Manipulating Fano resonance via fs–laser melting of hybrid oligomers at nanoscale

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Abstract. Here, the novel concept of asymmetric metal–dielectric (hybrid) nanoparticles is proposed. The experimental data and the results of numerical simulation of the optical properties of hybrid nanostructures are presented. The change of their optical response after fs-laser modification is shown. The possibility of manipulating Fano resonance in hybrid oligomers by the gold nanoparticles reshaping is demonstrated.

1. Introduction

Metallic nanostructures have proved to be an efficient tool for light manipulation at nanoscale. While these structures have some well-known advantages, e.g. very strong field localization, subwavelength dimensions, etc. [1], the main problem that prevents realization of practical applications on their basis is severe losses, especially at optical frequencies [2]. On the contrary, low dissipation losses in dielectric nanostructures make them promising materials for light manipulation [3–5]. Moreover, optical nanostructures based on nanoparticles with high-refractive index exhibit both electric and magnetic responses, which makes it possible to control both electric and magnetic components, simultaneously. [6–7]. The use of metal and dielectric materials together in hybrid nanostructures and metasurfaces opens a wide range of perspective applications for medicine, photonics, photovoltaics, etc [4, 8–9]. Initially plasmonic and all-dielectric nanostructures have been studied separately and only recently the idea of hybrid nanostructures with advantages from both of them has been introduced [10–12].

The novel concept of asymmetric hybrid nanodimer and fabrication methods of such nanostructures have been recently developed [13]. Hybrid nanodimer includes silicon (Si) nanocone and gold (Au) nanodisc. Important feature of such nanostructure is the possibility of modification of Au nanodisc to nanosphere via fs-laser irradiation of nanodimer. At the same time Si nanocone is almost not exposed to any impacts of the fs-laser radiation. It opens great opportunities for the control of the properties of such hybrid nanodimers.

Here, we study optical properties of modified and unmodified asymmetric hybrid nanodimers. Moreover, we demonstrate numerically how fs-laser modification of metal nanoparticle affects the Fano resonance in oligomers consisting of hybrid nanodimers.


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2. Optical characterization of hybrid nanodimer

First, we fabricated an array of hybrid nanodimers by the method proposed in Ref. [13]. We used the same geometrical parameters of nanoparticles: the bottom base diameter of the nanocone and the diameter of the nanodisc are d = 190 nm, the height of the nanocone is h = 200 nm, the diameter of the top nanocone base is a = 50 nm and the thickness of the nanodisc is l = 20 nm. Then, we performed fs-laser post-processing of the array in order to modify the structures. In both cases (reshaped and unreshaped arrays) we applied the method of dark-field microscopy to obtain the scattering spectra of a single hybrid nanoparticle (**Figure 1**(a,d)). We used the software package CST Microwave Studio for numerical calculations of reflection spectra, power patterns (**Figure 1**(b,e)) and electric field distributions (**Figure 1**(c,f)).

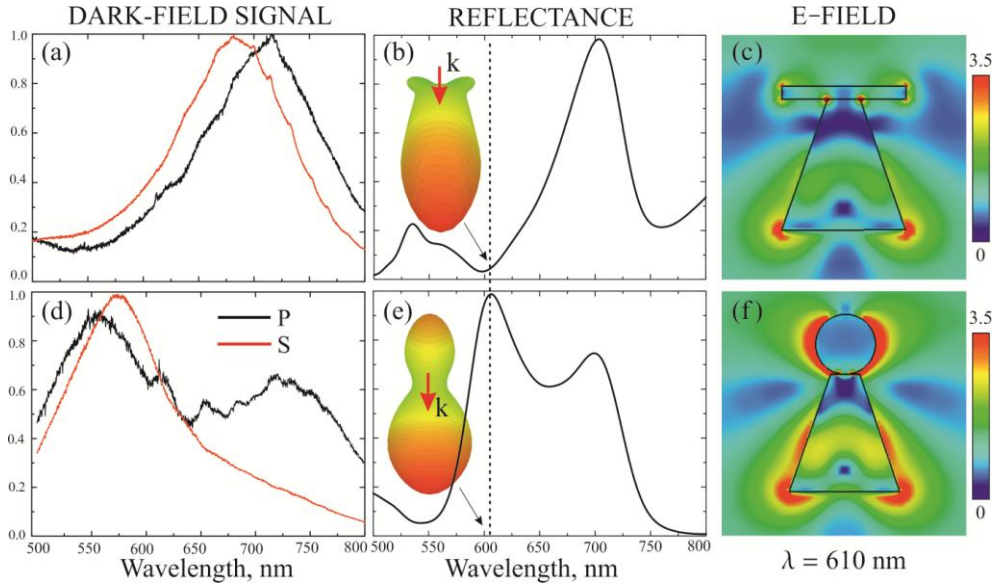

Figure 1. (a) Dark-field optical microscopy spectra for p- (black line) and s- (red line) polarized light; **(b)** Numerically calculated reflectance spectrum and **(c)** electric field distribution of the unreshaped hybrid nanodimer. **(d)** Dark-field spectra; **(e)** Reflectance spectrum and **(f)** electric field distribution of the reshaped hybrid nanodimer.

In case of unreshaped hybrid nanostructures, magnetic dipole resonance of silicon nanocone overlaps with electric dipole resonance of Au disk (**Figure 1**(a)). The light scattering by the Au nanodisc is dominant. The results of numerical modeling demonstrate that it appears in suppression of back reflectance from the structures at the wavelength of 610 nm (**Figure 1**(b)). Analysis of the electric field distribution of the unreshaped nanoparticle shows the absence of resonances at 610 nm (**Figure 1**(c)).In turn, the fs-laser reshaping of the gold nanodisc to nanosphere causes a shift of the electric dipole resonance of Au nanoparticle to the shorter wavelength region (**Figure 1**(d)). It changes the power pattern, which results in the apperance of the reflectance peak at the wavelength of 610 nm (**Figure 1**(e)). The electric field distribution at 610 nm confirms that the peak at this wavelength is caused by localized plasmonic resonance of nanosphere (**Figure 1**(f)).

Thus, we can tune the spectral position of the electric dipole resonance of Au nanoparticle as well as the power pattern of the hybrid structures. These results open the possibility of tuning the optical properties of hybride nanodimers and nanostructures.

3. Manipulating Fano resonance in hybrid oligomers

Then, we studied the optical properties of hybrid oligomers composed of reshaped and unreshaped nanodimers. The importance of all-dielectric and plasmonic oligomers has been recently discussed in works [14,15].

We considered six unreshaped hybrid nanodimers arranged in hexamer. The distance between the centers of the bottom bases of nanocones in this regular hexagonal structure is 200 nm. We carried out numerical simulation of the scattering spectrum of the hexamer by using CST Microwave Studio. The structure was excited by a plane wave along the axis of symmetry. The scattering spectrum of hybrid hexamer is shown in **Figure 2**(a). It is seen that magnetic dipole mode of Si nanocones is splitted into two broad low-Q magnetic modes as a result of interaction between nanocones.

Then, we simulated the hybrid nanodimer with smaller diameter of the bottom base of Si nanocone (d = 150 nm). The resonant wavelength of the dielectric nanoparticles is directly proportional to its size. Therefore, the scattering spectrum of the magnetic dipole resonance of a single nanoparticle is shifted to the shorter wavelength region relatively to the collective magnetic modes (**Figure 2**(b)).

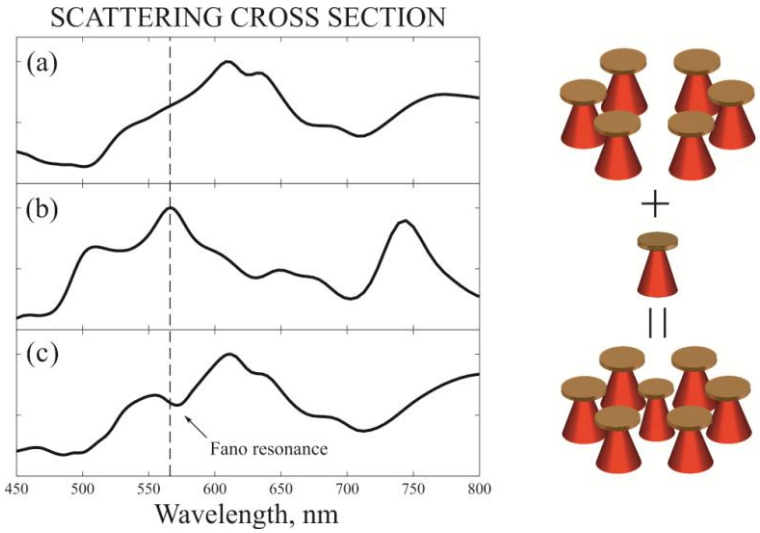

Figure 2. Numerically calculated scattering spectra of **(a)** hybrid gexamer, **(b)** single hybrid nanodimer and **(c)** hybrid oligomer.

Finally, we put nanodimer with a smaller diameter of the bottom base in the center of the hexamer. Numerically calculated scattering spectrum of such oligomer is presented in **Figure 2**(c). We observe that there is an asymmetrical Fano type resonance at the wavelength of the magnetic dipole resonance of the single nanodimer. Fano resonance in this nanostructure is caused by the existence of two scattering channels: scattering by the broad collective magnetic mode of hexamer and scattering by the narrow resonant magnetic mode of single nanodimer. Because of the spectral shift between the resonances of hexamer and nanodimer excited modes oscillate at the different wavelengths in the phase and antiphase. The minimum of Fano resonance in scattering spectrum at 572 nm is due to the destructive interference (**Figure 3**(b)), while the maximum at 553 nm is due to the constructive interference.

However, after reshaping of Au nanodiscs to nanospheres Fano resonance cannot be observed in the scattering spectrum (**Figure 3**(c)). It is caused by a shift of the electric dipole resonance of Au nanoparticles to the short wavelength region (**Figure 3**(d)).

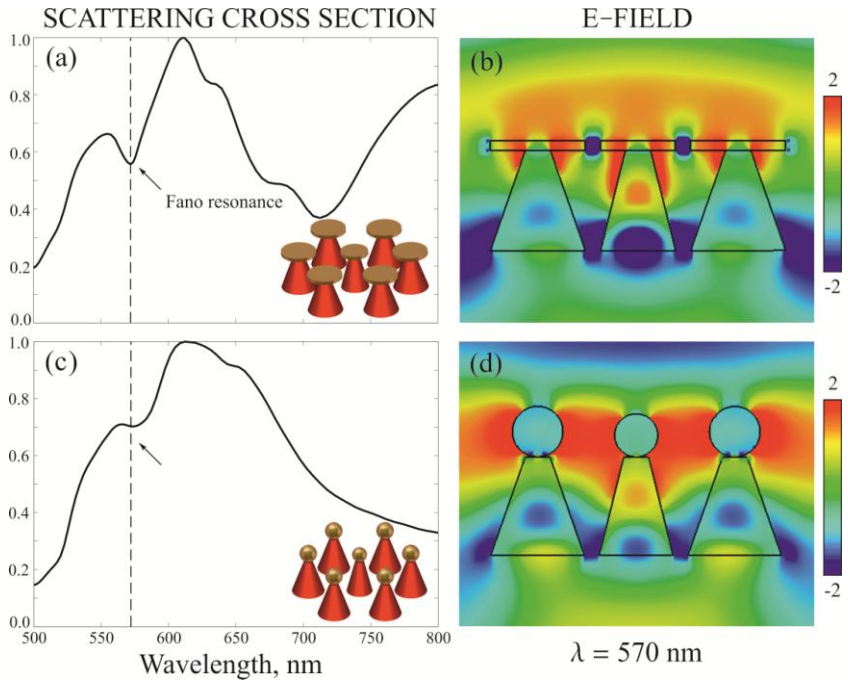

Figure 3. (a) Numerically calculated scattering spectrum and **(b)** electric field distribution of unreshaped hybrid heptamer. **(c)** Numerical calculated scattering spectrum and **(d)** electric field distribution of reshaped hybrid heptamer.

4. Conclusion

In summary, we have demonstrated the opportunity of Fano resonance tuning via fs-laser reshaping of Au nanoparticles in hybrid oligomers. Our results open a way for experimental realization of hybrid oligomers with specially engineered Fano resonances and for developing new switchable nanophotonic devices.

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