J. Environ. Nanotechnol.
Volume 4, No.1 (2015) pp. 76-79
ISSN (Print): 2279-0748
ISSN (Online): 2319-5541
doi: 10.13074/jent.2015.03.144117

Effect of Pupil Beam in the Focal Region of High Numerical Aperture Objective Lens

C. Amala Prathiba Janet[1], P. Suresh[2*] and T. V. S. Pillai[3]

[1]*Department of Physics, St.Xavier's Catholic College of Engineering, Nagercoil, TN, India.*
[2]*Department of ECE, National College of Engineering, Tirunelveli, TN, India.*
[3]*Department of Physics, University College of Engineering, Nagercoil, TN, India*

Received: 25.12.2014 Accepted: 28.01.2015 Published: 30-03-2015

Abstract

In this article, based on vector diffraction theory the focusing properties of double ring shaped higher order Laguerre – Gauss beam with radial varying polarization are investigated numerically. The numerical simulations show that the evolution of some interesting focal spot, focal split and focal patterns in the focal region by changing polarization rotation angle under tight focusing through the high NA lens. It is also shown that a subwavelength focal hole with a quite long depth of focus, multiple focal holes are achieved near the focus, when tuning β (is the ratio of the pupil radius to the beam waist) in the focal plane for different modes under tight focusing through the high NA lens. We found that when tuning, beam parameter or the polarization rotation angle of the incident beam, it is possible to generate some interesting novel focal patterns, including multiple intensity rings, dark hollow focus and cylindrical crust focus. Such kind of beams plays an important role in optical trapping, laser cutting and optical manipulation applications.

Keywords: *High NA lens; Polarization; Focal Pattern; Optical Trapping.*

1. INTRODUCTION

In recent years, the Optical tweezers technique has become a valuable tool and accelerated many major advances in numerous areas of science. Ashkin and coworkers accomplished optical tweezers experimentally (Ashkin *et al.* 1986). In many optical systems, the Intensity distribution in the focal region plays an important role (Rittweger *et al.* 2009). The intensity in the focal field is the forces that acting on the particles in light field includes two kinds of forces. The first one is the gradient force that is proportional to intensity gradient. The other one is the scattering force proportional to optical intensity (Visscher *et al.* 1992). Zhan and Leger (Zhan *et al.* 2002) reported a focus shaping technique using generalized cylindrical vector beams, in which a generalized cylindrical vector beam can be decomposed into radially polarized and azimuthally polarized components. Some of the applications of these beams include optical guiding and trapping, metal cutting, determination of the orientation of single molecules (Zhan *et al.* 2002). For the azimuthal polarization counterpart, a nondiffracting "dark channel" with a long DOF was recently achieved by tight focusing of a double-ring-shaped azimuthally polarized beam. Central zero intensity is also useful in optical trapping (Kuga *et al.* 1997) and lithography (Suresh *et al.* 2013). Therefore, the polarization distribution affects the focus shape very considerably. For controllable optical trapping we are in need to design a system with tunable optical intensity distribution in the focal region. To generate tunable optical intensity distribution in the focal region, we used double-ring-shaped radially polarized mode R-TEM11* beam. Recently, it has been observed that the double-ring-shaped radially polarized mode R-TEM11 *beam can effectively reduce the focal spot size (Levenson *et al*. 2004; Kozawa *et al.* 2006) and it is also observed experimentally that it is possible to generate directly from a laser cavity (Kozawa *et al.*

***P. Suresh** *Tel. no:+919442264501*
Email: suresh3982@yahoo.co.in

2007). Recently, focus shaping of Bessel–Gauss beam with radial varying polarization was discussed in detail (Moser *et al*. 2005). In the present paper, the focusing properties of double-ring-shaped radially polarized mode R-TEM11* beam with radial varying polarization are investigated in detail. In Section 2, the principle of the focusing system is given. In section 3, we discussed about the numerical evolution and its results of the proposed system in detail and conclusions are given in Section 4.

2. THEORY

According to the vectorial Debye theory, the double ring shaped radially polarized mode R-TEM11* beam with radial varying polarization of tightly focused through a high NA objective lens, by using the same analytical method as that in references, the electric field E (r, φ, z) near the focus can be written as (Kuga *et al.* 1997; Moser *et al*. 2005)

$$E(r,\varphi,z) = E_r e_r + E_\varphi e_\varphi + E_z e_z, \qquad (1)$$

Where e_r, e_φ and e_z are the unit vector are the unit vectors in the radial, azimuthal, and propagating directions, respectively; E_r, E_φ and E_z are the three orthogonal components of the electric fields and can be written as

$$E_r(r,z) = A\cos(\phi)\int_0^\alpha \sqrt{\cos(\theta)}\sin(2\theta)l(\theta)J_1(kr\sin\theta)\exp(ikz\cos\theta)d\theta, \qquad (2.a)$$

$$E_\varphi(r,z) = 2A\sin(\phi)\int_0^\alpha \sqrt{\cos(\theta)}\sin(\theta)l(\theta)J_1(kr\sin\theta)\exp(ikz\cos\theta)d\theta, \qquad (2.b)$$

$$E_\varphi(r,z) = 2iA\cos(\phi)\int_0^\alpha \sqrt{\cos(\theta)}\sin^2(\theta)l(\theta)J_0(kr\sin\theta)\exp(ikz\cos\theta)d\theta, \qquad (2.c)$$

where rand z are the radial and propagating coordinates of observation point in focal region, respectively; k is the wave number, *l(θ)* is TEMP1 mode Laguerre–Gaussian beam, its relative amplitude can be expressed as [7, 11]

$$l(\theta) = \beta^2 \frac{\sin\theta}{\sin^2\alpha}\exp\left[-\left(\beta\frac{\sin\theta}{\sin\alpha}\right)^2\right] L_p^1\left[2\left(\beta\frac{\sin\theta}{\sin\alpha}\right)^2\right], \qquad (3)$$

Where *α= arcsin (NA),* NA is the numerical aperture of the optical system. It should be noted that the beam parameters β is defined as the ratio of the pupil radius to the beam waist and L^1_P is the generalized Laguerre polynomial. For TEM11* mode LGBs, *P*=1. ϕ is the polarization rotation angle from radial direction, in this article, ϕ is the function of convergence angle θ, and is written as (Gao *et al.* 2010),

$$\phi = \left(C\left(\frac{\sin(\theta)}{\sin(\alpha)}\right)\pi \right), \qquad (4)$$

Where C is polarization parameter that indicates the speed of change of polarization angle. The optical intensity distribution in focal region is proportional to the modulus square of Eq. (1). Based on this equation, the focus shape can be investigated numerically.

3. RESULT

Without loss of validity and generality, based on vector diffraction theory, Eq. (1) is calculated numerically same as using parameters *A = 1, k = 2π/λ* and *λ = 1* for simplicity. It was supposed that the intensity distributions in the focal region of tightly focused double ring shaped radially polarized mode R-TEM11* beam with radial varying polarization is calculated for different polarization parameter *C*, we also studied the effect of pupil beam parameters *β* and numerical aperture NA and it is shown in below figures, the unit of coordinates in all figures is in wavelength. Firstly, we studied numerically the effect of lower NA (NA = 0.95) for different pupil beam (β = 1.3 and 1.8). Figure 1 shows the effect of different polarization *C* for *β = 1.3* and *NA = 0.95*. When *C = 0*, there is a six focal spot in the focal region of total electric field intensity distribution of the high NA lens with central intensity is zero shown in Figure 1 (a). However, upon increasing (*C = 0.5*) the focal spot in radial direction at *z = 0* starts disappears and it is shown in Figure 1 (b). On increasing C, the focal spot extends in transverse direction, and then one intensity spot changes into long focal depth with FWHM (> 4λ) each at (*r* = ± *1λ*) and it is shown in Figure 1 (c). When the parameter *C* increases continuously, the DOF of the focus increases firstly, and then decreases remarkably and forms two focal spot in radial direction it is shown in Figure 1 (d - f). In order to show the intensity more clearly for the pupil beam parameter for same NA and different C, then β is increased to 1.3 and 1.8 and their corresponding total electric field intensity profile is shown in Figure 3 respectively.

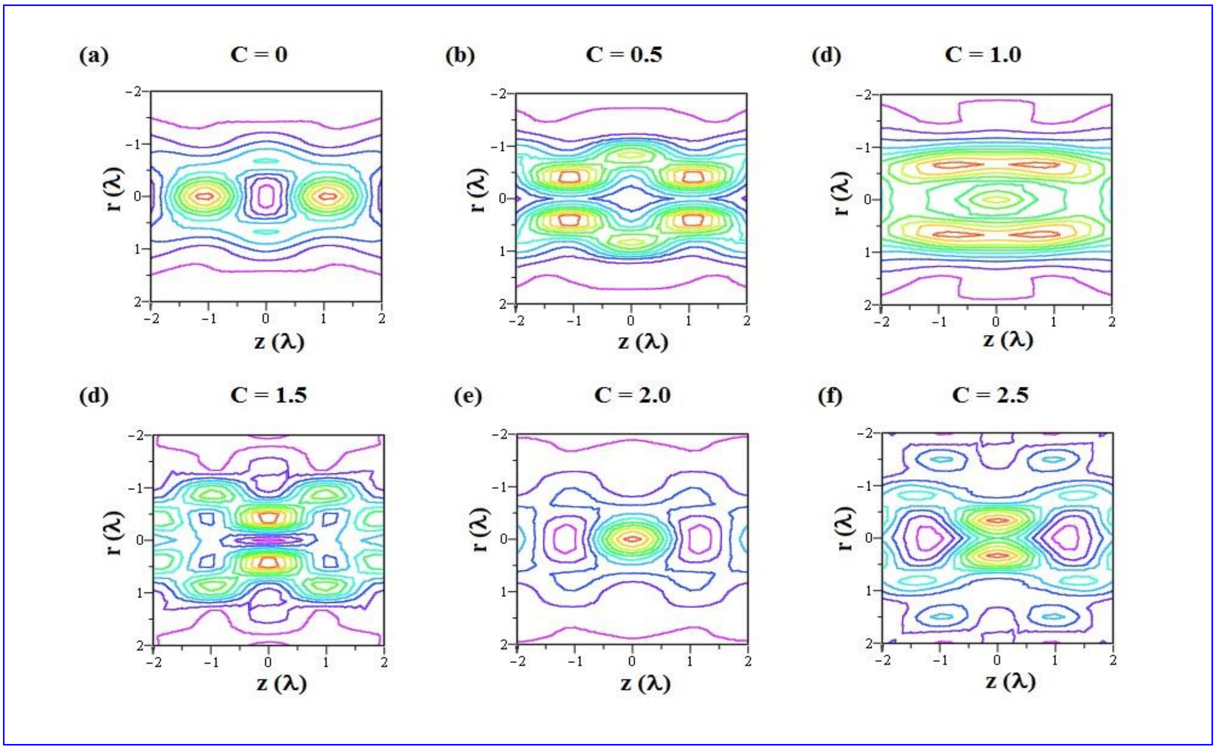

Fig. 1: Total electric field intensity profile for different C, NA = 0.95 and β = 1.3

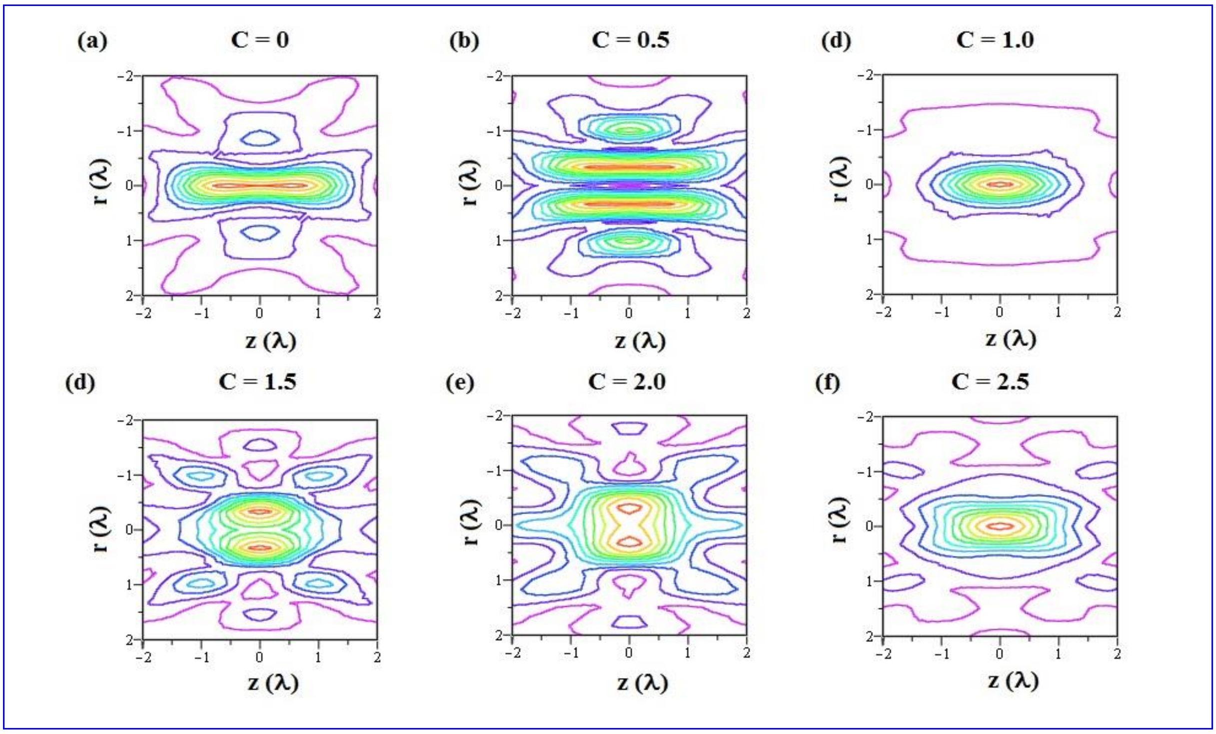

Fig. 2: Total electric field intensity profile for different C, NA = 0.95 and β = 1.8

From the above focal pattern evolution, it can be seen that the pupil beam parameter β, polarization parameter C that indicates the speed of change of polarization angle and numerical aperture NA affects focal pattern considerably, and some novel focal patterns occur, which may be used in optical tweezers technology.

4. CONCLUSION

The tight focusing properties of double ring shaped higher order Laguerre – Gauss beam with radial varying polarization are investigated numerically. It is observed that the total electric field intensity distribution in focal region can be altered considerably by the pupil beam parameter (β), numerical aperture (NA) and polarization parameter (C) that indicates the polarization change speed along radial direction. In the focal pattern evolution process by choosing the proper combination of the above parameters, some novel focal patterns may appear, cylindrical crust focus, dark hollow focus, including multiple intensity rings, the required focal structure can be obtained in the focal region of the high NA objective lens. These focusing properties may be useful in constructing optical traps, optical manipulation, laser machine and lithography.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Ashkin, A., Dziedzic, J. M., Bjorkholm, J. E. and Chu, S., Observation of a single-beam gradient force optical trap for dielectric particles, Opt. Lett., 11(5), 288–290 (1986).
doi:10.1364/OL.11.000288

Rittweger, E., Kyuyounghan, Irvines, E., Eggling, C. and Hells, W., STED microscopy reveals crystal colour centres with nanometric resolution, Nature Photonics, 3 (3), 144–147 (2009).
doi:10.1038/nphoton.2009.2

Visscher, K. and Brakenhoff, G. J., Theoretical study of optically induced forces on spherical particles in a single beam trap I: Rayleigh scatterers, Optik 89, 174–180 (1992).

Zhan, Q. and Leger, J. R., Focus shaping using cylindrical vector beams, Opt. Express, 10(7), 324–331 (2002).
doi:10.1364/OE.10.000324

Kuga, T., Torii, Y., Shiokawa, N., Hirano, T., Shimizu, Y. and Sasada, H., Novel optical trap of atoms with a doughnut beam, Phys. Rev. Lett., 78(25), 4713–4716 (1997).
doi:10.1103/PhysRevLett.78.4713

Suresh, P., Mariyal, C., Sivasubramonia Pillai, T. V., Rajesh, K. B. and Jaroszewicz, Z., Study on polarization effect of azimuthally polarized LG beam in high NA Lens system, Optik, 124(21), 5099– 5102 (2013).
doi:10.1016/j.ijleo.2013.03.139

Levenson, M. D., Ebihara, T., Dai, G., Morikawa, Y., Haayashi, N. and Tan, S. M., Optical vortex masks for via levels, Microlithogr. Micofabr. Microsyst., 3(2), 293-304 (2004).

Kozawa, Y. and Sato, S., Focusing property of a double-ring-shaped radially polarized beam, Opt. Lett., 31(6), 820–822 (2006).
doi:10.1364/OL.31.000820

Kozawa, Y. and Sato, S., Sharper focal spot formed by higher-order radially polarized laser beams, J. Opt. Soc. Am. A., 24(6), 1793 – 1798 (2007).
doi:10.1364/JOSAA.24.001793

Moser, T., Glur, H., Romano, V., Pigeon, F., Parriaux, O. and Ahmed, M. A., Polarization- selective grating mirrors used in the generation of radial polarization, Appl. Phys. B., 80(6), 707–13 (2005).
doi:10.1007/s00340-005-1794-5

Gao, X., Fu, R., Shen, H., Dong, X., Geng, T. and Zhuang, S., Focus shaping of Bessel–Gauss beam with radial varying polarization, Optica. Applicata., 42(3), 481– 491 (2012).

Gao, X., Hu, S., Li, J. S., Ding, Z. H., Guo, H. M. and Zhuang, S. L., Tunable optical gradient trap by radial varying polarization Bessel–Gauss beam, J. Biomedical Science and Engineering 3(5), 304–307 (2010).
doi:10.4236/jbise.2010.33041