

Tunable optical sorting and manipulation of nanoparticles via plasmon excitation

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We numerically investigate the optical forces exerted by an incident light beam on Rayleigh metallic particles over a dielectric substrate. In analogy with atom manipulation, we identify two different trapping regimes depending on whether the illumination is performed within the plasmon band or out of it. By adjusting the incident wavelength, the particles can be selectively guided, or immobilized, at the substrate interface. © 2006 Optical Society of America

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Due to their potential confinement down to subwavelength volumes, evanescent fields bound at interfaces open novel opportunities for efficient manipulation of nano-objects.¹⁻⁴ Lately, we have shown both theoretically and experimentally that plasmon fields at a metal/dielectric interface can be used to dramatically enhance the optical forces on a dielectric object.^{5,6} Selective manipulation of particles with a scanning tunneling microscope tip through the optical force induced by light, either in or out of resonance, has also been theoretically shown.^{7,8}

In this Letter we propose a novel concept for the manipulation of small metallic nanospheres sustaining plasmon resonances. Our results show that the dispersion of nanospheres can be exploited for their tunable optical manipulation without the use of external tip or surface structuration. Similarly to what is known for atoms, the incident wavelength has a dramatic influence on the nature of the forces that dominate the particle dynamics. In particular, we show that the particles can be selectively guided or more efficiently trapped compared with dielectric particles of the same size.

We consider a metal sphere immersed in water ($n_{\text{water}}=1.33$), floating at 15 nm from the surface of a heavy flint glass prism ($n_{\text{flint}}=1.8$). The illumination is performed from the glass under total internal reflection (TIR) by either a plane wave or a tightly focused three-dimensional Gaussian beam [see Fig. 1(A)] with an intensity of 10^{12} W/m².

The model that we use to calculate the optical forces combines the Green dyadic method with the Maxwell's stress tensor.⁹ This formalism accounts for multipolar contributions, which cannot be neglected for metal particles of diameter larger than a few tens of nanometers.¹⁰ Additionally, a surface correction on the Green tensor in a homogeneous medium includes multiple reflections in the gap space between the particle and the surface.

Figure 1 shows the scattering properties of an 80 nm diameter gold particle being illuminated by a plane wave under an incident angle of 50°. The scat-

tering power spectrum features a resonance centered around 550 nm associated with its first-order (dipolar) localized surface plasmon (LSP) mode. The distribution of the square modulus of the electric field around the sphere is dominated at resonance by higher values in the gap space, illustrating the strong influence of the surface.

Due to their dispersion, the optical forces that experience metal nanoparticles under illumination are susceptible to dramatic variations with the incident wavelength. For a small dielectric particle, using a dipolar approximation, the total force combines a gradient contribution that attracts the particle towards the highest field value and a scattering component that tends to push it along the incident wave vector. In the case of absorbing particles, an absorption force is added to the scattering component.

The evolution with the incident wavelength of the X and Z components of the total force exerted on an 80 nm diameter gold sphere is shown in Fig. 2. In

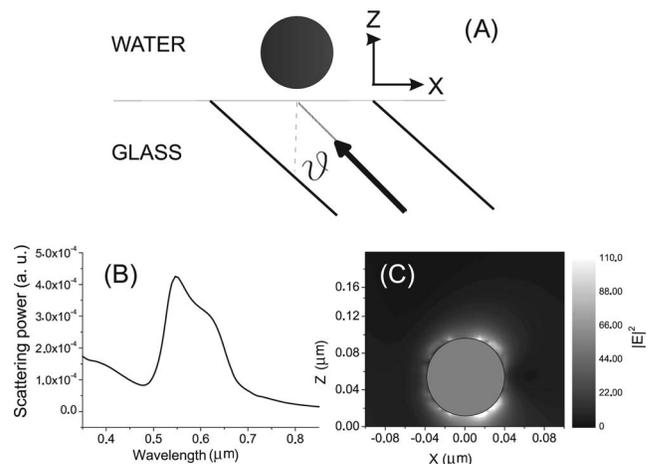


Fig. 1. (A) Optical configuration under plane-wave illumination. (B) Scattering power spectrum of an 80 nm diameter gold sphere located at 15 nm from the interface. (C) Square modulus of the electric field distribution around the particle (the normalization is done with respect to the field amplitude of the incident illumination).

agreement with previous work on smaller particles,^{8,10} both the X and Z forces feature a resonance. Similarly, F_Z is attractive over the whole spectrum and approximatively follows the behavior of the real part of the particle static polarizability $\alpha = a^3(\epsilon - 1)/(\epsilon + 2)$, a and ϵ standing for its radius and relative permittivity, respectively. However, the in-plane force F_X has a maximum governed by the particle extinction cross section itself dominated by the imaginary part of the radiation-reaction expression of the polarizability: $\alpha/[1 - (2/3)ik^3\alpha]$.¹¹ Therefore, since for metallic particles such as those considered here, the scattering cross section dominates; it is this process, rather than absorption, that mainly contributes to F_X . Notice, in addition, that the peaks of F_X and F_Z do not coincide. This is because these components are given by even and odd causal functions $Im\alpha$ and $Re\alpha$, respectively. Hence one can tune the incident wavelength to choose either F_X or F_Z to dominate.

The enhanced in-plane force F_X at the particle resonance (the enhancement factor is about 25 times with respect to a nonresonant illumination), is of much interest for an efficient optically driven transport of Rayleigh metallic spheres onto a surface. For a given incident power, resonant metal spheres would be moved much faster than dielectric spheres of the same dimensions. Additionally, because the force dependency is governed by the particle dispersion, particles of significantly different sizes, or from different materials, may experience a different acceleration and thus be efficiently sorted. To illustrate this concept, the acceleration has been computed for three different particles [see Fig. 2(C)] under different incidences. For $\lambda = 430$ nm, both gold particles experience an acceleration of several times smaller compared with the 50 nm silver particle, which is resonant at this same wavelength. This tendency is reversed at $\lambda = 625$ nm in which the largest gold sphere will move much faster.

In addition to transporting or sorting metal spheres at an interface, it is of interest to immobilize them in a stable optical trap. Due to the extinction (scattering/absorption) force, trapping is not ren-

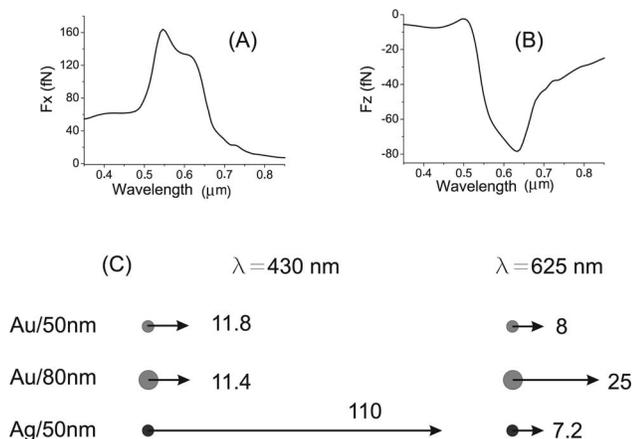


Fig. 2. Evolution with the incident wavelength of (A) F_X and (B) F_Z under a plane-wave illumination. (C) Resulting in-plane acceleration (unity 10^6 N kg⁻¹) for different metal particles at $\lambda = 430$ nm and $\lambda = 625$ nm.

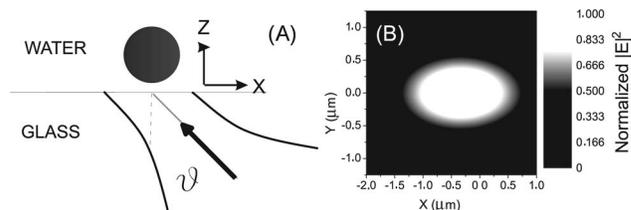


Fig. 3. (A) Optical configuration when the illumination is performed with a totally reflected Gaussian beam. (B) Square modulus of the electric field calculated 50 nm above the interface (beam waist 700 nm, p polarization), $\theta = 50^\circ$.

dered possible under an asymmetric illumination by a collimated beam. For this purpose, we consider in the following an illumination by a tightly focused 3D Gaussian beam under TIR at the glass/water interface (see Fig. 3). With a waist of 700 nm, this illumination is very similar to what can be achieved with a TIR objective lens. While the exponential decay of the evanescent field transmitted into the water ensures that the gradient force attracts the particle towards the surface, the in-plane confinement contributes to compensate for the repulsive extinction force. On the basis of our results for an incident plane wave, for trapping purposes, the illumination wavelength needs to be adjusted to minimize this latter contribution. Similarly to quasi-electrostatic optical traps in atom optics,¹² our approach consists of detuning the illumination wavelength out from the LSP band of the particle. Under these conditions, one can choose the incident wavelength to play with the competition between the beam trap gradient force and F_X , given in Fig. 2(A). As a result of the interplay between these forces, we obtain results like those shown in Fig. 4, where the force vector map is plotted when a 50 nm gold particle is located 15 nm above the dielectric interface. As expected, for an incident wavelength matching the LSP resonance of the particle ($\lambda = 525$ nm), the in-plane gradient forces cannot compensate for the enhanced extinction force and the particle is thus expelled from the illuminated area. For an incident wavelength sufficiently redshifted from the resonance, however, a stable trapping position, significantly shifted from the maximum field position, is found. For comparison, Fig. 4(C) shows, with the same scale, the force map for a polystyrene particle ($n_{PS} = 1.55$) of the same dimension.

In practice, the ability of an optical trap to retain an object depends on whether the restoration forces compensate for its Brownian motion. This is a major limitation when considering submicrometer objects, since at this scale the force magnitude falls to very small values. To address this crucial issue, we plot in Fig. 4(D) the potential energy profile along $Y = 0$ for both the gold and the dielectric particle at $\lambda = 1064$ nm. Our results show that for the gold sphere the potential is more than 5 times deeper than the Brownian amplitude and would thus permit stable trapping. On the contrary, under the same illumination condition, the dielectric particle would rapidly escape from the trap. This is fully consistent with some recent experiments using conventional optical tweezers.¹³

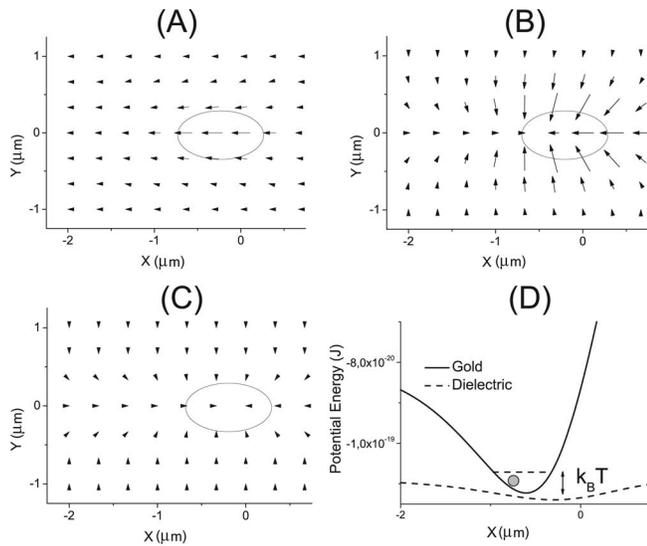


Fig. 4. Force vector map in the particle mid-cross-sectional plane under Gaussian illumination (same parameters as in Fig. 3): for a 50 nm diameter gold particle (A) at resonance ($\lambda=525$ nm) and (B) far from resonance ($\lambda=1064$ nm). (C) 50 nm diameter polystyrene particle at $\lambda=1064$ nm (same scale). (D) Energy potential profile along $Y=0$ for (B) and (C). k_B and T stand for the Boltzmann constant and the absolute temperature, respectively.

In conclusion, we have proposed a novel approach to optically manipulate Rayleigh metallic particles over a surface by exploiting their dispersion. An appropriate choice of the illuminating wavelength can either trap and bind or push them on a dielectric substrate plane. Conversely, a beam of a given wavelength will exert a different mechanical action on different particles over the plane, thus possessing the capability of sorting them according to their size and composition. We believe that both the guiding and

trapping regimes as addressed in this work will be of interest for applications where single resonant metal nanostructures in solution are used.

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