Enhancement of transverse trapping efficiency for a metallic particle using an obstructed laser beam

Min Gu,[a)] Dru Morrish, and Pu Chun Ke
Centre for Micro-Photonics, School of Biophysical Sciences and Electrical Engineering, Swinburne University of Technology, P.O. Box 218, Hawthorn, 3122, Australia

(Received 4 October 1999; accepted for publication 8 May 2000)

We report that the transverse trapping efficiency for a metallic particle can be enhanced by use of a laser beam obstructed by a circular opaque disk. In the case of gold particles, the enhancement factor for a *p*- or *s*-polarized trapping beam is at least 1.7 or 2.5, respectively. The dependence of the transverse trapping efficiency for gold particles (diameter=2 μm) on the size of the obstruction is measured and agrees with the theoretical prediction based on the ray-optics model. © *2000 American Institute of Physics.* [S0003-6951(00)01527-8]

It has been demonstrated by many researchers[1–4] that metallic Mie particles whose size is larger than the illumination wavelength can be trapped in two dimensions when a laser beam is focused near the bottom of a particle. Use of a trapped metallic particle as a near-field probe[5,6] can significantly increase image contrast in a particle trapped near-field microscope.[4] In this application, a high transverse trapping efficiency is needed to increase the scanning speed of the probe. Increasing the power of a trapping beam may increase the scanning speed but is not applicable in near-field microscopy as it may damage a sample under inspection. In this letter, we report on a method for enhancing the transverse trapping efficiency for a metallic particle without increasing trapping power.

The idea for the enhancement of the transverse trapping efficiency for a metallic particle is based on the use of an obstructed laser beam. In the case of trapping a dielectric particle, Ashkin predicated[7] that use of an obstructed beam (i.e., a ring beam) could increase the axial trapping efficiency but reduces the transverse trapping efficiency. The reason for this feature is that gradient force is dominant due to the multiple refraction on the surface of a trapped dielectric particle. Consequently, the projection of the net trapping force in the transverse direction of the trapping beam is decreased with the angle θ of a ray of convergence [Fig. 1(a)]. It can be found from the ray-optics model[7] that for a given trapping objective, the maximum transverse trapping efficiency for a dielectric particle decreases approximately by up to 23% and 21% for *p*- and *s*-polarized trapping beams, respectively (Fig. 2). Throughout this paper, *p*- and *s*-polarized trapping beams mean that the polarization direction of a trapping beam is parallel and perpendicular to the direction of the transverse displacement of a trapped particle, respectively.

However, the situation becomes complicated if a metallic particle is trapped. There are two physical reasons for this complication. First, a metallic particle has high reflection and a short skin depth, which leads to the dominance of scattering force on a metallic particle. As a result, when the angle θ of a ray of convergence is increased, the net transverse trapping force on a metallic particle is increased [Fig. 1(b)]. In other words, for a trapping beam of given power, the transverse trapping efficiency for a metallic particle may be enhanced, if a circular obstruction is co-axially placed in the illumination path. Such an enhancement becomes stronger as the radius of the obstruction becomes larger. Second, the reflection coefficient on a metallic surface is complex due to absorption,[8] which implies the existence of depolarization of an incident beam. Thus, the dependence of the transverse trapping efficiency for a metallic particle on the polarization state of a trapping beam becomes more complicated than that observed in Fig. 2 for a dielectric particle.

To demonstrate these features, we used the modified ray-optics model, the detail of which has been given elsewhere[3], to calculate the trapping efficiency for a gold particle. The numerical aperture of the objective which obeys the sine condition[8,9] is assumed to be 1.25. The refractive index for gold particles and water is $n=0.82+i1.59$ and 1.33, respectively, at the trapping wavelength of 488 nm,[10] so that the reflection coefficient of gold particles in water can be evaluated using the Fresnel formulas.[8] Under these conditions, the gradient and scattering trapping efficiencies for a gold particle as a function of the convergence angle θ in the plane of incidence are shown in Fig. 3 when a trapping beam is focused at the bottom of the particle. This figure confirms the

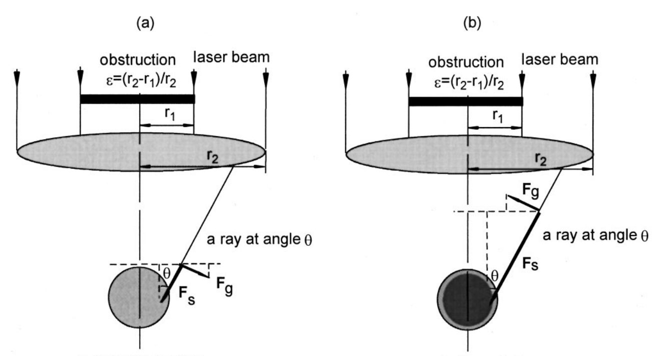

FIG. 1. Schematic diagram for demonstrating the difference of trapping forces between dielectric (a) and metallic (b) particles. $\mathbf{F}_g$ represents the gradient force and $\mathbf{F}_s$ represents the scattering force. θ is the angle of a ray of convergence. The outer ring of the metallic particle indicates its skin depth.

a)Electronic mail: mgu@swin.edu.au

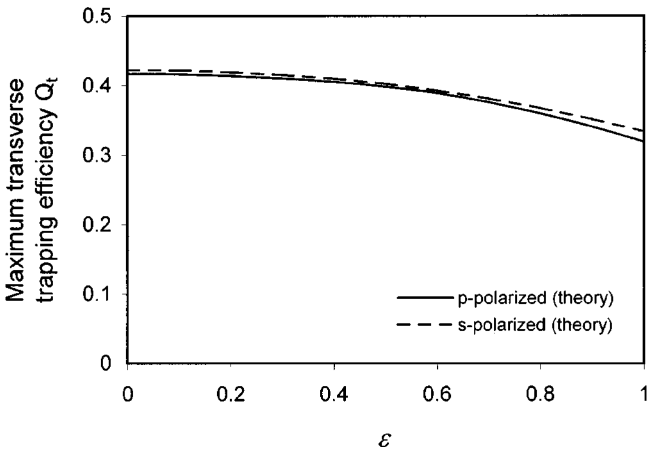

FIG. 2. Maximum transverse trapping efficiency as a function of the radius of the central obstruction ϵ for a dielectric ($n=1.59$) particle in water ($n=1.33$). The numerical aperture of the trapping objective is 1.25 at wavelength 488 nm.

dominance of scattering force on a gold particle, as schematically shown in Fig. 1(b).

Figure 4 shows the dependence of the maximum transverse trapping efficiency Q_t for a gold particle as a function of the radius of the central obstruction ϵ which is defined in Fig. 1. Q_t is obtained by varying the focal spot along the axial direction until the maximum value is found.[3] As expected, Q_t for $\epsilon=1$, i.e., for a thin ring beam, is enhanced by a factor of 1.9 and 2.8, respectively, for *p*- and *s*-polarized trapping beams, compared with that for $\epsilon=0$. Unlike the situation at $\epsilon=0$ in Fig. 2, Q_t for a *p*-polarized beam is 24% larger than that for an *s*-polarized beam. But the former becomes smaller than the latter as $\epsilon>0.3$. This phenomenon may be understandable as follows. For an objective of numerical aperture 1.25, the angle θ of a ray of convergence is approximately 15° when $\epsilon=0.3$. The reflectance on a gold surface under *s*-polarized beam illumination is much stronger than that for *p*-polarized beam illumination if the incident angle is larger than 15°.[8]

It should be pointed out that the enhancement factor α, defined as the ratio of $Q_t(\epsilon=1)$ to $Q_t(\epsilon=0)$, is decreased with the numerical aperture of a trapping objective, although $Q_t(\epsilon=1)$ and $Q_t(\epsilon=0)$ increase with the numerical aperture individually. According to Fig. 5, the minimum value of α is 1.7 and 2.5 for *p*- and *s*-polarized trapping beams, respectively, for numerical aperture 1.4.

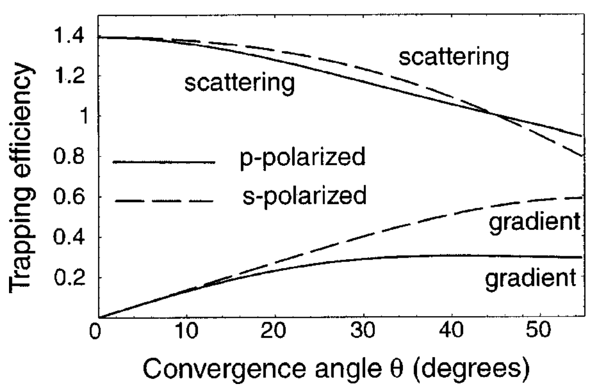

FIG. 3. Calculated gradient and scattering trapping efficiencies for a gold particle as a function of the convergence angle θ.

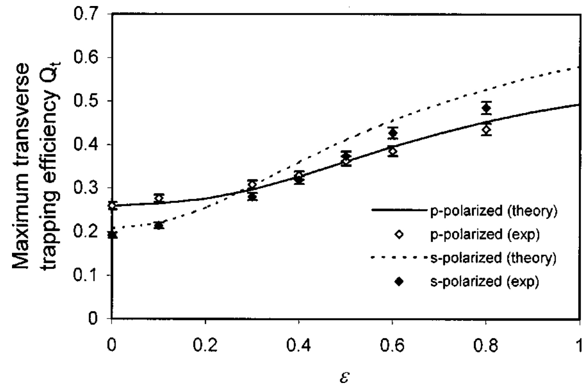

FIG. 4. Maximum transverse trapping efficiency as a function of the radius of the central obstruction ϵ for a gold particle in water.

In order to confirm the above theoretical prediction, we conducted trapping experiments with gold particles. The experimental setup was identical to that used in our previous study.[3,6] An Ar^+ laser beam at wavelength 488 nm (Spectra-Physics: Stabilite 2017, 1.5 W) was expanded and collimated to approximately 20 mm in diameter, so that it uniformly illuminates the entrance aperture of the trapping objective (Olympus oil-immersion objective, NA=1.25, 160/0.17). An opaque circular disk was coaxially placed within the entrance aperture to produce a ring illumination beam. The radius of the disk was varied so that the value of ϵ changes from 0 to 0.8. The trapping power at the focus of the trapping objective was maintained to be approximately 4.3 mW for all measurements.

A sample cell where gold particles of 2 μm in diameter were suspended in water was translated by a piezo-driven scanning stage.[3] Once a gold particle was trapped, the maximum translation speed of the scanning stage at which the particle fell out of the trap was measured.[3,11,12] The maximum transverse trapping force F on a trapped particle was then calculated by the Stokes law $F=6\pi R v \mu$,[12] where R is the radius of a trapped particle, v is the maximum translation speed, and μ is the viscosity of the surrounding medium ($\mu=1.3318\times10^{-3}$ Pa s in our experiment). The maximum transverse trapping efficiency Q_t was calculated by the expression $Q=Fc/nP$, where c is the speed of light in vacuum, n is the refractive index of the water medium inside the sample cell, and P is the trapping power in the focus of the trapping objective.

The measured dependence of the maximum transverse trapping efficiency Q_t on ϵ is depicted in Fig. 4. The error bars labeled in Fig. 4 were derived from 15 measurements for each experimental point under the same environmental condition. The main source of the measurement error results from the slight variation of the particle size, the obstructed beam size, and the illumination power. In addition, the heating effect caused by the trapping beam also leads to relative errors. This effect has been normalized using our previous method.[3]

It is seen from Fig. 4 that the enhancement of Q_t is 1.7 and 2.5, respectively, for *p*- and *s*-polarized trapping beams, which agrees well with the theoretical prediction. Figure 4 also confirms the dependence of Q_t on the polarization states of the trapping beams. When ϵ is small the measured values of Q_t fit well the theoretical values. However, there is a

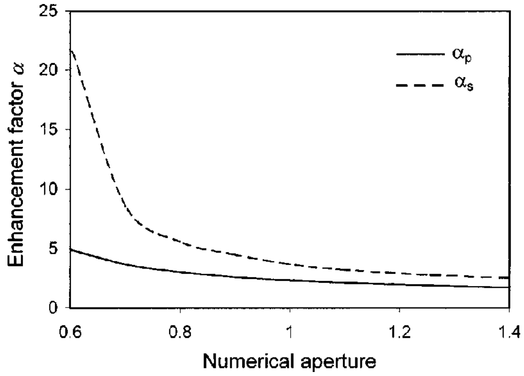

FIG. 5. Calculated enhancement factor α as a function of the numerical aperture of a trapping objective for a gold particle in water.

slight discrepancy between the experimental and theoretical results when ϵ becomes large. The discrepancy is caused by light diffraction in the focal region of the trapping objective,[13–15] which is not considered by the ray-optics model. According to diffraction theory,[14,15] the concentric power in the focal region of an obstructed beam decreases with the size of the central obstruction. For the particle size used in the experiment, the concentric power on the trapped particle for $\epsilon = 0.8$ can be up to 10% lower than that for $\epsilon = 0$,[14] so that the transverse trapping efficiency is accordingly reduced. This estimation is in agreement with the experimental observation in Fig. 4.

In conclusion, we have shown that using an obstructed beam for trapping a metallic particle leads to a significant enhancement of the maximum transverse trapping efficiency. This enhancement is caused by the fact that scattering force in trapping a metallic particle is much stronger than the gradient force. As a result of the depolarization upon reflection on a gold surface, the enhancement factor for an *s*-polarized trapping beam is larger than that for a *p*-polarized trapping beam.

The authors thank the Australian Research Council for its support. The experimental work presented in this paper was completed at Victoria University.

[1] S. Sato, Y. Harada, and Y. Waseda, Opt. Lett. **19**, 1807 (1994).
[2] H. Furukawa and I. Yamaguchi, Opt. Lett. **23**, 216 (1998).
[3] P. C. Ke and M. Gu, Appl. Opt. **38**, 160 (1999).
[4] M. Gu and P. C. Ke, Opt. Lett. **24**, 74 (1999).
[5] S. Kawata, Y. Inouye, and T. Sugiura, Jpn. J. Appl. Phys., Part 2 **33**, L1725 (1994).
[6] M. Gu and P. C. Ke, Appl. Phys. Lett. **75**, 175 (1999).
[7] A. Ashkin, Biophys. J. **61**, 569 (1992).
[8] M. Born and E. Wolf, *Principles of Optics* (Pergamon, New York, 1980).
[9] M. Gu, P. C. Ke, and X. S. Gan, Rev. Sci. Instrum. **68**, 3666 (1997).
[10] D. R. Lide, *CRC Handbook of Chemistry and Physics*, 77th ed. (CRC Press, Boca Raton, FL, 1996), Sec. 12, pp. 130–143.
[11] W. H. Wright and G. J. Sonek, Appl. Phys. Lett. **63**, 715 (1993).
[12] W. H. Wright, G. J. Sonek, and M. W. Berns, Appl. Opt. **33**, 1735 (1994).
[13] P. Török, P. Varga, Z. Laczik, and G. R. Booker, J. Opt. Soc. Am. A **12**, 325 (1995).
[14] B. L. Mehta, Appl. Opt. **13**, 736 (1974).
[15] M. Gu, *Advanced Optical Imaging Theory* (Springer, Heidelberg, 1999).