Physics Letters A 380 (2016) 311–315

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Optically induced rotation of Rayleigh particles by vortex beams with different states of polarization

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ARTICLE INFO

Article history:
Received 2 July 2015
Received in revised form 5 August 2015
Accepted 6 August 2015
Available online 28 August 2015
Communicated by V.A. Markel

Keywords:
Optical trapping
Optical vortex beam
State of polarization
Orbital angular momentum
Orbital motion

ABSTRACT

Optical vortex beams carry optical orbital angular momentum (OAM) and can induce an orbital motion of trapped particles in optical trapping. We show that the state of polarization (SOP) of vortex beams will affect the details of this optically induced orbital motion to some extent. Numerical results demonstrate that focusing the vortex beams with circular, radial or azimuthal polarizations can induce a uniform orbital motion on a trapped Rayleigh particle, while in the focal field of the vortex beam with linear polarization the particle experiences a non-uniform orbital motion. Among the formers, the vortex beam with circular polarization induces a maximum optical torque on the particle. Furthermore, by varying the topological charge of the vortex beams, the vortex beam with circular polarization gives rise to an optimum torque superior to those given by the other three vortex beams. These facts suggest that the circularly polarized vortex beam is more suitable for rotating particles.

1. Introduction

Since the first demonstration of optical trapping in 1970 [1], it has been drawing intensive attention for the ability to manipulate small objects in a non-invasive way [2]. Among optical manipulations, rotating of particles by the laser beam is of great importance for some practical microsystems [3–6]. The rotation techniques can be based on the shape asymmetry of trapped objects [7,8], birefringence of the particle [9], or the transfer of orbital angular momentum (OAM) carried by a laser beam with a particular phase structure [10–12]. In these methods, the transfer of OAM is most feasible, since it does not rely on the intrinsic properties of the particle [13–15].

In general, the OAM of laser beams is characterized by the vortex phase factor $\exp(im\phi)$, where m is the topological charge and ϕ the azimuthal angle. Such beams are considered to carry OAM of $m\hbar$ per photon [10]. When the vortex beam is focused by a high numerical aperture (NA) objective lens, an annular focal spot is formed. As a result, a particle in the focal region may be trapped on this circle and executes an orbital motion due to the transfer of OAM from the beam to it. Majority of previous works of optical rotation dynamics focused on beams with spatially homogeneous polarization states, such as linear, circular and elliptical polarizations [16,17] and limited to particles larger than 100 nm in size [18,19]. As we know, there are also some spatially inhomogeneous polarization distributions, e.g., radial or azimuthal polarizations. The state of polarization (SOP) of the beams will affect the focusing field distribution, leading to different trapping properties. Consequently, when the vortex beam is modulated with these spatial polarizations, its trapping properties including the rotation dynamics are also changed. In this paper, we make a theoretical investigation on the orbital motion of Rayleigh particles in the focal fields of highly focused vortex beams with different SOPs. A systematic analysis is also devoted to the influence of the characteristics of the particles and the optical beams on the rotation dynamics.

2. Optical force and orbital torque on a dielectric sphere

Consider a dielectric spherical particle of radius a with permittivity ε_2 placed in an extern field $\mathbf{E}$ propagating in a medium of permittivity ε_1. For the particle of radius a much smaller than the wavelength λ (usually $a < \lambda/20$), the optical force on the particle can be treated as an interaction of the external electric field $\mathbf{E}$ with the induced dipole $\mathbf{p} = \alpha\mathbf{E}$, that is, the Rayleigh model is applicable. With a harmonic time dependence $\exp(-i\omega t)$ of the field assumed, the time-averaged force can be expressed as [20]:

$$\langle F_i \rangle = \frac{1}{2}\mathrm{Re}\left[\alpha E_j \partial_i (E_j)^*\right], \tag{1}$$

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http://dx.doi.org/10.1016/j.physleta.2015.08.026
0375-9601/

here i, j denote the Cartesian components (x, y, z) and the dummy index means a summation over all three components, $*$ denotes the complex conjugate, and α is the modified polarizability [21]:

$$\alpha = \frac{\alpha_0}{1 - \frac{2}{3} i k^3 \alpha_0}, \tag{2}$$

with α_0 referring to the static molecular polarizability given by the equation [22]:

$$\alpha_0 = 4\pi \varepsilon_1 a^3 (\varepsilon - 1)/(\varepsilon + 2), \tag{3}$$

where $\varepsilon = \varepsilon_2/\varepsilon_1$ is the relative permittivity of the particle to the surrounding medium, and k is the wave number.

To obtain the orbital angular momentum of the field acting on the particle, we need to know the azimuthal component of the force in cylindrical coordinates. With the knowledge of the Cartesian components (1) of the force, the time-averaged azimuthal force is easily calculated to be $\langle F_\phi \rangle = -(\sin\phi)\langle F_x \rangle + (\cos\phi)\langle F_y \rangle$. Then, the orbital torque Γ_z on the particle [23]:

$$\langle \Gamma_z \rangle = \rho \langle F_\phi \rangle, \tag{4}$$

where ρ is the radial distance of the particle.

3. Focusing of vortex beams with different states of polarization

In actual optical trapping, a tightly focusing of the incident beam is needed. The focused field in the vicinity of the focus, according to Richards and Wolf [24,25], can be expressed in cylindrical coordinates as:

$$\mathbf{E}(\mathbf{r}) = \frac{-ikf}{2\pi} \int_0^{\theta_{\max}} \int_0^{2\pi} \mathbf{A}(\theta, \phi) \exp(i\mathbf{k} \cdot \mathbf{r}) \sin\theta \, d\phi \, d\theta, \tag{5}$$

where $k = 2\pi n_1/\lambda_0$ is the wave number in the image space with n_1 and λ_0 denoting the image space refractive index and free space wavelength, respectively; $\theta_{\max}$ is the maximal converging angle given by the NA of the objective lens, $\theta_{\max} = \sin^{-1}(\mathrm{NA}/n_1)$; f is the focal length; the vectors $\mathbf{k}$ and $\mathbf{r}$ designate wave vector and the observation point position in the image space. Note that the integral kernel $\mathbf{A}(\theta, \phi)$ stands for the apodization of input field $\mathbf{A}_0(\theta, \phi)$ at the entrance pupil of the lens. The relation between $\mathbf{A}$ and $\mathbf{A}_0$ can be expressed as follow. The incident field $\mathbf{A}_0$ may be written as $\mathbf{A}_0 = \mathbf{e}_\rho A_{0\rho} + \mathbf{e}_\phi A_{0\phi}$, where $\mathbf{e}_\rho$ and $\mathbf{e}_\phi$ are unit vectors in the radial and azimuthal directions at the pupil plane, and $A_{0\rho}$ and $A_{0\phi}$ are the field components along these two directions. After apodization, the input vector field $\mathbf{A}_0$ becomes the vector function $\mathbf{A}$, which is related to $\mathbf{A}_0$ according to [24,25], $\mathbf{A} = (\cos\theta)^{1/2}(\mathbf{e}_\theta A_{0\rho} + \mathbf{e}_\phi A_{0\phi})$ with $\mathbf{e}_\theta$ and $\mathbf{e}_\phi$ being unit vectors in the polar angle directions in spherical coordinates in the image space. We see that except for the $(\cos\theta)^{1/2}$ factor due to the conservation of energy, $\mathbf{A}$ is equal to $\mathbf{A}_0$ with the radial unit vector $\mathbf{e}_\rho$ replaced by the unit vector in θ direction $\mathbf{e}_\theta$.

For incident vortex beams, the input field $\mathbf{A}_0$ takes the form $\mathbf{A}_0 = \mathbf{u} l(\theta) \exp(im\phi)$, where $\mathbf{u}$ is the polarization vector; m is the topological charge of vortex beams. Different forms of $\mathbf{u}$ represent different states of polarization. In this paper, we discuss four kinds of polarized vortex beams, i.e., x-linearly polarized vortex (x-LPV), circularly polarized vortex (CPV), radially polarized vortex (RPV) and azimuthally polarized vortex (APV) beams. Then $\mathbf{u}$ takes $\mathbf{e}_x$, $(\mathbf{e}_x + i\mathbf{e}_y)/\sqrt{2}$, $\mathbf{e}_\rho$, and $\mathbf{e}_\phi$, respectively, where $\mathbf{e}_\rho(\mathbf{e}_\phi)$ stands for a unit vector along the radial (azimuthal) direction. The amplitude function $l(\theta)$ is assumed to have a form:

$$l(\theta) = (\sin\theta)^m \exp\left[-\left(\frac{\sin\theta}{\sin\theta_{\max}}\right)^2\right]. \tag{6}$$

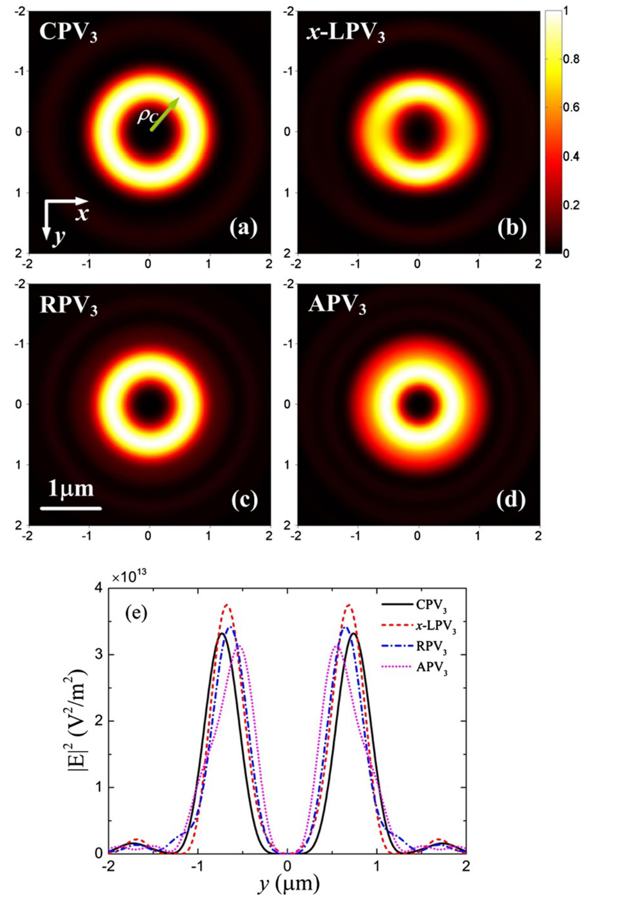

Fig. 1. Intensity distributions of highly focused vortex beams ($m = 3$) with different states of polarization. (a)–(d) are the intensity distributions in the focal plane for circular, x-linear, radial and azimuthal polarizations, respectively. (e) corresponds to the line scans along the y-axis.

In the following calculations, we set the free space wavelength of light $\lambda_0 = 1.064$ μm; the image space refractive index $n_1 = 1.33$; the incident power $P = 100$ mW and NA $= 1.26$.

Now we can make calculations to see the focusing properties of the vortex beams with different SOPs. Because the Eq. (5) integrating over ϕ results in an electric field involving the first kind of Bessel function, the topological charge m will also affect the distribution of the focusing field. For the x-LPV beam, when $m = 1$ or 2 (here we consider only the positive values of m), a hollow-like focusing distribution is obtained with the axial intensity not purely null. Only when $m \geq 3$, can a pure doughnut focusing distribution be obtained. For the RPV beam, the condition is $m \geq 2$ to obtain a pure doughnut focal spot. For the APV beam, since the z-component of the focused field is inevitably zero, the radial and azimuthal components of the electric field are related to the first kind of Bessel function with order of $m - 1$, the maximal intensity is located at the focus with $m = 1$ and it also requires $m \geq 2$ to obtain a pure doughnut focal spot. While the CPV beam, $m \geq 1$ can guarantee a pure doughnut focal spot. In the condition of $m = 3$, the four kinds of incident vortex beams CPV$_3$, x-LPV$_3$, RPV$_3$ and APV$_3$ all give a on-axis null annular focusing, as shown in Fig. 1, where the subscripts represent the values of topological charge m. It is obvious that the intensities of focused field of CPV$_3$, RPV$_3$ and APV$_3$ beams all exhibit cylindrical symmetry except for the x-LPV$_3$ beam. This can be understood by noting that the incident x-LPV$_3$ beam is not symmetrical in its polarization. In fact, the focal spot of the x-polarized incident beam is generally elongated along the x-axis. This indicates that on a circle of fixed radius the intensity is seen to attain its maximum on the y-axis, as illustrated