Nano-trapping by Plasmonic Field Enhancement:
(a) Large Trap Volume by Metallic Nano-ring Structure
(b) Optical Conveyor Belt

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Abstract

We propose and demonstrate the feasibility of trapping metal nanoparticles by using the gold nano-ring structure and the possibility of optical conveyor belt. We use 3D finite-difference time-domain (FDTD) and the Maxwell stress tensor (MST) in our analysis. First we show that the trapping potential well in a metal ring is as high as 1.31×10^{-19} J under a low laser power of 1mW/μm^2, which makes the optical trapping events much more efficient. Furthermore, the existence of multiple potential wells results in a very large active volume of ~10^6 nm^3 for trapping the target particles. The trapped gold nanoparticle (Au-NP) further leads to the formation of nano-gaps that offer a field enhancement of 160 times. Furthermore optical conveyor belt can be achieved in a series of metal disk of different sizes. By swtiching the polarzation and wavelength of the excitation beam, the trapped Au-NP can be passed around between adjacent disks.

Research Background

Optical tweezers, with excellent properties of manipulating the specimen in the microscale, have been widely used in the field of life science, biophysics and biochemistry [1-3]. The conventional OT can be simplified as "single-beam gradient force trap" As shown in Fig. 1, a transparent bead is pulled by the gradient force into the position where the light intensity is the largest. 3D trapping of micro beads therefore can be realized. However, the conventional optical tweezers focuses a very intense laser beam to a small spot in order to provide sufficent field gradient force to trap the object, and the trapping volume is diffraction-limited, i.e. trap diameter is comparable to wavelength of excitation beam.

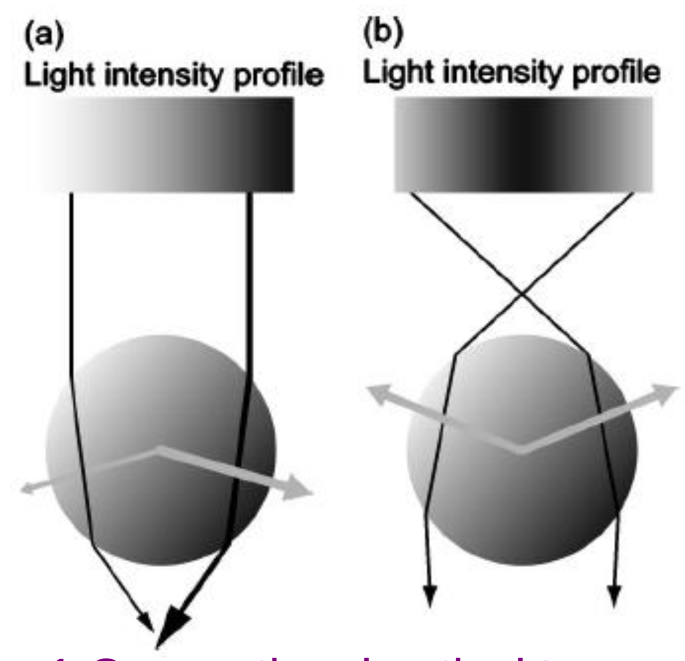

Fig. 1 Conventional optical tweezers

Gold Nano-ring - Trapping Properties

Fig. 2. shows (a) schematic of one unit cell of the gold nano-ring arrays and (b) extinction (solid curve) of the nano-ring arrays and the E^2 spectrum (dotted curve) of the nano-ring edge as indicated by a black dot in Fig. 2(a). Dimensions of nano-ring: D1=40 nm , D2=100 nm, t=35nm , and L=525nm. Excitation wavelength=785nm.

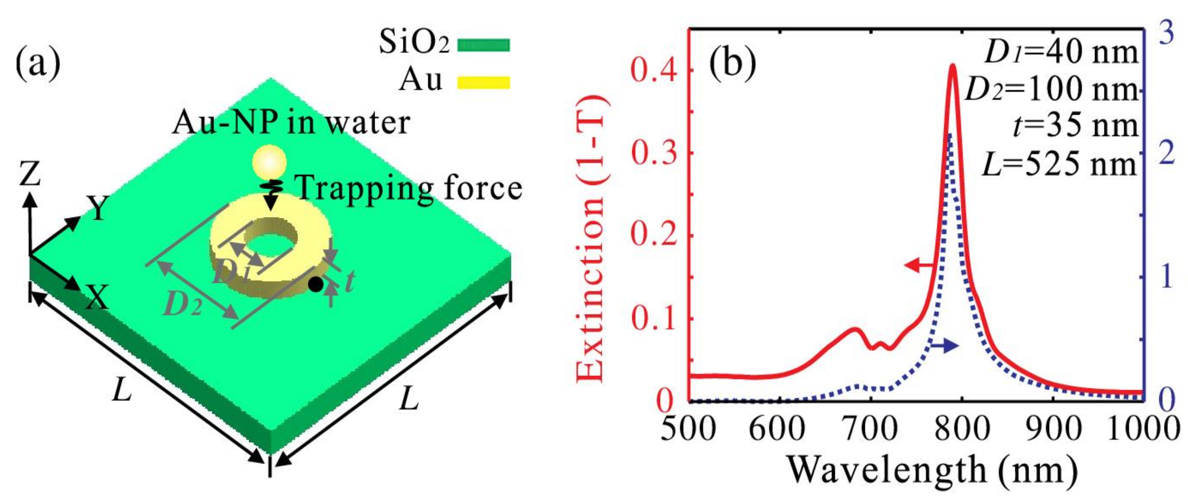

Fig. 2. (a) Schematic of one unit cell of the gold nano-ring arrays. (b) Extinction (solid curve) of the nano-ring arrays and the E^2 spectrum (dotted curve) of the nano-ring edge as indicated by a black dot.

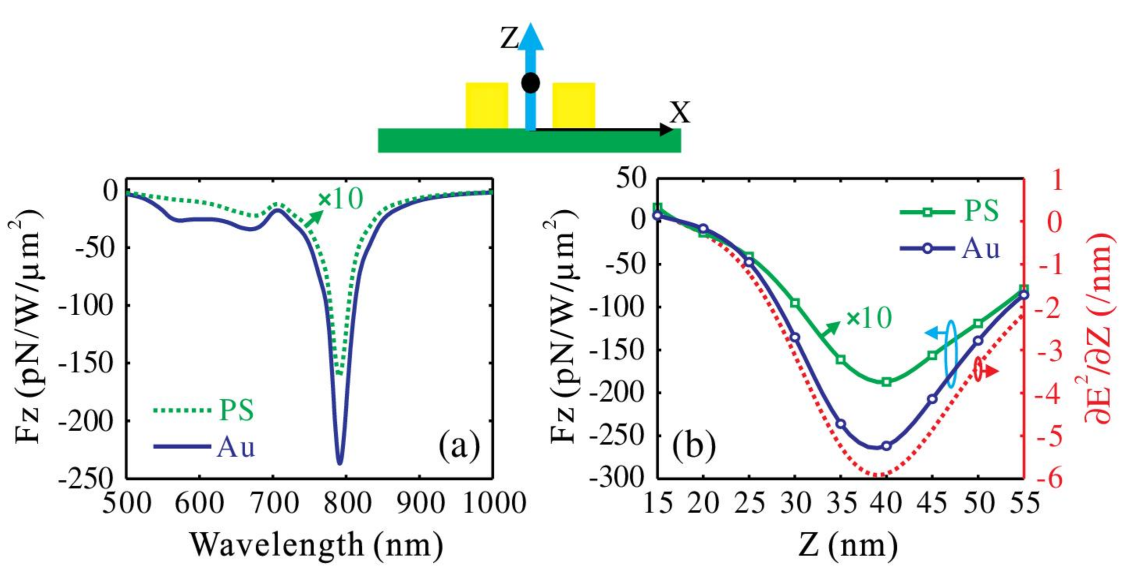

Fig. 3. (a) Fz acting on the Au-NP (solid curve) and the PS (dotted curve, magnified 10 times) as a function of incident wavelength. Both NPs have a diameter of 20nm and are located at coordinates of (0, 0, 35)nm as indicated by a dark dot in the cross-section schematic. (b) Spectra of Fz on the Au-NP (circles) and the PS (squares, magnified 10 times) as a function of position along the z axis (x=y=0) and the electric field intensity gradient along this axis (dotted curve) respectively.

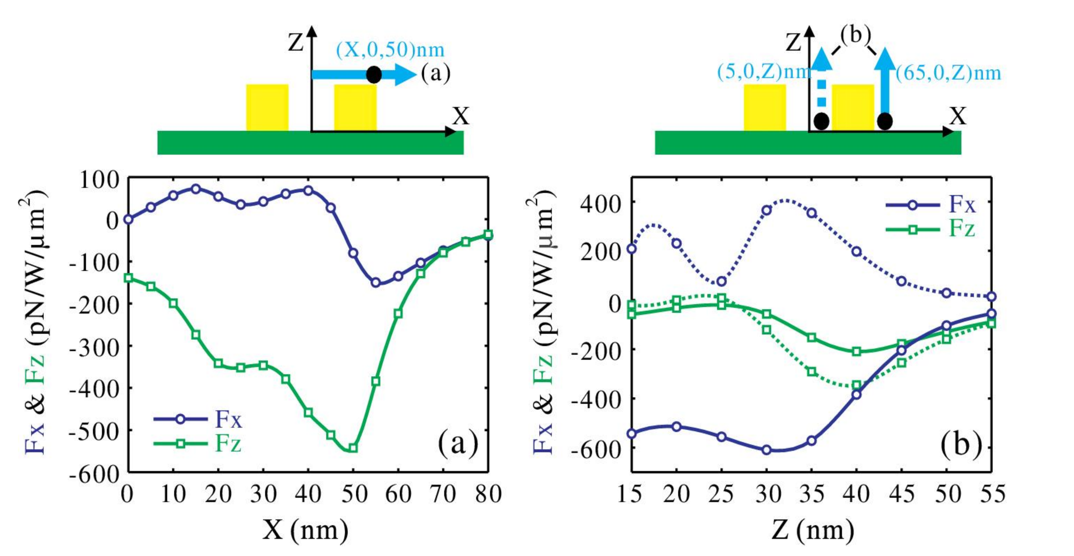

Fig. 4. (a) Spectra of Fx (circles) and Fz (squares) as a function of location along the axis of (x, 0, 50)nm (indicated by thick arrow in cross-section schematic). (b) Spectra of Fx and Fz as a function of position along the axes of (65, 0, z)nm (indicated by thick solid arrow) (circles for Fx and squares for Fz), and (5, 0, z)nm (indicated by thick dotted arrow) (dotted curve with circles for Fx and dot ted curve with squares for Fz), respectively

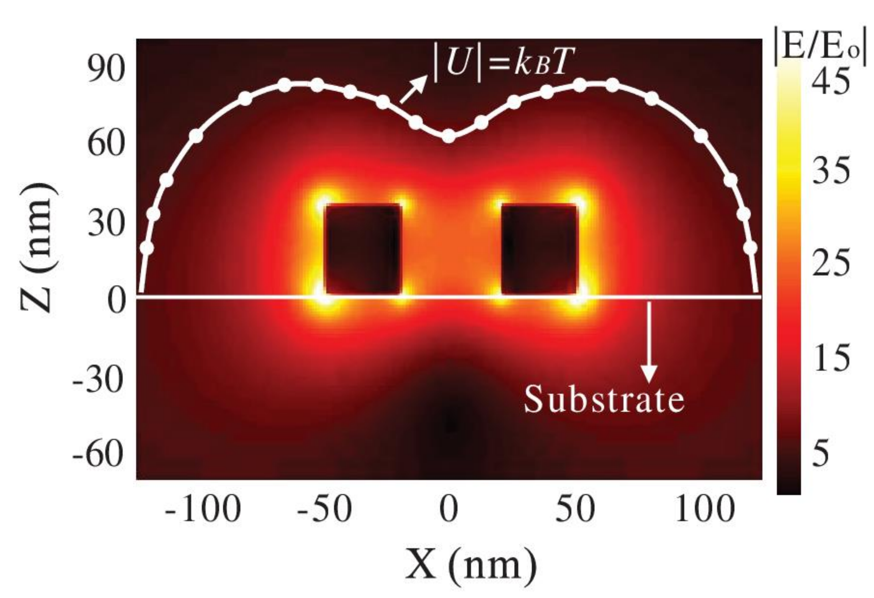

Fig. 5. Electric field distribution in the x-z plane and the trapping boundary (white circles) |U|=kBT. Power density is 1mW / μm ^{2}

Performance benefits:
(1) Ultra-large trap volume
(2) Low threshold

Optical Conveyor Belt

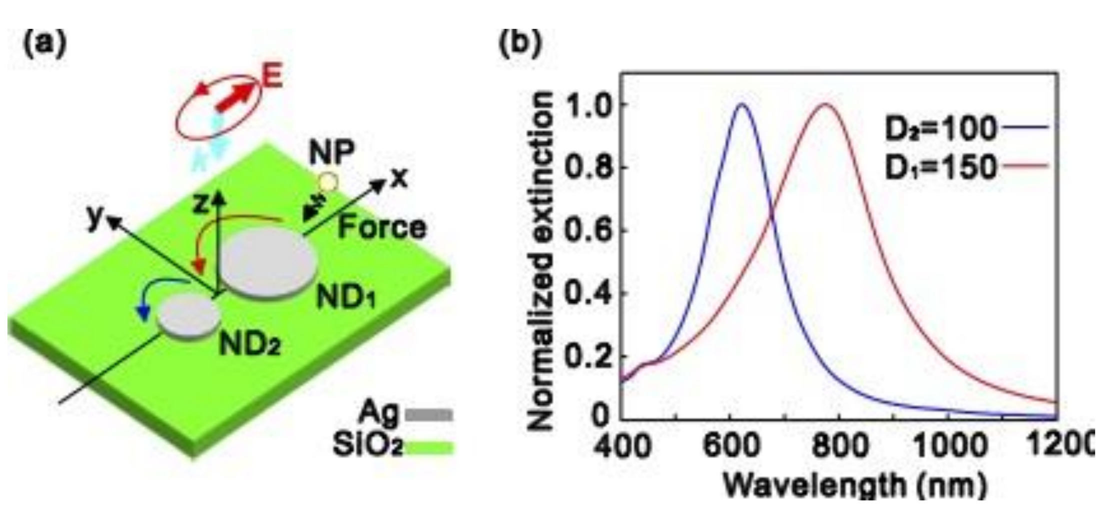

Fig. 6. (a) Schematic of our nano-optical conveyor belt based on a couple of graded silver NDs. (b) Normalized extinctions of ND1 (D1=150 nm, red line) and ND2 (D2=100 nm, blue line), respectively.

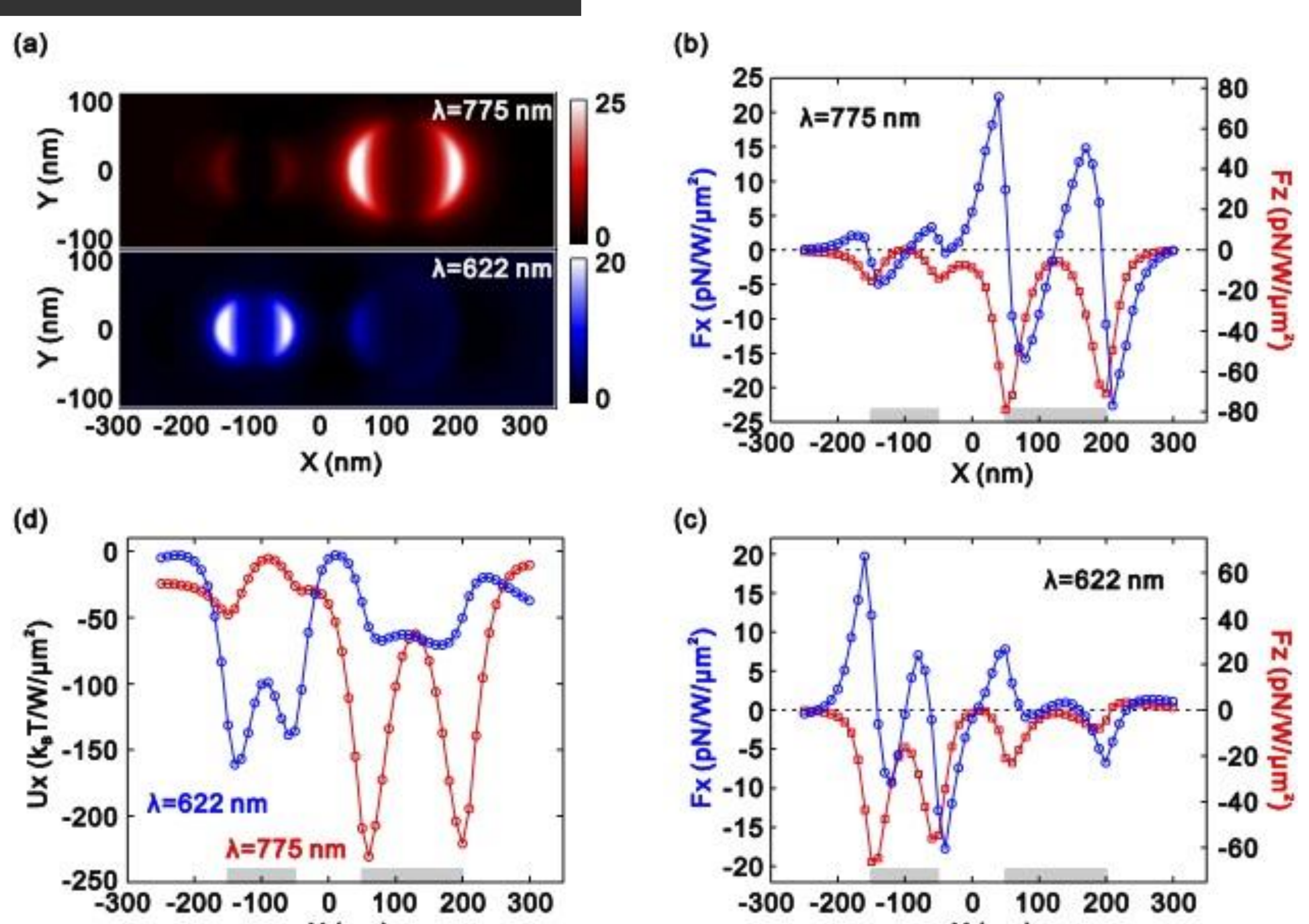

Fig. 7. (a) Electric field intensity distribution at 10 nm above the NDs under illumination by 775 and 622 nm light. (b)-(c) MST calculated force components Fx (blue –◯–) and Fz (red –□–) exerted on an Au-NP locating above the NDs with a 10 nm gap as a function of position along the X axis (Y=0) for λ=775 nm and 622 nm, respectively. (d) Trapping potential Ux as a function of position along the X axis (Y=0) for λ=775 nm (red –◯–) and 622 nm (blue –◯–), respectively. The incidences have X-polarization. The NDs are schematically shown in grey at the bottom. The gap between adjacent NDs is 100 nm.

Performance benefits:
(1) Nano-trap
(2) Simple design
(3) Simple operation: polarization rotation followed by excitation wavelength swithing

Conclusion

The proposed designs aim to address some of the shortcomings of present nano-optical traps. By adding basic functionalities including (1) very large trap volume and (2) passing the trapped target between adjacent traps, the new devices offer promising application potential for guided biosensing at predefined sites and surface enhanced Raman scattering as well as integration with lab-on-a-chip.

References: [1] Ashkin, A., Dziedzic, J. M., Bjorkholm, J. E., and Chu, S., Opt. Lett. 11, 288-290 (1986). [2] Grier, D. G., Nature 424, 810-816 (2003). [3] Perkins, T. T., Laser & Photon. Rev. 3 203-220 (2009).