Active control over nanofocusing with nanorod plasmonic antennas

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Abstract: Active control over light nanofocusing in a nanorod plasmonic antenna coupled to a photonic crystal cavity is proposed and demonstrated by means of full-vectorial 3D simulations. By varying the excitation of the cavity with laser beam spot size allows us to achieve a gradual control over light nanofocusing at the tip of the nanoantenna. The demonstrated control mechanism eliminates the need for nonlinear effects or mechanical reconfiguration and represents a step towards the implementation of reliable tunable subwavelength light sources.

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References and links

1. Introduction

Plasmonic nanoantennas [1] attract an increasing interest in nanophotonics due to their demonstrated capability to support surface plasmon polaritons (SPPs) and confine light into ultra-small volumes much beyond its free-space wavelength [2, 3]. Analogous to their radio and microwave counterparts [4], plasmonic nanoantennas efficiently convert free-propagating radiation to subwavelength-confined energy and vice-versa. Nanoantennas of various geometries have been applied successfully in nonlinear optics [5], nonclassical light emission [6], fluorescence enhancement [7], high-harmonic generation [8], nanoscale photodetectors [9] and single-molecule detection [10].

Of special interest for spectroscopy, optical communication, sensing and quantum information systems is active control over subwavelength optical fields. Depending on the application, nanoantennas are aimed to be spectral-tunable, directional-reconfigurable, and also capable of controlling light intensity at the nanoscale at will. Spectral tunability, variable directionality and related control mechanisms have been proposed and demonstrated in the optical, infrared and terahertz ranges. In the optical range, the control over plasmon resonances can be achieved by exploiting nonlinear optical effects in nanogap [11] and nanosphere-chain [12] antennas, planar metal-film structures [13] and hole arrays [14]. For single metal particles, ultrafast heating and coherent vibrations of small metal nanoparticles give rise to a spectral shift in plasmon resonances [15]. In the terahertz range, the conductivity of semiconductors can be used to control the transport of terahertz waves using coupling to plasmonic modes on surfaces and nanostructures [16].

These effects are however not efficient enough for full-optical control at practical pump powers and, more importantly, they do not offer any reliable mechanism for efficient control over light intensity in nano-hot-spot regions of nanoantennas. It hampers the implementation of nanoantennas in practice in situations where the hot-spot intensity may be critical and control...
over the intensity is highly desired.

In this paper, we propose and explore theoretically a plasmonic nanorod antenna capable of offering active control light enhancement at the tip. The nanoantenna is excited by an intermediate photonic crystal (PhC) cavity that ensures an optimal light-nanoantenna coupling [10] and allows tuning of light enhancement at the tip of the nanoantenna by altering cavity-mode excitation conditions. As the cavity without the nanoantenna sustains Fano resonances resulting from interactions between the continuum and the localized cavity states [17, 18], the physics of resonances is understood in the framework of the Fano theory applied to PhC cavities [19, 20] and the optimal agreement with experimental data in [19] is observed. These results are then applied to the hybrid antenna-cavity architecture and active control over the nanofocusing is demonstrated.

2. Design and numerical tools

The investigated architecture [see Fig. 1(a)] consists of a PhC nanocavity and a nanorod gold antenna precisely placed on the backbone of the nanocavity. The nanocavity is formed by missing three holes along the Γ-K direction of a triangular lattice of air holes in a Si$_3$N$_4$ dielectric membrane (100 nm thick, dielectric constant $\varepsilon = 4$ in the visible range). The lattice constant $a$ is 250 nm, and the hole radius $r$ is 0.3$a$. The efficiency of light enhancement at the tip of the nanoantenna depends drastically on the shape of the tip. A related discussion goes beyond the scope of this paper and can be found elsewhere [2, 21, 22]. In this work, the total height of the nanoantenna is $H = 1\mu$m: a 900 nm-long cylindrical gold nanorod with a diameter of $D = 135$ nm and a 100 nm-long oval tip.

Calculations of the transmission spectra and spatial distributions of the electromagnetic fields are performed by means of a 3D finite-difference time-domain (FDTD) method enforced with Convolution–Perfectly–Matched–Layers (CPML) absorbing boundary conditions [23]. The dielectric function of gold used in the simulations is based on a Drude model fit for the published optical constants of gold [24]. A $x$-polarized point field source is used in the design procedure to excite the cavity.

Figure 1(b) shows the calculated spectral response of the nanocavity with (red-solid line) and without (blue-solid line) the plasmonic nanoantenna. When the nanoantenna is absent, a strong peak is observed at about 2.3 eV corresponding to the fundamental TE cavity mode. However, in the presence of the nanoantenna the peak is strongly suppressed indicating that the energy of the PhC cavity mode has been converted into an SPP mode of the nanoantenna. The $|E_z|$ field
distribution of the fundamental TE mode calculated in the middle of the PhC cavity without the nanoantenna at 2.3 eV is shown in Fig. 1(c).

3. Isolated cavity

Hereafter we assume that the fundamental cavity mode is strongly suppressed in the presence of the nanoantenna independently of cavity-mode excitation conditions. Thus, we start the investigation of the transmission properties of the PhC cavity without the nanoantenna first. We excite the fundamental cavity mode by linearly (TE) polarized laser beams of different spot radii. In the FDTD model the laser beam spot is controlled such that its radius $R$ can be gradually changed between $2a$ and $6a$, where $a$ is the lattice constant of the PhC. As the optical properties of all materials are intensity-independent, the simulated laser power $P$, which is a constant in all calculations, can be taken arbitrarily. Two examples of beam spot areas are shown in Fig. 1(c). They correspond to the two opposite cases when the laser beam fully covers the cavity region ($R = 2a$) and when it covers the whole PhC structure ($R = 6a$).

Figure 2 shows the transmission spectra (green-solid lines) calculated for $R = 2a$ and $R = 6a$. Both profiles exhibit asymmetric lineshapes; so do the profiles for other radii. This asymmetry can be fully explained in the framework of the Fano model [17]: it results from an interplay between a resonant transmission through the cavity and a nonresonant transmission through the PhC slab [19]. The ratio between the strengths of the resonant and the nonresonant components is known in the literature as the Fano asymmetry parameter $q$ [17]. We fit the calculated transmission spectra with the Fano lineshape and analyze the obtained results in terms of $q$.

According to [19], we use a Fano-fit formula $F(E) = A_0 + F_0 \left( 2 + 2i \frac{E - E_0}{\Gamma} \right)^2$, where $E_0$ is the resonance energy of the cavity mode, $\Gamma$ is the resonance linewidth, and $A_0$ and $F_0$ are constant factors. It produces best-fit curves and allows determining the values of $q$, $E_0$ and $\Gamma$ for $R$ varying between $2a$ and $6a$.

The best-fit curves for $R = 2a$ and $R = 6a$ are plotted in Fig. 2 with red-dashed lines. We see that the curve-fitting produces good agreement between calculated and fitted data. The same agreement is obtained for the excitation with other radii. The curve-fitting also shows that $q$ is related to the change in the excitation area defined as $\pi R^2$. In order to further demonstrate this relation, in Fig. 3(a) we plot the normalized asymmetry Fano parameter $q_N = \frac{|q|}{|q_0|}$ and the
Fig. 3. Fano model parameters obtained by means of the curve-fitting: (a) normalized Fano $q_N$ factor (blue circles) and normalized excitation area ($S_N$) (red-solid line), (b) resonance linewidth $\Gamma$, (c) resonance energy $E_0$ and (d) peak amplitude as a function of the spot radius $R$ (in periods $a$ of the PhC lattice).

normalized excitation area $S_N = \frac{R_2^2}{R^2}$, where $R_2 = 2a$ and $q_2 = q(R_2)$. In Fig. 3(a) we observe that the values of $q_N$ at $R = 2a$ and $R = 6a$ are in very close correspondence with the corresponding values of $S_N$. This result is in the best agreement with the experiment performed on the same PhC-cavity architecture [19] but designed for telecom wavelengths.

Figures 3 (b)-(d) show the resonance linewidth $\Gamma$, the resonance energy $E_0$ and the peak amplitude of the cavity mode obtained by means of the curve-fitting and plotted as a function of the spot radius $R$. The calculated resonance energies and resonance linewidths are almost independent of the excitation conditions. This feature was also observed in the experiment [19] together with a decay of the maximum peak amplitude caused by the beam defocusing. Our calculations correctly reproduce this decay [blue circles in Fig. 3(a)], which follows the $\frac{1}{R}$ dependence (black-dashed line).

4. Nanoantenna with cavity

Once the physics of the resonances of the isolated cavity has been understood under different excitation conditions, we return our attention to the cavity with the nanoantenna [see Fig. 1(a)] and demonstrate that light enhancement at the tip of the nanoantenna can be controlled by altering the excitation conditions of the PhC cavity. In order to prove that a control over light enhancement is only possible when the nanoantenna is excited by the cavity, we also investigate the enhancement at the tip of the same antenna but placed on an uniform 100 nm thick Si$_3$N$_4$ membrane.

We calculate field intensity profiles for the resonance energy value 2.295eV predicted with the Fano model [see Fig. 3(c)]. The intensity detected by a monitor located at the very tip of the nanoantenna is plotted in Fig. 4(a) as a function of $R$. Red circles denote the intensity of the nanoantenna excited by the cavity. Blue squares denote the intensity of the same nanoantenna placed on the uniform membrane. The results are normalized such that the intensity at the tip of the nanoantenna with the cavity at $R = 2a$ corresponds to 0 dB.

In the presence of the cavity [red circles in Fig. 4(a)] we observe a gradual decrease of the intensity at the tip of the nanoantenna caused by the corresponding change in $R$. This finding convincingly supports our assumption that light nanofocusing at the nanoantenna tip can be controlled by altering the excitation conditions. As shown in Fig. 4(a) with blue squares, in contrast to the nanoantenna excited by the cavity the excitation of the nanoantenna with the uniform membrane is significantly less efficient and the intensity at the tip decreases much faster. The comparison of the intensities at the surface of the tip of the both antennas for $R = 2a$ [Fig. 4 (b)] additionally demonstrates a poor performance of the nanoantenna without the cavity.
We notice that light nanofocusing can be controlled by varying the spot size of a laser beam under practical technical conditions. It is enough to defocus the beam up to \( R = 6a \) in order to obtain the intensity level of about \(-20\) dB and turn off the antenna.

The change of the Fano lineshapes influenced by the defocusing of the laser beam also offers a spectral tuning. In order to demonstrate it, we plot the intensity at the very tip of the nanoantenna as a function of the laser frequency. We limit ourselves to considering the spot radii of \( 2a \), \( 3a \) and \( 4a \). Further laser spot defocusing results in low intensity levels where spectral tuning is not worth the effort. Figure 4(c) shows that the maximum of the intensity can be shifted by \( \sim 1.7\) nm by changing the spot radius (compare 2.284eV for \( R = 2a \) and 2.291eV for \( R = 4a \)). The significance of this result achieved by simple defocusing can be better understood by comparing the efforts made to obtain this shift with the efforts in achieving a comparable shift with a 2D nonlinear PhC pumped by a high-intensity laser [25]. According to [25], a shift of 1.5 nm can be achieved by locally lowering the refractive index of the cavity by 0.23%, a value which is hardly attainable. The observed light-controlled frequency shift is also comparable to that obtained with a chain of metal particles embedded into dielectric shells made of a Kerr optical material [26].

5. Conclusions

We have demonstrated a novel control mechanism over light nanofocusing in a nanorod plasmonic antenna excited by an intermediate photonic-crystal resonator structure. The investigated nanoantenna is fully compatible with atomic force microscopy (AFM) and Raman microscopy. It opens up a number of significant opportunities for nanoscale analysis of biological substances, where the intensity of nanofocused light may be critical. We believe that the explored control mechanism has a considerable potential for applications in which reliable tunable subwavelength visible light sources are of utmost importance.
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