Surface Plasmon Radiation Forces

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We report the first experimental observation of momentum transfer from a surface plasmon to a single dielectric sphere. Using a photonic force microscope, we measure the plasmon radiation forces on different polystyrene beads as a function of their distance from the metal surface. We show that the force magnitude at resonance is strongly enhanced compared to a nonresonant illumination. Measurements performed as a function of the probe particle size indicate that optical manipulation by plasmon fields has a strong potential for optical sorting.

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The momentum exchange between light waves and matter is a fundamental process that has been exploited for remarkable applications such as atom cooling [1] and optical tweezers [2,3]. Following recent advances in nanophotonics, optical manipulation by evanescent fields, instead of conventional propagating fields, has lately awoken an increasing interest [4,5]. The main motivations for using nonradiative fields are (i) the absence of the diffraction limit for the trapping volume, which may permit an effective manipulation of single subwavelength objects, and (ii) the intrinsic in-plane field confinement, which is of interest for lab-on-a-chip applications. Momentum transfer from evanescent fields to micro- and nanoparticles has been extensively investigated theoretically and experimentally both near the surface of a dielectric prism illuminated under total internal reflection and near to an optical waveguide [6–11].

In order to extend the range of in-plane optical manipulation it has lately been proposed to use surface plasmons (SP) [4,12–14]. SP are electromagnetic surface modes confined at a metal-dielectric interface due to the resonant interaction of the electromagnetic wave with the surface charges of the metal [15,16]. They give rise to a multifold increase of the transverse magnetic (TM)-polarized incident field that is expected to result in a significant enhancement of the radiation forces on a nearby object. Until now, SP forces exerted on 0.5 µm diameter metal or dielectric spheres have only been studied theoretically [17]. For a particle far enough from the surface, such that it does not perturb the plasmon field, the radiation forces are predicted to increase considerably in the presence of SP.

We report in this Letter the first experimental observation of the momentum transfer from a SP to a single dielectric object. Using a photonic force microscope (PFM), we have quantitatively measured the plasmon radiation forces on polystyrene beads of various sizes, when located at different distances from the metal surface. We show that the magnitude of the force at resonance on a 4.5 µm dielectric sphere is enhanced 40 times compared to nonresonant illumination.

The PFM uses a micron-sized particle optically trapped by a focused laser beam, as a local probe, whose position can be measured with great accuracy [18,19]. The analysis of the Brownian motion of this probe provides information on the local forces it experiences.

Our experimental setup, presented in Fig. 1, consists of three main parts: the sample, the SP illumination, and the optical tweezers and position detection (PFM).

The sample solution is prepared by adding a small amount of polystyrene beads of three sizes (diameter 4.5, 2.0, and 0.6 µm, refractive index \( n_b = 1.59 \)) to a 10% sodium dodecyl sulphate sterile solution in water (refractive index \( n_s = 1.33 \)). A drop (2 µl) of the resulting solution is placed between two coverslips (thickness 80 µm, refractive index \( n_c = 1.55 \)) separated by a 30 µm spacer and sealed with water-insoluble silicone vacuum grease to prevent an evaporation. The upper cover slip is coated with

![FIG. 1. Schematic of the experimental setup. Inset: close-up view of the chamber.](image-url)
a 40 nm layer of gold. This sample is placed onto a custom-
made sample holder between an oil immersion microscope
objective (×100, NA = 1.3) and a prism (n_p = 1.78) to
couple the SP. A piezoelectric stage (Tritor 102, Piezosystem Jena) is used for 3D-nanometer positioning
of the sample relative to the probe.

A linearly polarized beam from a He-Ne laser (wave-
length 632.8 nm, power 18 mW) illuminates the meta-
water interface through the prism at the plasmon resonance
angle (θ_{SP} = 70.8°). Mirrors M_1 and M_2 allow fine adjust-
ment of the incident angle, while a lens (L_1, focal distance
5 cm) focuses the beam to increase the intensity of the
evanescent wave. A half wave plate (HWP) permits us to
change the incident polarization between TM and TE. The
resulting wave generated at the metal surface is expected
from theory [15] to decay exponentially as e^{-β z} with a
penetration depth d_p = β^{-1} = \frac{1}{2π(n_\text{air}n_\text{gold}^2 - n_\text{gold}^2)^{1/2}} = 165 \text{ nm},
where λ is the wavelength in vacuum.

A 532 nm laser beam, focused by the objective, traps the
probe particle and positions it in close vicinity to the upper
cover slip. The back-scattered light from the particle is
collected by the same objective, passes through a series of
filters and a beam splitter (BS) and is detected by a quad-
rant photo-diode (QPD) (Silicon Sensors, QP50-6-SD). We
maintain a low-power (3 mW at the probe) of the trapping
beam to achieve a high sensitivity of the position detection
to external forces. The resulting sum and differential sig-
als carry the information about the particle coordinates.
This information, together with the knowledge of the tem-
perature and the viscosity of the surrounding medium,
allows us to reconstruct the optical trapping potential,
and to calibrate the trap. For each cartesian coordinate
the power spectral density (PSD) of the Brownian motion
of a bead in an optical trap is given by

\[ P(f) = \frac{D}{f_c^2 + f^2}, \]

where \( f_c = \kappa / 2πγ \) is the corner frequency, \( D = k_B T / γ \) is the diffusion coefficient, \( \kappa \) is the stiffness constant of the
trap in the given direction, \( γ \) is the friction coefficient of
the particle, \( T \) is the temperature of the sample, and \( k_B \) is
the Boltzmann constant. At each position of the optical trap
the PSD of the acquired time series (sampling frequency
f_s = 4096 Hz, number of samples \( N_s = 100\,000 \)) was
calculated and fitted to the theoretical Lorentzian shape,
getting the value for the calibration parameters [20–23].

This method depends upon the precise knowledge of the
viscous drag coefficient, and hence the friction coefficient
of the particle, the estimate of which is prone to large error
when close to a surface, as in our experiment. Its de-
pendence on the ratio between the particle size and distance
to the surface must be accounted for to calibrate accurately
the probe displacement. It is taken into account following
the methodology proposed in [21], which relies on the
expression of the diffusion coefficient for a sphere near a
surface [24]. The validity of this formula for experiments
similar to ours was confirmed in [25]. The uncertainty in
the determination of the distance between the particle and
the surface and hence the value of the diffusion coefficient
is the leading source of error in the absolute value of the
measured force. For example, for a 2 μm particle placed
at 500 nm from the surface, the relative error is estimated
to be around 12%.

An additional difficulty in the use of a PFM near a metal
surface is the reflection of the trapping beam from the
surface [4,9,26]. The reflected wave acts as an additional
external force that changes the equilibrium position of the
optical trap. This force is accounted for by calibrating the
optical trap independently for each position of the probe.
The sphere moves towards a new equilibrium position
under the effect of the plasmon radiation forces, which can
be calculated along each coordinate axis from the knowl-
edge of the displacement and the stiffness of the trap. In
practice, two potential profiles are reconstructed with and
without the SP field and their difference gives the SP
radiation force [9]. Other interactions related, for example,
to the gravitational force and the interaction with the
surface can be eliminated. In each experiment we use a
unique chamber with three types of probe particles so that
all changes of measured radiation forces may be mainly
assigned to the changes in momentum transfer, and not to
the changes of setup geometry. In the micron size range the
stiffness grows with the decrease of the probe size (see, for
example, [27]). Hence, measurements done with probes of
different sizes permit one to gain information on radiation
forces using the PFM with different sensitivity. The stiff-
nesses of the optical trap along the off-axis (x) direction
measured far from the surface are 1.1 pN/μm (4.5 μm),
1.3 pN/μm (2.0 μm), and 1.8 pN/μm (0.6 μm). These
values change considerably when approaching the surface.

A difficulty may arise due to the local increase of
temperature at the metal layer produced by the SP excita-
tion. A convection induced by such a local heater would
produce a force at the probe in all three directions.
However, we observe that the probe displacement occurs
only along the x and z directions (Fig. 2) so we consider the
local heating effects can be neglected when compared to
radiation forces.

Previously, various publications reported the experi-
mental analysis by PFM of the radiation pressure exerted on
dielectric and metallic particles within a homogeneous
evanescent field near a dielectric interface [9,28].
However, no studies have been done on radiation forces
induced by SP.

Figure 2 shows typical potential energy profiles in the x
and z directions with and without the SP wave when a
2 μm bead is used as a probe. In this experiment, the
incident angle is kept at resonance. When the distance
between the probe and the surface is large enough, i.e., ≥
500 nm, both the x potential [Fig. 2(a)] and the z potential
[Fig. 2(e)] can be well fitted to a parabolic function, and the
plasmon radiation pressure results in a shift of the potential
minima. When the probe is placed closer to the surface (the
The radiation force acting on a 2.0 μm polystyrene bead placed at 500 nm from the metal surface is plotted as a function of the incident angle. For the low-power optical trap we need, the 4.5 μm sphere is found to be the most appropriate probe to guarantee the stability of the trapping through such a long-run experiment. A comparison with the plasmon coupling efficiency (1 − R, where R is the reflectivity) at the gold-water interface clearly shows that the plasmon radiation force follows the dispersion of the SP mode. This fact confirms that the presence of the particle located at such a distance does not significantly affect the SP. Also, by changing the polarization of the incident wave from TM to TE the force falls to a value similar to the one measured at a nonresonant angle. From these data it is possible to estimate the enhancement factor of the forces due to the SP (the angular interval of the resonance is very narrow so that we can neglect the variation of the penetration depth of the electromagnetic field inside this interval), which results in being about 40, in good agreement with the theoretical prediction (about 30) of electric field intensity increase at the gold-water interface. Further information is contained in the evolution of the plasmon radiation force vector with the incident angle [Fig. 3(b)]. The z component at resonance is larger than the x component. Theoretical predictions made for 10 times smaller dielectric particles show the same feature [17]. For an equal probe-surface distance we observe the same property also for a 0.6 μm sphere, but the longitudinal force is found to be larger in the case of a 2.0 μm one. For a full understanding of this experimental result, calculations are required for micrometer particles, since in this range the radiation force in an evanescent field is not expected to be monotonous as a function of their diameter [33].

The radiation force depends on the distance separating the surface and the particle, but also on the dimensions of the upper surface of the probe. The potential profile along the x direction [Fig. 2(b)] does not change significantly, while the one along the z direction [Fig. 2(f)] reveals a more complicated behavior. This is attributed to the presence of additional forces of different natures exerted by the surface itself [29–31] as well as due to the interference between the incident and reflected trapping beams. Multiple scattering between the surface and the probe of the evanescent field could also contribute to these oscillations [32]. However, because the oscillations in the potential are observed also when the laser exciting the plasmon field is off [Fig. 2(f)], we attribute them mainly to the reflection of the trapping beam. A similar behavior of the potential profiles has been observed with the three sizes of probes. In the following treatment, we analyze only radiation forces obtained from measurements at distances from the surface where the potential profiles measured are harmonic.

To distinguish the contributions of the incident electromagnetic wave and the resonant charge density oscillations to the total momentum of the SP transferred to a dielectric particle, we exploit the fact that the SP can only be coupled (i) at a specific incidence angle, and (ii) for a TM-polarized incident electromagnetic field. Hence, the respective contributions can be decoupled by changing either the angle or the polarization of the incident beam. These two cases are shown in Fig. 3(a), where the modulus of the plasmon radiation force acting on a 4.5 μm polystyrene bead, placed at 500 nm from the metal surface, is plotted as a function of the incident angle.
the particle itself. Figs. 4(a) and 2(b) illustrate the evolution of the radiation force vector acting on a 2 μm particle with the distance from the metal surface. As expected, the modulus of the total force increases when the distance is reduced. The z dependencies of the two components are different: the increase along the x component is much sharper than the one along the z component. Both of them do not follow the exponential tail of the electromagnetic field. The same experiment, repeated with 4.5 and 0.6 μm beads, shows a similar tendency. For Rayleigh particle probes one would expect to observe an exponential decay of the force modulus following the exponential decay of the plasmon field. Indeed, in that case, the probe would act as a dipole which does not significantly modify the incident field and the force magnitude would then be determined by the incident field intensity at the probe position. In our experiments where the sizes of the probes are larger than the incident wavelength, the force magnitude results from a more complex process since the probe is big enough and the evanescent light can propagate inside it.

Figure 4(c) illustrates the force vector acting on the three kinds of particles, when the distance between the metal layer and the upper surface of all three particles is 500 nm. The total force modulus increases as the probe size decreases, over the range of dimensions we consider. The absolute value of the plasmon force measured for a 0.6 μm sphere is in reasonable agreement with the theoretical values [17]. Additionally, the force vector direction varies with the probe size. This effect can find application in optical sorting devices. A SP produced by a homogeneous metallic layer can act as a particle sorter since the velocity due to the plasmon radiation force of bigger particles will be considerably smaller than that of small particles: less force acting over more mass.

We believe that this study delivers an important contribution towards a better understanding and optimization of optical trapping forces produced by SP-enhanced evanescent waves, providing both a deeper understanding of the SP physics and an experimental approach to their implementation.

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