## Polarization characterization in the focal volume of high numerical aperture objectives

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**Abstract:** In this paper the polarization states of linearly and radially polarized plane wave and doughnut beams in the focal volume of high numerical aperture objectives are studied. Through manipulating the incident polarization states of laser beams as well as the apodization of an objective and adjusting the numerical aperture of an objective, focal fields dominantly with either one transverse component or one longitudinal component can be generated. Furthermore, tailored polarization distributions with three polarization components of the same strength are also found.

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#### **References and links**

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### 1. Introduction

Nowadays, high numerical aperture (NA) objectives have been extensively applied in optical systems to achieve highly localized fields of light in diverse disciplines, including optical microscopy and spectroscopy, nonlinear optical imaging, laser trapping and manipulations, micro/nano optical fabrication, optical data storage, laser diagnostics and therapy and plasmonic wave excitation [1–11]. Since most of these applications are polarization sensitive, it is highly motivated to investigate the polarization states in the focal volume of high NA objectives in order to understand better the light matter interactions.

A high NA objective normally refers to objectives with NA larger than 0.7 [12]. Under such a circumstance, the vectorial properties of light cannot be ignored any more. The vectorial Debye theory is necessary to accurately represent the field distribution in the focal volume of an objective. In the past several years, the field distributions in the focal volume of high NA objectives have been intensively studied under different apodization and laser mode illumination [13–17]. It was revealed that due to the tight focusing of a laser beam, the longitudinal polarization component can be induced, which complicates the overall field distributions. For example, the focal spot of a linearly polarized beam focused by a high NA objective can be split into two if annular illumination is applied [16,17]. In contrast to the intensive attention to the field distributions, there are only limited investigations on the polarization sparticular to single molecular detection and gold nanorod mediated data storage and biomedical imaging, diagnostics and therapy [5,9–11,19].

In this paper, by using the vectorial Debye diffraction theory [12], we investigate the polarization distributions in the focal volume of high NA objectives under the illumination of a series of popular laser beams, including linearly and radially polarized plane wave and doughnut beams. Through adjusting the incident polarizations of laser beams, the apodization of an objective and the NA of an objective, focal fields with either a dominant transverse component or a longitudinal component can be generated, providing a means of light-matter interaction with one particular polarization component in the focal volume. In addition, it is discovered that polarization distributions with three polarization components of the same strength are possible. This finding may prove useful for the highly efficient excitation of gold nanorod mediated data storage and biomedical imaging, diagnostics and therapy, because a beam with a similar polarization strength in three directions can provide a higher probability to interact with the three-dimensionally randomly oriented gold nanorods in the focal volume [9-11,20].

### 2. Electromagnetic field distributions in the focal volume

Figure 1 illustrates a radially polarized wave focused by a NA objective through an interface. z is the cylindrical coordinate of an observation point. In the paper, the interface is assumed to be at z = 0. Therefore, in the vectorial Debye diffraction theory, the electromagnetic (EM) field distribution of a monochromatic radially polarized doughnut beam in the focal volume of an objective through a dielectric interface can be expressed as Eq. (1) [12,14,15].

## $\boldsymbol{E}(r,\psi,z) = \frac{i}{\lambda_1} \int_{\alpha_1}^{\alpha_2} \int_{0}^{2\pi} \sqrt{\cos\theta_1} \exp(in\varphi) \exp[-ik_1 r \sin\theta_1 \cos(\varphi - \psi)] \exp(-ik_2 z \cos\theta_2)$ (1) ( $t_p \cos\theta_2 \cos\varphi \mathbf{i} + t_p \cos\theta_2 \sin\varphi \mathbf{j} + t_p \sin\theta_2 \mathbf{k}) \sin\theta_1 d\theta_1 d\varphi$

where *i*, *j* and *k* are the unit vectors in the *x*, *y* and *z* directions respectively.  $\varphi$  is the azimuthal coordinate on the spherical surface of an objective. *r* and  $\psi$  are the cylindrical coordinates of an observation point.  $\lambda_1$  is the wavelength in medium 1.  $\alpha_1$  represents the minimal angle of convergence for an objective and  $\alpha_2$  is the maximal angle of convergence determined by the NA of an objective.  $\varepsilon$  is defined as  $r_1/r_2$  (Fig. 1). Therefore,  $\alpha_1$  equals to  $Arcsin(\varepsilon \times NA/n_1)$  and  $\alpha_2$  can be expressed as  $Arcsin(NA/n_1)$ . If full aperture illumination is used,  $\varepsilon$  is equal to 0 and the integration for  $\theta_1$  ranges from 0 to  $\alpha_2$ .  $t_p$  is the amplitude transmission coefficient for the parallel polarization state [21] which is denoted as  $t_p = 2\sin\theta_2\cos\theta_1/[\sin(\theta_1 + \theta_2)\cos(\theta_1 - \theta_2)]$ . *n* is the topological charge of a doughnut beam. The intensity and the EM field strength mentioned in the paper are calculated from Eq. (1) and can be expressed as  $|E|^2$  and |E|, respectively.



Fig. 1. Schematic focusing of a radially polarized beam.  $\theta_1$  is the angle of convergence on the spherical surface of an objective and  $\theta_2$  is the angle of refraction at the interface.  $n_1$  and  $n_2$  are the refractive indices in media 1 and 2 before and after an interface, respectively. *f* is the focal length of the objective.  $r_1$  is the radius of obstructed part of the incident beam.  $r_2$  is the radius of the objective aperture. *d* is the distance between the interface and the observation plane.

# 3. Polarization distributions in the focal volume of linearly and radially polarized plane wave beams

Considering a general scenario in biophotonics system where the refractive index of samples is close to that of water, a linearly polarized (along the x direction) plane wave ( $\lambda = 780$  nm) is focused by high NA (NA = 1.0-1.4) immersion objectives at a coverglass/water interface ( $n_1/n_2 = 1.515/1.33$ ). Figure 2 presents the peak intensity ratio of the longitudinal component ( $I_z$ ) and the transverse y component ( $I_y$ ) versus the transverse x component ( $I_x$ ) in the focal volume. It can be clearly seen for a linearly polarized beam  $I_z$  becomes stronger as the NA increases due to the increasing depolarization effect [12]. However, even when NA is 1.4,  $I_z$  is only approximately 30% of  $I_x$  and the transverse y component  $I_y$  is still almost two orders of magnitude weaker than  $I_x$ , which means that the  $I_x$  component is dominant in the focal volume under linear polarization illumination.

It is well-known that the annular apodization of a beam can enhance the longitudinal component [12,22,23] which provides a way to manipulate the relative strength of each polarization component in the focal volume to realize either a polarization state dominantly along the longitudinal direction or a three-dimensional (3D) polarization state with a similar strength for the *x*, *y* and *z* components. In Fig. 2(b), the peak intensity  $I_z$  and  $I_y$  versus  $I_x$  are plotted for an objective of NA 1.3 at a coverglass/water interface  $(n_1/n_2 = 1.515/1.33)$  with different normalized annular sizes. Under linear polarization illumination, compared with full

aperture illumination case ( $\varepsilon = 0$ ),  $I_z$  increases to 67% of  $I_x$  in the focal volume for  $\varepsilon$  of 0.9. But  $I_y$  is only 5% of  $I_x$ .



Fig. 2. (a) Peak intensity ratio of  $I_2/I_x$  and  $I_3/I_x$  versus NA ranging from 1.0 to 1.4 at a coverglass/water interface  $(n_1/n_2 = 1.515/1.33)$  under linear and radial polarization illumination, respectively. (b) Peak intensity ratio of  $I_2/I_x$  and  $I_3/I_x$  versus  $\varepsilon$  with an objective of NA 1.3 at a coverglass/water interface  $(n_1/n_2 = 1.515/1.33)$  under linear and radial polarization illumination, respectively. Note: Peak intensity ratios of  $I_2/I_x$  under linear polarization illumination in (a) and (b) are 10 times magnified.

To make the y polarization component stronger, radially polarized beams, which have an equal strength for the x and y components in free space, can be employed. In the case of a tightly focused radially polarized beam, the longitudinal component is dominant in the focal volume. As shown in Fig. 2(a), even when NA is approximately 1,  $I_z$  is almost 1.5 times of  $I_x$ . So under the condition of NA larger than 1, it is impossible to achieve an equal strength for the three polarization components in the focal volume by further annular apodization. But it is worthwhile mentioning that by using an objective of NA 1.3  $I_z$  is 4.5 times of  $I_x$  ( $I_y$ ) for full aperture illumination ( $\varepsilon = 0$ ) and more than 20 times stronger than  $I_x$  ( $I_y$ ) when an annular beam with  $\varepsilon$  of 0.9 is used. In such a case, the radially polarized beam has the capability to interact with media with the longitudinal polarization.

Figure 3 presents the polarization distributions in the focal volume of an objective at a coverglass/water interface  $(n_1/n_2 = 1.515/1.33)$  for linear (NA = 1.1, full aperture ( $\varepsilon = 0$ )) and radial polarization illumination (NA = 1.3,  $\varepsilon = 0.8$ ). The arrows in the figures result from the projection of the 3D spatially distributed EM field in the corresponding intensity planes and their length represents the strength of the EM field vectors. It can be seen that the *x* component is dominating in the focal volume under linear polarization illumination [Figs. 3(a)–3(b)] while the *z* component is much stronger than the transverse component under radial polarization illumination [Figs. 3(c)–3(d)].

From Fig. 2(a) it can be seen that when NA is larger than 1, the radially polarized beam is not capable of generating three polarization components with a similar strength. However, it is possible when the beam is focused by a comparatively low NA objective. In Fig. 4(a) the peak intensity ratio of  $I_z$  to  $I_x$  is plotted as a function of NA (0<NA<1). When NA is approximately 0.65, a peak intensity ratio ( $I_z:I_x:I_y$ ) of 1:1:1 is achieved in the focal volume with a full width at the half maximum (FWHM) of 1.43 µm in the *x-y* plane. The three polarization components of the same strength can also be generated through the annular apodization of an objective with even lower NA. For example, as shown in Fig. 4(b), by employing an objective with NA = 0.6 and  $\varepsilon$  = 0.6, a focal field with the three polarization components of an equal strength can be obtained.



Fig. 3. Intensity and polarization distributions at a coverglass/water interface  $(n_1/n_2 = 1.515/1.33)$  in the focal volume. (a) and (b) are the EM field vectors projected in the *x*-*y* and the *x*-*z* planes, respectively, for NA = 1.1 and  $\varepsilon = 0$  under linear polarization illumination. (c) and (d) are the EM field vectors projected in the *x*-*y* and the *x*-*z* planes, respectively, for NA = 1.3 and  $\varepsilon = 0.8$  under radial polarization illumination. The maximal intensity is normalized to 1 for each case.



Fig. 4. (a) Peak intensity ratio of  $I_z/I_x$  ( $I_z/I_y$ ) and FWHM versus NA (0<NA<1) under radial polarization illumination. (b) Peak intensity ratio of  $I_z/I_x$  ( $I_z/I_y$ ) and FWHM versus  $\varepsilon$  under radial polarization illumination for NA of 0.6.

Figure 5 shows the polarization distributions in the focal volume of a radially polarized beam focused by an objective with NA = 0.65 and full aperture ( $\varepsilon = 0$ ). It can be seen that the EM field is radially polarized in the transverse *x*-*y* plane and the *x*, *y* and *z* components have a similar strength. In the *x*-*z* plane, the polarization of the EM field is rather complicated. The part on the optical axis is longitudinally polarized but the off-axis part is almost transversely polarized. Through composition of these three components of a similar strength, the 3D polarization state can be realized.



Fig. 5. Intensity and polarization distributions under radial polarization illumination with NA = 0.65 and  $\varepsilon$  = 0 in the focal volume. The arrows in (a) and (b) are the EM field vectors projected in the *x*-*y* and the *x*-*z* planes, respectively. The maximal intensity is normalized to 1.

# 4. Polarization distributions in the focal volume of linearly and radially polarized doughnut beams

Due to the advantage of carrying orbital angular momentum and a reduced heating effect to the trapping objects, doughnut beams have been extensively employed in laser trapping and manipulations of micro/nano objects [24], in which high NA objectives are essential to realize a large enough field gradient. It has been found that the depolarization effect associated with high NA objectives causes a pronounced impact on the EM field distributions of doughnut beams in the focal volume, which in turn affects the trapping behaviors [25,26]. Therefore, it is also of great importance to investigate and manipulate the polarization distributions in the focal volume of doughnut beams.

Figure 6 shows the peak intensity ratio of  $I_z$  to  $I_x$  as a function of NA lower than 1 and higher than 1 for linearly polarized doughnut beams of topological charges 1 and 2. The peak intensity ratio increases with NA for both the low NA and high NA cases and can range from 0 to 0.8. To generate polarization dominating in the x direction and in the mean time maintain the high resolution of the system, it is preferred to use objectives with NA approximately equal to 1.0 at a coverglass/water interface ( $n_1/n_2 = 1.515/1.33$ ) as shown in Fig. 6(b), where the longitudinal component is only less than 30% of the x polarization component.



Fig. 6. (a) Peak intensity ratio of  $I_z/I_x$  and  $I_y/I_x$  versus NA (0<NA<1) for a linearly polarized beam of topological charges 1 and 2. (b) Peak intensity ratio of  $I_z/I_x$  and  $I_y/I_x$  versus NA ranging from 1.0 to 1.4 at a coverglass/water interface  $(n_i/n_2 = 1.515/1.33)$  for a linearly polarized beam of topological charges 1 and 2. (c) Peak intensity ratio of  $I_z/I_x$  and  $I_y/I_x$  versus c for NA 1.3 at a coverglass/water interface  $(n_i/n_2 = 1.515/1.33)$  for a linearly polarized beam of topological charges 1 and 2. (c) Peak intensity ratio of  $I_z/I_x$  and  $I_y/I_x$  versus c for NA 1.3 at a coverglass/water interface  $(n_i/n_2 = 1.515/1.33)$  for a linearly polarized beam of topological charges 1 and 2.

The fact that the strength of the longitudinal component reaches 0.6 for an objective with NA of 1.3 under full aperture illumination ( $\varepsilon = 0$ ) suggests that it is possible to achieve an equal strength for the x and z components in the focal volume by using annular illumination. As shown in Fig. 6(c), at  $\varepsilon = 0.9$ , the strength of the z component is similar to that of the x component. But it is still impossible to make the y component as strong as the x component.

For radially polarized beams of topological charges 1 and 2, the longitudinal component becomes dominant in the focal volume. For example, the peak intensity ratio for topological charge 2 can reach up to 2.25 for objectives with NA lower than 1 without an interface [Fig. 7(a)] and up to 4 for objectives with NA higher than 1 at a coverglass/water interface  $(n_1/n_2 = 1.515/1.33)$  [Fig. 7(b)]. Under such a circumstance, the longitudinal dominant polarization can be easily achieved by further using the annular illumination, as shown in Fig. 7(c).



Fig. 7. (a) Peak intensity ratio of  $I_2/I_x$  ( $I_2/I_y$ ) versus NA (0<NA<1) for a radially polarized beam of topological charges 1 and 2. (b) Peak intensity ratio of  $I_2/I_x$  ( $I_2/I_y$ ) versus NA ranging from 1.0 to 1.4 at a coverglass/water interface (( $n_1/n_2 = 1.515/1.33$ ) for a radially polarized beam of topological charges 1 and 2. (c) Peak intensity ratio of  $I_2/I_x$  ( $I_2/I_y$ ) versus  $\varepsilon$  for NA 1.3 at a coverglass/water interface ( $n_1/n_2 = 1.515/1.33$ ) for a radially polarized beam of topological charges 1 and 2.



Fig. 8. Intensity and polarization distributions under radially polarized doughnut beam illumination with an objective of NA = 1.3 and  $\varepsilon$  = 0.8 at a coverglass/water interface ( $n_1/n_2$  = 1.515/1.33) in the focal volume. (a) and (b) are the EM field vectors projected in the *x*-*y* and the *x*-*z* planes for topological charge 1. (c) and (d) are the EM field vectors projected in the *x*-*y* and the *x*-*z* planes for topological charge 2. The maximal intensity is normalized to 1 for each case.

In Fig. 8 the intensity and polarization distributions of an objective with NA = 1.3 and  $\varepsilon$  = 0.8 under radially polarized doughnut beam illumination at a coverglass/water interface  $(n_l/n_2)$ 

= 1.515/1.33) are presented. The radially polarized beam of topological charge 1 looses its zero intensity on the beam axis [Fig. 8(a)] owing to the contribution from the transverse component [Fig. 8(b)]. For topological charge 2, a ring shaped focal spot appears as shown in Figs. 8(c) and 8(d). It can be clearly seen from Fig. 8(d) that the longitudinal component is dominant in the focal volume. This beam may find promising applications in particle acceleration [27]. When the topological charge becomes larger, the central intensity regains zero and the area of the singularity increases.

In addition, the polarization distributions with an equal strength in the *x*, *y* and *z* directions in the focal volume of radially polarized beams can be achieved under full aperture illumination ( $\varepsilon = 0$ ) only for the high NA case. For example, for topological charge 1, the *x*, *y* and *z* components acquire a similar strength at a coverglass/water interface ( $n_1/n_2 =$ 1.515/1.33) when NA of approximately 1.25 is used [Figs. 9(a) and 9(b)]. For topological charge 2, when NA is approximately 1.1, a 3D polarization distribution with a similar strength in the *x*, *y* and *z* directions can be obtained at a coverglass/water interface ( $n_1/n_2 =$ 1.515/1.33) [Figs. 9(c) and 9(d)].



Fig. 9. Intensity and polarization distributions under radially polarized doughnut beam illumination at a coverglass/water interface  $(n_1/n_2 = 1.515/1.33)$  for a similar strength of the *x*, *y* and *z* components in the focal volume. (a) and (b) are the EM field vectors projected in the *x*-*y* and the *x*-*z* planes for topological charge 1 with NA = 1.25 and  $\varepsilon = 0$ . (c) and (d) are the EM field vectors projected in the *x*-*y* and the *x*-*z* planes for topological charge 2 with NA = 1.1 and  $\varepsilon = 0$ . The maximal intensity is normalized to 1 for each case.

#### 5. Conclusions

In conclusion, by adjusting the incident polarization modes, the annular apodization and the NA of an objective, the strength of the transverse and the longitudinal light components can be manipulated to generate an EM field polarizing almost along one direction in the focal volume. Moreover, 3D polarization distributions with a similar strength in the x, y and z directions in the focal volume have been achieved, providing a useful insight into diverse polarization sensitive applications.

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