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Highly localized accelerating beams using nano-scale metallic gratings

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ABSTRACT

Spatially accelerating beams are non-diffracting beams whose intensity is localized along curvilinear trajectories, also incomplete circular trajectories, before diffraction broadening governs their propagation. In this paper we report on numerical simulations showing the conversion of a high-numerical-aperture focused beam into a nonparaxial shape-preserving accelerating beam having a beam-width near the diffraction limit. Beam shaping is induced near the focal region by a diffractive optical element that consists of a non-planar subwavelength grating enabling a Bessel signature.

1. Introduction

The accelerating optical beam belongs to a novel class of electromagnetic wave whose peak intensity follows a curved trajectory as it propagates in free space. Since the first accelerating beam proposed within a paraxial context and propagating along parabolic trajectories [1], more general classes of solutions have been obtained including elliptical trajectories [2,3], hyperbolic trajectories [4], and practically any arbitrary trajectory [5]. Recently Kaminer et al. presented nonparaxial spatially accelerating shape-preserving beams, which are solutions to the full Maxwell equations and propagate along a circular trajectory reaching angles near 90°, after which diffraction broadening takes over and the beams spread out [6]. Experimental evidences of these incomplete Bessel wave fields have been reported in Ref. [7]. In these studies, the caustic-curve radius driving the beam trajectory of the accelerating beam is several orders of magnitude higher than the wavelength. This leaves the open question of the generation of accelerating circular beams with a caustic curve radius near the wavelength, and its influence over the beam width approaching the diffraction limit.

In this paper we demonstrate that a high-localized accelerating beam may be generated along a circular caustic curve. The beam profile deviates from an Airy distribution and leaves a Bessel signature [8]. To generate an Airy beam in free space, an involving method cubic-phase wrapping to a Gaussian beam is typically used [9–11]. However, this previous method is not appropriate for using in a compact-sized system because bulky optical devices, such as femtosecond lasers and spatial light modulators, are required. Recently new methods are used for launching an accelerating wave packet that are based on the use of a metallic diffractive element [12,13]. Such planar diffracting structures have a slowly varying periodicity to induce a cubic dephase. In this paper, differently we propose a non-planar slit arrangement sustained by dispersion localities. Our multilayered metal–dielectric is piecewise periodic in the angular coordinate, thus enabling to transform a high-aperture focused beam into a near-diffraction-limited nonparaxial accelerating beam.

2. Accelerating beams with Bessel signature

In this paper we deal with accelerating beams that are the solutions to Maxwell's equations. At first we consider a harmonic wave field propagating in free space in the xy plane. Moreover its polarization will be transverse magnetic (TM), enabling the excitation of surface plasmon resonances, in such a way that the magnetic field may be set as $\mathbf{H}=\mathbf{z}h_z(x,y)$. Under these circumstances, the scalar wave field h_z satisfies the 2D Helmholtz equation $(k^2+\nabla_t^2)h_z=0$, where $k=2\pi/\lambda$ is the free-space wavenumber. A general expression for the scalar magnetic field in cylindrical coordinates is given by

$$h_z(r,\phi)=\int a(\theta)\exp(i\mathbf{k}\cdot\mathbf{r})\,\mathrm{d}\theta, \tag{1}$$

where $a(\theta)$ is the apodization function, $\mathbf{r}=(r,\phi)$ denotes the point under observation, and $\mathbf{k}$ is the wave vector of modulus k and azimuthal coordinate θ. Eq. (1) stands for a superposition of plane waves, whose amplitude is modulated azimuthally by a complex term a, provided that the wave vectors may be oriented in all

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directions. Eq. (1) gives a complete solution provided that h_z does not diverge at $r=0$.

The solutions for the Helmholtz equation in cylindrical coordinates include the Bessel functions in a natural way. For that purpose we point out that using the Jacobi–Anger identity, the Bessel beams can be represented in the form of a plane-wave Fourier expansion in the form of Eq. (1). Considering the phase-only linear term $a(\theta)=\exp(il\theta)$ we finally attain a magnetic field of the form $h_z=2\pi i^l\exp(il\phi)J_l(kr)$, where $J_l(\cdot)$ is a Bessel function of the first kind and order l. This field has an intensity profile with a maximum that follows a circular caustic curve of radius $r_l=|l|/k$. Let us now consider an incomplete Bessel wave field of a given order l. In this case, the apodization function is no longer a phase-only term. Here the apodization of the angular spectrum will be governed by a non-uniform amplitude distribution. Therefore we take Eq. (1), which may be set as

$$h_z=\int a_G(\theta)\exp[i\Theta(\theta)]\exp(ikx\cos\theta+iky\sin\theta)\,d\theta, \qquad (2)$$

For convenience, the apodization function is now factorized into a phase-only term of argument $\Theta(\theta)=l\theta$ and the real function $a_G(\theta)=(1/\sqrt{\pi}\Omega)\exp[-(\theta-\theta_0)^6/\Omega^6]$. The latter function has a super-Gaussian distribution with semi-angular aperture Ω within the domain of integration $|\theta-\theta_0|\le\pi$, and it is centered at $\theta_0=\pi/2$. The parametric representation of the associated caustic curve may be set as [8]

$$x=(l/k)\sin\theta \quad \text{and} \quad y=(-l/k)\cos\theta, \qquad (3)$$

drawing the beam trajectory for angles θ where $a_G(\theta)$ takes significant values. We point out that the acceleration of the beam does not modify its phase velocity along the caustic curve [14]. In Fig. 1 we show the amplitude $|h_z|$ corresponding to a complete Bessel wave field of order $l=30$ [subfigure (a)] along with the incomplete Bessel beam of semi-aperture $\Omega=\pi/2$ [subfigure (b)]. The accelerating beams propagate in free space at a wavelength $\lambda=531$ nm. We observe that the circular caustic curve in Fig. 1 (b) is also incomplete exhibiting the same angular range 2Ω of its spectral precursor $a_G(\theta)$. We indicate that the spatial acceleration might cease to occur for a low-Ω super-Gaussian distribution where the beam falls into a rectangular symmetry [8].

The role of $\exp(il\theta)$ in Eq. (2) is functionally identical to the phase term produced by a blazed grating achieving a maximum diffraction efficiency at $(l/k, 0)$. As a consequence, a circular blazed grating potentially transforms a focused beam, associated with an incomplete Bessel wave field of order $l=0$, into an accelerating beam. The latter represents the basis of our study. Note that an increasing order l leads to accelerating fields localized further from the origin of coordinates.

Unfortunately, a blazed grating cannot generate a linear dephase perfectly. From a practical point of view, it is convenient that the linear function $\Theta(\theta)$ will be substituted by a piecewise-uniform function. In the simple model followed schematically in Fig. 2, the diffractive optical element is segmented into regions of angular aperture $\Delta\theta=2\pi/lN$, where a flat phase response is generated in it. Therefore, the maximum number of segments will be lN enabling to induce an overall dephase of $2\pi l$ radians, which are associated with the angular phase distribution of a Bessel wave field of order l. In other words, a dephase $\Delta\Theta=2\pi/N$ from neighboring domains will be produced. We point out that the number N of steps used to achieve a 2π dephase is critical, as we will see below. Finally by increasing the step number $N\to\infty$ the phase distribution converges to the linear function $\Theta(\theta)=l\theta$.

Next we show some numerical experiments performed by a finite-element analysis commercial software [15], showing the field deviations produced by using a finite number N of steps when generating an incomplete Bessel beam. In order to excite the accelerating beam we used a non-uniform surface current of circular symmetry that is concentric with the origin of coordinates. In order to produce a beaming along the positive y-axis, the current distribution is apodized by a super-Gaussian distribution $a_G(\theta)$ that is centered at $\theta_0=-\pi/2$; in addition we set $\Omega=3\pi/8$ and the applied wavelength is 531 nm. Note that if the surface current has a flat phase distribution, the generated field will be focused at $r=0$. For that reason we stamp an additional modulation in the surface current of the form $\exp[i\Theta(\theta)]$. Thus we will have an appropriate orientation of the accelerating beam. Fig. 3 illustrates the resulting field distribution of $|h_z|$ from a circular

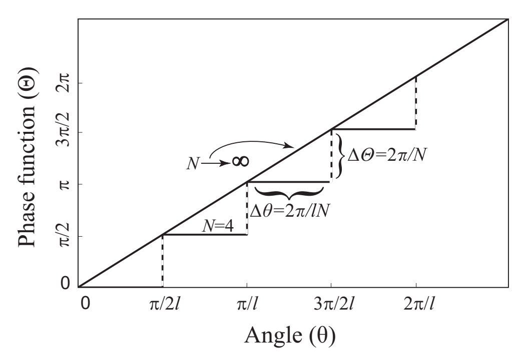

Fig. 2. Schematic representation of piecewise function Θ for $N=4$ and also for $N\to\infty$, leading to $\Theta(\theta)=l\theta$.

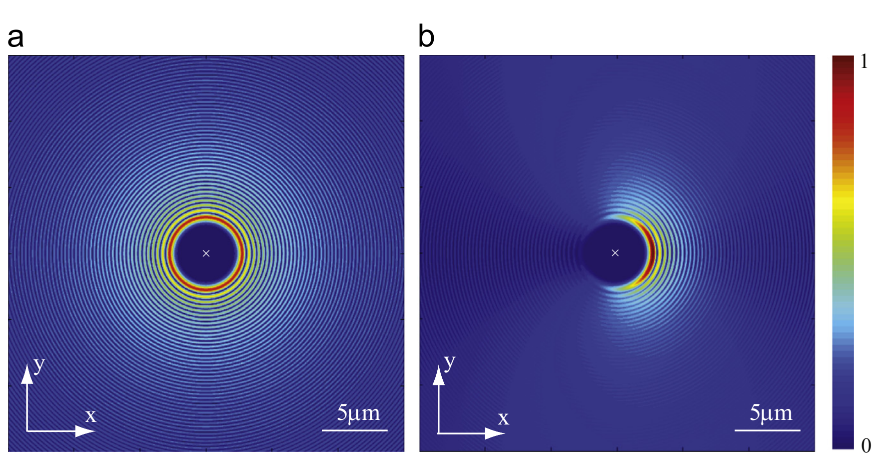

Fig. 1. The modulus of the magnetic field h_z corresponding to Bessel-driven accelerating beams of order $l=30$ propagating at $\lambda=531$ nm: (a) complete Bessel wave field and (b) incomplete Bessel wave field with semi-aperture $\Omega=\pi/2$. The centered white dot represents the origin of coordinates, $r=0$.