Известия Гомельского государственного университета имени
Ф.Скорины, 6(9), Проблемы взаимодействия излучения с веществом, 2001

Exotic composite materials: a review of recent developments

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Abstract

In this presentation we will review recent developments in the field of exotic composite materials, mainly of spatially dispersive composites with complex-shaped or loaded inclusions. The emphasis will be on two research directions: very thin (compared to the wavelength) layers and materials with unusual properties, such as materials in which both the permittivity and permeability are negative. We will show that certain arrays of planar metal particles located very near to a metal ground plane exhibit resonance properties due to interaction with the ground plane (usually, cancellation with the image currents occur). This opens a way to design very thin covering layers which transform electric walls into magnetic walls. Regarding complex volume composites, we will discuss, among other issues, the means to provide negative permittivity and permeability which can make it possible to design novel lenses.

In this paper, we present the results related to thin resonant coverings, and only briefly mention other topics to be presented in the conference.

1. Extremely thin resonant coverings

Let us consider an ideally conducting plane illuminated by a normally incident plane wave. Suppose we want to considerably modify the electromagnetic response of this reflector covering the surface by a very thin (compared to the wavelength) non-magnetic layer. In particular, we are interested in creating artificial magnetic surfaces in such a way. At first glance, this seems to be impossible simply because the electric field very near to the plane is very small, so that whatever structure we place here, it will be weakly excited.

However, there can exist a possibility for a very strong resonance response from an array of small particles positioned *very near* to an ideally conducting surface due to very strong interaction between the array particles and the ground plane. In other words, we can describe this situation using the image principle and say that the reactive impedance induced in the array particles by the image currents (plus the mutual impedance from all the other particles in the original array) can come into resonance with the proper impedance of the inclusions, if the array is positioned very close to the ground plane and the distance to the image sources is very small.

2. Numerical Results

In this study, we model the scatterers by electric dipoles. The equation for the reference dipole moment can be written in the form:

$$\alpha^{-1}p = E_{\text{ext}} + E_{p'} + \sum_{(m,n)\neq(0,0)} [E_{p_{m,n}} + E_{p'_{m,n}}] \tag{1}$$

where p is the reference scatterer's dipole moment, E_{ext} is the external (to the grid) electric field, $E_{p'}$ is the field of the reference scatterer's image dipole, $E_{p_{m,n}}$ and $E_{p'_{m,n}}$ are the fields of the other scatterers and their image dipoles, respectively. Field E_{ext} is formed by the incident plane wave field and the field of the incident wave reflected from the metal plane:

$$E_{\text{ext}} = 2j\sin(kh)\,E_{\text{inc}} \tag{2}$$

The electric fields of the scatterers and the image dipoles can be expressed through the dipole Green function $G(\omega,\mathbf{R})$: $E_p(\mathbf{R}) = G(\omega,\mathbf{R})p$. We consider the normal incidence, which means that all the dipole moments of scatterers are equal $p_{m,n} = p$. Thus, Equation (1) can be rewritten as:

$$\alpha^{-1}p = E_{\text{ext}} + \left\{-G(2h\mathbf{z}) + \sum_{(m,n)\neq(0,0)} [G(\mathbf{R}_{m,n}) - G(\mathbf{R}_{m,n} + 2h\mathbf{z})]\right\} p \tag{3}$$

Let us denote by C the expression in the brackets in the previous formula *(interaction constant)*:

$$C = -G(2h\mathbf{z}) + \sum_{(m,n)\neq(0,0)} [G(\mathbf{R}_{m,n}) - G(\mathbf{R}_{m,n} + 2h\mathbf{z})] \tag{4}$$

The reflection coefficient from the structure is equal to

$$R = -1 + \frac{k}{\varepsilon_0 a^2}\frac{2j\sin^2(kh)}{\alpha^{-1} - C} \tag{5}$$

Let us note that for small heights h the obtained formula contains a very small value of sin function of kh squared. Two physical phenomena are taken into account by this term. The first one is that acting to the grid external field is the sum of the incident wave and the corresponding reflected wave from the ground plane. The second one is that the plane wave produced by the grid also consists of the original wave and that reflected from the ground plane (this second term can be associated with the field produced by the grid of the image dipoles).

For lossless particles, the imaginary part of α^{-1} is determined by its radiation resistance only [1], and the reflection coefficient can be written as

$$R = -1 + \frac{2}{1 - j\varepsilon_0 a^2 \dfrac{\mathrm{Re}\{\alpha^{-1} - C\}}{k\sin^2 kh}} \tag{6}$$

In this study we are interested in the situation when all the sizes are very small compared to the wavelength ($ka \ll 1$), which means that we can use the corresponding quasi-static approximation for the interaction constant [2, 3] (here $R_0 = a/1.438$):

$$C = \frac{1}{4\varepsilon_0 a^2 R_0}\left[1 - \frac{1}{[1 + (2h/R_0)^2]^{3/2}}\right] + \frac{1}{4\pi\varepsilon_0(2h)^3} + j\left[\frac{k^3}{6\pi\varepsilon_0} - \frac{k}{\varepsilon_0 a^2}\sin^2(kh)\right] \tag{7}$$

2.1 Resonance condition

2.1.1 Point dipoles

From (7) we observe that the real part of quantity C is positive, so in principle it can match the positive real part of α^{-1}. If the polarizability value is small, its inverse value is large, and it cannot be compensated by the interaction constant. In this case the reflection coefficient is close to -1, which corresponds to an electric screen. For higher polarizabilities the resonance is possible when $\mathrm{Re}\{\alpha^{-1} - C\} = 0$. The reflection coefficient becomes equal to $+1$ which corresponds to magnetic screen. For point-dipole particles the resonance at small heights is always possible for arbitrary particle polarizabilities. Indeed, the near field of the closest image dipole (which is proportional to $1/h^3$) dominates at very small heights, see (7), and in the limit $h \to 0$ we have $\mathrm{Re}\{C\} \to \infty$. This means that for arbitary small polarizabilities α there exists a point where the resonance condition $\mathrm{Re}\{\alpha^{-1}\} = \mathrm{Re}\{C\}$ is satisfied. However, this reasoning assumes zero size of the particles.

One can suggest to use planar particles, like thin strips, so that the interaction constant can be increased by choosing a very small distance to the ground, smaller than the particle size. However, in this case the previous estimations for the interaction constant which showed unlimited increase of γ with decreasing the height are not valid. This is because in this case the near field of the mirror-image particle is not the point-source field. This problem can be easily studied numerically, but the result is anyway easy to predict. Taking for simplicity narrow strip particles, we observe that $\mathrm{Re}\{\alpha^{-1}\}$ is proportional to the imaginary part of the input impedance of a single strip considered as a dipole antenna. At very small heights, the interaction field is mainly the field created by the nearest image particle. Thus, the value of $\mathrm{Re}\{C\}$ is proportional to the imaginary part of the mutual impedance between the original strip and its mirrow image. Since the last quantity is always smaller than the proper impedance, we conclude that the resonance is not actually possible. This conclusion is quite general and is valid for arbitary shapes of inclusions.

From these considerations we see that to realize very thin magnetic layers we should find a way to increase the particle polarizability without increasing its size (since we should position the array very near to the ground plane to provide a large value of the interaction constant).

2.1.2 Arrays of short loaded wire antennas

We have suggested that this can be made possible by loading particles (short strip dipoles with capacitive input impedance) by bulk loads. If the load impedance is inductive, the particle polarizability near the particle resonance becomes large, and it becomes possible to fulfill the resonance condition for the grid over conducting plane.

Suppose that the array consists of short wire dipoles with total length $2l$ loaded by bulk reactive impedances Z, Fig. 1. For our purpose, the load impedance should be inductive, so we denote $Z = j\omega L$. Using the antenna model [4] for determination of the polarizability of loaded wires (for the real part of the polarizability's inverse value) we have:

$$\alpha = \left(\frac{C_{\mathrm{wire}}^{-1} - \omega^2 L}{l^2} + j\frac{k^3}{6\pi\varepsilon_0} \right)^{-1} \tag{8}$$

where $C_{\mathrm{wire}} = \pi l \varepsilon_0 / \log(l/r_0)$ is capacitance of the wire, L is the inductance of the load, l is the half length of wire and r_0 is the radius of wire.

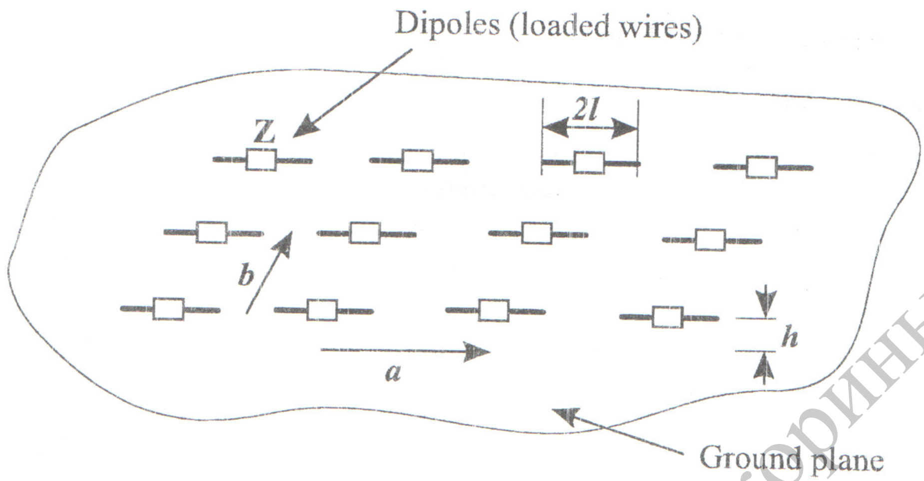

Figure 1. Geometry of the grid of loaded wires

One can see that indeed there is a resonance of the reflection coefficient with the central frequency

$$\omega_0 = \sqrt{\frac{C_{\rm wire}^{-1} - Cl^2}{L}} \tag{9}$$

It is important to note that this value is smaller than the resonance frequency of individual loaded wires $\omega_{\rm wire} = 1/\sqrt{LC_{\rm wire}}$ due to the field interaction between inclusions. The dependence of the resonance frequency shift $\omega_0/\omega_{\rm wire}$ on the thickness of the screen is plotted on Fig. 2.

When the height is large, the resonance is determined by the properties of the scatterer, with a small shift due to interactions within the array. At small heights, the field of the image dipole becomes large, and the resonance frequency of the reflection coefficient ω_0 becomes much smaller than the resonance frequency of a single array element $\omega_{\rm wire}$, and in theory the resonance frequency can approach zero. In practice this is restricted by the particle size.

3. Negative permittivity in arrays of wires and other topics

Recently, a new realization and new applications for composite media with negative permittivity and permeability were suggested [5, 6, 7]. One possible realization of materials with negative permittivity is the use of three-dimensional grids formed of thin parallel conducting wires. This structure is known in microwave engineering for a long time as an artificial dielectric. However, the existing models are limited by dense arrays and axial propagation. Here we report on the results of our efforts in this direction.

We consider "wire media": rectangular grids of infinite wires as depicted on Figure 3. The elementary cells have dimensions $\mathbf{a} \times \mathbf{b}$. The diameter of wires is $r_0 \ll a, b$. Our mail goal is to find the effective parameters: propagation constant and characteristic impedance for this artificial medium. Next, we will discuss possible descriptions of the material in terms of effective permittivity and permeability parameters.

Two main results will be presented in the conference. First, a general description of wire media capable to realize negative permittivity. The model takes into account general propagation direction, and both dense and sparse grids. Second, this system can be useful

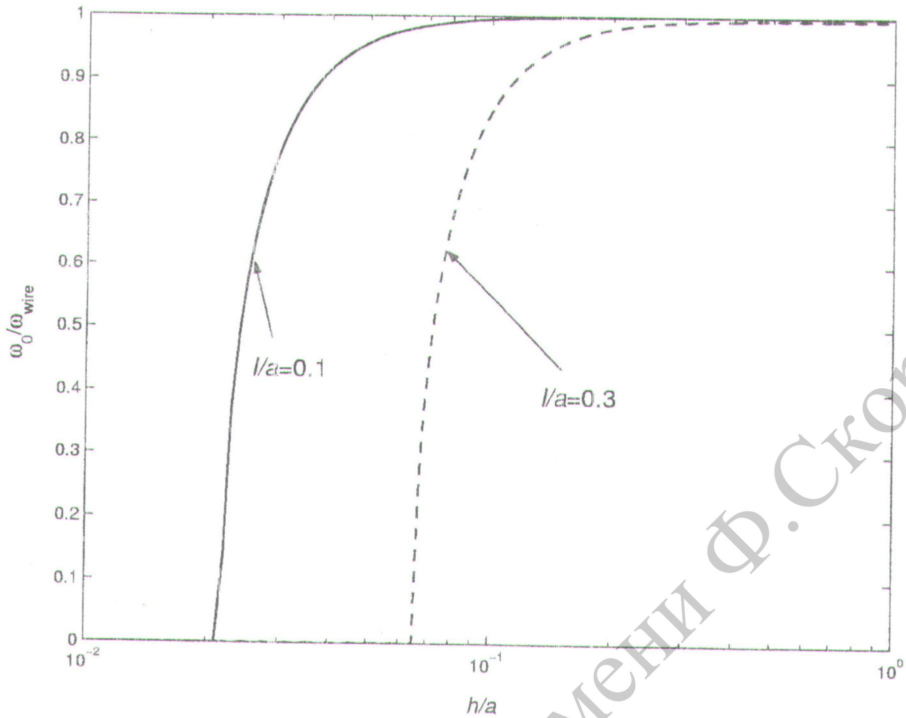

Figure 2. Dependence of the resonance frequency shift on the normalized thickness of the screen. In this example $l/r_0 = 10$.

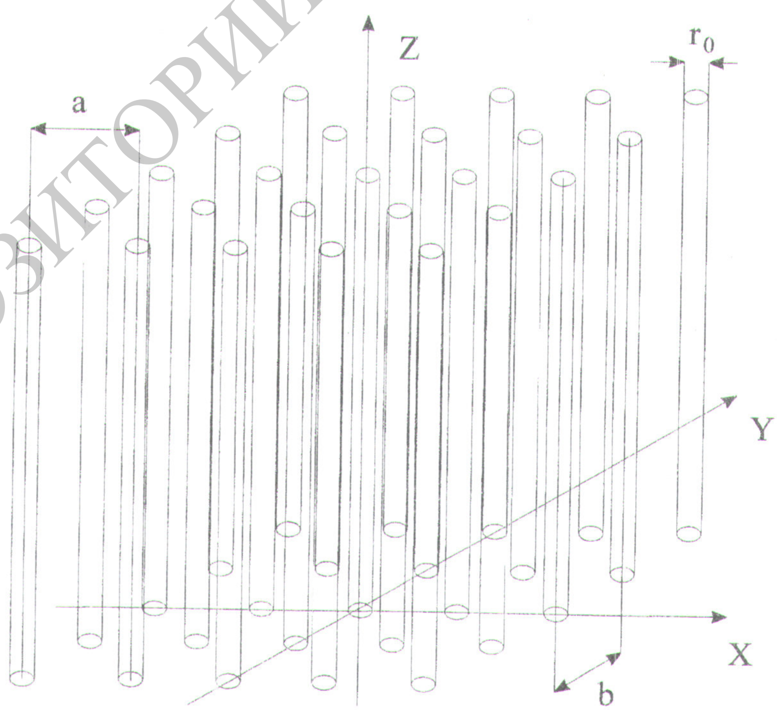

Figure 3. Inner geometry of wire media

as a simple model problem of spatially dispersive media, which allows analytical solutions. Different media descriptions can be easily analysed and compared.

Finally, other new developments in the field, such as nonreciprocal electromagnetic bandgap structures, will be briefly reviewed.

Ackowledgement

This paper is a review of recent studies made by the author together with P. Belov, S. Maslovski, and A. Viitanen.

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