

Experimental demonstration of an aberrated azimuthally polarized beam

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Abstract

Azimuthally polarized beams are light beams with axially symmetric polarization profile and a doughnut like intensity distribution in the focal plane. Owing to the unique properties, the azimuthally polarized beams have found applications in important areas such as in optical trapping, material processing, etc. In all the applications, the azimuthally polarized beams are treated as aberration free. However if aberrations are present in the lens system, they will also affect the focal volume properties. Thus, the applications using the azimuthally polarized beam, will also get affected by the aberrations. In this paper we experimentally demonstrate the aberration effect in the focal intensity distribution of an azimuthally polarized beam. The experimental results are compared with theoretical results obtained using the vectorial diffraction theory.

Key Words: Azimuthally polarized beam; primary aberrations; focal intensity distribution; low numerical aperture focusing condition; arbitrary vector beam forming setup.

1. Introduction

Azimuthally polarized beams are important members of cylindrical vector beams. The electric field (polarization) vector in the pupil plane of these beams points in the azimuthal direction, perpendicular to the radius vector. When focused these beams give rise to doughnut like intensity distribution for the entire range of numerical apertures i.e. from low to high [Young and Brown, 2000]. Due to this doughnut like structure in the focal plane and axially symmetric polarization profile near the focus, the azimuthally polarized beams have found applications in several fields, such as in optical trapping [Peng, et al., 2009], material processing [Meier et al., 2007], in dark field imaging [Biss et al., 20067], in the creation of narrow thin light tube like intensity distribution

[Khonina and Ustinov, 2013], in wave guide as pump beam [Mullen et al., 2013] and so on. In all the above applications the azimuthally polarized beams are assumed to be aberration free. However every optical system more or less suffers from various aberrations. Aberrations present in the lens system will invariably affect the focal volume properties of these beams and consequently corresponding applications will also be effected. Thus it is important to study the effect of aberrations on an azimuthally polarized beam. There are reported works where the effect of primary aberrations on an azimuthally polarized beam has been investigated theoretically [Singh et al., 2009(a) ; Singh et al., 2009(b)]. There are also studies which discuss the effect of combination of primary aberrations such as spherical aberration and defocus on an azimuthally polarized beams [Lalithambigai et al., 2015], and the effect of spherical aberration on tightly focused azimuthally polarized double ring shaped beam [Anitha et al., 2012]. In this paper we experimentally demonstrate the effect of primary aberrations on an azimuthally polarized beam by using an arbitrary vector beam forming setup [Kalita et al., 2016], in the low numerical aperture focusing condition. The experimental results are compared with theoretical results obtained using the Fourier transform form of the vectorial diffraction theory [Boruah and Neil, 2009].

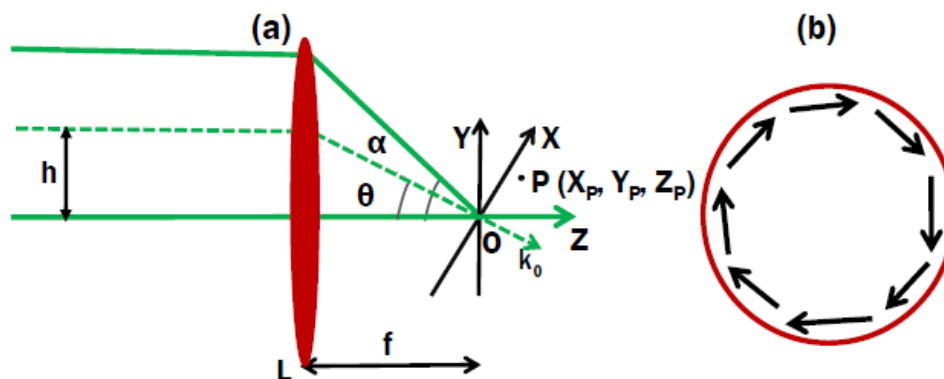


Figure 1. (a) Focusing of incident light by an aplanatic lens system, (b) Polarization profile in the pupil plane of an azimuthally polarized beam.

Table I

Zernike Polynomials representation of a few primary aberrations

j	$Z_j(x, y)$	Common Aberration
6	$\sqrt{6}(x^2 - y^2)$	Primary astigmatism at 0°
7	$\sqrt{8}(3(x^2 + y^2) - 2)y$	Primary y coma
10	$\sqrt{8}(x^3 - 3y^2x)$	Primary x trefoil
11	$\sqrt{5}(6(x^2 + y^2)^2 - 6(x^2 + y^2) + 1)$	Primary spherical aberration

2. Theory for numerical simulation and the experimental arrangement

2.1. Fourier transform of the Vectorial Diffraction Theory

Let a linearly polarized beam polarized along X axis is incident at a height h on an aplanatic lens system of semi angular aperture α as shown in Figure 1. Let us assume that f is the focal length of the lens (L) and k_0 is the wave number of the incident light. The expressions for the electric and magnetic field components at P near the focus of the aplanatic lens system, due to the X polarized incident beam were developed by Richards and Wolf [Richards and Wolf, 1959]. However these expressions are useful in the case of pupil functions, which have a simple analytical form. In the case of pupil functions, which have a complicated analytical form, such as the pupil function in the presence of aberrations, such expressions are not very useful. Thus it requires an easy and convenient theory, which can be applicable in all the above cases. It has been shown that the expressions by Richards and Wolf can be transformed into a Fourier transform (FT) form in Cartesian coordinate system [Boruah and Neil, 2009]. This Fourier transform form of the vectorial diffraction theory can be employed to compute the focal field components of beams with complicated pupil functions. By using readily available Fast Fourier Transform (FFT), one can easily and quickly compute the focal field expressions for pupil functions even in the presence of aberrations.

If the Cartesian coordinates in the pupil plane are (k_x, k_y) then $k_r = \sqrt{k_x^2 + k_y^2}$ and $k_0 \sin \alpha = 1$. Assuming $l_0(k_x, k_y)$ to be the pupil function for an X polarized beam, the electric field components at P are written as

$$\begin{aligned}
 EX_x(P) &= -iF \left[e^{ik_z z_P} l_0(k_x, k_y) \sqrt{\frac{k_0}{k_z} \frac{k_0 k_y^2 + k_z k_x^2}{k_0 k_r^2}} \right] \\
 EX_y(P) &= iF \left[e^{ik_z z_P} l_0(k_x, k_y) \sqrt{\frac{k_0}{k_z} \frac{(k_0 - k_z) k_x k_y}{k_0 k_r^2}} \right] \\
 EX_z(P) &= iF \left[e^{ik_z z_P} l_0(k_x, k_y) \sqrt{\frac{k_0}{k_z} \frac{k_x}{k_0}} \right]
 \end{aligned}$$

where $F \dots$ represents 2D Fourier transform of the expression in [...], l_0 is a 2D matrix and $k_z = \sqrt{k_0^2 - k_r^2}$.

We can extend this FT form of vectorial diffraction theory for a Y polarized beam and hence to an arbitrarily polarized beam by taking the vector sum of two orthogonally polarized pupil functions i.e. the X polarized function (say $l_0 = l_x$) and the Y polarized pupil function (say $l_0 = l_y$).

2.1.1. Focal field components of an azimuthally polarized beam

The axially symmetric polarization profile in the pupil plane of an azimuthally polarized beam is shown in Figure 1(b). The X and Y polarized fields in the pupil plane of the beam can be written by using Jones matrix representation as

$$\begin{pmatrix} -\sin\phi \\ \cos\phi \end{pmatrix}$$

where ϕ is the azimuthal angle. The focal field components of the azimuthally polarized beam can thus be obtained by using $l_x = -\sin\phi$ in the expressions of an X polarized beam and $l_y = \cos\phi$ in the expressions of a Y polarized beam. In the presence of aberrations, the pupil functions of an azimuthally polarized beam get modified as $l_x = -\sin\phi e^{i\Phi}$ and $l_y = \cos\phi e^{i\Phi}$. Here $\Phi = \phi_{rms} \times Z_j$, where ϕ_{rms} is the root mean square (RMS) amplitude of aberration and Z_j (where for the present

work, $j = 6, 7, 10,$ and 11) are the single indexed Zernike circular polynomials, defined over a unit circular area [Mahajan, 1994; Noll, 1976].

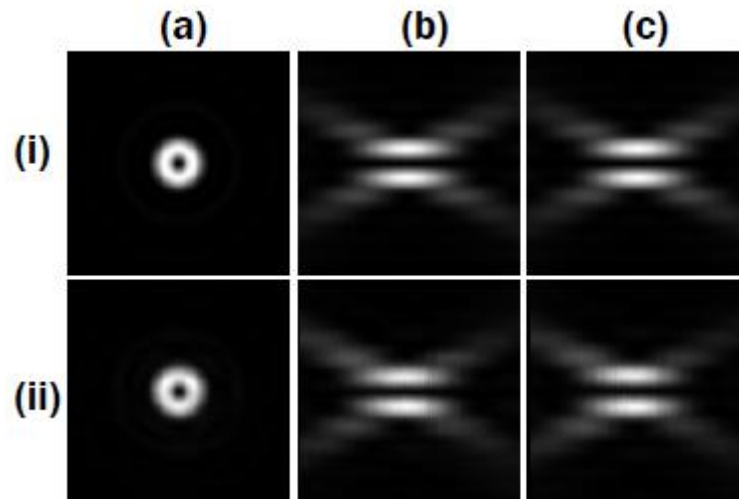


Figure 2. Intensity distribution of an azimuthally polarized beam in the (a) XY, (b) XZ and (c) YZ planes in the aberration free case, obtained (i) theoretically and (ii) experimentally.

2.2. Experimental Arrangement

There are several available methods to generate cylindrical vector beams, for instance, from two orthogonally polarized TEM_{01} modes [Tidwell et al., 1990], and from two circularly polarized beams [Bomzon and Hasmen, 2000]. However, by using these methods we can generate only specific types of vector beams. On the other hand there are reports that discuss the generation of cylindrical vector beams using spatial light modulators (SLMs) [Moreno et al, 2012, Rong et al, 2014, Wang et al., 2007] which can very well exploit the reconfigurability of the SLM device. However the vector beams using these schemes have a maximum power that is limited by the damage threshold of the SLM, while in a number of applications the energy of the beam plays an important role [Zhan, 2009]. We recently developed an experimental setup to generate arbitrary vector beams [Kalita, et al., 2016] using a single SLM. Here the arbitrary vector beam is generated using a division of wave front arrangement which facilitates efficient exploitation of the damage threshold of the SLM device. In this scheme a computer generated holography (CGH) technique [Neil, et al., 2000, Boruah, 2009] is used to generate a user defined complex amplitude profile corresponding to a linearly (say X) polarized beam. Thus by displaying two holograms side by side on the SLM panel it is possible to

generate two X polarized beams with user defined amplitude and phase profiles. These two beams travel through two different arms to have mutually orthogonal polarization states. This is achieved by introducing a half wave plate in one of the arms. Finally the vector sum of these two beams is realized via a polarizing beam splitter to generate the required vector beam. The vector beam is then focused by a lens onto a CCD camera. The setup thus can be used to generate a cylindrical vector beam whose pupil plane can optionally be aberrated with a Zernike mode aberration. The setup also has the provision of recording the focal intensity distribution not just over the nominal focal plane but also other planes parallel to the focal plane.

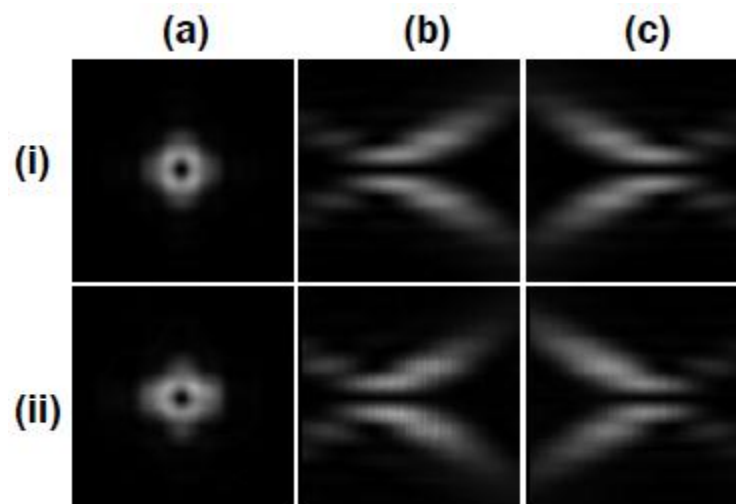


Figure 3. Intensity distribution of an azimuthally polarized beam in the (a) XY, (b) XZ and (c) YZ planes in the presence of primary astigmatism, obtained (i) theoretically and (ii) experimentally.

3. Results and Discussion

By using the above experimental arrangement an azimuthally polarized beam is generated and is focused by a low numerical aperture (NA) lens with $NA=0.0056$. The same numerical aperture is employed to compute the focal intensity distributions using the vectorial diffraction theory implemented in a Matlab Programme. The experimental and theoretical results compared with one other. In our investigation the intensity distributions in the focal volume extend over a volume described by $\Delta V, \Delta U = 38$ (where U and V are normalized optical co-ordinates along the transverse and optical axes), with the nominal focus as the centre of the volume. To investigate the effect of primary aberrations on the azimuthally polarized beam we have considered primary aberrations such

as primary astigmatism, primary coma, primary trefoil and primary spherical aberration. Zernike polynomials representation of these primary aberrations are shown in the table I. Focal intensity distributions are presented in three mutually orthogonal planes such as, XY plane which is also the focal plane, XZ plane (a plane passing through the optical axis and the X axis) and YZ plane (a plane passing through the optical axis and the Y axis). For all the planes the nominal focus is taken as the origin. The intensity distributions in the aberration free case as well as in the presence of aberrations are normalized by the respective maximum value of the total intensity in the aberration free case.

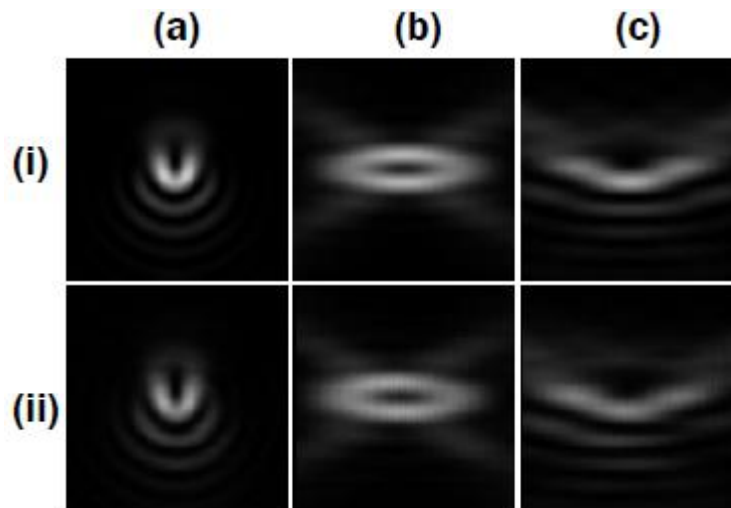


Figure 4. Intensity distribution of an azimuthally polarized beam in the (a) XY, (b) XZ and (c) YZ planes in the presence of primary coma, obtained (i) theoretically and (ii) experimentally.

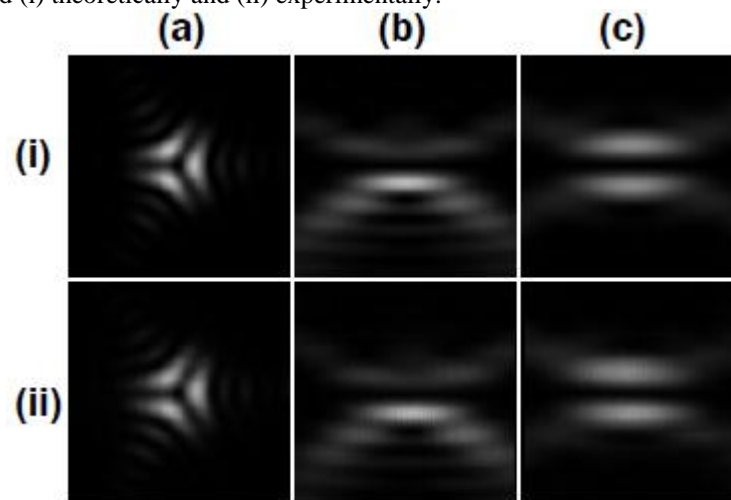


Figure 5. Intensity distribution of an azimuthally polarized beam in the (a) XY, (b) XZ and (c) YZ planes in the presence of primary trefoil, obtained (i) theoretically, and (ii) experimentally.

Figure 2 shows the intensity distribution of an azimuthally polarized beam in the (a) XY, (b) XZ and (c) YZ planes in the aberration free case, obtained (i) theoretically and (ii) experimentally. It is noticed that the Z polarized field component of an azimuthally polarized beam near the focus is zero and only X, Y polarized components contribute to the total intensity. The beam, in the focal plane has a circular symmetry and, in the XZ and YZ planes, have planar symmetry with respect to the optical and transverse axes.

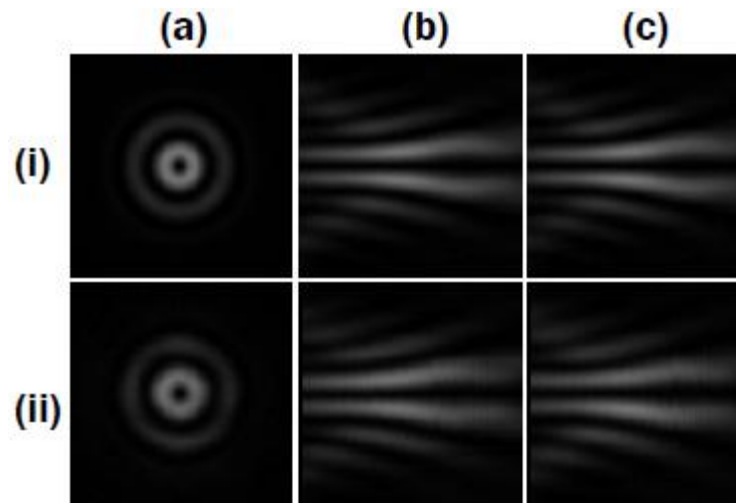


Figure 6. Intensity distribution of an azimuthally polarized beam in the (a) XY, (b) XZ and (c) YZ planes in the presence of primary spherical aberration, obtained (i) theoretically and (ii) experimentally.

Figure 3 shows the (i) theoretically and (ii) experimentally obtained intensity distributions of an azimuthally polarized beam in the (a) XY, (b) XZ and (c) YZ planes in the presence of primary astigmatism with RMS amplitude of 1 radian. It is noticed that in the presence of astigmatism also there is no intensity at the focal point as well as along the optical axis. However there is a disappearance in the circular symmetry of the intensity distribution in the focal (XY) plane, and as a result the intensity distribution has a four fold planar symmetry. In the XZ and YZ planes the intensity distributions are symmetric only with respect to optical axis. It is further noticed that there is a 180 degree rotation in XZ and YZ plane intensity distributions if we apply oppositely signed RMS amplitude.

Figure 4 shows the intensity distribution of an azimuthally polarized beam in the (a) XY, (b) XZ and (c) YZ planes in the presence of primary coma with RMS amplitude of 1 radian, obtained (i) theoretically and (ii) experimentally. Here we can see that in the presence of coma there is non-zero

intensity at the focal point and also along the optical axis. In the XY plane the circular symmetry of the focal spot is distorted and as a result it has one fold planer symmetry. In the XZ plane there exists a maximum intensity at two locations on the optical axis and in the YZ plane the intensity distribution exists only below the optical axis. In the XZ plane the intensity distribution is symmetric with respect to the transverse and optical axes, while in the YZ plane the intensity distribution is symmetric only with respect to transverse axis. The intensity distributions in the XZ and YZ planes in fact indicate the formation of a boat-shaped beam in the focal volume [Gaffar and Boruah, 2014].

Figure 5 shows the intensity distribution of an azimuthally polarized beam in the (a) XY, (b) XZ and (c) YZ planes in the presence of primary trefoil with RMS amplitude equal to 1 radian, obtained (i) theoretically and (ii) experimentally. It is noticed that in the presence of trefoil also there is no intensity at the focal point as well as along the optical axis. In the XY plane the intensity distribution has a 3 fold planar symmetry while in the XZ plane the intensity mainly exists below the optical axis. Thus in the XZ plane the intensity distribution has symmetry with respect to transverse axis and in the YZ plane it is symmetric with respect to the transverse and optical axes. Figure 6 shows the (i) theoretically and (ii) experimentally obtained intensity distributions of an azimuthally polarized beam in the (a) XY, (b) XZ and (c) YZ planes in the presence of primary spherical aberration with RMS amplitude of 1 radian. We see that in the focal plane the intensity distribution has a circular symmetry. Moreover in the XZ and YZ planes there is no intensity along the optical axis and the intensity distributions are symmetric with respect to the optical axis. Further as we go from left to right along the optical axis, the radius of the dark region increases gradually.

Comparing the theoretically and experimentally obtained intensity distributions in all the figures (i.e. Figures 2, 3, 4, 5, and 6) it is obvious that the experimental findings are very correctly predicted by the theory. Close similarity of the two results thus confirms the accuracy of the experimentally observed aberration effects on the focal intensity distribution of the azimuthally polarized beam.

4. Conclusion

In this paper we experimentally demonstrated the effect of primary aberrations on an azimuthally polarized beam under low numerical aperture focusing condition. Here we noticed that the primary astigmatism, coma and trefoil distort the circular symmetry of the focal spot while in the presence of

spherical aberration it maintains the circular symmetry. We also observed that in the presence of coma there appears some intensity along the optical axis. Thus all primary aberrations are to some extent affecting the intensity distribution of an azimuthally polarized beam, nevertheless, the effect of coma is more significant. Our experimental results agree very well with the theoretical results obtained under the same focusing condition. Our observations are expected to benefit applications related to optical trapping. The exact effect of aberrations on the optical trap using azimuthally polarized beam was not considered in this paper, however, the same can be a subject matter of a future investigation.

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