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Multiple Focal Segment Generation of Tightly Focused Non-Diffracting Transversely Polarized Beam with Diffractive Optical Element

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Abstract

The numerical investigation of tightly focused azimuthally polarized LG beam with modulating diffractive optical element (DOE)in the focal region of high NA lens based on the vector diffraction theory is presented in this paper. It is observed, that by controlling the angles of specially designed modulating DOE can generate multiple focal spot segment in the focal region. Such kind of subwavelength focal spot segment may find wide applications in optical traps, biological, atmospheric sciences and optical manipulation technology.

Keywords: *Diffractive Optical Element; Focal spot; Numerical Aperture; Objective lens.*

1. INTRODUCTION

In recent years, the Nondiffracting optical beams have been gaining much research interest for their practical applications in optical data storage (Wang *et al*. 2006; Sun and Liu, 2003) material processing (Erdelyi *et al*. 1997), optical coherencetomography (Liu *et al*. 2007), lithography (Suresh *et al*. 2013; 2014), laser cutting of metals (Suresh *et al*. 2013), particle acceleration (Suresh *et al*. 2014), fluorescent imaging (Biss and Brown, 2003), second harmonic generation (Biss and Brown, 2003; Yew and Sheppard, 2007), Raman spectroscopy (Hayazawa *et al*. 2004), etc,. Over the past few decades, to generate nondiffracting optical beams several methods have been proposed both the theoretical and experimental points of view (Suresh *et al*. 2013). Among these applications, particular interest has been given to the high numerical aperture (NA) focusing property of these beams and their application as a high resolution probe (Suresh *et al.*2013; Suresh *et al.* 2014). Recently, there is an increasing interest in the non-diffracting optical beams, mostly driven by the advances made in micro-fabrication techniques and theoretical modeling techniques that were not available with homogeneous polarization. Such an optical beams lack in generation of beam with long depth of focus (DOF). Several methods have been proposed to enhance the DOF (Suresh *et al*. 2013; Machavariani *et al*. 2007; Sheppard, 2001; Dom *et al*.2003; Suresh *et al*. 2014). The diffractive optical elements have also been used to achieve long DOFs, and they are able to reduce the compromise between the NA and the DOF (Suresh *et al*. 2013, Suresh *et al*. 2013). Nowadays, one of the most important topics among researchers and scientists is the generation of long focal depth with smaller spotor focal hole in the focal region of high NA lens.Recently the sub wavelength multiple focalspot is generated by tightly focused azimuthally polarized Bessel Gaussian beam in the focal region of high NA lens (Suresh *et al.* 2014). In this paper a sub wavelength multiple focal spot in the focal region of tightly focused azimuthally polarized LG beam with DOE is presented. The generated multiple focal spot may find wide applications in optical traps, biological, atmospheric sciences and optical manipulation technology.

2. THEORY

A schematic diagram of the suggested method is shown in Fig.1. Based on vector diffraction theory (Youngworth and Brown, 2000), the total electric field is given as

$$E(r,\phi,z) = E_r + E_\phi + E_z \qquad \text{...1}$$

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The analysis was performed on the basis ofRichards and Wolf's vectorial diffraction method (Richards and Wolf, 2003) widely usedfor high-NA lens system at arbitrary incident polarization.The electric field near the focus of tightly focused azimuthally polarized beam througha high NA lens system can be derived in cylindrical coordinates as

$$E(r,\phi,z)=\begin{bmatrix}E_r\\E_\phi\\E_Z\end{bmatrix}=\begin{bmatrix}-Ae^{i\phi}(I_0+I_2)\\-Ae^{i\phi}(I_0-I_2)\\0\end{bmatrix} \quad ..2$$

Where

$$I_n=\int_0^{\theta_m}\sqrt{\cos\theta}\sin\theta P(\theta)l_0(\theta)\exp(ik_0 z\cos\theta)J_n(k_0 r\sin\theta)d\theta$$

...3

Were θ_m represents maximum focal angle ($\theta_m = \alpha = arcsin\ (NA)$), where NA is the numerical aperture of high NA lens (NA = 0.95), K_0 is the wave number in free space,$J_n(\theta)$ denotes the nth-order Bessel function of the first kind and $l_0(\theta)$ denotes the apodization function of the LG_{11} beam, which is given as (Suresh et *al*. 2013; Youngworth and Brown *et al*. 2000),

$$A(\theta)=\beta^2\frac{\sin\theta}{\sin^2\theta}\exp\left[-\left(\beta\frac{\sin\theta}{\sin\alpha}\right)^2\right]L_p^1\left[2\left(\beta\frac{\sin\theta}{\sin\alpha}\right)^2\right] \quad ....4$$

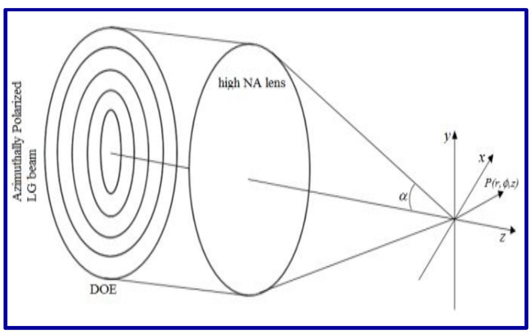

Fig.1: Schematic diagram of proposed system.

3. RESULT

In this article, we describe a numerical study, based on vector diffraction theory, the total electric field intensity distribution in the focal plane in the case of an ordinary spiral phase mask is calculated. We perform the integration of Eq. (1) numerically using parameters $P(\theta) = 1$, $\lambda = 1$, $NA=0.95$ and the wave number $k = 2\pi/\lambda$. r and z are the radial and z coordinates of observation point in focal region respectively. Here, for simplicity,we assume that the refractive index $n = 1$and $A = 1$.For all calculation in the length unit is normalized to λ and the energy density isnormalized to unity. The intensity profiles of the total electric field in the focal region of tightly focused azimuthally polarized beam are illustrated in Fig.2 and are in good agreement with Fig. 2 in (Yuan *et al.* 2011). Fig. 2 (a) shown the three dimensional total electric field contour profile of incident beam without any optical element with depth of focus (FWHM 1.38λ), corresponding focal spot size (FWHM 0.544λ) and it is shown in Fig 2. (b) and Fig 2. (c) respectively. Fig 2. (b) Shows the normalized two dimensional total electric field intensity distribution at r = 0λ and Fig 2. (c) Shows the normalized two dimensional total electric field intensity distribution at z = 0λ.

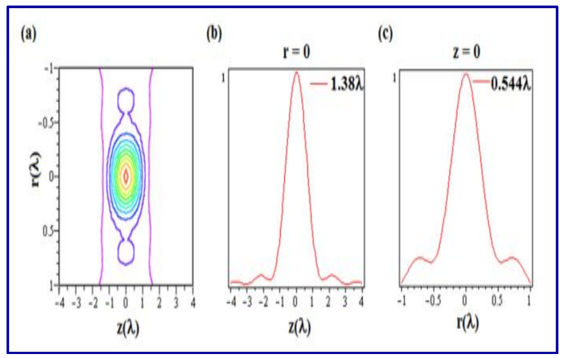

Fig. 2: Total electric field intensity distribution (a). Contour profile, (b). normalized two dimensional intensity distribution at r = 0 and (c). normalized two dimensional intensity distribution at z = 0.

Based on the above explicit formula (Eq. 1), we aimed to generate a beam with multiple focal spot in the focal region along optical axis. Thus, to have a "good" multiple focal spot of transversely polarized beam one should suppress the radial field component. We show that this is possible to do with additional phase modulation. A schematic diagram of the suggested method is shown in Fig.1. The effect of phase modulation on the tightly focused input azimuthally polarized beam by the high-NA lens is calculated numerically by replacing the function $P(\theta)$ by $P(\theta)T(\theta)$, where $T(\theta)$ is given by

$$T(\theta)=\begin{cases}1 & for \quad \theta_1\le\theta<\theta_2\\0 & for \quad 0\le\theta<\theta_1,\theta_2\le\theta<\theta_3\\-1 & for \quad \theta_3\le\theta<\alpha\end{cases} \quad ...5$$

The set of angles of specially designed optical element is optimized for the above mentioned focal segment using traditional Global Search Algorithm (Suresh *et al.*2014). Based on these algorithm we choose one structure with random values for θ_1 to θ_3 from all possibilities and simulate their focusing properties by vector diffraction theory. If the structure generates a sub wavelength multiple focal spot and satisfies the limiting conditions of side lobe intensity less than 15%, it is chosen as the initial structure during the optimization procedures. In the following steps, we continue to vary θ of one chosen zone to generate a multiple focal spot on axial focal field until generation of uniform intensity profile without affecting the limiting condition. In order to generate multiple focal spot we tuned the angles of specially designed phase modulating optical element ant it is shown in below figures. Generation of two focal spot intensity profiles of the total electric field in the focal region of tightly focused azimuthally polarized beam are illustrated in Fig.3. The three dimensional total electric field contour profile of incident phase modulated optical beam at the focus with angles θ_1=40.3°, θ_2=60.3°and θ_3=70.3°, is shown in Fig 3 (a) each focal spot having depth of focus (FWHM 1.38λ), corresponding focal spot size (FWHM 0.544λ) along optical axis, Fig 3 (b) Shows the normalized two dimensional total electric field intensity distribution at r = 0λ.

Fig. 4 shows the generation of three focal spot intensity profiles of the total electric field in the focal region of tightly focused azimuthally polarized beam are illustrated. The three dimensional total electric field contour profile of incident phase modulated optical beam at the focus with angles θ_1=32.1°, θ_2=52.2° andθ_3=60.3°, is shown in Fig 4 (a) with each focal spot having depth of focus (FWHM 1.32λ), corresponding focal spot size (FWHM 0.45λ) along optical axis. Fig 4 (b) Shows the normalized two dimensional total electric field intensity distribution at r = 0λ.

Fig 5. Shows the generation of fivefocal spot intensity profiles of the total electric field contour profilein the focal region of incident beam along optical axis with angles θ_1=39.8°, θ_2=49.5, and θ_3=69.3°. Fig 5 (a) shows the three dimensional contour profile with each focal spot having depth of focus (FWHM 1.32λ), corresponding focal spot size (FWHM 0.45λ) along optical axis. Fig 5 (b) Shows the normalized two dimensional total electric field intensity distribution at r = 0λ.

We further tuned the angles of specially designed DOE to generate multiple spot along optical axis and it is shown in Fig 6 with angles θ_1=49.3°, θ_2=50.3° and θ_3=71.5°.

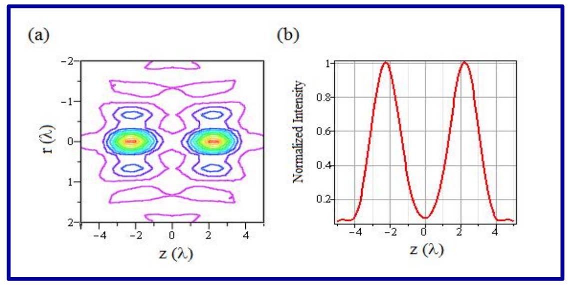

Fig. 3: Same as Fig 2. in the case of specially designed diffractive optical element with angles θ_1=40.3°, θ_2=60.3°, and θ_3=70.3°

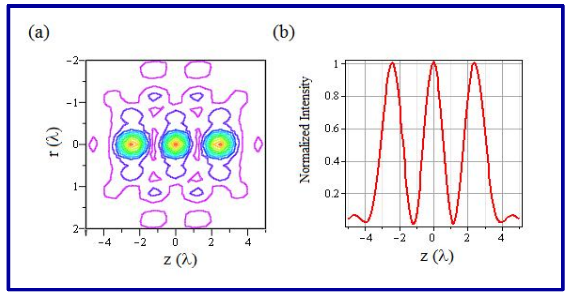

Fig. 4: Same as Fig 3. with angles θ_1=14.3, θ_2=26.5, θ_3=58.5, and θ_4=65.0

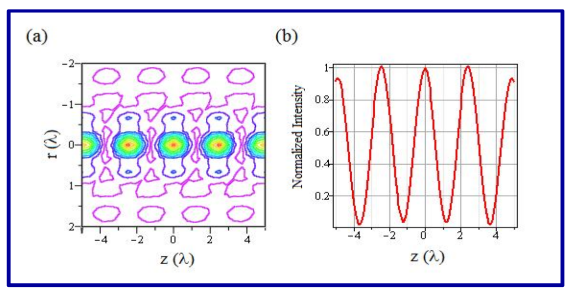

Fig. 5: Same as Fig 3. with angles θ_1=14.3, θ_2=26.5, θ_3=58.5, and θ_4=65.0

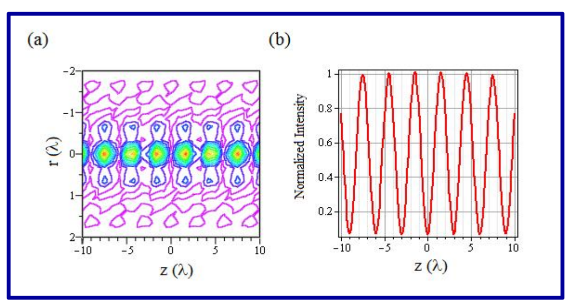

Fig. 6: Same as Fig 3. with angles θ_1=14.3, θ_2=26.5, θ_3=58.5, and θ_4=65.0

Fig 6 (a) shows the three dimensional contour plot with six focal spot. Fig 6 (b) shows the normalized two dimensional intensity profile at $r = 0$ with each spot having DOF (FWHM 1.18λ) and spot size (FWHM 0.86λ) respectively.

From the above analysis, we say that it is possible to generate the required no of multiple focal spot each having equal DOF and spot size by properly adjusting the angles of specially designed diffractive optical element. The above numerical calculations show that, by utilizing the DOE to modulate the phase of incident beam, the optical spot in the focal region canbe used as a powerful toolfor particle manipulation. Here, each particlein the focal spot is three dimensionally trappedseparatelywith a small space along z axis.In addition, multi focal spots can be able to trap multi particles synchronously. It's simple and flexible method of forming multiple focal spot in sub wavelength size introduced in this paper.This type of beam profile is useful in particle manipulation and optical trapping for high refractive index and low refractive index particles can be achieved precisely and controllablyto generate multiple focal spot

4. CONCLUSION

Based on Vector diffraction theory, the total electric field intensity distribution in the focal region of tightly focused phase modulated non-diffracting azimuthally polarized LG beam is studied numerically. By tuning the angles of DOE, a multiple focal spot segment isgenerated in the sub-wavelength scale and it is shown in above figures which finds wide applications in optical tweezers, micromanipulation, microscopy and optical data storage.

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