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Compensation of Reflection from an RF Absorbent Material with the Help of a Lattice of Double Split Rings

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Abstract—The frequency dependences of the coefficients of reflection from a lattice of double split rings excited by an RF magnetic field and from an RF-absorbent composite based on resistive films or fibers are analyzed. It is shown that partial reflections from the surface of the composite and the closely spaced lattice can compensate each other and, thus, the reflection from the composite can be significantly reduced. It is experimentally confirmed that the reflection can be decreased by more than 15 dB as compared to the reflection from the composite in the absence of the lattice.

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INTRODUCTION

The problem of reducing the electromagnetic-wave reflection from the interface between two media has been a longstanding problem and, despite its age, remains a topical one due to the multiplicity of media, frequency bands, and specific applications for which the problem is to be solved. In optics, the common solution is to use interference coatings with specified refraction indices and thicknesses [1]. A similar solution can be implemented in the RF band; however, the physical thickness of the coating in this case becomes rather large. Therefore, to compensate reflection, e.g., in the microwave band, capacitive and inductive lattices are widely used. The lattice location and type are determined by the specificity of the problem and by the electromagnetic characteristics of the material. Thus, to improve the transparency of radomes, the lattices are usually placed within the layer that is to be matched [2]. In this case, the reflections from both the outer and inner boundaries of this layer are compensated. At a different location of the lattices, reflections from each of the two surfaces of the layer being matched can be compensated. It is shown in study [3] that, in a certain frequency range, the matching capacitive lattices located close to both surfaces of a material with large values of the real and imaginary parts of the permittivity considerably increase the coefficient of transmission through the layer. This effect is due to the resonance between the lattice and the surface of the material similarly to that which occurs in artificial magnetic conductors based on capacitive lattices [4].

To improve the antireflective properties of materials in the infrared and terahertz regions, lattices of cruciform metal elements [5, 6] and layers of composite with a high refraction index [7] are used.

During the last few years, metamaterials with properties unavailable in the nature have become widely known, among them materials based on lattices of double split rings [8]. When excited by an RF magnetic field, such rings allow a medium exhibiting artificial magnetism to be obtained. This effect can be used in negative-refraction materials and structures [8, 9].

In the present study, we consider another important application of lattices based on double split rings, namely, matching lightweight RF absorbent materials (RFAMs) to free space. In this case, it is important to identify the type of excitation (by a magnetic or electric alternating field) [10], considering the difficulties encountered in performing direct measurements that involve the use of special samples [11].

1. LIGHTWEIGHT BULK RF ABSORBENT MATERIALS

Lightweight bulk RFAMs are manufactured with the use of resistive films or sections of resistive fibers embedded in a foamed-dielectric matrix. Simplified schematics of these RFAMs are presented in Fig. 1. Figure 1a shows a composite that is a multilayer structure consisting of resistive films (*2*) separated by foamed plastic (*1*). Figure 1b shows a composite containing sections of resistive fibers chaotically distributed in a foamed-dielectric matrix. With a small relative volume of resistive films and fibers, a composite can be obtained whose relative complex permittivity $\varepsilon = \varepsilon' - j\varepsilon''$ in the microwave band satisfies the conditions

$$\varepsilon' - 1 \ll 1 \text{ and } \varepsilon'' < 2, \quad (1)$$

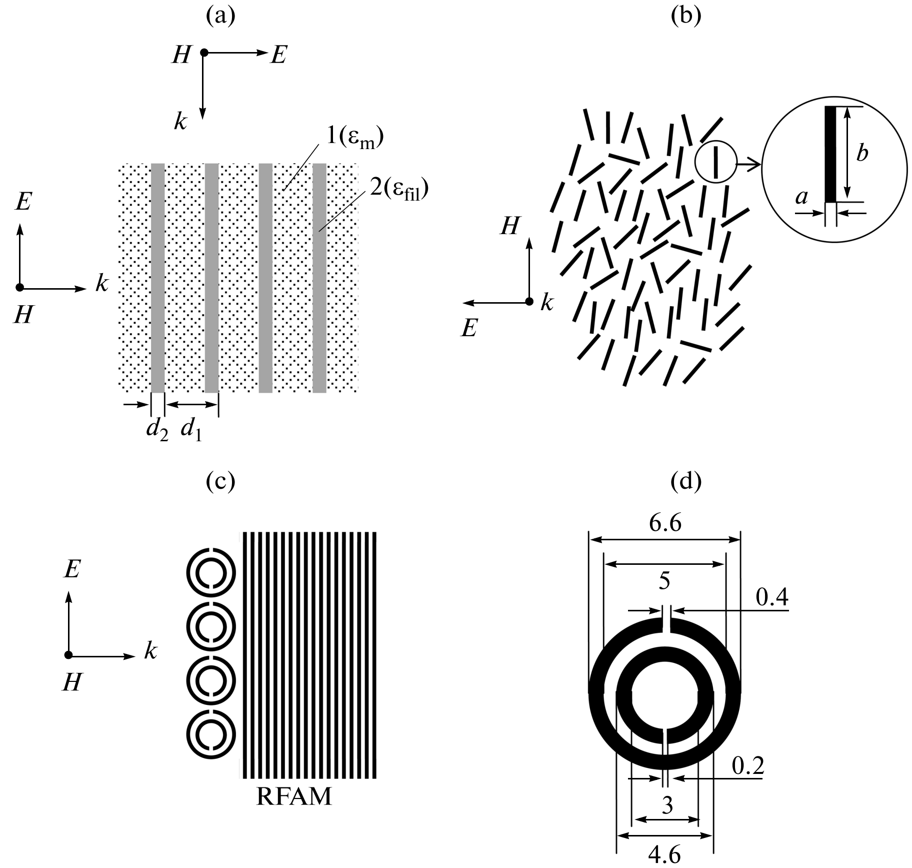

Fig. 1. RFAM schematics: (a) a composite based on resistive films, (b) a composite based on resistive fibers, (c) RFAM with a lattice of double split rings, and (d) double split ring.

and, thus, ensures low reflection from the plane interface between the composite and free space (about –10 dB or lower). Let us estimate the feasibility of conditions (1) for composites based on available resistive films and fibers. The permittivity of such filling material (resistive films and fibers) can be expressed in terms of conductivity σ (S/m) and frequency f (Hz) as

$$\varepsilon_{\rm fil} = -j\frac{1.8\times10^{10}\sigma}{f}. \quad (2)$$

For example, the relative permittivity of carbonized fiber with a conductivity of 10^4 S/m at a frequency of 10 GHz is $\varepsilon_{\rm fil} = -j1.8\times10^4$, whereas the imaginary part of the film in the form of carbonized paper with a conductivity of 30 S/m at the same frequency is $-j54$.

The effective permittivity $\varepsilon_{\rm eff}$ of the composite based on resistive films (see Fig. 1a) is defined by the known expression for a layered structure given, e.g., in [12]:

$$\varepsilon_{\rm eff} = \frac{\varepsilon_{\rm m}d_1 + \varepsilon_{\rm fil}d_2}{d_1 + d_2}. \quad (3)$$

Substituting expression (2) into formula (3) and taking into account that $d_1 \gg d_2$, we obtain

$$\varepsilon_{\rm eff} = \varepsilon_{\rm m} - j\frac{A}{f}, \quad A = 1.8\times10^{10}\sigma\frac{d_2}{d_1}. \quad (4)$$

Thus, at $\varepsilon_{\rm m} = 1.02$, $\sigma = 30$ S/m, and $d_2/d_1 = 0.01$, the complex permittivity of the composite at a frequency of 10 GHz is $\varepsilon_{\rm eff} = 1.02 - j0.54$ and satisfies condition (1).

The permittivity of the composite with a low concentration of filling resistive fibers (see Fig. 1b) (which is much lower than the percolation-threshold concentration) can be estimated with the use of the expression obtained from the Odelevskii's formula [13] with expression (2) taken into account:

$$\varepsilon_{\rm eff} = \varepsilon_{\rm m}\left(1 + \frac{C_{\rm c}}{3N(1+f^2/f_{\rm rel}^2)} - j\frac{C_{\rm c}f/f_{\rm rel}}{3N(1+f^2/f_{\rm rel}^2)}\right), \quad (5)$$

where $C_{\rm c}$ is the volume concentration of fibers in the composite, $N = \left(\frac{a}{b}\right)^2\left(\ln\frac{2b}{a} - 1\right)$ is the depolarization coefficient, and $f_{\rm rel} = 6\times10^9 N\sigma/\varepsilon_{\rm m}$ is the so-called relaxation frequency. At $\varepsilon_{\rm m} = 1.02$, $\sigma = 10^4$ S/m, $a =$

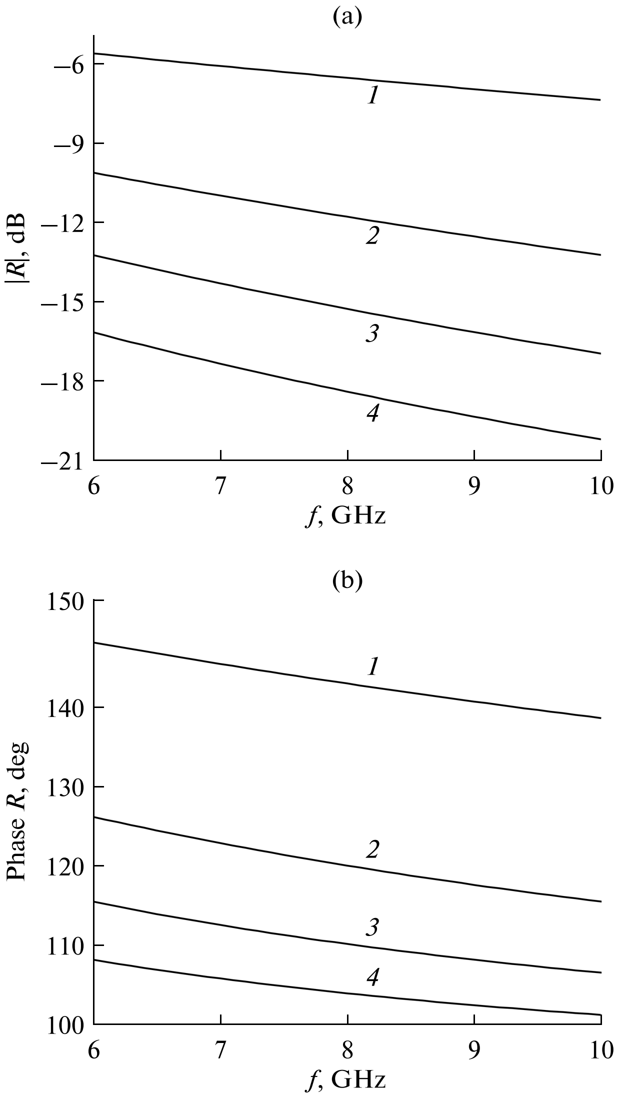

Fig. 2. Frequency dependence of the (a) magnitude and (b) phase of the coefficient of reflection from the RFAM based on resistive films calculated at A = (*1*) 3×10^{10}, (*2*) 1×10^{10}, (*3*) 0.6×10^{10}, and (*4*) 0.4×10^{10}.

0.008 mm, $b = 3$ mm, and $C_c = 3 \times 10^{-4}$, the permittivity of the composite at a frequency of 10 GHz is $\varepsilon_{eff} = 1.15 - j0.56$. A detailed study of RFAMs based on resistive fibers is presented in the Transactions of VIAM (All-Russian Scientific Research Institute of Aviation Materials), e.g., in [14, 15].

Figure 2 shows the frequency dependence of the magnitude and phase of the coefficient of reflection of a normally incident plane electromagnetic wave from the interface between a resistive-film RFAM and free space (see Fig. 1a) calculated by the formula

$$R = \frac{1 - \sqrt{\varepsilon_{eff}}}{1 + \sqrt{\varepsilon_{eff}}}. \quad (6)$$

Here, ε_{eff} is calculated with formula (4) for several values of parameter A. To simplify the calculation, it is assumed that $\varepsilon_m = 1$. As shown in Fig. 2, the magnitude and phase of the reflection coefficient decrease with increase in frequency, the value of the phase remaining in the second quadrant (90°–180°).

For a perfect matching of the RFAM under consideration to free space, it is desirable to use a structure with the inherent reflection coefficient whose magnitude is the same as the magnitude of the RFAM reflection coefficient, whereas the phases differ by 180°. In this case, the electromagnetic fields reflected from the RFAM and matching structure compensate each other. In the actual situation, when the magnitudes of the reflection coefficients differ and the phase difference is not 180°, the compensation effect is limited.

2. A LATTICE OF DOUBLE SPLIT RINGS

A significant effect of compensation of reflection from the RFAM over a sufficiently wide frequency range is observed when a lattice of double split rings is used as a matching structure. To produce this effect, the lattice is placed in the immediate vicinity of the free-space–RFAM interface (see Fig. 1c) so that the ring plane is parallel to vector $\vec{k}$ of the incident wave and normal to vector $\vec{H}$, whereas the gaps in the rings are oriented along vector $\vec{E}$ (RF magnetic excitation).

Figure 3 shows the frequency dependence of the inherent reflection coefficient of this lattice calculated for three values of the lattice pitch. The phase of the reflection coefficient is measured from the plane that passes through the centers of the ring elements. It is seen from the plots that, at the frequencies higher than the resonance one, the magnitude and phase of the reflection coefficient decrease; however, in this case, the phase value remains in the fourth quadrant (–90°–0°), i.e., the phase difference between the reflection coefficients of the RFAM and lattice is close to 180° and, therefore, the reflection from the RFAM is compensated. For better matching, the magnitudes of the lattice and RFAM reflection coefficients must be approximately the same, a requirement that can be satisfied by adjusting the lattice pitch.

3. MATCHING AN RFAM TO FREE SPACE

Figure 4 shows the frequency dependences of the coefficient of reflection from RFAMs with matching lattices calculated for the parameter $A = 0.6 \times 10^{10}$; 1×10^{10}; 1.5×10^{10}, and 3×10^{10} at the respective optimum values of the pitch P = 17, 14, 11, and 9 mm, which provide for the best matching of the RFAM to free space. For comparison, Fig. 4 also shows the frequency dependences of the coefficient of reflection from the same RFAMs without matching lattices.

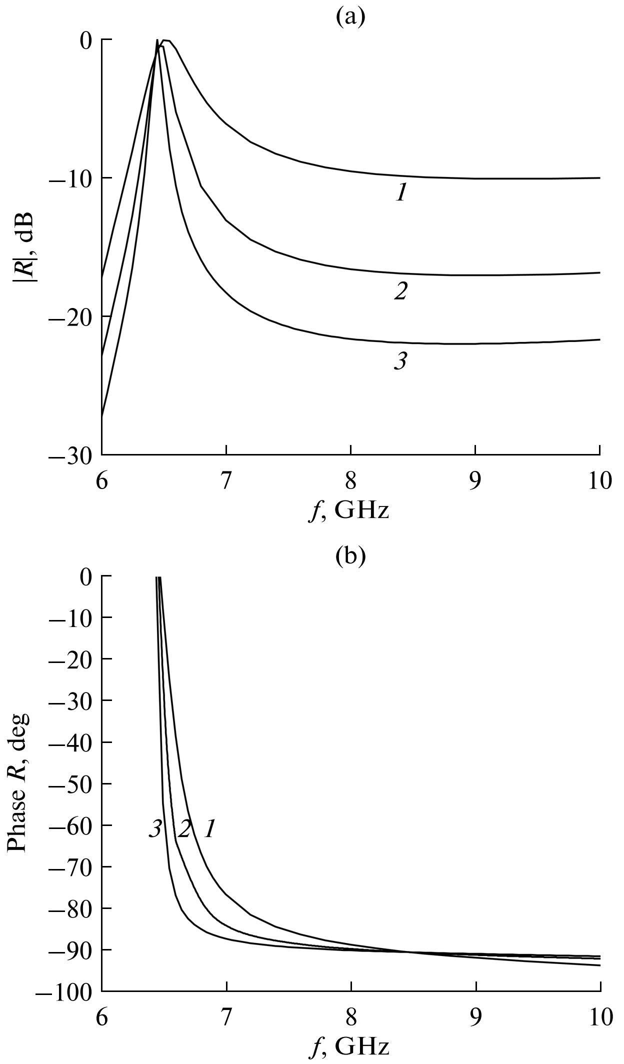

Fig. 3. Frequency dependence of the (a) magnitude and (b) phase of the coefficient of reflection from the lattice of double split rings calculated at the pitches P = (*1*) 10, (*2*) 15, and (*3*) 20 mm.

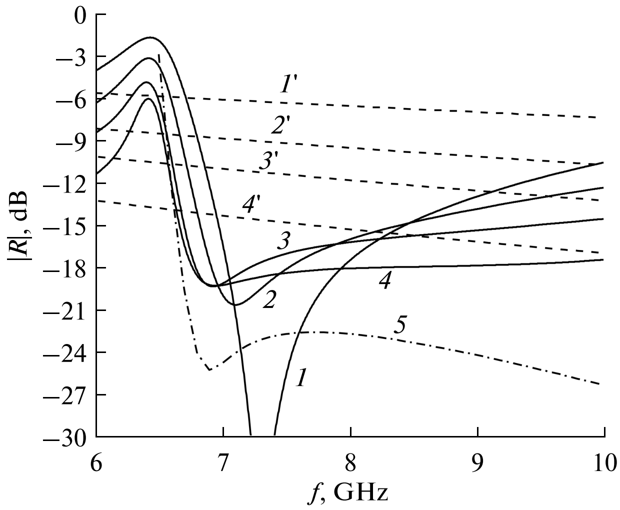

Fig. 4. Comparison of the calculated frequency dependences of the coefficient of reflection from the RFAM (*1–4*) with a matching lattice and (*1'–4'*) without a lattice; curve *5* is constructed without taking into account the phase incursion between the center of the lattice elements and the RFAM surface. Curves *1*, *1'* correspond to $A = 3 \times 10^{10}$, $P = 9$ mm; curves *2*, *2'* correspond to $A = 1.5 \times 10^{10}$, $P = 11$ mm; curves *3*, *3'* correspond to $A = 1 \times 10^{10}$, $P = 14$ mm; and curves *4*, *4'*, *5* correspond to $A = 3 \times 10^{10}$, $P = 17$ mm.

It should be noted that the matching results are significantly affected by the phase incursion between the centers of the lattice elements and the RFAM reflecting surface. Therefore, as parameter A decreases and, respectively, the optimum value of parameter P increases, the phase difference between the coefficients of reflection from the RFAM and from the lattice becomes smaller than 180°, a factor that weakens the effect of matching. Since this weakening of the effect depends on the electrical distance between the RFAM surface and the centers of the lattice elements, employment of small-sized elements, e.g., split rings loaded with capacitances [16, 17], noticeably improves the situation. This is verified by Fig. 4, which shows that curve *5* plotted without taking into account the phase incursion between the center of the lattice and the RFAM surface, differs from curve *4*.

The model of the layered composite was made of 0.07-mm-thick carbonized paper with a conductivity of 30 S/m and interlayers of foamed polystyrene with a permittivity of 1.02. The real part of the carbonized-paper permittivity in a frequency range of 5–15 GHz was about 15. Three RFAM models (no. 1, 2, and 3) were manufactured, which differed only by the thickness of the foamed-polystyrene interlayers with the effective permittivities $\varepsilon_{eff} = 2 - j3 \times 10^{10}/f$, $1.3 - j \times 10^{10}/f$, and $1.2 - j0.6 \times 10^{10}/f$, respectively.

Figure 5 shows the calculated frequency dependences of the coefficients of reflection from these models with the optimum matching lattices (solid curves) and without these lattices (dashed curves).

To test the proposed technique for matching the RFAM to free space, waveguide measurements of the coefficient of reflection from the RFAM models with a three-element lattice with the pitch $P_{mean} = 13$ mm averaged over two transverse waveguide coordinates were performed. The results of the reflection-coefficient measurement presented in Fig. 6 show that the best matching is obtained for material no. 2. It should be noted that the calculation of the coefficient of reflection from this material with a lattice under free-space conditions gave the same value of the pitch $P = 13$ mm for the optimum matching lattice.

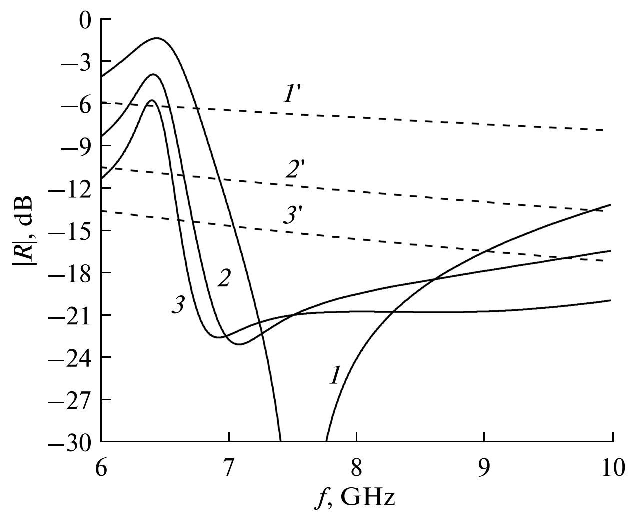

Fig. 5. Comparison of the calculated frequency dependences of the coefficient of reflection from three RFAM models (*1–3*) with a matching lattice and (*1'–3'*) without the lattice: (*1, 1'*) $\varepsilon_{eff} = 2 - j3 \times 10^{10}/f$, $P = 9$ mm; (*2, 2'*) $\varepsilon_{eff} = 1.3 - j10^{10}/f$, $P = 13$ mm; and (*3, 3'*) $\varepsilon_{eff} = 1.2 - j0.6 \times 10^{10}/f$, $P = 17$ mm.

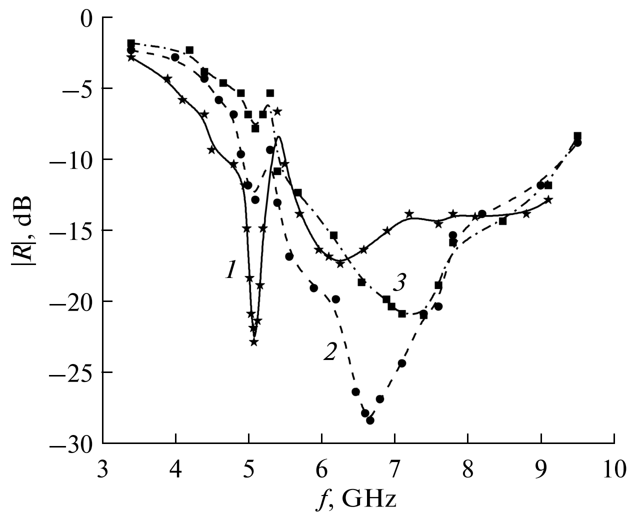

Fig. 6. Frequency dependences of the coefficients of reflection from three RFAM models with a matching lattice with the mean pitch $P_{mean} = 13$ mm measured by the waveguide technique at ε_{eff} = (*1*) $2 - j3 \times 10^{10}/f$, (*2*) $1.3 - j10^{10}/f$, and (*3*) $1.2 - j0.6 \times 10^{10}/f$.

CONCLUSIONS

The calculation and experiment have shown that the magnitude of the coefficient of reflection from a lattice based on double split rings magnetically excited at frequencies higher than the resonance one at first decreases as the frequency increases and, then, remains practically unchanged at a level dependent on the lattice pitch. In this case, the phase of the reflection coefficient, remaining in the forth quadrant, first rapidly decreases form 0° to the values close to −90° and, then, practically does not vary. The magnitude of the coefficient of reflection from the RF-absorbent composite based on resistive films or fibers smoothly decreases as the frequency increases, whereas the phase, remaining in the second quadrant, decreases toward +90°. In this case, the phase difference between the coefficients of reflection from the lattice and from the composite approaches 180°.

When the lattice is placed on the surface of the composite, the reflection from the composite is substantially compensated over a sufficiently wide frequency range.

The waveguide measurements of the reflection from the lattice–composite system have confirmed that this reflection is considerably lower (by more than 15 dB) as compared to the reflection from the composite without the lattice.

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