Magnetic and dielectric properties of composites based on magnetic microspheres

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Abstract. Composites with a filler based on a magnetic material ECOM-P and paraffin were investigated. The microstructure of the magnetic material was studied, the average particle size was determined. The influence of the concentration of magnetic filler on the scattering characteristics of electromagnetic waves in the frequency range from 15 MHz to 7 GHz is determined. The values of permittivity and permeability at frequencies of 1, 2 and 3 GHz are calculated.

1. Introduction

Microwave absorbing materials (MAM) are being actively investigated in connection with the possibility of their use to ensure electromagnetic compatibility, information security, biological protection, etc.

MAM are, as a rule, a composite material consisting of a polymer matrix and powder filler with magnetic and electrically conductive properties. To increase the microwave absorbing properties the magnification of the permittivity ($\varepsilon$) and/or permeability ($\mu$) of the MAM it is necessary. The expediency of such an approach is due both to the dependence of the reflection and transmission coefficients of the coating on $\varepsilon$ and $\mu$, and to the relationship between the attenuation coefficient of an electromagnetic wave in a material with the quantity (specific product) ($\varepsilon \cdot \mu$) [1].

Permittivity and permeability of the composite material is influenced by the concentration of the filler, which has magnetic and/or electrically conductive properties.

The aim of the work is to study the effect of the concentration of the magnetic material ECOM-P on the magnetic and dielectric properties of the composite material, as well as on the scattering characteristics of electromagnetic wave.
2. Material

The composite material is made of magnetic filler evenly distributed in a non-magnetic matrix. As a filler used industrially produced magnetic material ECOM-P (manufacturer – LLC Bolid (Russian Federation)).

A micrograph of the ECOM-P powder obtained using a scanning electron microscope “JEOL JSM – 7500F” is shown in figure 1. It can be seen that the ECOM-P powder consists of microspheres with an average diameter of 70 ± 15 µm.

![Figure 1. Micrograph of ECOM-P powder.](image)

Paraffin is used as a matrix in composites. The choice of paraffin as a matrix is due to: 1) a low melting point; 2) ease of manufacture of samples; 3) the proximity of the electromagnetic parameters of paraffin to similar parameters of engineering plastics such as polyalkenes (polyethylene, polypropylene, etc.).

Paraffin was heated to $T=90 \, ^\circ C$ and carefully altered with a filler to obtain a homogeneous composition.

From the obtained material were made toroidal samples. They had dimensions of internal and external diameters of 3.05 and 7 mm, thickness – 3 mm. The concentration of filler (C) by weight in the composites was controlled and varied from 50 to 80% with step 10%.

3. Experimental

Electromagnetic properties of samples from composite materials at microwave band were studied using the Deepace KC901V vector network analyzer. Measurements were made in the frequency range of 0.015–7 GHz in a matched-loaded coaxial line. S-parameters of the transmission line with an insert of composite materials were measured.

Using the experimentally measured values of S-parameters the reflection ($R$), transmission ($T$), absorption ($A$) and effective absorption ($A_{eff}$) coefficients were calculated:

$$R = |S_{11}|^2, \quad T = |S_{21}|^2, \quad A = 1 - R - T, \quad A_{eff} = \frac{1 - R - T}{1 - R}.$$ 

4. Results

The frequency dependences of the reflection, transmission, absorption, and effective absorption coefficients for different concentrations of the filler C are presented in figure 2.

An increase in the concentration of magnetic filler leads to: 1) an increase in the reflection $R$, absorption $A$ and effective absorption $A_{eff}$ coefficients, 2) a decrease in the transmission coefficient $T$. Saturation of the parameters $R$, $T$, $A$ and $A_{eff}$ is observed at frequencies above 6–7 GHz.
Figure 2. Frequency dependences of reflection (a), transmission (b), absorption (c) and effective absorption (d) coefficients of samples from ECOM-P/paraffin composites for different concentrations of filler.

Figure 3. Concentration dependences of permittivity (a) and permeability (c) and dielectric (b) and magnetic (d) loss tangents of composites ECOM-P/paraffin.
From the measured values of the S-parameters, the complex values of $\varepsilon = \varepsilon' + i\varepsilon''$ and $\mu = \mu' + i\mu''$ were calculated using the Nicholson-Ross-Weir algorithm [2]. The values of the magnetic and dielectric loss tangents were calculated by the formulas:

$$\tan\delta_\varepsilon = \frac{\varepsilon''}{\varepsilon'}, \quad \tan\delta_\mu = \frac{\mu''}{\mu'}.$$ 

The concentration dependences of values $\varepsilon$, $\mu$, $\tan\delta_\varepsilon$ and $\tan\delta_\mu$ are presented in figure 3.

From concentration dependences it is seen that increasing the concentration of the filler leads to an increase in $\varepsilon$ and $\mu$. As the frequency increases from 1 to 3 GHz, the permittivity remains almost unchanged, and the permeability decreases by 15÷30%.

The dielectric and magnetic loss tangents increase with increasing filler concentration. With increasing frequency of electromagnetic waves from 1 to 3 GHz, losses in composite materials (both dielectric and magnetic) increase. When comparing the values of dielectric and magnetic losses, it can be seen that at the same frequencies with the same concentration of magnetic filler $\tan\delta_\mu > \tan\delta_\varepsilon$.

In the studied samples, the filler has a higher electrical conductivity than the matrix. For this reason, an increase in the concentration of the filler leads to an increase in the electrical conductivity of the composite as a whole. Indeed, with an increase in the concentration of the filler, which has a higher electrical conductivity in comparison with the matrix, the electrical conductivity of the composite as a whole increases. In addition, an increase in electrical conductivity with increasing filler concentration is indicated by an increase in the of dielectric loss tangent. The dependence of electrical conductivity on the tangent of dielectric loss angle is expressed by the following formula [3]:

$$\sigma = 2\pi\varepsilon_0\varepsilon'e^* = 2\pi\varepsilon_0\frac{\varepsilon''}{\varepsilon'}\tan\delta_\varepsilon,$$

where $\varepsilon_0$ is the permittivity of vacuum.

The increase in electrical conductivity and permeability affects the scattering characteristics of electromagnetic wave.

It is known that the shielding effectiveness of an electromagnetic wave can be represented as the sum of the shielding effectiveness for deposits [4–6]:

$$SE = SE_R + SE_A + SE_M,$$

where $SE_R$ is shielding effectiveness for a single reflection of the electromagnetic wave from the surface of the coating, $SE_A$ is the shielding effectiveness due to losses of the absorption of an electromagnetic wave by the coating, $SE_M$ is the shielding effectiveness due to multiple reflections of the electromagnetic wave inside the coating.

The values of the shielding effectiveness $SE_R$ and $SE_A$ are determined from the coefficients $R$, $T$ and $A_{eff}$ by the following formulas:

$$SE_R = -10\log(1 - R)$$

$$SE_A = -10\log\left(\frac{T}{1 - R}\right) = -10\log(1 - A_{eff})$$

The shielding effectiveness for multiple reflections is determined by $SE_A$:

$$SE_M = 10\log\left[1 - 2 \times 10^{-0.1\times SE_A} \times \cos(0.23SE_A) + 10^{-0.2\times SE_A}\right].$$

The shielding effectiveness $SE_R$ and $SE_A$ are related to the values of permeability and electrical conductivity of the material:
where \( t \) is the thickness of the shielding coating, \( f \) is the frequency of the electromagnetic wave, \( \sigma_r \) is the relative electrical conductivity of the shielding material compared to copper, \( r \) is the distance between the source of electromagnetic radiation and the shielding material.

An increase in electrical conductivity of material to be expected leads to an increase in the reflection coefficient (according to formulas (1) and (3)) and an increase in the effective absorption coefficient (according to (2) and (4)). The scattering characteristics of electromagnetic wave on samples of the ECOM-P/paraffin composite are similar to those of carbonyl iron/polyvinylidene-fluoride based composite samples [7]. An increase in the concentration of carbonyl iron in the composite leads to an increase in the reflection and effective absorption coefficients of electromagnetic wave.

5. Conclusion

The magnetic material ECOM-P is a promising microwave absorbing material, since it has high values of permittivity and permeability. It has high magnetic losses in the SHF band. An increase in the concentration of magnetic filler in the composite leads to an increase in permittivity and permeability, as well as reflection and effective absorption coefficients of samples made of composite material.

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