Generation of Novel Focal Pattern for Nanolithography

C.Kanchana Devi, K.Gokulakrishnan, K.B.Rajesh

Abstract— Focusing properties of the azimuthally polarized beam induced by a Binary phase plate are investigated theoretically. The binary phase plate consists of five concentric portions, through which the azimuthally polarized beam is passed and it is focused by an full aperture lens, annular lens, High NA lens axicon. It generates sub wavelength focal hole having large uniform focal depth of 60λ without any annular aperture.Such a super long dark channel may find applications in particle guiding or trapping , scanning optical microscopy , lithography , laser cutting of metals, particle acceleration, biological, and atmospheric sciences.

Index Terms— AZIMUTHALLY POLARIZED BEAM, BINARY PHASE PLATE, FOCAL DEPTH, HIGH NA LENS AXICON,

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1 INTRODUCTION

In general, the polarization of light can be classified into two categories. The first type has spatially homogeneous distribution in terms of the state of polarization for the light wavefront. This type of polarization, including linear, circular and elliptical polarization, is most familiar to the optical community. Contrarily, the second type has spatially inhomogeneous polarization distribution. Traditionally, the second type of polarization was considered as a nuisance or aberrations in the optical design and has no drawn much research attention. However, there is an increasing interest in the spatially inhomogeneous polarization recently, mostly driven by the advances made in micro-fabrication techniques and theoretical modeling techniques that were not available previously. One example of such spatially inhomogeneous polarization that has attracted much of the interest is the so-called cylindrical vector (CV) beams. Cylindrical vector beams are solutions of Maxwell equations that obey cylindrical symmetry both in amplitude and polarization. Cylindrical vector beams can be divided into radial polarization, azimuthal polarization and generalized cylindrical polarization, according to the actual polarization pattern[1].

Due to the polarization symmetry of these beams, the electric field at focus has unique polarization properties. Young worth and Brown [2] calculated cylindrical vector fields, which shows that, in the particular case of a tightly focused radially polarized beam, the polarization shows large inhomogeneities in the focal region, while the azimuthally polarized beam is purely transverse even at very high numerical apertures. Azimuthal polarization has the polarization vector is tangential to the beam. If a laser is focused along the optic axis of a birefrigent material, the radial and azimuthal polarizations focus at different planes. Polarization that is perpendicular to a cylindrical radial axis. Azimuthal angle with respect to cylindrical axis is 180˚. In this letter, the ring focus evolution of the azimuthally polarized beam induced by a binary phase plate is investigated theoretically It should be noted that in some articles, phase plate is called optical diffractive element [3], circular Damman grating [4], pupil filter [5], phase mask [6], or phase filter [7] due to different function, optical system, even personal taste. From the point of device, they are similar. High numerical aperture (NA) focusing is used both in fundamental probes of matter and in applications such as confocal microscopy and optical data storage. Since such techniques often rely on light with large depth of focus and lateral super resolution, many studies on different strategies to obtain high focal depth based on the vector nature of the focused beam have been done.

In this letter, the binary phase plate consists of five concentric portions, through which the azimuthally polarized beam is passed and it is focused by an full aperture lens, annular lens, High NA lens axicon. It generates sub wavelength focal hole having large uniform focal depth of 60λ without any annular aperture. The ring focus altered by the binary phase plate evolves considerably, and can be used in optical manipulation and material processing technologies. Initially, axicons have been used in precision alignment systems for large telescopes. Thereafter, some scanning optical system used axicon to take advantage of their large depth of field. Axions are used to generate an optical trap which guides atoms or molecules. Reflective axions are used with ultra-short laser pulses to generate and study X-pulses properties. Axicons can also be used in medical applications. The principle of the optical focusing system is shown in Section 2. Section 3 indicates simulation results and discussions. Conclusions are summarized in Section 4.

2 PRINCIPLE OF THE FOCUSING SYSTEM

Fig.1 is the sketch of the optical focusing system we inves-

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tigated, in which an azimuthally polarized beam passes through a binary phase plate, and focused by an full aperture lens, annular lens. Then the same beam is focused through high NA lens axicon. The analysis was performed on the basis of Richards and Wolf's vectorial diffraction method [13] widely used for high-NA focusing systems at arbitrary incident polarization. In the case of the azimuthally incident polarization, adopting the cylindrical coordinates r, z, ϕ and the notations of Ref. [14],
The electric field in the vicinity of the focal region can be written as,

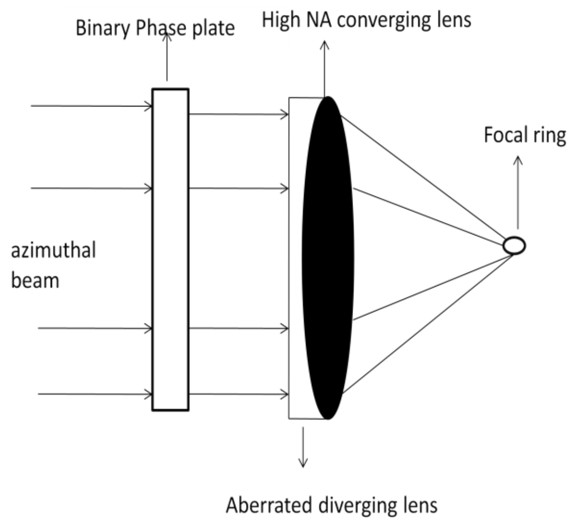

Figure 1. Sketch of the focusing optical system in which the azimuthally polarized beam passes through a binary phase plate, and focused by an lens axicon

$$\hat{E}_{(r,\varphi,z)} = E_{\varphi} \tag{1}$$

Where $\hat{e}_{\varphi}$ is the unit vector in the azimuthally propagating direction. E_{φ} is the amplitude and can be expressed as,

$$\begin{aligned} E\varphi = {} & 2A\int_0^{\theta 1}\sqrt{cos\theta}\,\sin\theta\, A(\theta)J_1\ (krsin\theta)e^{ikzcos\theta}d\theta - \\ & 2A\int_{\theta 1}^{\theta 2}\sqrt{cos\theta}\,\sin\theta\, A(\theta)J_1\ (krsin\theta)e^{ikzcos\theta}d\theta + \\ & 2A\int_{\theta 2}^{\theta 3}\sqrt{cos\theta}\,\sin\theta\, A(\theta)J_1\ (krsin\theta)e^{ikzcos\theta}d\theta - \\ & 2A\int_{\theta 3}^{\theta 4}\sqrt{cos\theta}\,\sin\theta\, A(\theta)J_1\ (krsin\theta)e^{ikzcos\theta}d\theta + \\ & 2A\int_{\theta 4}^{\alpha}\sqrt{cos\theta}\,\sin\theta\, A(\theta)J_1\ (krsin\theta)e^{ikzcos\theta}d\theta \end{aligned} \tag{2}$$

where δ distinguishes the presence or absence of annulus and α=arcsin(NA/n), where NA is the numerical aperture and n is the index of refraction between the lens and the sample.$J_0(\chi)$ and $J_1(\chi)$ denote the Bessel functions of zero and first order and the function A(θ) describes the amplitude modulation. r and z are the radial and z coordinates of observation point in the focal region, respectively. k is the wave number.(j = 1)represents the polar angle corresponding to the jth zone. For illumination by a double ring-shaped R-TEM11* beam with its waist in the pupil, this function is given by [15]

$$.A(\theta) = \beta^2\left(\frac{\sin\theta}{\sin^2\theta}\right)exp\left[\left(-\ \beta\frac{\sin\theta}{\sin\alpha}\right)^2\right]L_p^1\left[2\left(\frac{\beta\sin\theta}{\sin\alpha}\right)^2\right] \tag{3}$$

Where β is the parameter that denoted the ratio of pupil diameter to the beam diameter and L_p^1 is the generalized Laguerre polynomial.
The intensity distribution of the lens axicon is evaluated by the function TA,

$$TA = exp\ (I\left(\Psi\left(\frac{sin\theta}{sin\alpha}\right)^4\right) + \frac{1}{2f\left(\frac{sin\theta}{sin\alpha}\right)^2} \tag{4}$$

It can be seen that the electric field in the focal region of the azimuthally polarized beam only contains transverse component. It should be noted that the distance unit in all figures is k^{-1}, where k is wave number.

3 RESULTS AND DISCUSSIONS

The focusing properties of the azimuthally polarized beam are discussed. Where β is the parameter that denoted the ratio of pupil diameter to the beam diameter and L^1_p is the generalized Laguerre polynomial. We perform the integration of Eq.(1) numerically using parameters λ=1, NA=0.6 and β =1.2 . Here, for simplicity, we assume that the refractive index n = 1 and A = 1. Fig. (2-a) shows the contour plot of the total intensity distribution in the yz plane near the focus for the focusing system without annular aperture (δ = 0). It is observed that depth of focus (DOF) of the dark channel is about 30λ and the radii of the focal holes are not uniform along the dark channel. However, when δ = 0.75, the radius of the focal hole is shown to be not uniform along the dark channel, and its depth of focus about 36λ which is shown in Fig.(2-b). However it is estimated that almost 80% of the incident energy is blocked by the annular aperture which results in a poor intensity of the focal channel. We show that it is possible to generate high intense sub wavelength focal hole with large uniform focal depth without any annular aperture by using high NA lens axicon [16]. The high NA lens axicon is a doublet of aberrated diverging lens and a high NA converging lens.

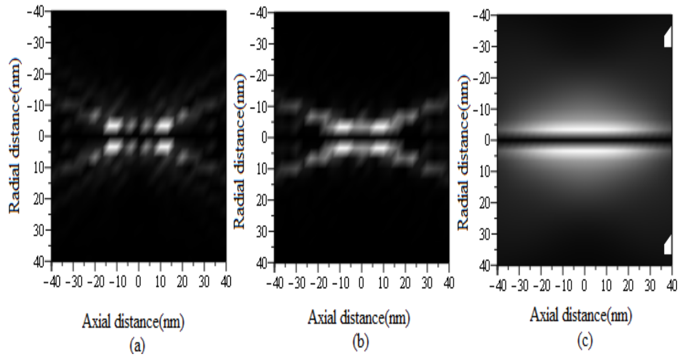

Fig.2. Intensity distribution of the focused field near focus for the double-ring-shaped azimuthally polarized beam focused with (a) δ = 0 (full aperture lens) (b) δ =0.7575 (annular lens) (c) High NA lens axicon. The other parameters are β = 1.2 and NA = 0.6.

Here we consider only systems that comprise a diverging lens that has third-order spherical aberration and a perfect high NA converging lens. The intensity distribution of the lens axicon is evaluated by replacing the function A(θ) by the function A(θ)T(θ) where is the non-paraxial transmittance function of the thin aberrated diverging lens [9-12].

Fig.(2-c) shows the contour plot of the total intensity distribution in the yz plane near the focus for the high NA lens axicon without any annular aperture (δ = 0). It is observed that the radius of the focal hole is shown to be almost uniform along the dark channel, the focal depth of the focal hole segment is measured as 60λ. The focal depth of the focal hole generated by the high NA lens axicon is almost 85% larger for the assumed set of parameters the focal depth of the focal hole generated by the annular lens.

Thus the proposed high NA lens axicon system generates sub wavelength super long dark channel without any annular truncation. Since such a long uniform sub wavelength focal hole segment is generated without any annular aperture, the intensity of the focal hole segment also remains very high when compared to the system proposed in [8].

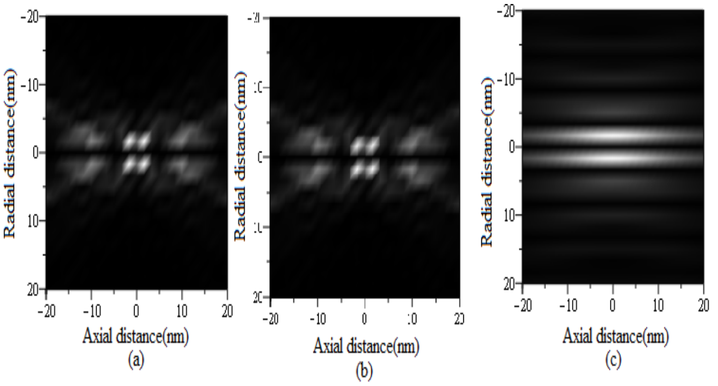

Fig.3. Intensity distribution of the focused field near focus for the double-ring-shaped azimuthally polarized beam focused by a high NA lens with (a) δ = 0(full aperture lens) (b) δ =0.7575 (annular lens) (c) High NA lens axicon. The other parameters are β = 1.2 and NA = 0.8.

We have also calculated the electric energy density profiles of the total field near the focus for the focusing system with NA = 0.8, β=1.2 and is shown in Fig.(3) is observed that the focal hole segment generated by the lens without any annular aperture is non uniform in nature with DOF around 6λ which is shown in Fig. (3-a).

However the presence of annular aperture with δ = 0.75 generates not uniform intensity focal hole segment and DOF around 6.7λ. The result is identical as in [8] and is shown in Fig.(3-b). Fig.(3-c) shows the focal segment generated by the proposed lens axicon system without any annular aperture. It is observed from the figure that focal depth drastically increased to 20λ.It is observed that the DOF is very large and is almost 3 times greater than the annular lens with equal NA and δ = 0.75.

Fig. (4-a) shows the contour plot of the total intensity distribution in the yz plane near the focus for the focusing system without annular aperture (δ = 0). It is observed that depth of focus (DOF) of the dark channel is about 5λ and the radii of the focal holes are not uniform along the dark channel. However, when δ = 0.75, the radius of the focal hole is shown to be not uniform along the dark channel, with its FWHM about 0.5λ and its depth of focus about 6λ which is shown in Fig.(4-b).

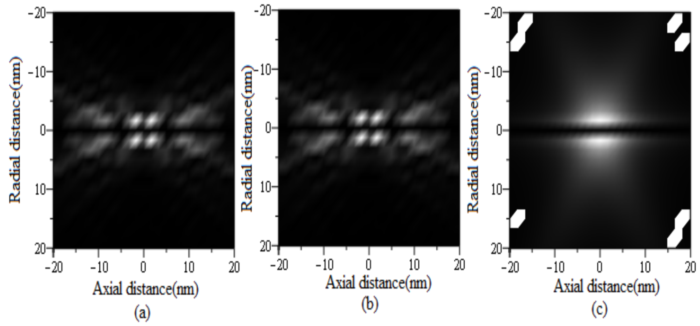

Fig.4. Intensity distribution of the focused field near focus for the double-ring-shaped azimuthally polarized beam focused by a high NA lens with (a) δ = 0(full aperture lens) (b) δ =0.7575 (annular lens) (c) High NA lens axicon. The other parameters are β = 1.2 and NA = 0.9.

Fig.(4-c) shows the contour plot of the total intensity distribution in the yz plane near the focus for the high NA lens axicon without any annular aperture (δ = 0). It is observed that the radius of the focal hole is shown to be almost uniform along the dark channel, the focal depth of the focal hole segment is measured as 8λ.

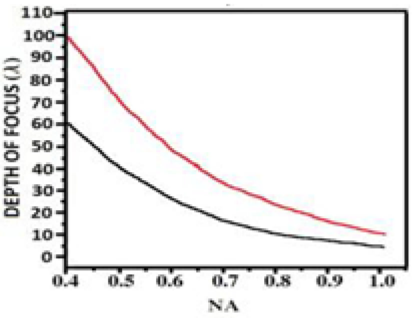

Fig.5. shows the DOF of the high NA lens axicon (Red line) is very much larger when compared to the annular aperture lens (black line).

4 CONCLUSIONS

The intensity distributions of azimuthally polarized beam that has a double-ring-shaped transverse mode pattern tightly focused by high NA lens axicon were calculated based on vector diffraction theory. We observed that the proposed high NA lens axicon without any annular aperture can generates Sub Wavelength Super-Long Dark Channel with FWHM of 0.5λ and DOF of 60λ. Such a super long dark channel may find applications in optical lithography, optical trapping, biological, and atmospheric sciences.

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