New Techniques in Optical Trapping and Sensing

Lulu Liu, Alexander Woolf, Federico Capasso
Harvard University - School of Engineering and Applied Sciences
9 Oxford Street, Cambridge, MA USA
lululiu@fas.harvard.edu

Abstract: Micrometer-sized dielectric scatterers suspended in fluid can act as sensitive, dynamic probes of surface forces and optical near-fields. We demonstrate several new techniques that expand our current capabilities of optical trapping and sensing. This includes the use of nearly diffractionless beams for particle confinement, effective optical traps for particles with lower index than surrounding fluid, and high precision tweezing and sensing near reflective/metallic surfaces. Finally, we demonstrate the application of a combination of these techniques in the successful measurement of near-field optical and double-layer forces.

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1. Nearly-Diffractionless Beams for Sensing

In 1986, Ashkin and his colleagues at Bell Labs created the first optical gradient trap [1]. Using a single, focused Gaussian beam of light, now called an optical tweezer, they trapped and manipulated micron-sized dielectric particles in fluid. More recently, Garcés-Chávez et. al. [3] expanded upon this work using a ”diffraction-less” Bessel beam, with which they simultaneously controlled micron-sized particles in chambers separated by several millimeters. However, the nearly-diffractionless nature of the Bessel beam has another advantage over the traditional Gaussian beam optical tweezer that is yet to be much exploited: the nearly constant light intensity along the axis of the central lobe allows a particle to move unhindered in one dimension while remaining tightly confined in the other two.

This sort of 2-D trap is ideal for Total Internal Reflection Microscopy (TIRM), a near-field sensing technique whereby a dielectric particle undergoing Brownian motion is sensed via the evanescent field generated at a smooth boundary between two materials [2]. TIRM allows one to find the potential energy (as a function of displacement) of the interaction between the particle and the nearby surface. Because the technique is sensitive only in the direction normal to the surface, one is motivated to confine motion along such a vector.

Figure 1 shows preliminary data comparing a standard Gaussian beam optical trap with a Bessel beam trap for the same dielectric particle under identical experimental conditions. The 2 μm polystyrene particle above a glass surface is naturally confined within a double-layer plus gravity potential. The optical trap (required to hold the particle in place for measurement) necessarily distorts the potential. In the case of the Bessel beam, the additional force is simply a position-independent radiation pressure term in the same direction as gravity. However, for the 3D Gaussian beam trap, in addition to radiation pressure, axial confinement contributes a spring-like term to the measured potential (Figure 1).

We have also demonstrated trapping of dielectric particles with index lower than surrounding fluid by introduction of an optical vortex into the nearly-diffractionless Bessel beam. Such a trap will allow us to probe novel optical forces for the first time, such as a contact-free measurement of the repulsive Casimir-Lifshitz force and the repulsive surface plasmon force.

2. Sensing near a reflective surface

A source of great difficulty in optical trapping and sensing is the nearby presence of a reflective metallic surface. Absorption causes undesirable heating and reflection creates standing waves and selective field enhancements that counfound even the best trapping and sensing techniques [4]. Additionally, field modulations, which disturb the precision of the optical tweezer, extend to distances many times the wavelength of light, and in some cases, to the length of the entire chamber. As the fields are non-exponential near a reflective surface TIRM measurements are unable to obtain realistic potential energy landscapes, leading to sparse research in front of reflective surfaces [5].

We propose a single solution to the problem of trapping and sensing near a reflective surface. Using the methods described in reference [6], we utilize the complex phase response of metals to turn the metallic surface into its own anti-reflection coating. All other properties of the metal surface are retained: surface plasmon generation and propagation, surface chemistry, electrical conductivity, thermal conductivity, etc. Figure 2 shows improved exponential response and low reflection for the anti reflection coating we have designed.

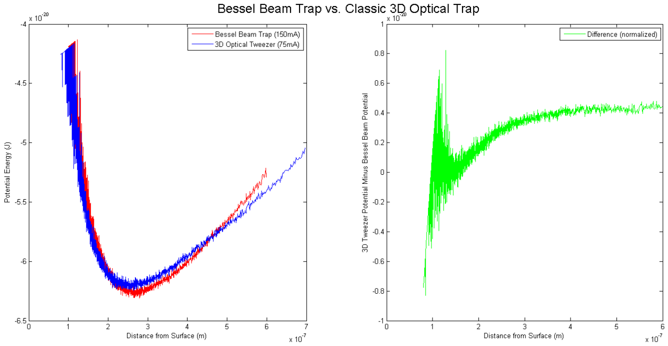

Fig. 1: Potential energy plot of a 2μm polystyrene bead immersed in water above glass. The single-beam Gaussian optical tweezer contributes an additional spring force whereas the Bessel beam optical trap does not. The difference is shown in the right figure.

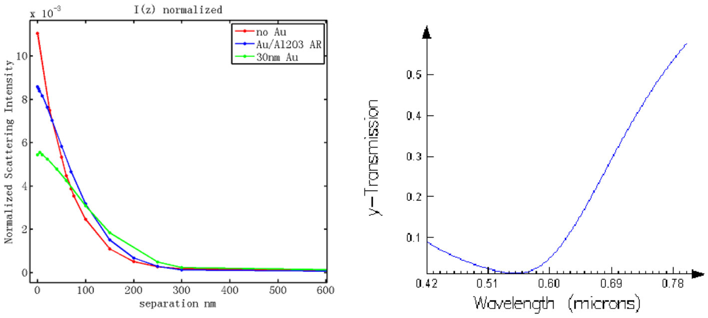

Fig. 2: Left: Simulation showing that the AR-coating is able to bring a non-exponential I(z) (scattered radiation in evanescent field as a function of distance from surface) closer to ideal. Right: Reflectivity as a function of wavelength for our anti-reflection gold stack.

3. Scientific Goals

It is with several scientific goals in mind that we developed our methods. First, we wish to conduct studies of surface interactions between dielectric particles and a metal. Specifically, our technique allows us measure the force exerted by a propagating surface plasmon upon a dielectric sphere. We expect that in a fluid that has lower index than the particle, the particle will experience an attraction to the surface when the surface plasmon is switched on, and conversely, when the fluid is higher index than the particle, the particle will be repelled. Figure 3 contains preliminary data which shows a clear change in the potential profile of a particle in the presence of a surface plasmon wave.

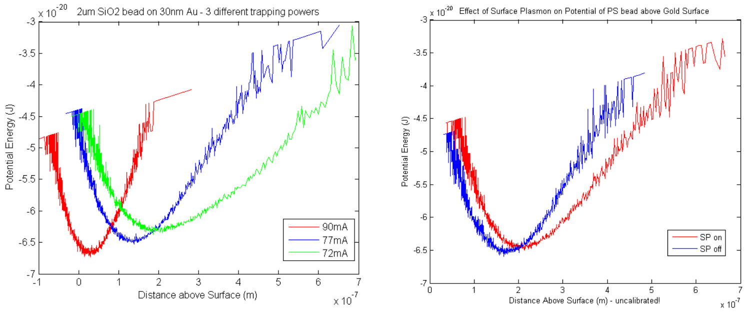

Fig. 3: Uncalibrated potentials taken above a reflective gold surface for a 2um SiO_2 bead. Left: Same bead within a Gaussian beam trap at three laser powers. Right: Same bead within a Gaussian beam trap with surface plasmon turned on and off. When properly calibrated such potentials can be subtracted to find the surface plasmon contribution.

References

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