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Trapping two types of particles with a focused generalized Multi-Gaussian Schell model beam

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ABSTRACT

We numerically investigate the trapping effect of the focused generalized Multi-Gaussian Schell model (GMGSM) beam of the first kind which produces dark hollow beam profile at the focal plane. By calculating the radiation forces on the Rayleigh dielectric sphere in the focused GMGSM beam, we show that such beam can trap low-refractive-index particles at the focus, and simultaneously capture high-index particles at different positions of the focal plane. The trapping range and stability depend on the values of the beam index N and the coherence width. Under the same conditions, the low limits of the radius of low-index and high-index particles for stable trapping are indicated to be different.

1. Introduction

Recently, a new type of optical beam named generalized Multi-Gaussian Schell model beam (GMGSM) was proposed theoretically and experimentally [1]. Being similar to the earlier model of the Multi-Gaussian Schell model beam (MGSM) [2,3], the degree of coherence of the GMGSM beam is presented in the form of multi-Gaussian function. However, the way of summation of multi-Gaussian functions and the weight coefficients of each Gaussian function are totally different from those of the MGSM beam, which makes the GMGSM beam of the first kind or the second kind generate far fields with dark hollow or flat-topped intensity profiles. Thus the GMGSM beam is more general than the MGSM beam which only forms intensity plateaus in the far field. It is pointed out that the GMGSM beam of the first kind differs from the previously described dark hollow beam, including the certain class of Laguerre–Gaussian (i.e., the doughnut beam) [4], high-order Bessel beams [5], and hollow Gaussian beams as a superposition of Laguerre–Gaussian modes, of which the dark region disappears in the far field [6].

In 1986, Ashkin first demonstrated how to trap the micrometer-sized particle by the radiation force from a single laser beam known as optical tweezers [7]. Since then, optical traps and tweezers have become an important tool for trapping and manipulating a variety of particles such as microsized dielectric sphere [8,9], neutral atoms and molecules [10–12] and metallic particles [13,14]. By now, besides the fundamental Gaussian beams, many kinds of special beams are studied to trap particles. For example, the Bessel beam possessing the ability of self-reconstruction was developed to manipulate particles in multiple axial sites [15]. The polarization-dependent beam was shown to be more suitable for axial optical trapping [16]. The vortex beam carrying orbit angular momentum could drive a Rayleigh particles revolve around the optical axis [17]. In addition, it is noted that some other beams such as the doughnut beams including hollow Gaussian beams and elegant Laguerre–Gaussian (ELG) beams [18,19], the bottle beam [20], double-ring-shaped radially polarized beam (R–TEM_{01}^*) [21], elegant-Hermite-cosine Gaussian beam [22] have been explored. Although these beams all can trap two types of particles with different refractive indices, each beam has its distinctive trapping feature. For instance, the downward and upward bottle beam was used as optical tweezers for high-index and low-index particles at multiple-intensity maxima and in the bottle regions respectively, and the focused R–TEM_{01}^* beam not only generates a sharper spot for trapping high-index particles but also can form a three-dimensional dark spot for trapping low-index particles by choosing a proper truncation parameter of the beam. Therefore, in terms of the GMGSM beam, as a kind of dark hollow beam owning unique characteristic, we think it will be significant to study the trapping effect of such beam. By performing calculations about the radiation forces on the high-index and low-index particles at the focal plane and comparing the

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radiation forces on the two types of particles for different values of the beam index N and the coherence width, some interesting and useful results are found.

2. Radiation forces produced by the focused GMGSM beam of the first kind

The cross-spectral density of the GMGSM beam of the first kind at two position vectors $\boldsymbol{\rho}_{10}$ and $\boldsymbol{\rho}_{20}$ of the lens plane ($z = 0$) is assumed to be of the form [1]

$$W^{(0)}(\boldsymbol{\rho}_{10}, \boldsymbol{\rho}_{20}) = I_0 \exp\left[- \frac{\boldsymbol{\rho}_{10}^2 + \boldsymbol{\rho}_{20}^2}{4\sigma^2} \right] \frac{1}{C_0} \sum_{n=1}^{2N} \sum_{m=1}^{2N} (-1)^{n+m} A_{mn} B_{mn} \exp\left[- \frac{B_{mn}(\boldsymbol{\rho}_{10} - \boldsymbol{\rho}_{20})^2}{2\delta^2} \right] \tag{1}$$

in which I_0 is determined by the input power P and the rms width of the source σ, and δ denotes the rms width of the correlation, for the GMGSM beam of the first kind, A_{mn}, B_{mn} and C_0 take the following form

$$A_{mn} = \binom{4N}{2n-1}\binom{4N}{2m-1}, \quad B_{mn} = \frac{2mn}{m+n}, \tag{2}$$

$$C_0 = \sum_{m=1}^{2N} \sum_{n=1}^{2N} (-1)^{m+n} A_{mn} B_{mn} \tag{3}$$

Employing Eq. (1) and the generalized Huygens–Fresnel principle [23], the output cross-spectral density of the GMGSM beam through the ABCD optical system is derived as follows

$$W(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2, z) = \frac{I_0}{C_0} \sum_{n=1}^{2N} \sum_{m=1}^{2N} (-1)^{m+n} \frac{A_{mn} B_{mn}}{\Delta_{mn}} \exp\left(- \frac{\boldsymbol{\rho}_1^2 + \boldsymbol{\rho}_2^2}{4\Delta_{mn}\sigma^2} \right) \exp\left(- \frac{|\boldsymbol{\rho}_2 - \boldsymbol{\rho}_1|^2}{2m\Delta_{mn}\delta^2} \right) \exp\left[- \frac{ik(\boldsymbol{\rho}_2^2 - \boldsymbol{\rho}_1^2)}{2R_{mn}} \right] \tag{4}$$

where $\Delta_{mn} = A^2 + \frac{B^2}{4\sigma^4 k^2}\left[1 + \frac{4B_{mn}\sigma^2}{\delta^2}\right]$ and $R_{mn} = \frac{B\Delta_{mn}}{D\Delta_{mn} - A}$ denote the beam-expansion coefficients and the generalized phase radii of curvature, respectively.

Based on Eq. (4) and the relation between the intensity and the cross-spectral density at any point of the output plane i.e., $I(\boldsymbol{\rho}, z) = W(\boldsymbol{\rho}, \boldsymbol{\rho}, z)$ [24], an expression for the intensity of the GMGSM beam through ABCD system is obtained

$$I_{out}(\boldsymbol{\rho}, z) = \frac{I_0}{C_0} \sum_{n=1}^{2N} \sum_{m=1}^{2N} (-1)^{m+n} \frac{A_{mn} B_{mn}}{\Delta_{mn}} \exp\left(- \frac{\boldsymbol{\rho}^2}{2\Delta_{mn}\sigma^2} \right) \tag{5}$$

Let us now consider the GMGSM beam of the first kind propagating through a lens system as shown in Fig. 1. The transfer matrix for this system is

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -1/f & 1 \end{bmatrix} = \begin{bmatrix} 1 - z/f & z \\ -1/f & 1 \end{bmatrix} \tag{6}$$

where z is the axial distance from the input plane to the output plane, f is focus length of the thin lens. On substituting Eq. (6) into Eq. (5), the intensity distribution of the GMGSM beam at the focal plane can be obtained. In our calculation, the values of the parameters are taken as $P = 100$ mW, $\lambda = 632.8$ nm, $f = 2$ mm, $\sigma = 2$ mm and $\delta = 2$ mm, unless otherwise stated in the text.

Fig. 1 displays that the intensity distribution of the GMGSM beam of the first kind has a Gaussian profile at the initial plane, but takes on an intense dark hollow profile at the focal plane which is similar to that of the partially coherent elegant Laguerre–Gaussian (ELG) beam at the focal plane [19]. Owing to this special focusing characteristic, we believe that the GMGSM beam of the first kind is able to trap particles with different refractive indices at the focal plane.

The dependence of the intensity distribution of the GMGSM beam of the first kind on the beam index N and the correlation width δ is described in Fig. 2. It is obvious that as the beam index N increases or the correlation width δ decreases the area of the dark region increases, but the magnitudes of intensity decrease. Moreover, the positions of the two sites of highest intensity have shifts when the values of N and δ change.

As is well known, the Rayleigh dielectric particle, whose radius is sufficiently smaller than the wavelength of light (generally $a < \lambda/20$), can be treated as a point dipole in the light fields. In this case, the radiation force exerted on the point dipole can be determined by the Rayleigh scattering model. In the Rayleigh scattering regime the radiation force can be divided into two types: the scattering and gradient force. The scattering forces tend to push the particles along the beam propagation, whereas the gradient forces act as the restoring forces responsible for drawing the particle back to the beam center. Assuming a homogeneous Rayleigh microsphere with refractive index n_p and radius a, the scattering force F_{sca} and the gradient force F_{grad} can be calculated by [9]

$$\vec{F}_{sca}(\boldsymbol{\rho}, z) = \vec{e}_z n_m \alpha I_{out}/c \tag{7}$$

$$\vec{F}_{grad}(\boldsymbol{\rho}, z) = 2\pi n_m \beta \nabla I_{out}/c \tag{8}$$

where $\vec{e}_z$ is a unity vector along the beam propagation, $\alpha = (128\pi^5 a^6/3\lambda^4)\left[(m_0^2 - 1)/(m_0^2 + 1)\right]^2$ and $\beta = a^3(m_0^2 - 1)/(m_0^2 + 2)$ are the scattering cross section and the

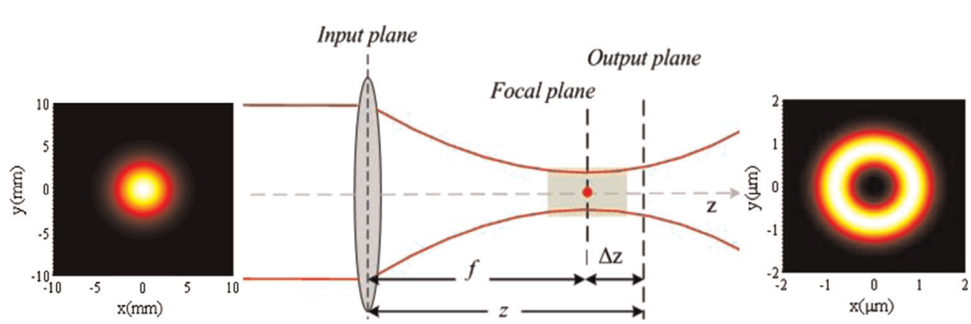

Fig. 1. Illustration of the focusing optical system. Profiles of the left and right are the intensity distribution of the GMGSM beam of the first kind at the input and focal planes.