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Radar Absorbing Materials Based on Metamaterials

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Abstract. The use of metamaterial for design of radar absorbing material (RAM) is discussed. The typical features of the frequency dependencies of ε′, ε″, μ′, μ″ of composites manufactured of different types of resonant inclusions are given as an example. The RAM characteristics obtained by the use of the composites are given. It is shown that it is possible to use for RAM design the metamaterials with both the positive values of ε′, μ′ and negative ones. Making use of the frequency band with negative ε and μ it is possible to create a RAM with low reflection coefficient in a wide range of the angles of electromagnetic wave incidence.

Introduction

The recently developed materials with negative values of permeability and permittivity have raised a huge amount of publications devoted to research of those materials in radio-, microwave, infrared and optical ranges of electromagnetic spectrum; they have also led to design of devices that promise remarkable applications. These so called metamaterials are featured by the inclusions that interact in a resonant manner with the electromagnetic wave propagating in the metamaterial. The metamaterials intended for functioning in the acoustic range have become the subject of the investigation recently [1, 2]. The metamaterials of that type should be composed of resonant inclusions, and thus all metamaterials should possess a strong frequency dispersion of material parameters and a resonant energy absorption. The considerable losses inherent to metamaterials hinder the realization of many attractive ideas relevant to their application. The realization of superresolution [3], the solution of cloaking problem [4], the creation of open resonators [5], omnidirectional antennas [6], etc. are restrained by principal limits due to unavoidable energy losses in metamaterials (see the discussion in [7-11]). However there are applications that imply a certain level of losses, e.g. creation of radar absorbing materials. Metamaterial with magnetic losses could be used for, so called, Salisbury screen [12], and a combination of proper values of ε and μ could result in a Dallenbach layer [12].

It should be noted that composites with negative ε and μ were created and used long before the appearance of the term “metamaterial”. Yet in 1952 a section was published in a widely known book [13], it dealt with the design of composites to enhance the operation of antennas. To create artificial magnetic permeability, it was suggested to use split-ring or horseshoe shaped inclusions, and the formulas given in [13] showed the typical resonance behavior with negative value of μ at high frequencies. In 1990 a book [10] was published in Russia which summarized some of the complex materials investigations. Partly the results contained there were published in English journals [15-18]. In 1997 both the theoretical and experimental data were published [19] for composites with inclusions in the shape of bifilar helixes, where negative values of μ and ε were obtained and formulas were given which well corresponded to experimental data. At zero pitch value and number of turns equal to one they turn into expressions for well-known split-ring resonators. The mentioned investigations were not aimed to study negative refraction but rather comprised a systematic work in order to obtain any desired values of permittivity and permeability in the scope of restrictions imposed by Kramers-Kronig relations. One of their possible applications is the creation of radar absorbing materials (RAM).

Typical frequency dispersions of metamaterials used to create RAM

Composites filled with the inclusions shown in Fig.1 were used in RAM design. The composites were characterized by the volume fraction of inclusions and by different shapes of inclusions.

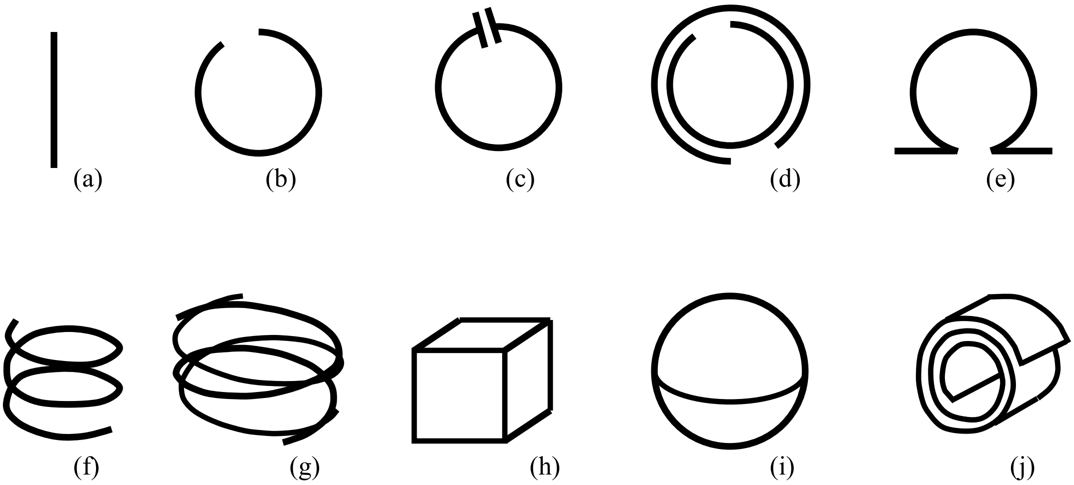


Fig. 1. Inclusions for RAM fabrication: wire (a), split ring (b), loaded ring (c), double split ring (d), Ω-inclusion (e), helix (f), bifilar helix (g), ferroelectric cube (h) and sphere (i), swiss roll (j)

The use of wires enables to create the required frequency dispersion of a composite permittivity and to get negative values of ε at above resonance frequencies. Split rings, loaded rings, double split rings, helixes, bi-helixes were used for creation of effective permeability. The same could be said with regards to swiss rolls inclusions [20].

Note that the use of helixes could result in negative values of ε thanks to the appearance of the dipole moment at the LC-resonance-causing lengths of the helix wire, where L is the helix inductance, C is the capacitance. Ferroelectric inclusions can be also used to achieve an artificial high-frequency magnetism. The appearance of the magnetic moment in particles with high values of ε at frequencies corresponding to magnetic mode resonance is rather known [21], however that phenomenon was discussed in metamaterials publications less frequently than the excitation of magnetic moment in inclusions of more common shapes, such as (b)-(e), Fig.1. The oscillations with frequencies coinciding to the eigenfrequencies of a spherical dielectric resonator can be excited in the dielectric particle of a proper radius with a high value of ε [22, 23]. The first magnetic TE-mode is a fundamental one for electromagnetic oscillations of a dielectric resonator. Note that cubes or parallelepipeds can also be used.

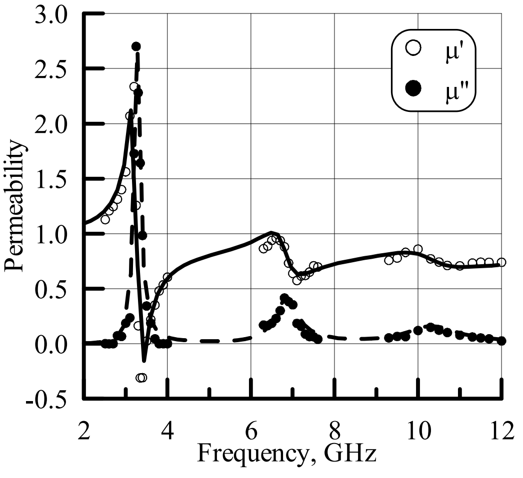
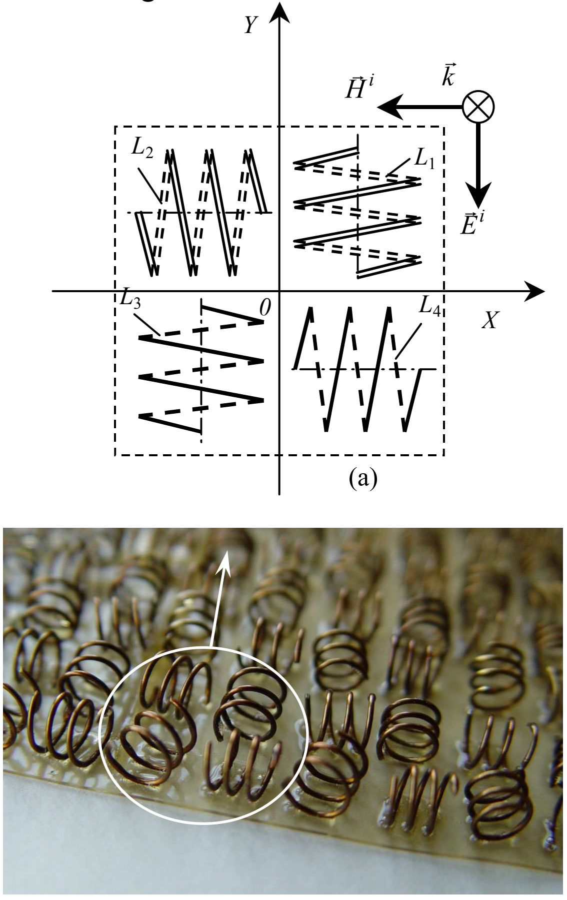


Fig.2. Effective permeability of a single-layer composite with ferroelectric inclusions of cubic shape

In Fig.2 the experimental results can be seen which obtained for the composite made of the $Ba_{i-x}Sr_xTiO_3$ ferroelectric cubes with $\varepsilon' \approx 3000$ and $\varepsilon'' / \varepsilon' \leq 0.05$. The cube edge size is 1.5 mm, the inclusion volume fraction is 68%. Here and below in the material parameter graphs the measured results are given by circle marks, the curves correspond to their analytical approximations resulted from electromagnetic modeling [23], [19]. The resonant behavior of μ′ and μ″ is perfectly seen. Note that with the help of inclusions of different sizes a magnetic mode can be excited in some of them, and the electric mode in others, as suggested in [24]. A metamaterial with negative values of ε and μ could be thus created. This is one of rather rare possibilities to obtain an isotropic metamaterial.

By applying an electric field we can control its resonant frequency. RAM made of that material is rather complex to produce despite the apparent simplicity, because it is necessary to manufacture inclusions of precise geometrical sizes of rigid ceramics; besides, that material could be too heavy. Composites made of single and bifilar helixes seem rather simple in manufacturing and light in weight. For the first time the information about such a RAM was published in [25]. It described the device for mass production of helix inclusions and the results of measuring the reflection coefficient of Dallenbach screen made of them.

We will now treat in more detail the properties of a composite filled with right- and left-handed wire helixes arranged in a certain order in the form of a single layer of inclusions (Fig. 3).



(b)

Fig. 3. Unit cell (a) and an experimental sample (b) of a composite made of wire helixes

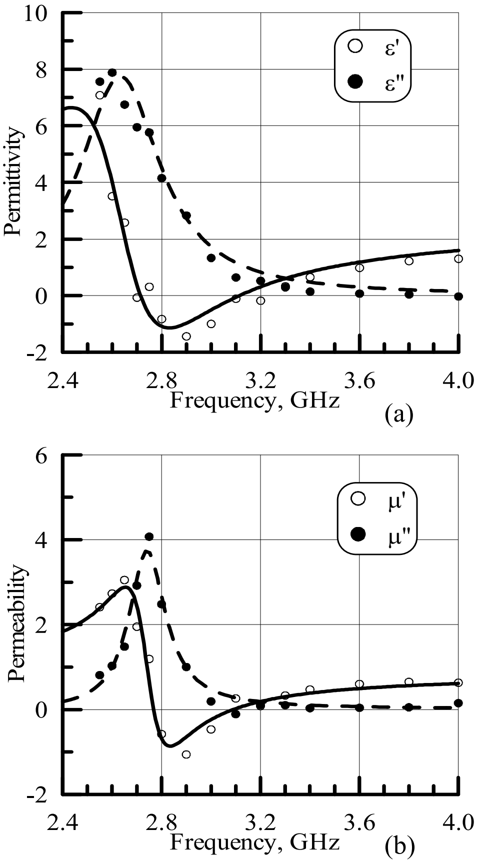


Fig. 4. Effective permittivity (a) and permeability (b) of an experimental sample of a composite made of wire helixes, each helix has three turns, the pitch of 2 mm and the diameter of 5 mm.

Each inclusion may be related to vectors of electric and magnetic moments. The components of these moments interact with the external electromagnetic field such that the macroscopic properties of the sample may be interpreted as the emergence of the effective permittivity and permeability of the composite. The results of measurements of the effective parameters of such a composite, given in Fig. 4, prove this inference.

The helixes are made of a high-resistance Nichrome wire 0.4 mm in diameter (because the composite was developed for the purpose of absorbing electromagnetic waves). The resonant electromagnetic properties of this composite show up fairly clearly. A singular feature of this material is that ε′ and μ′ reach their negative values simultaneously in one and the same frequency band. If a layer of the material is applied onto the metal the RAM the features presented in Fig. 5 will be obtained in an experiment. Naturally, the material is rather narrow-band, though it manifests the property which traditional RAMs do not possess. At low frequencies the dielectric and magnetic losses of the material are negligibly low, and the material becomes transparent for any low-frequency application. It makes the material highly promising for solving numerous electromagnetic compatibility problems.

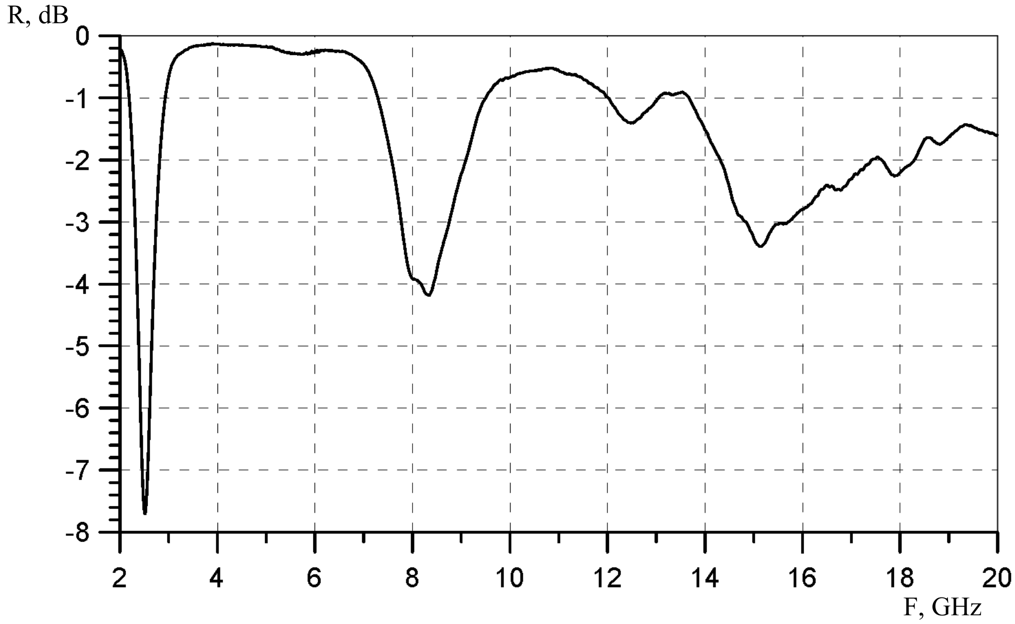


Fig. 5. Frequency dependence of the reflection coefficient of the helix-based coating

Trying to compare the measured and calculated reflection coefficient of a conducting plate coated with metamaterial we shall find that these quantities do not match each other if the calculations are performed by the use of the ε and μ values of the metamaterial layer derived from the free-space measurements. The reason for this is a change in the effective properties of the layer when a conducting substrate is placed nearby, thus invoking a strong interaction between each helix of the composite and its mirror counterpart. As a consequence, the resonant frequency is shifted and several new resonances may happen to appear. It is clearly demonstrated in Fig. 6, where the effective properties were extracted from the measurements of magnitude and phase of a flat electromagnetic wave reflected, firstly, from the layer placed in the free space and, secondly, from the same layer backed by a conducting substrate. The appearance of the extra resonances and changes in the features of the main resonance are perfectly seen (compare to Fig. 4).

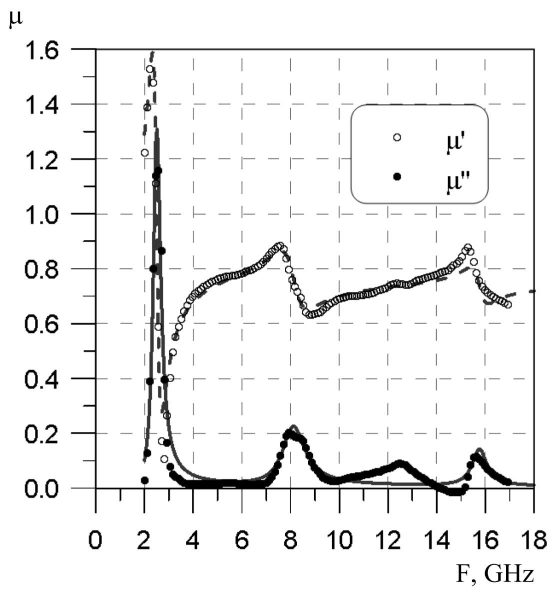
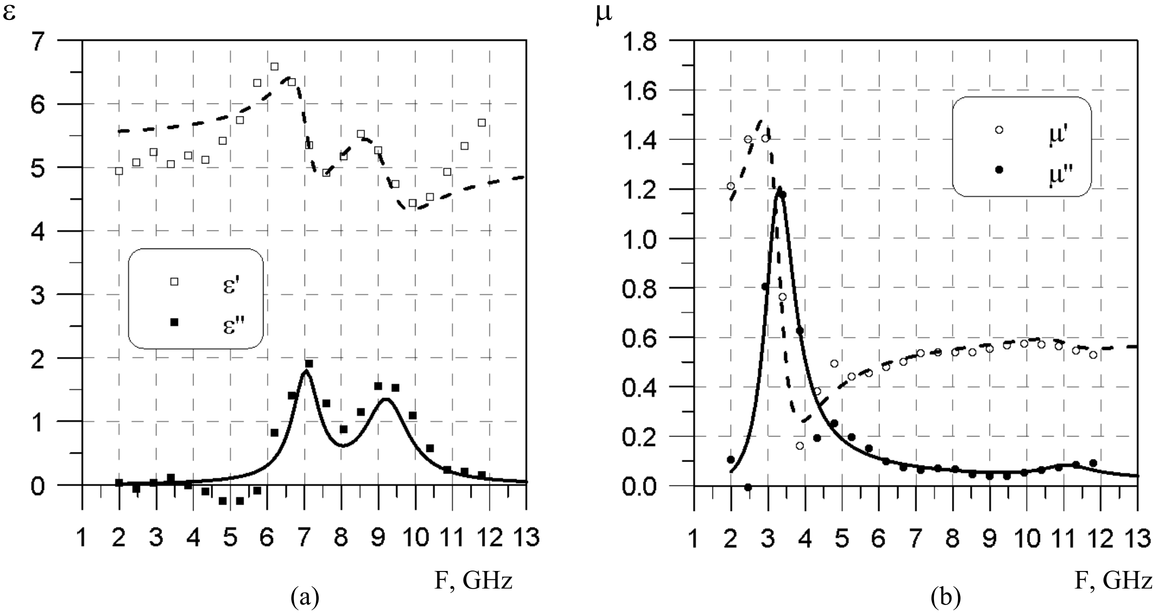


Fig. 6. Effective permeability of the helix-filled composite layer backed by a conducting substrate

Therefore the material properties of the metamaterials under discussion are of rather conditional. Here we will give effective parameters obtained by processing the values of complex reflection and transmission coefficients of the flat layers of the material while measured in the free space. Mind, that the flat electromagnetic wave incident onto the measured sample surface is distorted over specific scales that can exceed the sample layer thickness considerably [26]. Thus when the material plate is placed onto a metal surface or is applied to another similar plate to form a single sample it often causes some changes in effective parameters of the resulting layer. Therefore the precise computer RAM simulation becomes difficult.

By combining helixes of different sizes we can get rather interesting frequency features of values of ε′, ε″, μ′, μ″. They can differ in the position of minima and maxima of ε′, ε″, μ′, μ″ within a frequency band and in a great variety of metal-applied RAM reflection coefficient spectra. As an example the Fig. 7 shows the frequency dependencies of the material parameters of the sample consisting of the combination of bifilar helixes (bi-helixes) of different diameters, namely, 2 and 3 mm.



(a) (b)

Fig. 7. Frequency dependencies of the permittivity (a) and permeability (b) of a composite sample consisting of combined helixes of different diameters

The inclusions were made of 50 micrometers diameter manganin wire. The bi-helix with smaller diameter was inserted into the bigger one with their axes directed orthogonal to each other. Outer bi-helix consisted of two turns with the pitch of 1 mm. Inner bi-helix had 2.5 turns with 0.8 mm pitch. The inclusions made in that way were densely packed to form a one-layer coating. Fig. 8 shows the reflection coefficient of the coating applied onto metal. Each of the extrema is related to the specific extremum of the frequency dependence of material parameters. Note that in combining the layers prepared of helixes of different sizes we can get a coating with good wideband features.

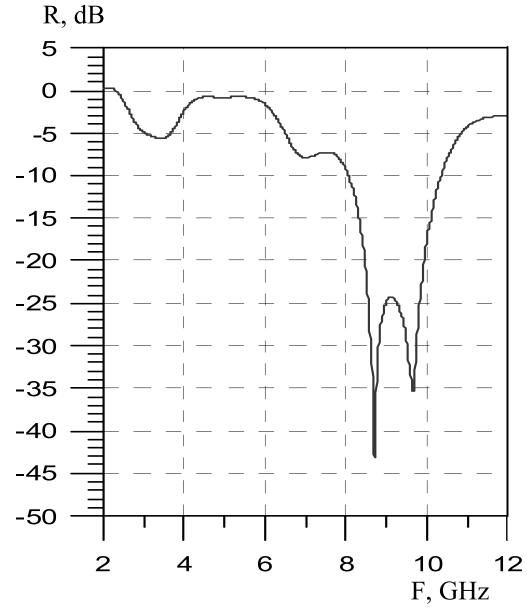
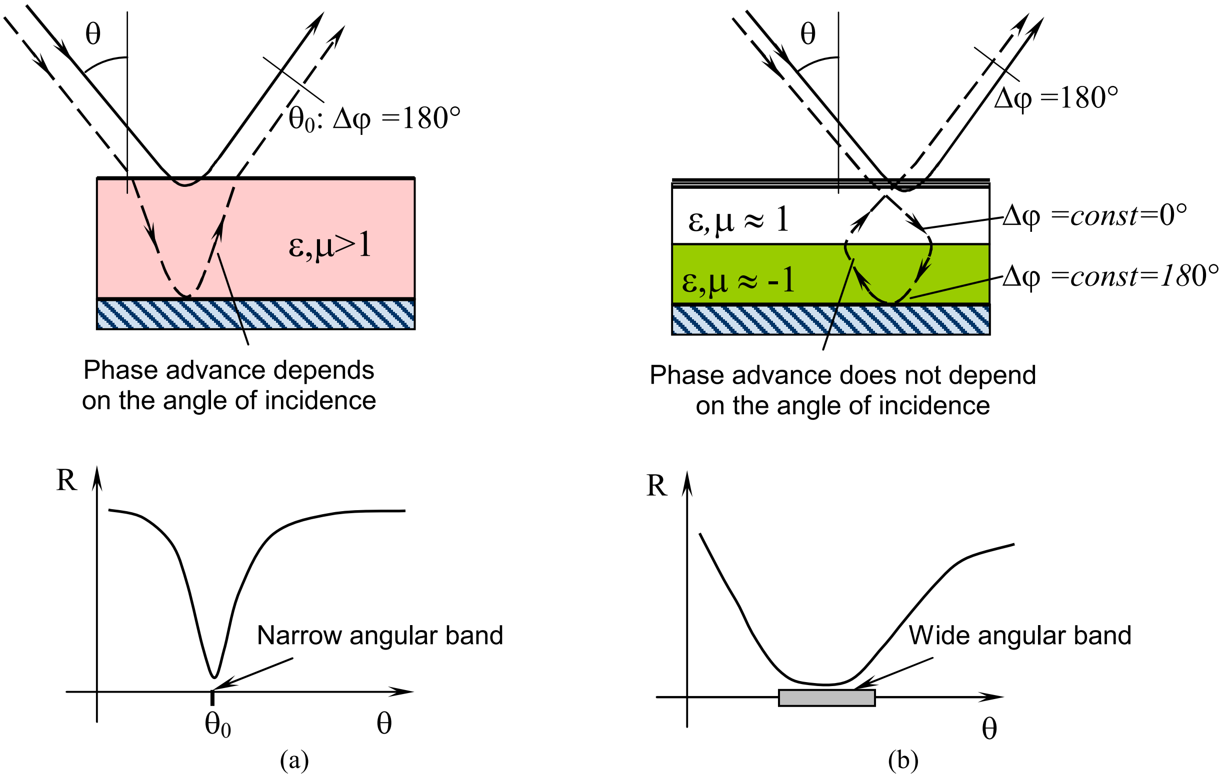


Fig. 8. Frequency dependence of the reflection coefficient of a composite sample consisting of combined helixes of different diameters

Wide angular band of the backward wave RAM

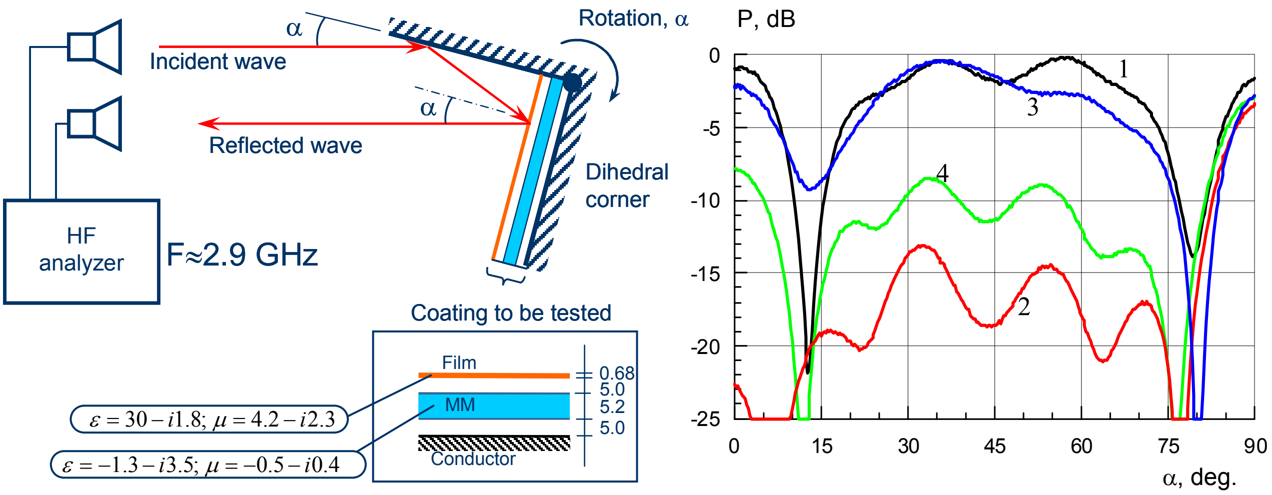
In the previous examples of RAM design no special attention was paid to the frequency region where the negative refraction manifests itself. Though, RAM can acquire absolutely remarkable properties in this specific region of negative values of ε and μ [5, 27]. Look at the Fig. 9*a*. The picture gives a schematic description of the functioning of an ordinary interference coating with $\varepsilon > 1$ and $\mu > 1$.



(a) (b)

Fig. 9. Schematic description of the functioning of an ordinary (a) and metamaterial-based (b) radar absorbing coatings of interference type

The thickness of the coating should be chosen as to provide the 180° phase difference of the wave reflected from the outer surface (solid line) and the wave that passed through the layer and reflected from the metal, the magnitudes should be close to each other to insure the minimum of the reflection coefficient. Let an incident wave frequency be constant. If the incident angle varies, the phase advance depends on the angle of the wave incidence provided the conventional coating is used. Correspondingly, angular dependencies are rather narrow. Let us consider the diagram shown in Fig. 9*b*. The coating consists of a thin semi-transparent magnetic film and two layers of equal thicknesses with ε, μ ≈1 and ε, μ ≈–1. In this case the total phase advance inside the layer does not depend on the incident angle due to mutual compensation caused by the negative phase velocity of the backward wave travelling in the metamaterial layer. Correspondingly, the reflection coefficient weakly depends on the incident angle, at least while the necessary magnitude relations are maintained. As there are no fundamental physical restrictions on the thickness of the described absorber, it can be made electrically thin at least, in principle, like the previously suggested system of complementary metamaterials [28].



(a) (b)

Fig. 10. Experimental setup (a) and the measured angular dependencies of the reflected power when different coatings are applied to the face of a dihedral corner

Our experimental investigations (Fig. 10) support these theoretical suggestions. The experimental setup is schematically shown in Fig. 10*a*. The angular dependency of the reflection coefficient of a coating can be measured via registering the power of the reflected wave in the course of the rotation of a dihedral corner one face of which is lined with a tested coating. An example of the measured reflected power (in dB) is depicted in Fig. 10*b*, curve 1 corresponds to the uncoated corner, curve 2: metamaterial-based multilayer coating is arranged as suggested above, curve 3: only semi-transparent film is placed parallel to the corner face, curve 4: only metamaterial layer is present on the face. The metamaterial sample was prepared using right- and left-handed helixes as shown in Fig. 3 and Fig. 4. The superiority of the sandwiched structure (curve 2) is clearly seen, one can observe a broad angular range of the efficient absorption. Note, the value of operational frequency (F=2.89 GHz) was chosen as to secure the negative phase advance of the wave penetrated into the metamaterial. The observed high performance of the coating significantly degraded when frequency was changed to the values (not far from the resonance) where the metamaterial reveals the properties of ordinary matter, i.e. ε, μ ≥ 1.

Conclusion

Thus, the possible application of the metamaterials is the creation of effective RAMs. The discussed results demonstrate that RAM of this type may exhibit a number of advantages over conventional materials, including the extensive design flexibility. In particular, one can create artificial composite materials with good absorption due to reasonably high dielectric and magnetic losses; besides, the materials can secure low reflection provided the input impedance of the coating is close to that of the free space owing to the proper ε and μ choice.

A novel approach to design radar absorbing coatings of interference type is introduced. The use of metamaterials enables one to obtain some specific features, e.g., wide angular operational range at small electrical thickness. The latter becomes possible because the required phase relationships for mutual compensation of waves reflected from the media interfaces can be achieved by the application of a backward wave medium rather than by increasing the thickness of the coating layers. Finally, a technique to achieve a weak angular dependency of the wave reflection from a RAM coating is shown and experimentally tested.

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