08

The influence of magnetic fields on the reflective properties of amorphous nanogranular composites

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The results of studies of the experimental effect of magnetic fields with induction up to 0.3 T on the reflection coefficient of microwave waves of amorphous nanogranulated composites $(CoFeB)_x+(SiO_2)_{1-x}$, $27.38 \le x \le 84.14$ at.%, 493−862 nm thick, sprayed onto a lavsan substrate 0.02 mm thick, in the frequency range 26−37 GHz are presented. The frequency dependences of the reflection coefficient of microwave waves are given. The effect of the ferromagnetic alloy content on the microwave reflective properties of films under the influence of a magnetic field is estimated. The ratio of the maximum value of the reflection coefficient of microwave waves to the minimum in the first extremes is determined. It is shown that magnetic fields can change the values of the reflection coefficient of composites by a factor of 1.43−1.92.

Keywords: composite films, reflection coefficient, magnetic field.

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In connection with development of novel small-size microwave devices, amorphous nanostructured materials have been actively studied in the last decades, which contain metal and dielectric granules [1,2]. A particularly interesting case is the case when the metal phase of the material for nanogranules is the elements or alloys from ferromagnetic metals [3–6], which provide for giant magnetoresistance in composites [3] and high level of microwave radiation absorption [4]. Ferromagnetic films and composites due to low losses are widely used in devices of microwave signal processing, resonant cavities, filters and phase shifting devices [5–7]. A shifting magnetic field is often necessary for operation of such devices and for tuning to the required frequency in the wide range. Exposure to the external magnetic field may change the screening properties of materials, in particular, high-frequency properties of composites with magnetic particles [8,9]. Therefore, paper [9] analyzes experimental dependences of reflection and transmission coefficients on the value of magnetic field on frequencies 12−38 GHz. There are also mechanisms making it possible to control the magnetic state of the system using the electric field [10].

This paper is dedicated to studies of microwave-reflecting properties of amorphous nanogranular composites $(CoFeB)_x+(SiO_2)_{1-x}$ and continues [11]. Magnetic properties of the studied films are determined first of all by concentration of ferromagnetic granules [12], and microwave-reflecting properties — by their size and gaps between granules and are due to current passage inside granules [11,13,14].

In paper [11] in connection with the features of the nanostructure and composition of composites $(CoFeB)_x+(SiO_2)_{1-x}$ reflection coefficient in the range 26−38 GHz varied from 10^{-6} to 0.08. Such value of the reflection coefficient is related to the content of boron half-metal (around 20% of the entire composition of ferromagnetic alloy, the concentration of which was 32.79−52.00 at.%) in the composite. This paper studied specimens with much wider range of ferromagnetic alloy concentration — 27.38−84.14 at.%, the boron content was from 3 to 5%, and the thicknesses of the studied specimens were 2.25−2.95 times less than in paper [11].

Composite granular films $(CoFeB)_x+(SiO_2)_{1-x}$ were made in the argon atmosphere at low vacuum (10^{-5} Torr) by method of ion-beam deposition in the Voronezh State Technical University. The elemental analysis was carried out using an energy-dispersive attachment to a scanning electron microscope Axia ChemiSEM ThermoFisher (Czech Republic). The film thickness was assessed using electron microscope Tescan MIRA 3 LMH SEM (Czech Republic). Reflection coefficient (by power) in the frequency range 26−37 GHz was measured in the rectangular waveguide [15]. Dependence of standing-wave ratio coefficient on frequency was recorded. To study the effect of the magnetic field on the microwave reflection coefficient a part of the waveguide with the studied specimen was placed into the electromagnet gap. Measurements were carried out under variation of the magnetic field inductance from 0 to 0.30 T with increment 0.05 T. The film making and measurement methods are described in more detail in the paper [15]. Content of the ferromagnetic alloy, thickness, electrical resistance and specific conductivity of the films are given in paper [16].

Figure 1 shows dependences of reflection coefficient R on frequency f in the range 26−37 GHz and on content of ferromagnetic alloy x. As one can see from the figure,

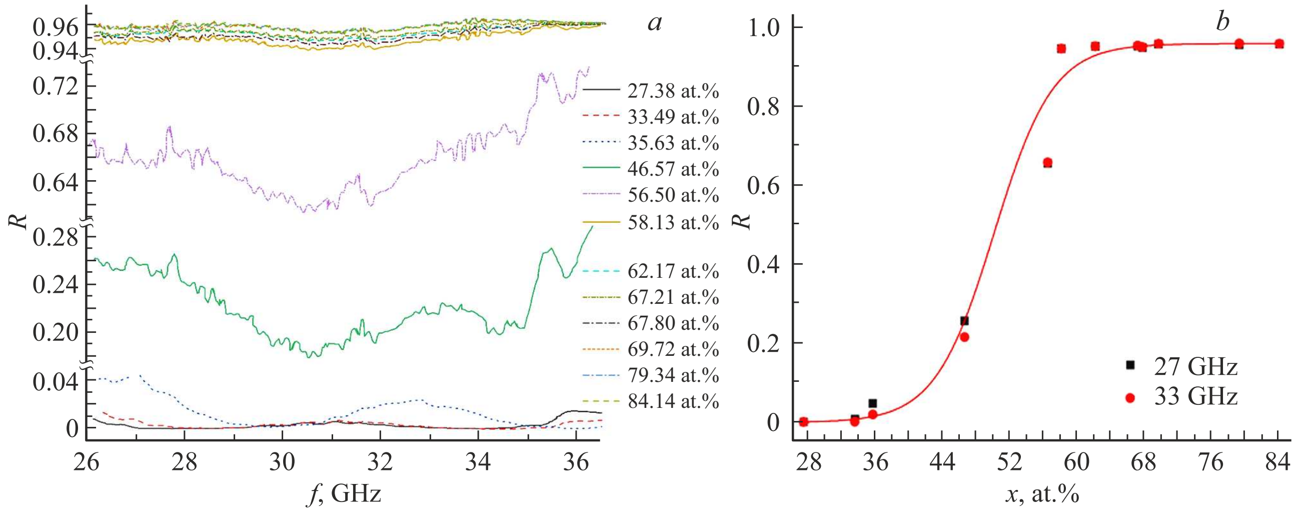

Figure 1. Dependences of reflection coefficient on frequency in range 26–37 GHz (a) and on content of ferromagnetic alloy (b).

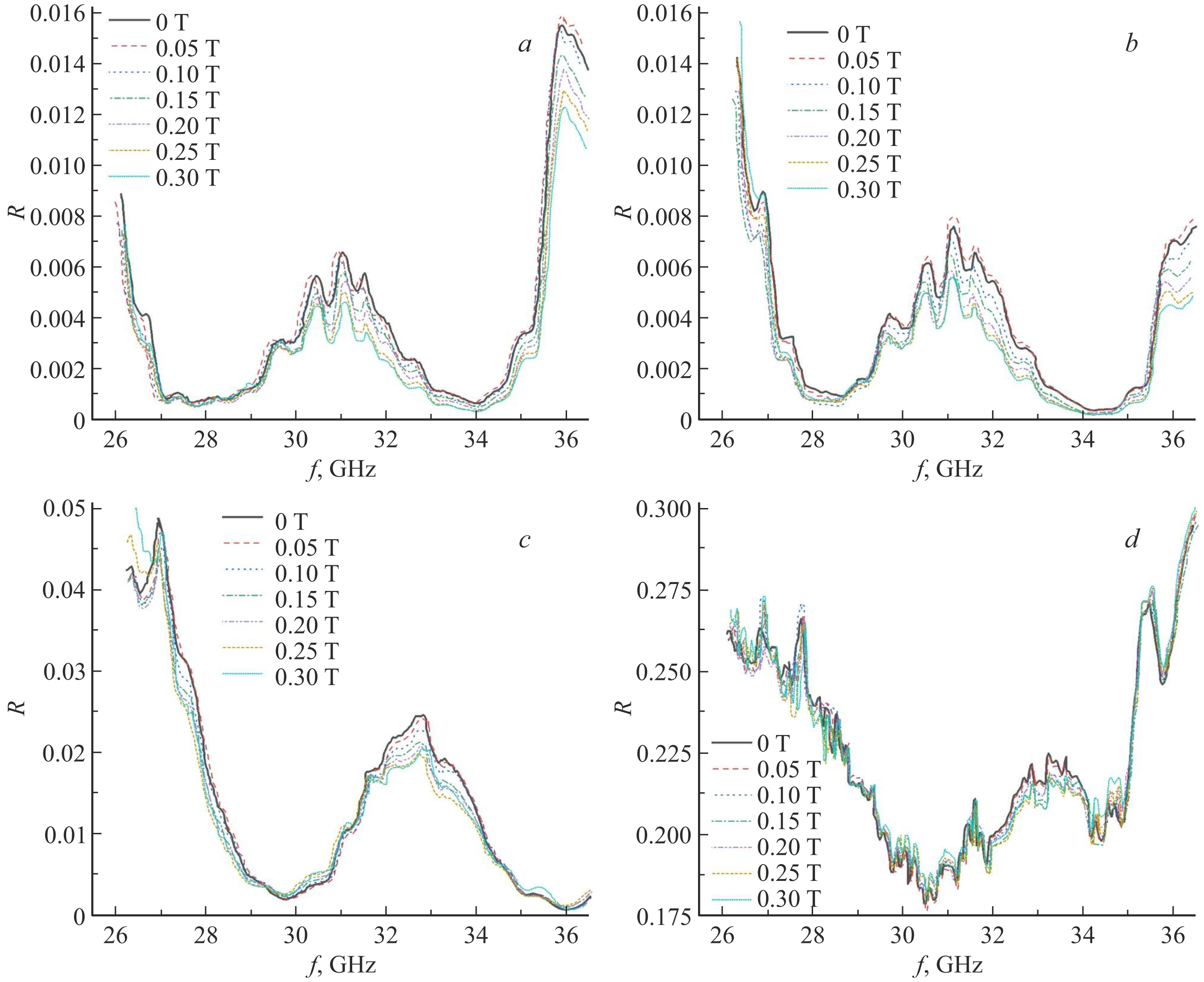

Figure 2. Dependences of reflection coefficient on frequency under exposure to magnetic field with inductance up to 0.3 T on composite films with ferromagnetic alloy content: a — 27.38 at.%, b — 33.49 at.%, c — 35.63 at.%, d — 46.57 at.%.

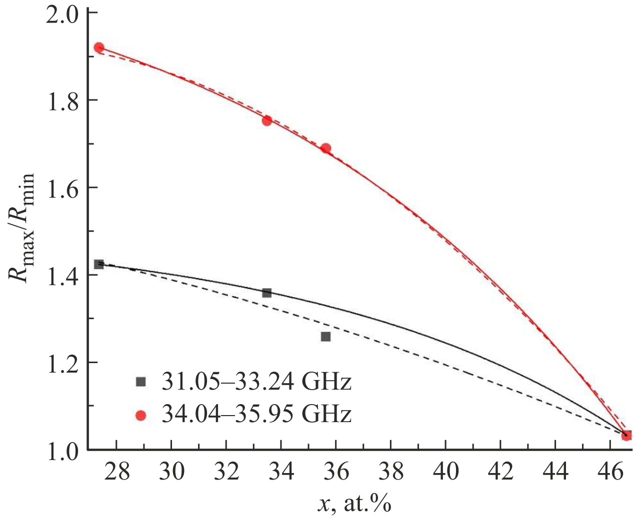

Figure 3. Dependences R_{max}/R_{min} in extrema (squares — maximum on frequencies 31.05–33.24 GHz, circles — minimum at frequencies 34.04–35.95 GHz) on the content of the ferromagnetic alloy when exposed to the magnetic field. Approximation was made with exponential dependence (solid curves) and second degree polynomial (dotted lines).

with growth of x the reflection coefficient R grows in the wide interval from $7 \cdot 10^{-4}$ to 0.97. The films studied in paper [11] in the similar frequency range reflected not more than 8% of the incident radiation at values x up to 52.00 at.%. Besides, the frequency dependences of the reflection coefficient demonstrated deep minima, the amplitude of which increased with the growth of the ferromagnetic alloy content. They are related to the interference of the antiphase electromagnetic waves reflected from the composite film and the lavsan substrate [11]. In these studies with growth of x the contribution to the reflection from the substrate becomes not so significant, therefore, frequency dependences R smooth gradually (Figure 1). At $x = 46.57-58.13$ at.% the reflection coefficient rises sharply. This concentration range may correspond to the percolation area, where in the composites the clusters and chains of granules appear together with individual granules, forming current-conducting channels, which promote substantial growth of conductivity and the reflection coefficient. At $x = 58.13$ at.% and above a metal matrix with dielectric inclusions is formed in the film structure. The microwave reflection coefficient for such composites hardly depends on the frequency or the change in the content of the ferromagnetic alloy, which is demonstrated by Figure 1.

Figure 2 presents the dependences of the reflection coefficient on the frequency when exposed to magnetic fields with inductance of up to 0.3 T on the films with various content of ferromagnetic alloy.

As one can see from Figure 2, practically for all the presented specimens the magnetic field effect is most noticeable in the extrema of reflection coefficients and manifests itself the stronger, the lower is the content of the ferromagnetic alloy. Besides, as the position of these extrema shifts towards higher frequencies with increase of x. The experimental study results prevent from making an unambiguous conclusion on who the magnetic field varies the reflection coefficient value. For the films with the lowest content of ferromagnetic alloy (27.38–33.49 at.%) the magnetic field increase leads to reflection coefficient decrease mostly, however, at $B = 0.05$ T certain growth of R occurs, especially in maxima (Figure 2, a, b). In the films with high content of ferromagnetic alloy (Figure 2, c, d) the magnetic field increase leads to reflection coefficient decrease in the maxima and increase in the minima of reflection, therefore, the amplitude of vibrations $R(f)$ decreases.

Such behavior of the reflection coefficient may be explained by high degree of magnetic inhomogeneity of the composite film due to the spread in the anisotropy value of individual granules. If the ferromagnetic alloy content is low, the composite granules are located quite far from each other, and their interaction is rather low, therefore in general the composite films are magnetized as superparamagnetics, and the composite exposure to the magnetic field causes substantial spread of the reflection coefficient values. The results of the numerical estimation show that in composites with the lowest content of ferromagnetic alloy (Figure 2, a) in the maximum at frequency 31.05 GHz the ratio of the maximum value of the reflection coefficient R_{max} to the minimum one R_{min} is 1.43, and in the next minimum at frequency 34.04 GHz — 1.92. As the content of ferromagnetic alloy increases due to the increase in the size of the granules and decrease of the gaps between them, the interaction between granules increases, and magnetization leads to decrease in the spread of the reflection coefficient values, and in the studied extrema the ratio R_{max}/R_{min} monotonously drops (Figure 3). When chains are formed from granules causing occurrence of current-conducting channels, the reflection coefficient values practically level.

One may assume that the studied composites prior to the percolation threshold will demonstrate superparamagnetic properties, and after the percolation threshold they will acquire the ferromagnetic properties. Such features of the granular system of ferromagnetic-dielectric in the region of low and high contents of the metal phase are confirmed by magnetooptical studies of the composites with ferromagnetic granules [17,18].

The paper studied the reflective properties of amorphous nanogranular composites $(CoFeB)_x+(SiO_2)_{1-x}$. It was shown that magnetic fields may substantially (1.43–1.92 times) vary the reflective properties of composites in the frequency range of 26–37 GHz, which is substantially higher than it was obtained for specimens of the same composition in paper [11] in the frequency range of 8–12 GHz (around 13%). For practical application of this effect, it is necessary to substantially expand the studies of microwave-reflecting properties of composites using magnetic fields with inductance up to 1 T and various temperature effects.

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Conflict of interest

The author declares that he has no conflict of interest.

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