Optical tuning of near and far fields form hybrid dimer nanoantennas via laser-induced melting

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Abstract. Hybrid nanophotonics based on metal-dielectric nanostructures unifies the advantages of plasmonics and all-dielectric nanophotonics providing strong localization of light, magnetic optical response and specifically designed scattering properties. Here, we propose a new method for optical properties tuning of hybrid dimer nanoantennas via laser-induced melting at the nanoscale. We demonstrate numerically that near- and farfield properties of a hybrid nanoantenna dramatically changes with fs-laser modification of Au particle. The results lay the groundwork for the fine-tuning of hybrid nanoantennas and can be applied for effective light manipulation at the nanoscale, as well as biomedical and energy applications.

1. Introduction

The concept of hybrid nanostructure, utilizing the advantages of both plasmonics and all-dielectric nanophotonics, has recived heightened interest because of unique optical properties of such type nanostructures [1-3]. These properties strongly depend on the geometrical parameters of each constituent part and their relative position. Therefore, one of the most important research directions here is the development of fabrication methods which are still poorly developed [3]. The most common methods of hybrid nanostructures fabrication are the high-throughput wet chemistry preparation [3, 4] and combination of conventional methods of lithography [5, 6]. However, wet-chemistry methods suffer on the lack of spatial arrangement, whereas designs of highly ordered lithographically produced nanostructures usually are limited by geometrical properties of masks. Such limitations can be avoided by means of additional cost-effective postprocessing of lithographically produced hybrid nanostructures. One of the most promising post-processing technique is femtosecond (fs) laser heating by tightly focused beam, which has been successfully implemented for plasmonic nanoparticles reshaping accompanied by a strong change in their optical properties. [7].

Recently, we have developed a new method of tuning of non-symmetrical hybrid nanostructures [8]. The method is based on fs-laser melting of gold nanodisc placed on the top of truncated silicon nanocone. Silicon nanocone has electric and magnetic dipole resonances, whereas gold nanodisc has only electric one in visible range. Laser melting makes it possible to change the position of the plasmon resonance and adjust the properties of the whole hybrid particle.

Here, we apply this method for tuning of hybrid dimer nanoantennas. We demonstrate numerically that near- and far-field properties of a hybrid nanoantenna dramatically changes with fs-laser modification of Au particle.

2. Tuning of optical properties of hybrid nanostructures via fs-laser reshaping

For numerical simulations, we have choosen the assymetrical (not a core-shell structure) hybrid nanoantenna proposed and fabricated in [7]. This concept (gold nanodisk placed on the tip of silicon nanocone) has a several advantages. At first, these nanostructures can be fabricated via the sequence of fabrication steps including standart methods of lithography: e-beam lithography, metal evaporation, lift-off procedure, gas phase chemical etching. The selective fs-laser modification (reshaping) of the metal components of the hybrid nanoparticles without affecting dielectric ones is applied to complete the
Scattering spectra of hybrid dimer nanoantennas have been calculated in range of wavelength 420-1000 nm for different values of gold particles forms (see Figure.1). The distance between the axes of the hybrid nanoparticles is 100 nm in all cases. The first plot on the Figure.1 is the scattering spectrum of hybrid dimer nanoantenna without reshaping (gold nanoparticle has a disk shape). The second plot is the scattering spectrum of hybrid dimer nanoantenna with gold particles in the form of nanocup. The third plot is the scattering spectrum of hybrid dimer nanoantenna in the final stage of reshaping. It is seen that the scattering spectral dramatically changes with reshaping of gold particle in the hybrid nanoantenna. Under reshaping, the electric dipole resonance of Au nanoparticle (point A on the Figure.1, 1st plot) shifts to magnetic dipole resonance of silicone one. The scattering spectrum of the hybrid dimer nanoantenna with gold nanocups (see Figure.1, 2nd plot) is more difficult because of complex form of Au nanoparticles. In the Figure.1 on the right the electric field distribution for the hybrid dimer nanoantennas with varying degrees of reshaping are presented. We have observed an increasing of a local electric field in the gap of the hybrid nanoantenna. Thus we have shown that the fs-laser melting of hybrid nanoantenna makes it possible to tune its farfield and nearfield properties.

Let’s study the changing of local density of states (LDOS) caused by fs-laser melting of hybrid dimer nanoantenna. The normalized LDOS describes by Purcell factor which is a measure of so-called Purcell effect. The Purcell effect is defined as a modification of the spontaneous emission lifetime of a quantum source induced by its interaction with environment. For calculation of Purcell factor we have used the method of its extraction from an input impedance of small dipole antenna (1):

\[
F = \frac{R_{in}}{R_{0,in}} \equiv \frac{\text{Re}Z_{in}}{\text{Re}Z_{0,in}}.
\]
where $R_{in}$ is the resistive part of the input impedance of the small dipole in presence of hybride nanoantenna, $R_{0,in}$ is the same in free space [9].

We have calculated the Purcell factor in the wavelength range of 420-1000 nm for two cases of the small dipole located close to (i) a single hybrid nanoparticle (Figure 2a), and (ii) to the hybrid dimer nanoantenna (Figure 2b). The results are presented for two distances between the dipole and nanostructure of 30 nm and 50 nm (black and red curve, respectively). We have observed that the position of Purcell factor resonances changes after the modification of gold nanoparticles. The value of Purcell factor strongly depends on the distance between dipole and nanoantenna and the gold nanoparticle shape. Thus, we have shown that the fs-laser melting of hybrid nanoantenna makes it possible to tune its Purcell factor.

3. Conclusions
In conclusion, we have proposed a new method of optical properties tuning of hybrid dimer nanoantennas via laser-induced melting at the nanoscale. We have demonstrated numerically that near- and far-field properties of a hybrid nanoantenna dramatically changes with fs-laser modification of Au particle. We believe that the results lay the groundwork for the fine-tuning of hybrid nanoantennas arrays and can be applied for effective light manipulation, as well as biomedical and energy applications.

Acknowledgements
This work was supported by the Ministry of Education and Science of the Russian Federation (project №14.584.21.0009 with unique identifier RFMEFI58414X0009).

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