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Nano-ring arrays for sub-micron particle trapping

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Abstract

Plasmonic tweezers based on nano-ring arrays on gold thin film are demonstrated. A cylindrical surface plasmon resonance is generated in the aperture of a nano-ring and a transmission peak results. When nano-slits are included to connect the nano-rings, the transmission peak becomes narrower. When the size of the aperture of the nano-ring is reduced, this peak is red-shifted. Both 0.5 μm and 1 μm polystyrene particles are trapped successfully by nano-ring arrays. A self-induced back-action effect is observed when a red-shifted laser beam is used. With multiple trapping sites provided by the nano-ring array, this type of plasmonic tweezers has huge potential to be integrated in lab-on-a-chip systems for life sciences research.

Keywords: plasmonic tweezers, nano-ring array, self-induced back-action, sub-micron particle trapping

I Introduction

Plasmonic optical tweezers based on nanostructures fabricated on thin metal films have been studied as an alternative system to conventional optical tweezers for nanoparticle trapping and manipulation[1-3]. The incident laser beam can be confined beyond the diffraction limit at the nano-apertures and the intensity of the local field is significantly enhanced because of the surface plasmon resonance (SPR) phenomenon. The plasmonic resonance frequency can be tuned by modifying the dimensions of the nano-structures and the period of the array. This feature is especially beneficial for trapping biological particles. To minimize photo damage to a trapped particle, the resonance frequency can be shifted into the near infrared region (NIR)[4, 5]. Besides the enhanced local field intensity, the self-induced back-action (SIBA) effect can be used to enhance the trap stiffness with a red-shifted incident frequency[6, 7].

In this work, we demonstrate a plasmonic tweezers based on an array of nano-rings connected by nano-size slits. For each nano-ring structure, a coaxial inner disk is fabricated inside a nano-hole. A cylindrical surface plasmonic (CSP) resonance is generated at the aperture of the nano-ring and a transmission peak is observed[8]. This peak becomes narrower with the presence of the nano-slit. When the size of the aperture is reduced, this peak is red-shifted. The trap stiffness is compared between two nano-ring arrays with different diameters of inner disks. The SIBA effect is observed for the nano-ring array under the red-shifted incident laser condition. Combined with other sensing technologies, plasmonic tweezers based on these nano-ring arrays have huge potential as components in a lab-on-a-chip system.

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II Experiment

The array of nano-apertures is fabricated on a 50 nm gold thin film using a focused ion beam (FIB). More details of the fabrication process are described in our earlier work[9, 10]. Scanning electron microscope (SEM) images of the nano-ring arrays with 147.2 ± 9.7 nm and 187.3 ± 1.9 nm inner disks are shown in Fig. 1(a) and (b), respectively. The average diameter of the nano-hole is 293.3 ± 13.3 nm, the period is 361.2 ± 3.1 nm, and the width of the connecting slit is 39.6 ± 4.6 nm. The connecting slits are only fabricated along the vertical direction and horizontally polarized incident light is used for experiments.

A finite-difference time-domain (FDTD) simulation is used to obtain the transmission spectra. Dimensions from SEM images are used for the simulation. As shown in Fig. 1(c), the CSP resonance peak is narrower for nano-ring arrays with 147.2 nm inner disks when connecting slits are present. With bigger inner disks, the CSP resonance peak is shifted towards the red. A Ti: Sapphire laser at 980 nm, which is red shifted for the nano-ring array with 147.2 nm inner disks and close to the resonance for the nano-ring array with 187.3 nm inner disks, is used for

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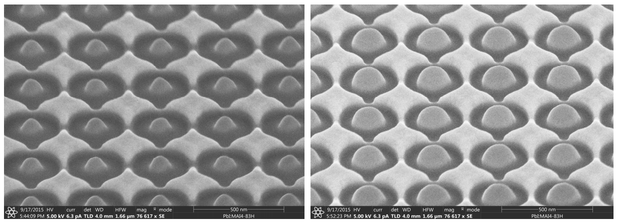
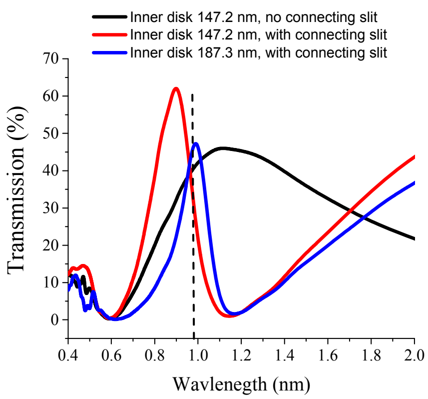
experiments and is shown as the black dashed line in Fig. 1(c).



(a) (b)



(c)

Figure 1: (a) SEM images of nano-ring arrays with (a) 147.2 nm inner disks and (b) with 187.3 nm inner disks. The polarization of the incident beam is along the horizontal direction. (c) Simulated transmission spectra for the nano-ring array with a 147.2 nm inner disks without a connecting slit (black curve) and with a connecting slit (red curve), and the nano-ring array with a 187.3 nm inner disk with a connecting slit (blue curve).

The Thorlabs optical tweezers kit (OTKB) with an oil immersion objective lens (100 X, N.A =1.25) is used. A half wave plate is used so that the incident beam is polarized along the horizontal direction. The plasmonic tweezers chip is packed in a sample cuvette with mean size 1 μm (0.0625% solid content) or 0.5 μm (0.0125% solid content) diameter polystyrene particles (with refractive index of 1.55) in heavy water (D_2O) to minimize heating. We use a surfactant (Tween®20) with 0.1% concentration to prevent the particles from clustering. The sample cuvette is mounted on top of a piezo stage. The transmission of the trapping laser is measured by an avalanche photodetector and recorded. The sample rate of the data collection program is set at 1 kHz. The image of the trapped particle is collected by a CMOS camera and recorded.

In order to experimentally determine the trap stiffness of the plasmonic tweezers on the trapped particles, the transmission data is used to obtain the power spectral density (PSD) and a Lorentzian fit is used to obtain the corner frequency, f_0. Using Eq. (1), the trap stiffness, α, can be determined.

$$\alpha=2\pi f_0\beta \qquad (1)$$

Here, β is the hydrodynamic drag coefficient, as expressed in Eq. (2), where a is the radius of the particle and μ is the viscosity of the solution.

$$\beta=6\pi a\varepsilon(a,h)\mu \qquad (2)$$

Since the particle is trapped near the surface of the nanoring plasmonic tweezers, β needs to be adjusted based on lubrication theory since the gap is much smaller than the radius of the particle. The correction factor, $\varepsilon(a,h)$ is shown in Eq. (3), where h (assumed to be 20 nm) is the distance from the center of the particle to the surface of the device[11].

$$\varepsilon(a,h)=8/15\ln((h-a)/a)-0.9588 \qquad (3)$$

III Results

The trap stiffness for 1 μm and 0.5 μm polystyrene particles are plotted for nano-ring arrays with 147.2 nm (black squares) and 187.3 nm (red squares) inner disks, as shown in Fig. 2. As expected, a bigger particle experiences a larger trapping force for both nano-ring arrays. For the nano-ring array containing the 147.2 nm inner disks, the ratio of the trap stiffnesses for the 1 μm and 0.5 μm particles is 4.37 ± 0.11. This ratio is 2.64 ± 0.05 for nano-rings containing 187.3 nm inner disks. We would expect ratio is expected to be a constant if only optical intensity plays a role in particle trapping. Our results indicate that the SIBA effect also plays a role in particle trapping using these devices. With a larger particle, the SIBA effect should be stronger and this matches our observations.

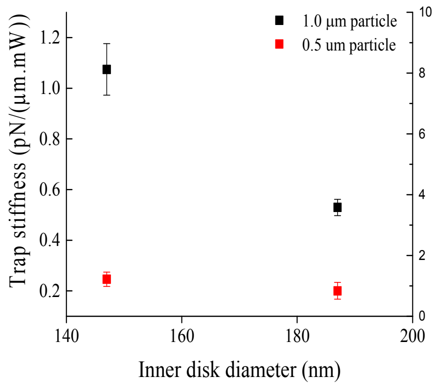


Figure 2: Trap stiffness for 1 μm (black squares) and 0.5 μm (red squares) particles based on 147.2 nm and 187.3 nm inner disk nano-ring arrays.

IV Conclusion

We have shown that plasmonic optical tweezers based on nano-ring arrays can successfully trap sub-micron polystyrene particles. The SIBA effect has been observed when the laser is red-shifted relative to the CSP resonance frequency. These plasmonic tweezers can provide multiple trapping sites, which could be an advantage for trapping large sized or irregular shaped samples. It also could be modified and combined with other sensing methods. A lab-on-a-chip design is also worth exploring for studies of single proteins inside a living cell.

Acknowledgement

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