Coupled Plasmon Hybrid Modes in Aggregates of Metal Nanowires

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***Abstract*— Investigation of the plasmonic resonances in aggregates of metal nanowires is presented. Mechanism of plasmonic mode coupling in a system of metal wires that can be considered as hybridization combinations of isolated wire plasmons is investigated.**

Keywords: surface plasmons; plasmon resonances; eigenfrequency; cluster

I. INTRODUCTION

Amazing advances in fabrication have spawned a widespread interest in nanotechnology which involves a broad range of disciplines. In particular, metallic nanostructures are the subject of immense interest in recent years due to the possibility of a strong light localization beyond the diffraction limit via the excitation of localized and surface plasmons (SP) [1]. For example in the review article of Mark Stockman [2] summarizes recent advances in nanoplasmonics. This field of research has recently exhibited the practical demonstration of many new and exciting concepts and emerged as an extremely promising technology with several main fields of application: information technologies [3, 4], energy, life sciences [5, 6] and security.

The interaction of metal nanostructures with light leads to the excitation of SPs with different resonance frequencies in the form of propagating waves or localized oscillations that associated with collective oscillations of the electrons. Most metals possess a negative dielectric constant at optical frequency as the plasma frequency of the conduction electron gas lies in this range. The noble metals (silver or gold) have been most closely used in plasmonics because their plasmon resonances lie close to the visible region of the spectrum and can be excited by ordinary optical sources. The plasmon resonances of nanoparticles with dimensions down to 2 nm can be investigated using classical Maxwell's theory [7]. When the illumination frequency passes nearby the plasma frequency of the metal the real part of the dielectric permittivity becomes negative and plasmon resonances can be excited. The plasmon frequencies are strongly dependent on the particle size and shape. The plasmonic modes of coupled nanoobjects can be considered as symmetric and antisymmetric combinations of plasmons of isolated objects with different frequencies and field portraits [8-13].

Plasmonic structures of different forms (nanowires, nanorods, nanospheres, nanoshells) can be produced by various fabrication techniques. If nanoparticles or nanowires are collected in an optically coupled assembly, the plasmon resonances split and their locations and strengths can significantly vary. Enhancement can occur if, additionally, such an assembly has an ordered structure. At present, the optical properties of single metal nanospheres and their clusters [14-16], nanospheroids [17], nanoellipsoids [18] and some other nanobodies [19, 20] have been studied well enough from an analytical point of view. Many other nanoparticles shapes and nanoparticle clusters have been investigated only numerically. Unfortunately, numerical simulations often do not allow us to gain an understanding of the physical nature of interesting and complicated phenomena in the area.

II. PROBLEM FORMULATION AND METHOD OF THE SOLUTION

In this paper, we consider plasmon resonances in a pair of wires and in a cluster of metal wires with triangular or square configuration. It is known that SPs can exist on a metal wire that can be considered as a plasma infinite-long cylinder (column) in the optical region. The radius of each wire is a; the separation distance between nanowires is d. Fig. 1, 2 and 3 represent the schematic diagrams of the structures with a pair of coupled metal wires and triangle/square clusters, respectively. Wires with ordinary nonmagnetic metal is characterised by a negative permittivity $\varepsilon < 0$. The frequency dependent plasma permittivity ε_p is described by the Drude model

$$\varepsilon_p = 1 - \omega_p^2 \cdot (\omega(\omega - i\gamma))^{-1}, \qquad (1)$$

Here ω_p represents the plasma frequency, γ is the material absorption. Sub-wavelength resonances are possible when $\varepsilon(\omega) < 0$ (or equivalently $\omega_p > \omega$), they are called plasmon resonances or surface plasmons. The ambient medium is free space. H-polarized fields are considered. We present the z-component of the internal field as

$$H(\rho_l, \varphi_l) = \sum_{s=-\infty}^{+\infty} K_s^{(l)} J_s(k_p \rho_l) e^{is\varphi_l} \qquad (2)$$

and the external field as

$$H(\rho_l,\varphi_l)=\sum_{l=1}^{N}\sum_{s=-\infty}^{+\infty} M_s^{(l)} H_s^{(2)}(k\rho_l)e^{is\varphi l}\,. \qquad (3)$$

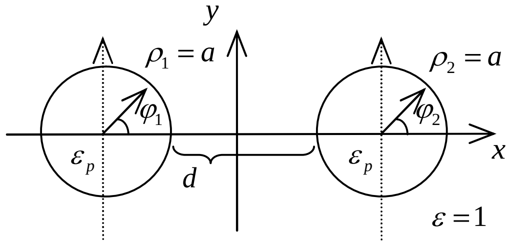


Fig. 1. Schematic diagram of the structure: a pair of metal wires.

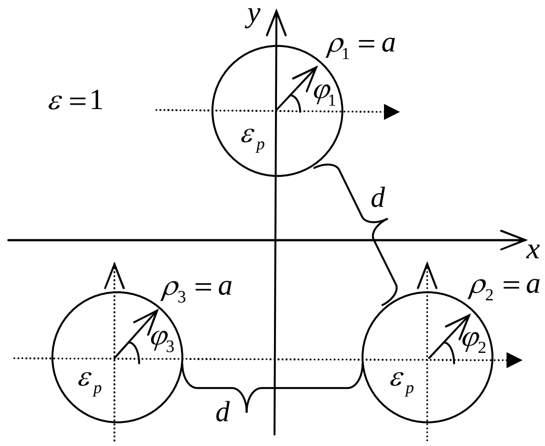


Fig. 2. Schematic diagram of the structure: a cluster of square configuration.

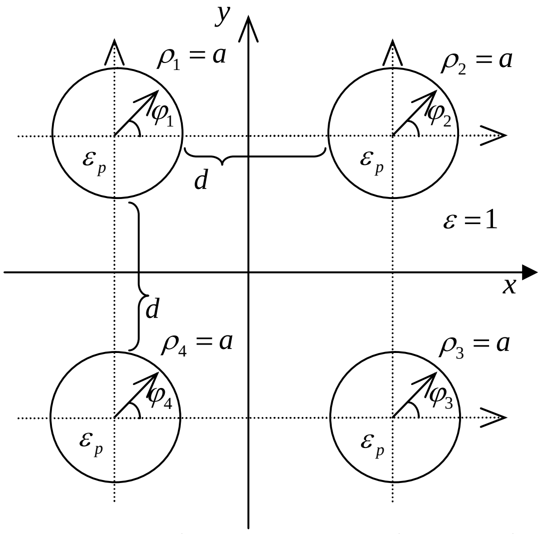


Fig. 3. Schematic diagram of the structure: a cluster of triangle configuration.

Here (ρ_l,φ_l) are set of N polar systems of coordinates ($N=2$, $N=3$ or $N=4$), associated with each cylindrical columns ($l=1...N$), $z-$axis is parallel to the cylinders, $k=\omega\cdot c^{-1}$, $k_p=n_p\omega c^{-1}$, c is light velocity in a vacuum, $n_p=\sqrt{\varepsilon_p(\omega)}$, $\varepsilon_p(\omega)$ is defined by formula (1), time dependence is $e^{i\omega t}$.

Unknown coefficients K_s and M_s are found from the boundary conditions, requiring the continuity of the tangential components of the total electric and magnetic fields at each cylindrical column's surface. Using the addition theorem for the Bessel functions we arrive to an infinite system of algebraic equations that can be truncated in order to provide a controlled numerical precision.

We have to mention that all eigenfrequencies are complex $\omega=\omega'+i\omega''$, where $\omega''>0$ represents damping and ω' is associated with the eigen oscillation frequencies. *Q*-factor of plasmons can be evaluated through the formula $Q=\omega'/2\omega''$.

The plasmonic properties of wires and particles have recently been investigated using a variety of methods [21]. However, there is a lack of investigations in terms of quality (Q) factors of SPs, though these characteristics are of crucial importance in problems associated with spectral resolution of sensors, stimulated emission enhancement, etc.

III. RESULTS

A. *Eigenvalues of a pair of coupled metal nanowires*

For the case of two coupled metal wires the structure has two symmetry axes that causes four classes of excited plasmons with different symmetry: EE (even symmetry with respect to x and y axes), EO (x – even; y - odd), OE (x – odd; y - even), OO (x – odd; y - odd) (see Fig. 4). Similar symmetry classes exist in the photonic molecules of coupled microdisk resonators [11]. Total number of dipole SPs is four for pair of coupled metal wires.

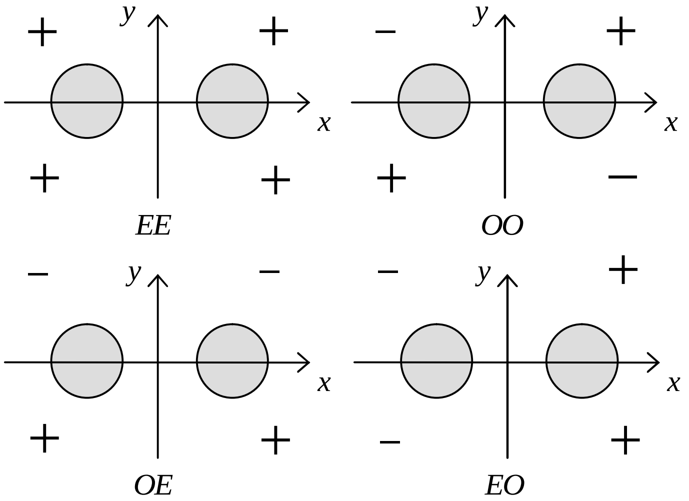


Fig. 4. Classes of symmetry of the field for the pair of coupled metal nanowires.

For modeling results we use the normalized parameter $w_p=\omega_p ac^{-1}$ that we will call the size parameter and normalized separation distance d/a.

The near-field distributions of different plasmons ($s=1$) of pair metal wires are shown in the Fig. 5. Figure 6 demonstrates real values of the eigenfrequencies versus normalized frequency (*ka*) for different values of a normalized separation distance of the different plasmons for two coupled wires ($w_p = 1$) for $s = 1$. Here s indicates the number of angular field variations of corresponding plasmonic mode. The plasmons of the coupled nanowires can be viewed as bonding and antibonding combinations of plasmons of isolated wire. It is clearly seen that for distant wires eigenfrequencies are nearly identical for all four symmetry classes. As separation distance d becomes smaller, the frequency shift of the coupled plasmons becomes much stronger.

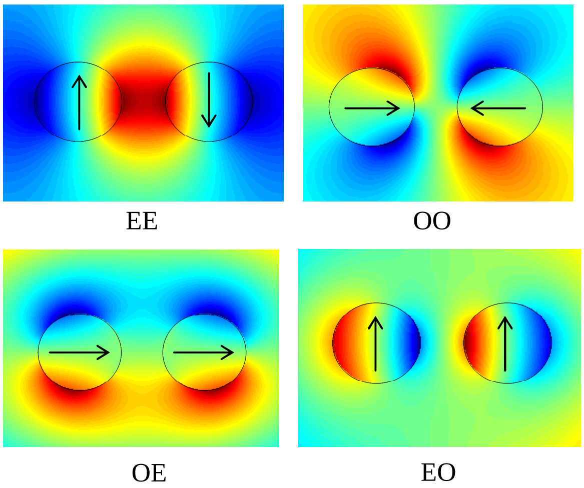


Fig. 4. Classes of symmetry of the field for the pair of coupled metal nanowires.

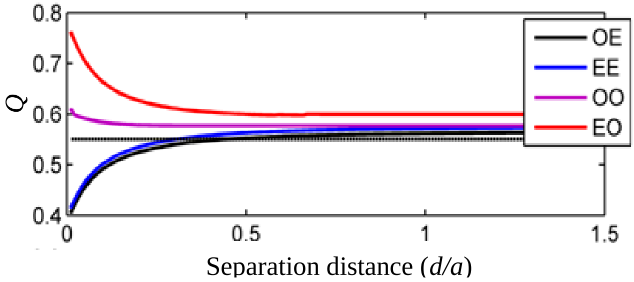


Fig. 6. The normalized frequency versus the normalized separation distance between the pair of metal wires for EE, OE, EO, OO plasmons ($s = 1$).

The *Q*-factor of dipole plasmons in two coupled metal nanowires ($s = 1$) is shown in Fig. 7. For distant plasma cylinders *Q* of coupled plasmonic modes is evidently smaller than *Q*-factor of corresponding plasmons of the isolated metal wire. Peaks of *Q* are observable for the case when separation distance tends to the wavelength.

B .Eigenvalues of a cluster of triangle/square configuration

For the case of cluster of triangular configuration shown in Fig. 3 the structure has three symmetry axes x_1, x_2, x_3 (see Fig. 8). Axes of symmetry pass through the centre of each column and a midpoint of the opposite side of a triangle. For the case of square cluster shown in Fig. 2 the structure has four symmetry axes associated with horizontal, vertical, and oblique axes x_1, x_2, x_3, x_4 (see Fig. 10). Similar symmetry classes were considered for the photonic molecules of coupled microdisk resonators in the [12]. Total number of SPs is four for the triangular cluster and six for the square one [22] (with the same number s of angular variations of the field). Among the possible excited plasmons there exists e.g. plasmons with completely symmetrical fields with respect to all the axes of symmetry (*EEE* or *EEEE* , see Fig. 9 (c) and Fig. 11 (c)) and with totally antisymmetrical ones (*OOO* or *OOOO* , see Fig. 9 (d) and Fig. 11 (d)).

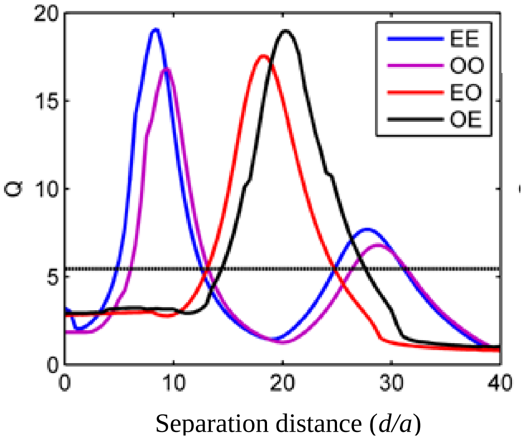


Fig. 7. The *Q*-factor of the two coupled metal wires for EE, OE, EO, OO plasmons ($s = 1$).

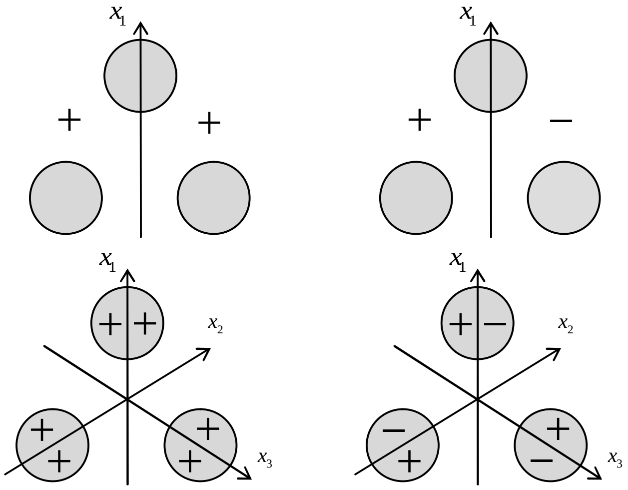
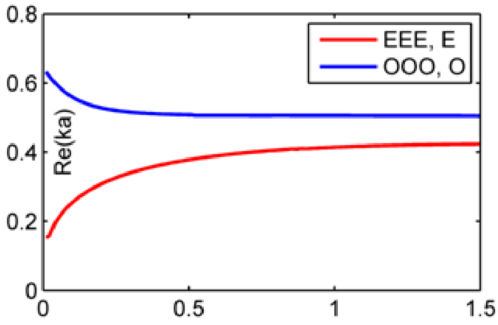


Fig. 8. Classes of symmetry of the field for the cluster with triangular configuration.

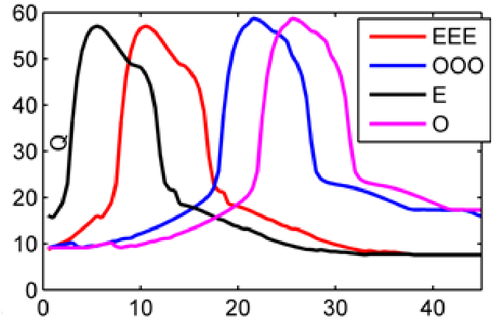
Fig. 9 and 11 show the near-field distributions of dipole SPs of cluster triangular and square configurations respectively ($w_p = 1$). These SPs are symmetric and asymmetric combinations of SPs of individual wire. The orientations of their dipole moments are shown.

Fig. 12 characterizes the dependence of the normalized frequencies (their real parts) and Q -factors on the normalized separation distance between coupled metal wires for the triangular cluster ($w_p = 1$, $\gamma = w_p \cdot 10^{-3}$, $s = 1$) for dipole SPs.

As normalized separation distance d/a becomes smaller, the frequency shift of the coupled SPs becomes much stronger. Dramatical enhancement of Q is observable when $d/a = 1.1\lambda$ for EEE, $d/a = 2.15\lambda$ for OOO, $d/a = 0.52\lambda$ for E and $d/a = 2.62\lambda$ for O modes, where λ is the wavelength.



(a) Separation distance (*d/a*)



(b) Separation distance (*d/a*)

Fig. 12. Dependence of the (a) normalized frequency and (b) Q -factor on the normalized separation distance between coupled metal wires for the triangular cluster ($w_p = 1$, $\gamma = w_p \cdot 10^{-3}$, $s = 1$).

IV. CONCLUSION

The following structures have been considered: a pair of coupled metal wires; a cluster of triangular or square configuration. All possible plasmon modes of the wire configurations have been described. It has been shown that individual plasmons of isolated wire interact and form bonding and antibonding plasmonic coupled modes of different types. Frequency characteristics plasmonic modes in a pair of wires and cluster of triangular or square configurations have been studied.

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