Hybrid Plasmons in Assemblies of Coupled Metal Nanowires

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***Abstract*—This paper presents an accurate study of plasmon hybridization in assemblies of coupled metal nanowires. Our modeling provides results in terms of eigenfrequencies and quality factors. For this eigenvalue problem that follows from Maxwell's equations has been solved. Possibility of quality factor enhancement in optimized assemble configurations has been demonstrated.**

I. INTRODUCTION

Remarkable advances in fabrication have resultedin a widespread interest in nano-technology which involves a broad range of applications. In particular, metallic nanostructures are the subject of immense interest inrecent yearsdue to thepossibility of a strong light localization beyond the diffraction limit via the excitation of plasmons. A review article of Mark Stockman [1] 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.

Plasmons are the collective oscillations of free electrons in metals coupled with electric field that can be optically excited over thin films of nanometers thickness and nanostructures. Various elements such as plasmonic waveguides [2], subwavelength resonators [3] and optical nanoantennas [4] have been studied recently. Plasmons have been explored for their potential in a single molecule detection [5], biomolecular interaction studies [6], early stage cancer detection [7], transmissions through the subwavelength apertures [8], subwavelength imaging [9] etc.

II. RESULTS AND DISCUSSION

Plasmonic structures of different shapes (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. The plasmonic modes of coupled nano-objects can be considered as symmetric or antisymmetric combinations of surface plasmons (SP) of isolated objects with different frequencies and field portraits [10-12].

The plasmonic properties of nanowires and nanoparticles have recently been investigated using a variety of methods. However, there is a lack of investigations in terms of quality (Q) factors of SPs, though these characteristic is of crucial importance in problems associated with spectral resolution of sensors, stimulated emission enhancement etc. Many authors find SPs by investigating resonance peaks in Scattering Cross Section. This study cannot be considered as a complete one, because in this way only 'bright' plasmons can be seen, 'dark' plasmons that do not couple efficiently to incident wave cannot be discovered in such a description.

We developed nonquasistatical expressions for the eigenvalues of SPs that includes finding of eigenfrequencies and Q. Using this approach all possible SPs can be found and investigated, including 'dark' and multipole ones.

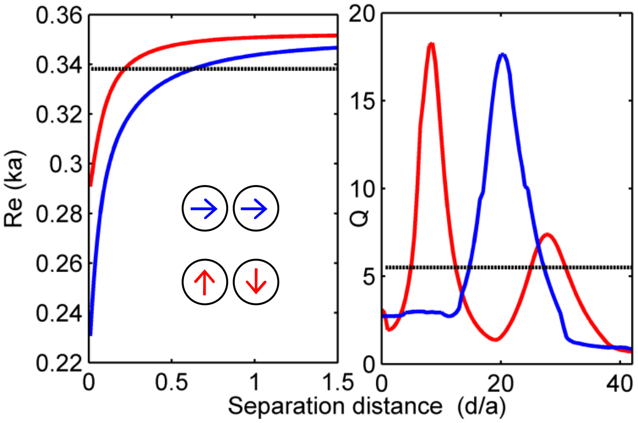

Fig. 1.Normalized frequency (left panel) and Q (right panel) for transversal opposite-phase and longitudinal in-phase SPs, $\omega_p a/c=0.5$, $\gamma=10^{-3}\omega_p$.

We consider SP resonances in a finite linear chain of coupled nanowires and in assembles of square and triangular configuration (see insets in Fig. 1 and Fig. 2). The radius of each wire is a, the separation distance between them is d.The frequency dependent metal's permittivity ε_p is described by the Drude model

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

here ω_p represents the plasma frequency, γ is the material absorption.

Appropriate number of polar system of coordinates associated with each wire is introduced. Electromagnetic field for each wire will be presented in the ordinary form of the Rayleigh series with unknown coefficients. Using the addition theorem for the Bessel functions we will arrive at an infinite system of algebraic equations for unknowncoefficients. These systems will be written in the Fredholm second kind matrix equations. They can be truncated so that approximate solution will converge to exact solution with increasing of the truncation number. The truncation number is determined by the wire radii and the distance between them. Problem of finding the eigenfrequencies of coupled wires is rather complicated. To simplify it we will use the symmetry reasons that can reduce the matrix dimension.

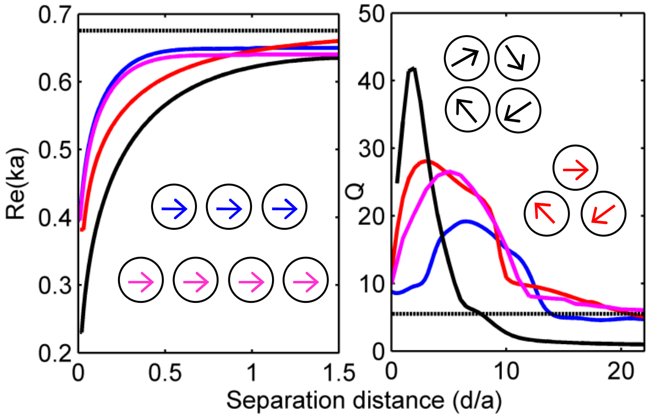

Fig.2.Normalized frequency (left panel) and Q (right panel), dipole orientations and assemble morphologies are shown in the insets, $\omega_p a/c = 1$, $\gamma = 10^{-3}\omega_p$.

All eigenfrequencies are complex $\omega = \omega' + i\omega''$, where $\omega'' > 0$ represents damping and ω' is associated with the eigen oscillation frequencies. Q of plasmons can be evaluated through the formula $Q = \omega'/2\omega''$.

There are four SPs with different dipole orientation in pair of coupled nanowires. Two of them are bright ones: transversal opposite-phase and longitudinal in-phase SPs (see inset in Fig. 1). Fig. 1 demonstrates the real values of the normalized eigenfrequencies (left panel) and Q (right panel) for bright SPs, $k = \omega/c$ is wavenumber. Black dashed line represents data for individual wire. For distant wires eigenfrequencies are nearly identical for all SPs. As separation distance becomes smaller, the frequency shift of coupled SPs becomes much stronger. Increasing of Q is observable for certain separation distances.

Total number of dipole plasmons in a finite linear chain of N nanowires equals to 2N (for details see [13]). In Fig. 2 we present report real part of the normalized frequency and Q forlongitudinal in-phase SP in a linear chain. It is clearly seen downward frequency shift if nanowires are brought together. Enhancement of Q is observable with appearance of each additional wire in a chain.

Arrangement of nanowires into deterministic assemblies with defined morphologies results in structures with tailored physical properties. Assembles as clusters of triangular or square configurations possessboth rotation and reflection symmetries. Total number of dipole SPs is four and six for cluster of triangular and square configurations respectively [14]. In Fig. 2 we present data for SP of the particular orientation. It is seen, the placement of nanowires at the vertices of triangle or square results in additional enhancement of Q.

In conclusion, the spectral characteristics of hybrid plasmonic modes of assembles of coupled nanowires have been analyzed. Accurate analysis of the influence of thecoupling on their spectrum for variety of plasmon resonances is presented.

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