



Tight Focusing of Radially Polarized Pair of Vortices Beam through a Dielectric Interface

C. A. P. Janet¹, M. Udhayakumar², K. B. Rajesh^{2*}

¹Department of Physics, St.Xavier's Catholic College of Engineering, Nagercoil, TN, India

²Department of Physics, Chikkanna Government Arts College, Trippur, TN, India

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*rajeshkb@gmail.com

ABSTRACT

Tight focusing properties of radially polarized Gaussian beam with a pair of vortices through dielectric interface is theoretically investigated by vector diffraction theory. For an incident beam with a pair of vortices of opposite topological charges, the vortices move toward each other, annihilate and revive in the vicinity of the focal plane, which results in the generation of many novel focal patterns. The usable focal structures generated through the tight focusing of the double-vortex beams may find applications in micro-particle trapping, manipulation, Nano material processing etc.

Keywords: Dielectric interface; Radially polarized *Gaussian beam*.

1. INTRODUCTION

In researches, the incident light is focused into a uniform medium of refractive index n . However, in many practical applications, an objective is used to focus an incident light beam through an interface between different media of different refractive index. For instance, in the case of laser trapping, a light beam is focused through an interface between glass and water (Ke and Gu, 1998). After that, many researches on the focusing of light beams through dielectric interfaces have been carried out (Biss and Brown, 2001; Wiersma *et al.* 1997; Helseth, 2001; Petrov, 2004; Petrov, 2005). Biss and Brown discussed the focusing of cylindrical vector beams (CVBs) through a dielectric interface (Biss and Brown, 2001). Zhang *et al.* presented the tight focusing of radially and azimuthally polarized vortex beams through a dielectric interface and a uniaxial birefringent crystal, respectively (Zhang *et al.* 2008a; Zhang *et al.* 2008b). Moreover, in many practical applications, an objective is used to focus an incident light beam through an interface between different media of different refractive indices. For example, in the application of semiconductor inspection, light beams are focused from the air onto a silicon substrate. Torok *et al.* developed the theoretical method for studying the focusing of an electromagnetic wave through dielectric interfaces. (Torok *et al.* 1995a; Torok *et al.* 1995b; Torok *et al.* 1995c). For its unique properties, tightly focused

light beam. For its unique properties, tightly focused light beams have wide potential applications in optical data storage, microscopy, material processing, micro-particle trapping manipulation, etc. (Zhang *et al.* 2008; Ganic *et al.* 2003; Helseth 2000). On the other hand, a great deal of attention has been given to the research of the vortex beam since 1992. The vortex beam, also known as the helical beam, has a continuous spiral phase wavefront, which carries an orbital angular momentum (OAM) (Allen *et al.* 1992; Stephen *et al.* 1994). In recent years there has been much research on tight focusing of different kinds of vortex beams, such as linearly polarized, circularly polarized, elliptical polarized vortex beams (Zhang *et al.* 2008; Singh *et al.* 2009; Chen and Pu, 2009). An optical vortex dipole (a pair of vortices with opposite topological charges) propagating in a Gaussian beam may produce a variety of possible trajectories different from that of canonical vortex beams.

2. THEORY

Assume the interface between two dielectric media of refractive indices $n_1 = 1$ and $n_2 = 3.55$, such as focusing in the air onto silicon substrate in the application of semiconductor inspection. The geometric focus of the objective without the interface is located at the origin of the coordinate system.

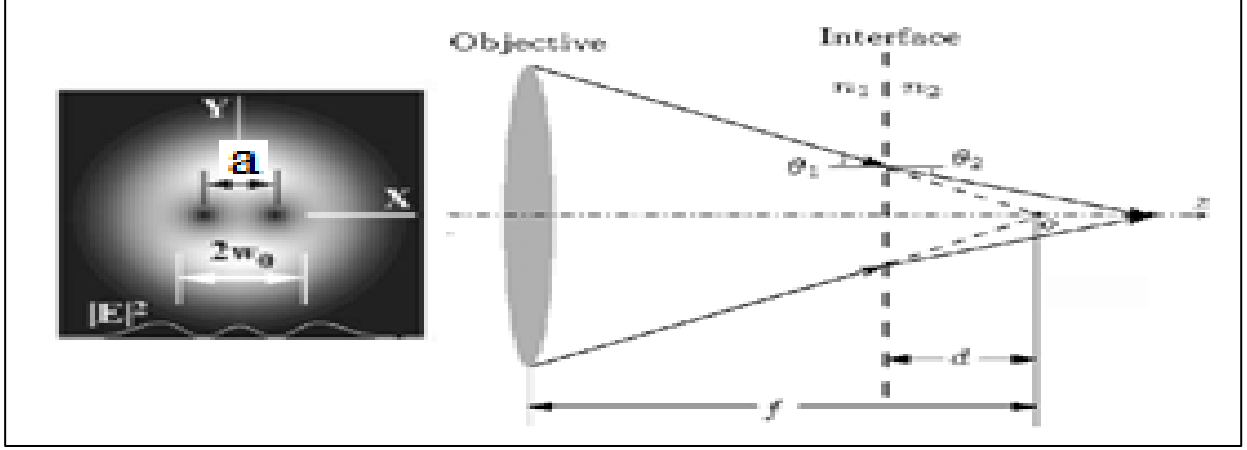


Fig. 1: Schematic Diagram for a POV nested in Radially Polarized Gaussian beam focused by a high NA lens

$$E(r, \psi, z) = \begin{bmatrix} E_x(r, \psi, z) \\ E_y(r, \psi, z) \\ E_z(r, \psi, z) \end{bmatrix} = \frac{-iE_0}{\pi} \int_0^\alpha \int_0^{2\pi} \exp[-ik_0 \Phi(\theta_1, \theta_2)] \times \sin \theta_1 \sqrt{\cos \theta_1} A(\theta_1) \times t_p [ik_2 z \cos \theta_2 + ik_1 r \sin \theta_1 \cos(\psi - \phi)] \times \begin{bmatrix} \cos \theta_2 \cos \phi \\ \cos \theta_2 \sin \phi \\ \sin \theta_2 \end{bmatrix} d\phi d\theta_1 \quad (1)$$

Where $k_i = n_i k_0$ is the wavenumber, $J_n(x)$ is the Bessel function of the first kind of order n , $\alpha = \arcsin(\text{NA})$ is the maximal angle determined by the NA of the objective; this the amplitude transmission coefficients for parallel polarization states, which is given by the Fresnel equations [16]

$$t_p = \frac{2 \sin \theta_2 \cos \theta_1}{\sin(\theta_1 + \theta_2) \cos(\theta_1 - \theta_2)}$$

$$t_s = \frac{2 \sin \theta_2 \cos \theta_1}{\sin(\theta_1 + \theta_2)} \quad (2)$$

The function $\Phi(\theta_1, \theta_2)$ is given by

$$\Phi(\theta_1, \theta_2) = -d(n_1 \cos \theta_1 - n_2 \cos \theta_2) \quad (3)$$

Representing the so-called aberration function caused by the mismatch of the refractive indices n_1 and n_2 . Here θ_1 and θ_2 are related by the well-known Snell law. Here $A(\theta_1)$ describe the pair of vortices. It is considered that two vortices of topological charge $m = \pm 1$ locate at $x = \pm a$, embedded in a Gaussian beam, the

electric field can be expressed as (Amala Prathiba Janet, 2016; Cheng, 2011).

$$A(\theta_1) = \exp\left(-\frac{r^2}{w^2}\right) [r \exp(i\varphi) - a] [r \exp(-i\varphi) + a] \quad (4)$$

w is a constant denoting the beam size, and the distance between the two vortices is decided by a . The two vortices will separate with the increment of a , and two dark cores emerge gradually in the beam. Since the objectives are often designed to obey sine condition, we get $r = f \sin \theta$, where f is the focal length of the high NA objective, and θ is the numerical-aperture.

3. RESULTS AND DISCUSSIONS

Without loss of generality and validity, it is proposed that the parameters are chosen as $\lambda=632.8\text{nm}$, $\omega=2\text{mm}$, $f=2\text{mm}$, $\text{NA}=0.9$ and $m=1$. The effect of location of the vortices on the beam pattern in the focal region is shown in Fig 2. It is observed that when $a=0$, the two vortex of the same topological charge, i.e., $m=1$, overlaps each other and become a Gaussian beam with topological charge $m=2$. It is observed from Fig. 2(a) the Generated focal segment is a focal hole. Fig. 2(e) shows the intensity plot calculated in the radial direction at the position of

maximum intensity, and the FWHM of the generated focal hole is measured as 1.12λ . Fig. 2(i) shows the on-axial intensity calculated at $z=4.4\lambda$ measures the DOF as 10.2λ . It is observed that by setting $a=0.21w$, the weights of E_x and E_y components are adjusted in such a way that the generated focal spot has a flat top profile having DOF as 9.7λ and the spot size as 0.92λ and are shown in fig 2(b), (f) and (j) respectively. We observed that further increasing a to $0.35w$, the E_y component with central minimum get reduced and generated highly confined focal spot having a

dominating E_x component. The FWHM of the focal spot is measured as 0.75λ and the focal depths of the focal spot is 8.5λ and are shown in fig (2c),(2g)&(2k) respectively. We also noted that further increasing a to $0.8w$ generated a focal segment bumpy structure of focal depth 6.3λ . Since then, the directly transmitted azimuthally polarized component should become much stronger and dominate the total field. Such a transversely polarized focal spot having no longitudinal component is highly useful in applications such as imaging the silicon integrated circuit.

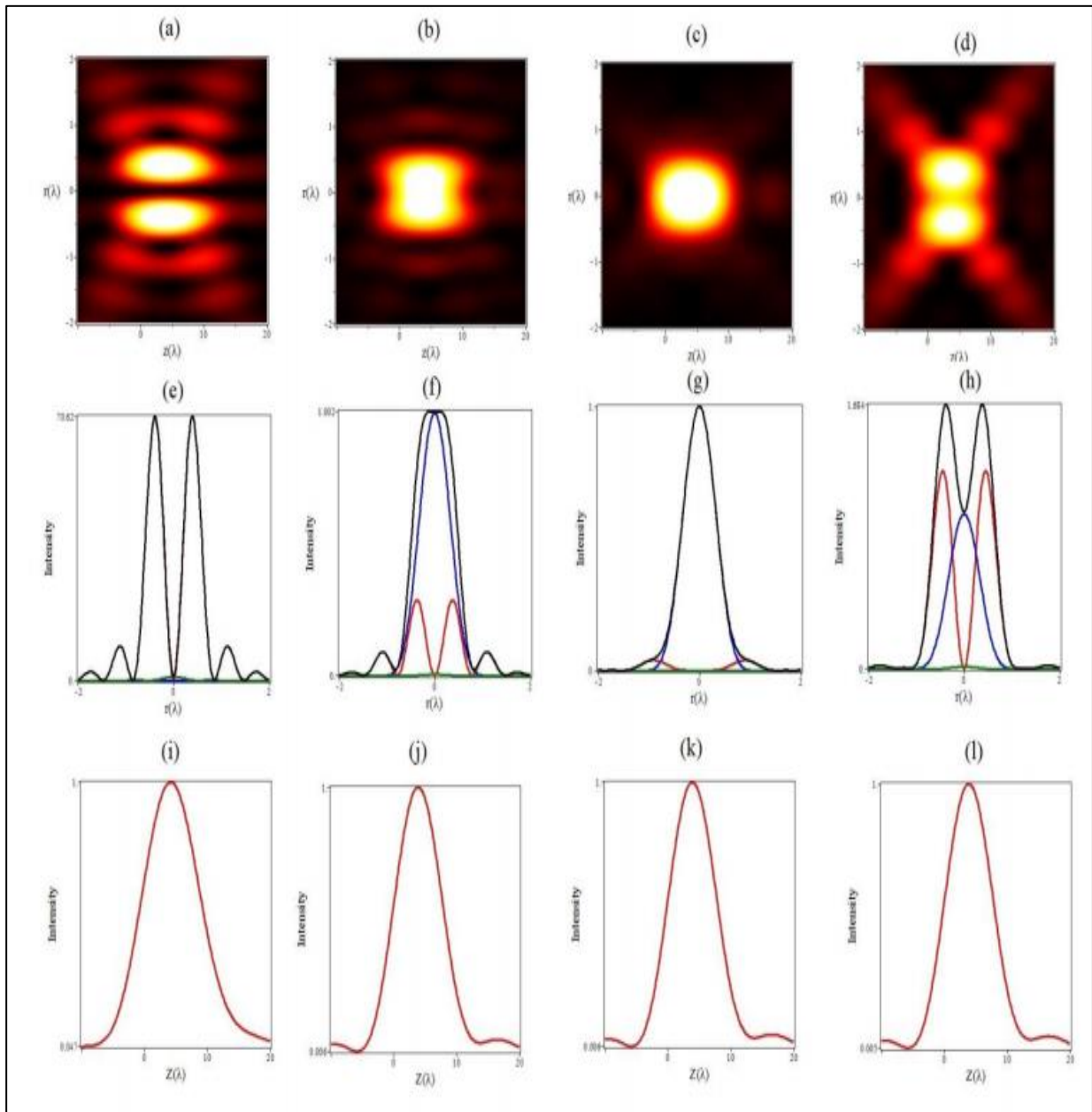


Fig. 2(a-d): shows the 3D intensity distribution in the r - z plane corresponding to $a= 0, 0.21w, 0.4w$ and $0.8w$ (e-h): shows the corresponding intensity measured along the radial axis at $z=0$ and (i-l): shows the corresponding axial intensity distribution., The other parameters are chosen as $\lambda = 632.8 \text{ nm}$, $w = 2 \text{ mm}$, $f = 2 \text{ mm}$, $NA = 0.95$.

This is because though the radially polarized beam produced sharper focal spot, the strong longitudinal component of the radially polarized beam suffers discontinuity at the interface of two neighboring media and enlarges the focal spot in the high NA medium. Hence beam with strong longitudinal polarization is limited in applications such as silicon integrated circuit (Qin et al 2000). Thus by manipulating the location of the vortices, one can tune the focal pattern from a subwavelength focal hole to a sub-wavelength transversely polarized focal spot. This is due to the fact that initially, only one dark core is observed in the focal plane when two vortices with opposite topological charges are both located in the center of the incident beam. It then gradually disappeared and formed a sharp focal spot structure as the vortices move away from the center.

4. CONCLUSION

The focusing properties of the radially polarized optical vortex dipole through a dielectric interface is investigated theoretically by vector diffraction theory. It is observed that by properly manipulating the distance between the vortex dipoles, one can generate many novel focal patterns such as a focal hole, flat top profile and highly confined focal spot suitable for microparticle trapping, manipulation, material processing etc

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