Optical trapping force with annular and doughnut laser beams based on vectorial diffraction

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Abstract: The inadequacy of the optical trapping model based on ray optics in the case of describing the optical trapping performance of annular and doughnut laser beams is discussed. The inadequacy originates from neglecting the complex focused field distributions of such beams, such as polarization and phase, and thus leads to erroneous predictions of trapping force. Instead, the optical trapping model based on the vectorial diffraction theory, which considers the exact field distributions of a beam in the focal region, needs to be employed for the determination of the trapping force exerted on small particles. The theoretical predictions of such a trapping model agree with the experimentally measured results.

OCIS codes: (260.1960) Diffraction theory; (110.0180) Microscopy; (140.7010) Trapping

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1. Introduction

Trapping micrometer-sized particles using tightly focused laser beams has become an important and a useful tool for particle micro-manipulation in many scientific disciplines such as chemistry, physics and biology [1]. Spatially modified laser beams such as obstructed laser beams, also known as annular or ring beams [2, 3], and doughnut laser beams [4] are becoming popular in novel optical trapping systems [5-8]. At present, the trapping performance of those trapping beams has been studied or predicted only based on Ashkin's ray optics (RO) [2]. It has been predicted that the use of an annular beam leads to a slight decrease in the maximal transverse trapping efficiency (TTE) [2]. The trapping efficiency being defined as a dimensionless factor Q, given by $Q = cF/n_2 P$, where c denotes the speed of light in vacuum, n_2 is the refractive index of the suspending medium, F is the trapping force and P is the incident laser power at the focus. The decrease in the maximal TTE for the largest size of obstruction is predicted to be approximately 20% [3] for s and p polarization states of trapping beams. Using the same theory, Ashkin has shown that the use of a doughnut laser beam of topological charge 1 results in the TTE comparable to the one achieved with a highly obstructed laser beam [2]. This conclusion is a consequence of the RO model which treats the focal distribution of a high numerical aperture (NA) objective as a single point.

While the RO approach may be appropriate for particles whose size is much larger than the illumination wavelength, it is inadequate to consider the case when the particle size is comparable or a few times larger than the illumination wavelength, i.e. in the Mie regime. In the latter case, the complex field distributions in the focal region, physically caused by the polarization and phase features of an illumination beam incident on the back aperture of a trapping objective, play a significant role. For example, the depolarization effect [9] caused by an annular beam focused by a high NA objective leads to the splitting and elongation of the focus. Furthermore, the intensity of a focused doughnut beam does not necessarily show the zero value at the focus as predicted by the scalar diffraction theory [10]. The effect of these physical features caused by vectorial diffraction on trapping force on a Mie particle has not been dealt with.

In this letter we use the approach based on the vectorial diffraction theory [11] for trapping force determination of highly focused annular and doughnut laser beams and comparing their performance. The mathematical details of this approach are given elsewhere [11].

2. Transverse trapping efficiency of annular laser beams

Figure 1(a) shows the theoretical comparison between the RO model and the vectorial diffraction approach for a polystyrene particle of 2 μm in diameter immersed in water and illuminated by a highly convergent laser beam with NA of 1.25 and the illumination wavelength of λ=532 nm.

Clearly, the two models predict a very different behavior of the maximal TTE for increasing the obstruction size. Furthermore, the RO model predicts a small difference in the maximal TTE for the two polarization states with the s polarization giving a slightly larger transverse force. The vectorial diffraction model, on the other hand, indicates a considerably larger transverse force for the p polarized beam when no obstruction is present or for small obstruction size. The theoretical dependence in Fig. 1(a) given by the vectorial diffraction approach agrees well with our experimental results measured using the same experimental setup as the one used by Gu *et al*. [3, 7] (Fig. 1(b)).

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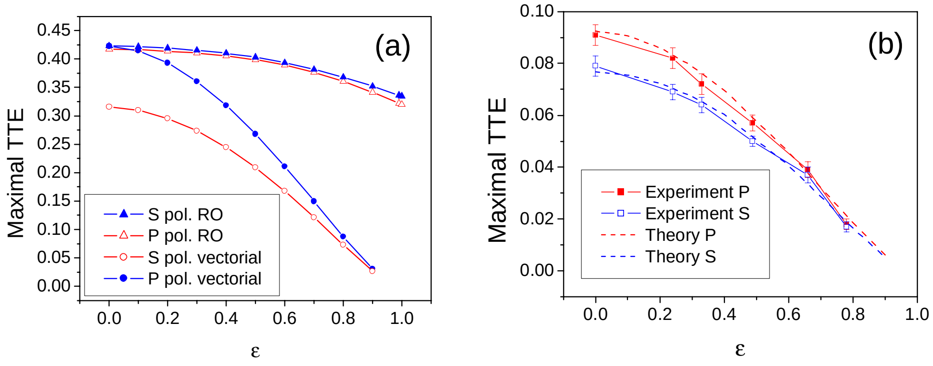

Fig. 1. The maximal TTE as a function of the normalized obstruction size ε (the inner radius of the obstruction normalized by its outer radius) for a polystyrene particle of radius 1 μm immersed in water and illuminated by a focused laser beam at λ=532 nm. (a) Theoretical comparison between the RO and vectorial diffraction models with NA=1.25. The maximal TTE for the two models are normalized to start from the same point at ε=0. (b) Experimental measurements with NA=1.2. The theoretical values are normalized by the experimental p value at ε=0.

3. Trapping efficiency of doughnut laser beams

Now let us turn to trapping force with a doughnut beam. A comparison of the maximal backward axial trapping efficiency (ATE) of polystyrene particles between a tightly focused doughnut beam of charge 1, an unobstructed plane wave and an annular beam is shown in Fig. 2(a).

The difference between the plane wave and the doughnut beam is larger for smaller particles due to the reduced interaction of smaller particles with a central low-intensity field region of a tightly focused doughnut beam [11]. The annular beam has a much lower backward ATE compared with either the plane wave or the doughnut beam, which contradicts the result given by the RO approach. The RO model, which completely ignores the field distribution in the focal region [2], indicates that in the case of a large obstruction the backward ATE is approximately 1.6 and 1.2 times larger than that achieved by the plane wave or the doughnut beam respectively [2]. As can be seen from Fig. 2(a), the maximal backward ATE is actually reduced when an annular beam is used for comparing with either the plane wave or a doughnut beam of charge 1. Such a reduction of the maximal backward ATE with the use of an annular beam is due to the focal spot elongation in the axial direction which leads to a reduced intensity gradient in this direction.

The dependence of the ATE on the topological charge of a doughnut beam is given in Fig. 2(b). The ATE in the forward direction is larger for a higher topological charge, while the ATE in the backward direction is relatively unchanged. This result is consistent with the experimental findings of the backward ATE [12] and the forward ATE [13] of large microparticles.

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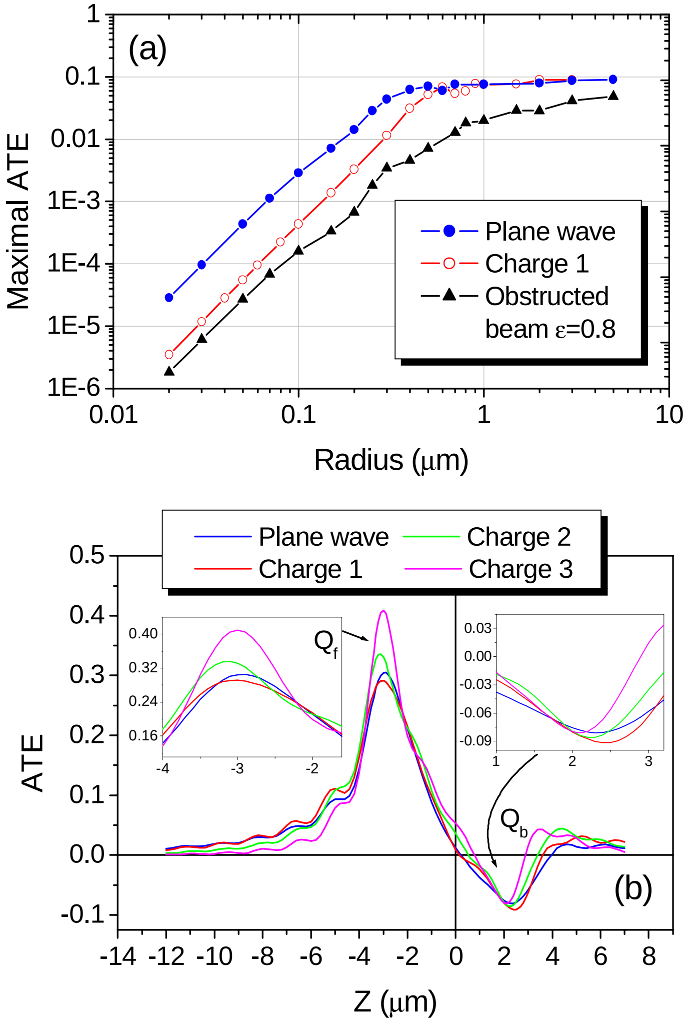

Fig. 2. ATE of polystyrene particles suspended in water and illuminated by a highly focused laser beam. NA=1.2 and λ=1.064 μm. (a) The maximal backward ATE as a function of the particle radius. (b) ATE of a 2 μm radius particle as a function of the focusing position.

The TTE, on the other hand, is reduced for higher topological charges in the either scanning direction (Figs. 3(a) and (b)). Similar to the maximal backward ATE in Fig. 2(a), the maximal TTE of an annular beam is reduced compared to the doughnut beam of charge 1. The RO model indicates that the ratio of the maximal TTE of an annular beam with a large obstruction size to the one achieved by a doughnut beam of charge 1 is approximately 0.8 [2]. The vectorial diffraction model, which considers the exact electromagnetic field distribution in the focal region of a high NA objective, gives this ratio as approximately 0.26.

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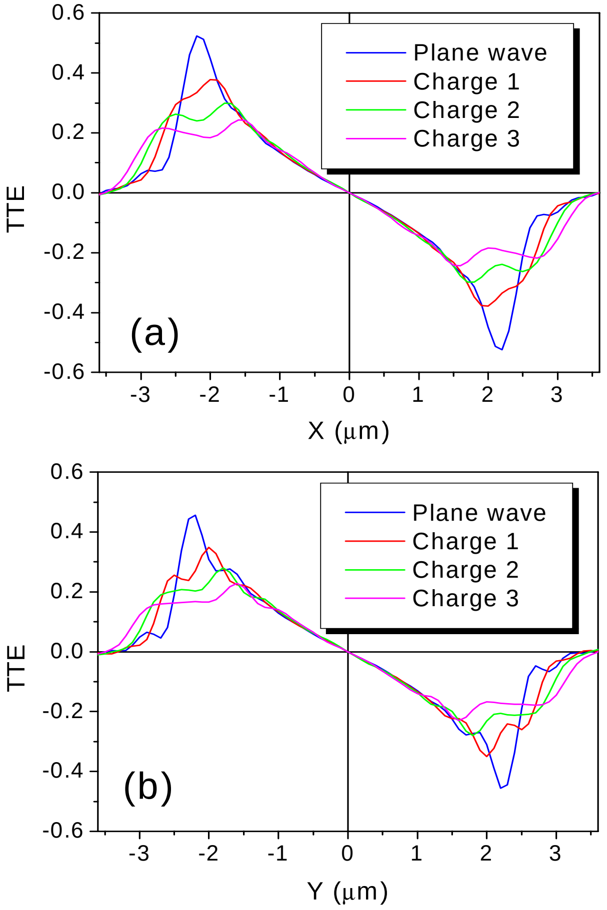

Fig. 3. TTE of a 2 μm radius polystyrene particle suspended in water and illuminated by a highly focused laser beam as a function of the focusing position. NA=1.2 and λ=1.064 μm. (a) In the polarization direction. (b) In the direction perpendicular to the polarization direction.

4. Experimental measurements with a doughnut laser beam

To confirm this feature, we used the same experimental setup as the previous one [3] for the trapping force measurements of a doughnut beam with or without the obstruction. A reflection spatial phase modulator (SPM) was inserted into the beam path to convert the plane wave into the doughnut beam of topological charge 1.

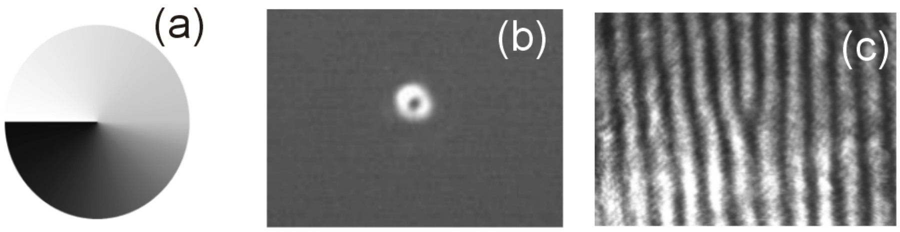

Fig. 4. Generation of a doughnut beam of charge 1 using a computer controlled SPM. (a) Applied phase-ramp with 256 phase levels. (b) Intensity profile. (c) Interference pattern.

The conversion of the plane wave into a doughnut beam was achieved by applying a phase ramp to a SPM similar to the one given in Ref.[2] (Fig. 4(a)). Such a conversion process gives a nearly 100% conversion efficiency.

Figure 4(b) shows a doughnut beam of topological charge 1, achieved using a reflection type SPM (Hamamatsu PPM X8267 series) with a 256 levels phase-ramp. The interference pattern of a plane wave with such a generated beam reveals a characteristic fringe splitting, which confirms that the generated beam is a doughnut beam of topological charge 1 (Fig. 4(c)).

Table 1. The maximal TTE for an annular beam and a doughnut beam of charge 1.

Illumination	Radius = 1 μm
$Q_p(A)$ exp.	0.018 ± 0.002
$Q_p(D)$ exp.	0.079 ± 0.005
$Q_s(A)$ exp.	0.017 ± 0.002
$Q_s(D)$ exp.	0.057 ± 0.005
$Q_p(A)/Q_p(D)$ exp.	0.23 ± 0.04
$Q_p(A)/Q_p(D)$ th.	0.257
$Q_s(A)/Q_s(D)$ exp.	0.30 ± 0.07
$Q_s(A)/Q_s(D)$ th.	0.260

Annular beam = A, doughnut beam of charge 1 = D.
exp.-experimentally measured results, th.-theoretically calculated results.

Using such a doughnut beam and an obstructed beam (ε =0.78) under s and p polarization illumination, we measured the TTE of a particle of radius 1 μm for NA = 1.2 and λ = 532 nm. A comparison of the measured TTE results is summarized in Table 1. It is clear that the ratio of the measured TTE between the annular and doughnut beam illumination agrees well with the theoretical results predicted by the vectorial theory (Table 1).

5. Conclusion

In conclusion, the RO model for determination of the trapping force of spatially modified laser beams such as annular and doughnut laser beams is inadequate because of the polarization and phase complexity of the focal field distribution. It has been both theoretically and experimentally demonstrated that in order to deal with such complex laser beams, one needs to use the trapping force model that is based on vectorial diffraction and consider the exact focal field distribution and its interaction with a microparticle.

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