OBSERVATION OF FANO RESONANCE IN A DIMER BASED ON METALLIC NANOCONES

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ABSTRACT

Theoretical study of the plasmonic properties of two closely adjacent metallic nanoparticles has been investigated. The plasmon modes of the first nanocone couple primarily with the plasmon modes of the second nanocone due to which a broad peak and a narrow peak emerges in the extinction spectrum, which can be categorized as bright and dark plasmon modes. The coupling and interference between the bright and dark modes of the dimer results in a sharp Fano dip in the spectrum. The Fano resonance can be switched on and off either by changing the incident field polarization or the dimer separation. The dimer nanostructure may be used for applications like plasmon sensing, electromagnetic induced transparency (EIT), switching and surface enhance Raman spectroscopy (SERS).

Keywords: Plasmonics, dimer, plasmon hybridization, Fano resonance, dark mode.

1. INTRODUCTION

Surface plasmons, which are the electron oscillations in metal nanoparticles, excited by the electromagnetic waves are currently of great interest for a broad range of emerging applications from chemical and bimolecular sensing (Loo et al, 2005) to photo thermal cancer therapy (Gobin et al, 2007) to surface enhance Raman spectroscopy (Banaee & Crozier, 2010). When the two metal nanoparticles are placed in close proximities, their optical properties are highly changed because the plasmon resonances of both the metals couple together and forming new hybridized plasmon modes. The coupling and interference between the bright (finite dipole moments) and dark (zero dipole moments) modes results in Fano resonances in the optical spectrum, which are typically more sensitive to the nanoparticle shape and refractive index of the surrounding medium. This phenomenon was first realized by Ugo Fano in a quantum mechanical study of the auto-ionizing states of atom (Fano, 1961). Recently, Fano resonances have been realized in various plasmonic nanostructures such as ring/disk nanocavities (Han et al, 2009), multilayered nanoshells (Khan & Miano, 2011), (Mukherjee et al, 2010), nanoparticles on dielectric substrate (Zhang et al, 2011), dimers ((Banaee & Crozier, 2010), (Yang et al, 2011), trimmers (Sheikholeslami et al, 2011) and nanoparticle chains (Wang et al, 2011). The asymmetric Fano line shape may give rise to plasmon induced transparency, which is analogues to electromagnetic induced transparency (EIT) examined in atomic systems (Chen et al, 2011).

In this paper, we studied theoretically the observation of Fano resonance in plasmonic nanocone dimer. The plasmon coupling increases with the decrease of the gap between the two nanoparticles, which results in the red-shift of the modes and Fano resonance. The Fano resonance can be switched on and off either by changing the polarization of the incident light or by varying the interparticle gap. This kind of nanostructure has received a huge attention for surface-enhanced Raman spectroscopy applications due to the hot spot produced in the gap between nanoparticles when incident light is polarized along the dimer axis((Banaee & Crozier, 2010), (Yang et al, 2011), (Brown et al, 2010), (Hu et al, 2010).

The optical properties of the proposed nanostructure were carried out in COMSOL Multiphysics software with the RF module. COMSOL Multiphysics is a numerical simulation software based on Finite Element Method (FEM), which accurately solves electromagnetic problems at the nanoscale level. This software has been employed by several research groups working on plasmonic nanostructures (Khan & Miano, 2011), (Zhang et al, 2011), (Brown et al, 2010), (Hu et al, 2010), (Knight & Halas, 2008). For the far field optical properties, we used scattered field formulation. The 3D simulation space is composed of the dimer nanostructure surrounded by two spherical volumes: an embedding medium and a perfectly matched layer (PML). Discretization of the simulation space was performed using the built-in meshing algorithm in COMSOL, which divided the simulation space into a set of tetrahedral finite elements. The scattering spectra is calculated on spherical boundary enclosing the structure by integrating the time average radiated

field power density in the far- field region. The absorption spectra is calculated by integrating the time average resistive heating. The extinction spectra is obtained by summing the scattering and absorption spectra. Johnson and Christy data have been utilized for the dielectric constant of the gold (Johnson & Christy, 1972). The embedding medium considered is air.

2. RESULTS AND DISCUSSION

Figure 1 shows the schematic diagram of the gold homo nanodimer. The dimensions of the homo dimer are such that 'H' is the height, 'R' is the radius and 'α' is the semi angle. The gap between the two nanocones is 'G'. The illuminating electromagnetic wave is linearly polarized, the electric field is directed along x and the wave propagates in the z-direction.

2.1. Optical properties of the dimer:

Figure 2 shows the extinction cross section of the dimer for two values of G at fixed R/H = 50/60 nm, and $\alpha = 27^{o}$. For G = 6 nm (blue line), we obtained a single dipole peak near 620 nm, which is obtained by the interaction of the dipole mode of the first nanocone and the dipole mode of the second nanocone. In this case, the dimer acts as a monomer. By decreasing the value of G to 2 nm, the dipole peak red-shift to around 670 nm and a new peak emerges near 570 nm, which represents a quadrupole mode. Due to the near-field coupling between the dipole and quadrupole modes, a Fano resonance appears in the spectrum near 607 nm. Thus, by decreasing the value of G, the interactions between the two nanocones increases, which results in the emergence of higher order modes.

2.1.1. Plasmon hybridization

The plasmon interactions of the dimer can be understood by the plasmon hybridization model. Figure 3 shows the plasmon hybridization model of the dimer (top view). For large value of G, the interaction between the two nanocones are very week, which results in a small splitting of the plasmon mode into high energy antibonding modes and low energy bonding modes. Here the interactions will occur between the modes having same angular momenta. Therefore, the dipole mode of the first nanocone interacts with the dipole mode of the second nanocone. Similarly, the quadrupole mode of the first nanocone interacts with the quadrupole mode of the second nanocone and so on. The bonding plasmon modes have large dipole moments and are usually visualized as the surface plasmon resonant peak in the spectrum. On the other hand, the antibonding modes have a small dipole moment and cannot be visualized in the spectrum. By decreasing the value of G, different order modes will mix. For instance, the dipole mode of the first nanocone will not only interact with the dipole mode of the second nanocone but also with the higher order modes of the second nanocone like the quadrupole and octupole modes etc. The increased interactions will also red-shift the lower energy modes.

Figure 4 shows the extinction spectra of the dimer for different values of G. By decreasing the value of G, the dipole peak strongly red-shift and the higher order modes arises in the spectrum. Thus, the Fano resonance can be controlled by changing the value of G.

2.1.2. Effect of polarization

Figure 5 shows the extinction spectra of the dimer for two different polarizations at fixed G = 2 nm. The blue line corresponds to axial polarization where the incident field is polarized along the dimer axis, while the red line corresponds to transverse polarization where the incident field is polarized perpendicular to the dimer axis. For transverse polarization, we observed only a single dipole peak near 555 nm. The higher order hybridized modes remain absent in this case. So for the transverse polarization, the dimer acts as a monomer. Thus, the Fano resonance can be switched on and off by changing the polarization of the incident field due to which it may be used as photonic nanodiode in nanophotonic circuits.

3. CONCLUSION

We have investigated the optical properties of the dimer based on gold nanocones using plasmon hybridization model. The plasmon oscillations in a dimer can be increased by decreasing the interparticle gap due to which dark hybridized modes will appear in the spectrum, which couple to the bright mode and induces a Fano resonance in the extinction spectrum. The gap between the two nanoparticles can be changed to enhance and control the modulation depth of the Fano resonance. The dimer nanostructure is also found to be highly sensitive to the incident field polarization. The results obtained in this work open up the advantageous possibility of using the Fano resonance band for plasmon sensing, EIT, switching and SERS applications instead of (or together with) the conventional surface plasmon resonant peak.

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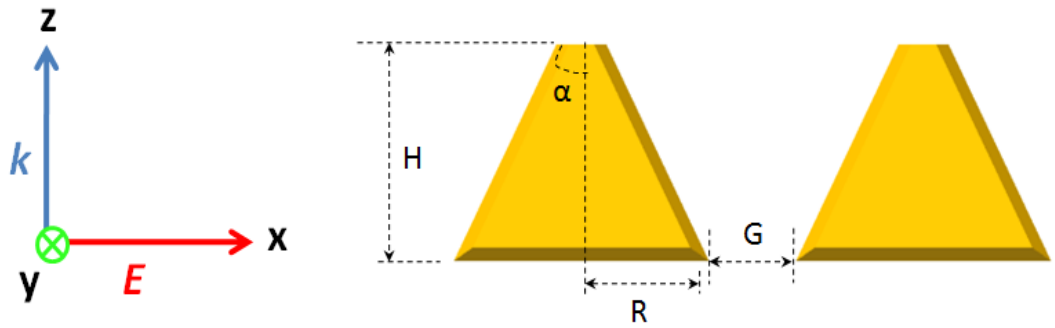

Fig 1. Schematic illustration of homo nanodimer. R and H shows the dimensions of the dimer. The incident field is polarized along x and propagates in z-direction.

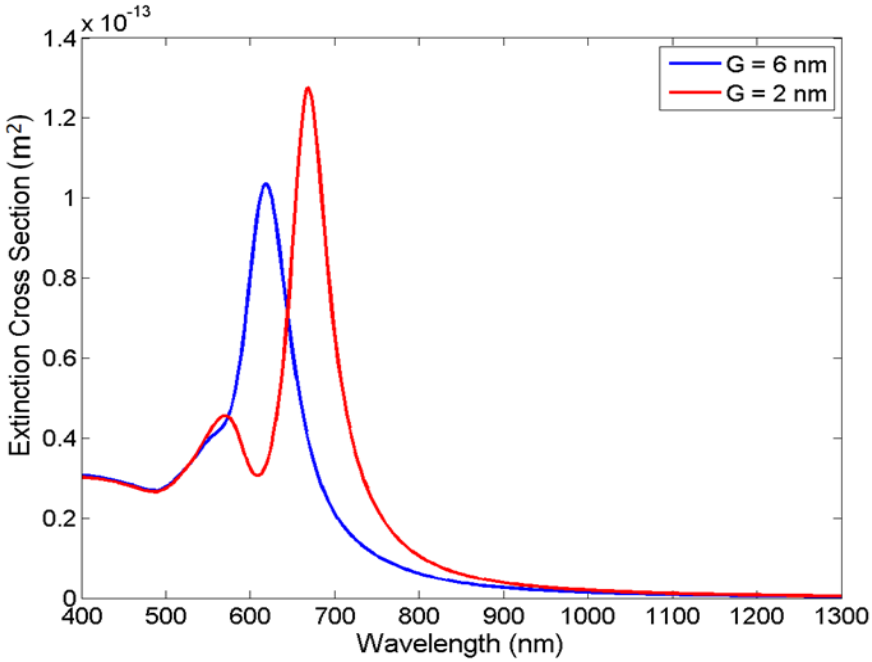

Fig 2. Extinction cross section of the dimer with G = 6 nm and 2 nm for longitudinally polarized incident field.

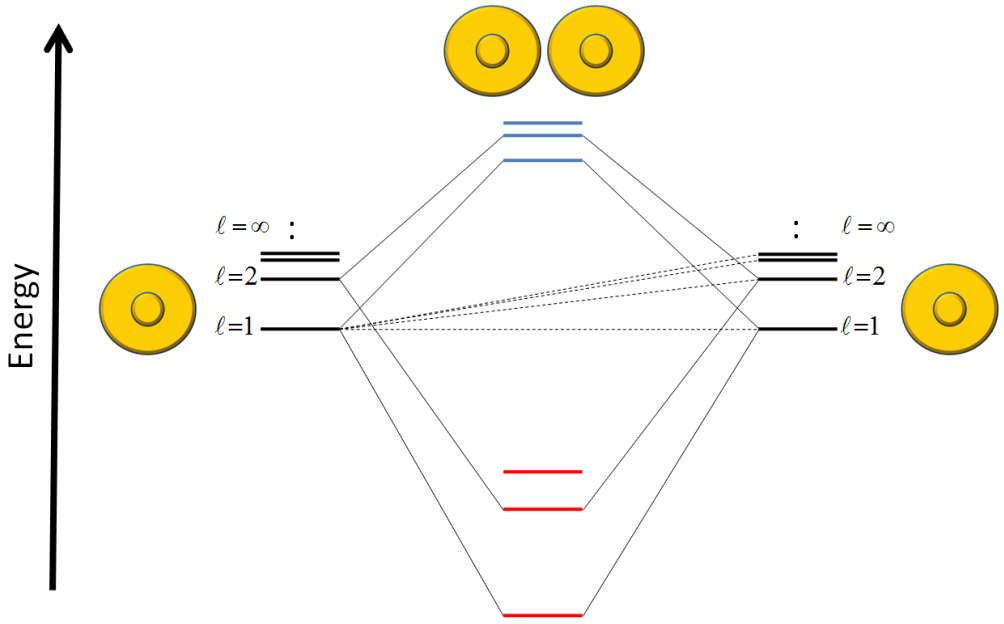

Fig 3. Plasmon hybridization model of the dimer with interaction between modes having different angular momenta. Energy increases from bottom to top.

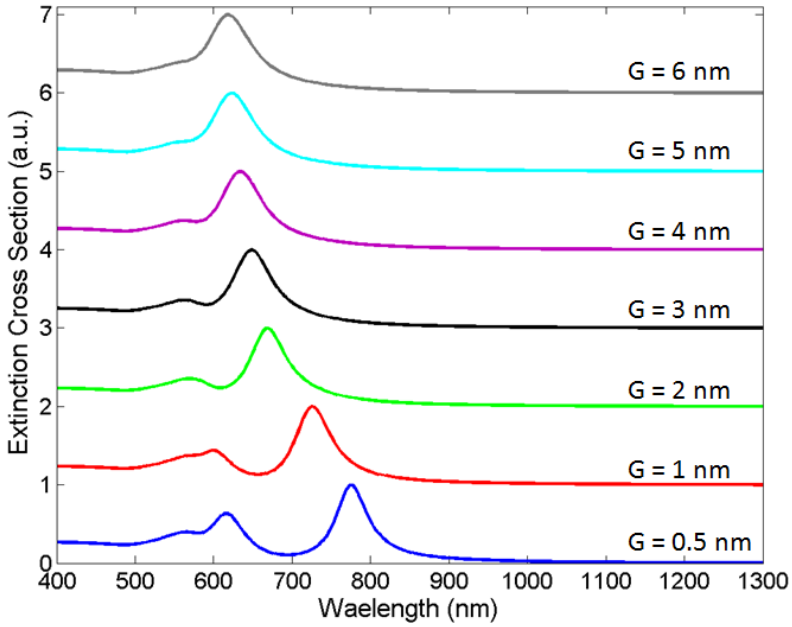

Fig 4. Extinction spectra of the dimer at different values of G for longitudinal polarization of the incident field.

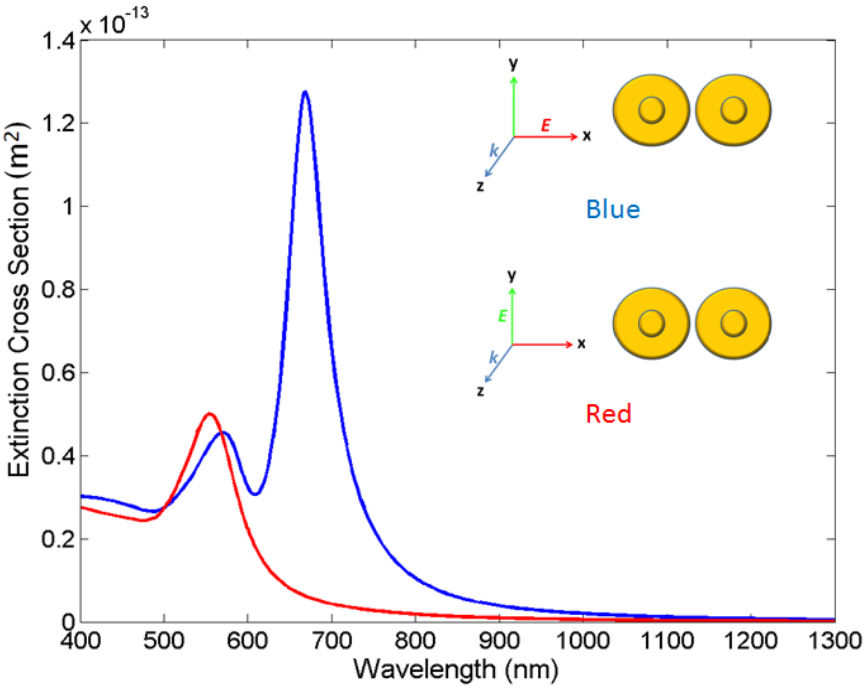

Fig 5. Extinction spectra of the dimer. Blue, incident light is axially polarized along the dimer axis. Red, incident light is transversely polarized with respect to the dimer axis.