



Generation of multiple focal hole segment by tight focusing of azimuthally polarized double ring shaped beam

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Abstract

Based on the vector diffraction theory, the effect of phase modulation on the intensity distribution of TEM₁₁ mode azimuthally polarized Laguerre-Gaussian beam in the focal region of high NA lens is investigated theoretically. It is observed that a properly designed complex phase filter can generate multiple focal hole segment and it is useful for the manipulation of optical traps.

Keywords : polarized double ring shaped beam, radial electric field component

1. INTRODUCTION

Growing interest in the generation of three-dimensional (3-D) optical beams that are dark regions in space surrounded by light are driven by wide ranging applications including dark optical traps for atoms (N. Friedman et.al. 2002), manipulation, guiding and binding of micro-particles and biological cells (T.Cizmar et.al. 2012), erase beams for super-resolution fluorescence microscopy (T. Watanabe et.al. 2003), etc. Over the past years, a variety of techniques have been proposed for generating such optical bottle beams for applications in optical tweezers and atom traps (J. Arlt et.al. 2000, B. Ahluwalia et.al. 2004, P. Rudy et.al. 2001; D. Yelin et.al. 2004; J.X.Pu et.al. 2005; L.Isenhower et.al.2009; P.Xu et.al. 2010;V.G.Shvedov et.al 2010). However, stable trapping of a single particle is expected if we can make the bottles small enough and comparable to the particlesize. Such “microbottles” were established recently with the volume speckle field (B. Tian, et.al 2011). Recently, a sub wavelength focal hole (0.5 λ) with a quite long depth of focus (48 λ)

is achieved near the focus by tight focusing of double ring shaped azimuthally polarized beam with high NA lens axicon (K. Lalithambigai et.al 2012). The objective of the study reported in this Letter is to investigate the effect of complex phase filter in the focal properties of the tightly focused azimuthally polarized double ring shaped beam. We observe that our proposed system generates a sub wavelength multiple focal holes. We also observed that by properly designing the complex phase filters one can achieve many novel focal patterns including splitting of focal rings and generation of multi ring structures.

2. THEORY

A schematic diagram of the suggested method is shown in (Fig 1). The analysis was performed on the basis of Richards and Wolf’s vectorial diffraction method widely used for high-NA focusing systems at arbitrary incident polarization (B. Richards et.al. 1959). Shown in (Fig. 1), if a complex pupil filter is placed at the pupil plane, where the polarized states of the incident beams in the area of inner and outer rings are reverse, so as to cause the destructive interference in the focal region. In the case of the

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$$E(r, \varphi, z) = \begin{bmatrix} E_r \\ E_\varphi \\ E_z \end{bmatrix} = \begin{bmatrix} -Ae^{i\phi} (I_0 + I_2) \\ -iAe^{i\phi} (I_0 - I_2) \\ 0 \end{bmatrix} = \begin{bmatrix} A \int_0^\alpha \cos^{\frac{1}{2}}(\theta) \sin(2\theta) A(\theta) J_1(kr \sin \theta) e^{ikz \cos \theta} d\theta \\ 2A \int_0^\alpha \cos^{\frac{1}{2}}(\theta) \sin(\theta) A(\theta) J_1(kr \sin \theta) e^{ikz \cos \theta} d\theta \\ 0 \end{bmatrix} \rightarrow (1)$$

Fig. 1. (black and gray line) Schematic Diagram of the proposed system. Azimuthally polarized double ring shaped beam passes through a multibelt spiral complex filter and is subsequently focused by a high-NA lens.

azimuthally incident polarization, adopting the cylindrical coordinates r, z, ϕ and the notations.

Where NA is the numerical aperture for $\alpha = \arcsin(NA/n)$ and n is the index of refraction between the lens and the sample. $J_0(x)$ and $J_1(x)$ denote the Bessel functions of the first kind of orders 0 and 1, respectively. The function $A(\theta)$ describes the amplitude modulation.

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

For illumination by a double ring-shaped R-TEM11* beam with its waist in the pupil, this

function is given by (K. B. Rajesh et.al 2008). Where β is the parameter that denoted the ratio of pupil diameter to the beam diameter and L_p is the generalized Laguerre polynomial. If $p=1$, the incident azimuthally polarized beam is a double-ring azimuthally polarized. It is seen from Eq. (1) that an additional radial electric field component is produced after introducing the phase filter (G. H. Yuan, et.al 2011). Owing to this radial component, the polarization near the focal plane is rather complicated and space variant.

3. RESULTS

We perform the integration of Eq. (1) numerically using parameters $\lambda=1$, $\beta=1.4$ and NA of the objective is 0.9. Here, for simplicity, we assume

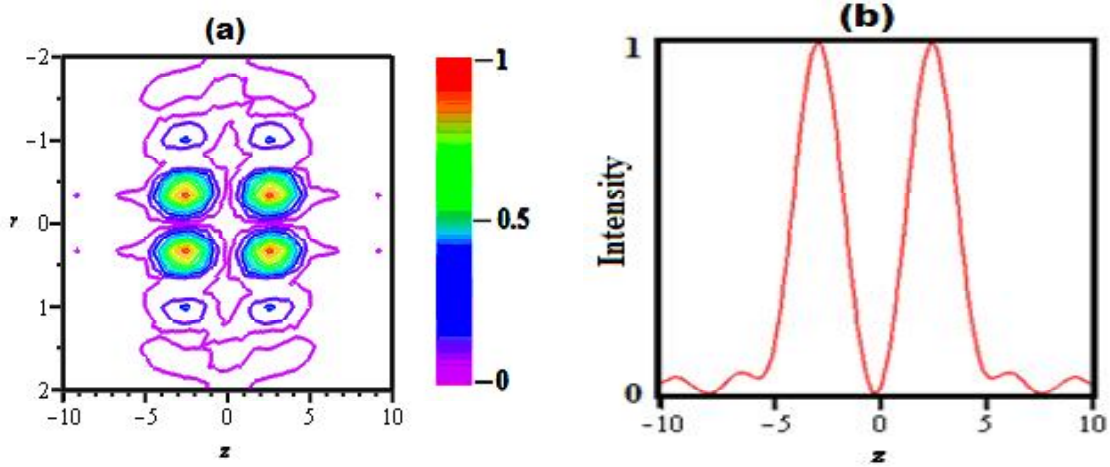


Fig 2. (a) Shows the contour plot of the total intensity distribution in the yz plane near the focus for the focusing system with complex phase filters. (b) Shows on axial intensity distribution ($E_r + E_\phi$) at $r=0.3\lambda$.

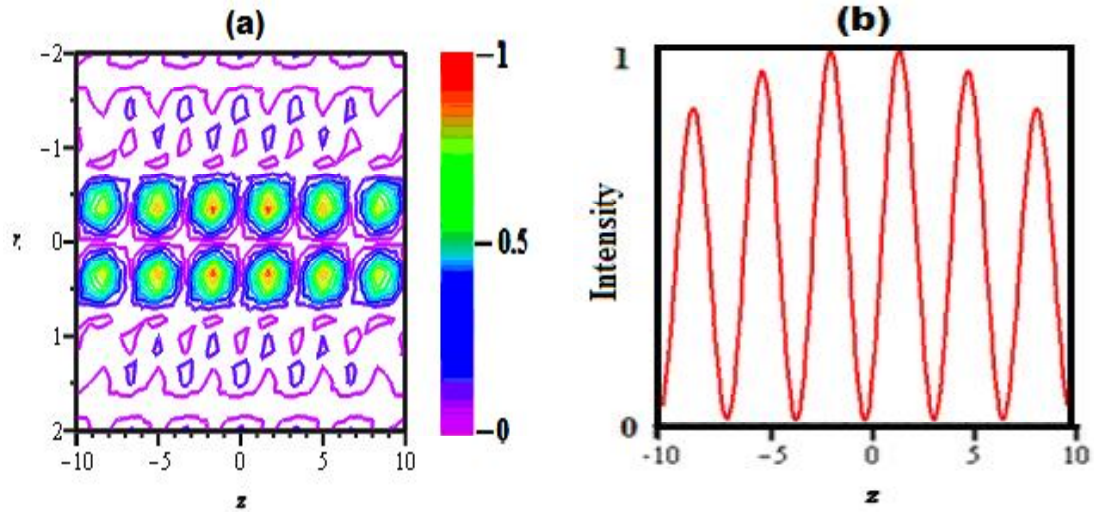


Fig. 3. (a) The contour plot of total intensity distribution for the focusing system. (b) Shows an on axial intensity distribution ($E_r + E_\phi$) at $r=0.3\lambda$.

that the refractive index $n=1$ and $A=1$. The effect of complex filter on the input azimuthally polarized double ring beam is evaluated by replacing the function $A(\theta)$ by $A(\theta) CF(\theta)$ where $CF(\theta)$ is given by

$$CF(\theta) = \begin{cases} 0, & \text{for } 0 < \theta < \theta_1, \theta_2 < \theta < \theta_3, \\ 1, & \text{for } \theta_1 < \theta < \theta_2, \\ -1 & \text{for } \theta_3 < \theta < \alpha \end{cases} \quad (3)$$

Fig (2-a) shows the total intensity distribution of the focal hole segment generated by the proposed high NA lens in combination with dedicated complex phase filter (CPF). Such a sub wavelength super long dark channel may find applications in optical, biological, and atmospheric sciences. Fig (2-a) shows the splitting of focal hole segment generated by the high NA lens for the complex filter with $\theta_1 = 35.82^\circ$, $\theta_2 = 54.83^\circ$ and

$\theta_3=61.91^\circ$. It is observed from the figure that the FWHM of each ring is 0.374λ .

The axial distance between two ring structures is 5.2λ and is shown in Fig. (2-b). Fig (3-a) shows the array of focal hole segment generated by the high NA lens for the complex filter with $\theta_1=40.82^\circ, \theta_2=42.83^\circ$ and $\theta_3=61.91^\circ$. From the figure we measure the FWHM of each ring is 0.372λ and are separated by the axial distance of 3.8λ between them.

The on axial intensity of the generated focal hole segment at $r = 0.3\lambda$ is shown in fig (3-b). It is observed from the figure that the focal hole near focus and the one at the extreme end ($z=10\lambda$) is only 0.90%. Hence it is possible to generate multiple focal hole segment with almost uniform intensity.

4. CONCLUSION

In conclusion the generation of sub wavelength super long focal hole segment is demonstrated for the proposed high NA lens and a dedicated complex phase filter. We have also showed the possibility of generated multiple sub wavelength focal hole segment through properly designed complex phase filter. The authors expect the proposed work to find its application in manipulation of optical traps.

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