Creation of Sub Wavelength Focal Spot Segment Using Longitudinally Polarized Multi Gaussian Beam

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ABSTRACT: We investigated the focusing properties of a radially polarized multi gaussian beam through an annular high Numerical Aperture (NA) objective lens based on vector diffraction theory. It is observed that our proposed system can generate sub wavelength focal spot segment with long focal depth (26λ) is achieved. This kind of non diffracting focal segments is called as dark channel, which may have application in atom trapping, nanolithography, trapping and manipulating particles.

Keywords: vector diffraction theory, High Numerical Aperture, optical trapping, nanolithography

1.INTRODUCTION

Focusing light to a very tight spot is one of the most important topics for optical researches and applications. A small focal spot is useful in a multitude of applications, including microscopy, data storage, imaging, and lithography. The size of a focal spot decreases with increasing aperture angle and decreasing wavelength. Therefore, properties of laser beams focused by a high numerical aperture (NA) objective have attracted much attention [1-3]. For example, in a recent paper, Wang et al. [4] created a uniform and non-diffracting axial light beam with a sub diffraction beam size ~0.43λ by focusing a radially polarized Bessel-Gaussian beam with a combination of a binary-phase optical element and a high-numerical aperture (NA) lens. Recently, a sub wavelength light needle with a depth of focus of about 4λ has been generated by focusing a radially polarized beam [5]. In another study, a sub-wavelength light needle with a longer depth of focus (over 9.5λ) has been generated using dual beam focusing [6]. An annular aperture is a common amplitude modulating device for creating a strong longitudinal component of the RP beam at the focus [7-12]. A stronger longitudinal field of the RP beam results in a sharper focus and lower focal depth. Dorn et al. [12] experimentally demonstrate a tightly focused spot down to 0.161λ in size with a large annular factor (the ratio of the inner and outer radii of the ring). Kitamura et al. [8] show an optical needle, a tight focal spot with long depth of focus formed by the longitudinal electric field with a similar annular aperture. The effects of pupil functions [10] and apodizations [11] on the focal spot size are demonstrated, which are close to the reality and become guidance for the experiments. Meanwhile, the formation of non-diffracting quasi-circularly polarized beams with a long DOF (7.23λ) was showed by utilizing an amplitude modulated spiral phase hologram, by which similar transversal spot size (0.587λ) was generated [13]. Tian and Pu [14] used a double-ring-shaped azimuthally polarized Laguerre-Gaussian (LG) beam with a high Numerical Aperture (NA) aplanatic objective to form a sub-wavelength focal hole with a long DOF. Zhang et al [15] manifested that the designed three-zone phase-only filter can not only increase the DOF of the solid immersion lens, but also effectively reduce the spreading of the focal spot and suppress the side-lobe intensity. Most recently, Zha et al [16] showed that the generation of longitudinally polarized beam can be achieved by tightly focusing a radially polarized BG beam with a high NA lens and a ternary optical element. The radially and azimuthally 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 [17-19]. In this Letter, we theoretically investigate the focused properties of a radially polarized multi gaussian beam by an annular high NA objective lens. We find that the depth of focus of the sub wavelength dark channel can be extremely extended to 26λ. In addition, we also find that the polarization direction of the focused electric field can be controlled by changing the central radius of pupil apodization of the objective lens.

2. THEORETICAL ANALYSIS

A schematic diagram is shown in Figure 1. The radially polarized multi Gaussian beam is focused through an annular...
The annular Multi-Gaussian beams consist of a small sum of finite-width annular Gaussian beams side by side each of which represents an intuitive component of the entire beam. On the basis of the vector diffraction theory [20] the electric field of the radially polarized beam in the focal region can be expressed as [5,8] 

\[ E_r, z = A \int_{\delta_0}^{\alpha} \cos^m \theta P \theta \sin \theta e^{ikz \theta} d\theta \rightarrow (2) \]

\[ E_r, z = 2iA \int_{\delta_0}^{\alpha} \cos^m \theta P \theta \sin^2 \theta J_n k r \sin \theta e^{ikz \theta} d\theta \rightarrow (3) \]

Where \( \delta \) distinguishes the presence or absence of annulus and \( k = 2\pi/\lambda \) 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. \( P(\theta) \) describes the amplitude-modulated annular multi-Gaussian beam, this function is given by [17]

\[ P(\theta) = \left( \frac{\theta}{\theta_0} \right)^m \sum_{n=-N}^{N} \exp \left[-\left(\frac{\theta - \theta_0 - n\theta_0}{\theta_0}\right)^2\right] \rightarrow (4) \]

Here, \( \theta \) is the converging semi-angle. We denote the maximum converging semi-angle as \( \theta_{\text{max}} \) which is related to objective numerical aperture by \( \alpha = \arcsin (\text{NA}) \). \( \theta_0 \) is an angle which, along with integer \( m \), determines the shape of the modulation function. \( \theta_0 \) is usually chosen to be slightly smaller than \( \alpha \). \( \theta_0 \) determines the radial position translation of the \( P(\theta) \). Here, we take \( \theta_0 = \alpha/2 \), \( w_0 \) is the waist width of single Gaussian beam which is calculated by the following formula

\[ \omega_0 := 1/2 \times \frac{\alpha}{N + \left(1 - \ln \left[ \sum_{n=-N}^{N} \exp(-n^2) \right] \right)^{1/2}} \rightarrow (5) \]

For all calculation in the length unit is normalized to \( \lambda \) and the energy density is normalized to unity. Figure 2, illustrates the evolution of three-dimensional light intensity distribution of high NA lens for the incident plane radially polarized beam without annular abstraction. The total intensity distribution in the \( r-z \) plane has shown in Figure 2(a) reveals that the generated focal segment is a focal spot. It is observed From Figures 2(b & c) we measure the radial component is 36% of the total intensity and the FWHM of the focal spot is 0.76\( \lambda \) and its corresponding focal depth is 1.7\( \lambda \) respectively. However, Figures 3(a-c) shows generated focal segment for the incident radially polarized amplitude modulated annular multi Gaussian beam with \( \theta_0 = 60^\circ \) and \( \theta = \alpha / 2 \), \( w_0 = 0.02710 \), \( N = 20 \) and \( m = 40 \). Since the focal depth of the focal segments is found to be much smaller and many application demands longer focal depth. However, the presence of an annular aperture with the annular apodization with \( \delta = 0.75 \) is adapted and the results are reported in Figure.3. The total

Figure 2 (a) Density plot for the total intensity distribution in the \( r-z \) plane. (b) Normalized two dimensional total intensity distributions at \( z = 0 \) (c) The axial intensity distribution at \( r=0 \) for high NA lens without annular abstraction.

3. RESULTS AND DISCUSSION

We perform the integration of Eq.(1) numerically for \( \text{NA}=0.9 \) and \( \lambda =1 \), \( \alpha = \arcsin (\text{NA}) \). Here, for simplicity, we assume that the refractive index \( n = 1 \) and \( A = 1 \). It is obvious that some parameters of the focusing system affect the intensity distribution remarkably. We focus on the influence of the parameter \( \delta \) on the focused intensity distribution. For all calculation in the length unit is normalized to \( \lambda \) and the energy density is normalized to unity. Figure 2, illustrates the evolution of three-dimensional light intensity distribution of high NA lens for the incident plane radially polarized beam without annular abstraction. The total intensity distribution in the \( r-z \) plane has shown in Figure 2(a) reveals that the generated focal segment is a focal spot. It is observed From Figures 2(b & c) we measure the radial component is 36% of the total intensity and the FWHM of the focal spot is 0.76\( \lambda \) and its corresponding focal depth is 1.7\( \lambda \) respectively. However, Figures 3(a-c) shows generated focal segment for the incident radially polarized amplitude modulated annular multi Gaussian beam with \( \theta_0 = 60^\circ \) and \( \theta = \alpha / 2 \), \( w_0 = 0.02710 \), \( N = 20 \) and \( m = 40 \). Since the focal depth of the focal segments is found to be much smaller and many application demands longer focal depth. However, the presence of an annular aperture with the annular apodization with \( \delta = 0.75 \) is adapted and the results are reported in Figure.3. The total
intensity distribution in the r–z plane shown in Figure 3(a) reveals that the generated focal segment is a strong longitudinal focal spot. It is observed from the Figure 3(b) and 3(c) show that the FWHM of the generated focal spot as 0.58λ and its focal depth much improved and is measured as 26 λ respectively. The generated focal depth (DOF) is much larger than the previously proposed methods [4,5,8]. Moreover, it is observed from the Figure (3b) that the radial component is only 20% of the total intensity. However, for the case of 0.75, the FWHM of the focal spot along the dark channel is nearly unchanged. Such a needle of longitudinally polarized field with a strong intensity, which can be used to accelerate the particles efficiently [21] and improve coupling light to scanning near-field optical microscopes [22] and focusing in second-harmonic generation polarization microscopy [11]. In Figure 4, we plot the electric energy density profiles of the total field near the focus for the focusing system with m=20 and 30. We find that the increase in the value of m results in the increase of the depth of focus and the FWHM is decrease. It is shown that when m=20, the depth of focus is shortened to 12.5λ and the corresponding FWHM of the focal spot is 0.706λ, and that when m=30, the depth of focus is increase to18λ and the focal spot size is 0.66λ. Hence, we can achieve highly confined longitudinal focal field with very large focal depth which finds application in particle trapping, data storage, biomedical imaging, laser drilling, and machining.

4. CONCLUSION

Based on vector diffraction theory, tight focusing of radially polarized multi gaussian beam by a high NA lens is studied theoretically. The total optical intensity distribution in the focal region is illustrated by numerical calculations without and with annular apodization for different beam parameter
It is observed that the proposed system generates subwavelength focal spot (0.58λ) with large focal depth (26λ). We expect such a beam with small spot size and long focal depth can be widely used in applications such as optical trapping, data storage, biomedical imaging, laser cutting, microscopy and the manipulation of optical traps of high refractive index particles.

**REFERENCE**


