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Controlled optical trapping and transport of a single 100 nm particle across an array of silicon nanoantennas

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Abstract: We experimentally demonstrate the optical trapping and transport of a single 100 nm polystyrene nanosphere across an array of silicon nanoantennas. Our device is all silicon and produces negligible local heating.

OCIS codes: (350.4855) Optical tweezers or optical manipulation; (310.6628) Subwavelength structures, nanostructures;

1. Introduction

The ability to optical manipulate nanoscale objects presents interesting opportunities for nanoscience [1]. Various approaches have been employed [2,3], including plasmonic nanoantennas [4,5]. Plasmonic nanotweezers face the challenge however of Joule heating. Indeed, loss is recognized as an issue faced by the field of plasmonics in general, motivating recent interest in all-dielectric metasurfaces [6]. Here, we report the optical trapping and transport of an individual polystyrene nanosphere (NS) with a diameter of 100 nm (Life Technologies, FluoSpheres, Carboxylate-Modified, F8800) across an array of silicon (Si) nanoantennas (Fig.1a&b). These are fabricated by e-beam lithography and reactive ion etching. A single NS is optically trapped around a Si nanoantenna that is illuminated by a laser (wavelength 1064 nm). We demonstrate that the NS can be transported, i.e. made to visit different nanoantennas within the array, as achieved by software-controlled movement of the Si chip. We track the NS position by fluorescence microscopy, thereby illustrating the dynamics of the process in which the NS is released by one Si nanoantenna and trapped by the next in the array. We also demonstrate the simultaneous trapping of two NSs by a Si nanoantenna. Our results confirm that Si nanonantenna arrays are robust as optical nanotweezers.

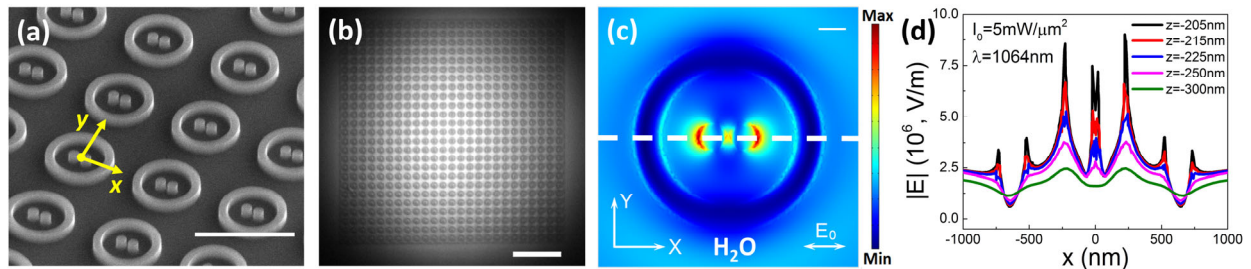


Fig.1. (a) SEM image (45° tilt) of Si nanoantenna array. Periodicities in x - and y -directions are both 2 μm . Each antenna consists of two identical Si cylinders with diameters of 200 nm, heights of 200 nm and a 50 nm gap in between, surrounded by a Si ring, all on a Si wafer. Ring has inner and outer radii of 0.525 and 0.725 μm , respectively, and height 200 nm. Scale bar: 2 μm . (b) Microscope image of nanoantenna array chip immersed in water. Scale bar: 10 μm . (c) Simulation of electric field ($|E|$) distribution in the xy -plane, at 15 nm above top surface of antenna. Scale bar: 200 nm. (d) Electric field line profile along x -axis (indicated by white dashed line in panel c) for $y=0$ and at different z distance. For panels c & d, nanoantenna (embedded in water) is illuminated by x -polarized plane wave at normal incidence (travelling in $-z$ direction), with $I_0=5\text{mW}/\mu\text{m}^2$ and at a wavelength of 1064 nm.

2. Numerical simulations: near field distribution

We simulate our Si nanoantennas using COMSOL Multiphysics. The gap (50 nm wide) is smaller than NS diameter (100 nm) and thus NSs are blocked from reaching the gap center. In Fig. 1c, we show the electric field amplitude distribution in the xy -plane, at 15 nm from the antenna surface ($z=-215$ nm). In Fig. 1d, we plot the absolute value of electric field vs x -distance, showing that there are three main hotspots. These comprise two main maxima at the outer ends of cylinders, and one secondary maximum at the gap. There are also minor hotspots around the ring. We also perform simulations of the heating, predicting a max. temp. rise of only ~ 0.02 K for illumination at 5 $\text{mW}/\mu\text{m}^2$.

3. Experimental results: optical trapping, transport and release of 100 nm NSs

Fig. 2a provides a schematic of the experimental configuration. An x -polarized laser beam ($\lambda=1064$ nm) is focused by an oil immersion objective (100 \times , NA 1.3), forming a spot diameter of ~ 1.2 μm , into a ~ 15 μm thick perfusion chamber (4 mm \times 16 mm) containing distilled water, polystyrene NSs and Tween 20 (surfactant). A green laser beam ($\lambda=532$ nm) is loosely focused along the same optical path to excite fluorescence. An electron multiplying camera

(EM-CCD) operated at 30 fps is used to record the trapping process. We show that a single NS can be made to visit different nanoantennas within an array. To illustrate the process, we show several EM-CCD frames as Fig. 2b. The NS is initially moving randomly under Brownian motion (Fig. 2b, time *i*). The trapping laser is initially focused on a Si nanoantenna (“first antenna”), whose position is indicated by black squares in Fig. 2b. At time *ii*, the NS enters the vicinity of the first antenna and becomes trapped by optical forces. At time *iii*, the piezoelectric stage on which the Si nanoantenna chip is mounted is translated in the *x*-direction by 2 μm , i.e. so that the next antenna (“second antenna”) in the array is illuminated. This results in the NS being released and moving under Brownian motion, until it is trapped by the second antenna at time *iv*. In Fig.2c, we plot a typical fluorescence time trace integrated over a 14×14 pixel ($2.24 \times 2.24 \mu\text{m}$) cross section centered over the (single) Si nanoantenna that is performing the trapping. Step-like increases and decreases in fluorescence indicate the trapping and release of a single NS respectively, as it is made to visit six different antennas (total distance 10 μm). In Fig. 2d, we show a two-dimensional plot of the measured NS center positions over a time interval of 43 s, as found by analyzing 1300 EM-CCD frames. The cluster at $(x,y) \sim (1500\text{nm}, 1000\text{nm})$ represents when the NS is trapped by the antenna. Further insight into the trapping process can be obtained from Fig. 2e&f. The yellow shaded region denotes the approx. time interval during which the NS has been released by the antenna and diffuses under Brownian motion and is then re-trapped. It can be seen that there is variability in how long it takes for the NS to be re-trapped by the next nanoantenna.

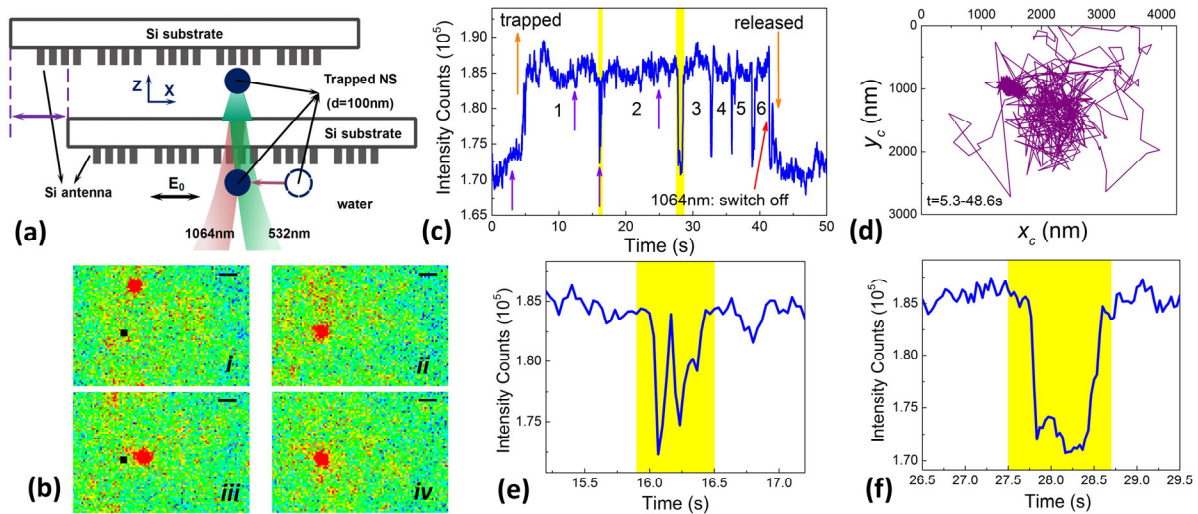


Fig.2. (a) Schematic of trapping and transport of single NSs across an array of Si nanoantennas. (b) Four selected EM-CCD frames (time indicated by violet arrows in c) showing optical trapping and transport of a single 100 nm NS. Illuminated antenna & trapping laser: black square. Scale bar: 1.6 μm . (c) Fluorescence intensity vs time for a single NS trapping, transport and release, exposure time ~ 30 ms. (d) Corresponding NS position trace extracted from EM-CCD frames. (e)&(f) Zoom-in of (c) showing NS release, Brownian diffusion and transport from one illuminated antenna to another. Trapping intensity $I = 5 \text{ mW}/\mu\text{m}^2$.

We next show two NSs (each 100 nm) being simultaneously trapped (Fig. 3a), released (due to chip movement of 18 μm , Fig. 3b), and re-trapped (by new antenna, Fig. 3c). NSs are released when the laser is switched off (Fig. 3d).

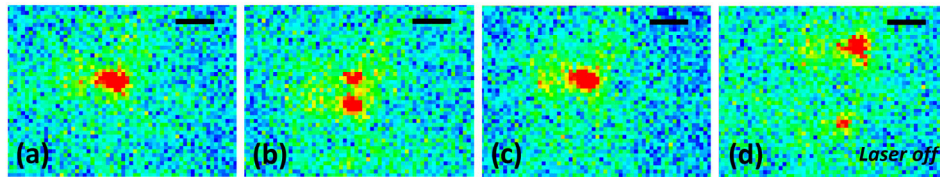


Fig.3. Four selected EM-CCD frames showing the simultaneous trapping, transport and release of two 100 nm NSs, exposure time ~ 30 ms. Trapping laser is switched off in panel d). Scale bar: 1.6 μm . Trapping intensity $I = 8.3 \text{ mW}/\mu\text{m}^2$.

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