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Optical spin torque induced by vector Bessel (vortex) beams with selective polarizations on a light-absorptive sphere of arbitrary size

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ABSTRACT

The optical spin torque (OST) induced by vector Bessel (vortex) beams can cause a particle to rotate around its center of mass. Previous works have considered the OST on a Rayleigh absorptive dielectric sphere by a vector Bessel (vortex) beam, however, it is of some importance to analyze the OST components for a sphere of *arbitrary size*. In this work, the generalized Lorenz-Mie theory (GLMT) is used to compute the OST induced by vector Bessel (vortex) beams on an absorptive dielectric sphere of arbitrary size, with particular emphasis on the beam order, the polarization of the plane wave component forming the beam, and the half-cone angle. The OST is expressed as the integration of the moment of the time-averaged Maxwell stress tensor, and the beam shape coefficients (BSCs) are calculated using the angular spectrum decomposition method (ASDM). Using this theory, the OST exerted on the light-absorptive dielectric sphere in the Rayleigh, Mie or the geometrical optics regimes can be considered. The axial and transverse OSTs are numerically calculated with particular emphasis on the sign reversal of the axial OST and the vortex-like character of the transverse OST, and the effects of polarization, beam order, and half-cone angle are discussed in detail. Numerical results show that by choosing an appropriate polarization, order and half-cone angle, the sign of the axial OST can be reversed, meaning that the sphere would spin in opposite handedness of the angular momentum carried by the incident beam. The vortex-like structure of the total transverse OSTs can be observed for all cases. When the sphere moves radially away from the beam axis, it may rotate around its center of mass in either the counter-clockwise or the clockwise direction. Conditions are also predicted where the absorptive sphere experiences no spinning. Potential applications in particle manipulation and rotation in optical tweezers and tractor beams would benefit from the results.

1. Introduction

The optical spin torque (OST), which arises from the transfer of angular momentum from a light beam to a particle, causes its rotation around its center of mass. This effect may be exploited in particle characterization and handling in applications in biology, the development of micro-mechanical machines and biochemistry to name a few examples. A vector vortex beam [1,2] is a polarized beam with helical phase characterized by the phase factor $exp(il\phi)$, where l is the beam order (or the topological charge), and ϕ is the azimuthal angle. The quantitative prediction of the OST generated by a vector vortex beam is of particular significance to improve the ability of optical manipulation and rotation, and to design novel optical tweezers systems and tractor beam devices.

One particular kind of vector vortex beams [3–5], is the Bessel vortex beam [6,1,7–15], that can generate an OST, since it carries both spin and orbital angular momenta [16,17]. A vector quasi-Bessel beam can be experimentally synthesized using an axicon [18,2,19–23], or a spatial light modulator (SLM) [24–26]. To emphasize the effect of polarization, the electromagnetic fields of an axicon-generated vector Bessel beam (AGVBB) were derived using the angular spectrum decomposition method (ASDM) [10,27]. In the previous works [14,28], we investigated the OST exerted on an absorptive Rayleigh dielectric [14,28] or a magneto-dielectric [29] sphere by an AGVBB, with particular emphasis on the sign reversal of the axial OSTs and the vortex-like behavior of the total transverse OSTs for various polarization types. However, these results are *only* valid for a particle much smaller than the wavelength of the incident beam. The aim of this investigation is therefore directed towards analyzing and computing numerically the OST on an absorptive sphere of *any size* placed in an AGVBB with selective

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polarizations. Numerical calculations of the axial and transverse OSTs are presented for an absorptive dielectric sphere in an AGVBB with particular emphasis on the sign reversal of the axial OST and the vortex-like character of the total transverse OST. The effect of polarization of the plane-wave component forming the Bessel beam, order, and half-cone angle are analyzed and discussed.

The rest of the paper is organized as follows. In Section 2, the theoretical background of the OSTs induced by an AGVBB is introduced. Section 3 presents and discusses the numerical results. In this section, the axial and transverse components of the OSTs are analyzed, with particular emphasis on the sign reversal of the axial OSTs and the vortex-like character of the transverse OSTs. Section 4 is devoted to the conclusion of this work.

2. Optical spin torque by a vector Bessel (vortex) beam

Consider a sphere with a radius a and complex refractive index m_1 illuminated by an AGBB with half-cone angle α_0 and wavelength λ in the surrounding medium, as shown in Fig. 1. The center of the sphere is located at O_P, origin of the Cartesian coordinate system $O_P - xyz$. The beam center is at O_G, origin of coordinate system $O_G - uvw$, with u axis parallel to x and similarly for the others. The coordinates of O_G in the system $O_P - xyz$ is (x_0, y_0, z_0). The refractive index of the surrounding media is m_2.

According to the conservation law of angular momentum, the OST is equal to the average rate at which the angular momentum carried by the incident field is conveyed to the sphere. Mathematically, the OST can be expressed as the moment of Maxwell's radiation stress tensor by [30,31]

$$<\mathbf{T}> = -\oint_S \hat{\mathbf{n}} \cdot <\overleftrightarrow{\mathbf{A}}> \times \mathbf{r} dS \tag{1}$$

where <> represents a time-average, $\hat{\mathbf{n}}$ is the outward normal unit vector, and S is a surface enclosing the particle. The Maxwell stress tensor $\overleftrightarrow{\mathbf{A}}$ is given by

$$\overleftrightarrow{\mathbf{A}} = \frac{1}{4\pi}\left(\varepsilon \mathbf{E} \otimes \mathbf{E} + \mu \mathbf{H} \otimes \mathbf{H} - \frac{1}{2}\left(\varepsilon E^2 + \mu H^2\right)\overleftrightarrow{\mathbf{I}}\right) \tag{2}$$

where the $\mathbf{E}$ and $\mathbf{H}$ are the total electromagnetic fields, namely the sum of the incident and scattered fields, outside the particle. $\overleftrightarrow{\mathbf{I}}$ is the unit tensor, and μ and ε are the permeability and permittivity of the surrounding media, respectively. The symbol $\otimes$ represents a tensor product.

Substituting the electromagnetic fields, which are expanded in terms of vector spherical harmonic functions in the framework of GLMT [32], into (Eqs. (1) and 2), and performing the integration over the surface S of radius $r \to \infty$, the Cartesian components of the OSTs are obtained as [33–36]

$$T_x^u = \frac{4m_2}{c}\frac{\pi}{k^3}\sum_{n=1}^{\infty}\sum_{m=1}^{n} C_n^m \Re(A_n^{m,u}) \tag{3}$$

$$T_y^u = \frac{4m_2}{c}\frac{\pi}{k^3}\sum_{n=1}^{\infty}\sum_{m=1}^{n} C_n^m \Im(A_n^{m,u}) \tag{4}$$

$$T_z^u = -\frac{4m_2}{c}\frac{\pi}{k^3}\sum_{n=1}^{\infty}\sum_{m=1}^{n} m C_n^m B_n^{m,u} \tag{5}$$

where

$$C_n^m = \frac{2n+1}{n(n+1)}\frac{(n+|m|)!}{(n-|m|)!} \tag{6}$$

$$A_n^{m,u} = A_n\left(g_{n,TM}^{m-1,u} g_{n,TM}^{m,u*} - g_{n,TM}^{-m,u} g_{n,TM}^{-m+1,u*}\right) + B_n\left(g_{n,TE}^{m-1,u} g_{n,TE}^{m,u*} - g_{n,TE}^{-m,u} g_{n,TE}^{-m+1,u*}\right) \tag{7}$$

$$B_n^{m,u} = A_n\left(\left|g_{n,TM}^{m,u}\right|^2 - \left|g_{n,TM}^{-m,u}\right|^2\right) + B_n\left(\left|g_{n,TE}^{m,u}\right|^2 - \left|g_{n,TE}^{-m,u}\right|^2\right) \tag{8}$$

$$A_n = \Re(a_n) - |a_n|^2 \tag{9}$$

$$B_n = \Re(b_n) - |b_n|^2 \tag{10}$$

where, $k = 2\pi/\lambda = \omega_0/c$ is the wavenumber in the medium surrounding the sphere, with ω_0 being the angular frequency and c being the light speed. $\Re$ denotes the real component, and the superscript $*$ denotes the complex conjugate. The superscript u represents the polarization type. The parameters a_n and b_n are the Mie scattering coefficients [37,38], and $g_{n,TM}^{m,u}$ and $g_{n,TE}^{m,u}$ are the BSCs

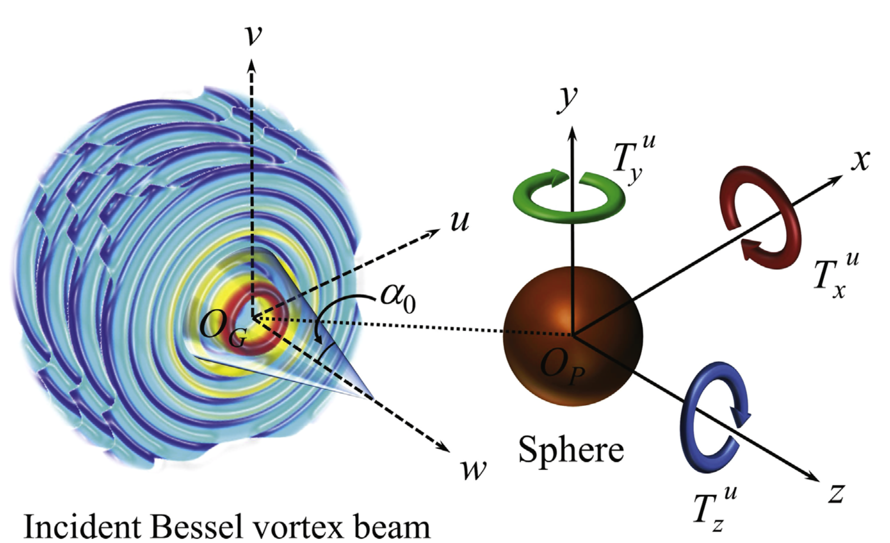

Fig. 1. The schematic describing the interaction of a vector Bessel (vortex) beam with a light-absorptive sphere of arbitrary size.