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Resonance scattering of a dielectric sphere illuminated by electromagnetic Bessel non-diffracting (vortex) beams with arbitrary incidence and selective polarizations

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ABSTRACT

A complete description of vector Bessel (vortex) beams in the context of the generalized Lorenz–Mie theory (GLMT) for the electromagnetic (EM) resonance scattering by a dielectric sphere is presented, using the method of separation of variables and the subtraction of a non-resonant background (corresponding to a perfectly conducting sphere of the same size) from the standard Mie scattering coefficients. Unlike the conventional results of standard optical radiation, the *resonance* scattering of a dielectric sphere in air in the field of EM Bessel beams is examined and demonstrated with particular emphasis on the EM field's polarization and beam order (or topological charge). Linear, circular, radial, azimuthal polarizations as well as unpolarized Bessel vortex beams are considered. The conditions required for the resonance scattering are analyzed, stemming from the vectorial description of the EM field using the angular spectrum decomposition, the derivation of the beam-shape coefficients (BSCs) using the integral localized approximation (ILA) and Neumann–Graf's addition theorem, and the determination of the scattering coefficients of the sphere using Debye series. In contrast with the standard scattering theory, the *resonance* method presented here allows the quantitative description

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of the scattering using Debye series by separating diffraction effects from the external and internal reflections from the sphere. Furthermore, the analysis is extended to include rainbow formation in Bessel beams and the derivation of a generalized formula for the deviation angle of high-order rainbows. Potential applications for this analysis include Bessel beam-based laser imaging spectroscopy, atom cooling and quantum optics, electromagnetic instrumentation and profilometry, optical tweezers and tractor beams, to name a few emerging areas of research.

1. Introduction

Breakthroughs and advances in physics have been mostly accomplished by using wave scattering phenomena, as one of the most efficient strategies to probe and characterize a particle of a collection of particles. Moreover, diffraction in systems involving any kind of wave propagation (i.e., electromagnetic/optical [1], mechanical/acoustical, gravitational) is recognized as one of the limiting factors for various industrial and technological advances. For example, in electromagnetic (EM)/optical laser beams and pulses, diffraction, manifested by a gradual spatial broadening of the beam, decreases image resolution and collimation quality in imaging, holography, microscopy, tweezers and lithography to name a few applications. Thus, it is of utmost importance to develop novel adequate techniques, operational devices and apparatuses capable of alleviating the beam distortion and the resulting degradation effects.

Those challenges have fueled physicists and engineers to investigate unconventional beam solutions and improved instrumentation tools that resist diffraction over an extended region in space. At present, such "non-diffracting" waves [2] are well established both theoretically and experimentally, and innovative applications in fundamental and applied physics are increasingly burgeoning, demonstrating the ability to resist not only diffraction but also the simultaneous effects of attenuation and dispersion in liquid, elastic and viscoelastic dispersive media.

A particular example that received significant attention is known as the Bessel beam (BB), which originates in the scalar wave diffraction theory as an exact solution of the wave equation [3–6], $\Box^2\Psi_i = 0$, where Ψ_i is a scalar wave function which describes the propagating field, the d'Alembertian operator is denoted by $\Box^2 = \nabla^2 - c^{-2}\partial/\partial t$, and c is the wave speed in the medium of wave propagation. For a BB propagating in a Cartesian coordinate system along the axial z direction, the generalized mathematical expression for the scalar field of vortex (spiraling) type is given by $\Psi_i = \Psi_{BB} = \Psi_0 J_m\left(k_\rho \rho\right) e^{i(k_z z + m\phi - \omega t)}$, where Ψ_0 is the field amplitude, $J_m(\cdot)$ is the cylindrical Bessel function of order m, which determines the order (known also as the topological charge) of the beam. The fundamental solution ($m = 0$) has a maximum in amplitude (or intensity) at the center of the beam, whereas the higher-order solutions ($|m| \neq 0$) possess a central null [6,7]. The parameter $\rho = \sqrt{x^2 + y^2}$ is the distance to a point in the transverse plane (x, y), the azimuthal angle is $\phi = \tan^{-1}(y/x)$, the exponential $e^{-i\omega t}$ denotes the time-dependence where ω is the angular frequency, $k_\rho = k \sin\alpha_0$ and $k_z = k\cos\alpha_0$ are the radial and axial wavenumbers, respectively, k is the wavenumber, and α_0 is the half-cone angle defined with respect to the axis of wave propagation z, such that $\alpha_0 = 0$ corresponds to plane waves propagating along z.

Note that Ψ_{BB} is the result of a superposition of plane waves over a cone with half-angle α_0 [4], so as the resulting interference on the axis of wave propagation z produces an amplitude (or intensity) maximum for the zeroth-order beam (denoted in the following by J_0) resulting from a constructive interference when the plane waves are all in phase, or a null in axial amplitude (or intensity) for the higher-order beams (denoted in the following by J_m) resulting from a destructive interference when the plane waves are phase-shifted with respect to one another, in such a way that the phase shift around the cone is equal to $2\pi m$.