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Optical lifting force under focused evanescent wave illumination: A ray optics model

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We propose a ray optics model to calculate the trapping force on a dielectric particle located on the interface between two media and illuminated by a focused evanescent field beam. Such a focused evanescent beam is produced by a high numerical aperture objective with a central obstruction whose size satisfies the total internal reflection condition on the interface. The dependence of the lifting force on the obstruction size, the particle size, and the distance of the particle from the interface is revealed. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1863453]

I. INTRODUCTION

The technique of optical trapping has become a revolutionary and unique tool to control the dynamics of microparticles since the pioneering work of Ashkin in 1970.[1] The manipulation of micron-sized particles using trapping has its most significant application in biology[2,3] where it makes it possible to apply forces on cells, parts of cells, or on biological molecules without causing any damage to them. This far field laser trapping is remotely accessible but it would be difficult to manipulate single molecules or cells due to the elongated trapping spot that may lead to a significant background in those applications. This is why near-field trapping or evanescent wave trapping becomes significant,[4–7] since in this case the trapping volume would be much less, as an evanescent wave decays exponentially, and hence it would be easier to optically control the dynamics of single molecules.

Although an evanescent wave generated by total internal reflection on a prism can be used to move a microparticle, it is difficult to trap a particle laterally.[4] A nanoaperture[5] and a metallic tip[6] have been proposed to perform near-field trapping and manipulation but these mechanisms have not been experimentally confirmed because a near-field probe is located too close to the sample. In the case of metallic probes, they may generate a heating effect, which may adversely affect the stability of trapping. Recently, we have experimentally reported on a near-field trapping technique using focused evanescent illumination produced by a high numerical aperture (NA) objective, obstructed by an opaque disk whose size satisfies total internal reflection condition.[7] The advantage of this method is that a microparticle can be confined to the center of the evanescent focal spot and therefore the manipulation of a trapped particle becomes possible.[7] Due to the focused illumination, the evanescent wave strength is stronger than the evanescent field generated using total internal reflection on a prism.

In addition, because of the fast decaying nature of the evanescent wave, a trapped particle is pulled toward the interface where the total internal reflection occurs. In the case of an upright trapping geometry as shown in Fig. 1, the pulling force can lift the trapped particle. Such a three-dimensional confinement in the near-field region may be proven useful if the magnitude of the pulling force can be quantitatively understood. In this article, we present a method for calculating the lifting force according to Ashkin's ray optics model.[8] Consequently, the dependence of the lifting force on the obstruction size, on the particle size, and on the location of the particle is investigated.

II. RAY OPTICS MODEL FOR LIFTING FORCE

The schematic diagram of our trapping system is shown in Fig 1. A plane wave illumination focused by a high NA objective (NA=1.65) is incident on a particle of radius a, immersed in water. The refractive index of the cover slip of the 1.65 NA objective is 1.78. Therefore when the normalized obstruction radius ε, defined as the ratio of the radius of the disk to the radius of the back aperture of the objective, is greater than 0.806, light undergoes total internal reflection as it passes from a medium of higher refractive index (n_1 =1.78) to one of lower refractive index (n_2=1.33) for supercritical angles. The beam is focused at the interface axially

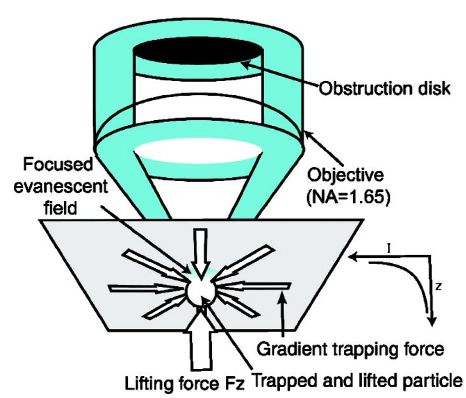

FIG. 1. (Color online) Schematic diagram of an upright trapping system under focused evanescent beam illumination. The beam is obstructed coaxially by an opaque disk of radius ε, normalized by the radius of the back aperture of the objective. NA=1.65, n_1=1.78, n_2=1.33, and n_3=1.52, ε_c =0.806. The evanescent field decays exponentially with distance z from the interface and the net trapping force is upwards.

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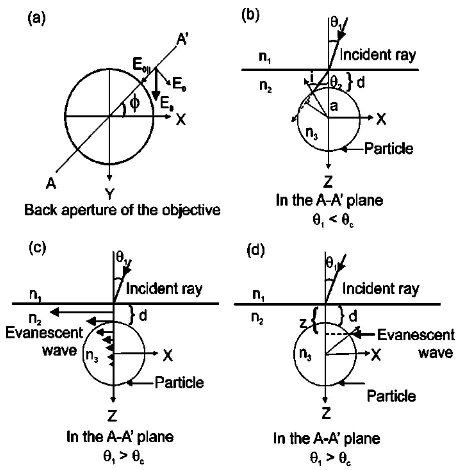

FIG. 2. (a) Illustration of the coordinates in the back aperture of an objective, showing a plane of incidence (i.e., the A-A′ plane) at an azimuthal angle ϕ. (b) A schematic diagram of the convergence of a ray at angle θ_1 in the plane of incidence (i.e., the A-A′ plane) when θ_1 is less than the critical angle θ_c. It also illustrates the generation of the radiation force by the incident ray. (c) A ray incident at the interface at a supercritical angle undergoes total internal reflection and gives rise to an evanescent wave that propagates on the interface and interacts with a particle with a strength decaying exponentially along the z axis. (d) Illustration of the radiation force generated by an evanescent wave at distance z in the plane of incidence (i.e., the A-A′ plane) when θ_1 is greater than the critical angle θ_c.

with respect to the particle. Although there are two methods for calculating the trapping force, the ray optics method[8] and the electromagnetic wave method,[9] we adopt the former in this article as it leads to a reasonable prediction for a particle of Mie size.[10,11]

Assume that a linearly polarized beam (along the Y axis) of incident power P_0 is incident on the objective aperture [Fig. 2(a)]. Consider a ray incident at azimuthal angle ϕ with respect to the x axis and at a convergent angle θ_1 on the interface between the cover slip (n_1) and the immersion water (n_2), as shown in Figs. 2(a) and 2(b). The ray undergoes refraction and gets transmitted with transmittances as given by

$$P_{\parallel}(\theta_1) = P_0 \sin^2\phi T_{\parallel} = P_0 \sin^2\phi \frac{n_2\cos\theta_2}{n_1\cos\theta_1}\left[\frac{2n_1\cos\theta_1}{n_1\cos\theta_2 + n_2\cos\theta_1}\right]^2, \quad (1)$$

$$P_{\perp}(\theta_1) = P_0 \cos^2\phi T_{\perp} = P_0 \cos^2\phi \frac{n_2\cos\theta_2}{n_1\cos\theta_1}\left[\frac{2n_1\cos\theta_1}{n_1\cos\theta_1 + n_2\cos\theta_2}\right]^2, \quad (2)$$

where the subscripts $\parallel$ and $\perp$ denotes the two components parallel and perpendicular to the plane of incidence, which is the A-A′ plane in Fig. 2(a).

When the angle of incidence θ_1 is less than the critical angle, that is 48.35° in the present case, the axial trapping force can be calculated using the formula of the scattering and gradient forces given by Ashkin[8]

$$F_s = \frac{n_2 P(\theta_1)}{c}\left[1 + R\cos 2i - \frac{T^2[\cos(2i-2r) + R\cos 2i]}{1 + R^2 + 2R\cos 2r}\right], \quad (3)$$

$$F_g = \frac{n_2 P(\theta_1)}{c}\left[R\sin 2i - T^2\frac{[\sin(2i-2r) + R\sin 2i]}{1 + R^2 + 2R\cos 2r}\right], \quad (4)$$

where $P(\theta_1)$ is given by Eq. (1) or (2). The angles i and r are the angles of incidence and refraction of a ray on the surface of the particle, as depicted in Fig. 2(b). Here i is related to the following:

$$a\sin i = (a+d)\sin\theta_2. \quad (5)$$

R and T are the Fresnel reflectance and transmittance of the particle surface at i. The axial trapping force for a ray incident at angle θ_1 is given by

$$f_Z = F_s\cos\theta_2 + F_g\sin\theta_2. \quad (6)$$

The net trapping force F_Z can be obtained by the integration of Eq. (6) over the convergence angle θ_1 and the azimuthal angle ϕ within the aperture of the objective[8] and is directed upward when the focal spot of the incident beam is located on the interface.[8–10] Note that the net transverse trapping force is zero as the particle is on the Z-axis.

When the incident angle θ_1 is greater than the critical angle θ_c, the corresponding ray undergoes total internal reflection and generates an evanescent wave. Hence each ray incident at the interface at a supercritical angle gives rise to an evanescent wave propagating in the X-Y plane and decays exponentially with the distance from the interface [Fig. 2(c)]. The strength of an evanescent wave at the distance z ($z=a-Z+d$) is given, for two orthogonal polarization states with respect to a plane of incidence at azimuthal angle ϕ, by[12]

$$P_{\parallel}(\theta_1) = P_0\sin^2\phi\left\{\frac{4n_1^2\cos^2\theta_1}{n_1^2-1}\left[\frac{1}{n_1^2-(n_1^2+1)\cos^2\theta_1}\right]\right\} \times \exp(-\beta z), \quad (7)$$

$$P_{\perp}(\theta_1) = P_0\cos^2\phi\left\{\frac{4n_1^2\cos^2\theta_1}{n_1^2-1}\right\}\exp(-\beta z), \quad (8)$$

where $\beta=(4\pi n_2/\lambda)\sqrt{(n_1/n_2)^2\sin^2\theta_1-1}$ is the decay constant of the evanescent wave.

Because an evanescent wave propagates on the interface, the radiation force resulting from an evanescent wave at distance z can be calculated by Eqs. (3) and (4), where $P(\theta_1)$ is given by Eqs. (7) and (8) and the incident angle i on the particle [see Fig. 2(d)] is represented by

$$\sin i = |Z|/a. \quad (9)$$

According to Fig. 2(d), only the gradient force generated by the evanescent wave at distance z from the interface contributes to the axial trapping force, and the total axial trapping force of an evanescent wave produced by an incident ray at angle θ_1 is the sum given by

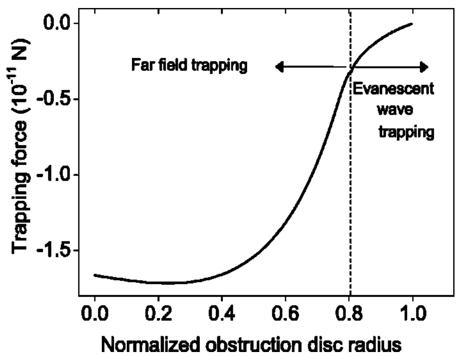

FIG. 3. Lifting force as a function of the normalized obstruction radius ε for a particle of diameter 1 μm, immersed in water. $\lambda = 532$ nm. NA=1.65. Incident power=15 mW.

$$f_Z = \int_{z=-a}^{z=a} F_g dZ. \tag{10}$$

The total trapping force F_Z is given by the integration of Eq. (10) over the azimuthal angle ϕ and the convergence angle θ_1 above the critical angle.

III. RESULTS AND DISCUSSION

For the objective and other experimental conditions described in Fig. 1, the dependence of the axial trapping force on the radius of the obstruction disk is demonstrated in Fig. 3. The negative value of the force means that the force points upward, confirming the lifting nature of the force in the upright trapping system. For the normalized obstruction radius $\varepsilon < 0.8$ the force results from the far field as well as near field illumination components, whereas for $\varepsilon > 0.8$, it originates purely from the evanescent field component. It should be pointed out that the strength of the lifting force at $\varepsilon = \varepsilon_c$ is only three times weaker than that in the far field. This reduction of the force can be compensated for by increasing the laser trapping power, without necessarily damaging the trapped particle.

The variation of the lifting force under focused evanescent illumination ($\varepsilon > 0.8$) with the distance of the location of the particle from the interface is demonstrated in Fig. 4. Here each incident ray undergoes total internal reflection and gives rise to evanescent illumination. The lifting force is a maximum when the particle is at the interface and decreases with the increase in the distance of the particle from the interface, as may be expected for the decrease in the evanescent field. The lifting force drops to e^{-1} of the value at the interface at a distance of approximately 100 nm from the interface. This result clearly demonstrates the reduced trapping volume of evanescent wave trapping, which will enable the technique to become a powerful tool to handle microscopic biological specimens with a reduced background.

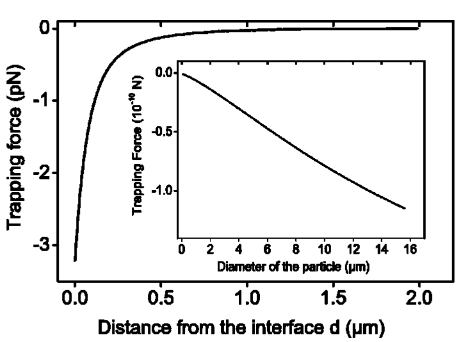

FIG. 4. Lifting force as a function of the distance of the location of the particle from the interface ($\varepsilon = \varepsilon_c$). The inset shows the lifting force as a function of the particle diameter. All the other parameters are same as those for Fig. 3.

The inset in Fig. 4 shows the variation of the lifting force with the particle size at $d = 0$. The magnitude of the force shows a linear increase with the particle size. This relation is different from that for trapping under far-field illumination[10] and can be understood from the evanescent nature of illumination. As the particle size increases, the cross-sectional area of interaction of a small particle with the evanescent field also increases linearly, and this accounts for the linear relation between the particle size and the lifting force. According to this figure, the trapping force under evanescent field illumination for a particle of diameter 10 μm is approximately 70 pN, which is large enough for trapping such a particle.

To determine if a trapped particle can be lifted up, let us take into account the effect of gravity. The weight of a polystyrene latex bead of 1 μm in diameter is calculated to be about 5 pN, and the maximum lifting force calculated by our model is 1.7×10^{-11} N in the far-field region and 0.32×10^{-11} N in the evanescent field region for a laser beam of power 15 mW. This implies that the particle can well be lifted up against gravity even under focused evanescent illumination. This trapping method can become a useful tool for holding biological molecules in three dimensions against the interface when an evanescent wave is generated.

It should be pointed out that the current model ignores the effects of diffraction by a high NA objective such as apodization, depolarization, and aberration, which become pronounced[13] when NA$>$0.7. These effects do not play a significant role when the size of a particle is larger than the size of the focal spot, which is the case considered in this article (i.e., the focal spot of a NA=1.65 objective is smaller than the particle of diameter 1 μm). When the particle size is much smaller than the focal spot, the Brownian force also plays a noticeable role, which is not included in the ray optics model. Further, the current model is not applicable to trapping a metallic particle because of the effect of surface plasmon polariton resonance. In order to investigate the above-listed effects, one should adopt an electromagnetic model proposed by Barton *et al.*[9] for focused evanescent trapping.

IV. CONCLUSION

In conclusion we have generalized the ray optics model proposed by Ashkin[8] to trapping under focused evanescent illumination. This model predicts that the upward trapping force produced by an evanescent focal spot is strong enough to lift a particle of Mie size for a laser beam of power of a few milliwatts. Such a lifting force increases linearly with the size of a particle and exists effectively within 100 nm from the interface for an objective of NA=1.65, such that it significantly reduces the trapping volume.

ACKNOWLEDGMENT

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