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Generation of optical bubbles by vector beams and pure phase filter

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ABSTRACT

Based on the combination of generalized cylindrical vector beams and radial polarized beams, the designed three-zone pure phase filter, and interferences effect, we present a theoretical approach to generate optical bubble. Simulation results show that two small optical bubbles can be obtained with the designed optical system when objective lens with NA = 0.8. The optical bubble size defined by full width half maximum of the intensity is calculated to be λ. It can be used in microscopy techniques such as stimulated emission depletion microscopy.

1. Introduction

Focusing properties of cylindrical vector beams have attracted great attention and quickly became the subject of extensive worldwide research due to their applications in lithography [1], optical storage [2], scanning optical microscopy [3], material processing [4,5], optical trapping and optical tweezers [6–8], optical storage [9], stimulated emission depletion (STED) microscope [10,11]. In reference [11], based on cylindrical vector polarization and phase modulation, extended depth of focus was generated. In reference [12], a pure longitudinal light beam with subdiffraction beam size was achieved by focusing a radially polarized Bessel–Gaussian beam with a combination of a binary-phase optical element and a high-numerical-aperture lens. In our previous published paper [13,14], tunable optical superresolution, extended focal depth, focal shift of cylindrical vector axisymmetric Bessel-modulated Gaussian beam and tunable optical trapping gradient force were obtained with the pure phase plate by scalar diffraction theory [15] or Richards–Wolf vector diffraction theory [16,17].

It is well known that the cylindrical vector beams are vector beam solutions of Maxwell's equations that obey axial symmetry in both amplitude and phase [18–20]. The rapid increase of interest in cylindrical vector beams was driven largely by the unique focusing properties of such beams discovered recently. Particularly, it was found that radially polarized light [21] can be focused into a tighter spot than those of spatially homogeneous polarization because of the creation of a strong and localized longitudinal component [22]. In addition, the longitudinal component experiences an apodization effect that is different from the transversal component and is spatially separated from the transversal focal field.

In this paper, based on the combination of generalized cylindrical vector beams and radial polarized beams, the designed three-zone pure phase filter, and interferences effect, two small optical bubbles can be obtained. Simulation results show that two small optical bubbles of stronger light intensity around dark spots can be obtained with the designed optical system when objective lens with NA = 0.8. The optical bubble size defined by full width half maximum of the intensity is calculated to be λ. It can be used in microscopy techniques such as stimulated emission depletion microscopy.

2. Principle of focusing system

In the focusing system as shown in Fig. 1, the generalized cylindrical vector beams (Fig. 2) passes through the designed diffraction optical element (Fig. 3), and then convergences through an objective lens with high numerical aperture.

The electric field of the generalized cylindrical vector beam can be expressed in cylindrical coordinate system as [20]

$$\vec{E}(r,\varphi) = L(r)[\cos\phi\vec{e}_r + \sin\phi\vec{e}_\varphi] \quad (1)$$

where $\vec{e}_r$ is the unit vector in the radial direction and $\vec{e}_\varphi$ is the unit vector in the azimuthal direction. $L(r)$ is the pupil function denoting the relative amplitude of the field that only depends on radial position. ϕ is the polarization rotation angle from radial direction, when $\phi = 0$, it is radially polarized beam; $\phi = \pi/2$, it is azimuthally polarized beams. Thus, a generalized cylindrical vector beam can be

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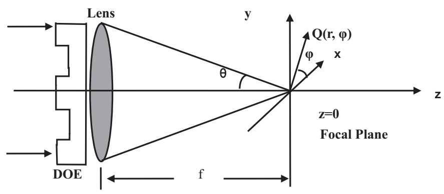

Fig. 1. Setup of focusing system with a diffraction optical element.

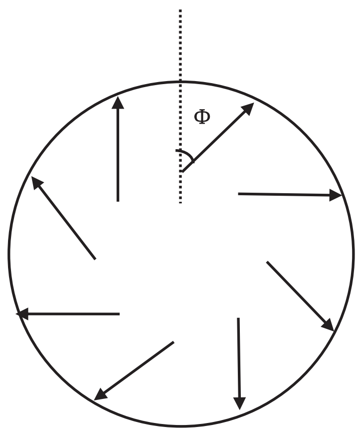

Fig. 2. Generalized cylindrical vector beam.

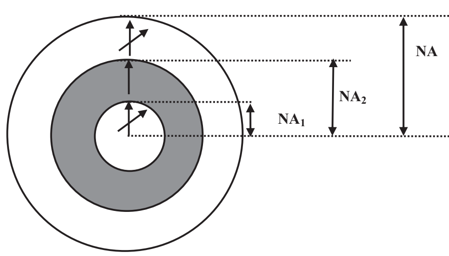

Fig. 3. Pure phase plate with three concentric regions.

decomposed into a radial polarized beam and an azimuthal polarized beam. On the basis of the classical vector diffraction theory of polarized beams [17], in cylindrical coordinates the electric fields in the focal region for the high NA objective lens illuminated by a generalized cylindrical vector beams can be expressed as

$$\vec{E}(r,\varphi,z) = E_r\vec{e}_r + E_\varphi\vec{e}_\varphi + E_z\vec{e}_z \tag{2}$$

where $\vec{e}_r$, $\vec{e}_\varphi$ and $\vec{e}_z$ are the unit vectors in the radial, azimuthal and propagating directions respectively. E_r, E_φ and E_z are amplitudes of the three orthogonal components and given by

$$E_r = B\int_0^\alpha \cos^{1/2}\theta P(\theta) l_0(\theta)\exp(ikz\cos\theta)\sin(2\theta)J_1(kr\sin\theta)\cos\phi d\theta \tag{3}$$

$$E_\varphi = 2B\int_0^\alpha \cos^{1/2}\theta P(\theta) l_0(\theta)\exp(ikz\cos\theta)J_1(kr\sin\theta)\sin\theta\sin\phi d\theta \tag{4}$$

$$E_z = 2iB\int_0^\alpha \cos^{1/2}\theta P(\theta) l_0(\theta)\exp(ikz\cos\theta)\sin^2\theta J_0(kr\sin\theta)\cos\phi d\theta \tag{5}$$

B is a constant, which we set $B = 1$. α is the maximum convergence angle of the beam, $\alpha = \arcsin(NA/n)$; NA is the numerical aperture of the lens; k is the wave number, where $k = 2\pi/\lambda$. $l_0(\theta)$ is the relative amplitude of the field, which is assumed to be dependent on the radial position only, $P(\theta)$ is the pupil apodization function. Without losing generality and validity, it is supposed that $P(\theta) = 1$. $J_n(x)$ is the Bessel function of the first kind with order n. And for radially polarized beams $E_\varphi = 0$, $\phi = 0°$.

In this paper the designed three-zone pure phase filter (Fig. 3), which used as the diffraction optical element in Fig. 1, consists of one center circular zone, one inner annular zone and one outer annular zone with the phase variation 0, π, 0 for each zone, respectively. NA_1, NA_2 and NA, are the numerical aperture for each zone. Due to the continuity requirement, the on-axis electric field of cylindrical polarization is zero. The actual distribution of this hollow center depends on how the cylindrical polarization is generated. To simplify the simulation, the intensity of incident light is supposed to be flat-top distributed, where

$$l_0(\theta) = \begin{cases} 1 & \arcsin(0.2) \le \theta \le \arcsin(NA) \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

where $NA_0 = 0.2$ for our simulation. This means that the center of the lens pupil aperture is blocked to simulate this dark hollow center [20].

The function of transmission shows as

$$T(\theta) = \begin{cases} 1 & 0 \le \theta \le \theta_1, \theta_2 \le \theta \le \arcsin(NA) \\ -1 & \theta_1 \le \theta \le \theta_2 \end{cases} \tag{7}$$

where θ_1 and θ_2 is the angular transition points determined by the inner and outer transition points of the corresponding concentric region of the designed phase filter. The integration limits are given by $\theta_1 = \arcsin(NA_1)$ and $\theta_2 = \arcsin(NA_2)$, respectively. In order to get a field of long focal depth and optical bubble, the radial component and the angular component should be increased, while the axial component should be suppressed. We can achieve this by adjusting the size of the θ_1 and θ_2.

3. Results and discussion

Based on the above analysis, the focusing property of the generalized cylindrical vector beams and radial polarized beams as incident beams can be calculated without difficulty. It should be noted that all of the three zones contain radial polarized vector beams, but the center circle and outer annular zone also contain generalized cylindrical vector beams as shown in Fig. 3. We choose an objective lens that satisfies the sine condition, with the optimum parameters $NA = 0.8$, $\phi = 38°$, $\theta_1 = \arcsin(0.557)$ and $\theta_2 = \arcsin(0.719)$. Fig. 4(a) and (c) describes the intensity distribution of the focal spot in the rz plane for the longitudinal component, transverse component, and the total intensity, respectively.

It is well known that the phase variation will enormously intensify the intensity distribution around the focal spot, so from Fig. 2(a) it can be found that the original focal spot is separated into three parts along the propagating axis with the designed three-zone pure phase filter and combination of two kinds of polarized beams, and these bright spots are connected to one another through the radial field component that are pushed away from the optical axis, leaving dark spots between those bright spots and forming an optical chain distribution. And such optical chain can be used to trap multiple particles simultaneously. Compare with the longitudinal component, the transversal component is zero on the optical axis and remains negligible near the optical axis, so a tunnel of light is generated. This creates an ideal situation for three dimensional trapping of metallic nanoparticles. Considering the designed three-zone pure phase filter, the middle ring can increase the destructive