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Multiple 3D optical trapping using higher polarization order axially-symmetric polarized beams

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Abstract: We propose a novel single-beam multiple 3D optical trapping scheme using higher polarization order axially-symmetric polarized beams in an aplanatic focusing system. We calculate numerically the intensity distribution near the focus which presents a multi-focus-spot pattern and provides the possibility of multiple optical trapping. We also calculate the corresponding gradient force distribution near the focus. Finally we introduce a 3D optical chain by combining the single-beam system with a single diffractive optical element.

Key words: optical trapping; axially-symmetric polarized beam; optical imaging

1 Introduction

Optical trapping, or optical tweezer[1,2], is a noncontact technique for manipulating microparticles using the radiation pressure force from a tightly focused laser beam, and has proved to be a powerful tool for many applications in numerous areas of science, such as biology[3,4] and colloid chemistry. As a result, many varieties of optical tweezers have been developed. To extend the capability of optical tweezers, some multiple optical trapping schemes have also been proposed relying on very different techniques, including diffractive optical elements[5], interfering beams[6], VCSEL arrays[7], microlens arrays[8] or optical fibre bundles[9]. Certain optical trapping schemes even allow for the generation of multiple traps that are computer-reconfigurable using laser scanning[10] and spatial light modulators[11].

In general, single-beam optical tweezers are only used for individual particle trapping. Further, the very limited field-of-view of high numerical aperture objective lenses commonly employed for optical trapping restricts the number and the size of particles that can be trapped simultaneously, while some single-beam optical tweezers with several trapping sites have also been presented[12-14]. In this paper, we purpose a multiple optical trapping scheme based on the single-beam configuration but using higher polarization order axially-symmetric polarized beams in an aplanatic focusing system. We study the high numerical aperture focusing properties of such beams, and calculate numerically the intensity distribution near

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the focus. We find some unique focusing properties of multi-focus-spot patterns, which provide the possibility of multiple 3D optical trapping. Meanwhile, the number and sizes of spots can easily be changed in order to satisfy different applications by modifying several parameters of the system, such as the polarization order number of the incident beams and the numerical aperture of the lens, which provides a solution for massively parallel trapping of nanometer-sized particles. In addition, more trapping flexibility is achieved in combination with Diffractive Optical Elements (DOEs). Finally, we present a typical three-dimensional optical chain.

2 Basic theory

Axially-symmetric Polarized Beams (ASPB) are space-variant polarized beams with axial symmetry where the symmetric axis is the propagation axis of the light beam. For an ASPB, as shown in Fig. 1,

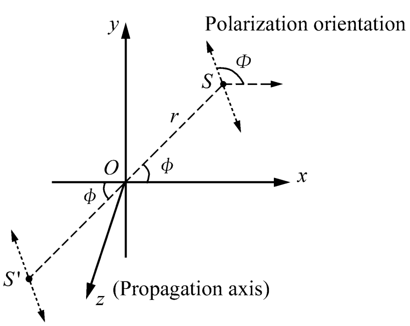


Fig. 1　Polarization orientation of an ASPB.

the polarization orientation is the same for two arbitrary axially-symmetric points of the beam profile, S and S', and the polarization orientation angle $\Phi(r,\phi)$ of the electric field only depends on the azimuthal angle ϕ as $\Phi(r,\phi) = P\phi + \phi_0$, where P is the polarization order number, and ϕ_0 is the initial polarization orientation for $\phi = 0$. Well-known radially polarized beams and azimuthally polarized beams are axially-symmetric polarized beams with polarization order 1.

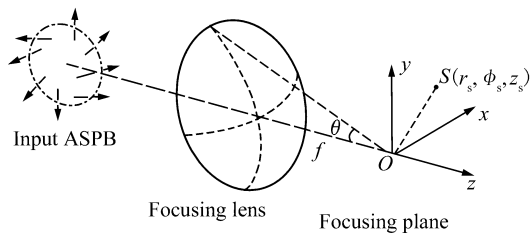


Fig. 2　Focusing of an ASPB. In the diagram, f is the focal length of the focusing lens, $S(r_s, \phi_s, z_s)$ is an observation point near the focusing plane.

Fig. 2 shows the focusing of an ASPB. The incident field is an ASPB, which is assumed to have a planar phase front and f is the focal length of the focusing lens. $S(r_s, \phi_s, z_s)$ is an arbitrary observation point near the focus, ϕ_s denotes the azimuthal angle with respect to the x-axis, and θ represents the polar angle. Following the theory of Richards & Wolf[15], the electric field at the point S can be written as

$$\boldsymbol{E}(r,\phi,z) = E_r\boldsymbol{e}_r + E_\phi\boldsymbol{e}_\phi + E_z\boldsymbol{e}_z \qquad (1)$$

where $\boldsymbol{e}_r$, $\boldsymbol{e}_\phi$ *and* $\boldsymbol{e}_z$ are unit vectors in the radial, azimuthally and longitudinal directions, respectively. E_r, E_ϕ and E_z are the amplitudes of the three orthogonal components that can be expressed as

$$E_r(r,\phi,z) = \frac{-\mathrm{i}A}{2\pi}\int_{\theta_{\min}}^{\theta_{\max}}\int_0^{2\pi} l(\theta)\sin 2\theta\sqrt{\cos\theta}\,\mathrm{e}^{\mathrm{i}k[z_s\cos\theta + r_s\sin\theta\cos(\phi-\phi_s)]}\cos[(P-1)\phi+\phi_0]\cos(\phi-\phi_s)\,\mathrm{d}\theta\mathrm{d}\phi$$

$$E_\phi(r,\phi,z) = \frac{-\mathrm{i}A}{\pi}\int_{\theta_{\min}}^{\theta_{\max}}\int_0^{2\pi} l(\theta)\sin\theta\sqrt{\cos\theta}\,\mathrm{e}^{\mathrm{i}k[z_s\cos\theta + r_s\sin\theta\cos(\phi-\phi_s)]}\sin[(P-1)\phi+\phi_0]\cos(\phi-\phi_s)\,\mathrm{d}\theta\mathrm{d}\phi$$

$$E_z(r,\phi,z) = \frac{-\mathrm{i}A}{\pi}\int_{\theta_{\min}}^{\theta_{\max}}\int_0^{2\pi} l(\theta)\sin^2\theta\sqrt{\cos\theta}\,\mathrm{e}^{\mathrm{i}k[z_s\cos\theta + r_s\sin\theta\cos(\phi-\phi_s)]}\cos[(P-1)\phi+\phi_0]\,\mathrm{d}\theta\mathrm{d}\phi \qquad (2)$$

where $l(\theta)$ is the pupil apodization function that denotes the relative amplitude and phase of the field, and k is the wavelength number. $\theta_{\max}$ and $\theta_{\min}$ are the maximum and minimum polar angles determined by the numerical aperture of the objective lens.

Based on above equations, we can calculate the intensity and amplitude distributions corresponding to different components as well as the total field near the focus for different polarization order ASPBs.

3 Numerical simulations

We calculate numerically the intensity distribution of the total field near the focus for the ASPB with different polarization order number P. Fig. 3 shows the intensity distribution for NA = 0.90 and P = 4 and 10 respectively, where we assume the refractive index n of the medium and the incident wavelength are 1. Obviously, the focusing field presents a multi-focus-spot pattern which is different from that of radially polarized beams. The number of focal spots is related to the polarization order number as $2\times(P-1)$. The multi-focus-spot property provides the possibility of multiple parallel manipulations of particles, such as trapping, rotation, and accelera-tion.

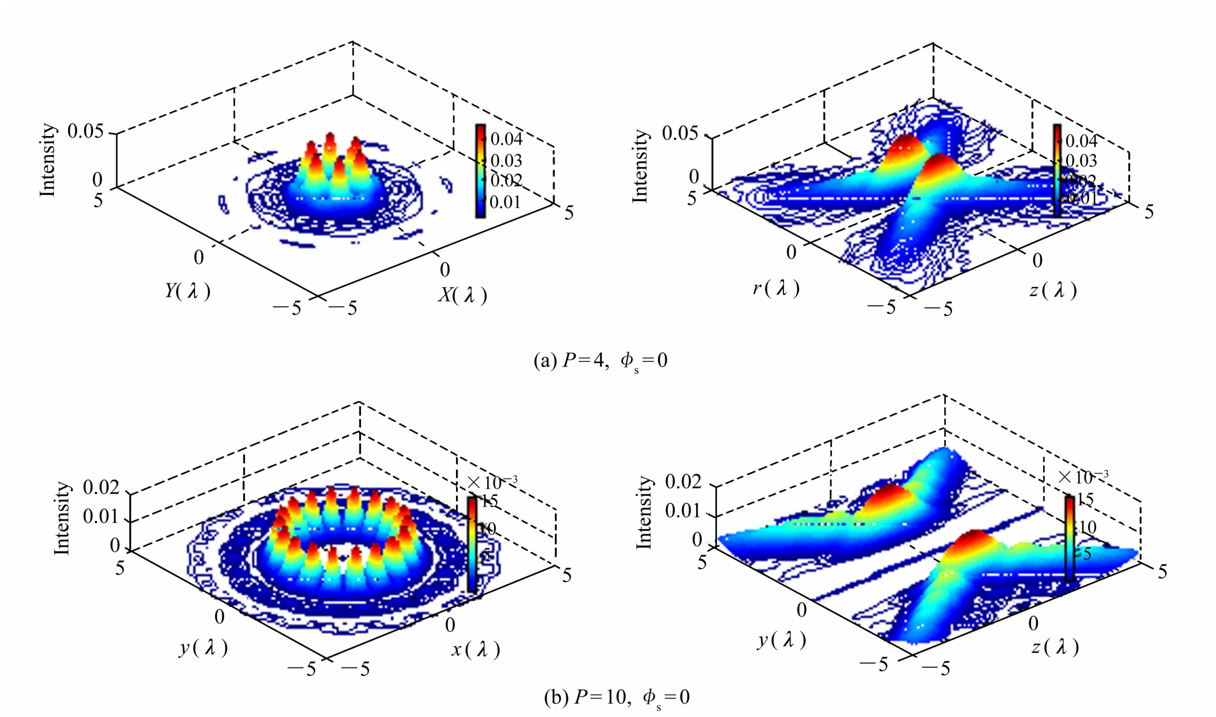


Fig. 3 Intensity distribution of total field for different polarization order numbers at focus (the left column) and through focus (the right column).

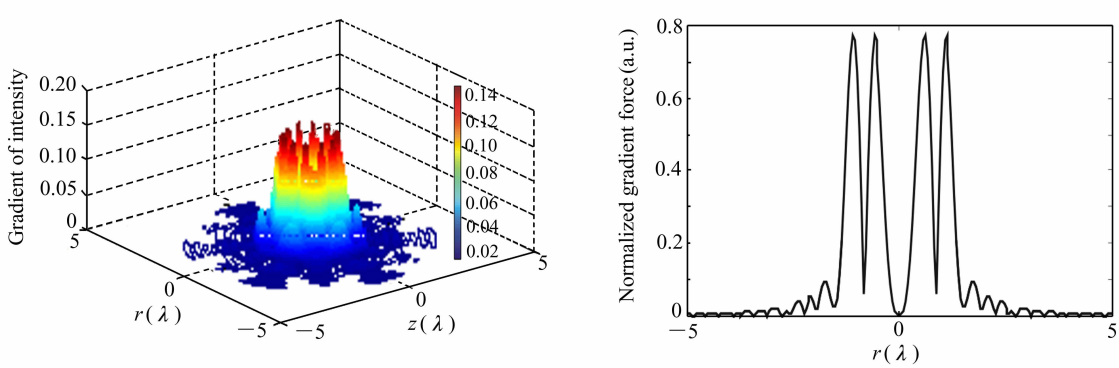


Fig. 4 Gradient force at focus for $m=4$, $\phi_0=0$.

When the trapped particle is much smaller than the wavelength of the trapping lasers, *i. e.*, $r \ll \lambda$, the conditions for Raleigh scattering are satisfied, and the scattering and gradient force components are expressed as[2],

$$F_{scatt} = \frac{I_0}{c}\frac{128\pi^5 r^6}{3\lambda^4}\left(\frac{m^2-1}{m^2+2}\right)n_m$$
$$F_{grad} = \frac{n_m^3 r^3}{2}\left(\frac{m^2-1}{m^2+2}\right)\nabla |E|^2 \qquad (3)$$

where I_0 is the intensity of the incident beam, n_m is the refractive index of the medium, r is the radius of the particle, c is the speed of light in vacuum and m is the ratio of the refractive index of the particle to the refractive index of the medium (n_p/n_m). The scattering force F_{scatt} is in the direction of propagation of the incident light and is proportional to the intensity, while the gradient force F_{grad} is proportional to the intensity gradient and is parallel to the increasing gradient when $m>1$. Fig. 4 shows numerically the normalized gradient force on the particle corresponding to $m=4$, and we choose $n_p=1.59$, $\lambda=1$, $r=0.1\lambda$.

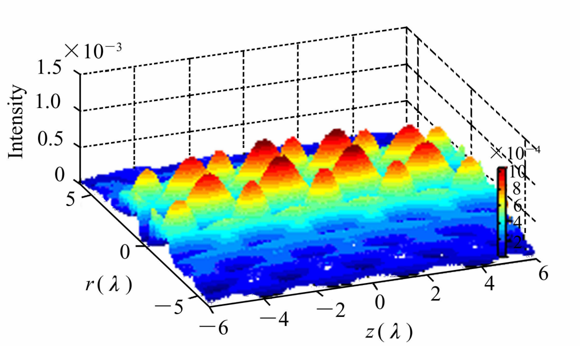
In addition, we can use the DOEs to control the 3D focusing field distribution near the focus more freely, such as a three-dimensional optical chain. The transmission function of the DOE is expressed as,

$$T(\theta) = \begin{cases} a_1\exp(i\varphi_1) & \theta \in [0,\theta_1] \\ a_2\exp(i\varphi_2) & \theta \in [\theta_1,\theta_2] \\ \cdots\cdots & \\ a_n\exp(i\varphi_n) & \theta \in [\theta_{n-1},\theta_n] \end{cases} \qquad (4)$$

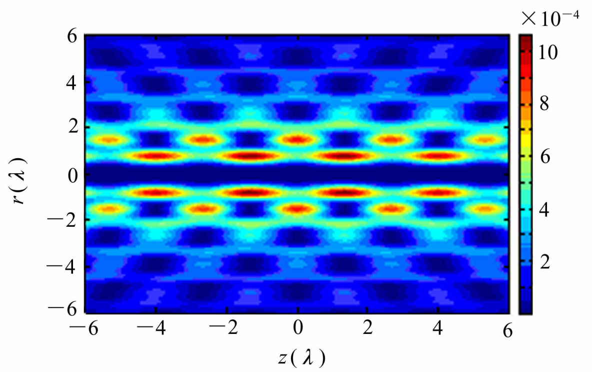
where, a_i and φ_i are the transmission efficiency and phase of the ith belt of the DOE respectively. We use a five-belt structure as

$$T(\theta) = \begin{cases} 1 & \theta \in [0, 0.4\theta_{max}] \\ 0 & \theta \in [0.4\theta_{max}, 0.8\theta_{max}] \\ 1 & \theta \in [0.8\theta_{max}, 09\theta_{max}] \\ 0 & \theta \in [0.9\theta_{max}, 0.95\theta_{max}] \\ 1 & \theta \in [0.95\theta_{max}, \theta_{max}] \end{cases} \qquad (5)$$

where θ_{max} is the maximal polar angle determined by the NA of objective lens. Fig. 5 presents the field distribution of the three-dimensional optical chain through the focus. It can carry out multiple 3D optical trapping.



(a) 3D optical chain



(b) 2D optical chain

Fig. 5　Intensity distribution of designed optical chain through focus.

4　Conclusions

We demonstrate a multiple 3D optical trapping scheme based on higher polarization order ASPBs, which overcomes the traditional limits of single-beam configuration on the number and size of trapped particles because of the limited field-of-view of high numerical aperture objective lenses. We can easily change the number and sizes of spots by modifying the polarization order number of incident beams and numerical aperture of the lens. In addition, some interesting multiple optical trapping structures can be produced in combination with a diffractive optical element, such as a three-dimensional optical chain, which provides a solution for massively parallel trapping of nanometer-sized particles.

References:

[1] ASHKIN A. Acceleration and trapping of particles by radiation pressure[J]. *Phys. Rev. Lett.*,1970,24(4):156-159.

[2] ASHKIN A,DZIEDZIC J M,BJORKHOLM J E,*et al.*. Observation of a single-beam gradient force optical trap for dielectric particles[J]. *Opt. Lett.*,1986,11(5),288-290.

[3] GRIER D G. A revolution in optical manipulation[J]. *Nature*,2003,424(6950):810-816.

[4] ASHKIN A,DZIEDZIC J M,YAMANE T. Optical trapping and manipulation of single cells using infrared laser beams[J]. *Nature*,1987,330(6150):769-771.

[5] DUFRESNE E R,GRIER D G. Optical tweezer arrays and optical substrates created with diffractive optics[J]. *Rev. Sci. Instrum.*,1998,69(5):1974-1977.

[6] MELLOR C D,BAIN C D. Array formation in evanescent waves[J]. *Chem. Phys.*,2006,7(2):329-332.

[7] OGURA Y,KAGAWA K,TANIDA J. Optical manipulation of microscopic objects by means of vertical-cavity surface-emitting laser array sources[J]. *Appl. Opt.*,2001,40(30):5430-5435.

[8] SOW C H,BETTIOL A A,LE Y Y G,*et al.*. Multiple-spot optical tweezers created with microlens arrays fabricated by proton beam writing[J]. *Appl. Phys. B*,2004,78(6):705-709.

[9] TAM J M,BIRAN I,WALT D R. An imaging fiber-based optical tweezer array for microparticle array assembly[J]. *Appl. Phys. Lett.*,2004,84(21):4289-4291.

[10] SASAKI K,KOSHIOKA M,MISAWA H,*et al.*. Pattern-formation and flow-control of fine particles by laser-scanning micromanipulation[J]. *Opt. Lett.*,1991,16(19):1463-1465.

[11] REICHERTER M,HAIST T,WAGEMANN E U,*et al.*. Optical particle trapping with computer-generated holograms written on a liquid-crystal display[J]. *Opt. Lett.*,1999,24(9):608-610.

[12] RODRIGO P J,DARIA V R,GLÜCKSTAD J. Real-time three-dimensional optical micromanipulation of multiple particles and living cells[J]. *Opt. Lett.*,2004,29(19):2270-2272.

[13] MACDONALD M P,PATERSON L,VOLKE-SEPULVEDA K,*et al.*. Creation and enhanced manipulation of 3-dimensional optically trapped structures[J]. *Science*,2002,296:1101-1103.

[14] ZHAO Y Q,ZHAN Q W,ZHANG L Y,*et al.*. Creation of a three-dimensional optical chain for controllable particle delivery[J]. *Opt. Lett.*,2005,30(8):848-850.

[15] RICHARDS B,WOLF E. Electromagnetic diffraction in optical systems II. Structure of the image field in an aplanatic system[J]. *Proc. Roy. Soc A*,1959,253(1274):358-279.

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