

COUPLED PLASMA CYLINDRICAL COLUMNS AS SUB-WAVELENGTH ANTENNA

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Abstract

We theoretically study the resonant properties of an aggregate of coupled cylinders filled with negative permittivity plasma. Such a problem has applications in optical and plasma antennas, intelligent antenna systems, and pulse-driven antenna arrays. Chain of columns of plasma can be used in the design of both transmitting and receiving antennas with a very broad frequency range and tunability that allows switching it on and off very fast. The Mie series expansion is used to derive the solution. Electromagnetic analysis of the spectrum of different plasmon resonances is presented.

Keywords: sub-wavelength antenna, plasma, surface plasmon, eigenfrequency.

1. INTRODUCTION

The extensive interest in the interaction between electromagnetic waves and plasmas is due to their wide area of applications. Tuning of resonant characteristics of microdisk resonators by free carrier plasma injections has applications in active switchers and tunable filters [1]. Transient phenomena in plasma lead to the frequency up-shifting possibility and the wave generation [2, 3]. Using resonators composed of negative permittivity materials such as plasma can form the basis of effective small antenna elements [4]. Suitable columns of plasma can be used in the design of both transmitting and receiving antennas [5]. The main advantage of a plasma antenna over the conventional antennas is due to possibility to control antenna parameters by tuning plasma properties. It has been shown experimentally that arrays of vertical plasma antennas produce more directive radiation patterns than a single plasma antenna [6].

2. PROBLEM FORMULATION AND METHOD OF SOLUTION

The purpose of this paper is to study the properties of antenna configuration in the form of N coupled identical equidistant infinite-long plasma cylindrical columns. Radius of each column is a , separation distance between them is d . The ambient medium is free space. The main focus is the study the sub-wavelength regimes when the antenna receives the wavelengths that are much greater than its size ($ka < 1$, where k is the free space wave number).

We use the Drude model to describe plasma

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

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.

In this paper, we find surface plasmons using two approaches: (i) we consider plane wave scattering on the structure above, (ii) we find eigenfrequencies of the structure. H-polarized fields are considered. We present the z-component of the internal field

$$H(\rho_j, \varphi_j) = \sum_{s=-\infty}^{+\infty} A_s^{(j)} J_s(k_p \rho_j) e^{is\varphi_j} \quad (2)$$

and the external field

$$H(\rho_j, \varphi_j) = \sum_{j=1}^N \sum_{s=-\infty}^{+\infty} B_s^{(j)} H_s^{(2)}(k\rho_j) e^{is\varphi_j} \quad (3)$$

using Mie's series expansions.

Here (ρ_j, φ_j) are set of N polar systems of coordinates, associated with each cylindrical columns ($j = 1 \dots N$), 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, $n_p = \sqrt{\varepsilon_p(\omega)}$, time dependence is $e^{i\omega t}$.

Unknown coefficients $A_s^{(j)}$ and $B_s^{(j)}$ are found from the boundary conditions, requiring the tangential components of the total electric and magnetic fields to be continuous at each cylindrical column's surface. Using the addition theorem for Bessel functions we arrive to an infinite system of algebraic equations that can be truncated in order to provide a controlled numerical precision.

3. RESULTS

3.1. SINGLE PLASMA CYLINDRICAL COLUMN

We first study the problem of plane wave scattering on isolated plasma column. Fig. 1 shows scattering cross section versus normalized frequency (ka) for different values of $w_p = \omega_p ac^{-1}$ that we will call further a normalized plasma frequency. It is seen that with decreasing of w_p we observe the red-shifting of the resonance.

To describe properties of the excited fields in detail we find the eigenfrequencies of the isolated plasma cylinder. This problem is rather straightforward and can be solved analytically. We present z-component of the excited field in the following form:

$$H = \begin{cases} AJ_s(k_p \rho) \cos s\varphi \\ H_s^{(2)}(k\rho) \cos s\varphi \end{cases} \quad (4)$$

Applying the boundary conditions we obtain that $A = H_s^{(2)}(ka) / J_s(k_p a)$ and equation for eigenfrequencies can be written in the form

$$H_s^{(2)}(ka) J_s'(n_p ka) - n_p H_s^{(2)'}(ka) J_s(n_p ka) = 0. \quad (5)$$

The prime here represents differentiation with respect to the argument. Equation (5) defines all modes of the plasma column. All solutions of the equation are complex-valued. Plasmons are excited when $w_p > \text{real}(ka)$. We have to stress that the equation above has no plasmonic solution for $s = 0$ (s is a number of angular field variations) however it has solutions for $s = 1, 2, 3 \dots$

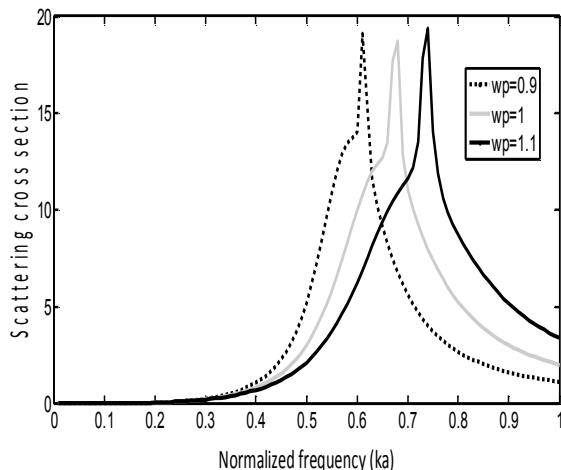


Fig. 1. Scattering cross section of isolated plasma column versus normalized frequency (ka) for different values of the normalized plasma frequency.

Fig. 2 illustrates the value of the real part of plasmon eigenfrequency that is the solution of the equation (5) versus the number of the angular field variations (s) for the same values of the normalized plasma frequency

w_p as in Fig. 1. We see that plasmon resonances for different values of s are closely spaced. Comparing Fig. 1 and Fig. 2 we conclude that due to the plane wave illumination of the plasma column plasmon resonances of the different types can be excited.

Field portraits of the plasmons are shown in the inset of Fig. 2 (upper left-hand corner for $s=1$, lower right-hand corner for $s=2$).

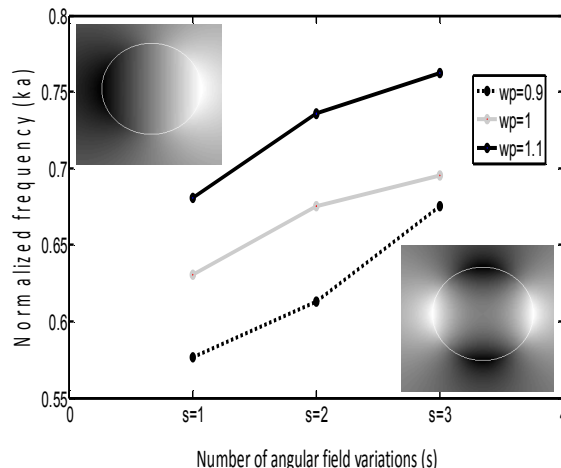


Fig. 2. Dependence of the eigenfrequency on the number of angular field variations for different values of the normalized plasma frequency w_p .

3.2. TWO COUPLED PLASMA CYLINDRICAL COLUMNS

For the case of two coupled plasma cylinders the structure has two symmetry axis 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).

Fig. 3 demonstrates real values of the eigenfrequencies of the EE, EO, OE, OO plasmons ($s=1$) for two plasma columns ($w_p=1$). It is clearly seen that for distant columns eigenfrequencies are nearly identical for all four symmetry classes. It should be mentioned that they are close to the corresponding plasmon frequency of isolated column (see Fig. 2). With the decreasing of the separation distance between the plasma cylinders we see decreasing of the resonant frequency for EE and OE plasmons and increasing for the OO and EO plasmons.

3.3. LINEAR CHAIN OF COUPLED PLASMA CYLINDRICAL COLUMNS

In Fig. 4 we present scattering cross section for two, five and six coupled columns (illumination direction is shown in the inset). It is seen that for coupled columns two resonances are observable in the spectrum. We

observe the field enhancement with growing of the columns in a chain.

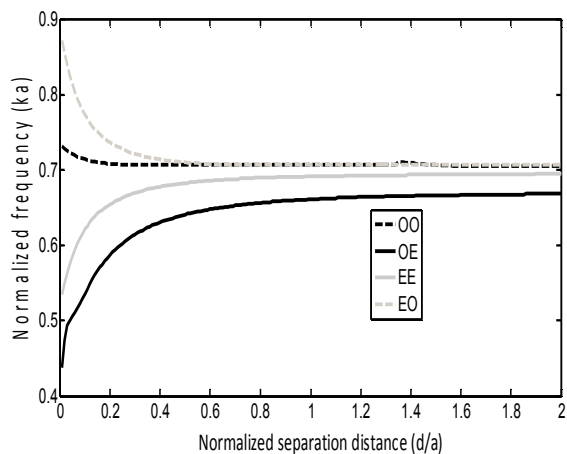


Fig. 3. Dependence of the normalized frequency on the normalized separation distance between the coupled plasma cylindrical columns for EE, OE, EO, OO plasmons ($s=1$).

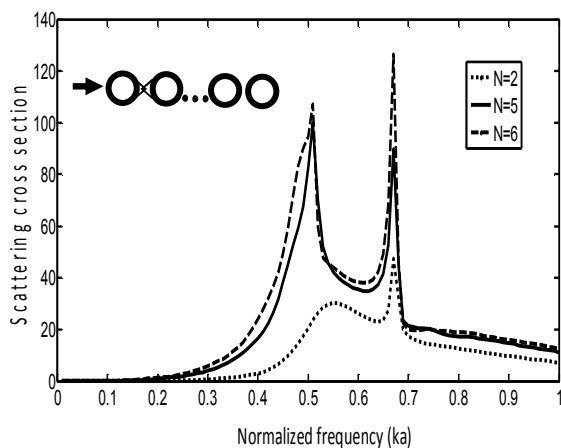


Fig. 4. Scattering cross section of two, five and six coupled columns with a normalized separation distance $d \cdot a^{-1} = 1.6$. Illumination is along the major axis.

Fig. 5 illustrates eigenfrequencies of EE plasmon ($s=1$) for different number of coupled plasma columns (this plasmon corresponds to the right-hand peak in Fig. 4). Inset shows the field distribution of EE plasmon in a chain of six plasma columns. It is seen that eigenfrequencies decrease with increasing the number of plasma columns.

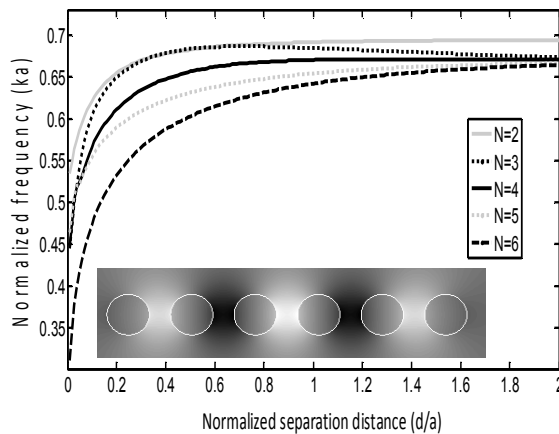


Fig. 5. Dependence of the normalized frequency of the normalized separation distance between the coupled plasma cylindrical columns for EE plasmons ($s=1$).

4. CONCLUSIONS

We analyze the resonant properties of an aggregate of coupled cylinders filled with negative permittivity plasma. Such a structure is a simple model of sub-wavelength plasma antenna. The properties of plasmon resonances are investigated.

ACKNOWLEDGMENT

This work was supported by the Ukrainian National Target Program “Nanotechnologies and Nanomaterials” and the State Agency for Science, Ukraine. Ms. N. Stogniy acknowledges the support of this research by IEEE AP-Society through Doctoral Award.

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