Plasmonic Properties of Coupled Metal Wires in the Cluster with Triangular or Square Configuration

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Abstract—This paper presents a theoretical investigation and a straightforward analysis of the plasmonic properties of coupled metal wires in the cluster with triangular or square configuration. Solution of the eigenvalue problem in form of matrix equations is received. Eigenoscillationg frequencies and quality factors of the nanowires of such configurations are studied. Possibility of quality factor enhancement in optimized assemble configurations has been demonstrated.

Keywords—plasma; surface plasmons; plasmon resonances; eigenfrequency; cluster

I. Introduction

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 surface plasmons (SPs) [1, 2]. Over the last few years, much interest is devoted to metallic nanostructures and, in particular, to the strong electromagnetic enhancement they can provide via the excitations of plasmon resonances [3 - 6]. The possibility of using plasmons to create an effective optical nanoantenna [7], subwavelength resonators [8], spacer [9] and to increase the sensitivity of biosensors [10] are widely discussed recently. Surface and localized plasmons have been explored for their potential in single molecule detection [11], biomolecular interaction studies and early stage cancer detection [12]. The problem of interaction of two or more closely spaced wires is of great importance. Such configurations give rise to tunable spectral shifts of the plasmon bands and to exceptionally strong field enhancements.

II. Mathematical Background: Formulation and Solution

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. In this paper, we consider SPs in the cluster of metal wires with triangular or square configuration. The radius of each wire, embedded in a vacuum, is a; the separation distance between nanowires is d. The time dependence is $e^{i\omega t}$. Figures 1 and 2 represent the schematic diagrams of the structure with triangular or square configurations 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

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

where ω_p represents the plasma frequency, γ is the material absorption. To describe the fields the polar system of coordinates (ρ, φ) associated with each wire is introduced. The solution is presented in the form of a series of the Bessel functions inside each wire and the second-order Hankel functions in outer medium

$$H(\rho_n, \varphi_n) = \sum_{s=-\infty}^{+\infty} A_s^{(n)} J_s(n_p k \rho_n) e^{is\varphi_n} \tag{2}$$

$$H(\rho_n, \varphi_n) = \sum_{n=1}^{N} \sum_{s=-\infty}^{+\infty} \bar{A}_s^{(n)} H_s^{(2)}(k\rho_n) e^{is\varphi_n} \tag{3}$$

Here $k = \omega \cdot c^{-1}$, $n_p = \sqrt{\varepsilon_p}$, c is light velocity in a vacuum.

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.

The plasmonic properties of wires and particles have recently been investigated using a variety of methods [3], [13]. 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. Many authors find SPs investigating resonance peaks in scattering cross section (SCS). 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.

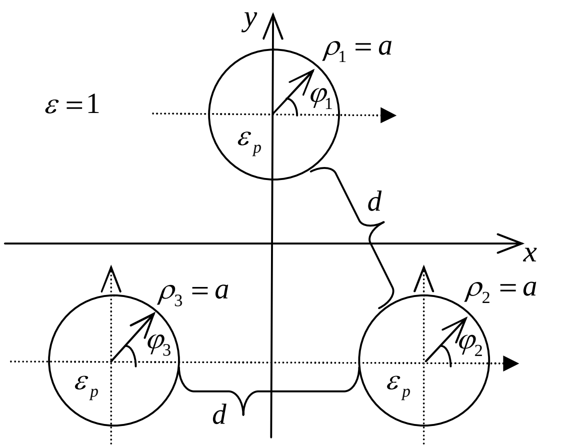

Fig. 1. Schematic diagram of the structure: a cluster of triangular configuration.

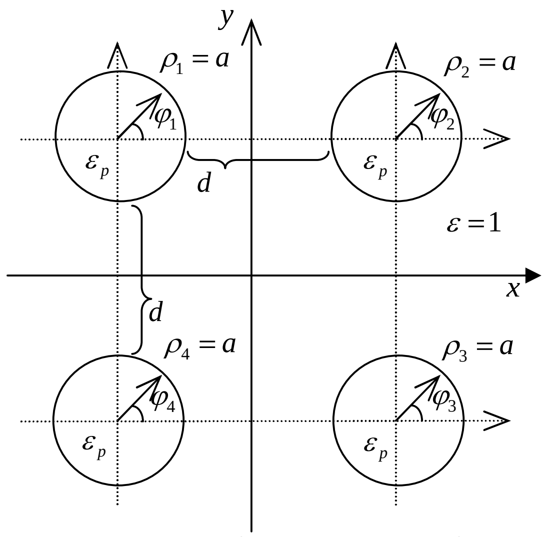

Fig. 2. Schematic diagram of the structure: a cluster of square configuration.

The main goal of this investigation is to develop 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.

III. NUMERICAL RESULTS AND DISSCUSION

For the case of triangular cluster shown in Fig. 1 the structure has three symmetry axes x_1, x_2, x_3 (see Fig. 3); 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. 4). Similar symmetry classes exist in the photonic molecules of coupled microdisk resonators [14, 15]. Total number of dipole SPs is four and six for cluster of triangular and square configurations respectively [16] (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. 5 (c) and Fig. 6 (c)) and with totally antisymmetrical ones (OOO or $OOOO$, see Fig. 5 (d) and Fig. 6 (d)).

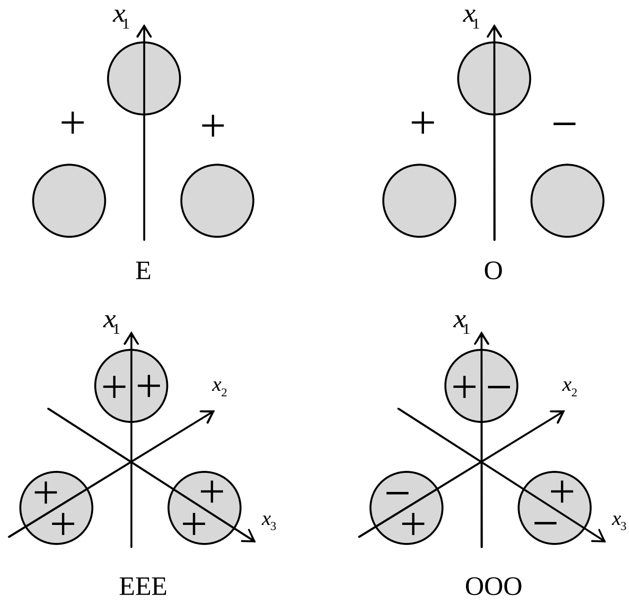

Fig. 3. Classes of symmetry of the field for the cluster with triangular configuration.

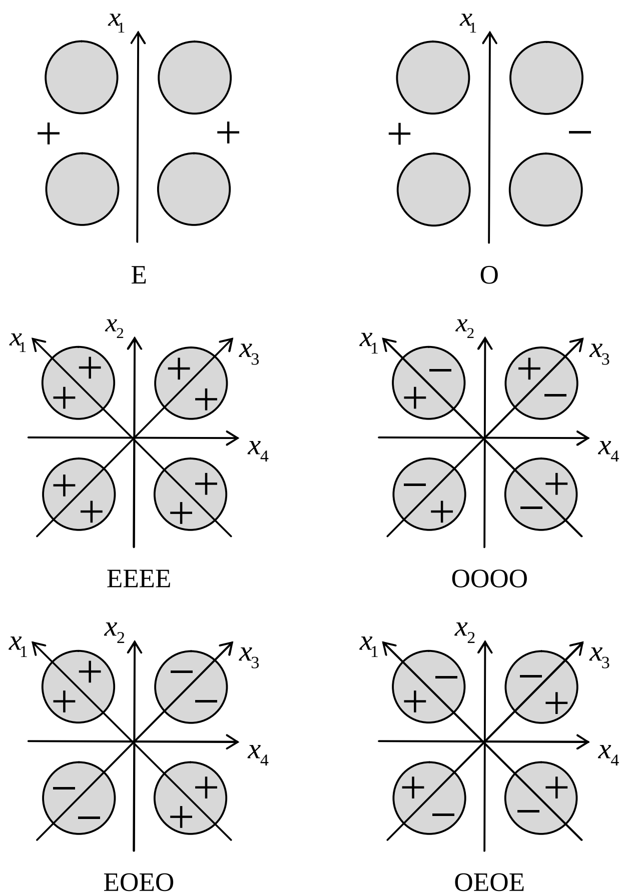

Fig. 4. Classes of symmetry of the field for the cluster with square configuration.

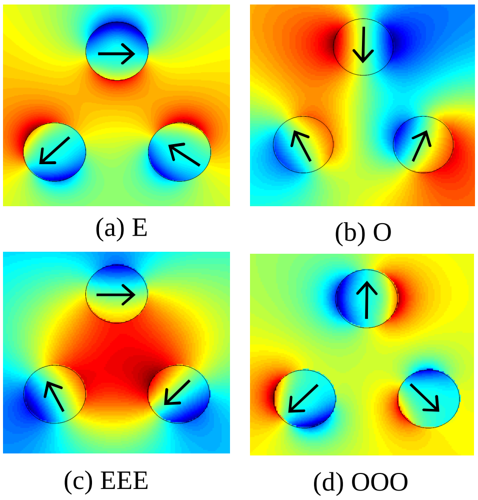

Fig. 5. The near-field distributions of dipole SPs of cluster with triangular configuration ($d/a = 2$).

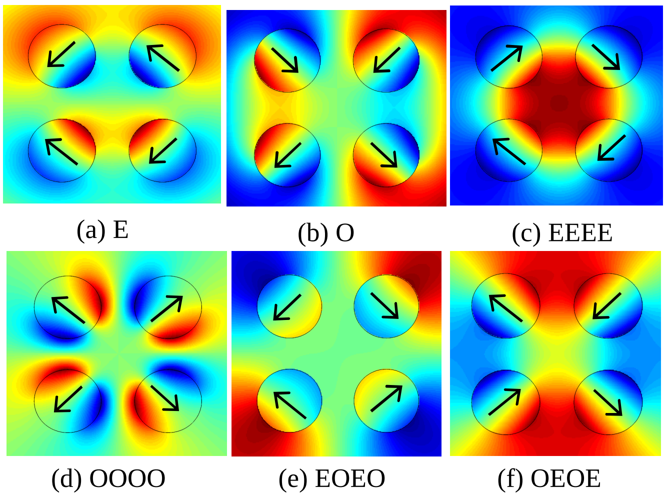

Fig. 6. The near-field distributions of dipole SPs of cluster with square configuration ($d/a = 1$).

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

Figures 5 and 6 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.

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

Figure 7 demonstrates 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.

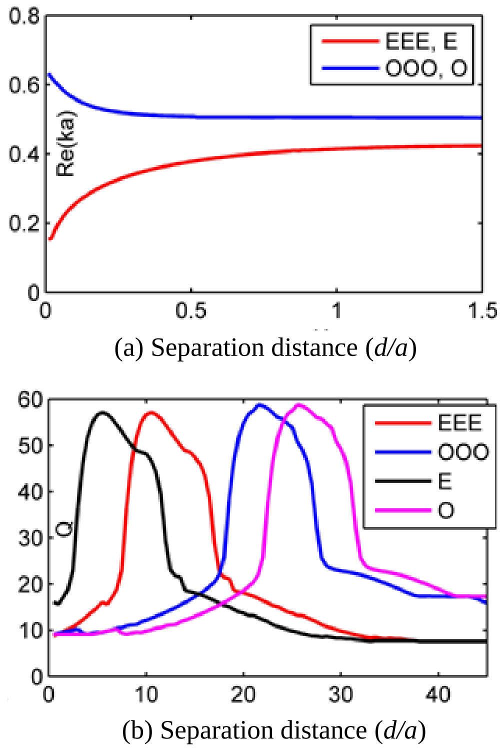

Fig. 7. Dependence of the (a) normalized frequency and (b) Q -factor on the normalized separation distance between coupled metal wires for the triangular cluster ($w_p = 1$, $\gamma = w_p \cdot 10^{-3}$, $s = 1$).

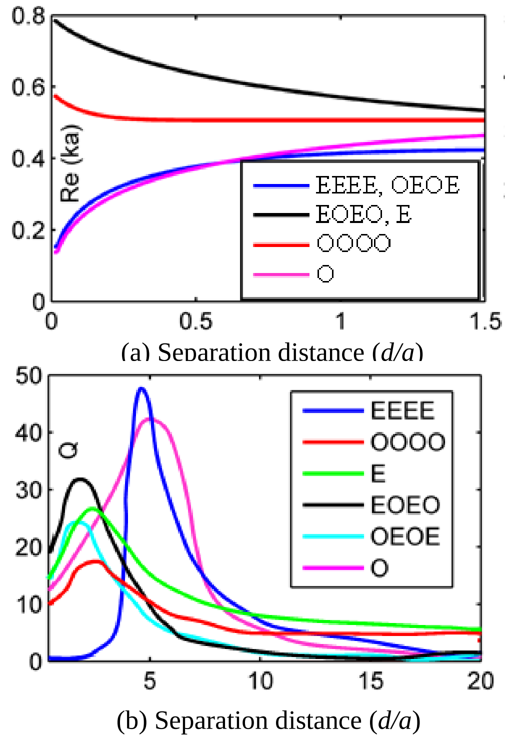

Fig. 8. Dependence of the (a) normalized frequency and (b) Q -factor on the normalized separation distance between coupled metal wires for the square cluster ($w_p = 1$, $\gamma = w_p \cdot 10^{-3}$, $s = 1$).

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.

Figure 8 characterizes the eigenfrequencies (their real parts) and Q-factors of the all possible dipole SPs in a cluster with square configuration of coupled metal wires. It can be seen that the upward shift in frequency is much faster than downward shift for dipole modes if wires are brought together. Enhancement of Q is observable when $d/a = 0.5\lambda$ for $EEEE$, $d/a = 0.27\lambda$ for $OOOO$, $d/a = 0.24\lambda$ for E, $d/a = 0.58\lambda$ for O, $d/a = 0.25\lambda$ for EOEO and $d/a = 0.34\lambda$ for OEOE modes. Maximum peak of Q-factor is seen for $EEEE$ plasmon.

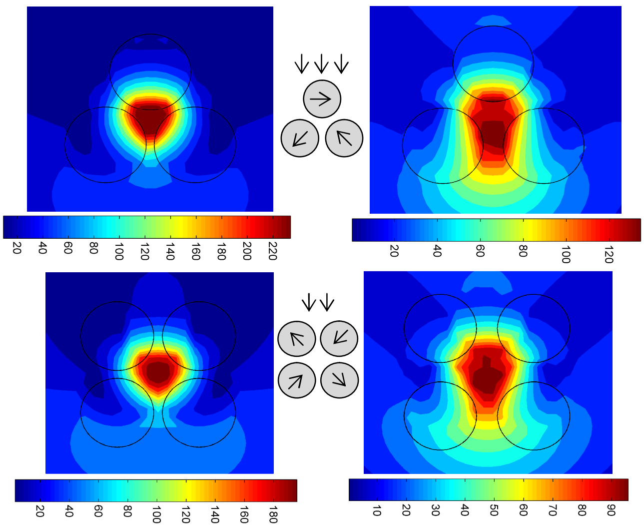

Fig. 9. The near-field distributions of plane wave scattering on coupled metal wires of the cluster triangular or square configuration ($w_p = 1$, $\gamma = w_p \cdot 10^{-3}$, $d/a = 2$).

Figure 9 shows the near-field distributions of plane wave scattering on coupled metal wires of the cluster triangular and square configurations for resonant wavelength. The direction of Illumination of plane wave is shown in the inset. As the distance between the metal wires decreases, the intensity of fields in 'hot spots' increases. The local field enhancement is more profound in the triangular cluster in comparison with the square one.

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Conclusions

We have systematically analyzed the plasmonic properties of the coupled metal wires arranged in triangular or square cluster within the Drude model. For this, we have derived matrix equations that allow thorough investigation of SPs. Our modeling provides results in terms of eigenoscillating frequencies and Q. It is shown that SP of coupled wires results from symmetric and antisymmetric combinations of the plasmons of individual wire and strongly depend on interwire separation. It has revealed the possibility of Q dramatic enhancement by virtue of placing the wires at certain distances. All possible SPs (including 'dark' and multipole ones) of cluster with triangular and square configurations have been analyzed. Near and far fields of hybrid plasmonic modes have been investigated.

References

[1] A. Zayats and I. Smolyaninov, "Near-field photonics: surface plasmon polaritons and localized surface plasmons," J. Opt. A, Pure App. Opt., vol. 5, pp. 16–50, 2003.

[2] W. Barnes, A. Dereux, and T. Ebbesen, "Surface plasmon subwavelength optics," Nature, vol. 424, pp. 824–830, 2003.

[3] J.P. Kottmann and J.F. Martin, "Plasmon resonant coupling in metallic nanowires," Opt. Expr., vol. 8, no. 12, June 2001.

[4] N.P. Stognii and N.K. Sakhnenko, "Plasmon resonances and their quality factors in a finite linear chain of coupled metal wires," IEEE J. Sel. Topics Quantum Electron., vol. 19, no. 3, 4602207, 2013.

[5] N.P. Stognii and N.K. Sakhnenko, "Sensitivity of hybrid plasmons in nanowire based triangular/square clusters to surrounding dielectric environment," URSI General Assembly and Scientific Symp. (URSI-GASS-2014), URSI_paper_2065, Beijing, China, August 16-23, 2014.

[6] N.P. Stognii and N.K. Sakhnenko, "Hybrid plasmons in assemblies of coupled metal nanowires," Int. Symp. on Antennas and Propagation (AP-S-2014), pp. 352-353, Memphis, Fennessee, USA, July 6-11, 2014.

[7] P. Muhlschlegel, H. Eisler, O. Martin, B. Hecht, and D. Pohl, "Resonant optical antennas," Science, vol. 308, pp. 1607-1609, 2005.

[8] J. Li and N. Engheta, "Ultracompact sub-wavelength plasmonic cavity resonator on a nanowire," Phys. Rev. B, vol. 74, pp. 115125, 2006.

[9] M. Noginov, G. Zhu, A. Belgrave, R. Bakker, V. Shalaev, E. Narimanov, S. Stout, E. Herz, T. Suteewong, and Wiesner, "Demonstration of a spaser-based nanolaser," Nature, vol. 460, pp. 1110-1113, 2009.

[10] K. Kim, S.J. Yoon, and D. Kim, "Nanowire-based enhancement of localized surface plasmon resonance for highly sensitive detection: a theoretical study," Opt. Expr., vol. 14, no. 25, pp. 12419-12431, 2006.

[11] K. Kneipp, Y. Wang, H. Kneipp, L. Perelman, I. Itzkan, R. Dasari, and M. Feld, "Single molecule detection using surface-enhanced Raman scattering (SERS)," Phys. Rev. Lett., vol. 78, pp. 1667–1670, 1997.

[12] S. Mallidi, T. Larson, J. Tam, P. Joshi, A. Karpiouk, K. Sokolov, and S. Emelianov, "Multiwavelength photoacoustic imaging and plasmon resonance coupling of gold nanoparticles for selective detection of cancer," Nano Lett., vol. 9(8), pp. 2825-2831, 2009.

[13] B. Rolly, N. Bonod, and B. Stout, "Dispersion relations in metal nano-particle chains: Necessity of the multipole approach," JOSA B, vol. 29, no. 5, pp. 1012–1019, 2012.

[14] E.I. Smotrova, A.I. Nosich, T.M. Benson, and P. Sewell, "Ultralow lasing thresholds of the pi-type supermodes in cyclic photonic molecules composed of sub-micron disks with monopole and dipole modes," IEEE Phot. Techn. Lett., vol. 18, no. 19, pp. 1993-1995, 2006.

[15] S.V. Boriskina, "Symmetry, degeneracy and optical confinement of modes in coupled microdisk resonators and photonic crystal cavities," IEEE J. Sel. Topics Quantum Electron., vol. 12, no. 6, pp. 1175-1182, 2006.

[16] P. McIsaac, "Symmetry-indused modal charachteristics of uniform waveguides -1: Summary of results," IEEE Trans. On MTT, vol. 23, no. 5, pp. 421–429, 1975.