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Optical trapping two types of particles using a focused vortex beam

Hanghang Zhang [a], Jinhong Li [a,*], Miaojun Guo [a], Meiling Duan [b], Zhifang Feng [a], Wen Yang [a]

[a] Department of Physics, Taiyuan University of Science and Technology, Taiyuan 030024, China
[b] Department of Physics, North University of China, Taiyuan 030051, China

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ABSTRACT

Propagations of Gaussian Schell-model (GSM) vortex beams through a focusing optical system are formulated. The radiation force acting on Rayleigh dielectric sphere with different refractive indices produced by focused GSM vortex beams is investigated theoretically. Numerical results demonstrate that the focused GSM non-vortex beam can not trap the low index of refraction particles, but can capture the high index of refraction particles. The focused GSM vortex beam can be used to trap high index of refraction particles to a bright ring of the focal plane, and simultaneously capture low index of refraction particles to z-axis. The larger the topological charge m is, the larger the value of the spatial correlation length σ_0 is, the easier it is to trap two types of particles is. Trapping stability is also analyzed.

1. Introduction

In 1970, Ashkin first observed the acceleration and trapping of particles by radiation forces from continuous-wave visible laser [1]. Since then, optical traps and manipulation have become an important tool for manipulating a wide variety of particles, including neutral atoms and molecules [2–5], microsized dielectric particles [6,7], and living cells [8–10]. As far as we know, light has momentum and energy, and light radiation force is produced by the exchange of energy and momentum between photons and particles. Because the fundamental Gaussian beam has a peak in the intensity profile, usually most optical traps and manipulation use a focused fundamental Gaussian beam. However, for the fundamental Gaussian beam it is only suitable for trapping high index of refraction particles (the particle with refractive index n_p bigger than that the ambient n_m, namely, the particle with relative refractive index $n_r = n_p/n_m > 1$). In order to trap the low index of refraction particles (the particle with relative refractive index $n_r < 1$), laser beams with a hollow-like intensity profile are proposed in the trapping and manipulating processes [11,12]. Recently many works are devoted to radiation forces acted on spherical particles. For example, the Bessel beam having the ability of self-reconstruction has been developed to manipulate particles in multiple axial sites [13]. Liu and Zhao numerically investigated the trapping effect of the focused generalized Multi-Gaussian Schell model beam at the focal plane [14]. The radiation force of modified circular Airy beams (MCAB) exerted on both a high index of refraction particle and a low index of refraction particle have been analyzed by Jiang et al., and it is shown that the two kinds of particles can be simultaneously stably trapped by MCAB at different positions [15].

* Corresponding author.
E-mail address: jinhongli@live.cn (J. Li).

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Vortex beams possess spiralling wavefronts and orbital angular momentum, which are widely used in applications such as micronsized particle manipulation, photon counting, optical data storage and optical communications, etc. [16–23]. The much interest in the propagation characteristics of vortex beams through free space and biological tissues have been exhibited from theoretical and applicative aspects [24–26]. The GSM vortex beam as a typical example of singularity beams owning unique characteristic, so we think that it will be significant to study the trapping effect of such beam. By performing calculations about the radiation forces on the high and low index of refraction particles at the focal plane and comparing the radiation forces exerted on the two types of particles for different values of the topological charge m and the spatial correlation length σ_0, some interesting and useful results are found. Finally we analyze the condition of the stable trapping.

2. Intensity of Gaussian Schell-model vortex beams via optical system

The initial field distribution of Laguerre–Gaussian (LG) beam at $z = 0$ can be expressed as [27,28]

$$\boldsymbol{E}(s,\theta,z=0)=E_0\left(\frac{\sqrt{2}s}{w_0}\right)^m L_n^m\left(\frac{2s^2}{w_0^2}\right)\exp\left(-\frac{s^2}{w_0^2}\right)\exp(im\theta), \tag{1}$$

where s and θ are the radial coordinate and azimuthal coordinate, respectively. w_0 denotes the waist width, L_n^m denotes the Laguerre polynomial with mode orders n and m. LG beam is a typical mixed circular edge-screw dislocations beam, for $m \neq 0$ and $n = 0$, Eq. (1) reduces to the initial field distribution of Gaussian vortex beam (screw dislocation beam), m is topological charge of vortex beam; for $m = 0$ and $n \neq 0$, Eq. (1) degenerates to the initial field distribution of circular edge dislocations beam, n is the number of circular edge dislocation; for $m = 0$ and $n = 0$, Eq. (1) degenerates to the initial field of fundamental Gaussian beam.

Using the relations between Laguerre polynomial and Hermite polynomial [29]

$$\exp\left(im\theta\right)\boldsymbol{s}^m L_n^m\left(S^2\right)=\frac{(-1)^n}{2^{2n+m}n!}\sum_{t=0}^{n}\sum_{r=0}^{m}\mathrm{i}^r\binom{n}{t}\binom{m}{r}H_{2t+m-r}\left(S_x\right)H_{2n-2t+r}\left(S_y\right), \tag{2}$$

with H_t being the Hermite polynomial of order t, $\binom{n}{t}\binom{m}{r}$ being binomial coefficients, the initial field distribution of Gaussian vortex beam can be expressed in following alternative form in Cartesian coordinates

$$\boldsymbol{E}\left(\boldsymbol{s},z=0\right)=E_0\frac{1}{2^m}\sum_{r=0}^{m}\mathrm{i}^r\binom{m}{r}H_{2t+m-r}\left(\frac{\sqrt{2}s_x}{w_0}\right)H_{-2t+r}\left(\frac{\sqrt{2}s_y}{w_0}\right)\exp\left(-\frac{\boldsymbol{s}^2}{w_0^2}\right). \tag{3}$$

Introducing the Schell model correlator [30], the cross-spectral density function of a Gaussian Schell-model (GSM) vortex beam at the source plane $z = 0$ is expressed as

$$\begin{aligned}W_0(\boldsymbol{s}_1,\boldsymbol{s}_2,0)&=\langle E(\boldsymbol{s}_1,0)^*\bullet E(\boldsymbol{s}_2,0)\rangle\\&=\frac{1}{2^{2m}}E_0^2\sum_{r_1=0}^{m}\sum_{r_2=0}^{m}(-\mathrm{i})^{r_1}\mathrm{i}^{r_2}\binom{m}{r_1}\binom{m}{r_2}H_{m-r_1}\left(\frac{\sqrt{2}s_{1x}}{w_0}\right)H_{m-r_2}\left(\frac{\sqrt{2}s_{2x}}{w_0}\right)\\&\times H_{r_1}\left(\frac{\sqrt{2}s_{1y}}{w_0}\right)H_{r_2}\left(\frac{\sqrt{2}s_{2y}}{w_0}\right)\exp\left(-\frac{\boldsymbol{s}_1^2+\boldsymbol{s}_2^2}{w_0^2}\right)\exp\left[-\frac{(s_1-s_2)^2}{2\sigma_0^2}\right],\end{aligned} \tag{4}$$

where σ_0 is the spatial correlation length. For $m = 0$, Eq. (4) degenerates to the cross-spectral density function of GSM non-vortex beam.

According to the extended Huygens-Fresnel principle and in the paraxial approximation [31], the cross-spectral density function of the GSM vortex beam via the ABCD optical system can be expressed as

$$\begin{aligned}W\left(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2,z\right)&=\left(\frac{k}{2\pi B}\right)^2\int\int\int\int W_0\left(\boldsymbol{s}_1,\boldsymbol{s}_2,0\right)\exp\left[-\frac{\mathrm{i}kD}{2z}\left(\boldsymbol{\rho}_1^2-\boldsymbol{\rho}_2^2\right)\right]\\&\times\exp\left\{-\frac{\mathrm{i}k}{2B}\left[A\left(\boldsymbol{s}_1^2-\boldsymbol{s}_2^2\right)-2\left(\rho_{1x}s_{1x}+\rho_{1y}s_{1y}-\rho_{2x}s_{2x}-\rho_{2y}s_{2y}\right)\right]\right\}ds_{1x}ds_{1y}ds_{2x}ds_{2y},\end{aligned} \tag{5}$$

where $\boldsymbol{\rho}_1 = (\rho_{1x}, \rho_{1y})$ and $\boldsymbol{\rho}_2 = (\rho_{2x}, \rho_{2y})$ 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–D are the transfer matrix elements of the optical system.

On substituting Eq. (4) into Eq. (5), using the relation between the intensity and the cross-spectral density at any point of the output plane $I(\boldsymbol{\rho}, z) = W(\boldsymbol{\rho}, \boldsymbol{\rho}, z)$, we obtain the intensity of GSM vortex beams via an ABCD optical system as follow

$$I\left(\rho_x,\rho_y,z\right)=E_0^2\left(\frac{k}{2\pi B}\right)^2\frac{1}{2^{2m}}\sum_{r_1=0}^{m}\sum_{r_2=0}^{m}(-\mathrm{i})^{r_1}\mathrm{i}^{r_2}\binom{m}{r_1}\binom{m}{r_2}Q_1Q_2, \tag{6}$$