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Radiation forces of highly focused Bessel–Gaussian beams on a dielectric sphere

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Abstract

The radiation force of highly focused Bessel–Gaussian beams (BGBs) on a dielectric sphere in the Rayleigh scattering regime is theoretically investigated. Numerical results demonstrate that the focused BGBs can be used to trap and manipulate the particles with the refractive index lower than that of the ambient. The radiation force caused by the low-order focused BGBs has been studied under different input parameters and different focus lengths of thin lens. The stability conditions of trapping the particles are also analyzed.

Keywords: Radiation force; Bessel–Gaussian beam; Optical trap

1. Introduction

Trapping and manipulating variety of particles using the highly focused laser beams has become an important and powerful tool in many scientific disciplines such as neutral atoms [1] and molecules [2], micron-sized dielectric particles [3], and living biological cells [4]. It is well known that the light radiation force (including both the scattering and gradient forces) is originated from the exchange of light momentum and energy between photons and particles. Usually most of optical traps and optical tweezers use a focused Gaussian beam, because a Gaussian beam has a peak on the transverse profile. However, Gaussian beams are only suitable for trapping the particle with the index of refraction higher than the ambient [5]. In order to trap the particle with the index of refraction lower than the ambient, one has to use annular or ring beams [6,7] and doughnut laser beams [8]. There are many theoretical works of radiation forces on spherical particles [9,10]. In this study, we consider the radiation force produced by highly focused Bessel–Gaussian beams (BGBs) in the Rayleigh scattering regime. The BGB known as a new type of solution of the paraxial wave equation was introduced by Gori et al. [11], and it can be generated by resonators constructed with aspheric phase-conjugating mirrors [12]. In the present study, to the best of our knowledge, it has been the first time the radiation force produced by the highly focused BGBs is being considered. We show that the highly focused BGBs can be used to trap and manipulate the particles with the refractive index lower than that of the ambient. We also analyze the change of the radiation force caused by the low-order focused BGBs under different parameters. Finally, we analyze the stability conditions of trapping the particles.

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2. Radiation force produced by BGBs

Under the paraxial approximation, the electric field of BGB that passes through an ABCD optical system in a cylinder coordinate system can be expressed as [13]

$$E(r,\theta,z) = -\frac{i\pi E_0}{\lambda B(1/w_0^2 - ikA/2B)}\exp(ikz)\exp(-in\theta) \times \exp\left(\frac{ikDr^2}{2B}\right)\exp\left[-\frac{\alpha^2+(kr/B)^2}{4(1/w_0^2 - ikA/2B)}\right] \times J_n\left(\frac{k\alpha r}{2B(-i/w_0^2 - kA/B)}\right), \quad (1)$$

where J_n is the Bessel function of the first kind of order n. E_0 and α are two arbitrary parameters, $k = 2\pi/\lambda$ is the wave number, λ is the wavelength, and A, B, C, and D are the transfer matrix elements of the paraxial optical system between the input and the output plane. Here, z is the distance from the input to the output plane.

Now we consider the BGB propagating through a lens as shown in Fig. 1. The transfer matrix for a lens system can be given by

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} -z_1/f & (-z_1/f)s + f + z_1 \\ -1/f & 1 - s/f \end{bmatrix}, \quad (2)$$

where s is the axial distance from the input plane to the thin lens, f is the focus length of the thin lens, and z_1 is the axial distance from the focus plane to the output plane. Point F in Fig. 1 is the focus. Substituting Eq. (2) by Eq. (1), we can obtain the intensity distribution of a focused BGB through a lens optical system (see Fig. 2). In our calculation, we choose $\alpha = 1$, $w_0 = 20\,\text{mm}$, $\lambda = 1.06\,\mu\text{m}$, $f = 4\,\text{mm}$, $s = 100\,\text{mm}$, and the input power of the BGBs is assumed to be 1 W. Fig. 2 shows the intensity distributions of high-order ($n = 10$) and low-order ($n = 1$) BGBs at the focus plane. Obviously, there is a dark region at the centers of the beam profiles, which can be controlled by changing the order of n.

We assumed that the radius of the particles is much smaller than the wavelength of the laser, i.e., $a \ll \lambda$. In this case, it is the Rayleigh scattering and the particle can be treated as a point dipole, and the scattering and gradient forces can be separated. Denote by n_2 the refractive index of the particle and by n_1 the refractive index of the ambient. The scattering force F_{scat} is proportional to light intensity and its direction is along the propagating direction of light. Then F_{scat} can be expressed as [14–16]

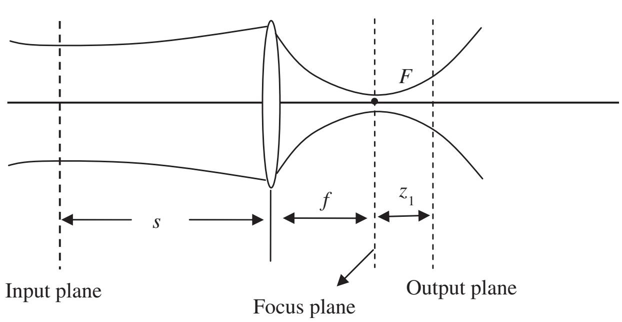

Fig. 1. Schematic of a lens optical system, where $s = 100\,\text{mm}$ and $f = 4\,\text{mm}$.

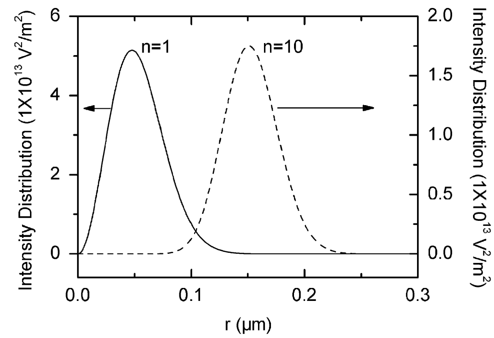

Fig. 2. Intensity distributions of the high-order ($n = 10$) and low-order ($n = 1$) focused BGB at the focus plane.

$$\vec{F}_{\text{scat}}(r,z) = \vec{e}_{\vec{k}} C_{\text{pr}} I(r,z) n_1/c = \vec{e}_{\vec{k}} \frac{4}{3}\pi n_1^2 \varepsilon_0 k^4 a^6 \left(\frac{m^2-1}{m^2+2}\right)^2 |E(r)|^2, \quad (3)$$

where $\vec{e}_{\vec{k}}$ is a unity vector along the wave vector and $m = n_2/n_1$ is the relative index.

The gradient force F_{grad}, which is due to non-uniform electromagnetic fields, can be expressed as [17]

$$F_{\text{grad}}(\vec{r}) = \frac{1}{2}\pi n_1^2 \varepsilon_0 a^3 \left(\frac{m^2-1}{m^2+2}\right)\nabla|\vec{E}(\vec{r})|^2. \quad (4)$$

Using Eqs. (1)–(4), we can calculate the radiation force produced by focused BGBs on a Rayleigh dielectric microsphere. Without loss of the generality, we choose $a = 50\,\text{nm}$, $n_2 = 1$, and $n_1 = 1.33$ (for example, water) in the following numerical calculation.

In Fig. 3(a, b), we plot the transverse gradient force at the focus plane $z_1 = 0$ and the longitudinal gradient force along the z-axis for both the high-order ($n = 10$, solid curve) and low-order ($n = 1$, dashed curve) BGBs. It is clear that the particle with the refractive index lower than the ambient can be confined within the dark region of the focused BGBs by the transverse gradient force; however, it cannot be trapped only by such one beam due to zero longitudinal gradient force along the z-axis for both the low-order and high-order BGBs (see Fig. 3(b)). If one needs to trap or manipulate the particle in a three-dimensional space, three focused BGBs (orthogonally each other) are necessary to form a closed-dark region, which can stably trap the particle with the refractive index lower than the ambient.

Now we study the effect of different input beam waist and focus length on the gradient force. Fig. 4(a) shows the change in gradient force under different input beam