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Dressing plasmon resonance with particle-microcavity architecture for efficient nano-optical trapping and sensing

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We propose a particle-microcavity scheme for efficient optical trapping and sensing. When a resonant plasmonic nanoparticle (NP) is placed inside a microcavity with high Q -factor, sensitivity is enhanced in the far-field extinction while near-field around the NP is barely affected. Stable near-field and high sensitivity for optical trapping and ultrasensitive detection of nanosized targets are therefore realized simultaneously. Such a particle-microcavity system opens up a new hybrid nanophotonic device platform that combines the unique merits of conventional and plasmonic integrated photonics. © 2014 Optical Society of America

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Probing and capturing of very small particles or sensing minute variations of optical properties is one of the grand challenges of biophotonics and nanophotonics [1]. Because of collective oscillations of free electrons, surface plasmons generate confined electromagnetic (EM) resonances, which give rise to important applications, such as sensing [2] and trapping [3]. Conventionally, plasmonic sensing measures the shift in resonance in either two-dimensions (Kretschmann configuration [4]), or one-dimension (nanowires [5]). On the other hand, localized plasmon resonance (LPR) in a metallic nanoparticle (NP) yields the zero-dimensional sensing because of its capability for high spatial resolution detection [6]. In fact, LPR-based nanosensors may also serve as nanotweezers, if we can make use of the gradient field associated with localization. Clearly, it becomes very attractive if one can perform both trapping and sensing simultaneously at the same site [3]. In this Letter, we show the conditions for having such dual-function particles, sensing-trapping (ST) NP.

Most LPR-based nanosensors employ spectral interrogation by monitoring the spectral shift of the resonance ($\Delta\lambda$) caused by changes in the effective refractive index (Δn) of the environment. To maximize detection sensitivity, current efforts are focused on optimizing the NP itself (material, shape, size, etc.). However, the overall performance of the sensor, evaluated by the figure-of-merit (FOM), is primarily limited by the broad resonance linewidth. To further improve the performance of nanosensors, Maier *et al.* took the approach of placing a NP on a dielectric Fabry–Perot cavity, which is formed between the top and bottom surfaces of a thin film, to modify the Q -factor [7]. However, in their experiment, based on dark-field spectroscopy, the NP merely served as a scattering center for directing light into the far field. Changes inside the thin film resulted in a shift in the spectral characteristics of the Fabry–Perot cavity and was detected by

analyzing the far field spectrum. However, the feature of high spatial resolution detection, aimed at probing local information, was not truly realized. On the other hand, Zhang *et al.* demonstrated simultaneous trapping and sensing of 10-nm-NPs using ST NP [8]. Two optical beams were used separately for trapping and spectral interrogation. Interestingly, the concepts of trapping and sensing are seemingly contradictory from the viewpoint of resonance. LPR-based tweezers should work best at a wavelength that induces near-field resonance, as this will result in the highest gradient force for trapping. On the other hand, a good sensor should produce as large a resonance shift as possible upon capturing a target. This also renders detuning of the resonant wavelength for trapping. Although ideally the intrinsic dual functions of ST-NP can be realized with a single beam, for ordinary ST-NP with high sensitivity, these paradoxical requirements certainly have deleterious effects on trapping performance. Consequently, the only solution is either to use two light sources with each taking care of trapping and sensing separately, or to compromise the linewidth of the ST-NP system.

In this Letter, we propose a hybrid ST-NP configuration in which the ST-NP is placed in an external cavity comprising a split microring. We call the split microring a “dressing” device. Modification of the LPR of the ST-NP is hence termed as “dressing plasmon resonance [9].” Instead of spectral shift, the proposed ST-NP monitors the intensity variation ΔI of the extinction. Compared with the dual beam configuration, our scheme results in higher FOM. More importantly, the structural configuration in our design enables a single monochromatic beam for the ST-NP system. Our scheme also enables real LPR-based sensing in nanometric scale, as compared with a reference [7].

A schematic of the device is illustrated in Fig. 1. An ST-NP (silver NP with radius of 25 nm) is placed at

Fig. 1. Schematic of the hybrid ST-NP configuration. The microring has a height of 180 nm, a gap width of 120 nm, and an outer and inner radii of 0.9 and 0.5 μm , respectively. The silver ST-NP has a radius of 25 nm. The incident cone of light is used for dark-field spectroscopy.

the center of a nanosized detection volume, around which, a dressing ring (with a refractive index of 1.7–2.0) is constructed to serve as a cavity. The dark-field spectrum of the structure is calculated using finite-difference time-domain method [10]. A linearly polarized total-field/scattered-field plane wave illuminates the ST-NP and the detection volume from top at normal incidence. A surface monitor parallel with the ring is placed directly below the gap for scattering calculations. A 3D surface enclosing the detection volume is set up to calculate absorptions. The scattering and absorption of the structure could then yield the corresponding extinction spectrum. A point monitor is placed 2 nm away from the vertex of the ST-NP (in the y -direction) to record near-field amplitudes. Dielectric permittivities of gold or silver are taken from those reported by Johnson and Christy [11]. It is assumed that the whole structure is immersed in water. For high simulation accuracy, local sub-grid meshing of up to 20 cells is applied in critical meshes, where appropriate.

Figure 2 shows sensing responses from the two configurations: (i) bare ST-NP and (ii) ST-NP with dressing ring cavity. The ring is made of Si_3N_4 , which has a refractive index of 2.0. In both cases, the sensing event involves

Fig. 2. (a) Extinction spectra of the C + ST-NP + NP and C + ST-NP systems with the dressing ring index $n = 2.0$. (b) Extinction spectra of the ST-NP and ST-NP + NP systems; inset shows the ST-NP's near-field distribution in the equatorial plane parallel with the substrate.

the trapping of a gold NP with a diameter of 10 nm. For simplicity, we abbreviate (i) the bare ST-NP sensor with a trapped NP as the “ST-NP + NP” and (ii) the ST-NP in dressing ring cavity case as the “C + ST-NP”, so that (iii) “C + ST-NP + NP” represents the ultimate case of NP being trapped and sensed by a C + ST-NP system. The extinction spectra are calculated by eliminating the intrinsic extinction of the gap from their respective overall extinctions and then normalized to the minimum intensity reference in the spectral range. As seen from Figs. 2(a) and 2(b), the dressing cavity has introduced a series of peaks in the spectrum of the extinction intensity (I). On the other hand, Fig. 2(b) shows that, when a NP is trapped by a simple ST-NP system, the extinction peak changes slightly. However, Fig. 2(a) shows that the C + ST-NP configuration exhibits a much larger extinction intensity change (ΔI) caused by the trapped NP. In a typical dual-beam trap-and-sense setup, the determining factor of sensing performances concerned with relative extinction intensity variations, i.e., $\Delta I/I$. Therefore, to make a fair comparison between sensors, we adopt the FOM in terms of $\Delta I/I$ [12]. Calculation reveals a FOM of 7.30 for the C + ST-NP + NP system compared with the bare ST-NP case at the wavelength of 410 nm [normalized to the value of $\Delta I'/I'$ in Fig. 2(b)]. For single-beam operation in the C + ST-NP system, ΔI is much larger. Compared with the case of bare ST-NP (intensity change denoted as $\Delta I'$), C + ST-NP offers 6.83 times higher sensitivity (i.e., $\Delta I/\Delta I'$). Actually, the oscillating behavior of Fig. 2(a) originates from a discretization effect imposed by the ring resonance modes on the single peak profile of Fig. 2(b). In Fig. 2(b), the left half of the curve shows little intensity difference between the two systems, thus revealing negligible changes when the dressing ring is added. Note that the peak positions are solely related to the frequency selection outcome upon fulfilling the dressing ring's resonance conditions. Even though the trapped small NP will introduce a slight redshift in the extinction peak, as shown in Fig. 2(b), the resonance peaks of the dressed system do not exhibit any horizontal shift. The near-field distribution of a ST-NP system is shown in the inset of Fig. 2(b). The distribution and value of the EM field are in line with results from Mie theory [13].

Figures 3(a)–3(c) show another group of extinction spectra for the C + ST-NP + NP and C + ST-NP cases with the refractive index of the dressing ring taking values of $n = 1.9, 1.8$, and 1.7 . Figure 4(d) shows the near-field amplitude of the C + ST-NP system. We observe that the waveguide mode becomes more confined as the refractive index of the dressing ring increases, thus resulting in stronger cavity resonances, and as evidenced by the periodic peaks. The peaks within the ST-NP extinction spectrum as well as the near-field response have now become more pronounced. For a bare plasmonic NP system, it is generally accepted that the far field extinction peak coincides with the resonance of the near field (~ 410 nm). However, as shown in Figs. 3(a)–3(d), this is not the case for a complex system. The reason is that, for smaller ring indices, poor mode confinement in the dressing ring requires that the NP scatters more light into the ring, resulting in larger ring assisted extinction. This requirement cannot be fulfilled at its near-field resonant wavelength

Fig. 3. Evolution of extinction spectra of the C + ST-NP + NP and C + ST-NP systems with the refractive index of the dressing ring (a) 1.9; (b) 1.8; (c) 1.7; and (d) near-field amplitude of the C + ST-NP system (data recorded by the point monitor).

where is of the best photon confinement. FOM at 410 nm are calculated and labeled in Figs. 3(a)–3(c). Applying the $\Delta I/\Delta I'$ operation, we also get a sensitivity ratio of 4.6, 3.7, and 3.1, respectively.

The enhanced ΔI for the proposed C + ST-NP configuration can be straightforwardly explained by the Purcell effect [14]. The famous Purcell factor characterizes the enhancement of emission rate of a spontaneous emitter inside a cavity and is given by $F_p = 3\lambda^3 Q/4\pi^2 n^3 V$ (where λ is the wavelength, n is the refractive index of the environment, and Q and V the quality factor and mode volume of the cavity, respectively). The Purcell effect was originally introduced from its classical counterpart [14]. The emission rate is proportional to the local density of states (LDOS) while the LDOS is proportional to the power emitted by the source. Therefore, the Purcell factor of a specific structure (i.e., the dressing ring in our case) is calculated as the ratio of emitted power by a dipole source (i.e., ST-NP) when the structure is inside an environment and when the structure is absent from the environment. This effect has been discussed from both classical and quantum mechanics viewpoints, with both arriving at the same conclusion [15,16]. In the case of the hybrid ST-NP sensor, change in the Purcell factor accounts for the enhancement of extinction variation, given by the relation, $\Delta I \propto (\Delta[F_p(\text{ext}_{\text{ST-NP}} - \text{abs}_{\text{ST-NP}}) + \text{abs}_{\text{C+ST-NP}}]/\Delta n_{\text{eff}})$, where $\text{ext}_{\text{ST-NP}}$ and $\text{abs}_{\text{ST-NP}}$ are extinction and absorption of the ST-NP, respectively, hence their difference is equal to the power scattered by the ST-NP (extinction = scattering + absorption); $\text{abs}_{\text{C+ST-NP}}$ is the absorption of the dressed ST-NP; Δn_{eff} represents the differential induced by the trapped NP to n_{eff} , and n_{eff} is the effective index of the optical configuration around the scattering object. Since $\text{ext}_{\text{ST-NP}}$, $\text{abs}_{\text{ST-NP}}$ and $\text{abs}_{\text{C+ST-NP}}$ are almost constant with respect to small Δn_{eff} . For a dressing ring with certain refractive index,

the relation becomes $\Delta I \propto (\Delta F_p/\Delta n_{\text{eff}}) = (\lambda^3 Q/n_{\text{eff}}^4 V)$; namely, for certain wavelengths, the extinction variation is inversely proportional to n_{eff} but proportional to the factor Q/V . Note that n_{eff} of the ring takes a value that is equal to the ratio between the propagation constant of the mode and the wave vector in vacuum, and is obtained from simulations. Its value is different for each mode, and depends on the index of the environment. Figures 4(a) and 4(b) show the different Q -factors and mode profiles of the ring cross section at 410 nm for a ring (without NPs) with indices of 2.0 and 1.9, respectively. The mode pattern and the total mode volume in the ring (V) is calculated using the Marcattili method [17]. Thus, the ΔI values (normalized with ΔF_p) can be calculated as shown in Fig. 4(c). It can be seen from our simulation results that both ΔI and Q/V increase with increasing ring index. As the Q -factor of the dressing ring increases, the presence of Purcell effect becomes more evident, and the two curves overlap more with each other. In this sense, further optimization is expected to be possible if the ring has higher Q or higher coupling efficiency with the NP's scattering characteristics.

The dressing ring produces much larger changes (ΔI) to the far-field extinction, while imposing little impact on the near-field of the dressed plasmon resonance. This is due to the fact that the same resonance-induced current radiates a different amount of power, depending on the surrounding geometry. The resonant LDOS of the whole system relies not only on the plasmon, but also the contributions from environmental “dressing.” During the trap-and-sense operation, spectral shift is no longer a required parameter for the proposed C + ST-NP system. With the near-field LPR wavelength remaining almost constant, the trapping force can always be kept at its strongest level. The insets in Figs. 1(b) and 4(d) show the near-field distributions of the bare ST-NP, C + ST-NP, and C + ST-NP + NP systems at the same resonance

Fig. 4. Resonance spectra and mode profiles from a cross section of the ring when the refractive index of the ring is (a) 2, and (b) 1.9. (c) Extinction variation ΔI calculated from simulation (black) and analysis (red), with values of Q/V factors and n_{eff} for rings with different refractive indices also listed as (Q/V , n_{eff}). (d) Local-field distribution pattern at the middle section of C + ST-NP and C + ST-NP + NP systems.

wavelength (410 nm). The induced trapping force is proportional to the gradient of the electric field intensity [18] and given by the equation

$$F_{\text{grad}} = \frac{1}{4} \alpha \nabla E^2,$$

where $\alpha = 4\pi a^3 \epsilon \epsilon_0 (\epsilon_{\text{NP}} - \epsilon / \epsilon_{\text{NP}} + 2\epsilon)$ is the polarizability of the target with a radius a , ϵ_{NP} and ϵ are the relative permittivity of NP and surrounding, respectively, and ϵ_0 is the absolute permittivity of vacuum. The values of ϵ_{NP} and ϵ do not change much between ST-NP + NP and C + ST-NP + NP configurations, even though their far-field behaviors have changed significantly; hence, ensuring stable F_{grad} as well as other scattering/absorption forces [19] for robust trapping.

In conclusion, we propose and investigate a hybrid ST-NP configuration. The introduction of an external cavity, which takes the form of a dressing microring, will greatly enhance the sensing performance of the ST-NP in terms of far-field radiation modulation. The dressing ring cavity offers a sensitivity FOM, defined as $\Delta I/I$, of 10 after trapping a target NP. This design has made it possible to obtain a sensing signal through detecting intensity changes rather than spectral shifts. Consequently, one can perform sensing and stable trapping simultaneously with a single monochromatic beam, thus greatly reducing the complexity of the final optical design. To our best knowledge, this is the first time the Purcell effect has been used for analyzing the characteristics of a nanophotonic sensing system. Without loss of generality, the proposed hybrid configuration is a versatile platform for coherent coupling between photonic and plasmonic resonances and possibly provides a new design strategy for integrated plasmonic-photonic devices. More importantly, specific opportunities also exist for high sensitivity LPR-based sensing with nanometric spatial resolution.

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