DESIGN OF LENS AXICON FOR NEAR-Filed OPTICAL RECORDING
CHAPTER-VI

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In this chapter we presents a design of lens axicon for near-field optical recording. The proposed system is a doublet of a diverging abberated lens and a high NA converging lens. The optical distribution of the near field probe of the proposed system is analyzed using vector diffraction theory and its dependence on the various pupil functions is also presented.

6.1 Generation of sub-wavelength and super-resolution longitudinally polarized non-diffraction beam using Lens Axicon

Most of the near field applications such as optical data storage, bio medical imaging and lithography demands sub wavelength beam with large depth of focus. Overcoming the limits imposed by diffraction has been the aim of many research efforts during the last decades. The super resolution was extensively investigated using amplitude apertures [67, 68], phase apertures [68], or their combination [69, 70]. It is observed that a strong longitudinal component appears at the focal region of a tightly focused laser beam [71-73]. It also arises with focusing of radially polarized light [74-76]. The longitudinal field can be suppressed or enhanced by amplitude, polarization and phase modulation of the incident beam. For example, a longitudinal field can be completely suppressed in an azimuthally polarized beam [76, 77].
Several methods to enhance the longitudinal field component have been suggested [78, 79], however all of them have insufficient optical efficiency (on the level of a few percents) and non-uniform axial field strength. An axicon is an optical element generating a narrow focal line along the optical axis. The axicon, energy wise, is the most efficient method for generating a diffraction free beam. The focal line generated by the axicon can be approximated by a zero-order Bessel type beam that preserves its transverse distribution along the axis. The idea of using spherical aberration to produce an axicon from ordinary lenses was first suggested by Steel in 1960 [80]. It has been thoroughly investigated both analytically and numerically [81–83]. However, this analysis only specifies the focal length and the amount of spherical aberration required but the experimental aspect of designing the lens axicon is investigated in [84]. The advantage of such a system is that spherical surfaces are routinely produced in any optical workshop, so the lens axicon is easy and inexpensive to manufacture.

A possible design, presented in this work, is a cemented doublet-lens axicon, where the virtual focal segment created by the aberrated diverging lens can be converted to a real focal segment, of the forward type with a nano scale resolution, by adding a high Numerical Aperture (NA) converging lens. In addition, we consider only systems that comprise a diverging lens that has third-order spherical aberration and a perfect high NA converging lens illuminated by a radially polarized beam.
Figure (6.1): Schematic diagram of a lens axicon composed of an aberrated diverging lens and a high NA converging lens.

The schematic diagram of the lens axicon is shown in Fig.6.1. It was shown that for radial incident polarization, a Fresnel Zone Plate (FZP) has focusing properties superior to high NA lens [85]. This is due to a large apodization factor of an FZP for high NA, which gives larger weight to higher spatial components. Owing to phase nature of an FZP, the resolution improvement is achieved without reduction in intensity. However when compared with FZP, the proposed lens axicon system is simple to fabricate, mount and align.

The analysis was performed on the basis of Richards and Wolf's vectorial diffraction method [86] widely used for high-NA focusing systems at arbitrary incident polarization [87, 88]. In the case of the radial incident polarization, adopting the cylindrical coordinates $r$, $z$ and the notations used in the reference[89], radial and longitudinal components of the electric field $E_r(r, z)$ and $E_z(r, z)$ in the vicinity of the focal spot can be written as
\[ E_r(r, z) = A \int_{a_1}^{a_2} \cos^{1/2} (\theta) \sin(2\theta) \times l(\theta) \times J_1(kr \sin \theta) e^{ikz \cos \theta} d\theta \]

\[ E_z(r, z) = 2ia \int_{a_1}^{a_2} \cos^{1/2} (\theta) \sin^2 (\theta) \times l(\theta) \times J_0(kr \sin \theta) e^{ikz \cos \theta} d\theta \] (6.1)

Where \(a_1\) distinguish the presence or absence of annulus and \(a_2 = \arcsin(NA/n)\), where \(NA\) is the numerical aperture and \(n\) is the index of refraction between the lens and the sample. \(J_0(x)\) and \(J_1(x)\) denote Bessel functions of zero and first order and the function \(l(\theta)\) describes amplitude modulation. For illumination by a Bessel-Gaussian beam with its waist in the pupil this function is given by [89].

\[ l(\theta) = \exp \left[ \left( -\frac{\xi_2^2}{\sin \alpha} \right)^2 \right] J_1 \left( 2\frac{\xi_2 \sin \theta}{\sin \alpha} \right) \] (6.2)

for a Gaussian beam with its waits in the pupil

\[ l(\theta) = \exp \left[ -\left( \frac{\xi_3 \sin \theta}{\sin \alpha_2} \right)^2 \right] \] (6.3)

and for the uniform beam \(l(\theta) = 1\). \(\xi_1, \xi_2, \xi_3\) are the parameters that denoted the ratio of pupil diameter to the beam diameter and in our calculation we take it as unity.

6.1.1 Results and Discussion

We perform the integration numerically using parameters \(\lambda = 405\) nm, \(NA = 0.90\) (corresponding to \(a_2 = 64.15\)) and \(n = 1\). The corresponding field distribution is shown in Fig.6.2. From the Fig.6.2 (a,b,c) it is observed that the intensity of longitudinal component is high for all three type of beam illumination
but the parasite radial field intensity is about 36.3%, 43.6%, 39.2% corresponding to plane, Gaussian and Bessel–Gauss beam. This radial field leads to a broadening of the total intensity distribution. As a result the total intensity spot size becomes 0.83λ, 0.98λ, 0.88λ corresponding to plane, Gauss and Bessel–Gauss illumination. It is observed that the FWHM is smallest for the case of uniform amplitude profile, while the Gauss beam results in the largest FWHM. More over the contour plot of the total intensity distribution in yz plane in Fig.6.2 (d, e, f) shows that the field changes from a converging spherical wave front to a diverging front within a very short distance (~ λ). Thus to have a good longitudinally polarized beam with better depth of focus, one should suppress the radial field component. We show that this is possible in lens axicon by making a doublet of aberrated diverging lens and a high NA converging lens. The intensity distribution of the lens axicon is evaluated by replacing the function \( I(\theta) \) by the function \( I(\theta)T(\theta) \) where \( T(\theta) \) is the non paraxial transmittance function of the thin aberrated diverging lens.

\[
T(\theta) = \exp\left( I.k. \left( \beta. \left( \frac{\sin(\theta)}{\sin \alpha_2} \right) \right)^4 + \left( \frac{1}{2.f} \left( \frac{\sin(\theta)}{\sin \alpha_2} \right)^2 \right) \right)
\]

(6.4)

Where \( k=2\pi/\lambda, f \) is the focal length and \( \beta \) is the aberration coefficient. In our calculation we take \( f = 18.4\text{mm}, \beta = 6.667 \times 10^{-5}\text{mm}^{-3} \) and \( n=1.5 \). This results in an equiconcave diverging lens which is simple to manufacture [81]. The focal distribution of the lens axicon is calculated by including the transmission function
of the aberrated diverging lens on the aperture of the high NA focusing lens. The intensity profile of the radial component, the longitudinal component and the total field of the longitudinally polarized beam in the focal cross section are shown in Fig. (6.3). It is observed that the parasite radial field intensity is reduced to 15.3%, 16%, 15.6% corresponding to plane, Gaussian and Bessel –Gauss beam and the spot size are 0.43\(\lambda\), 0.44\(\lambda\), 0.43\(\lambda\), respectively. The intensity contour plot as shown in Fig. 6.3(d, e, f) depicts that the spot size is constant within certain region, implying that the diffractive spreading is eliminated and a non diffractive beam propagates in this region. The non-diffractive region extends to 2\(\lambda\), 2\(\lambda\), 1.8\(\lambda\) corresponding to plane, Gaussian and Bessel- gauss beam. Outside the region where the axial intensity is constant, the field diverges almost as fast as it does in the original system.

In conclusion, a method to obtain a sub wavelength and super resolution longitudinally polarized non-diffracting beam within a limited space is proposed and demonstrated numerically. This is achieved by placing a diverging aberrated lens in front of a high NA converging lens. The method of our calculation was based on vector diffraction theory, which is suitable to be used in both paraxial and non-paraxial focusing and imaging system. We expect such a beam with small spot size and longer depth of focus could be widely used in application such as data storage, biomedical imaging, laser drilling and machining.
Figure (6.2): Intensity profile of the radial component, longitudinal component and the total field on the focal plane of the $NA=0.90$ lens for radial polarized (a) uniform (b) Gauss and (c) Bessel Gaussian Beam. (d), (e) and (f) are their corresponding contour plot of total intensity.
Figure 6.3: Intensity profile of the radial component, longitudinal component and the total field on the focal plane of the lens axicon for radial polarized (a) uniform (b) Gauss and (c) Bessel Gaussian Beam. (d), (e) and (f) are their corresponding contour plot of total intensity.
6.2 Adjustable generation of high resolution optical virtual probe

using Lens Axicon

Overcoming the limits imposed by diffraction in imaging systems has long been a topic of much interest because of its potential use in a number of important applications. In optical data storage, there is a considerable amount of effort dedicated to the design of well-corrected objective lenses with high numerical aperture to obtain an optical stylus with cross-sectional dimensions of the order of a micrometer or less [90]. However, such lenses present a strong sensitivity to aberrations and misalignment. Near-field techniques that enhance localized surface plasmons are also potential candidates to obtain intense optical spots beyond the diffraction limit for optical storage. Optical super-resolution techniques [91-92] offer alternative means to reduce the focused spot size with respect to the diffraction limit embodied in the Airy disk pattern by changing the properties of the focused beam distribution.

The Diffraction Free Beam (DFB) is truly unique in that its resolution is beyond the classical diffraction limit and more importantly that the beam essentially does not spread as it propagates. Conventional addressing, using Gaussian beams, particularly very narrow ones, is degraded by diffraction spreading. Since a high numerical aperture lens is used to focus the beam, the depth of focus becomes very small, requiring precise (thus slow) up and down movement of the lens, and the diffraction of the system sets a limit on how small the focus spot can be. It has been proved that the simple method of producing
axicon-like system is to make use of lens with spherical aberrations (SAs), adjusted to produce image field whose characteristics is similar to that generated by axicon[93-96]. Such a lens is termed as lens axicon.

In this work, a lens axicon is introduced for the generation of high resolution optical virtual probe. Based on the numerical calculation, we can evaluate the intensity distribution along the diffracted field behind the axicon. It is shown that near-Bessel beams of nanoscale resolution with adjustable depth of focus can be obtained and the rapid decay of axial intensity along the propagating axis can be eliminated with suitable apodization. The spot size ratio of the shaped beam and the depth of focus are discussed.

A schematic of the beam shaping using lens axicon is depicted in Fig.1. A Gaussian beam from the laser is transmitted through a spherical lens with a aberration co-efficient $\beta$ and having paraxial focal length $f_o$ is diffracted into the required shaped beam intensity distribution at focal plane II of the lens. It is assumed that the waist of the Gaussian beam is located just at the lens plane and $r_1, r_2$ are the inner and outer radii of the aperture. The optical field in front of the axicon is given by
Figure (6.4): Illustration of the geometry of the lens axicon.

\[ U_o(\rho') = A_0 \exp(-\rho'^2 / \omega^2) \]  \hspace{1cm} (6.5)

Where \( A_0 \) is the constant amplitude factor, \( \rho' \) is radial coordinate, and \( \omega \) is the beam radius, defined as the distance from the beam center to the point where the normal irradiance equals \( \exp(-2) = 0.135 \). If \( \beta \) is positive the lens axicon is forward-type and the amount of optical path difference produced by the lens axicon is given by

\[ r(\rho') = \exp[ik(-\rho'^2 / 2f_o + \beta \rho'^4)], \rho' \in (r_1, r_2), \]

\[ = 0 \quad \text{otherwise}. \]  \hspace{1cm} (6.6)

Where, \( r_1 \) and \( r_2 \) are the inner and outer radii of the lens axicon. According to the Fresnel diffraction theory, the field intensity of the beam at a plane behind the lens can be determined as
\[ I(r,z) = \frac{k^2 A_0^2}{z^2} \left| \int \frac{J_0(k \rho \rho'/z) \exp(-\rho^2/\omega^2)}{\rho'} \exp[i k \psi(\rho', z)] \rho' d\rho' \right|^2 \]  \hfill (6.7)

Where,
\[ \psi(\rho', z) = \beta \rho'^4 - \left( \frac{1}{2f_0} - \frac{1}{2z} \right) \rho'^2 \]  \hfill (6.8)

The particular values of \( \beta \) and \( f_0 \) are determined by \( d_1, 2 \) and \( r_1, 2 \) and are given by [79]

\[ \beta = \frac{d_2 - d_1}{4d_1 d_2 (r_2^2 - r_1^2)} \]  \hfill (6.9)

\[ f_0 = \frac{d_1 d_2 (r_2^2 - r_1^2)}{d_2 r_2^2 - d_1 r_1^2} \]  \hfill (6.10)

6.2.1 Results and Discussion

The characteristics of the axicon used is analyzed by means of numerical calculation by evaluating the diffraction integral of equation (6.7), describing the diffractive field. The parameters of the focal segment are chosen as \( d_1 = 4 \) mm, \( d_2 = 6 \) mm, \( r_1 = 0.25 \) mm, and \( r_2 = 0.50 \) mm, which result in \( \beta = 1.12 \times 10^5 \) mm, and \( f_0 = 3.6 \) mm. The axial intensity distribution of the focal segment generated by the axicon corresponding to these parameters for a Gaussian beam incidence with radius \( \omega = 1 \) mm from laser source of \( \lambda = 405 \) nm is shown in Fig.(6.5-a). It is seen that the axial intensity distributions apart from rapid oscillation decreases faster with the increasing Z- axis. The contour plot of the total intensity distribution of the diffraction field shown in Fig. (6.5-b) depicts that the FWHM of the spot size remains constant around 1.6\( \mu \)m within the region of 4mm to 6mm along the Z-
axis. However, the figure shows that the intensity distribution is not uniform and much of the total intensity is concentrated at the beginning of the focal segment \((z=4\text{mm})\). It is shown that, by Gaussian beam illumination of appropriated beam radii, and by using suitable apodization function, we can make axial intensity distribution of the focal segment much uniform and exhibits less oscillation.

In order to achieve this, an apodization with annular super-Gaussian amplitude function is chosen [80]. The apodization function

\[
T_{\text{ap}}(\rho) = \exp \left[-\left(\frac{\rho - R}{\Omega}\right)^n\right]
\]

(6.11)

Where \(R = (r_1 + r_2)/2\) and \(\Omega = (r_2 - r_1)/2\) is introduced in to the diffraction integral of equation (6.7) and the result is shown in Fig (6.5-c). From the Fig. (3-c), it is found that the rapid oscillation and fast decay of on axial intensity is reduced by choosing \(n=1\) in the apodization function. The contour plot of total intensity in Fig (6.5-d) depicts that the spot size remains constant around \(1.6\mu\text{m}\) and propagates with much uniform intensity distribution along the focal segment. This implies that the diffractive spreading is eliminated and a high resolution virtual optical probe with uniform intensity is generated within the focal segment. It is observed that by fixing the parameters \(\beta\) and \(f_0\) constant and by changing the values of \(r_1\) and \(r_2\), it is possible to truncate the DFB to a desired length and localize the beamlet at a particular Z-position within its full range. This is illustrated in Fig. (6.6) where the axial and the total intensity distributions are plotted by changing the values of \(r_1\& r_2\) as \(0.2\text{mm}\) and \(0.4\text{mm}\) respectively and by
keeping the values of all other parameters same as mentioned above. It is observed from the Fig (6.6-a) that the on-axial intensity decays rapidly but improved to give a much uniform distribution when Super Gaussian apodization with n=1 is used and is shown in Fig (6.6-c). The contour plot of total intensity distribution in Fig. (6.6-d) shows that the generated optical virtual probe has FWHM around 1.6μm and it extends from 4mm to 4.8mm along the Z- axis. Fig (6.7) shows the axial and the total intensity distribution at the diffractive field of the lens axicon having r₁ & r₂ as 0.2mm and 0.6mm respectively. The rapid decay of on axial intensity shown in Fig (6.7-a) is improved to give a much uniform on axial intensity distribution by using Super Gaussian apodization with n=1 and is shown in Fig. (6.7-c). The contour plot of total intensity distribution in Fig. (6.7-d) shows that the generated optical virtual probe has FWHM around 1.6μm but it is found to extends from 4mm to 8mm along the Z- axis.

Hence it is observed that the feasibility of localizing the DFB at a specific depth within its range is possible. This can be achieved without any mechanical movement (i.e., by using a variable ring aperture mask, which could be implemented using a liquid crystal shutter). Hence it is demonstrated that, because of the long depth of focus of the Bessel beam, the beam length can be localized at varying depths.

In conclusion, a method to obtain a high resolution optical virtual probe with adjustable Depth of focus within the focal segment is proposed and demonstrated numerically. This is achieved by means of lens axicon that utilizes
spherical aberration to duplicate the performance of an axicon and to create an extended focal line. This Localized generation of the Bessel beam will allow depth addressing for multilayer storage media, without dynamic focusing of a lens. Thus we expect a totally new way of accessing a multilayer optical memory disk.
Figure (6.5): (a) & (b) Axial and total intensity distribution at the diffraction field without Super Gaussian apodization. (c) & (d) Axial and total intensity distribution at the diffraction field with Super Gaussian apodization ($n=1$). The parameters are $\omega = 1 \text{mm}$, $d_1 = 1 \text{ mm}$, $d_2 = 4 \text{ mm}$, $r_1 = 0.25 \text{ mm}$, and $r_2 = 0.5 \text{ mm}$, which result in $\beta = 1.12 \times 10^5 \text{ mm}$, and $f_0 = 3.6 \text{ mm}$. 
Figure (6.6): (a) & (b) Axial and total intensity distribution at the diffraction field without Super Gaussian apodization. (c) & (d) Axial and total intensity distribution at the diffraction field with Super Gaussian apodization \((n=1)\). \((r_1=0.2\text{mm} \text{ & } r_2=0.4\text{mm})\). Other parameters are same as in figure (6.5).
Figure (6.7): (a) & (b) Axial and total intensity distribution at the diffraction field without Super Gaussian apodization. (c) & (d) Axial and total intensity distribution at the diffraction field with Super Gaussian apodization (n=1). (r₁=0.2mm & r₂=0.6mm. Other parameters are same as in figure-6.5).