Trapping force and optical lifting under focused evanescent wave illumination

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Abstract: A physical model is presented to understand and calculate trapping force exerted on a dielectric micro-particle under focused evanescent wave illumination. This model is based on our recent vectorial diffraction model by a high numerical aperture objective operating under the total internal condition. As a result, trapping force in a focused evanescent spot generated by both plane wave (TEM_{00}) and doughnut beam (TEM^{*}_{01}) illumination is calculated, showing an agreement with the measured results. It is also revealed by this model that unlike optical trapping in the far-field region, optical axial trapping force in an evanescent focal spot increases linearly with the size of a trapped particle. This prediction shows that it is possible to overcome the force of gravity to lift a polystyrene particle of up to 800 nm in radius with a laser beam of power 10 μW.

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

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1. Introduction

Small particle trapping and manipulation based on the radiation pressure mechanisms has been demonstrated for quite some time now [1]. This phenomenon, also known as the optical tweezers, is today widely used in the fields of modern physics, chemistry and biology for confinement and manipulation of micro-particles, biological cells and molecules [2-5]. Recently advanced trapping techniques that use carefully sculpted wavefronts of light promise to bring the optical tweezers from the laboratories and into the mainstream of manufacturing and diagnostics [6].

Trapping force generated by a conventional high numerical-aperture (NA) objective can be determined using the ray-optics [7] or the electromagnetic [8,9] approach depending on the trapped particle size and the characteristics of incident illumination. The trapping volume of this far-field laser trapping geometry is approximately three times larger in the axial direction than that in the transverse direction. Such trapping volume elongation leads to a significant background and poses difficulties in the observations of the single-molecule dynamics. Recently, a new trapping mechanism that utilizes the evanescent wave illumination, also called near-field illumination, has been proposed [10-13] and demonstrated [13]. The near-field trapping mechanism can be classified into three categories based on the different ways to generate a localized near-field.

In the first category, a metallic tip is proposed to enhance the evanescent field produced at an interface between two different media under the total internal reflection condition. The evanescent field enhanced by the surface plasmon effect enables trapping of nanometer-sized particles suspended in air and in water [10]. The near-field trapping force is evaluated using a coupled-dipole and multiple multipole method [10]. The near-field trapping proposed in the second category can be achieved by the use of the evanescent field generated by a nanoaperture and is investigated using the finite-difference time-domain method [11,12]. Both of these near-field trapping methods are difficult to implement in practice due to the complexity in controlling the distance between a probe and a sample and the trapping stability caused by the heating induced by the surface plasmon effect.

The third near-field trapping category demonstrated recently [13] is based on the use of a focused evanescent field produced by a high NA objective with a central obstruction The size of the obstruction is large enough to ensure that the minimum angle of convergence of each incident ray is larger than the critical angle determined by the total internal reflection condition between two media. This method leads to the reduced trapping volume and offers additional advantages over other near-field trapping methods in terms of the heating and the distance regulation problems. However, contrary to the first two categories, this near-field trapping method lacks an appropriate theoretical treatment.

In this letter we present an insight into a physical model to investigate the radiation near-field trapping force under focused evanescent wave illumination. This model is based on the vectorial diffraction approach [9] and is therefore able to treat the arbitrary sculpted wavefronts of light in a trapping system. This physical model predicts that the axial trapping force exerted on a particle in an upright trapping system is strong enough to facilitate the particle lifting against the force of gravity. In addition to the focused evanescent field generated by a plane wave (TM_{00}), we also investigate the trapping force under the focused evanescent field obtained by the use of a so-called doughnut laser beam (TM^{*}_{01}). Doughnut beams, characterized by a helical phase distribution [14], are increasingly used in the novel laser trapping arrangements [6,15] because they offer a controllable laser trapping technique.

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The new model includes two physical processes, vectorial diffraction by a high NA objective under the total internal reflection condition and scattering by a small particle with a focused evanescent wave. The theoretical treatment of the first process is similar to that given elsewhere [16] except that a double integral is needed when a doughnut beam is considered [17]. Based on the scattering process of a small particle with the evanescent focal spot, one can determinate the electromagnetic field inside and outside a particle [8] and thus the trapping force exerted on the particle [9].

2. Trapping efficiency mapping

Now let us consider that a small particle interacts with a focused evanescent illumination generated at the coverslip interface of a centrally obstructed high NA objective (NA=1.65). An axial force caused by the fast decaying nature of such an illumination and a transverse gradient force resulting from the focal shape are exerted on the particle.

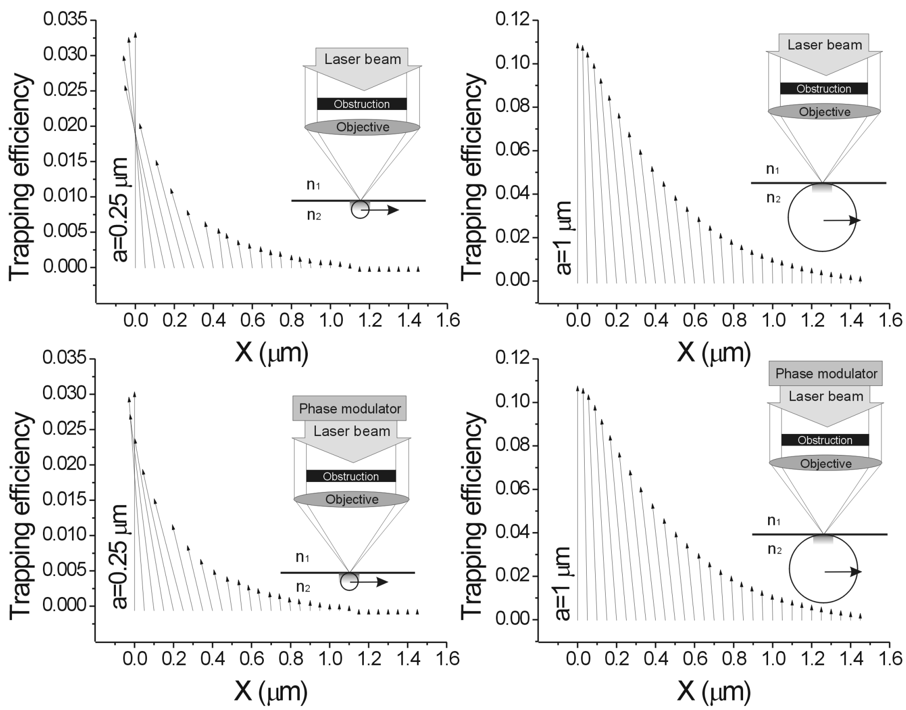

Fig. 1. Trapping efficiency mapping for a small and a large polystyrene particle of radius a, scanned in the X direction (light polarization direction) across the focused evanescent field. NA=1.65, λ=532 nm, ε=0.85, n_1=1.78 and n_2=1.33.

Figure 1 shows the trapping efficiency mapping, when a small and large polystyrene particle is transversally scanned in the X direction across the focused evanescent field distribution, generated by placing a central obstruction (ε=0.85) perpendicularly to the path of an incoming laser beam. ε is defined as the obstruction radius normalized by the radius of the back aperture of the trapping objective, and it produces the focused evanescent field for ε>0.8 (the refractive indices of the coverslip and immersion water are n_1=1.78 and n_2=1.33). The trapping efficiency is related to the trapping force and power by $Q = Fc/n_2P$, where c is the speed of light in vacuum, n_2 is the surrounding medium refractive index, F is the trapping

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force and P is the incident power. The laser beam (λ=532 nm) propagates in the Z direction and we consider two cases; the first one being an ordinary plane wave, while the second one is a phase modulated doughnut beam of charge 1 [15].

For both small and large particles the axial trapping efficiency (ATE) is slightly larger for plane wave illumination when compared with a doughnut beam illumination. However, in the case of small particles the ATE also decreases slightly faster with the plane wave illumination when the particle is scanned in X direction. Not only is the ATE for large particles stronger, the force mapping structure in the case of large particles is markedly different from the small particle case due to the larger interaction cross section of the small particle with the focused evanescent field. The maximal transverse trapping efficiency (TTE) for small particles is much larger relative to the ATE than that for large particles. The maximal TTE constitutes 16.8 % and 14.8 % of the maximal ATE for small particles in the case of the plane wave and doughnut beam illuminations respectively, compared to the 7.4 % and 7.2 % for large particles.

3. Dependence of trapping efficiency on obstruction size

The dependence of the maximal TTE on the obstruction size ε is critical to capture a particle in the evanescent focal spot and is shown in Fig. 2 for both plane wave and doughnut beam illumination for polystyrene particles of diameter 2 μm.

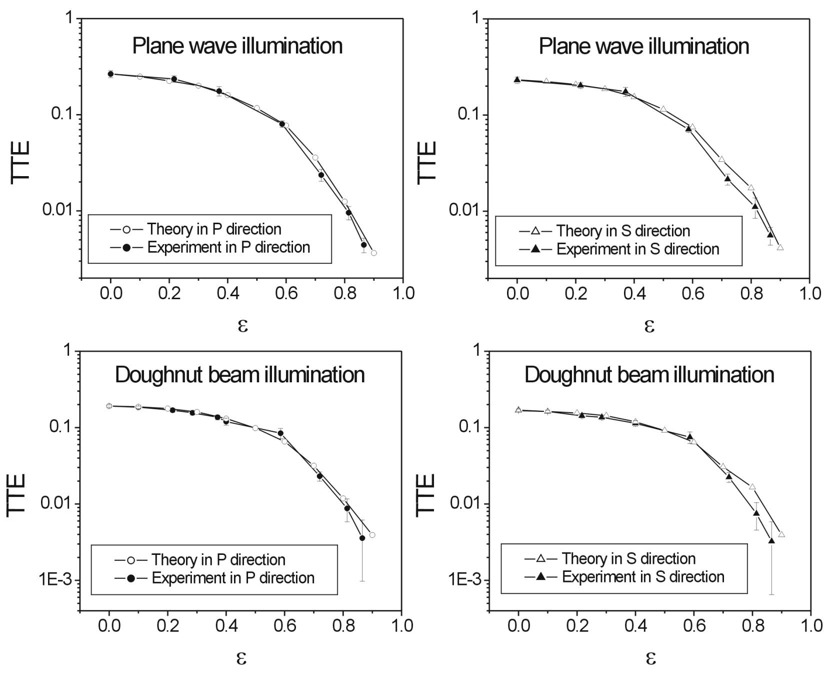

Fig. 2. The calculated and measured maximal TTE of a polystyrene particle of 1 μm in radius as a function of the obstruction size ε for P and S scanning directions under plane wave and the doughnut beam illumination. The other conditions are the same as Fig. 1.

The maximal TTE decreases with increasing the size of the beam obstruction due to the reduced contribution of the propagating component to the transverse force and because the high angle rays are less efficient in the transverse trapping of a dielectric particle [18]. The maximal TTE for the plane wave case is generally slightly larger than that obtained with the doughnut beam illumination for both P and S directions defined as the directions parallel (P)

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and perpendicular (S) to the incident polarization, respectively. The difference in the maximal TTE for the plane wave and doughnut beam cases is largest when no obstruction is present (plane wave TTE being 1.4 times larger) and becomes smaller for the increasing obstruction size. In the near-field trapping regime (ε>0.8) this difference nearly vanishes. The theoretical dependence shown in Fig. 2 agrees well with the experimental results obtained in the near-field trapping system [13] (a reflection mode phase modulator was inserted into the beam path to switch between the plane wave and the doughnut beam illumination), which confirms the validity of the model.

The dependence of the maximal ATE on the obstruction size ε is at first relatively unchanged until ε~0.6, at which point the maximal ATE decreases for increasing ε (Fig. 3(a)). At the focused evanescent field condition, i.e. when ε > 0.8, the maximal ATE is still approximately 43% of the far-field case when no obstruction is present.

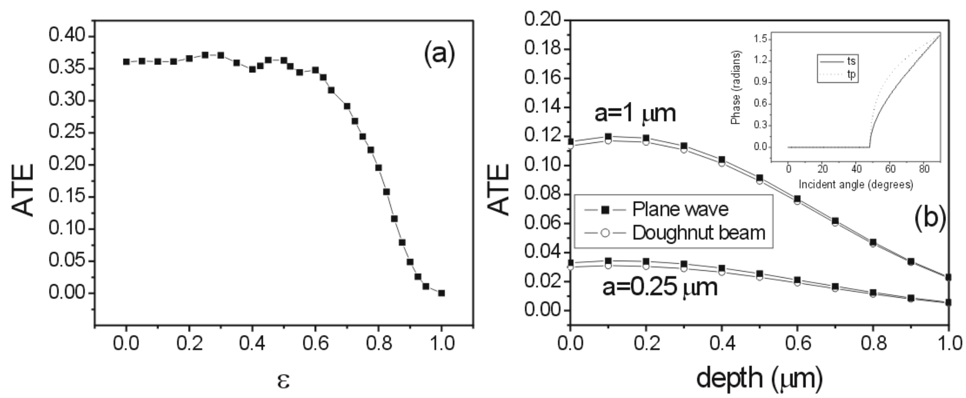

Fig. 3. (a) The maximal ATE of a polystyrene particle of 1 μm in radius as a function of the obstruction size ε. (b) Dependence of the ATE on the virtual focus position for a small and large polystyrene particle (ε=0.85). The inset shows the phase of the Fresnel transmission coefficients as a function of the incident angle. The other conditions are the same as Fig. 1.

So far only the case when the obstructed beam, with ε corresponding to the minimum convergence angle larger than the critical angle, is focused onto the interface between two media is considered, i.e. the geometrical focus position is on the interface. When this geometrical focus position is brought into the suspension medium, the fast decaying evanescent field is slightly defocused at the interface. Since there is no propagating component, the field is localized at the interface and the geometrical focus becomes virtual. The relationship between the depth of such a virtual focus and the ATE for both small and large dielectric particles is revealed in Fig. 3(b). Both plane wave and doughnut beam illumination cases follow a similar trend with plane wave illumination showing generally a slightly higher ATE, and converge at a larger depth. It is interesting to note, however, that the highest ATE does not occur when the geometric focus is at the interface, but it occurs for a slightly defocused evanescent field, focused at a virtual depth of ~100 nm into the suspension medium. This physics of this phenomenon originates from phase shifts under TIR (Fig. 3(b) inset) [19]. Consequently, the constructive interference of the focused rays depends on a certain depth d of the virtual focus. It can be shown that for the given maximum convergence angle in our case, the total phase accumulated gives the maximum field at the interface for the depth d=62 nm.

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4. Dependence of axial force on particle size

The dependence of the maximal near-field ATE on the polystyrene particle size is illustrated in Fig. 4(a). The relationship between the maximal near-field ATE is nearly linear in nature for both types of illumination and the particle size range considered, which is different from the far-field force relationship that depends on the cubic of the particle size. This linear relationship can be qualitatively explained by examining the particle interaction cross-section area (*A*). If the evanescent field depth is denoted by *h*, it can be shown that the interaction cross-section area is given by $A = \pi(4ah - h^2)$, where *a* is the particle radius (Fig. 4(a) inset). It can be estimated from Fig. 4(a) that an input laser power of 10 μW is sufficient to overcome the gravity (including the buoyancy) force and lift a polystyrene particle of 800 nm in radius or smaller (Fig. 4(b)) in an upright trapping system.

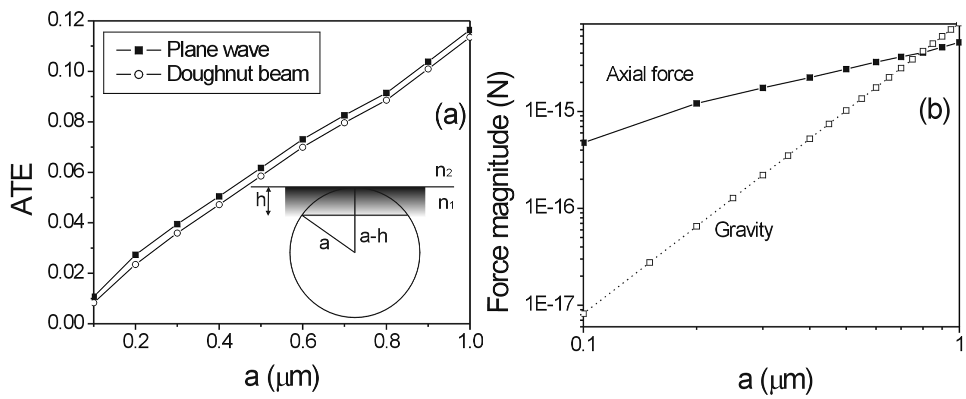

Fig. 4. (a) The maximal ATE as a function of a polystyrene particle size (ε=0.85). The inset shows a schematic relation between the interaction cross-section area and the particle size. (b) The magnitudes of the axial force for a plane wave of power 10 μW and the gravity force for different particle sizes. The other conditions are the same as Fig. 1.

5. Conclusion

In conclusion, a physical model based on vectorial diffraction of an evanescent wave and scattering of a focused evanescent focal spot with a small particle has been developed to understand the trapping performance under focused evanescent wave illumination. As a result, trapping force in an evanescent focal spot has been calculated for both TEM_{00} and TEM^*_{01} beam illumination and demonstrated to be in a good agreement with experimental results. The dependence of the maximal ATE on the particle size is nearly linear under focused evanescent wave illumination. It is predicted that an input laser power of 10 μW is sufficient to overcome the gravity force acting on a polystyrene particle of 800 nm in radius or smaller, thus enabling the particle lifting in an upright system.

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