AIP Conference Proceedings

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Citation: AIP Conf. Proc. **1475**, 164 (2012); doi: 10.1063/1.4750131
View online: http://dx.doi.org/10.1063/1.4750131
View Table of Contents: http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=1475&Issue=1
Published by the American Institute of Physics.

Bonding and Antibonding Combinations of Plasmons in Aggregates of Plasma Columns

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Abstract. Theoretical investigation of the plasmonic resonances of coupled cylindrical plasma columns is presented. Mechanism of plasmonic mode coupling in a pair of coupled plasma columns and in a cluster with square configuration that can be considered as bonding and antibonding combinations of isolated column plasmons is investigated.

Keywords: Plasma, surface plasmons, eigenfrequency, plasmon resonances.
PACS: 36.40.Gk, 71.45.Gm.

INTRODUCTION

Metallic nanostructures are the subject of growing studies in recent years due to the possibility of strong light localization beyond the diffraction limit via the excitation of surface plasmons [1]. Various elements such as plasmonic waveguides [2] and optical nanoantennas [3] have been studied recently. Using resonators composed of negative permittivity materials such as plasma can form the basis of effective small-size antenna elements [4]. The main advantage of a plasma antenna over the conventional antennas is due to possibility to control antenna parameters by tuning plasma properties. Plasmonic nanowire structure can be considered as a plasmon biosensor to monitor tiny biomolecular interactions [5] and as a novel modulator for control of the intensity of the transmitted surface plasmon polaritons through a nanowire array [6]. Therefore, accurate modeling that provides a valuable insight into fundamental processes is of great importance.

MATHEMATICAL BACKGROUND

In this paper we solve the eigenvalue problem for pair of coupled plasma columns and cluster with square configuration of coupled cylindrical plasma columns. Radius of each column is a, separation distance between them is d, the surrounding space is a vacuum, the time dependence is $e^{i\omega t}$. Figures 1 and 2 represent schematic diagrams of the structures with a pair of coupled plasma columns and square configuration respectively. Plasma is described by the permittivity ε_p that is given by the Drude model

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

here ω_p represents the plasma frequency, γ is the material absorption. H-polarized fields are considered.

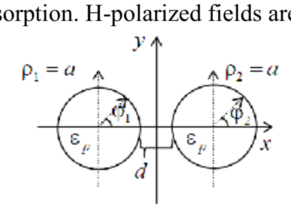

FIGURE 1. Schematic diagram of the structure: a pair of coupled plasma columns.

To describe the fields we introduce N (N=2 or N=4) cylindrical coordinate systems associated with each infinite column. The solution is presented in the following form inside and outside each column respectively

$$H^{in}(\rho_n, \varphi_n) = \sum_{s=-\infty}^{+\infty} A_s^{(n)} J_s(k_p \rho_n) e^{is\varphi_n} \qquad (2)$$

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

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

Unknown coefficients A_s and $\overline{A}_s$ 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

The Fifth International Workshop on Theoretical and Computational Nano-Photonics
AIP Conf. Proc. 1475, 164-166 (2012); doi: 10.1063/1.4750131

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 $Q = \omega'/2\omega''$.

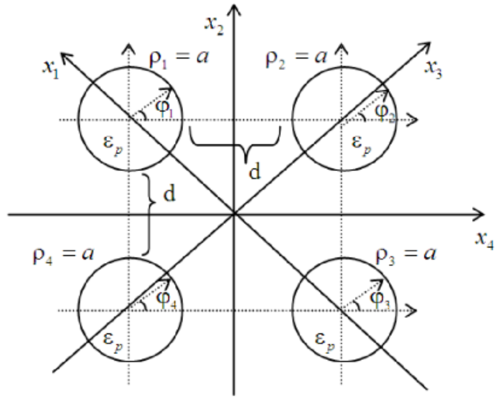

FIGURE 2. Schematic diagram of the structure: a cluster of square configuration.

RESULTS AND DISSCUSION

For the case of two coupled cylinders 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. 3).

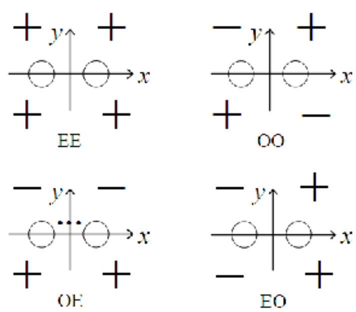

FIGURE 3. Four classes of symmetry of the field for the pair of coupled plasma columns.

Figure 4 demonstrates real values of the eigenfrequencies versus normalized frequency (ka) for different values of $w_p = \omega_p a c^{-1}$ that we will call further a normalized plasma frequency of the different plasmons for two coupled columns ($w_p = 1$) and for isolated column for $s = 1$. Here s indicates the number of angular field variations of corresponding plasmonic mode. The plasmons of the coupled columns can be viewed as bonding and antibonding combinations of plasmons of isolated column. 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.

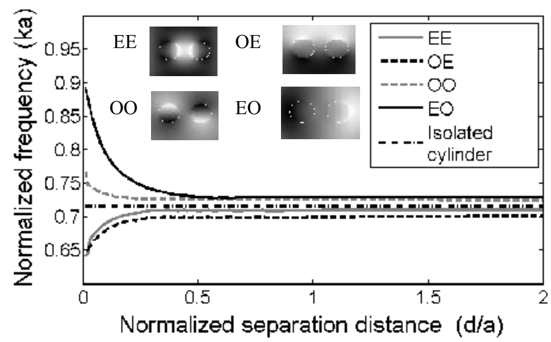

FIGURE 4. The normalized frequency versus the normalized separation distance between the two coupled plasma cylinders for EE, OE, EO, OO plasmons (s=1).

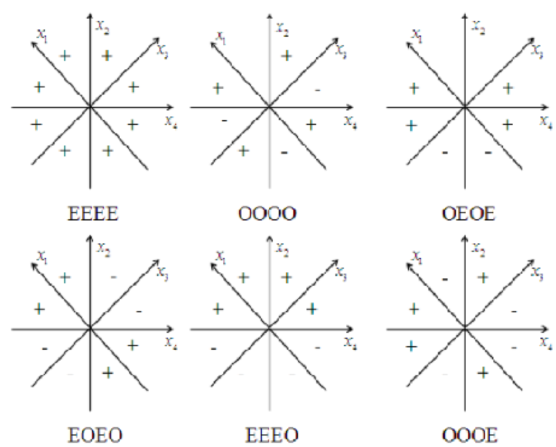

FIGURE 5. Six classes of symmetry of the field for the cluster for four coupled columns.

The near-field distributions of different plasmons ($s = 1$) of two plasma columns are shown in the inset in Fig. 4.

For the case of square cluster shown in Fig. 2 the structure has four symmetry axes associated with horizontal, vertical, and oblique axes that causes six classes of excited plasmons with different symmetry: EEEE (x_1, x_2, x_3, x_4 - even), OOOO (x_1, x_2, x_3, x_4 - odd), OEOE (x_1, x_3 - odd, x_2, x_4 - even), EOEO (x_1, x_3 - even, x_2, x_4 - odd), EEEO (x_1, x_2, x_3 - even,

x_4 - odd), OOOE (x_1 , x_2 , x_3 -odd, x_4 -even) (see Fig. 5).

Figure 6 illustrates the value of the real part of plasmon eigenfrequency for coupled plasma columns of square configurations for $s = 2$. For cluster of square configuration with the decreasing of the separation distance between the plasma cylinders we see decreasing of the resonant frequency for EEEE, OEOE, EEEO and OOOE plasmons and increasing for the OOOO and EOEO plasmons.

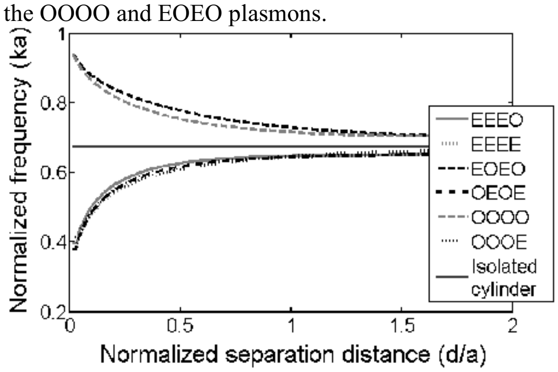

FIGURE 6. The normalized frequency versus the normalized separation distance between the coupled plasma cylinders in a cluster for different plasmons (*s*=2).

It is seen that for large separation distances between cylinders eigenfrequencies of all modes tend to the eigenfrequency of plasmon of an isolated plasma cylinder.

Figure 7 presents the Q-factor of four coupled plasma cylinders ($s = 2$). Maximum peak of Q-factor is seen for OOOE plasmon. The increasing of Q is observable for distant columns in a cluster of square configuration it is nearly 5 wavelength.

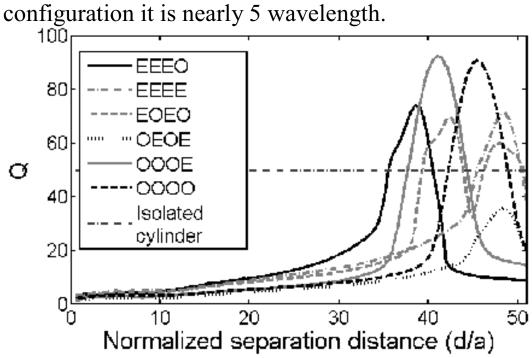

FIGURE 7. Q-factor for cluster of four coupled plasma columns (s=2, w_p =1).

Figure 8 demonstrate the near-field portraits of different plasmons of cluster with square configuration for $s = 2$ for $d/a = 0.5$.

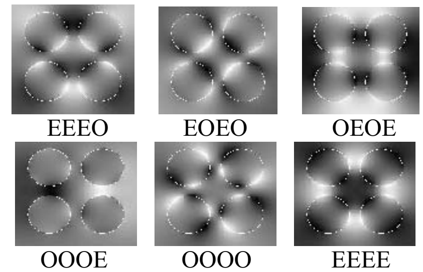

FIGURE 8. The near-field distributions of plasmons of cluster of four coupled plasma columns for $s = 2$, $d/a = 0.5$.

CONCLUSION

The eigenfrequencies of the coupled cylindrical columns with square configuration and pair coupled columns filled with negative permittivity plasma have been analyzed. It has been shown that individual plasmons of isolated column interact and form bonding and antibonding plasmonic coupled modes of different types.

ACKNOWLEDGMENTS

Ms. N. Stognii is thankful to the German Academic Exchange Service (DAAD). Dr. N. K. Sakhnenko acknowledges financial support by the European Science Foundation Research Networking Programme PLASMON-BIONANOSENSE.

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