Journal of Quantitative Spectroscopy & Radiative Transfer 182 (2016) 172–179

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Negative optical spin torque wrench of a non-diffracting non-paraxial fractional Bessel vortex beam

F.G. Mitri

Chevron, Area 52 Technology – ETC, 5 Bisbee Ct., Santa Fe, NM 87508, USA

ARTICLE INFO

Article history:
Received 4 May 2016
Received in revised form
28 May 2016
Accepted 28 May 2016
Available online 3 June 2016

Keywords:
Negative spin torque
Dielectric sphere
Dipole approximation

ABSTRACT

An absorptive Rayleigh dielectric sphere in a non-diffracting non-paraxial fractional Bessel vortex beam experiences a spin torque. The axial and transverse radiation spin torque components are evaluated in the dipole approximation using the radiative correction of the electric field. Particular emphasis is given on the polarization as well as changing the topological charge α and the half-cone angle of the beam. When α is zero, the *axial* spin torque component vanishes. However, when α becomes a real positive number, the vortex beam induces *left-handed* (negative) axial spin torque as the sphere shifts off-axially from the center of the beam. The results show that a non-diffracting non-paraxial fractional Bessel vortex beam is capable of inducing a spin reversal of an absorptive Rayleigh sphere placed arbitrarily in its path. Potential applications are yet to be explored in particle manipulation, rotation in optical tweezers, optical tractor beams, and the design of optically-engineered metamaterials to name a few areas.

The optical radiation torque [1] which arises from the transfer of angular momentum of light to a sphere has received significant attention in optical levitation [2–4] and particle rotation applications in atomic physics [5,6], cell biology [7] and other areas [8,9]. In common optical laser beams, and under some conditions related to the particle absorption properties, a *spin* torque causing the particle to rotate around its center of mass arises, in addition to an orbital component causing the particle to rotate around the beam's axis of wave propagation [1]. Note that the orbital torque component exerted on the sphere vanishes at the center of the beam. Moreover, the sphere should be absorptive in order to experience a *spin* torque [1]. Various standard types of laser beams have been suggested and investigated for this purpose [10,11]. Examples of beams also include optical vortices of Gaussian-like [12,13] and nondiffracting beams [14].

A particular kind of vortices with fractional topological charge (or order) has received increasing attention due to their special features and potential use in applications ranging from optical manipulation [15,16], quantum entanglement [17], digital spiral imaging [18] among other topics. Typically, such types of vortices [15,16] exhibit a diffractive slit opening while they propagate so the beam's cross-section becomes asymmetric.

In contrast, another class for factional vortex beams (which can be realized experimentally using blazed-phase hologram encoded in a programmable liquid crystal display illuminated with a He-Ne laser [19]) and displays *limited-diffracting* features during propagation exists [19,20]. The physically-realizable apodized beam carrying finite energy preserves the nondiffracting propagation property. It is also known as a high-order Bessel vortex beam of fractional type α (HOBVB-Fα) [21–23]. A HOBVB-Fα with fractional order α connects standard nondiffracting Bessel (vortex) beams (Fig. 1) of successive integer order in a smooth transition. It also generates individual

E-mail address: F.G.Mitri@ieee.org

http://dx.doi.org/10.1016/j.jqsrt.2016.05.033

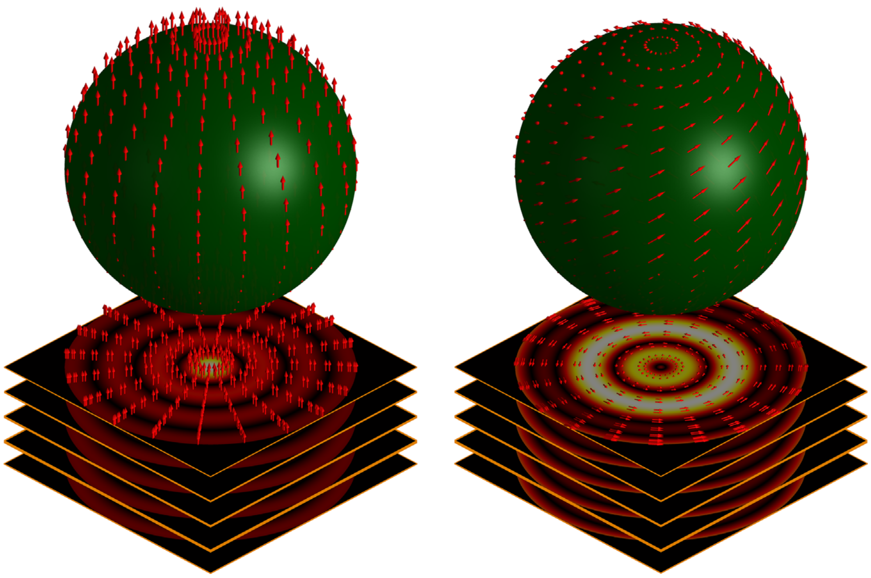

Fig. 1. The left panel shows the computational plot for the incident intensity field on a sphere with stereographic projection superimposed on the cross-sectional profile of a zeroth-order (non-vortex) Bessel beam. The right panel corresponds to the case of a first-order Bessel vortex beam.

vortices in the (lateral) plane perpendicular to the axis of wave propagation corresponding to a cross-section of the incident nondiffracting beam [19]. This specific feature provides the impetus to analyze the optical radiation *spin* torque exerted on a small dielectric absorptive sphere from the standpoint of the counter-intuitive "negative" optical radiation torque generation, meaning that the sphere would rotate around its center of mass in opposite handedness of the angular momentum carried by the beam [24]. Notice that this phenomenon has been originally observed from the standpoint of *acoustical* radiation spin torque theory using Bessel vortex beams [25]. The aim here is to suggest the optical HOBVB-Fα as a potential candidate for the generation of a left-handed (negative) optical *spin* torque for applications yet to explore in particle manipulation and rotation using optical tweezers and tractor beams. Since the optical *orbital* torque component does not contribute to the rotation of the sphere around its center of mass, it will not be considered here. This topic, however, will be the subject of a forthcoming investigation.

The analysis is started by considering the dipole approximation with the *modified* particle polarizability [26], which accounts for the radiative nature of the external field when it varies in time. The expression for the *spin* torque [27] is therefore given as,

$$\mathbf{T}^u|_{spin} = \frac{1}{2}|\alpha_e|^2 \Re\left\{\frac{1}{\alpha_e^{0*}}\mathbf{E}^u \times \mathbf{E}^{u*}\right\}, \tag{1}$$

where the modified electric polarizability is $\alpha_e = \alpha_e^0\left[1 - i\left(\frac{k^3\alpha_e^0}{6\pi\varepsilon_0}\right)\right]^{-1}$, $\alpha_e^0 = 4\pi\varepsilon_0 a^3(\varepsilon-1)/(\varepsilon+2)$, the superscript * denotes a conjugate of a complex number, a is the radius of the sphere, k is the wavenumber and ε is the relative complex permittivity coefficient, corresponding to the ratio of the particle permittivity to that of the surrounding medium with permittivity ε_0. The spin torque can be evaluated directly from the expressions of the electric field components. In a Cartesian system of coordinates, where a *transverse* polarization scheme has been considered for the vector potential from which the electric (and magnetic) field can be derived, the electric field components are expressed as [21],

$$E_x^{xy} = \frac{1}{2}E_0 \sum_{m=-\infty}^{+\infty} \left\{ \begin{array}{l} i^{(\alpha-m)} sinc(\alpha-m) \exp\left[i(k_z z + m\phi)\right] \\ \times \left[\begin{array}{l} \left(1 + \frac{k_z}{k} - \frac{k_r^2 x^2}{k^2 R^2} + \frac{m(m-1)(x-iy)^2}{k^2 R^4}\right) J_m(k_r R) \\ - \frac{k_r(y^2 - x^2 - 2imxy)}{k^2 R^3} J_{m+1}(k_r R) \end{array} \right] \end{array} \right\}, \tag{2}$$

$$E_y^{xy} = \frac{1}{2}E_0 xy \sum_{m=-\infty}^{+\infty} \left\{ \begin{array}{l} i^{(\alpha-m)} sinc(\alpha-m) \exp\left[i(k_z z + m\phi)\right] \\ \times \left[\begin{array}{l} \left(\frac{m(m-1)[2 + i(x^2 - y^2)/(xy)] - k_r^2 R^2}{k^2 R^4}\right) J_m(k_r R) \\ + \frac{k_r[2 + im(y^2 - x^2)/(xy)]}{k^2 R^3} J_{m+1}(k_r R) \end{array} \right] \end{array} \right\}, \tag{3}$$

$$E_z^{xy} = \frac{1}{2} i E_0 \frac{x}{kR}\left(1 + \frac{k_z}{k}\right) \sum_{m=-\infty}^{+\infty} \left\{ \begin{array}{l} i^{(\alpha-m)} sinc(\alpha-m) \exp\left[i(k_z z + m\phi)\right] \\ \times \left[\left(\frac{m(1 - iy/x)}{R}\right) J_m(k_r R) - k_r J_{m+1}(k_r R)\right] \end{array} \right\}, \tag{4}$$

where $E_0 = ikA_0$, A_0 is the vector potential amplitude, $R = \sqrt{x^2 + y^2}$, $k_r = k \sin\beta$, $k_z = k \cos\beta$ and β is the half-cone angle of the beam. Thus, for this configuration, the superscript u in Eq. (1) would denote xy indicating the state of polarization of the vector potential.

A different scheme is also chosen, in which an axial polarization scheme is considered for which u corresponds to zz. The expressions for the electric field in the axial