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Fano Resonance-Assisted Plasmonic Trapping of Nanoparticles

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Abstract Plasmonic optical trapping is widely applied in the field of bioscience, microfluidics, and quantum optics. It can play a vital role to extend optical manipulation tools from micrometer to nanometer scale level. Currently, it is a challenge to obtain the highly stable optical trapping with low power and less damage. In this paper, we propose Fano resonance-assisted self-induced back-action (FASIBA) method, through which a single 40-nm gold particle can be trapped in hole-slit nano-aperture milled on metallic film. It is used to achieve ultra-accurate positioning of nanoparticle, metallic nanostructures at wide infrared wavelength range, quite effectively and evidently. The stable plasmonic trapping is achieved by tuning the transmission wavelengths and modifications of nanoslit, indicating that the depth of potential well can be increased from minus 8KT to 12KT, with the input power of 10^9 W/m^2. This can be attributed to great modifications in Fano resonance transmissions according to self-induced back-action (SIBA) theory. The results are basically helpful to facilitate the trapping with lower power and less damage to the objects, which enables new scenario for the treatment of undesirable spread of a single nanoscale creature, such as virus.

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Optical trapping has been used for the placement and three-dimensional manipulations of micrometer-sized objects such as particles, cells and bacteria [1]. Optical trapping is helpful for sorting in microfluidics channels and it plays a key role in the development of future integrated analytical platform, known as "lab-on-a-chip" [2]. The recent efforts turned towards the near-field trapping properties of plasmonic nanostructures, which are known as new developments in the field of plasmonic optical trapping [3]. Plasmonic trapping typically relies on evanescent waves around nanostructures within tens or a few hundred nanometers, which produces localized intensities to enhance the optical trapping forces in nanoscale. However, in some cases where manipulations of temperature-sensitive objects (biological samples) are needed, as high power beam cannot be used. Therefore, methods that enable stable trapping with extremely low input intensity are needed. In recent years, self-induced back-action (SIBA) was newly demonstrated using a nano-aperture in a metallic film, which could generate great trapping forces with a low input power [4]. SIBA trapping relies on high sensitivity of the aperture transmission to surroundings characterized by their dielectric permittivity [5]. The presence of nanoparticle can evidently modify the effective refractive index of surroundings within the aperture, leading to the great modification of aperture transmission. As a result, the momentum of transmitting plasmonic photons interacting with the particle experiences considerable changes as the particle moves inward and outward in the trap zone, in which the particle is trapped and leads to automatic positive back-action trap [2, 6]. The SIBA effect accepts capable and efficient trapping of 100- and 50-nm polystyrene particles with low incident laser powers, showing a notable characteristic as compared to previous conventional optical trapping [7–9]. However, previous investigations on SIBA trapping focus on few incidents of wavelengths for certain nanostructures. Wavelength tunabilities of SIBA trapping in a wide wavelength range, which holds potential in applications of plasmonic trapping with different kinds of lasers, are still an unrevealed topic.

Recently, it has been proved that the Fano peaks can be tuned flexibly in a wide IR wavelength range. This approach emphasis on the plasmon overlapping between superradiant (discrete mode) and subradiant (continuum mode), which could be a new idea for stable trapping applications [10]. Moreover, the Fano transmission peak is highly sensitive to modify its surrounding medium, which has shown great applications in all-optical switching and sensors [11]. SIBA highly relies on the modification of transmissions in nano-aperture with the presence of gold particle. It is reasonable for tunability of nano-aperture with Fano resonance properties and could contribute to a more efficient trapping with a low input power in an IR wavelength range. Fano resonance-assisted self-induced back-action (FASIBA) mechanism provides superior stable plasmonic trapping for nanoscale particles, with improved performance as the model size is modified with infrared wavelength tunabilities. However, the potential interest of optical trapping based on SIBA mechanism with respect to the Fano resonance is not completely understood and deserves to be studied more deeply as it may give rise to interactions of different nature with the possible observations of new plasmonic optical trapping phenomena, which could be important from both scientific and technological aspects.

In this paper, self-induced back-action (SIBA) trapping of gold nanoparticle with radius of 40 nm relying on Fano resonance is studied within IR wavelength range to obtain stable optical trapping. This plasmonic trapping mechanism is developed by subwavelength metallic nano-aperture based on FASIBA that is carefully analyzed. Induced methods allow potential well with considerable depths to realize strong trapping. Using this approach, nano-aperture has been used to trap particles with a diameter of 40 nm.

By means of finite element method (FEM), the near-field optical trapping properties of hole-slit nano-aperture milled on a gold film are theoretically studied. Firstly, we built the geometry of hole-slit nano-aperture surrounded by ambient medium. A perfect matching layer (PML) is set at the outer region of geometrical hole-slit nano-aperture, through which the scattering light from the aperture is absorbed without any reflection. The Helmholtz equation is used in this complete geometry for describing the near scattering field within the hole-slit nano-aperture geometry. The Helmholtz equation is discretized at every mesh point to form a large sparse matrix and in final phase, we obtained the numerical solution of the Helmholtz equation through FEM technique. The boundary condition at the interface between the nano-aperture and ambient mediums is treated as superradiant one. The incident wave is along the Z direction, which is vertical to the surface of the gold film (shown in Fig. 1a). The schematic illustration of hole-slit nano-aperture is also shown in Fig. 1a. “*R*” is the radius of the nano-hole, and “*W*” and “*L*” are the width and length of the nanoslit, respectively. *R* and *W* are set to be constants at 100 nm and 150 nm throughout the paper. L is considered as variation to modify the optical trapping properties such as the potential well and resonance wavelength. The hole-slit nano-aperture is immersed in water, which is the utmost possible case for optical trapping of living cells in tissues. The background refractive index was 1.33 here for water medium.

In Fig. 1b, it shows two schematic illustrations. The left one shows the e-field distribution of the hole-slit nano-aperture embedded with a gold nanoparticle. Moreover, the right one is compared without the presence of a nanoparticle. It is revealed that the interactions between light and hole-slit nano-

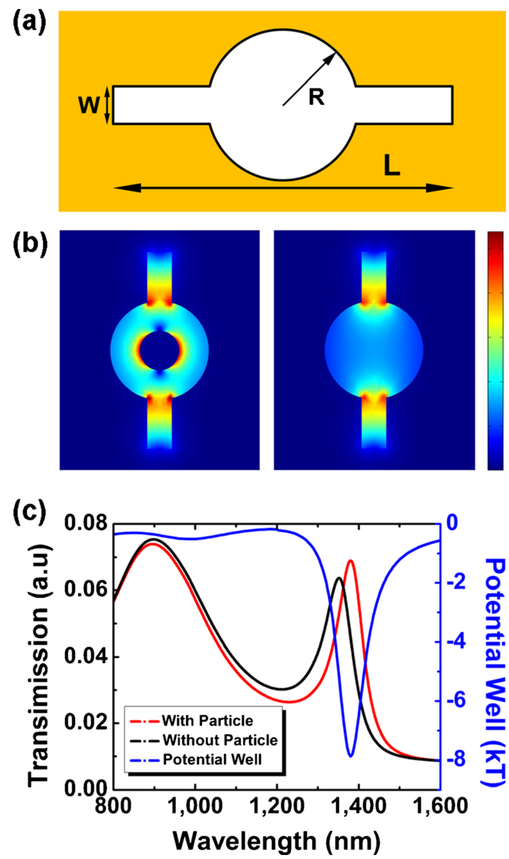

Fig. 1 **a** Sketch of characterization and the main parameter of the nanostructure of hole-slit nano-aperture. *R* = 100 nm, *W* = 150 nm, “*L*” is variant (400–550 nm). The direction of the incident light is vertical to the surface. **b** Calculated electric field distribution in nano-aperture with nanoparticle (*left*) and without nanoparticle (*right*). **c** Transmission spectrum of hole-slit nano-aperture and the depth of trapping potential well (*blue line*) depending on the incident wavelength. The *red line* indicates the Fano resonance profile with nanoparticle and *black line* indicates the Fano resonance profile without nanoparticle. The radius of the gold nanoparticle r is 40 nm, the input power *P* is 10^9 W/m^2, and the illumination is polarized along Z direction

aperture shows a unique ability to curb light into subwavelength-scale region and strong near-field distribution around plasmonics geometry. It shows potential in trapping nanoparticles in subwavelength scale, which will be explored in detail in the following section. It is clear that there is a stronger electric field of hole-slit nano-aperture with a nanoparticle comparing it without the presence of nanoparticle, because of plasmon interaction between F-P mode [12, 13] in hole-slit nano-aperture and a dipole mode of nanoparticle. Interestingly, it indicates that the e-field distributions depending on the presence or absence of a nanoparticle will lead to the modification of the transmission spectrum of Fano profile, which has been shown in Fig. 1c. By carefully designing the parameters of the size of both nanohole and nanoslit, the broad superradiant (hole) and narrow subradiant (slit) plasmon modes can overlap and give rise to strong asymmetric Fano line, which appears in the transmission e-field of hole-slit nano-aperture. With the presence or absence of the nanoparticle, the Fano resonance shift with respect to transmission is measured within the wavelength range of 1300 nm to 1400 nm. Owing to the presence of nanoparticle and its strong impact on the aperture resonance, the Fano line (red) has an evident red shift from 1350 nm to 1380 nm. Fano resonance in the past demonstrated with different nanostructures for realizing tunable of Fano resonance, such as using nanoslit [14] and nanowire timers [10, 15]. In addition, it is observed that significant attribution to the plasmon interactions between nanoparticle and nano-aperture for the stronger transmission peaks with the presence of nanoparticle is compared with the absence of nanoparticle. Interestingly, the induced Fano peak shift allows the presence of the nanoparticle within the trap because the presence of a nanoparticle in the aperture regime can be trapped by changing the strong e-field transmission of hole-slit nano-aperture based on the self-induced back-action (SIBA) theory [4]. Trapping efficiency increases by proper engineering of the plasmonic modes. The deepest potential well is minus 8KT under the wavelength of 1380 nm. Because the potential of depth is capable of stable plasmonic trapping when it reaches to minus 10KT, according to the related reference [2], the model is applicable for efficient trapping approach.

The Fano resonance related transmissions peak of the hole-slit nano-aperture with respect to the modification of the length of the nanoslit "*L*" is shown in Fig. 2. Fano resonance profiles of the hole-slit nano-aperture with nanoparticle (red line) and without nanoparticle (blue line) are both specified. It is observed by different transmission spectrums that peak shift induced by plasmon interaction between aperture and nanoparticle is more clearly defined and strongly related to the length of the nanoslit. With the increasing length of nanoslit "*L*" from 400 nm to 550 nm, the transmissions peak of Fano resonance varies in the infrared wavelength range from 1380 nm to 1880 nm. The transmission spectrum of hole-slit

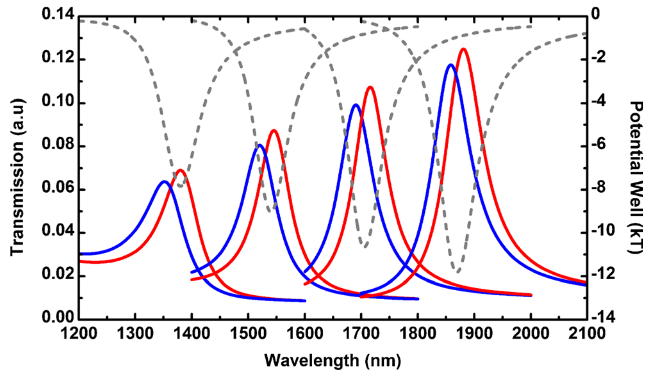

Fig. 2 The transmission spectra (*red line* for that with the presence of nanoparticle and *black line* for that with the absence of nanoparticle) and trapping potential well (*dash line*) of hole-slit nano-aperture depending on the length of nanoslit, "*L*" changing as 400 nm, 450 nm, 500 nm and 550 nm from left to right. The radius of the gold nanoparticle r is 40 nm, the input power P is 10^9 W/m^2 and the illumination is polarized along Z direction

nano-aperture can substantially be modified with the absence or presence of nanoparticle. Comparing the absence of nanoparticle, with the Fano resonance profiles of transmission spectrum exhibits red shift of approximately 30 nm as the presence of nanoparticle, due to the strong plasmon interaction. In addition, the transmissions with respect to the resonance wavelengths exhibit an evident increase from 0.07 to 0.13 with increasing "*L*" from 400 nm to 550 nm. The result shows that Fano resonance can be excited and effected by the aperture-particle interaction in a wide wavelength range in IR area. The potential wells can also correspond to Fano resonances with different lengths of the nanoslit with respect to the change of "*L*". Considerable potential well exists at the wavelength range where an abundant shift of transmission spectrum happens. Moreover, by increasing "*L*", the depth of the potential also increases from minus 8KT to minus 12KT, which could be attributed with the increasing of transmission spectrum and more evident Fano shift. The results illustrate that as the Fano peaks, the potential wells depth proportional to transmission spectrum can be tuned continuously by the length of nanoslit, which shows strong applicabilities in the wide infrared wavelength range.

The detailed information about stable plasmonic trapping properties of hole-slit nano-aperture with different geometrical parameters are also examined. Figure 3 shows the wavelength with respect to the deepest potential well, namely, the peak trapping wavelength, and the corresponding well depth as a function of the length nanoslit. The length of the nanoslit, "*L*," is tuned from 400 nm to 550 nm. With an increased length of the nanoslit "*L*," peak trapping wavelength is evidently red-shifted from 1380 nm to 1880 nm. A linear fit can be obtained between peak trapping wavelength and the length of nanoslit. The results show that considerable potential well can be recognized from 1380 nm to 1880 nm by tuning "*L*," indicating great advantages in realization of optical trapping instrument

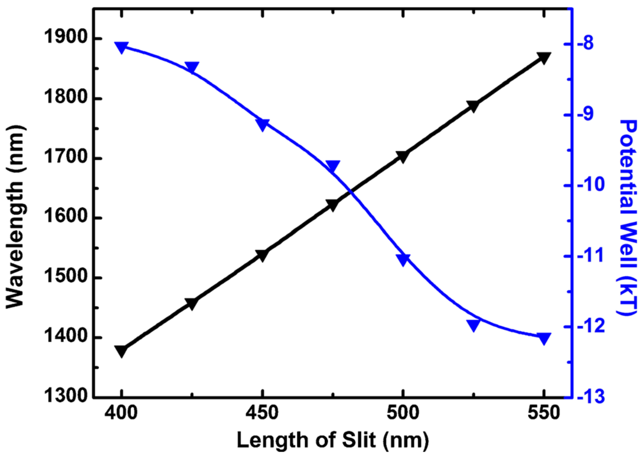

Fig. 3 Peak trapping wavelength (*black line*) and the corresponding potential well depths (*blue line*) are a function of the lengths of slit. The length of slit "*L*" varies from 400 nm to 500 nm. The radius of hole "*R*" and the width of slit "*W*" contains to be at constant in this paper of 100 nm and 50 nm, respectively. The radius of the gold nanoparticle r is 40 nm, and the input power *P* is 10^9 W/m^2

in a wide IR wavelength range. The evident tunabilities of the trapping peak wavelength can attribute to the tunable Fano resonance as well as to the transmission spectrum which is shown in Fig. 2. The trapping forces become stronger with increasing of "*L*." It can be observed that by tuning the length of nanoslit from 400 nm to 550 nm, the depth of potential well can be increased from minus 8KT to minus 12KT. With the input power as low as 10^9 W/m^2, considerable potential well can be acquired, indicating that this type of trapping forces are strong enough to confine particle precisely in water media within a wide IR wavelength range.

In conclusion, self-induced back-action (SIBA) trapping of metallic nanoparticle based on Fano resonance is studied. Stable plasmonic trapping of metallic nanoparticle can be recognized in a wide IR wavelength range, which could be attributed to the prominent modification of the Fano transmission spectrum based on SIBA theory. Peak trapping wavelength can be tuned flexibly by changing the length of the nanoslit "*L*" due to the great tunabilities of the Fano resonance in hole-slit nano-aperture. This method allows considerable depth of potential well with different "*L*" to realize stable plasmonic trapping with very low input power. The results can be important for understanding and recognition of optical trapping properties for hole-slit nano-aperture geometry. This type of trapping enables new opportunities of plasmonic optical trapping and develops a significant tool in the field of microfluidics and routing of single cell. This work also promotes the wide range of applications for sensors to trap nanoscale creatures and inspection of biological nanoscale entities, such as viruses.

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