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Optical pulling force on a magneto-dielectric Rayleigh sphere in Bessel tractor polarized beams

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ABSTRACT

The optical radiation force induced by Bessel (vortex) beams on a magneto-dielectric sub-wavelength sphere is investigated with particular emphasis on the beam polarization and order *l* (or topological charge). The analysis is focused on identifying the regions and some of the conditions to achieve retrograde motion of the sphere centered on the axis of wave propagation of the incident beam, or shifted off-axially. Exact non-paraxial analytical solutions are established, and computations for linear, circular, radial, azimuthal and mixed polarizations of the individual plane wave components forming the Bessel (vortex) beams by means of the angular spectrum decomposition method (ASDM) illustrate the theory with particular emphasis on the tractor (i.e. reversal) behavior of the force. This effect results in the pulling of the magneto-dielectric sphere against the forward linear momentum density flux associated with the incoming waves. Should some conditions related to the choice of the beam parameters as well as the permittivity and permeability of the sphere be met, the optical force vanishes and reverses sign. Moreover, the beam polarization is shown to affect differently the axial negative pulling force for either the zeroth- or the first-order Bessel beam. When the sphere is centered on the beam's axis, the axial force component is always negative for the zeroth-order Bessel beam except for the radial and azimuthal polarization configurations. Nonetheless, for the first-order Bessel beam, the axial force is negative for the radial polarization case only. Additional tractor beam effects arise when the sphere departs from the center of the beam. It is also demonstrated that the tractor beam effect arises from the force component originating from the cross-interaction between the electric and magnetic dipoles. Potential applications are in particle manipulation, optical levitation, tractor beam tweezers, and other emergent technologies using polarized Bessel beams on a small (Rayleigh) magneto-dielectric particle.

1. Introduction

Pulling or pushing a particle illuminated by a single optical or electromagnetic (EM) beam of progressive (traveling) waves from a distance is a topic of significant importance in particle manipulation and sorting ever since groundbreaking works [1,2] reported the attraction, immobilization and repulsion of dust particles in a He–Ne laser cavity due to

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photophoresis. Substantial experimental works confirmed the emergence of pulling, trapping and pushing forces on neutral particles in optical photonic laser beams [3–9].

Intensity gradients of the optical field create a pulling (negative) force acting in opposite direction of the beam propagation [10]. Such gradients form traps in which a particle is drawn towards potential energy minima (i.e. wells) [11], and this phenomenon constitutes the basis of optical trapping using a conservative force in optical tweezers [12].

Another effect associated with the generation of an attractive force on a particle is caused by the production of axial intensity oscillations (Fig. 3 in [13]) in optical beams with propagation invariance, so that the scattering may be enhanced in the forward direction. Should some specific conditions related to the beam's parameter, the scatterer physical properties, as well as the redirection of the linear momentum flux be met, a pulling non-conservative force is generated. This force is generally associated with the reduction of the optical scattering in the backwards direction, and the induced reaction of this effect causes the generation of the pulling force based on Newton's third law of motion (i.e. action-reaction law). This force, which is distinct from the gradient force, forms the basis of the tractor pulling beam concept [14–16].

While the pulling, trapping or pushing a particle have been demonstrated using conventional beams (such as Gaussian, focused beams, or others) [6,12,17,18], the use of structured light fields [19], such as Bessel light beams [20], has shown its efficacy in optimizing the generation of the negative radiation force and achieve efficient pulling or trapping with a single beam in 3D [21].

Bessel beams possess several advantages over conventional Gaussian (or other) beams [21,22], which provided the impetus to examine the optical radiation force on a sphere in progressive waves in the Rayleigh (i.e. dipole) approximation limit [23,24], the Mie regime for paraxial [25–28] and for non-paraxial [29–31] beams, or in the geometrical (ray) optics region [32,33]. In practice, Bessel beams with limited diffraction can be generated using axicons [34–36] illuminated by standard Gaussian beams and their radiation force properties do not differ significantly from the infinite Bessel beam case [27,28]. Those properties are examined throughout the Generalized Lorenz Mie Theories (GLMTs) [37] based on the rigorous solutions of Maxwell's equations.

The fundamental (i.e. zeroth-order) Bessel beam solution has a bright spot at the center of the beam, whereas for high-order beam solutions, the center corresponds to a field null as expected from the high-order Bessel functions [20,38]. Because of the axial intensity (or amplitude) null, a particle or multiple particles can be trapped in the hollow region [21]. Also, the higher-order Bessel beams are of vortex (i.e. spiral) type and carry angular momenta [39–41] that set a particle into rotation. It is the combination of these intriguing properties that has made Bessel beams the focus of much research over the past decade and has poised them to make a particular impact in the development of optical tractor beams and tweezers in particle manipulation and sorting.

Despite the earlier investigations dedicated to the optical radiation force of Bessel beams, it is of some importance to consider a thorough analysis considering the *tractor* beam behavior with particular emphasis on the state of polarization of the incident field for a small Rayleigh particle. To investigate the effects of polarization in optical (Bessel) beams, a vectorial treatment [42] is required which accounts for the vectorial nature of EM waves. Several approaches have been developed, based on the decomposition into transverse electromagnetic (TEM) [43], or transverse electric (TE; with the electric field polarized transverse to the direction of wave propagation) and transverse magnetic (TM; with the magnetic field polarized transverse to the direction of wave propagation) modes [44]. This type of superposition of TE and TM modes provides a general propagation-invariant Bessel beam with complex polarizations [39,45], that can produce a negative pulling force [15,46,47] in tractor beams. This approach is typically used in the description of propagation modes in bounded media like optical fibers. A second approach uses the angular spectrum decomposition method (ASDM) [48,49], in single [24,27,28,31,50] and dual-Bessel (vortex) beam optical tweezers [23,30]. In this second approach, the polarization characteristic of the resulting field is explicitly emphasized, and the obtained EM field components are the kinds of fields generated commonly by the use of axicons in unbounded isotropic media [23,34,36]. It must be emphasized that both approaches provide adequate means to derive vector Bessel beams expressions, nevertheless, their corresponding field components and radiation force characteristics are not exactly the same, as it will be mentioned later. There also exist other vectorial approaches based on Hertz vector potentials [51,52] as well as the dual field method [53–61] which could be investigated from the standpoint of radiation force theory, however, for the purpose of the present study, the ASDM is considered.

The aim here is to further identify the regions and some of the conditions so as to achieve retrograde motion of a *magneto-dielectric* Rayleigh sphere placed arbitrarily in the field of an illuminating *vector* non-paraxial Bessel beam of any order $l \geq 0$. Magneto-dielectric (i.e. semiconductor [62]) spheres present unique scattering properties such that the back-scattering or the forward scattering field may be enhanced or suppressed depending on the sphere's index of refraction and its size with respect to the wavelength of the incident radiation [63,64]. Since the prediction of the optical force relies on such effects, it is anticipated that the results of the present investigation have particular relevance in emergent technologies for particle manipulation, imaging, optical laser devices and tweezers using Bessel tractor beams, to name a few areas.

2. Incident polarized Bessel beams

As discussed previously, the mathematical description of polarization in EM beams requires a vectorial development [42,65], based on suitable solutions of Maxwell's equations. For Bessel beams, there exist various available models [49,53–56,58,66,67],