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Microwave properties of composite structures of metal-insulator

Исследованы СВЧ свойства композитных структур металл-диэлектрик. Представлены результаты экспериментальных исследований металлодиэлектрических структур на основе полимерной матрицы с включениями в виде нанодисперсного порошка металла и металлических пластин в диапазонах частот 8…10 ГГц и 25…37 ГГц.

The microwave properties of composite structures of metal-insulator transition are investigated. The results of experimental studies of metal-based structures of the polymer matrix with metallic inclusions in the form of nanopowder metal and metal plates in the frequency bands 8…10 GHz and 25…37 GHz are presented.

Keys: *composite structure, reflection coefficient, transmission coefficient*

Introduction

Electronic systems are increasingly used in various spheres of human life. This places new demands on electronic devices and their components. First of all this concerned to improve mass-dimensional characteristics, increasing the degree of integration [1], increasing reliability and noise immunity of electronic devices, reducing the mutual influence of electronic circuits, environmental protection from electromagnetic radiation, protection of electronic systems from unauthorized reading of information [2, 3]. One of the most effective methods of protection from electromagnetic radiation, increasing the degree of electromagnetic compatibility of electronic devices and protection against unauthorized access to information is a shielding. The effectiveness of shielding greatly affects both the reliability of the electronic equipment and to protect information processed by electronic systems.

One of the necessary conditions for good shielding is the use of new materials with improved shielding properties. New and promising approach to solving this problem is to create composite materials based on metal-insulator structures, properties which can be controlled over a wide range by changing the component composition of these structures and their production technology [4, 5]. It is caused by properties both of metal phase and the matrix material.

However, when creating such materials, a number of problems related to the incompleteness of comprehensive studies of their properties, absence of adequate model of such structures, which would give opportunity for analysis and prediction of their properties in the microwave range [6, 7].

Therefore, the purpose of this work is to study the properties of composite metal-dielectric structures in the microwave range.

Properties of Composite Metal-Insulator

In general, the shielding properties of the material depends on its impedance (Z) and thickness (d). Wave impedance of the material, in turn, depends on the effective value of complex dielectric permittivity ε^*_{ef} and complex magnetic permittivity of the material μ^*_{ef}:

$$Z = \sqrt{\frac{\mu_0 \mu^*_{ef}}{\varepsilon_0 \varepsilon^*_{ef}}}. \qquad (1)$$

According to the Maxwell - Garnett theory the dielectric and magnetic permittivities of two-component metal-insulator composite structures depend on its composition and structure:

$$\varepsilon^*_{ef} = \frac{(1-q)\varepsilon^*_M + q\beta\varepsilon^*_f}{1-q+q\beta}, \qquad (2)$$

where ε^*_M is the complex dielectric permittivity of the matrix material, ε^*_f is the complex dielectric permittivity of the filler material, β is the form factor of the filler particles, q is the volume fraction of the filler material in the composite.

From (1) and (2) it is implied, that microwave properties of the composite metal-insulator structures depend on:

- properties of the matrix material;
- properties of metal;
- volume part of the metal in the structure;
- size and shape of metallic inclusions.

Thus, changing any of these factors can effectively manage the properties of the metal-insulator composite structures. This raises the interest to study such structures in order to develop materials with the necessary properties based on them. However, this issue has not been studied sufficiently. Therefore in this paper the dependence of the microwave properties of metal-insulator structures on volume part of metal in the structure and the form factor of metallic inclusions are investigated. It deals with two cases:

- spherical metal particle with the diameter is much smaller than the wavelength;
- metal stripes extending about half the wavelength.

Samples of metal-dielectric composite materials were produced by the electromechanical mixing metallic phase with the matrix material. Hardening of samples took place at room temperature. The polymers with low dielectric permittivity (epoxy and foamed plastics) were used as the matrix material. The aluminum granules with the size 60…800 nm, and copper stripes were used as the metallic inclusion. The dimensions of samples were 23x10x2 mm.

Properties of metal-insulator structures were studied with the aid of network analyzer (Fig. 1) by determining the reflection coefficient (parameter S_{11}) and transmission coefficient (parameter S_{21}) of the samples placed in a split waveguide.

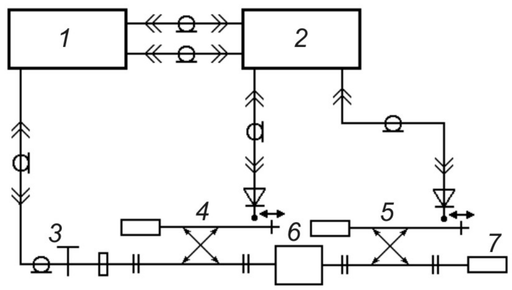

Fig. 1. Block diagram of network analyzer: 1 is the microwave generator, 2 is the weakening indicator, 3 is the coaxial waveguide transition 4 is the directed coupler "incident wave", 5 is the directed coupler "reflected wave", 6 is the measuring unit of the sample, 7 is the termination

Rectangular samples (Fig. 2) were placed in the split waveguide (Fig. 3). The waveguide cross-section was completely filled with the sample's material.

Measurements were carried out in the frequency range 8…10 GHz and 25…37 GHz. Test results are presented in the Tab. 1, 2 and in the Fig. 4, 5. The results are used to determine the coefficients of the shielding for these structures:

$$K = 10\lg\left(\frac{P_{s0}}{P_s}\right), \qquad (3)$$

where K is the shielding coefficients, P_{s0} is the power of microwave field in the investigated point of space without the shield; P_s is the power of microwave field in the investigated point of space if the shield used.

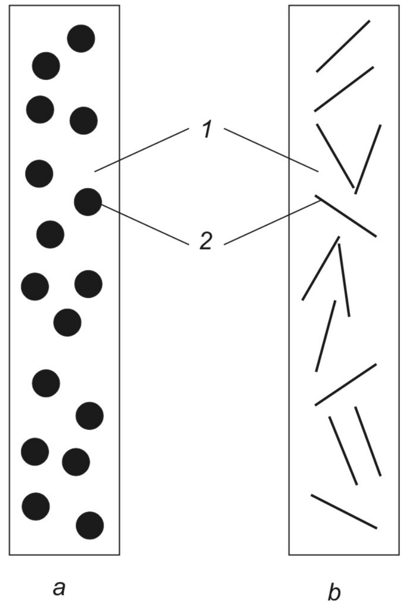

Fig. 2. Schematic representation of samples: *a* - is the structure with the metal nanodispersed powder; *b* - is the structure with metal stripes; *1* - is the matrix; *2* - is the metallic filler

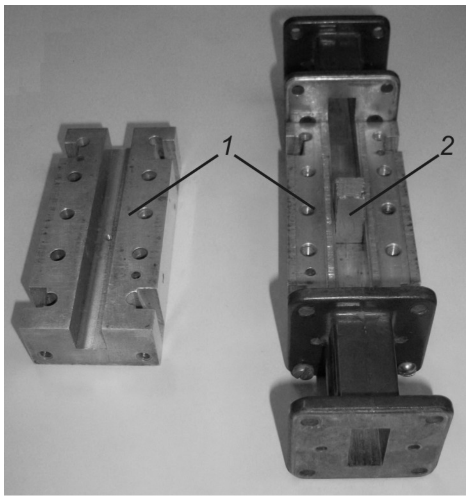

Fig. 3. The split waveguide with sample: *1* is the split waveguide; *2* is the test sample

The dependence of reflection and transmission coefficients on volume part of the metallic dispersed phase within the composite material for samples with thickness of 2 mm and the dispersed metallic phase in the form of spherical granules with the diameters of 60…800 nm are showed in Fig. 4. The figure shows that with increasing of volume part of metallic phase in the composite material increases the reflection coefficient of electromagnetic energy from the sample surface and decreases the transmission coefficient of electromagnetic energy through the sample. All tested samples with the metallic phase in the form of spheres with a radius much smaller than the wavelength had a weak dependence of the parameters S_{11} and S_{21} on the frequency. This makes it possible to form materials with desired shielding coefficients in a wide range of wavelengths (Fig. 6).

Table 1. The reflection and transmission coefficients of samples with metallic dispersed phase in the form of spherical granules at different volume part of metal within the composite

Volume part of metal q	Frequency range, GHz	Reflection coefficient (parameter S_{11}), dB	Transmission coefficient (parameter S_{21}), dB
0	8…10	– 6,8	– 11,3
	25…37	– 6,5	– 12,9
0,25	8…10	– 5,9	– 14,1
	25…37	– 5,6	– 16,2
0,29	8…10	– 5,2	– 12,8
	25…37	– 4,9	– 14,7
0,4	8…10	– 3,4	– 15,4
	25…37	– 3,2	– 17,7
0,56	8…10	– 3,7	– 18,2
	25…37	– 3,5	– 20,9
0,7	8…10	– 2,2	– 23,8
	25…37	– 2,1	– 27,3

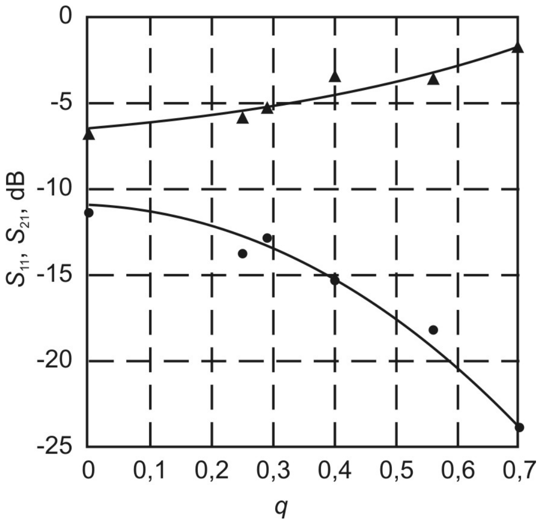

Fig. 4. Dependence of reflection and transmission coefficients (parameters S_{11} and S_{21}, respectively) of the volume fraction of metal in the frequency range 8…10 GHz for samples with metallic dispersed phase in the form of spherical granules (▲ is the S_{11}, ● is the S_{21})

The measurements results for samples of composites with a filler in the form of metal stripes are presented in Tab. 2 and Fig. 5. As it is seen from Tab. 2 in these samples high *Q*-resonance with the wavelength equal to approximately double length of metallic stripes occurs. Therefore these materials are promising in terms of their use for the development of selective microwave coatings. Typical shielding coefficients frequency dependence of the electric field component for the protective coatings based on metal-dielectric composites with metal inclusions in the form of spheres and plates are showed in Fig. 6.

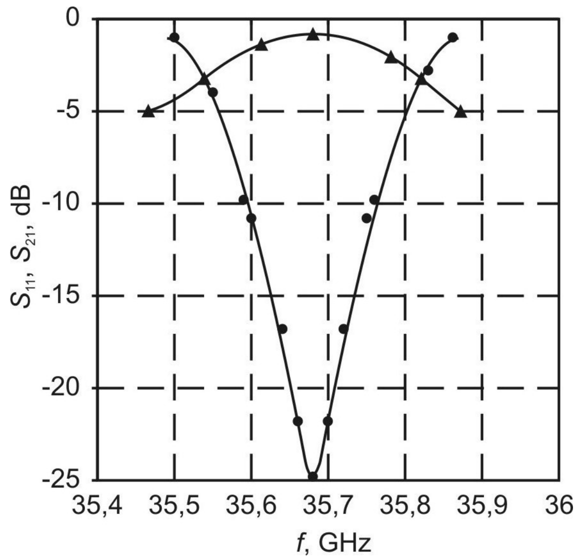

Fig. 5. Frequency dependence of reflection and transmission coefficients (parameters S_{11} and S_{21}, respectively) for samples with filler in the form of metal stripes. The volume part of metal in the samples q = 0,05 (▲ is the S_{11}, ● is the S_{21})

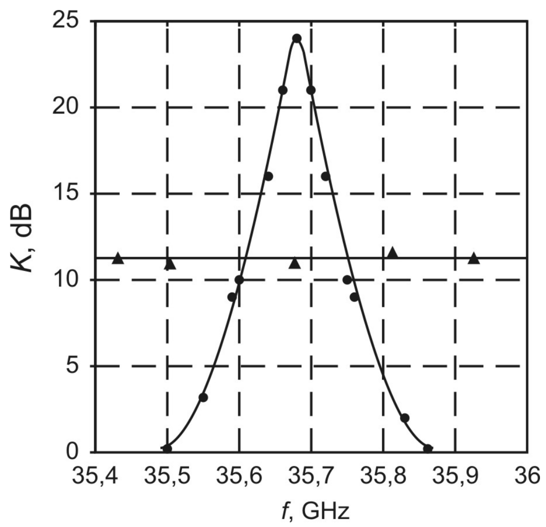

Fig. 6. Frequency dependence of the shielding coefficients of protective coatings based on metal-insulator composites for samples of different types of metallic inclusions. The volume part of metal in the samples q = 0,05 (▲ is the spheres, ● is the stripes)

Table 2. Resonance properties of composite materials with filler in the form of metallic stripes (*h* is the strip thickness; *L* is the strip length; *W* is the strip width; f_0 is the resonance frequency; *Q* is the quality factor)

Sample's №	Metal	Dimensions of stripes			Results of measurements	
		h, mm	*L*, mm	*W*,mm	f_0, GHz	*Q*
1	copper	1,70	12,20	4,30	9,293	2323
2	copper	0,05	13,80	5,00	8,892	1270
3	copper	0,10	3,60	1,30	30,99	1216
4	copper	0,10	3,40	1,30	35,68	1270
5	copper	0,10	2,80	1,30	37,38	1013
6	copper	0,10	10,00	4,00	11,21	2243
7	copper	0,10	11,00	3,00	10,47	2125

Conclusions

1. With increasing volume part of metal in the metal-dielectric composite structure reflection coefficient increases and the transmission coefficient decreases.
2. Metal-dielectric composite structure with the filler in the form of nanodispersed metallic powders have good shielding properties in the microwave a range that makes them promising for use in developing of shielding coatings to protect components of electronic circuits from mutual electromagnetic interference.
3. Metal-dielectric composite structure with the filler in the form of thin metallic stripes in the microwave range have pronounced resonance properties with the high value of Q, which makes materials based on them promising for use in the manufacturing of resonance structures and selective protective coatings of microwave range.
4. Resonance properties of metal-dielectric composite structures with filler in the form of thin metal stripes due to the peculiarities of the electromagnetic field distribution inside the structures and require more detailed investigation.

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