Dipole-quadrupole plasmon coupling and Fano resonance in nanorods of T-like configuration

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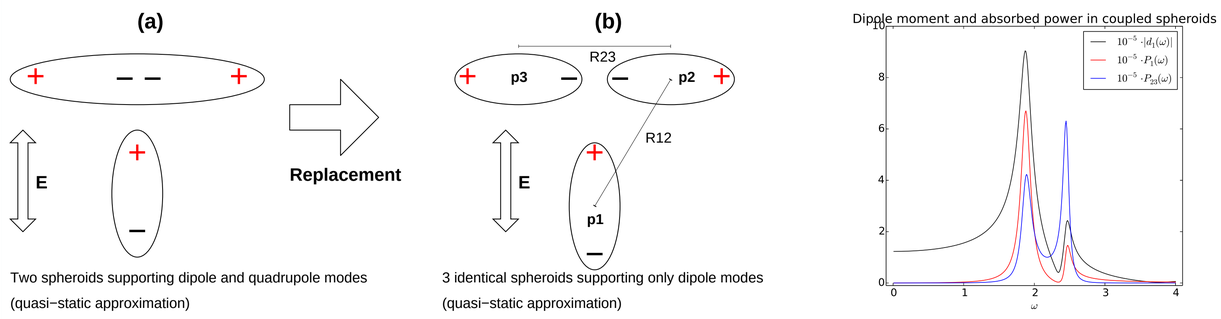
Introduction

- Fano resonances have been found in many plasmonic structures
  B. Luk'yanchuk et al., *Nature. Mater.* **9**, 707–715 (2010).
  B. Gallinet and O. J. F. Martin, *Phys. Rev. B* **83**, 235427 (2011).
  J. Zhao et al., *Adv. Mater.* **24**, OP247–OP252 (2012).
- Gold nanorods are one of the most versatile geometry of plasmonic nanostructures, which by adequate tailoring may present plasmonic resonances from visible to far IR.
  A. Melikyan and H. Minassian, *Chem. Phys. Lett.* **452**, 139 (2008).
  J. Perez-Juste et al., *Coord. Chem. Rev.* **249**, 1870 (2005).
- Fano resonances, arising by coupling between 1st and 3rd order multipoles plasmon modes, on spheroids and rods have been already investigated.
  F. López-Tejeira et al., *New J. Phys.* **14**, 023035 (2012).
  On the other hand, quadrupole and other multipole modes are not always excited, but only under some symmetry conditions.
  B. N. Khlebtsov and N. G. Khlebtsov, *J. Phys. Chem. C* **111**, 11516–11527, (2007).
- We propose a simple system for Fano resonance based on two rods and show how to tailor the particles in order to achieve the near-field coupling between a dipole mode and a quadrupole mode.

Fano resonance in spheroids: theoretical background

We consider T-like configuration with nanorods smaller than the wavelength to apply the quasi-static approximation [V. Klimov, *Nanoplasmonics*, Pan Stanford Publishing (2014).] and replace them by spheroids to describe plasmon modes analytically. To obtain the coupling conditions between the dipole and quadrupole modes of two spheroids in (a) we replace the top one by two shorter and identical spheroids (b).



The polarizabilities, dipole moment of the bottom spheroid and the absorbed powers read,

$$\alpha_1(\omega)=\varepsilon_0\frac{\varepsilon_1(\omega)-\varepsilon_m}{\varepsilon_m+\xi[\varepsilon_1(\omega)-\varepsilon_m]}V,\quad P_1(\omega)=-\omega\left|1+\frac{27}{8R_{12}^6}\frac{\alpha_1(\omega)\alpha_2(\omega)}{K}\right|^2E_0(\omega)^2\Im\{\alpha_1(\omega)\},\quad d_1(\omega)=\frac{[1+2\alpha_2(\omega)/R_{23}^3]\alpha_1(\omega)}{K}\varepsilon_mE_0(\omega)$$

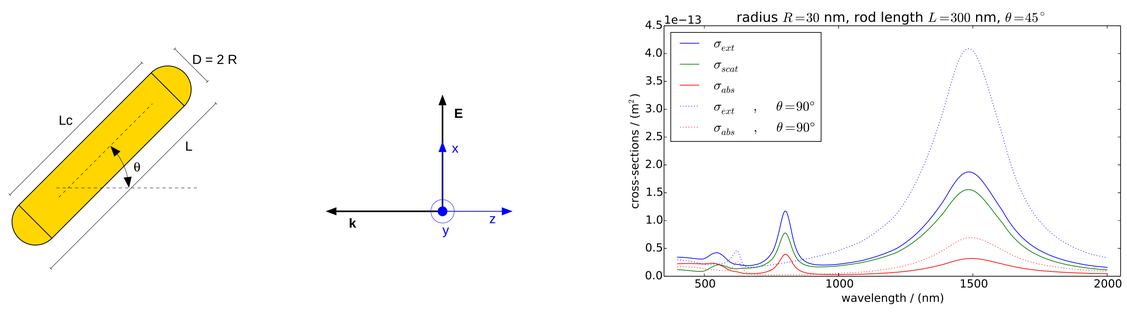
$$\alpha_2(\omega)=\varepsilon_0\frac{\varepsilon_2(\omega)-\varepsilon_m}{\varepsilon_m+\xi[\varepsilon_2(\omega)-\varepsilon_m]}V,\quad P_{23}(\omega)=-\omega\frac{27}{8R_{12}^6}\left|\frac{\alpha_1(\omega)\varepsilon_mE_0(\omega)}{K}\right|^2\Im\{\alpha_2(\omega)\},\quad K=1+\frac{2\alpha_2(\omega)}{R_{23}^3}-\frac{27}{8}\frac{\alpha_1(\omega)\alpha_2(\omega)}{R_{12}^6}$$

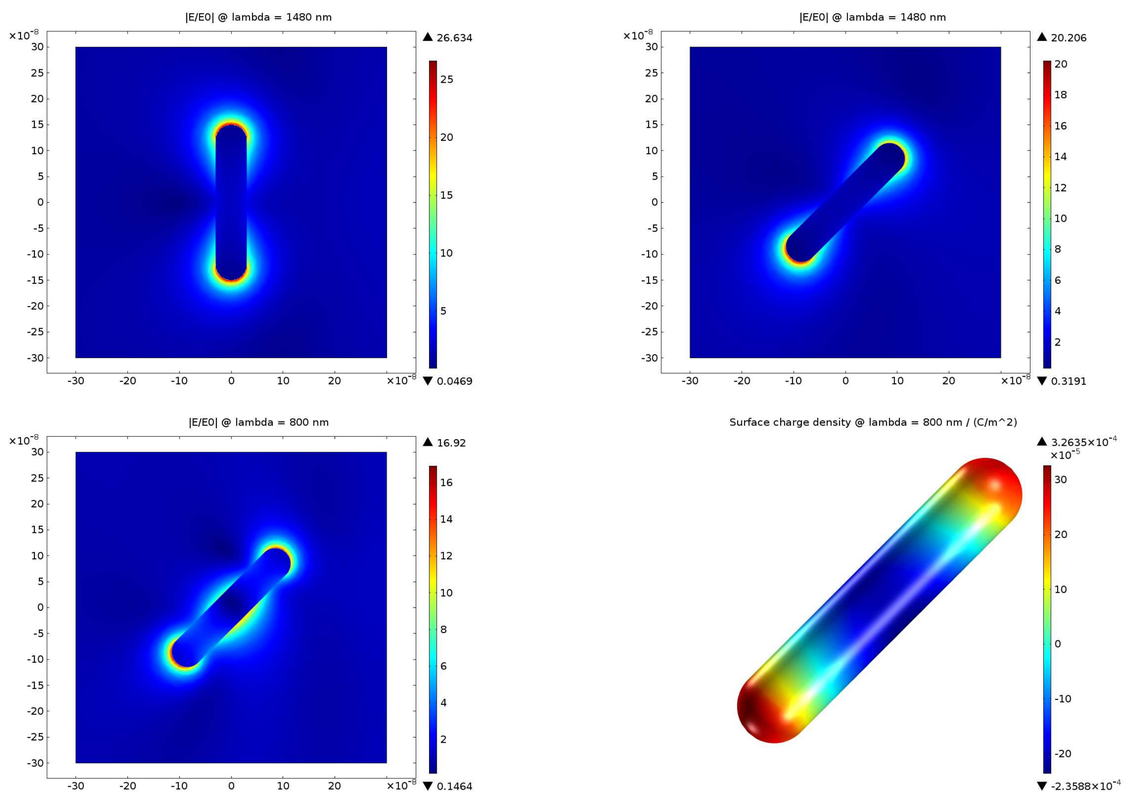
The plots at right showing a Fano resonance, were obtained for the following values of the spheroids: $a=b=10$, $c=20$, $E_0=1$, $R_{12}=R_{23}=60$, $\varepsilon_0=1$, $V=4\pi abc/3$. The plasma frequency and damping constants are $\omega_p=9$, $\gamma_1=0.2$, and $\gamma_2=0.07$, respectively. The dielectric functions are $\varepsilon_1=8-\omega_p^2/[\omega(\omega-i\gamma_1)]$ and $\varepsilon_2=8-\omega_p^2/[\omega(\omega-i\gamma_2)]$, and the parameter ξ is

$$\xi=\frac{1-e^2}{e^2}\left[-\frac{1}{2e}\ln\left(\frac{1-e}{1+e}\right)-1\right],\quad \text{with}\quad e=\sqrt{1-(b/c)^2}.$$

Gold rods and their multipole resonances

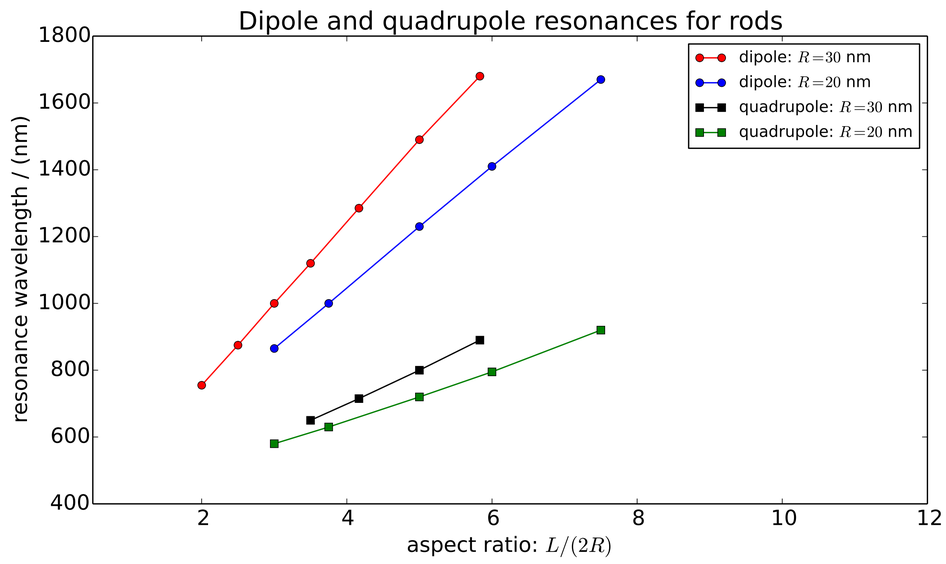
Multipolar resonances of gold rods were investigated solving Maxwell's equations without approximations using COMSOL Multiphysics (optical constants from Johnson and Christy). For the two symmetrical cases ($\theta=0°$) and ($\theta=90°$), either only the longitudinal dipole mode or the transverse mode are excited. For intermediate angles, in special $\theta=45°$, quadrupole or higher multipole resonances arise.





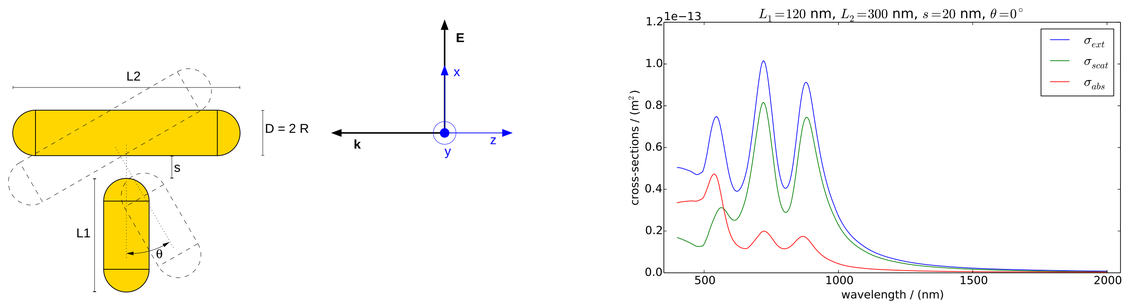
Tailoring rods size for dipole-quadrupole coupling

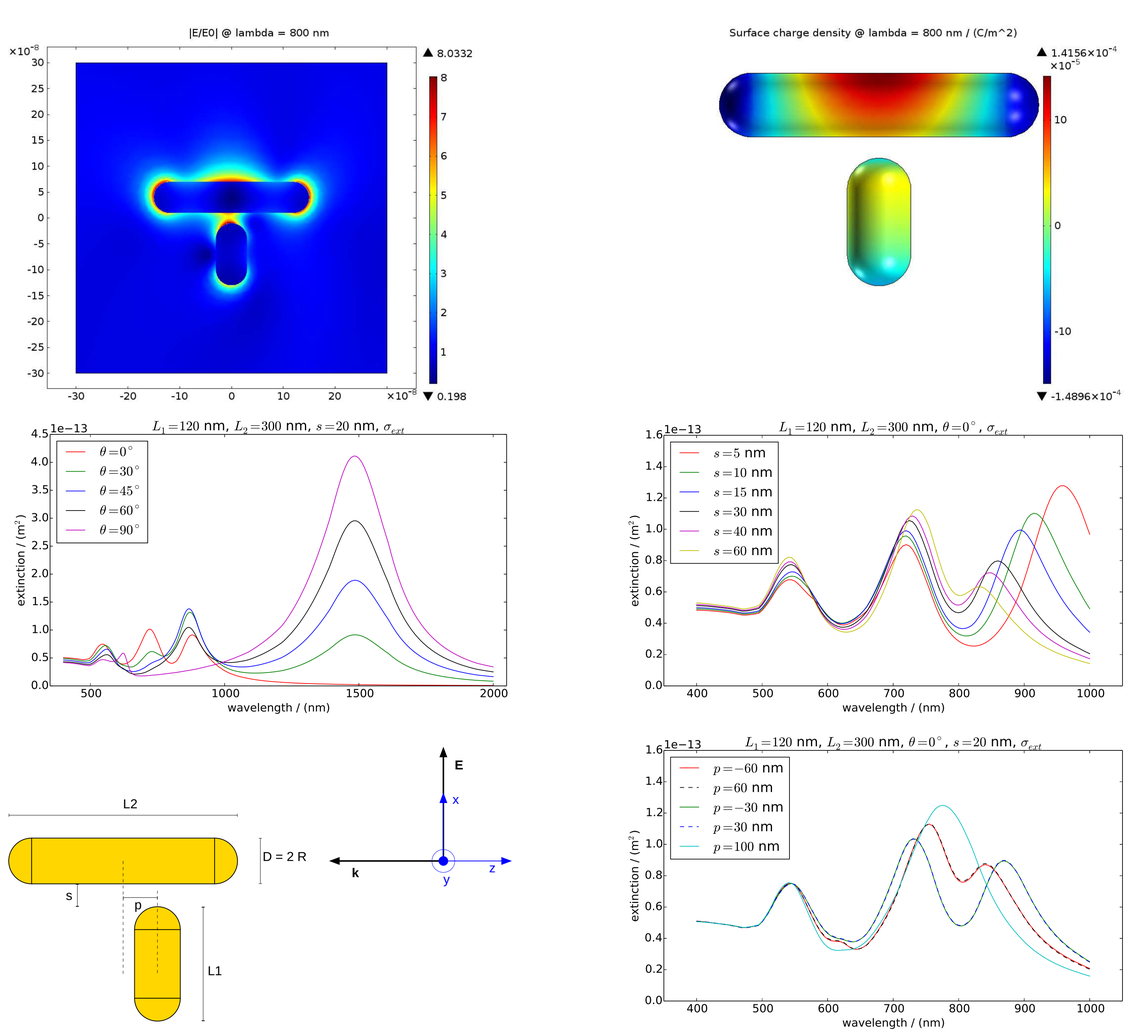
- The approximately linear dependence of the dipole and quadrupole resonances on the rod aspect ratio eases the selection of appropriate sizes to achieve near-field coupling between the radiant and sub-radiant modes.
- The points of the figure below are the peak of the resonances based on the calculations of the cross-sections using FEM.



Fano resonances in a T-like configuration of two gold rods

The T-like configuration of two rods of lengths $L_1=120$ nm and $L_2=300$ nm presents a well pronounced Fano resonance for $\lambda\sim800$ nm. At the Fano dip, the near-field coupling leads to a stronger electric field strength around the top rod.
We have investigated the dependence of the Fano resonance on the relative angle of incidence of the plane wave θ, on the interparticle separation s, and on the shift of the bottom rod away from the symmetry axis denoted by p. The Fano resonance is relatively robust, vanishing only for long s or p.





Conclusions

- Fano resonances in T-like configuration of gold nanorods arise due to near-field coupling between a dipolar and a quadrupolar mode, if the rod sizes are adequately tailored.
- At the Fano resonance the total extinction decreases and the near-field pattern is more concentrated at the top rod. The energy is transfered from the radiating dipole mode to a dark quadrupole mode.
- The T-like structure constitutes one of the simplest plasmonic systems presenting near-field coupling and Fano resonances in the visible and NIR and can be envisaged in sensing applications.
- Experiments using gold rods fabricated by electron-beam lithography and FIB are currently underway.

Acknowledgements

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