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Tight focusing properties of cylindrically polarized annular multi-Gaussian beam

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ABSTRACT

Focusing properties of cylindrically polarized annular multi gaussian beam with high numerical aperture lens system is investigated theoretically by vector diffraction theory. Results show that intensity distribution in focal region can be tailored considerably by appropriately adjusting the polarization angle. Peak-centered, donut and flattop focal shapes with extended focal depth, potentially useful in optical tweezers, material processing and laser printing can be obtained using this technique.

1. Introduction

In recent years, more and more attention has been paid to the cylindrical vector beam (CVB) [1], which is the solutions of vector wave equation and has cylindrical symmetry in both amplitude and polarization. It is observed that the intensity pattern in the vicinity of the focal spot can be tailored by changing the polarization direction of the cylindrical vector beam [2,3]. Recently, Intensity distribution in focal region plays an important role in many optical systems, such as in optical tweezers. Focusing an incoming light into a smaller spot or focal hole with long depth of focus (DOF) is always one of the most important topics for optical engineers and scientists. This makes an increasing interest in laser beams with cylindrical polarization symmetry because the electric field in focal region of such cylindrical vector beam have unique properties, and find wide applications, such as particle guiding or trapping [4–8] scanning optical microscopy [9] lithography [10] laser cutting of metals [11,12] particle acceleration [13]. Among these applications, particular interest has been given to high numerical aperture (NA) focusing property of these beams and their application as a high-resolution probe. CV beams can be generated by active or passive methods [14]. Up to now, several theoretical models (e.g. Laguerre–Gaussian model, Bessel–Gaussian and Modified Bessel–Gaussian models) which are all the solutions of Maxwell's equation have been proposed to describe the CV beams [15–17], and much work has been devoted to experimental achievement of the CV beams including active and passive technique [18–23]. The longitudinal field can be suppressed or enhanced by amplitude,

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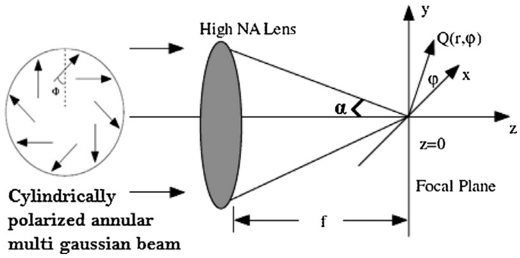

Fig. 1. Focusing of a cylindrically polarized annular multi gaussian beam with high NA lens.

polarization and phase modulations of the incident beam. For example, a longitudinal field can be completely suppressed in an azimuthally polarized beam [24,25]. Several methods to enhance the longitudinal field component have been suggested [26,27] however all of them have insufficient optical efficiency (on the level of a few percents) and non- uniform axial field strength. Recently, radially polarized and amplitude-modulated annular multi-Gaussian beam mode is proposed for illuminating the pupil plane of the objective to achieve sub wavelength longitudinal beam with long focal depth [28]. Generally, those specially designed apodizers are quite complex in phase and amplitude transmittance, so fabricating them is difficult and their efficiency is low. Moreover, the presence of a physical annular apodization or phase filter makes some applications more complicated or even impossible. In this paper we describe a numerical study, based on vector diffraction theory, of a property of a cylindrically polarized annular multi gaussian beam that is tightly focused by a high-NA-lens. It is observed that by using annular multi gaussian beam profile and by proper tuning of polarization angle of the incident CVB, it is possible to generate focal spot or focal hole with sub wavelength structure and long focal depth.

2. Principle of the optical focusing system

A schematic diagram of the suggested method is shown in Fig. 1. The cylindrically polarized annular multi Gaussian beam is focused through a high NA lens system. The annular multi-Gaussian beams consist of a small sum of finite-width anular Gaussian beams side by side each of which represents an intuitive component of the entire beam. The analysis is performed on the basis of Richards and Wolf's vectorial diffraction method [29] widely used for high-NA lens system at arbitrary incident polarization. In case of incident polarization, adopting the cylindrical coordinates r,z,ϕ and the notations of [15], the focal field of a cylindrically polarized vortex beam can be written as

$$\vec{E}(r,z,\phi)=E_r\vec{e}_r+E_z\vec{e}_z+E_\phi\vec{e}_\phi \tag{1}$$

Where E_r, E_z and E_ϕ are the amplitudes of the three orthogonal components and $\vec{e}_r$,$\vec{e}_z$ $\vec{e}_\phi$, are their corresponding unit vectors. The three orthogonal components of the electric field are given as

$$E_r(r,\phi,z)=A\cos\varphi\int_0^{\theta max}\cos^{1/2}(\theta)\,P(\theta)\,\sin 2\theta J_1\left(kr\sin\theta\right)e^{ikz\cos\theta}d\theta \tag{2}$$

$$E_z(r,\phi,z)=2iA\cos\varphi\int_0^{\theta max}\cos^{1/2}(\theta)\,P(\theta)\,\sin^2\theta J_0\left(kr\sin\theta\right)e^{ikz\cos\theta}d\theta \tag{3}$$

$$E_\phi(r,\phi,z)=2A\sin\varphi\int_0^{\theta max}\cos^{1/2}(\theta)\,P(\theta)\,\sin(\theta)\,J_1\left(kr\sin\theta\right)e^{ikz\cos\theta}d\theta \tag{4}$$

Where $k=2\pi/\lambda$ is the wave number and $J_n(x)$ is the Bessel function of the first kind with order n. r and z are the radial and z coordinates of observation point in focal region, respectively. φ represents the polarization angle and $P(\theta)$ describes the amplitude-modulated annular multi-Gaussian beam, this function is given by [28,30,31]

$$P(\theta)=\left(\frac{\theta}{\theta_0}\right)^m\sum_{n=-N}^{N}\exp\left[-\left(\frac{\theta-\theta_c-n\omega_0}{\omega_0}\right)^2\right] \tag{5}$$

Here, θ is the converging semi-angle. We denote the maximum converging semi-angle as θ_{max} which is related to objective numerical aperture by θ_{max} = $arcsin(NA)$. θ_0 is an angle which, along with integer m, determines the shape of the modulation