

# Sensitivity of Hybrid Plasmons in Nanowire Based Triangular/Square Clusters to Surrounding Dielectric Environment

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## Abstract

This paper presents investigation of plasmonic properties of coupled metal nanowires arranged to form the cluster of triangular or square configuration. Plasmon resonances of such structures embedded into dielectrics with different dielectric permittivity are studied. The main goal of the paper is to validate true potential of plasmon nanowire-based structures in sensing applications and reveal optimized configurations with narrowband plasmonic resonances and enhanced sensitivity.

## 1. Introduction

Surface plasmons have been the subject of significant interest in recent years as they exhibit properties ideal for a wide range of potential applications. These include: plasmonic waveguides [1], subwavelength resonators [2] and optical nanoantennas [3]. Moreover, surface and localized plasmons have been explored for their potential in a single molecule detection including use of the Surface Enhanced Raman Scattering (SERS) effect [4], transmissions through the subwavelength apertures [5], etc. The silver nanowire structure is a candidate for key components in future ultra-compact photonic devices [6]. It can be considered as a plasmon biosensor to monitor tiny biomolecular interactions [7] and as a novel modulator to control the intensity of the transmitted surface plasmon polaritons through a nanowire array [8]. Plasmons have been explored for their potential in single molecule detection, biomolecular interaction studies.

Theoretical studies of modern nanoscale devices require highly accurate simulations that are complicated by open nature of the structures. It leads to very long simulation times with purely numerical approaches. Alternatively, analytical solutions can give conceptually informative solutions and provide valuable insight but they can be obtained as a rule only to very simple canonical cases. In this paper we use numerical-analytical schemes combining analytical and numerical solutions together to qualitatively reveal the underlying physical principles involved.

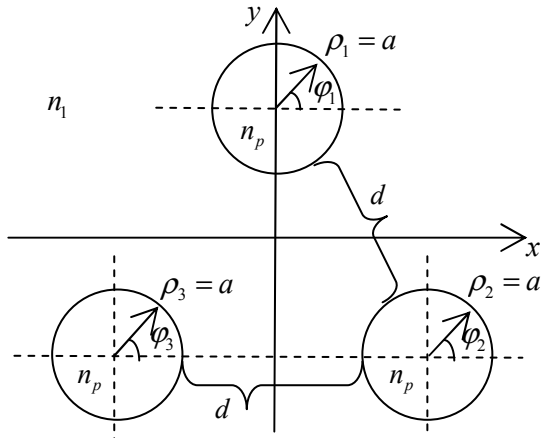
## 2. Mathematical Background: Formulation and Solution

In this paper, we consider surface plasmons (SPs) in nanowire clusters of triangular (Fig. 1) and square (Fig. 2) configurations. Radius of each wire is  $a = 20$  nm, the separation distance between nanowires is  $d$ . Refractive index of metal  $n_p$  is taken from the experimental data obtained by Jonson and Christie [9] for bulk silver, permittivity of outer space is  $n_1$ , time dependence is  $e^{i\omega t}$ . To describe the fields the polar system of coordinates associated with each wire is introduced. The solution is presented in the form of a series of the Bessel functions inside each nanowire and the second-order Hankel functions in outer medium

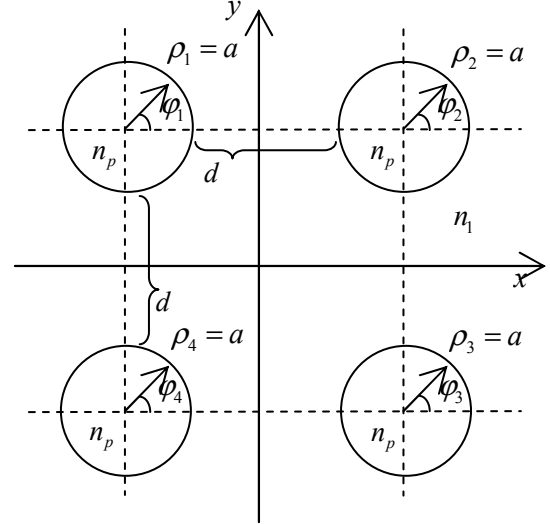
$$H(\rho_k, \varphi_k) = \sum_{s=-\infty}^{+\infty} A_s^{(n)} J_s(n_p k \rho_k) e^{is\varphi_k}, \quad (1)$$

$$H(\rho, \varphi) = \sum_{n=1}^N \sum_{s=-\infty}^{+\infty} \bar{A}_s^{(n)} H_s^{(2)}(n_1 k \rho_k) e^{is\varphi_k}. \quad (2)$$

Here  $k = \omega \cdot c^{-1}$ ,  $c$  is light velocity,  $k = 1, \dots, N$ ,  $N = 3$  or  $N = 4$ .



**Fig. 1. Schematic diagram of the structure: a cluster of triangular configuration.**

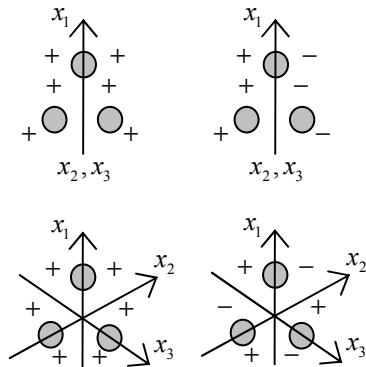


**Fig. 2. Schematic diagram of the structure: a cluster of square configuration.**

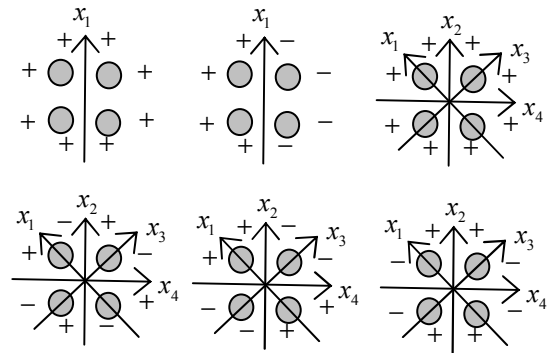
Unknown coefficients  $A_s$  and  $\bar{A}_s$  are found from the boundary conditions, requiring the continuity of the tangential components of the total electric and magnetic fields at each surface. Using the addition theorem for the Bessel functions we arrive to an infinite system of algebraic equations that can be truncated in order to provide a controlled numerical precision.

### 3. Numerical Results and Discussion

The structures under consideration possess two types of spatial symmetries: rotations and reflections. Cluster with triangular configuration has three symmetry axes  $x_1, x_2, x_3$  (see Fig. 3) and square cluster has four symmetry axes associated with horizontal, vertical and oblique axes  $x_1, x_2, x_3, x_4$  (see Fig. 4). Similar symmetry classes exist in the photonic molecules of coupled microdisk resonators [10, 11]. Total number of dipole SPs is four and six for cluster of triangular and square configurations respectively [12] (with the same number  $s$  of angular variations of the field). Among the possible excited plasmons there exists e.g. such plasmons with completely symmetrical fields with respect to all the axes of symmetry (Fig. 5 (c) and Fig. 6 (c)) and with totally asymmetrical ones (Fig. 5 (d) and Fig. 6 (d)).



**Fig. 3. Classes of symmetry of the field for the cluster with triangular configuration.**



**Fig. 4. Classes of symmetry of the field for the cluster with square configuration.**

Figures 5 and 6 show the near-field distributions of dipole SPs of cluster triangular and square configurations, respectively. These SPs are symmetric and asymmetric combinations of SPs of individual silver wires. The orientations of their dipole moments are shown. Similar combinations of SPs exist in the coupled metal wires of a finite linear chain [13].

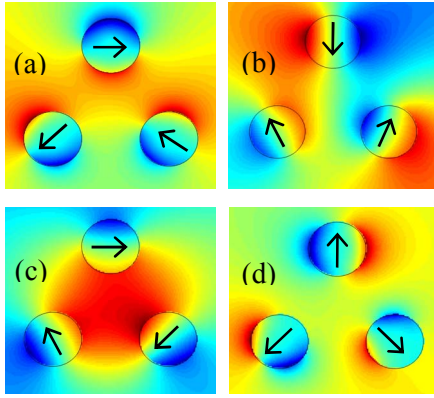


Fig. 5. The near-field distributions of dipole SPs of cluster with triangular configuration ( $d = 40$  nm).

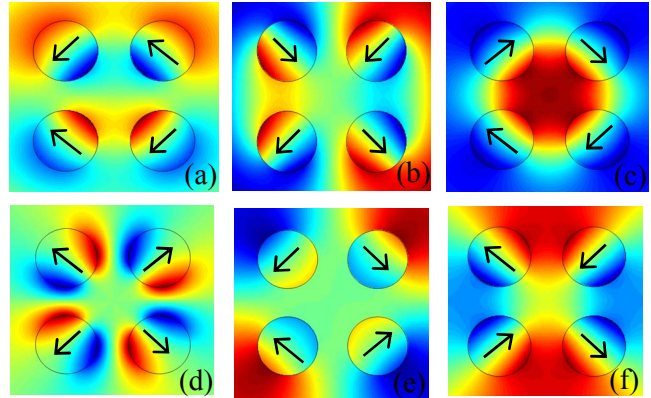


Fig. 6. The near-field distributions of dipole SPs of cluster with square configuration ( $d = 20$  nm).

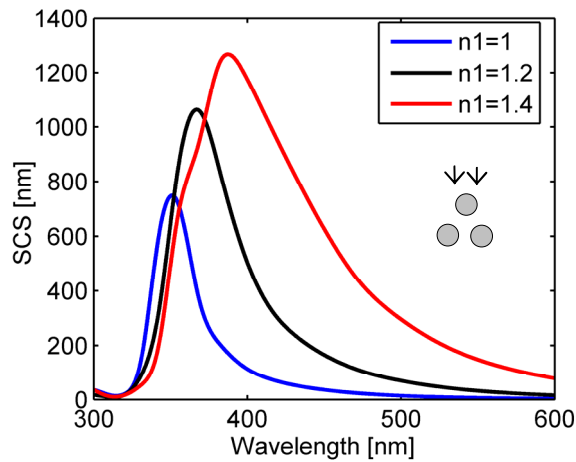


Fig. 7. SCS of coupled three silver wires of cluster with triangular configuration for different values of permittivity of environment.

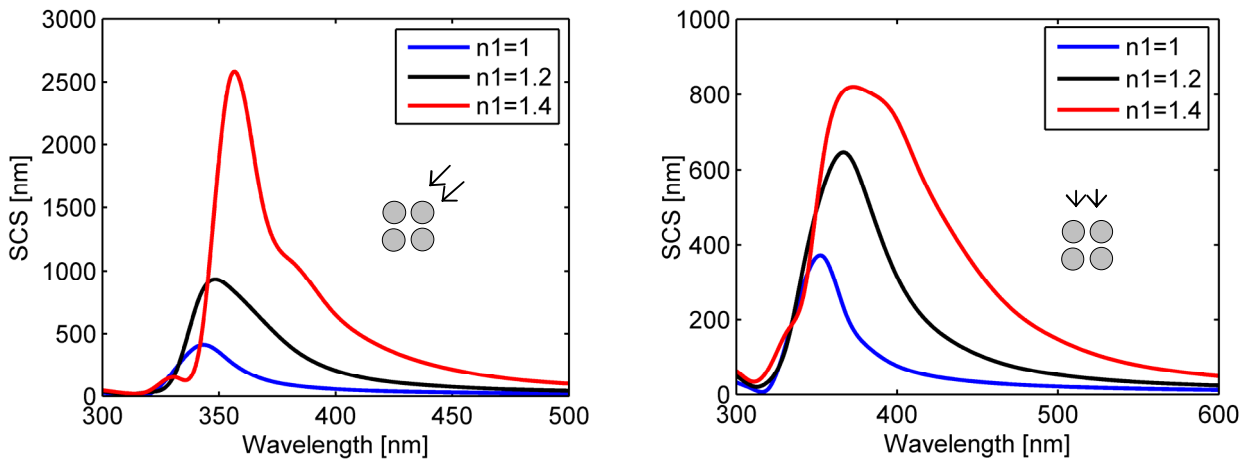


Fig. 8. SCS of coupled four silver wires of cluster with square configuration for different values of permittivity of environment.

Most of these plasmons are ‘dark’ ones that do not couple efficiently to incident wave. Figure 7 represents the scattering cross section (SCS) of triangular cluster ( $d = 60$  nm). Illumination direction is shown in the inset. In this case ‘bright’ plasmon (Fig. 5 (c)) is excited. Shift of plasmon resonance is observable from  $\lambda = 350$  nm to  $\lambda = 388$  nm while refractive index of environment changes from value  $n_1 = 1$  to  $n_1 = 1.4$ .

Figure 8 shows SCS of the square cluster ( $d = 60$  nm). Due to the illumination, shown in the inset in the left panel, 'bright' plasmon presented in Fig. 6(c) is excited. Right panel inset represents another 'bright' plasmon (Fig. 6(f)). Maximum shift of plasmon resonance is observable for square cluster at illumination shown in the right panel of Fig. 8: from  $\lambda = 352$  nm to  $\lambda = 373$  nm. Obviously, the triangular cluster is most sensitive to the environment properties.

## 4. Conclusions

The plasmonic properties of the coupled silver nanowires arranged in triangular or square cluster have been analyzed. Hybrid plasmonic modes of the coupled silver nanowires of such configurations are studied. Maximum shift of plasmon resonances is observable for triangular cluster of silver nanowires.

## 5. Acknowledgment

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