Plasmonic Nano-Tweezers for Dielectric or Metallic Nano-Objects Trapping

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***Abstract*— Optical tweezing is an emerging application of plasmonic nanostructures that aims at the exploitation of the enhanced light-matter interaction to trap nano-objects for sensing, biosensing, and spectroscopy purposes. In this contribution, we report the numerical analysis of efficient tweezing of subwavelength nanoparticles with radii smaller than 50 nm, in localized surface plasmon nanoantennas strongly coupled with Silicon on Insulator (SOI) waveguides. This integrated scheme ensures an intense excitation of the plasmonic resonators. Moreover, the dimer-like topology of the plasmonic nanoantenna further enhances the nearfield, leading to an ultra-efficient trapping.**

Keywords-Optical tweezers; Optical manipulation; Plasmonics; Integrated optics devices.

I. INTRODUCTION

As firstly demonstrated in [1], focused laser beams can trap small particles released into liquid. The interaction between light and objects results in optical forces that arise from their momentum exchange. In general, the tweezing action depends on the electromagnetic nature of both the trap and the particle. To evaluate and quantify the tweezers performance, we can consider three linked quantities: the total force, the stiffness, and the potential energy.

The total force accounts for the contribution of two components, namely the scattering and the gradient force. In particular, the gradient force occurs when a displaceable object experiences a localized electromagnetic field. It is proportional to the cube of the particle radius *r* and to the gradient of the electric field modulus:

$$F_g \propto r^3 \nabla |E|^2.$$

The stiffness, representing the restoring action intensity of the trap, also gives an idea of both its efficiency and its spatial extent. The following expression holds for the stiffness calculated along the *i* direction:

$$k_i \propto r^3 \frac{d}{di} \nabla |E|^2.$$

The potential energy, which can be expressed as

$$U \propto r^3 |\mathrm{E}_\omega|^2 ,$$

gives an idea of the trap stability. According to the Ashkin criterion [2], the potential energy well must be much deeper (at least 10 times) than the thermal energy $k_B T$ of the system.

In order to ensure a stable trapping, in fact, it is imperative to compensate for the random kicks the particle receives in the presence of thermal agitation. It is worth pointing out that smaller particles are more difficult to trap since the gradient term depends on the cube of the particle radius. In order to compensate for the effect of the particle size, we can achieve stronger gradients by increasing the field localization.

Plasmonic structures are particularly efficient in concentrating the electromagnetic field in deep subwavelength volumes thanks to Surface Plasmon Polaritons (SPPs) and Localized Surface Plasmons (LSPs) at the interface between a dielectric material and Noble Metal Nanoparticles (NMPs). The excitation of the NMPs can be achieved by internal total reflection or, more effectively, by coupling the NMPs with a Silicon on Insulator (SOI) waveguide, as demonstrated by the authors in [3]-[5].

Here, we propose a plasmonic dimer configuration (i.e., nanoantenna) coupled to a silicon waveguide, which is capable of strongly enhancing the near field in the proximity of the dimer gap and, therefore, of achieving a stable trapping of subwavelength particles. In this contribution, we investigate the effect of the particle position, with respect to

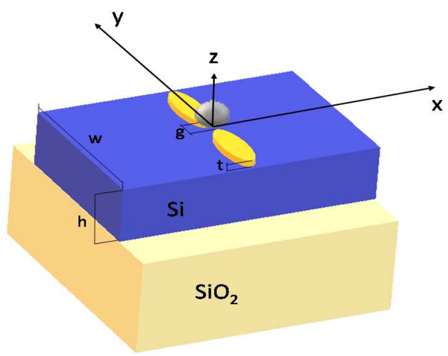

Figure 1. Scheme of the plasmonic gold dimer coupled to the SOI waveguide. A trapped particle is also rapresented (grey sphere).

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the nanoantenna, on the trapping efficiency of dielectric and metallic nanoparticles dispersed in water.

In Section II, we report the results of the design and of the numerical simulations of plasmonic nano-tweezers, whereas, the conclusion is reported in Section III.

II. Integrated Plasmonic Nano-Tweezers

The proposed plasmonic tweezers configuration is schematized in Figure 1. In particular, the considered dimer is constituted by two gold ellipsoidal nano-cylinders aligned along the y-axis and separated by a gap g=25 nm. The geometrical sizes of each nano-cylinder are: radii r_x=30 nm and r_y=90 nm and thickness t=30 nm. The particle to be trapped is also schematized as a sphere of radius r.

The dimer is coupled to a silicon waveguide having width w=500 nm and height h=220 nm. The geometrical sizes were optimized to achieve the optimal coupling between the Si waveguide and the dimer around the wavelength λ=1.55 µm.

We simulated the integrated dimer structure by three-dimensional Finite Difference Time Domain (FDTD) in presence of either a dielectric (polystyrene with refractive index n_p=1.59) or a metallic (gold) spherical particle. The calculation of the total force F acting on the bead was performed from the total electromagnetic field, for a set of discrete positions of the bead. In all the simulations, we considered water as superstrate with refractive index n=1.33.

As an example, the numerical results obtained by the simulation of a polystyrene sphere immersed in water are reported in Figure 2. In particular, Figure 2 (a-c) show, respectively, the x component of the total force F_x, the x component of the stiffness k_x, and the z component of the total force F_z, as a function of the position x and of the wavelength λ when y=0. Similarly, Figure 2 (d-f) show F_y, k_y, and F_z, as a function of the position y and of the wavelength λ, when x=0.

In Figure 2 (d-f), where we consider a displacement of the particle along the *y* direction, we report the positions with positive values of y for the sake of reducing the computational time. Nonetheless, the behavior is symmetric with respect to the x-axis.

In Figure 2, the white solid lines correspond to the center of the dimer gap, the dotted blue lines denote the zeros of the stiffness and the solid green curves denote the equilibrium locus (i.e., the total force along x or y is zero). Since the corresponding stiffness is negative (see Figure 2(b)), along the green curve the object lies on a minimum of the potential energy, which also satisfies the Ashkin criterion for stable trapping as long as λ >1.57µm.

III. Conclusion

The proposed dimer configuration is capable of efficiently trapping polystyrene nanoparticles in the middle of the dimer gap. Similar analyses were performed in the case of metallic nanoparticles, showing that the achieved optomechanical energy is one order of magnitude greater (in modulus) than in the case of dielectric particle trapping. Moreover, this effect is associated with a significant variation of the SOI waveguide transmittance, thus allowing the detection and the monitoring of the particle-trapping event.

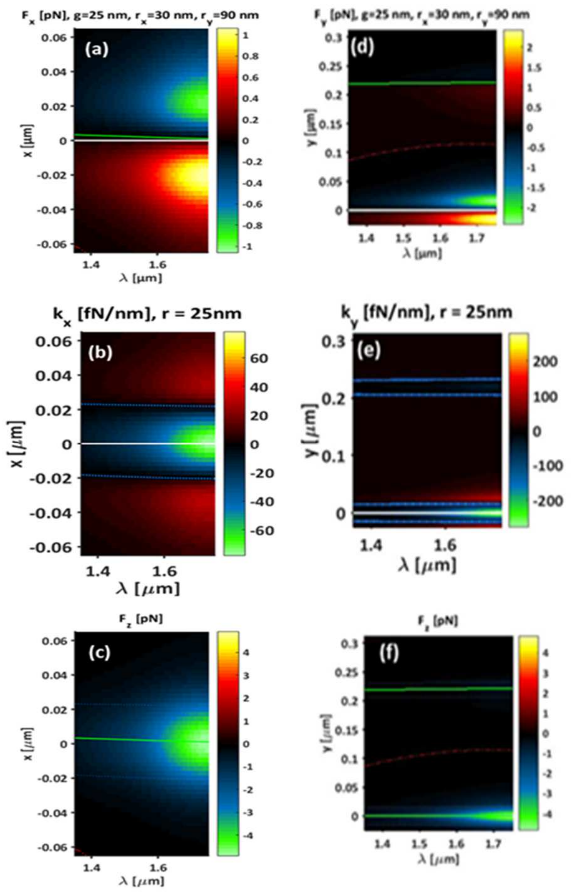

Figure 2. (a) Total force Fx, (b) stiffness k_x, and (c) total force F_z as a function of the position x and of the wavelength λ, and (d) Total force F_y, (e) stiffness k_y, and (f) total force F_z as a function of the position y and of the wavelength λ, for a polystyrene sphere of radius r=25 nm.

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