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Plasmonic optical trap having very large active volume realized with nano-ring structure

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The feasibility of using gold nano-rings as plasmonic nano-optical tweezers is investigated. We found that at a resonant wavelength of $\lambda = 785$ nm, the nano-ring produces a maximum trapping potential of $\sim 32k_{\text{B}}T$ on gold nanoparticles. The existence of multiple potential wells results in a very large active volume of $\sim 10^6$ nm$^3$ for trapping the target particles. The report nano-ring design provides an effective approach for manipulating nano-objects in very low concentration into the high-field region and is well suited for integration with microfluidics for lab-on-a-chip applications. © 2012 Optical Society of America

Plasmonic nano-optical tweezers (PNOTs) have attracted much research interest recently because of their ability to immobilize nano-sized objects with ultrahigh accuracy, thus showing potential applications in chemosensing and biosensing and life sciences [1,2]. Optical trapping strength is dictated primarily by the depth of the trapping potential well associated with the field intensity gradient, which is further aided by localized surface plasmons (LSP) [1–4]. Until now, PNOTs based on metal dipole antennas [23], thin films [5], sharp tips [6], cavities [7], holes [8], disks [9,10], and hybrid waveguides [11] have been realized theoretically and/or experimentally. However, to the best of our knowledge, there is no report on optical trapping using metal nano-rings despite that they may offer performance merits including polarization-insensitive characteristics, widely tunable resonance, strong and uniform field enhancement around and inside the ring cavity, and ease of fabrication [11,12,13].

In addition, gold nanoparticles (Au-NPs) are widely adopted as optical signal enhancement agents due to their plasmonic resonance and various chemical functionalization possibilities. Hence, trapping and immobilizing Au-NPs to a predefined region of high sensitivity plays an important role in achieving high detection signal levels. It has been reported that 10 nm Au-NPs can be trapped inside the gap of a plasmonic dipole antenna, and the trapping effect is monitored by measuring the shift of Rayleigh scattering [3]. This kind of PNOT provides a detection limit in the particles’ size of 5 nm for plasmonic NPs and 6.5 nm for dielectric NPs [14]. However, the active trap volume is small due to the narrow gap used [3,14]. In this Letter, we demonstrate a new kind of PNOT based on gold nano-ring array for three-dimensional (3D) optical trapping of Au-NPs. Results obtained using 3D finite-difference time-domain (FDTD) simulation [15] and the Maxwell stress tensor (MST) [5,11] indicate that the nano-ring PNOT exhibits strong trapping potential well and very large active volume, and thus is effective for bringing NPs that are of low concentrations into the high-field region. The device has strong application potential in the field of biodetection and molecular spectroscopy.

Figure 1(a) shows the structure of the proposed gold nano-ring. The overall device is in a two-dimensional array format so that resonance modes also occur between nano-ring elements and many optical traps may be energized simultaneously with a focused laser spot. The structural parameters are periodicity $L$, thickness $t$, and inner and outer diameters $D_1$ and $D_2$, respectively. Note that the origin of the coordinate has been offset to the left corner for clarity and is actually located at the ring center and the substrate ($\text{SiO}_2$, $n = 1.5$) surface. The environment is water ($n = 1.33$) containing free Au-NPs. In our simulation study, periodic boundary conditions are used in the $x$ and $y$ directions, and perfect matching layers in the $z$ direction. The relative permittivity of Au is based on reported experimental data [16]. The light source is a plane wave illuminating from the top along the normal direction with electric field (amplitude 1 V/m) polarized along the $x$ axis.

Figure 1(b) shows typical extinction (solid curve) and electric field intensity ($E^2$, dotted curve) spectra at the nano-ring edge [marked by a black dot in Fig. 1(a)] as appropriate structural parameters are chosen, namely, $D_1 = 40$ nm, $D_2 = 100$ nm, $t = 35$ nm, and $L = 525$ nm in order to produce a narrow dominating resonance peak at $\lambda = 785$ nm because of the excitation of LSPs and plasmonic interference within the nano-ring array [17]. The edges have been rounded to a radius of 4 nm. Actually

![Figure 1](https://example.com/figure1.png)

**Fig. 1.** (Color online) (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 in Fig. 1(a). Dimensions of nano-ring: $D_1 = 40$ nm, $D_2 = 100$ nm, $t = 35$ nm, and $L = 525$ nm.
the resonance can be readily tuned by varying the dimensional parameters. Increasing the diameters (or ring width) or reducing the device thickness or corner sharpness will redshift the resonance, and vice versa (data not shown). The choice of 785 nm is due to the availability of commercial laser sources and relative lower plasmonic energy dissipation as compared to visible wavelengths. Moreover, the chosen parameters have also taken into account typical fabrication constraints [12,13].

We next use the MST to calculate the trapping forces experienced by the NP due to enhanced local field. Figure 2(a) shows the spectra of vertical forces \( F_z \) acting on a Au-NP (solid curve) and a polystyrene sphere (PS; \( n = 1.6 \), dotted curve, magnified 10 times) as a function of incident wavelength. PS provides a reference case for quantifying the contribution of plasmonic effects. The data have been normalized to incident intensity and illumination area. The NPs used in this case have a diameter of 20 nm and are located at \((0,0,35)\) nm (marked by black dot). One can see that \( F_z \) increases significantly when the wavelength changes towards resonance at \( \lambda = 785 \) nm. The Au-NP experiences a maximum vertical force \( F_z \) as high as 236 \( \text{pN} / \text{W/\mu m}^2 \), which is \( \sim 15 \) times larger than that seen by the PS because of higher polarizability of gold [3,4,11]. The negative sign of \( F_z \) is consistent with the trapping nature of \( F_z \) along the \(-z\) direction. The other force components \( F_x \) and \( F_y \) are zero due to symmetry of the structure.

To examine the spatial distribution of the trapping force, we fix the wavelength at \( \lambda = 785 \) nm. Figure 2(b) shows the spectra of \( F_z \) experienced by the Au-NP (circles) and the PS (squares, magnified 10 times) as a function of location along the \( z \) axis \((z = y = 0)\), and the gradient of electric field intensity along this direction \((\partial E^2 / \partial z)\) (dotted curve). Consistent with previous results, the PS NP experiences smaller trapping force. Obviously, excellent correlation occurs between the electric field intensity gradient and \( F_z \) because of the fact that trapping force is proportional to the gradient of \( E^2 \) \((F = -CV E^2\), with coefficient \( C \) taking into account the NP’s polarizability and the surrounding refractive index) [4,11]. At \( z = 38 \) nm the gradient is at its maximum, indicating that this is the location of highest \( F_z \). At \( z = 17.5 \) nm, both the gradient and \( F_z \) return to zero, followed by a change of sign from “−” to “+” for the region of \( z < 17.5 \) nm. This means that the NP will be trapped slightly above the substrate surface.

In order to calculate the effective trapping strength, we find the trapping potential \( U \) experienced by the Au-NP at a distance \( r_0 \) using \( U = - \int_0^{r_0} F(r) \, dr \) [4,6,11]. At \( z = 38 \) nm, the trapping force is 265 \( \text{pN/\mu m}^2 \), which corresponds to a trapping potential of \( 4.4 \times 10^{-17} \text{J/\mu m}^2 \). If one uses a low laser power density such as \( 1 \text{mW/\mu m}^2 \), the trapping potential will be \( 4.4 \times 10^{-20} \text{J} \), which is \( \sim 11 \) times larger than the kinetic energy of Brownian motion \((k_B T = 4.1 \times 10^{-21} \text{J} \text{ at room temperature, where } k_B \text{ is the Boltzmann constant and } T \text{ is absolute temperature})

Figure 3. (Color online) (a) Spectra of \( F_x \) (circles) and \( F_z \) (squares) as a function of location along the axis of \((x,0,50)\) nm (indicated by thick solid arrow) (circles for \( F_x \) and squares for \( F_z \)) and \((5,0,z)\) nm (indicated by thick dotted arrow) (dotted curve with circles for \( F_x \) and dotted curve with squares for \( F_z \)), respectively. The incident wavelength is 785 nm.

Fig. 2. (Color online) (a) \( F_z \) 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 20 nm and are located at coordinates of \((0,0,35)\) nm as indicated by a dark dot in the cross-section schematic. (b) Spectra of \( F_z \) on the Au-NP (circles) and the PS (squares, magnified 10 times) as a function of position along the \( z \) axis \((z = y = 0)\) and the electric field intensity gradient along this axis (dotted curve), respectively. Excitation wavelength: 785 nm.
around the nano-ring the Au-NP will be trapped by other sites near the substrate surface.

The other two paths are along the axes of (65, 0, z) nm and (5, 0, z) nm as indicated in Fig. 3(b) by the thick solid and dotted arrows. The variations of $F_x$ (solid and dotted curves with circles) and $F_z$ (solid and dotted curves with squares) as a function of location along the two axes are also shown in Fig. 3(b). Note that solid curves correspond to the (65, 0, z) case, while the dotted curves correspond to the (5, 0, z) case. One can see that any Au-NP travelling along these two axes will experience a maximum $F_z$ at 5 nm above the nano-ring (i.e., $z = 40$ nm) and be pulled towards the substrate (i.e., negative $F_z$).

On the other hand, $F_x$ is negative for the case of (65, 0, z) (solid circles) but positive for (5, 0, z) (dotted circles), which suggests that the Au-NP will be driven towards the edge of the nano-ring until the two finally make contact with each other. The overall effect of $F_x$ and $F_z$ is to bring the Au-NP to the bottom corners if it arrives at any location below the top surface of the nano-ring (i.e., $z < 35$ nm). These trapping locations are highlighted by two black dots in Fig. 3(b).

Because the nano-ring has multiple trapping zones as revealed in the above analysis, the total volume as well as surface area of the final optical trap will be enlarged substantially. For example, for any Au-NP at a distance of 30 nm from the nano-ring [see Fig. 3(a), $x = 80$ nm], it will experience a strong trapping force of 40 pN/W/$\mu$m$^2$, which corresponds to a trapping potential of $4.8 \times 10^{-21}$ J with an incident power density of 1 mW/$\mu$m$^2$. This is still larger than the kinetic energy of the Brownian motion. If we define the trapping boundary as $|U| = k_B T$ [4], that is, trapping potential having the same value as the Brownian motion, and the Au-NP can be trapped by the nano-ring whenever it is within the range of $|U| > k_B T$, we can readily obtain the size of the trapping volume. Figure 4 shows the electric field distribution in the $xz$ plane and the calculated trapping boundary (white circles). The trapping volume, which takes a symmetric shape for the structure considered, is of the order $10^6$ nm$^3$. This is $10^4$ and $10^5$ times larger than those of the silver nanoaggregates ($\sim 100$ nm$^3$) [4] and dipole antennas ($\sim 10^4$ nm$^3$) [3, 14] respectively. Such large active volume is very attractive for low-concentration operation as the trapping probability of NPs will be increased significantly. While trapping of a single Au-NP within a volume of 0.1 to 1 $\mu$m$^3$ has been reported previously [3], the large active volume from our nano-ring therefore may offer single Au-NP trapping a very low concentration of $10^{-11}$ to $10^{-12}$ mol/L. Potential applications including NP (or biomolecule-functionalized Au-NP) manipulation or detection with single-molecule sensitivity may become possible. Moreover, it is worth mentioning that our emphasis is on trapping of NPs, whereas previous work was mainly concerned with trapping of micro-PSs or yeast cells using microdisks [9, 10]. In addition, an array of the proposed nano-rings, apart from being capable of performing parallel trapping of many NPs, can trap micro-objects through a mechanism similar to the antenna case [1].

It is worth pointing out that large active volume always occurs within a wide spectral range as long as the resonance condition is fulfilled (as governed by the choice of dimensional parameters) because the enhanced volume is essentially due to strong field coupling between the inner and outer surfaces of the nano-ring (see Fig. 4). On the other hand, for antennas or nano-disks of the same size, the field is only localized within the gap or the outer surface without the presence of such coupling effects.

In conclusion, we have numerically demonstrated a gold nano-ring PNOT device operating at $z = 785$ nm for 3D optical trapping of Au-NPs. The device exhibits multiple trapping locations and has a very large active trapping volume of $\sim 10^6$ nm$^3$, thus providing effective manipulation of nano-objects at very low concentrations into the high-field region and offering application potential in the field of microfluidics and lab-on-a-chip for biodetection.

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