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Tight focusing of a quasi-cylindrical optical vortex

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ABSTRACT

In this article, we numerically investigate the tight focusing of a quasi-cylindrical optical vortex with azimuthal polarization and a wavelength of 532 nm using a Fresnel zone plate with a numerical aperture of NA = 0.95. It is shown that the focal spot produced by a beam with six sectors does not differ from the ideally azimuthally polarized optical vortex; a difference in the focal spot diameter does not exceed 0.001 of the wavelength.

1. Introduction

Cylindrical vector beams (beams with polarization with a radial direction of symmetry) are currently an active topic of research [1]. Recent years have also seen an increased interest in the study of azimuthally and radially polarized optical vortices. It should be noted that a radially polarized beam forms a sharp peak in a focal spot, whereas azimuthally polarized light forms a ring in a focal spot. Thus, an azimuthally polarized beam needs a phase singularity to produce a peak in the focal spot.

In [2], it was shown that an azimuthally polarized optical vortex produces a focal spot whose area ($0.147\lambda^2$) is 13.5% smaller than a focal spot from a radially polarized beam ($0.17\lambda^2$). Optical needles generated by azimuthally polarized vortices were investigated in [3]. These needles have a depth of 12λ and a subwavelength width which varies from 0.42λ to 0.49λ. In [4], an azimuthally polarized beam propagated through a multibelt phase hologram and high NA lens (NA = 0.95) was used to generate a focal spot with a depth of focus (DOF) of 4.84λ and a subwavelength width of 0.53λ. In [5], a similar multibelt phase hologram combined with an axicon lens was used to generate an optical needle with a large DOF of 11λ and a small width of 0.38λ. An optical needle with a subwavelength diameter of 0.38λ and a longitudinal depth of 7.48λ was obtained in [6]. A focal spot limited by sub-diffraction was obtained in [7].

The authors of [8] used 4π focusing to focus a radially polarized optical vortex into a spot with a width of 0.43λ and a depth of 0.45λ. This type of focusing was also used in [9] to produce spherical and sub-wavelength longitudinal magnetization. Solid immersion lens (SIL) was used in [10] to produce a focal spot with a diameter of 0.305λ. The effect of coma on a tightly focused cylindrically polarized vortex beams was investigated in [11]. A beam quality measuring technique was introduced in [12]. The conversion of cylindrically polarized laser beams from radial to azimuthal polarization was demonstrated in [13] by introducing a higher-order vortex phase singularity.

There are several ways to obtain beams with sectoral azimuthal or radial polarization (or quasi-cylindrical vector beams), including the use of half-wave plates [14–17], nonlinear optical crystals [18], polarizing films [19] and subwavelength gratings [20–22]. In addition sectoral binary elements could be added to a lens to obtain smaller focal spot [23,24].

The tight focusing of quasi-cylindrically polarized beams was previously investigated in detail in [25] using numerical analysis. It was shown that a deviation of an eight-sector beam does not exceed 5.3% from the ideal beam. However, azimuthally polarized optical vortices have not been previously investigated.

In this paper, we numerically investigate the tight focusing of a quasi-azimuthally polarized optical vortex with a wavelength of 532 nm using a Fresnel zone plate with NA = 0.95. It is shown that the focal spot produced by a beam with six sectors does not differ from the ideally azimuthally polarized optical vortex; the difference in the focal spot diameter does not exceed 0.001λ. For a four-sectoral beam, the difference does not exceed 0.03λ.

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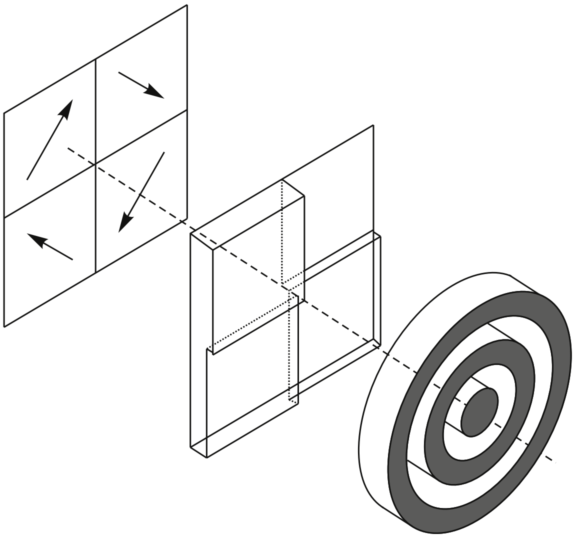

Fig. 1. Sketch of the simulation: the four-sector azimuthally polarized beam and four-sector SPP.

2. Numerical simulation

Our numerical simulation was performed using the Richards–Wolf formula [26]:

$$\mathbf{E}(\rho,\psi,z) = -\frac{if}{\lambda}\int_0^{\alpha}\int_0^{2\pi} B(\theta,\varphi)\,T(\theta)\,\mathbf{P}(\theta,\varphi) \times\exp\{ik[\rho\sin\theta\cos(\varphi-\psi)+z\cos\theta]\}\sin\theta\, d\theta\, d\varphi \tag{1}$$

Table 1

Maximum error in the intensity distribution of the focus.

	Number of sectors	Maximum relative error
Sector SPP, sector polarization	4	18,0
	6	8,6
Continuous SPP, sector polarization	4	18,9
	6	8,8
Sector SPP, continuous polarization	4	18,9
	6	8,8

where $B(\theta,\varphi)$ is the electrical field of focused light (θ is the polar angle and φ is the azimuthal angle), $T(\theta)$ is apodization function, f is the focal length, $k = 2\pi/\lambda$ is the wavenumber, and $\mathbf{P}(\theta,\varphi)$ is the polarization matrix:

$$\mathbf{P}(\theta,\varphi) = \begin{bmatrix} \left[1+\cos^2\varphi(\cos\theta-1)\right]a(\theta,\varphi) \\ \quad +\sin\varphi\cos\varphi(\cos\theta-1)\,b(\theta,\varphi) \\ \sin\varphi\cos\varphi(\cos\theta-1)\,a(\theta,\varphi) \\ \quad +\left[1+\sin^2\varphi(\cos\theta-1)\right]b(\theta,\varphi) \\ -\sin\theta\cos\varphi a(\theta,\varphi)-\sin\theta\sin\varphi b(\theta,\varphi) \end{bmatrix} \tag{2}$$

where $a(\theta,\varphi)$ and $b(\theta,\varphi)$ are polarization functions for the x- and y-components of the focused beam. In the simulation, we assume that a Fresnel zone plate ($T(\theta) = \cos^{-3/2}(\theta)$, NA = 0.95 is same as in [3–7]) is illuminated using a plane wave that has a different polarization and phase in each sector. In this case, a four-sector beam, for example, will have $a(\theta,\varphi)$, $b(\theta,\varphi)$ and $B(\theta,\varphi)$ as follows:

$$a(\theta,\varphi) = \begin{cases} -1, & 0 \le \varphi < \frac{\pi}{2} \\ -1, & \frac{\pi}{2} \le \varphi < \pi \\ 1, & \pi \le \varphi < \frac{3\pi}{2} \\ 1, & \frac{3\pi}{2} \le \varphi < 2\pi \end{cases} \tag{3}$$

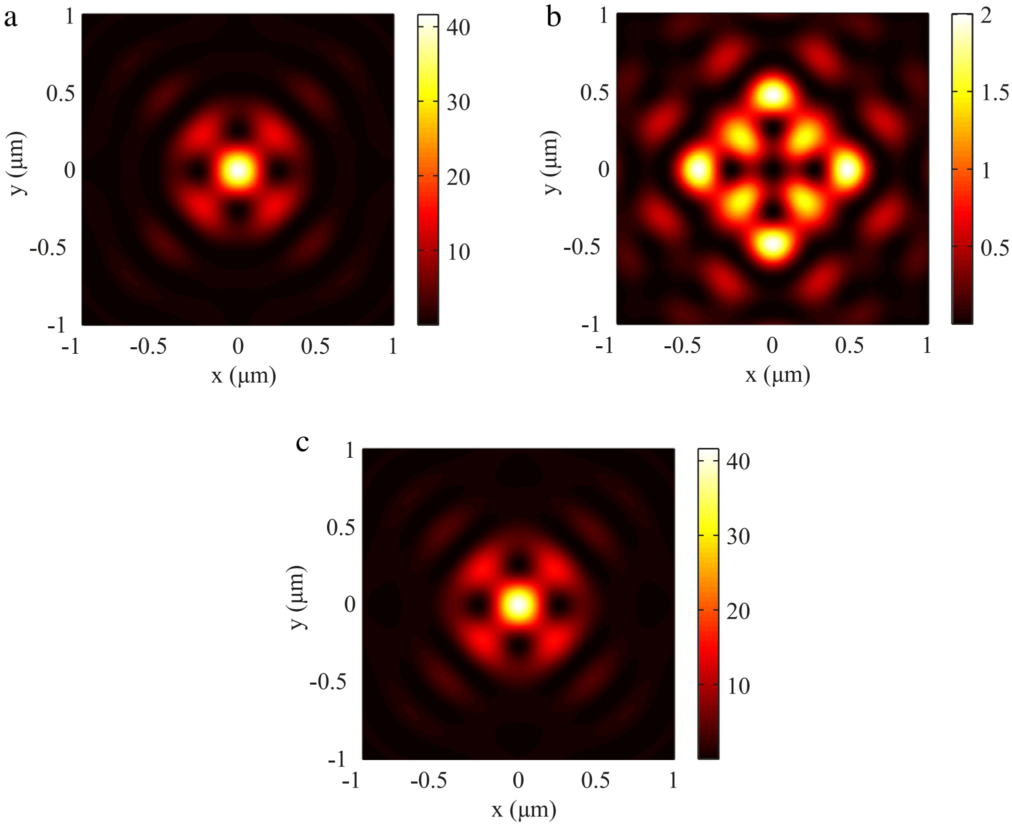

Fig. 2. Intensity in the focal plane for $I_r(a)$, $I_z(b)$, $I(c)$. Focusing of a four-sector polarized beam transmitted through the four-sector SPP.