 1. Schematic of focus system.

2. Theory

Recently, we have designed a novel polarized convertor (PC) [15] which can produce high quality of annular CV beams. The output CV beams are naturally modulated by the phase various parameter of $\cos\varphi + ih\sin\varphi$ which is related to the polarized state of incident beam. In this letter, the focal properties of CV beams generated by the above convertor are theoretically investigated. Due to the special design of polarized convertor, there is no loss of light intensity to form the valuable focal patterns by focusing the annular beams in high NA optical system.

Before calculating the focal light intensity of the output CV beam, we first derive the phase various parameters for different incident beams. Assumed that the incident vector light with the polarization state of $\mathbf{E}_i = \begin{bmatrix} 1 & ih \end{bmatrix}^T$ propagate through the PC along the optical axis, the corresponding output field can be written as $\mathbf{E} = \mathbf{ME}_i$ where $\mathbf{M}$ is the Jones matrix of PC. For the two cases of o and e light, $\mathbf{M}$ can be described as follows [15]:

$$\mathbf{M}_o = \begin{bmatrix} \cos^2\varphi & \sin\varphi\cos\varphi \\ \sin\varphi\cos\varphi & \sin^2\varphi \end{bmatrix} \tag{1}$$

$$\mathbf{M}_e = \begin{bmatrix} \sin^2\varphi & -\sin\varphi\cos\varphi \\ -\sin\varphi\cos\varphi & \cos^2\varphi \end{bmatrix} \tag{2}$$

The Jones matrixes of the output field with different incident light can be described as follows:

$$\mathbf{E}_o = (\cos\varphi + ih\sin\varphi)\begin{bmatrix} \cos\varphi & \sin\varphi \end{bmatrix}^T \tag{3}$$

$$\mathbf{E}_e = ih\left(\cos\varphi + \frac{i\sin\varphi}{h}\right)\begin{bmatrix} -\sin\varphi & \cos\varphi \end{bmatrix}^T \tag{4}$$

where the superscript T denotes the transpose. Both of above equations are the electric field of TM_{01} mode radially polarized light and TE_{01} mode azimuthally polarized light, respectively, which contain the phase variety parameters $\cos\varphi + ih\sin\varphi$ and $\left(\cos\varphi + \left(i\sin\varphi/h\right)\right)$, where h is a real number. Both of the phase variety parameters are actually the same if only the image part of both phase variety parameters are equal. $\exp(im\varphi)$. When such CV beams go through the vortex phase plate (VP) with transmission of and two half-wave plates (HWPs), the final electric field from the whole setup is illustrated as [16]

$$\mathbf{E}_{\text{out}} = T_c\left(\cos\phi_0\boldsymbol{e}_r + \sin\phi_0\boldsymbol{e}_a\right) \tag{5}$$

where $T_c = \exp(im\varphi)(\cos\varphi + ih\sin\varphi)$, $\phi_0 = 2\Delta\varphi$, $\Delta\varphi$ is the angle between fast axis of two HWPs, $\boldsymbol{e}_r$ and $\boldsymbol{e}_a$ are the unit vector in the radial and azimuthal direction, respectively. m is the topological number of vortex phase plate VP. If the incident vector light is circularly polarized, namely $h = 1$, the natural phase variety parameters $\exp(i\varphi)$ generated by the incident beams can be compensated by VP with the topological number $m = -1$. Hence, the normal CV beams are obtained.

As shown in Fig. 1, an incident beam with propagating along $+z$ axis is focused into the image plane by the lens obeying sine condition. Note that the CV beams produced by PC is modulated by two factors. One is $\cos(\varphi) + ih\sin(\varphi)$, which is relative to the polarized state of incident light; the other is vortex phase plate the transmission of which is $\exp(im\varphi)$. Meanwhile, the polarized state of CV beam can be adjusted by the double half-wave plates (HWPs). Based on the vector diffractive theory [13,17], the electric field for arbitrary point $P\begin{pmatrix} \rho_s & \phi_s & z \end{pmatrix}$ in the focal region can be expressed as

$$\mathbf{E} = \frac{-iG}{\pi}\int_b^{\alpha}\int_0^{2\pi} T_c D\left(\theta\right) e^{\left[ik\rho_s\sin\theta\cos(\varphi-\phi_s)\right]}\mathbf{V}\mathrm{d}\theta\mathrm{d}\varphi \tag{6}$$

where G is normalize const. $D\left(\theta\right) = \sqrt{\cos\theta}\sin\theta l_0\left(\theta\right)e^{ikz_s\cos\theta}$ The maximum aperture angle $\alpha = a\sin(\mathrm{NA}/n)$ and $b = a\sin\left(\varepsilon\sin(\alpha)\right)$ is relative to the radii of inner ring and ε is the ratio of the radii of inner ring and outer ring for the annular CV beams. The wave number $k = 2\pi n/\lambda$, n is the refractive index in the image space. The focusing matrix can be described as:
$\mathbf{V} = \begin{bmatrix} -A\cos\varphi - B\sin\varphi \\ -A\sin\varphi + B\cos\varphi \\ C \end{bmatrix}$, where $A = \cos\left(\theta\right)\cos\left(\phi_0\right)$; $B = \sin\left(\phi_0\right)$; $C = \sin\theta\cos\phi_0$.

The integrate over φ can be accomplished by

$$\int_0^{2\pi}\cos n\varphi e^{im\varphi}e^{i\rho_s\cos(\varphi-\phi_s)}\mathrm{d}\varphi = \pi i^{n+m}J_{n+m}(\rho_s)e^{i(n+m)\phi_s} + \pi i^{m-n}J_{m-n}(\rho_s)e^{i(m-n)\phi_s} \tag{7}$$

$$\int_0^{2\pi}\sin n\varphi e^{im\varphi}e^{i\rho_s\cos(\varphi-\phi_s)}\mathrm{d}\varphi = -\pi i^{n+m+1}J_{n+m}(\rho_s)e^{i(n+m)\phi_s} + \pi i^{m-n+1}J_{m-n}(\rho_s)e^{i(m-n)\phi_s} \tag{8}$$

Therefore, the electric field near focus can be simplified as

$$\begin{aligned} E_x &= \frac{1}{2}iG\int_b^a D(\theta)\left\{i^{2+m}J_{2+m}\left(k\rho_p\sin\theta\right)\exp[i(2+m)\phi_s](A-iB)(h+1)\right. \\ &\quad + i^{m-2}J_{m-2}\left(k\rho_p\sin\theta\right)\exp[i(m-2)\phi_s](A+iB)(-h+1) \\ &\quad \left. + 2(A+ihB)\,i^mJ_m\left(k\rho_p\sin\theta\right)\exp(im\phi_s)\right\}\mathrm{d}\theta \end{aligned} \tag{9}$$

$$\begin{aligned} E_y &= -\frac{1}{2}iG\int_b^a D(\theta)\{i^{2+m}J_{2+m}(\rho_p)\exp[i(2+m)\phi_p](Ai+B)(h+1) \\ &\quad + i^{m-2}J_{m-2}(\rho_p)\exp[i(m-2)\phi_p](-iA+B)(-h+1) \\ &\quad + 2(-ihA+B)i^mJ_m\left(k\rho_p\sin\theta\right)\exp(im\phi_s)\}\mathrm{d}\theta \end{aligned} \tag{10}$$

$$\begin{aligned} E_z &= -iG\int_b^a D\left(\theta\right)C\{i^{1+m}J_{1+m}(\rho_p)\exp[i(1+m)\phi_p](h+1) \\ &\quad + i^{m-1}J_{m-1}(\rho_p)\exp[i(m-1)\phi_p](-h+1)]\}\mathrm{d}\theta \end{aligned} \tag{11}$$

where $J_n(\bullet)$ is Bessel function of first kind and order n. Note that when passing through the polarized convertor PC (see Fig. 1 in Ref. [15]), the incident beam experiences two processes. One is the light intensity of incident beam is compressed. Therefore, the light intensity of output CV beam is magnified by M, where $M = 1/(1-\varepsilon)$ and ε is the ratio of the radii of inner ring and outer ring for the output annular CV beam. Another is the central light intensity of incident beam can be shifted to the outer ring to form the annular CV beam. Hence, the parameters of incident beam can be written as