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Analysis of lateral binding force exerted on multilayered spheres induced by high-order Bessel beams with arbitrary polarization angles

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ABSTRACT

Based on the generalized multi-particle Mie equation (GMM) and Electromagnetic Momentum (EM) theory, the lateral binding force (BF) exerted on multilayered spheres induced by an arbitrary polarized high-order Bessel beam (HOBB) is investigated with particular emphasis on the half-conical angle of the wave number components and the order (or topological charge) of the beam. The illuminating HOBB with arbitrary polarization angle is described in terms of beam shape coefficients (BSCs) within the framework of generalized Lorenz-Mie theories (GLMT). Utilizing the addition theorem of the spherical vector wave functions (SVWFs), the interactive scattering coefficients are derived through the continuous boundary conditions on which the interaction of the multilayered spheres is considered. Numerical results concerning the influences of different parameters of the incident Bessel beam and of the binding body on the lateral BF are displayed in detail. The observed dependence of the separation of optically bound particles on the incidence of HOBB is in agreement with earlier theoretical prediction. Accurate investigation of BF induced by HOBB exerted on multilayered spheres could provide key support for further research on optical binding between more complex multilayered biological cells, which plays an important role in using optical manipulation on stratified particle self-assembly.

1. Introduction

Since the pioneering work of Burns and co-workers [1–3], optical binding force (BF) has attracted considerable attention and has been extensively applied in various fields such as physics, biology, and optofluidics. In principle, optical binding denotes a significant phenomenon of light-matter interaction which can lead to the self-arrangement of particles into optically conjunct states [4–6]. This intriguing self-arrangement is based upon the delicate equilibrium between the optical forces resulting both from the incident beam and from the light re-scattered by the other objects. Accurate prediction of the optical BF enables better understanding of the physical mechanism of self-organization, and may offer important applications towards contact-free storage of biological cells [7,8] and ion traps for quantum computing [9].

Different approaches have been developed for the theoretical prediction of BF exerted on multi-particle system. Geometrical optics (GO) [10,11] can be employed to the prediction of BF in the ray optics regime, which requires the particles be much larger than the incident wavelength i.e. $d \gg 10\lambda$ with d the diameter of particles and λ the wavelength. Conversely, the Rayleigh dipole approximation (RDA) [12,13] can be employed to the prediction of BF exerted on particles which are much smaller than the wavelength, i.e. $d \ll \lambda$. For particles whose sizes are of incident wavelength order, both GO and RDA are inapplicable, because diffraction phenomenon cannot be neglected in this case. In order to cover the whole d/λ range, some researchers have been devoted to the rigorous prediction of BF stemming from the solution of Maxwell's equations which is suitable for modeling arbitrary number of particles of arbitrary sizes without additional approximation. For example, based on the Lorenz Mie theory [14] and the Maxwell stress tensor approach, Jack investigated BF between bisphere cluster of arbitrary size under the illumination of a plane wave [15,16]. Xu introduced the additional theorem to explore the interaction of collective homogeneous spheres [17,18]. Besides, the generalized multi-particle Mie equation (GMM) between an incident beam with arbitrary profile and an assembly of spheres had already been developed by Gouesbet et al. [19,20], with taking advantage of many ingredients developed for the spherical GLMT [21–23]. Following this work, Xu and Käll [24,25] put forward the extended Mie theory to calculate BF between closely spaced silver nanoparticle aggregates. Chvatal et al. presented the binding self-arrangement of a pair of Au particles in a wide Gaussian stand-

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ing wave [26]. Despite the great wealth of knowledge obtained from these works, the investigations on BF in the previous studies are mainly focused on homogeneous spherical particles with plane wave or Gaussian beam incidence.

Recently, due to the special characteristics of non-diffraction and self-reconstruction, Bessel beams have attracted growing attention since its naissance by Durnin [27] and have been widely applied in various fields, including optical trapping and manipulation, particle sizing and nonlinear optics [28–31]. Motivated by the features and applications of such a beam, analytical and numerical analysis are undertaken to investigate the beam expansion, field description, scattering and radiation in acoustic, optics, and microwave. Accurate description of a Bessel beam can be obtained by the beam shape coefficients (BSCs) as a double quadrature over spherical coordinates [32], which is the original method used in the GLMTs [33,34]. In order to overcome the time-consuming and complexity in the numerical calculation [35], many researchers have devoted to the analytical description of BSCs [36–38], Lock [39] analyzed the BSCs of general zero-order Bessel beams based on the angular spectrum representation (ASR). The similar procedure was also extended by Ma and Li [40] to investigate the scattering of un-polarized HOBB by spheres. Besides, Gouesbet and Lock [41,42] established the dark theorem in terms of BSCs and predicted the existence of high-order non-vortex Bessel beams. Wang derived the general description of circularly symmetric Bessel beams of arbitrary order [43,44]. From related considerations, the scattering problem for acoustical Bessel beams [45,46] was extended to the scattering of electromagnetic waves by dielectric and uniaxial anisotropic spheres [47] as well as concentric spheres [48]. These have been investigated extensively by using the analytical approach. In addition, some studies have also been carried out on the trapping force induced by Bessel beams using the Rayleigh model [49], the geometrical optics [50,51] or acoustical theory [52–54] that have been extended to EM theory. Nevertheless, the published work to which we have referred mainly focused on cases of single spherical particle. Manipulation of multiple particles simultaneously is both very different and much less mastered than that of singular sphere, especially for the case of assembly multilayered spheres. Considering the fact that electromagnetic interactions with aggregated stratified spheres have recently become a subject of great interest because of the increasing number of technological and biological applications of these models [55]. Accurate prediction of BF exerted on assembly multilayered spheres induced by HOBB with arbitrary polarization angles may have some significance in guiding practice and is of great help for the efficient generation of optical manipulation system operating with non-diffracting beam.

In this paper, we will rely on the general description of HOBB derived by Wang et al. [56], who succeed in dealing analytically with BSCs by using quadrature expressions in the classical framework of GLMT [21,57], using GMM equations and EM theories to analyze lateral BF exerted on an arbitrary number of multilayered spheres induced by HOBB in detail. The remainder of this paper is organized as follows. In Section 2, two kinds of descriptions on the profile of a HOBB are given. Moreover, the expansion expression and coefficients of the arbitrary polarized incident field in terms of SVWFs are given within the framework of GLMTs. Based on the GMM equation, Section 3 derives the analytical solutions to the scattering problem of a HOBB by collect multilayered spherical particles. Section 4 investigates the theoretical expressions of lateral BF between multilayered spheres induced by a HOBB using the EM theory. Section 5 establishes the discussions for numerical effects of various parameters and comparisons of our numerical results with earlier theoretical prediction. Finally, a conclusion is shown in Section 6.

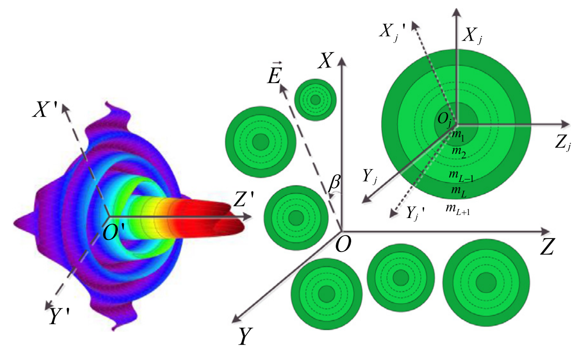

Fig. 1. Configuration of an aggregate of multilayered spheres induced by a HOBB. θ: Angle between the polarization direction and x-axis orientation. The set displaying is the intensity of a first-order x-polarized Bessel beam.

2. Theoretical analysis

A Cartesian coordinate system $Oxyz$ is built with a fixed global coordinate system to indicate the randomness of the polarized direction of incident Bessel beam and the configuration of an arbitrary number of multilayered sphere system [Fig. 1]. Considering the multilayered particle coordinate system $O_jx_jy_jz_j$ is established parallel to the primary system $Oxyz$, and the center of the j-th sphere O_j is located at (x_j,y_j,z_j). in which, a_l and m_l are respectively the outer radius of the l-th layer and the refractive index of the medium in the l-th layer relative to the refractive index m_{L+1} of the surrounding medium. The size parameter of l-th layer is characterized by $x_l = 2\pi a_l/\lambda$, $(l = 1, 2, \bullet\bullet\bullet L)$, where λ is the wavelength of the incident beam and the layer number is assumed to be L. The magnetic permeability of every layer for multilayered sphere is assumed to have the free-space value $\mu = \mu_0$. The particles are vertically illuminated by a polarized HOBB that propagates in the z'-direction in the Cartesian coordinate system $O'x'y'z'$, which is known as the beam coordinate system. The coordinates of beam centerO'in $Oxyz$ are (x', y', z'), and the angle between the polarization direction of HOBB and the x-axis is represented by β. This pseudo-polarization angle can then determine the polarization mode of the wave and may be regarded as a real polarization angle. For the vertical incidence, the beam is in transverse magnetic mode (TM) when $\beta = 0^0$, which corresponds to the case in which the electric vector vibrates in the incident plane (i.e. the $x'O'z'$-plane). Then, the beam is in the transverse electric mode (TE) when $\beta = 90^0$, which corresponds to the case where the magnetic vector vibrates in the incident plane (i.e. the $y'O'z'$-plane). When β presents other values, it represents another polarization mode.

The Bessel beam is assumed to propagate in an isotropic homogeneous medium and is scattered by an aggregate of multilayered spheres. Electromagnetic fields outside and inside the particles must satisfy the vector wave equations (or Helmholtz equations): $\nabla^2\vec{E} + k^2\vec{E} = 0$, $\nabla^2\vec{H} + k^2\vec{H} = 0$, where k is the wave number. The solutions can be derived by introducing the SVWFs, whose expressions used here are the same as those used in Ref. [58] Eqs. (1) and ((2) there).

$$\vec{M}_{mn}^{(l)}(kr,\theta,\phi) = (-1)^m\left[im\pi_n^m(\cos\theta)\hat{i}_\theta - \tau_n^m(\cos\theta)\hat{i}_\phi\right]z_n^{(l)}(kr)e^{im\phi}$$

$$\vec{N}_{mn}^{(1)}(kr,\theta,\phi) = (-1)^m\left[\frac{n(n+1)}{kr}z_n^{(l)}(kr)P_n^m(\cos\theta)\hat{i}_r + \frac{1}{kr}\frac{d\left[rz_n^{(l)}(kr)\right]}{dr}\right.$$
$$\left.\left[\tau_n^m(\cos\theta)\hat{i}_\theta + im\pi_n^m(\cos\theta)\hat{i}_\phi\right]e^{im\phi}\right] \quad (1)$$

where $z_n^{(l)}(kr)$ represents an appropriate kind of spherical Bessel functions: the first kind j_n, the second kind y_n, or the third kind $h_n^{(1)}$ and $h_n^{(2)}$(also known as the spherical Hankel functions), denoted by $l = 1$, 2, 3 or 4 respectively. $P_n^m(\cos\theta)$ is the associated