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RADIO PHENOMENA IN SOLIDS AND PLASMA

A Layer Radiowave Absorber Based on Double-Period Lattices of Resistive Squares

Yu. N. Kazantsev[a], V. A. Babayan[b], N. E. Kazantseva[a], O. A. D'yakonova[a], R. Mouchka[b], Ya. Vilčáková[b], and P. Sáha[b]

[a] *Fryazino Branch of Kotel'nikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, pl. Vvedenskogo 1, Fryazino, Moscow oblast, 141190 Russia*

[b] *Tomas Bata University in Zlin, T.G. Masaryk's square 275, Zlin, 76272 Czeck Republic*

e-mail: doa52@mail.ru

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Abstract—A radiowave-absorbing composite material based on double-period lattices of resistive squares is considered. Methods of the electric circuit and long line theories are applied to obtain expressions for the estimate of the effective permittivity of such a composite. It is shown that the frequency dependence of the effective permittivity of the realized composite is close to the relaxation value. The reflection characteristics of a radiowave absorber based on a composite with double-period lattices of resistive squares are investigated. It is found that, for such a radiowave absorber, the ratio of the difference of the extreme wavelengths of its operating band (corresponding to the minus-10-dB reflection level) to the thickness of the radiowave absorber is within an interval of 4.2–4.5.

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INTRODUCTION

It is known that one of the methods for expanding the operating frequency band of radiowave absorbers (RAs) is application of composites with frequency dispersions of permeability μ and permittivity ε [1–9]. In practice, the application of magnetic composites for RAs is often hampered by their substantial weight, and, therefore, investigation of various nonmagnetic composites with frequency dispersion of ε is a quite important problem. In studies [8, 9], the effect of expansion of the operating frequency band is theoretically analyzed for RAs based on materials with the relaxation and resonance laws of frequency dispersion of ε. This type of dispersion of ε can be realized in composites filled with carbon fibers of a certain length and conductivity [7]. Fabrication of composites with carbon fibers is technologically impeded by the fiber fragility, which causes smearing of the dispersion region. This problem is not encountered when composites are synthesized on the basis of periodic lattices of resistive elements. The *RC* and *RLC* types of lattices are applied in RAs called circuit analog absorbers (CAAs) [10, 11]. In CAAs, two or three lattices of a certain configuration and position provide for a low-reflection operating band that is close to a U-shaped one. In study [12], it is shown that the angular stability of a CAA can be enhanced and, hence, its substantial drawback can be reduced.

In this study, we propose and realize a layer RA based on a composite of identical double-period lattices with resistive elements of a square shape. The character of the frequency dispersion of the effective permittivity of such a composite is close to the relaxation one, a circumstance that provides for a certain expansion of the operating band of the RA compared to the case without relaxation of ε.

1. CALCULATION OF THE EFFECTIVE PERMITTIVITY OF A LATTICE OF RESISTIVE ELEMENTS BY MEANS OF THE ELECTRIC CIRCUIT AND LONG LINE METHODS

Figures 1a and 1b display a double-period lattice of square resistive elements and the corresponding equivalent circuit. In the equivalent circuit, r is the resistance of a square element, C is the capacitance between two neighboring elements, $Z = r - j/\omega C$, ω is the circular frequency, and W is the wave impedance of the medium in which the lattice is located. It is assumed that the dimensions of the structure are small compared to the wavelength and that the inductance can be disregarded. Input impedance Z_{in} and reflection coefficient R in section *1–1*, are

$$Z_{\text{in}} = \frac{WZ}{W + Z}, \qquad (1)$$

$$R = \frac{Z_{\text{in}} - W}{Z_{\text{in}} + W}, \qquad (2)$$

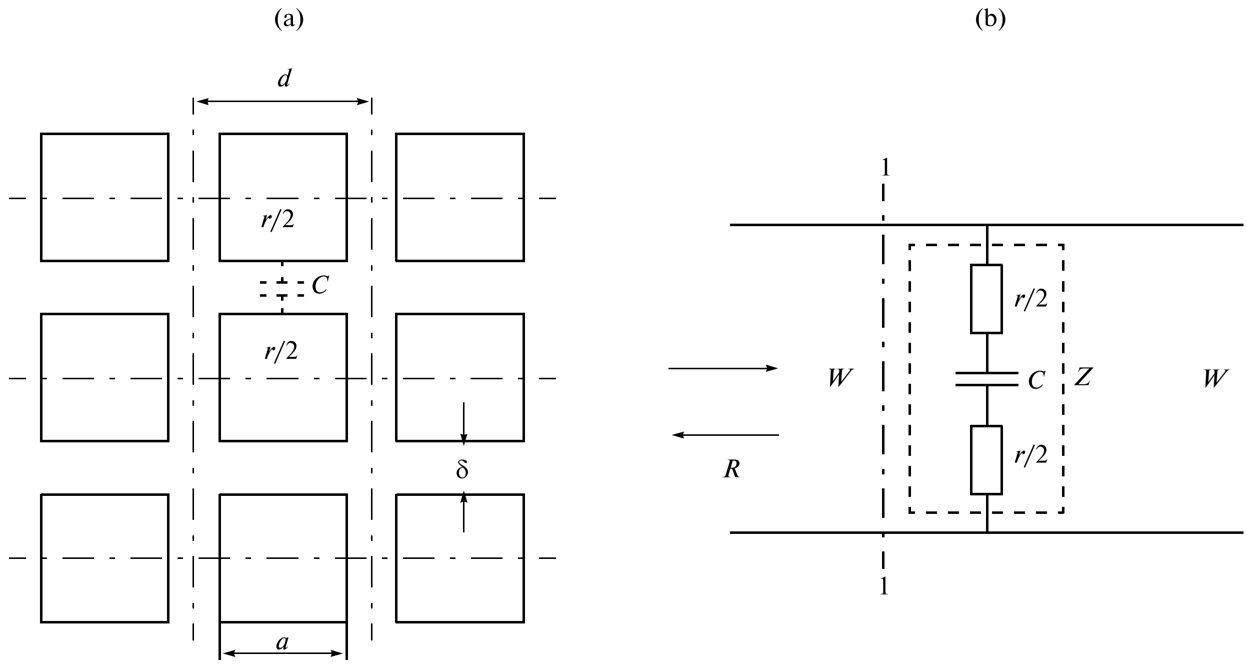

Fig. 1. Lattice of resistive squares: (a) the geometry of the lattice and (b) the equivalent circuit.

respectively. The substitution of expression (1) for Z_{in} into formula (2) yields

$$R = -\frac{1}{\left(2\frac{r}{W}+1\right) - \frac{2j}{W\omega C}}. \quad (3)$$

If a lattice of thickness l_1 is replaced by a homogeneous dielectric layer of the same thickness with the permittivity $\varepsilon_1 = \varepsilon_1' - j\varepsilon_1''$, the reflection coefficient of this layer calculated by means of the long line method is determined from the formula

$$R = -\frac{1}{1 + \frac{2c}{\omega l_1}\frac{\varepsilon_1''}{(\varepsilon_1')^2 + (\varepsilon_1'')^2} - j\frac{2c}{\omega l_1}\frac{\varepsilon_1'}{(\varepsilon_1')^2 + (\varepsilon_1'')^2}}, \quad (4)$$

where c is the velocity of light.

Equating expressions (3) and (4) for the reflection coefficient, we find the effective permittivity of the lattice from the obtained equation:

$$\varepsilon_1' = WC\frac{c}{l_1}\frac{1}{1+(r\omega C)^2}, \quad (5)$$

$$\varepsilon_1'' = WC\frac{c}{l_1}\frac{r\omega C}{1+(r\omega C)^2}. \quad (6)$$

Introducing the notation

$$A = WC\frac{c}{l_1} \text{ and } X = r\omega C, \quad (7)$$

we can represent formulas (5) and (6) as follows:

$$\varepsilon_1' = A\frac{1}{1+X^2}, \quad (8)$$

$$\varepsilon_1'' = A\frac{X}{1+X^2}. \quad (9)$$

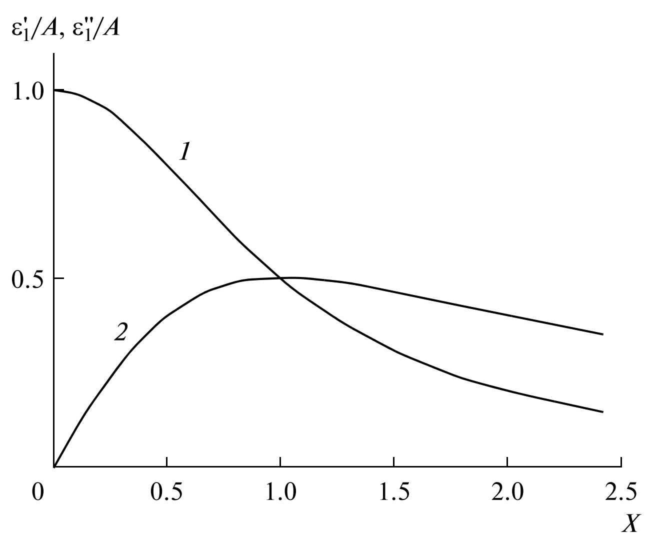

Fig. 2. Normalized frequency dependences of the (curve *1*) real and (curve *2*) imaginary parts of the effective permittivity of a lattice of resistive squares.

Functions ε_1'/A (curve *1*) and ε_1''/A (curve *2*) are plotted in Fig. 2. These plots are typical relaxation curves such that the maximum of the dependence ε_1''/A

coincides with the point of the maximum curvature of ε_1'/A.

In practice, a lattice of resistive elements is located on a substrate that is a dielectric film of thickness l_2 with permittivity ε_2. In this case, the effective permittivity of a lattice on a substrate with ε_e is determined from the averaging formulas

$$\varepsilon_e' = \frac{\varepsilon_1' l_1 + \varepsilon_2' l_2}{l_1 + l_2},$$

$$\varepsilon_e'' = \frac{\varepsilon_1'' l_1}{l_1 + l_2}. \quad (10)$$

It is obvious that, when the permittivity of the substrate does not depend on frequency, the maximum of ε_e'' coincides with the maximum of ε_1'' and the point of the maximum curvature of ε_e' coincides with the analogous point of ε_1'.

2. SYNTHESIS OF A COMPOSTE ON THE BASIS OF LATTICES OF RESISTIVE ELEMENTS

A composite based on lattices of resistive elements is a multilayer structure of alternate lattices and dielectric layers. The complex permittivity of the composite can readily be calculated from the known formulas presented, for example, in monograph [13]. The frequency dispersion of the permittivity of the composite is determined by the characteristics of both the lattices and the dielectric layers between them. It is obvious that, the larger gaps between lattices and the larger their permittivity, the smaller the relative value of the dispersion of the permittivity of the composite. As follows from formula (7), the effective permittivity of a lattice is determined by capacitance C between the elements of the lattice. This circumstance is natural: the denser the lattice, the larger ε. At the same time, the frequency region of the maximum dispersion of ε depends on the ratio of the resistance of the lattice elements to the capacitive reactance of the space between these elements. When a composite is applied as an RA, its operating band should be chosen near the relaxation frequency $f_r = 1/(2\pi cr)$, where r is determined by the specific conductance and thickness of a square element, and capacitance C is additionally determined by the distance between elements. In the synthesis of a lattice, capacitance C can be approximately estimated with the help of the following formula for a lattice of conducting strips located in free space:

$$C \simeq \frac{a}{2\pi^2} \ln \frac{2d}{\pi\delta} [\text{pF}], \quad (11)$$

where dimensions a [cm], d, and δ are indicated in Fig. 1a. This formula is obtained from the expressions for the reflection and transmission coefficients presented in monograph [14].

3. REALIZATION OF LATTICES OF RESISTIVE SQUARES AND MEASUREMENT OF THEIR CHARACTERISTICS

Coaly paper with a volume conductivity of 20 S was used for fabricating lattices. Resistance r of a 0.12-mm-thick square element was about 400 Ω per square. Setting the relaxation frequency $f_r = 15$ GHz, we obtain the desired capacitance $C = 0.027$ pF. With the chosen lattice period $d = 7$ mm and the square dimension $a = 5$ mm, we obtain a smaller value of the capacitance (0.02 pF) according to the estimate from formula (11) with disregard of the dielectric of substrates.

Three variants (1, 2, and 3) of substrates of the respective thicknesses 0.2, 0.4, and 0.6 mm were fabricated, and their effective permittivities were measured. The frequency dependences of ε' and ε'' of these lattices and their linear approximations are depicted in Figs. 3a–3c. From these dependences, we can readily obtain for $\varepsilon_2' = 2.5$ the frequency dependences of the intrinsic effective permittivities of the lattices (without substrates) with the use of formula (10) and, from the latter dependences, determine the relaxation frequency and the capacitance between lattice elements. The results of this calculation performed at two frequencies are summarized in the table for each of the variants. The values of relaxation frequency f_r and capacitance C do not contradict the previous estimates $f_r = 15$ GHz and $C = 0.027$ pF.

4. REALIZATION OF A RADIOWAVE ABSORBER AND MEASUREMENT OF ITS REFLECTION CHARACTERISTICS

A radiowave-absorbing material is fabricated from four double-period lattices with square resistive elements corresponding to variants 1, 2, and 3. The lattices are glued with a dielectric binding material and located one under another. The glue between lattices increases the total thickness of samples: 1.5, 2.4, and 3.4 mm for variants 1, 2, and 3 of lattices, respectively. The measurement of the frequency dependences of the effective permittivities of these samples revealed the following. As should be expected, the measured frequency dependences of ε' and ε'' are located above similar dependences for single lattices. This circumstance is due to the fact that the capacitances between neighboring lattice elements in a sample consisting of four lattices are larger than the corresponding quantities in a single lattice. Therefore, amplitude A in the expressions for the effective permittivity of lattices in the sample is also larger. As an example, Fig. 4 shows measured ε' (curve *1*) and ε'' (curve *2*) and their linear approximations (straight lines *1*' and *2*', respectively) for a sample consisting of four lattices according to variant 2.

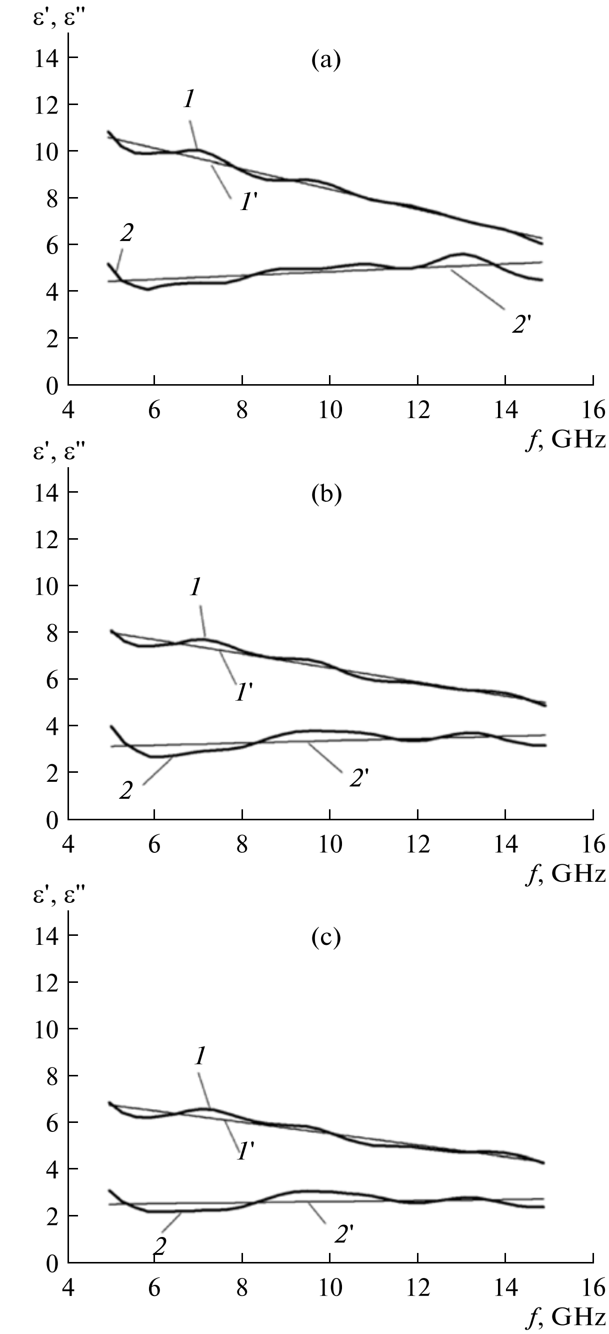

Fig. 3. Measured frequency dependences of the effective complex permittivities for lattice variants (a) 1, (b) 2, and (c) 3. Curve *1* is the real part of the permittivity, curve *1*' is its linear approximation, curve *2* is the imaginary part of the permittivity, and curve *2*' is its linear approximation.

Radiowave absorbers based on the multilayer composites described above are implemented via metallization of their back surfaces. Figure 5 shows the measured frequency dependences of the reflection coefficients of RA samples based on lattice variants 1, 2, and 3. This figure also shows the calculated (dashed) curve for a sample with variant-2 lattices that corresponds to

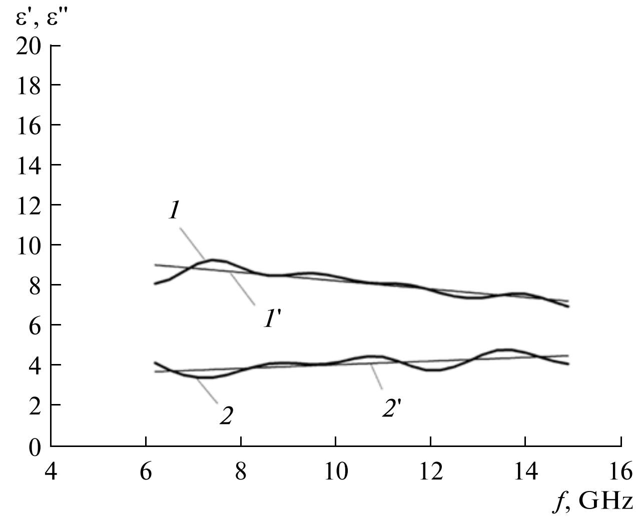

Fig. 4. Measured frequency dependences of the effective complex permittivities for composite sample of four variant-2 lattices. Curve *1* is the real part of the permittivity, curve *1*' is its linear approximation, curve *2* is the imaginary part of the permittivity, and curve *2*' is its linear approximation.

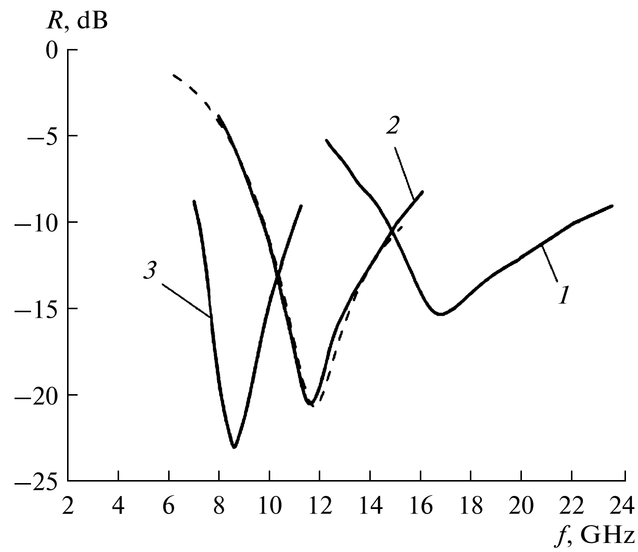

Fig. 5. Frequency dependences of the reflection coefficients for RA samples. Curves *1, 2*, and *3* correspond to sample variants 1, 2, and 3, respectively.

the frequency dependence of ε from Fig. 4. It is a common practice to estimate the RA efficiency from the ratio of difference $\Delta\lambda$ of the extreme wavelengths of the operating band (usually, corresponding to the minus-10-dB reflection level) to RA thickness d ($\Delta\lambda/d$). For all of the samples, this quantity is within an interval of 4.2–4.5. Note that, in the case of a homogeneous material without dispersion of ε, this ratio can be only 3.3 in the presence of perfect matching with free space at the center frequency of the operating band of an RA.

The effective permittivity for lattices of resistive squares calculated from measured frequency dependences

Lattice variant	f, GHz	ε_e'	ε_e''	$\varepsilon_e'/\varepsilon_e''$	ε_1'	ε_1''	$\frac{\varepsilon_1'}{\varepsilon_1''} = \frac{1}{X}$	f_r, GHz	C, pF	A
1	10	8.5	5.0	1.7	16.5	11.7	1.41	14.1	0.028	21.1
	15	6.3	5.4	1.17	11.4	12.6	0.90	13.5	0.029	21.9
2	10	6.5	3.5	1.85	17.2	12.8	1.34	13.4	0.030	22.6
	15	5.0	3.7	1.35	11.7	13.6	0.86	12.9	0.031	23.4
3	10	5.5	2.7	2.03	17.5	13.5	1.3	13.0	0.031	23.4
	15	4.4	2.8	1.57	12.0	14.0	0.87	13.1	0.031	23.4

5. DEVICES AND MEASURING INSTRUMENTS

The complex permittivity of individual lattices was measured under the free space conditions with the use of a double-horn setup combined with a vector Agilent N5230A net analyzer. The frequency dependences of the reflection coefficients of RA samples were measured by means of the horn method with the use of R-2 scalar net analyzers.

CONCLUSIONS

The electric circuit and long line methods have been applied to derive expressions for the estimation of the effective permittivity of a layer composite based on double-period lattices of resistive squares. The frequency dependence of the effective permittivity for such a composite has been measured, and it has been shown that the character of this dependence is close to the relaxation one. The frequency dependences of the reflection coefficients have been obtained for three variants of RAs with different dielectric gaps between lattices. It has been shown that the ratios $\Delta\lambda/d$ corresponding to the minus-10-dB reflection level for these RAs are within an interval of 4.2–4.5; whereas similar ratio $\Delta\lambda/d$ for an RA matched at the center frequency is 3.3 in the absence of the frequency dispersion of the permittivity.

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