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Review

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Specially shaped Bessel-like self-accelerating beams along predesigned trajectories

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Abstract Over the past several years, spatially shaped self-accelerating beams along different trajectories have been studied extensively. Due to their useful properties such as resistance to diffraction, self-healing, and self-bending even in free space, these beams have attracted great attention with many proposed applications. Interestingly, some of these beams could be designed with controllable spatial profiles and thus propagate along various desired trajectories such as parabolic, snake-like, hyperbolic, hyperbolic secant, three-dimensional spiraling, and even self-propelling trajectories. Experimentally, such beams are realized typically by using a spatial light modulator so as to imprint a desired phase distribution on a Gaussian-like input wave front propagating under paraxial or nonparaxial conditions. In this paper, we provide a brief overview of our recent work on specially shaped self-accelerating beams, including Bessel-like, breathing Bessel-like, and vortex Bessel-like beams. In addition, we propose and demonstrate a new type of dynamical Bessel-like beams that can exhibit not only self-accelerating but also self-propelling during propagation. Both theoretical and experimental results are presented along with a brief discussion of potential applications.

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1 Introduction

In 1979, Berry and Balazs [1] theoretically predicted a self-accelerating wave solution for the free space Schrödinger equation in the context of quantum mechanics. Such an interesting wave packet, described mathematically by an Airy function, evolves in time without spreading while accelerating transversely along a parabolic trajectory. The acceleration (or self-bending) occurs in spite of the fact that the center of gravity of these truncated waves remains invariant in agreement with Ehrenfest's theorem. This accelerating behavior can persist over long distances until diffraction effects eventually take over and can be explained through the principle of equivalence [2], in which a stationary Airy wave packet associated with a quantum mechanical particle in a constant gravitational field can be perceived as accelerating upwards by a free-falling observer. Unfortunately, this ideal Airy wave packet in quantum physics is supposed to carry infinite energy which makes it more like a theoretical elegance rather than a physically realizable entity. The interest in this field was revived in 2007, when Christodoulides and co-workers introduced the concept of Airy wave packets into optics by theoretically proposing and experimentally demonstrating the finite-energy self-accelerating optical Airy beams [3, 4]. Since then, the interest in such nonconventional self-accelerating beams has blossomed [5–7], gifted with the ability to resist diffraction while undergoing self-acceleration and self-healing, alongside with numerous proposed applications [7–16], including particle manipulation, curved plasma generation, bending surface plasmons and electrons, single molecule imaging, and light-sheet microscopy.

In the past several years, great efforts have been made to uncover new accelerating wave solutions. In particular, apart from the paraxial Airy beams [3–5], nonparaxial self-accelerating beams in general capable of following curved trajectories with large bending angles were also found directly for the Maxwell equations and demonstrated experimentally [17–20], followed by other types of nonparaxial accelerating beams such as Mathieu and Weber beams [21–23]. Unfortunately, most of these solutions cannot be used to design beams with arbitrary trajectories. The latter are most efficiently designed using ray optics and the concept of caustics [24]. It should be noted that accelerating beams based on ray caustics are usually characterized by highly asymmetric transverse intensity profiles (such as the Airy beams with one or two oscillating tails). An intriguing question arises naturally: can we design accelerating beams that propagate along arbitrary trajectories and yet have controllable and possibly symmetric transverse profiles (such as Bessel-like or donut-shaped beam profiles)?

Earlier works have showed that Bessel-like beam patterns can be delivered along sinusoidal [25] or spiraling trajectories [26]. An even earlier work suggested snaking beams made of the series cascade of the so-called sword beams [27]. These beams are formed by a different ray structure, named conical-interference ray structure, which sets them clearly apart from the optical caustic beams. Quite recently, we proposed and demonstrated the self-accelerating Bessel-like beams with arbitrary trajectories [28, 29]. Using the concept of conical superposition, angular momentum can also be loaded onto such beams resulting in accelerating vortex Bessel-like beams [30, 31]. Indeed, tremendous efforts have been made for shaping the light with various desired structures and properties [32–41], and these studies have fueled the research interest in beam synthesis and engineering as one of the interdisciplinary areas beyond optics and photonics.

In this paper, we provide a brief overview of our recent work on spatially shaped accelerating beams along arbitrary trajectories, including the self-accelerating Bessel-like beams (self-bending in transverse direction) with or without vorticity, self-breathing Bessel-like beams (with self-pulsating peak intensity along propagation direction), as well as nonparaxial (with large bending angles) Bessel-like beams [37]. In addition, we propose and demonstrate a new class of self-accelerating beams that can also undergo self-propelling (with multiple rotating intensity blades) during propagation. Based on the phase modulation and superposition method, the ability of designing various kinds of accelerating beams with arbitrary trajectories and symmetric transverse profile is illustrated. These spatially shaped dynamical beams are gifted with properties such as resistance to diffraction, capability of self-healing, controllable beam profiles and tunable trajectories, which make them particularly attractive for many applications.

2 Paraxial accelerating beams

Under the paraxial approximation, the propagation of an optical beam obeys the Fresnel diffraction integral:

$$u(X,Y,Z)=\frac{1}{2\pi \mathrm{i}Z}\iint u(x,y,0)\mathrm{e}^{\mathrm{i}\frac{(X-x)^2+(Y-y)^2}{2Z}}\mathrm{d}x\mathrm{d}y, \quad (1)$$

where $u(x,y,0)=\exp(-(x^2+y^2)/w^2)\exp(\mathrm{i}Q(x,y))$ is a phase-modulated input optical field with the transverse (X, Y; x, y) and longitudinal (Z) coordinates being scaled from real coordinate (x', y', z') by α and $k\alpha^2$, respectively. Here, w is the beam width, k is the wave number and α is an arbitrary length scale. The input phase pattern $Q(x, y)$ determines the ray trajectories in free space. These rays can be designed to create a focal curve ($f(Z)$, $g(Z)$, Z) and Bessel function profile, namely Bessel-like beam, as shown in Fig. 1. Specifically, any point on this curve is the apex of a conical ray bundle emanating from a circle on the input plane. The radius and the location of the center of this circle are determined by the formulas derived in Refs. [28, 29]. The center in particular is the point at which the tangent of the trajectory at ($f(Z)$, $g(Z)$, Z) intersects the input plane. This scenario is schematically plotted in Fig. 1a. In this context, if the input condition is obstructed along some of these circles, the main lobe at the corresponding distance will disappear. By removing input annuli (groups of these expanding circles) in a periodic fashion, energy periodically disappeared from the curved trajectory which exhibits a pulsating and breathing central lobe and a discrete curved focal line, namely breathing self-accelerating Bessel-like beam, as shown in Fig. 1b [32]. On the other hand, the rays from a circle at the input plane can also be given angular momentum to create hyperboloids (Fig. 1c) with a minimum waist (Fig. 1c) that guides along a