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Trapping two types of particles using a focused partially coherent modified Bessel-Gaussian beam

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A R T I C L E I N F O

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A B S T R A C T

Using the extended Huygens-Fresnel principle and Rayleigh scattering regime, the analytical expressions for the intensity and radiation forces of a focused partially coherent modified Bessel-Gaussian (MBG) beam have been derived, and used to study the optical trapping effect of the focused partially coherent MBG beams acting on dielectric sphere with different refractive indices. The results show that the focused partially coherent MBG beam with $m = 0$ cannot capture the low index of refraction particles, but can trap the high index of refraction particles. The focused partially coherent MBG beam with $m \geq 1$ can trap the high index of refraction particles to a ring on the focal plane, and simultaneously capture the low index of refraction particles to z-axis. When the topological charge m increases, the radiation force decreases while the transverse trapping range increases for low and high index of refractive particles. Besides, larger the value of the spectral degree of coherence ξ is, the easier the two types of particles are trapped by the focused partially coherent MBG beam. Trapping stability is also analysed. The obtained results are useful for analysing the trapping efficiency of focused partially coherent MBG beam applied in micromanipulation and biotechnology.

1. Introduction

Since Ashkin's first invention on the use of optical tweezers to trap the dielectric sphere near the focus in 1986 [1], optical traps (or tweezers) have become an important tool to investigate the biological cells [2–6], neutral atoms [7–9], aerosols [10], DNA molecules [11,12] and other micro-sized dielectric particles [13,14]. Optical traps have unique advantages as they operate in noncontact mode and are also non-invasive [15–19]. Previously, optical traps were constructed with fundamental Gaussian beams, however, theoretical and experimental investigations demonstrated that the performance of optical traps can be well improved and some new optical micromanipulation techniques can be realized by means of some special laser beams. For example, the Bessel beam having the ability of self-reconstruction has been designed to manipulate particles in multiple axial sites [20]. Baumgartl et al. investigated that the Airy beam can be used to guide particles along an accelerating trajectory [21]. Liu and Zhao numerically investigated the trapping effect of the focused generalized Multi-Gaussian Schell model beam of the first kind which produces dark hollow beam profile at the focal plane, and shown that such beam can trap low-refractive-index particles (the particles with refraction index lower than the ambient) at the focus, and simultaneously capture high-index particles (the particles with refraction index higher than the ambient) at different positions of the focal plane [22]. In addition, the radiation force of the hollow Gaussian beams [23,24], vortex beams [17,25], radially polarized beams [26,27], and other beams [28–30] on the micro particles also have been explored. Therefore, optical traps with special laser beams will play an increasingly important role in scientific research in the future.

Ponomarenko introduced a class of partially coherent Modified Bessel-Gaussian (MBG) beams carrying optical vortices [31]. Wang and co-workers researched on propagation properties of partially coherent MBG beams through a paraxial optical ABCD system [32]. Eyyuboğlu and Hardalac investigated the propagation characteristics of MBG beams traveling in an atmospheric turbulence [33]. Wang et al. analysed focal switching of partially coherent MBG beams passing an astigmatic lens with circular aperture [34]. Eyyuboğlu and Ji studied the radius of curvature of Bessel and MBG beams, and reported that generally MBG beams have larger radius of curvature values than Bessel Gaussian beams [35]. The partially coherent MBG beam is a kind of special laser beam, which possesses the remarkable properties. For example, the spectral degree of coherence does not depend on the relative orientation of a pair of points at the transversal plane, and the beam with

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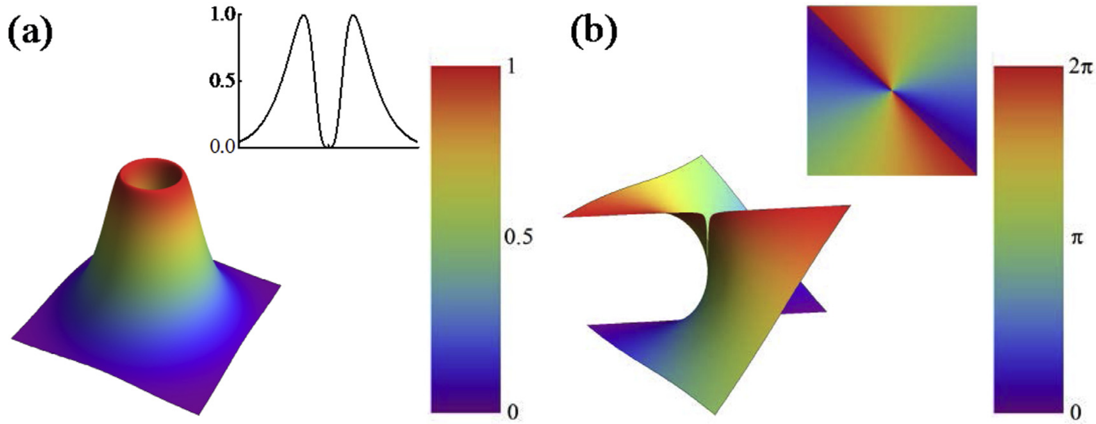

Fig. 1. Intensity and phase distribution of a partially coherent MBG beam at the source plane.

little spreading when propagating over large distance. Therefore, it will be meaningful to study the trapping effect of such beam.

This paper is devoted to studying the radiation force on Rayleigh dielectric sphere with different refractive indices produced by focused partially coherent MBG beams in Rayleigh scattering regime. In Section. 2, the analytical expression for the intensity of partially coherent MBG beams via optical system is derived. Radiation forces on high and low index of refraction particles produced by focused partially coherent MBG beams are analysed and illustrated by numerical examples in Section. 3 and Section. 4. The condition of the trapping stability is analysed in Section. 5. Finally, Section 6 provides the concluding remarks.

2. Intensity of partially coherent MBG beams via optical system

The cross-spectral density function of partially coherent MBG beams at the source plane $z=0$ is expressed as [31,32,34]

$$W_0(s_1,s_2,0) = E_0^2\frac{\xi^{-m/2}}{1-\xi}\exp[-im(\theta_1-\theta_2)]\exp\left[-\frac{1+\xi}{1-\xi}\frac{r_1^2+r_2^2}{w_0^2}\right] I_m\left(\frac{4\sqrt{\xi}}{1-\xi}\frac{r_1r_2}{w_0^2}\right), \tag{1}$$

where $\mathbf{s}_i=(r_i,\ \theta_i)$ is a position vector of a point in the source plane, E_0 is a positive constant, w_0 denotes the waist width of the Gaussian part, ξ is the spectral degree of coherence, $0<\xi<1$, and two limiting cases $\xi\to 0$ and $\xi\to 1$ correspond to the fully coherent and incoherent cases, respectively. I_m is a modified Bessel function of order m, m is topological charge of optical vortex [31,36]. The phase of the cross-spectral density of the partially coherent Modified Bessel-Gaussian beam only depends on a factor $\exp[-im(\theta_1-\theta_2)]$. Eq (1) was originally reported in a Ref. [31]. The cross spectral density was obtained by applying a Mercer series summation over the coherent combination of Laguerre Gaussian beam field expressions. Since the obtained cross spectral density contains the modified Bessel function, it was named as the cross spectral density of the partially coherent Modified Bessel-Gaussian beam in references [32] and [34].

Fig. 1 gives the intensity and phase of the cross-spectral density of partially coherent MBG beams at the source plane. The calculation parameters are $w_0=0.5\,\mathrm{mm}$, $\xi=0.5$, $m=2$. From Fig. 1, we can see that partially coherent MBG beam with $m=2$ has a point defect in the phase diagram, and phase changes 4π in counter clockwise direction around the point, namely, the beam is an optical vortex beam with helical phase structure. In this case, the partially coherent MBG beam has the ability to rotate the particle.

Based on the extended Huygens-Fresnel principle [37], under the paraxial approximation, the cross-spectral density function of partially coherent MBG beam via the ABCD optical system is given by

$$W(\rho_1,\rho_2,z) = \left(\frac{k}{2\pi B}\right)^2\int\int\int\int W_0(s_1,s_2,0) \exp\left[-\frac{ikA}{2B}(r_1^2-r_2^2)-\frac{ikD}{2B}(\rho_1^2-\rho_2^2)\right] \times\exp\left[\frac{ik}{B}r_1\rho_1\cos(\varphi_1-\theta_1)-\frac{ik}{B}r_2\rho_2\cos(\varphi_2-\theta_2)\right] r_1r_2dr_1dr_2d\theta_1d\theta_2 \tag{2}$$

where $\rho_1=(\rho_1,\ \varphi_1)$ and $\rho_2=(\rho_2,\ \varphi_2)$ denote the position vector at the z plane, k is the wave number related to the wavelength λ_0 of input laser by $k=2\pi/\lambda_0$, A, B, C and D are the transfer matrix elements of the optical system.

Applying the integral formula [38]

$$\int_0^{2\pi}\exp[ix\cos(\varphi-\theta)-im\theta]d\theta = 2\pi i^m\exp(-im\varphi)J_m(x), \tag{3}$$

$$\int_0^{\infty}\exp(-\beta x^2)J_m(xy)I_m(\alpha x)xdx = \frac{1}{2\beta}\exp\left(\frac{\alpha^2-\beta^2}{4\beta}\right)I_m\left(\frac{\alpha y}{2\beta}\right), \tag{4}$$

$$\int_0^{\infty}x^{1/2}\exp\left(-qx^2\right)J_m(xh)J_m(gx)(xh)^{1/2}dx = \frac{h^{1/2}}{2q}\exp\left(-\frac{h^2+g^2}{4q}\right) I_m\left(\frac{gh}{2q}\right), \tag{5}$$

to substituting Eq. (1) into Eq. (2), we obtain the cross-spectral density function of partially coherent MBG beams through the focused system as follow

$$W(\rho_1,\rho_2,z) = E_0^2\frac{k^2}{4M_1M_2B^2}\frac{\xi^{-m/2}}{1-\xi}\exp[-im(\varphi_1-\varphi_2)] \exp\left[-\frac{ikD}{2B}(\rho_1^2-\rho_2^2)\right] \times\exp\left[-\frac{k^2\rho_1^2}{4M_1B^2}-\frac{k^2\rho_2^2}{4M_2B^2}\right] \exp\left[-\frac{k^2\rho_1^2\xi}{(1-\xi)^2w_0^4M_1^2M_2B^2}\right]I_m\left[\frac{\sqrt{\xi}}{1-\xi}\frac{k^2\rho_1\rho_2}{B^2M_1M_2w_0^2}\right], \tag{6}$$

where

$$M_1 = \frac{1+\xi}{(1-\xi)w_0^2}+\frac{ikA}{2B}, \tag{7a}$$

$$M_2 = \frac{1+\xi}{(1-\xi)w_0^2}-\frac{ikA}{2B}-\frac{4\xi}{M_1(1-\xi)^2w_0^4}. \tag{7b}$$