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Resonance Scattering Effects in a Periodic Array of Gyrotropic Cylinders Irradiated by a Filamentary Electric-Dipole Source

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Abstract

Resonance scattering of a cylindrical wave, which is excited by a filamentary electric-dipole source, from a planar array of gyrotropic cylinders located equidistantly in free space is studied. The field patterns of such a system are calculated in the case where the source frequency is close to one of the surface plasmon resonance frequencies of the array elements. The influence of the gyrotropic cylindrical scatterers on the radiation characteristics of the filamentary source is discussed with application to the plasma-based radiating systems operated in the radio-frequency range.

1 Introduction

Recently, there has been shown increased interest in plasma-based antennas operated in the radio-frequency (RF) and microwave ranges [1]. Such systems, which usually consist of the plasma-filled discharge tubes, may have some potential advantages over conventional metal antennas, e.g., due to ability of controlling the electromagnetic characteristics through variation in the plasma parameters. In particular, the influence of axially magnetized plasma scatterers on the radiation characteristics of given electromagnetic sources has recently been discussed in [2, 3]. It is important that a resonant response of the magnetized plasma-filled elements, which possess gyrotropic properties, to the source-excited field can play a predominant role in the formation of directional properties of such radiating structures [3]. In this regard, the study of the resonance scattering effects in arrays of gyrotropic cylinders irradiated by the source-excited field can be of special interest for creation of promising plasma-based antenna systems.

It is the purpose of the present work to extend the analysis which has been performed for systems with one or a few scattering cylinders [3] to the case of a filamentary electric-dipole source operated in the presence of a relatively large number of gyrotropic cylinders forming a finite one-dimensional periodic array. It is assumed that such cylindrical elements are filled with a cold collisionless magnetoplasma and have the surface plasmon resonances, at which enhanced scattering of the incident source-excited field occurs.

2 Basic Formulation and Numerical Results

Consider a planar array of N identical, infinitely long circular plasma cylinders, which are located equidistantly in free space. The cylinders are aligned with an external static magnetic field $\mathbf{B}_0$, which is parallel to the z axis of a Cartesian coordinate system (x,y,z). It is assumed that the origin of this coordinate system coincides with the center of the array so that the axes of the cylinders, separated by distance L, lie in the xz plane. The cold collisionless magnetoplasma inside each cylinder is described by a permittivity tensor with the nonzero elements $\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_0\varepsilon$, $\varepsilon_{xy} = -\varepsilon_{yx} = -i\varepsilon_0 g$, and $\varepsilon_{zz} = \varepsilon_0\eta$, where ε_0 is the electric constant, $\varepsilon = 1 - \omega_p^2/(\omega^2 - \omega_H^2)$, $g = \omega_p^2\omega_H/[(\omega^2 - \omega_H^2)\omega]$, and $\eta = 1 - \omega_p^2/\omega^2$. Here, ω is the angular frequency, ω_p and ω_H are the plasma frequency and the gyrofrequency of electrons, respectively, and the contribution of the motion of ions to the plasma permittivity tensor is neglected.

The array is irradiated by an electric-dipole filament of infinite length located in free space parallel to the z axis. It is assumed that such a source is placed opposite the array center at distance d from the array plane and has the electric-current density $\mathbf{J} = i\omega p_0(\mathbf{x}_0\cos\theta + \mathbf{y}_0\sin\theta)\delta(x)\delta(y+d)$. Here, p_0 is the electric dipole moment per unit length, θ is the angle specifying the dipole moment orientation, δ is the Dirac function, $\mathbf{x}_0$ and $\mathbf{y}_0$ are the unit vectors of the x and y axes, respectively, and the $\exp(i\omega t)$ time dependence is dropped. The total electromagnetic field outside the array elements can be written as a superposition of an H-polarized cylindrical wave, which is excited by the filamentary source, and a field scattered from the plasma cylinders. To determine the total field, we employ the multiple scattering technique, according to which the problem can be reduced to finding the Fourier–Bessel expansion coefficients of the scattered field for all the array elements. This method, which has recently been used for simpler configurations of the filamentary sources and the plasma cylinders in [3], allows us to calculate readily the radiation pattern of the system in the horizontal plane ($z = 0$).

Numerical calculations of the radiation characteristics of the described system have been performed for the dimensionless parameters $\omega_p a/c = 0.5$ and $\omega_H/\omega_p \leq 0.4$, where a is the radius of the plasma cylinders and c is the speed of

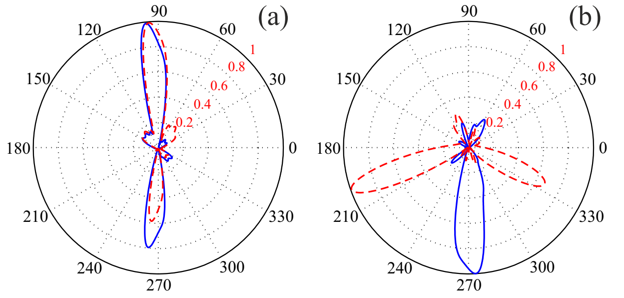

Figure 1. Normalized radiation patterns for $k_0d/2\pi = 0.085$ (a) and $k_0d/2\pi = 0.7$ (b) if $k_0L/2\pi = 0.8$ and $\omega_H/\omega_p = 0.4$. The blue solid lines and the red dashed lines correspond to the dipole-moment orientation angles $\theta = 0$ and $\theta = \pi/2$, respectively.

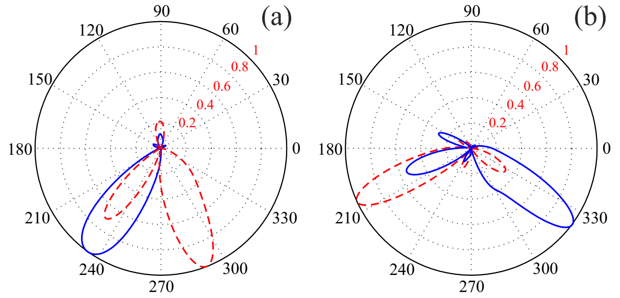

Figure 2. Normalized radiation patterns for $\theta = 0$ (a) and $\theta = \pi/2$ (b) if $k_0d/2\pi = 0.5$ and $k_0L/2\pi = 0.5$. The blue solid lines and the red dashed lines correspond to the different values of the external static magnetic field, for which $\omega_H/\omega_p = 0.4$ and $\omega_H/\omega_p = 0.365$, respectively.

light in free space. The chosen values of the parameters can easily be realized in RF-discharge plasma structures under laboratory conditions. It is assumed that the array consists of $N = 11$ plasma scatterers. Recall that for $k_0a \ll 1$, where k_0 is the wave number in free space, each cylinder has surface plasmon resonance frequencies, hereafter denoted as $\omega_{\mathrm{SP},m}$, where m is the azimuthal index [3]. In what follows, we give some numerical examples demonstrating the effects of the resonance scattering for different locations of the filamentary source. The values of the static magnetic field are chosen such that $\omega_H/\omega_p = 0.4$ or $\omega_H/\omega_p = 0.365$. With these values, the source frequency $\omega = 0.9\omega_p$ used for calculations is close to one the surface-plasmon resonance frequencies, $\omega_{\mathrm{SP},1}$ or $\omega_{\mathrm{SP},2}$, respectively.

Figures 1(a) and 1(b) show the normalized radiation patterns of the electric-dipole filament in the presence of $N = 11$ plasma cylinders for two source positions when $k_0d/2\pi = 0.085$ and $k_0d/2\pi = 0.7$, respectively. If the filamentary source is placed in the close vicinity of the array center [see Figure 1(a)], the shape of the radiation pattern, which is determined by the dominant contribution of the field resonantly scattered by the cylinders, depends only weakly on the dipole-moment orientation angle θ. On the contrary, if the source is located at a distance $k_0d/2\pi = 0.7$ that is comparable with the array period $k_0L/2\pi = 0.8$ [see Figure 1(b)], the radiation patterns are significantly different for $\theta = 0$ and $\theta = \pi/2$. It is seen in Figure 1(b) that the main lobes of the radiation patterns are located in the half-space containing the filamentary source ($y < 0$), so that the cylindrical wave excited by the source is almost completely reflected from the array as a result of the resonance scattering by the magnetized plasma cylinders.

Figure 2 shows the normalized radiation patterns for the dipole-moment orientation angles $\theta = 0$ and $\theta = \pi/2$ and different values of the external static magnetic field. Since the single-cylinder resonant frequencies $\omega_{\mathrm{SP},m}$ depend on the external magnetic field, even small variations in its magnitude can lead to that the unchanged source frequency ω becomes sequentially equal to the resonant frequencies $\omega_{\mathrm{SP},m}$ corresponding to different azimuthal indices m. At the values $\omega_H/\omega_p = 0.4$ and $\omega_H/\omega_p = 0.365$, which are chosen for plotting the radiation patterns in Figure 2, we have $\omega \approx \omega_{\mathrm{SP},1}$ and $\omega \approx \omega_{\mathrm{SP},2}$, respectively. The corresponding transformations in the radiation patterns, which are caused by switchover from the $m = 1$ to $m = 2$ resonance, are clearly seen in Figure 2.

3 Conclusion

In this work, we have studied the resonance scattering effects in the system consisting of a finite periodic array of gyrotropic plasma cylinders and an electric-dipole filament. The influence of the dipole-moment orientation and the position of the source on its radiation pattern has been discussed. The results obtained demonstrate the possibility to control efficiently the radiation pattern of the described system by means of variations in the external static magnetic field superimposed on the scattering cylinders.

4 Acknowledgements

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