Journal of Quantitative Spectroscopy & Radiative Transfer 162 (2015) 114–121

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Optical trapping in secondary maxima of focused laser beam

Martin Šiler*, Pavel Zemánek

ASCR, Institute of Scientific Instruments, Královopolská 147, 612 64 Brno, Czech Republic

A R T I C L E I N F O

Article history:
Received 1 December 2014
Received in revised form
19 February 2015
Accepted 2 March 2015
Available online 10 March 2015

Keywords:
Optical tweezers
Optical traps
Optical trap stiffness
Focused beam

A B S T R A C T

Single beam optical tweezers hold particles behind the focal plane due to the high gradients of optical intensity present in a focused laser beam. However, description of this optical field based on a vectorial theory of diffraction reveals that the high intensity focal area is accompanied by several secondary maxima on the optical axis as well as by a structure of rings away of the optical axis. Such a structure can be found in beams exhibiting spherical aberrations as well as in beams where aberration is corrected. Here, we discuss possibility to use these secondary maxima of aberration-corrected beams as the optical traps. We present the properties of such traps created by objective lenses of various numerical apertures that are focusing plane waves.

1. Introduction

Nano- or micro-particle exposed to a focused laser light is affected by the forces originating in the transfer of light momentum. Optical tweezers [1–5] is a tool of choice for many applications because it enables to hold and move microparticles in microscopes or lab-on-a-chip systems. Similarly, optical conveyors [6–8], or sieves [9–13] may be used for particle delivery or sorting. The particles may be even pulled against the light propagation direction in the so-called tractor beams [14–18]. If the particle is exposed to the complex light field that is created e.g. by interference, the so-called size-effect can be observed [6,19]. It means that the particles of certain sizes are pushed with their centers to the intensity maxima, particles of different sizes are posed to the intensity minima and some particles move freely across the light fringes. This effect is often utilized for particle sorting [2,6,11–13,20]. However, if the angular spectrum formalism is used to describe the electromagnetic field, any light field may be considered as an interference of infinite number of plane waves. Therefore, we expect to observe a manifestation of the size effect in any optical fields as well, such as in the optical tweezers.

The angular spectrum description of light focusing through objective lens corresponds to the Debye approximation of the diffraction of a convergent spherical wave on a circular aperture [21,22]. In this description several oscillations of light intensity along beam propagation axis are present and the light rings are also present in the transversal planes out of focus. Similarly, these rings are present in the experiments. However, the experimental distribution of light intensity near focus is usually broadened and changed by the spherical aberrations originating in the refractive index mismatch in between air or immersion oil behind the microscope objective and other media where the observation is performed. This consequently modifies the optical forces, trap stiffness and depth [23] and causes asymmetry of the optical trap [24–26]. The aberrations may be corrected for by using a spatial light modulator [27–29] and, therefore, the description of a particle behavior in such beam (without the presence of aberrations) may prove to be useful. Recently, Kyrsting et al. [30] observed a trapping of golden nanoparticles in front of beam focal plane as well as out of the

* Corresponding author. Tel.: +420 541514240.
E-mail address: siler@isibrno.cz (M. Šiler).
URL: http://www.isibrno.cz/omitec (M. Šiler).

http://dx.doi.org/10.1016/j.jqsrt.2015.03.003

beam axis due to the presence of aberrations. Similarly, Haldar et al. [31] observed a formation of a self-assembled ring of particles pushed against the cover slip in one of the rings out of focal plane of aberrated beam. Further, we [32] have observed trapping in air of liquid nano-droplets with low NA, aberration corrected, optical tweezers in different planes and different positions with respect to the beam axis.

In this paper, we study the force interaction of a microparticle placed into a focused, aberration-corrected, laser beam described by the angular spectrum method. We show that in this description the field near the focal point does not vary smoothly but intensity oscillations and rings are present even in the case of low NA focusing optics. These oscillations were also mentioned previously, see e.g. [26,33], but their influence on the optical trapping was not pursued. The inhomogeneities enhance possibilities of particle trapping and, moreover, such local maxima of intensity create several new locations, where submicrometer sized particle may be trapped. We analyze occurrences and properties of these new trapping sites.

2. Angular spectrum description of a focused beam

The Debye approximation of the diffraction of a convergent spherical wave on a circular aperture [21,22] is considered as highly appropriate for the description of a strongly focused beam without aberrations. The components of electric field vector polarized along the x-axis are given as follows:

$$E_x(x,y,z) = -\frac{\mathrm{i}}{2}k\left(I_0 + I_2\frac{x^2-y^2}{x^2+y^2}\right), \tag{1}$$

$$E_y(x,y,z) = -\mathrm{i}kI_2\frac{xy}{x^2+y^2}, \tag{2}$$

$$E_z(x,y,z) = -kI_1\frac{x}{\sqrt{x^2+y^2}}, \tag{3}$$

where

$$I_0(r,z) = \int_0^{\Theta} A(\alpha)\sin\alpha(1+\cos\alpha)J_0(kr\sin\alpha) \times\exp(\mathrm{i}kz\cos\alpha)\,\mathrm{d}\alpha, \tag{4}$$

$$I_1(r,z) = \int_0^{\Theta} A(\alpha)\sin^2\alpha J_1(kr\sin\alpha) \times\exp(\mathrm{i}kz\cos\alpha)\,\mathrm{d}\alpha, \tag{5}$$

$$I_2(r,z) = \int_0^{\Theta} A(\alpha)\sin\alpha(1-\cos\alpha)J_2(kr\sin\alpha) \times\exp(\mathrm{i}kz\cos\alpha)\,\mathrm{d}\alpha, \tag{6}$$

and $r=\sqrt{x^2+y^2}$ denotes the radial distance from the optical axis z, $k=2\pi n/\lambda_{vac}$ is the wave vector (with n being the refractive index of surrounding medium and λ_{vac} the vacuum wavelength of the trapping beam). Θ is the angular aperture of the focusing optics that is connected to the numerical aperture NA by $\mathrm{NA}=n_i\sin\Theta$, where n_i is the refractive index of the immersion medium. Further, J_ν denotes the Bessel function of the first kind and ν-th order, and the angular amplitude distribution in the aplanatic projection follows [22]

$$A(\alpha) = A_0\sqrt{\cos\alpha}. \tag{7}$$

Here we assume the constant value of A_0 which corresponds to the focusing of a plane wave. In the optical tweezers experiments the laser beam of Gaussian profile is typically expanded in a way that it overfills the objective back focal aperture and, thus, the intensity profile can be approximated by the plane wave. The amplitude A_0 can be related to the electric field intensity at the beam focus $E_x(0,0,0)$ using Eqs. (1)–(6) [34]:

$$E_x(0,0,0) = \frac{k}{15}A_0\left(8-3\cos^{5/2}\Theta-5\cos^{3/2}\Theta\right). \tag{8}$$

Fig. 1 shows the sections of optical intensity near focal points of objectives having numerical apertures NA= 0.3 and 1.2 calculated using Eqs. (1)–(8). In the case of NA=1.2 we consider water immersion objective ($n_i=1.33$). Wavelength $\lambda_{vac}=1064$ nm is the same in both cases as is the total focused laser power of $P=1$ W. The sections along the beam propagation axis are shown in logarithmic scale while transversal sections are plotted in linear scale but normalized to one in each transversal plane. One can see that for both low and high NA objectives the intensity oscillates and creates sets of local maxima and minima. In the transversal direction sets of light rings are created. These rings may have high or low (even zero) intensity points on the optical axes. Moreover, even for low NA the intensity of these rings is uneven and highest on the y-axis, i.e. in the direction perpendicular to the beam polarization. Further, for high NA objective the focal spot is elliptical and tighter in the y direction, see also [24–26].

3. Optical forces

To express the optical force acting upon a spherical dielectric particle placed into the focused beam we use the Generalized Lorenz–Mie Theory in Barton's approach [35]. The key step is to expand the incident field into series of spherical harmonic functions which are described by the scattered field coefficients A_{lm} and B_{lm}, where

$$A_{lm} = \frac{a^2}{\psi_l(ka)l(l+1)}\int_0^{2\pi}\mathrm{d}\phi\int_0^{\pi}\mathrm{d}\theta E_r^i(a,\theta,\phi)Y_{lm}^*(\theta,\phi)\sin\theta. \tag{9}$$

where $Y_{lm}^*(\theta,\phi)$ is the complexly conjugated spherical harmonic function, $\psi_l(ka)$ is the Riccati–Bessel function, $E_r^i(a,\theta,\phi)$ is a radial component of incident field expressed over a particle surface, and a is the particle radius; B_{lm} is expressed similarly with E_r^i replaced by H_r^i. Further, the coefficients describing scattered field (a_{lm}, b_{lm}) are expressed from the coefficients describing incident field, see [36,37]. The optical force acting on such a particle is expressed using a Maxwell stress tensor integrated over a particle surface. We used analytical formulas given by Eqs. (5) and (6) in [35] that include a summation of series whose terms include various multiples of the field coefficients. If we place focused field given by Eqs. (1)–(6) into definition of coefficients A_{lm} in Eq. (9) triple integration is required. However, by switching the order of integration it is possible to perform integrals over particle surface