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Bessel beams: Effects of polarization

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ABSTRACT

An approximation to a Bessel beam produced by tightly focusing linearly polarized light is known to produce a smaller central lobe than focusing plane polarized light. This is because the plane polarized wave gives a broad central lobe caused mainly by a parasitic longitudinal field component. It is known that this problem can be overcome by focusing radially polarized light. Here we demonstrate that other polarization distributions based on a linear combination of transverse electric (TE1) and transverse magnetic (TM1) fields can give a beam even narrower than for the radially polarized case. Special cases of this combination are identified, corresponding to the smallest width (TE1), and the maximum peak intensity compared with the side lobes (electric dipole polarization). Axially-symmetric forms can be generated by illumination with elliptically polarized light. A particular case is azimuthal polarization with a phase singularity, which is equivalent to TE1. For a semi-angular aperture of 60°, the TE1 case gives a central lobe width 9% narrower than for radially polarized illumination, while for plane polarized illumination it is 12% wider than the radially polarized case.

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1. Introduction

Bessel beams (so-called non-diffracting, or diffraction-free beams) combine the desirable properties of a small focal spot with a very long depth of focus [1–6]. They have many potential applications, such as in the physics of optical/atom interactions, microlithography, materials processing, data storage and microscopy. A Bessel beam is a rigorous solution of the wave equation, and approximations to it can be produced by various methods, including placing a narrow annulus in the front focal plane of a lens [1,4–6], using an axicon (a conical prism) [2], or using a diffractive optic structure [3]. A large angle of convergence is required to achieve a small Bessel beam, and then polarization effects become significant. So what polarization is the best for producing a Bessel beam? If linearly polarized light is focused by a lens of high aperture with an annular pupil to generate a Bessel beam, cross components of polarization, especially the longitudinal field component, increase the size of the focal spot, and cause the central lobe to split into two [5] (also reproduced in Ref. [7]). Fontana and Pantel [8] proposed using a Bessel beam with strong longitudinal electric field component for particle acceleration. This corresponds to a Bessel beam formed by tight focusing of radially polarized light [9], and called here a radially polarized Bessel beam for simplicity. Many recent papers [9–15] have shown how radially polarized light can be used to give a smaller focal spot than linearly polarized light, but this work demonstrates that other polarizations of the input electric field can give Bessel beams with even smaller cross-section. In addition, in some applications, for example excitation of a transversely oriented dipole, a transverse, rather than a longitudinal, on-axis electric field is desirable, so it is necessary to consider focusing of other polarizations than radial polarization.

2. Polarized Bessel beams

Bessel beams are solutions of Maxwell's equations. In this section we consider the field structure of the Bessel beams, without considering any particular method of generating them. The TEm, TMm modes of a circular metallic waveguide, where m is the angular mode number [16,17], are equivalent to Bessel beams. The TM0 and TE0 waveguide modes both exhibit a dark central spot for low apertures, with a predominantly radial or azimuthal electric field, respectively, but the TM0 mode develops a strong on-axis longitudinally polarized electric field for high apertures [8,9,16,17]. The TM0 and TE0 modes correspond to the radially and azimuthally polarized cases, respectively: Grosjean and Courjon [15] pointed out that radially polarized illumination only gives a narrow Bessel

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beam for numerical apertures greater than 0.8. A similar behaviour is known to occur for focusing by a lens with a circular aperture [11–14].

Any polarized Bessel beam can be considered as a superposition of TE and TM modes. Focusing plane polarized light by a lens introduces cross polarization components with an azimuthal variation of first order in cylindrical coordinates, so here we consider a combination of the first order modes, TE1 and TM1. Higher azimuthal orders do not result in a zero order Bessel term, and so do not produce a beam with a bright centre [9]. We consider radiation polarized approximately in the x direction with unit vector $\mathbf{i}$. The optical axis is taken in the z direction, given by unit vector $\mathbf{k}$, and the y axis has unit vector $\mathbf{j}$. The angle φ is the azimuthal angle about the z axis measured from the x axis. The electric field of transverse electric (TE1) and transverse magnetic (TM1) Bessel beam can be written

$$\begin{aligned} E_x &= I_0 + I_2\cos 2\varphi, \\ E_y &= I_2 \sin 2\varphi, \\ E_z &= -2iI_1\cos\varphi, \end{aligned} \tag{1}$$

where for TE1

$$\begin{aligned} I_0 &= J_0(kr\sin\alpha)e^{ikz\cos\alpha}, \\ I_1 &= 0, \\ I_2 &= J_2(kr\sin\alpha)e^{ikz\cos\alpha}, \end{aligned} \tag{2}$$

and for TM1

$$\begin{aligned} I_0 &= \cos\alpha J_0(kr\sin\alpha)e^{ikz\cos\alpha}, \\ I_1 &= \sin\alpha J_1(kr\sin\alpha)e^{ikz\cos\alpha}, \\ I_2 &= -\cos\alpha J_2(kr\sin\alpha)e^{ikz\cos\alpha}, \end{aligned} \tag{3}$$

with J_n a Bessel function of the first kind of order n, r the cylindrical radius and α the semi-angular aperture of the beam. These equations represent a Bessel beam that propagates over an unlimited distance without spreading, as the transverse variation in the field is independent of the axial coordinate z.

For a linear combination consisting of a TE1 beam of (amplitude) strength $(1+S)(1+\cos\alpha)$ and a TM1 beam of strength $(1-S)(1+\cos\alpha)$, we have

$$\begin{aligned} I_0 &= (1+St^2)J_0(kr\sin\alpha)e^{ikz\cos\alpha}, \\ I_1 &= (1-S)tJ_1(kr\sin\alpha)e^{ikz\cos\alpha}, \\ I_2 &= (S+t^2)J_2(kr\sin\alpha)e^{ikz\cos\alpha}, \end{aligned} \tag{4}$$

where $t = \tan(\alpha/2)$. Then $S = 1$ corresponds to a pure TE1 beam of strength $4/(1+t^2)$, and analogously for the TM1 beam with $S = -1$. The case when $S = 0$, corresponding to TE1 and TM1 components of equal strength, gives a Bessel beam with the same polarization as would be produced by focusing plane polarized light [5]:

$$\begin{aligned} I_0 &= (1+\cos\alpha)^2 J_0(kr\sin\alpha)e^{ikz\cos\alpha}, \\ I_1 &= (1+\cos\alpha)\sin\alpha J_1(kr\sin\alpha)e^{ikz\cos\alpha}, \\ I_2 &= (1-\cos^2\alpha)J_2(kr\sin\alpha)e^{ikz\cos\alpha}. \end{aligned} \tag{5}$$

It has been shown that the polarization of the angular spectrum needed to generate this case is the same as that of the sum of the electric fields of an electric dipole oriented along the x axis and a magnetic dipole oriented along the y axis (as might be expected from consideration of the symmetry of electric and magnetic fields) [5,7]. This has been called a mixed dipole field. Although the polarization is the same as for focusing plane polarized light, the absolute value of the amplitude is different. The electric or magnetic dipole fields alone correspond to $S = t^2$ and $S = -t^2$, respectively. It has been demonstrated elsewhere that some improvement in focusing with a circular pupil can be achieved by generating the polarization of an electric dipole alone [18,19], which couples more efficiently to the electric field at the focus. We find that the effects are much stronger for the Bessel beam than for the case of a circular pupil, because the angular spectrum is concentrated at high angles of incidence. Expansion into electric/magnetic dipole fields can be considered as the lowest orders of a multipole expansion, higher orders of which do not contribute to the field at the focus. A combination of transverse electric and magnetic dipole fields is equivalent to a combination of TE1 and TM1 fields, so the two expansions are equivalent.

The magnetic dipole field is identical to the well-known hybrid HE1 mode of dielectric waveguides [20]. For dielectric optical fibres, the HE1 and EH1 modes can be considered to be composed of TE1 and TM1 components. The relative strength of the magnetic to electric longitudinal field components is given by the parameter P [20], where

$$S = -\frac{P+\cos\alpha}{P-\cos\alpha}. \tag{6}$$

For $S = -1/t^2$, $P = 1$, which gives a polarization singularity of charge two in the focused field [21]. This corresponds to the EH1 mode of a dielectric waveguide far from cut-off. The HE1 mode ($P = -1$, $S = -t^2$) corresponds to the magnetic dipole case.

The time-averaged electric energy density of the beam is [22]

$$W_E = \left(I_0^2 + 2I_1^2 + I_2^2\right) + \left(I_1^2 + I_0 I_2\right)\cos 2\varphi. \tag{7}$$

If we average the electric energy density over all angles, the cosine term cancels out [22]:

$$W_E = I_0^2 + 2I_1^2 + I_2^2. \tag{8}$$

In general, I_1 controls the width of the central lobe, and I_2 the strength of the first bright ring.

As for the case of circular pupils [23,24], we can introduce various performance parameters to describe the properties of the Bessel beams. The parabolic central lobe is of the form

$$W_E = 1 - \frac{1}{3}\left[G_x(kx)^2 + G_y(ky)^2\right], \tag{9}$$

where G_x, G_y are called the transverse gains. The normalization of these gain parameters is chosen so that they are unity for a complete spherical scalar field, which exhibits an intensity variation $[\sin kr/(kr)]^2 \approx 1-(kr)^2/3$ in the focal region. The transverse gain averaged over all angles is $G_T = (G_x + G_y)/2$. Then the harmonic mean transverse width of the parabolic focal spot is proportional to $1/\sqrt{G_T}$. The gains can be calculated by expanding the Bessel functions in power series [25]. Fig. 1 shows the behaviour for different types of Bessel beam. It is seen that for all values of $\alpha \neq 90^\circ$ the value of G_T is greater for the TE1 case than the radially polarized case, so that the width of the central lobe is slightly smaller. We can show analytically that the harmonic mean full width at half maximum (FWHM) of the central lobe is minimized for any combination of TE1 and TM1 at $S = 1$, corresponding to the TE1 case, for any value of angular aperture.

For circular pupils, another useful parameter is the ratio of the intensity at the focus to the total integrated intensity over the focal plane. This parameter is not appropriate for Bessel beams as a consequence of the infinite total energy in the side lobes. Instead, we introduce a new parameter. From Eqs. (4) and (8), the electric energy density of the outer rings relative to the paraxial case (which we call SL) is

$$SL = \frac{(1+S^2)(1+t^2)^2}{(1+St^2)^2}. \tag{10}$$

By differentiation of Eq. (10), we see that the strength of the outer rings for any combination of TE1 and TM1 is minimized for

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