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TENDENCIES IN CREATING MODERN RADIO ABSORBING MATERIALS AND COATINGS

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Designation of radio absorbing materials (RAM) and coatings (RAC)

According to the Act of the Russian Federation "About the state regulation in the field of ensuring electromagnetic compatibility of technical means" [1], requirements for the level of electromagnetic radiation of available electronic and electrical appliances become tougher. The Act is directed to the coordinated operation of devices and appliances, as well as to the protection of people against electromagnetic radiation. It is known that the electromagnetic radiation of the technogenic type damages the coordinated operation of all the systems in a human body [2]. Tests for compliance with the requirements are carried out in the anechoic chambers whose walls are coated with RAM and RAC necessary for the protection of the personnel and measuring devices against the re-reflected electromagnetic radiation (EMR). The anechoic chambers are also used for testing and tuning of sensitive and high-precision systems which include satellite systems, georadars, marine radio buoys etc.[3].

Many countries apply shielding for the purpose of health protection of people and protection of sensitive devices against electromagnetic radiation (EMR). The shielded buildings are also necessary for protection against unauthorized picking-up of information from processing devices, data transmission devices and data storage units.

Electromagnetic shielding

When choosing shielding materials, it is generally assumed that at frequencies up to 1 MHz a dominating factor is magnetic permeability, and at frequencies over 1 MHz it is conductivity of a material. For a long time in practice of electromagnetic shielding metal sheets have been considered traditional materials. However, a high level of shielding (more than 50-60 dB), serious technical problems arise in case of maintaining electrical hermeticity of a circuit. When this condition is not maintained, radiation, which has penetrated in the shielded volume, due to re-reflection from high-conductivity walls will form standing waves, whereas the shielding construction acts as a resonator at certain radiation frequencies.

Due to accumulation of energy in the chamber as in a resonator with a certain Q factor the power of electromagnetic radiation increases because of possible fissures, gappings between parts of the shield, holes and other non-uniformities of an electromagnetic circuit:

$$Q = 2\pi \frac{W_\Sigma}{W_1}, \tag{1}$$

where W_Σ is the electromagnetic energy accumulated in the formed circuit (resonator), W_1 is the energy dispersed during one period of radiation. The use of radio-absorbing materials in shielding constructions will make it possible to reduce the Q factor of a circuit, the accumulated energy of W_Σ and the field intensity in a circuit.

For the purpose of creating an electrical hermetic shielding circuit it is expedient to make a choice in favor of composite materials on the basis of polymeric binding and fillers on the basis of magnetic alloys (for example, the magnetoamorphous alloys containing Fe, Si, B, Cu) or ferrites characterized by high magnetic losses, technological effectiveness of manufacture and rather a low price. Shielding efficiency S is usually defined by the sum:

$$S = A + R + B, \tag{2}$$

where A is the weakening of radiation connected to absorption of electromagnetic energy within the shield; R is the value of losses caused by reflection of an electromagnetic wave from both sides of the shield; B is the value of losses connected to repeated re-reflections within the screen.

The use of small magnetic particles (for example, from a ferrite) in the capacity of a filler in the composite polymeric matrix (CPM) can be considered as a future-oriented study in the technology of electromagnetic shielding in the range of frequencies more than 1 GHz. Radio-absorbing materials on the basis of Ni-Zn ferrites are characterized by technological effectiveness of manufacture, small mass-dimensional characteristics (with the mass no more than 36 kg/m^2 and the thickness no more than 6 mm) and a wide interval of operating frequencies (10 MHz – 1GHz). In some cases Ni-Zn ferrites can be replaced with Mg-Zn ferrites whose price is about 30% less, and in whose composition there is no scarce oxide of nickel (III). These ferrites are effective in the range of frequencies 40 MHz – 1500 MHz. There are also compositions of Mn-Zn ferrites which do not contain scarce nickel and are close in their parameters to Ni-Zn ferrites.

Tendencies in creating RAC and RAM

At present it is possible to single out the following tendencies in increasing absorption of electromagnetic energy of RAC and RAM:

1. At the expense of increasing the imaginary part of dielectric permeability ε'', which leads to an increase in dielectric losses of a material. However, an increase in conductivity and, thermal losses respectively, leads to an increase in reflection from the front surface of the material. To lower this conductivity it is expedient to use the interference phenomena. At a certain thickness of RAC the waves reflected from the front and from the back surfaces of RAC, will be in an antiphase, which means dependence of thickness of an absorbing layer on frequency. Therefore, acceptable values of the absorption coefficient can achieved only at some fixed frequencies.

2. At the expense of increasing the imaginary part of magnetic permeability μ'' and magnetic losses. The magnetic fillers providing big magnetic losses are introduced into composite materials and amorphous alloys designed for shielding and absorption of electromagnetic energy. This tendency in creating RAM is rather promising. However, nowadays there are no theoretical models which satisfactorily describe absorption of electromagnetic radiation (EMR) as a function of parameters of the microstructure of the material and of the impressed electromagnetic field.

Available models are rather of a qualitative character [4]. Empirical formulas for calculation of the reflection coefficient and the thickness of layers are bulky, have many restrictions and assumptions and show high (to 50 %) miscalculation [4].

3. Due to coordination of wave resistances of a coating material with the propagation medium of electromagnetic waves. To lower the level of a signal reflected from the boundary interface and caused by a jump of the wave resistance, it is common to use multi-layer materials whose first layer has smaller ε and, consequently, smaller reflection from the boundary surface. The extreme cases are materials of the gradient type whose characteristics continuously change correspondingly with the depth of the material. For this purpose there are used constructions in the form of pyramids or truncated cones which provide a smooth change in electrical characteristics along the propagation of a wave.

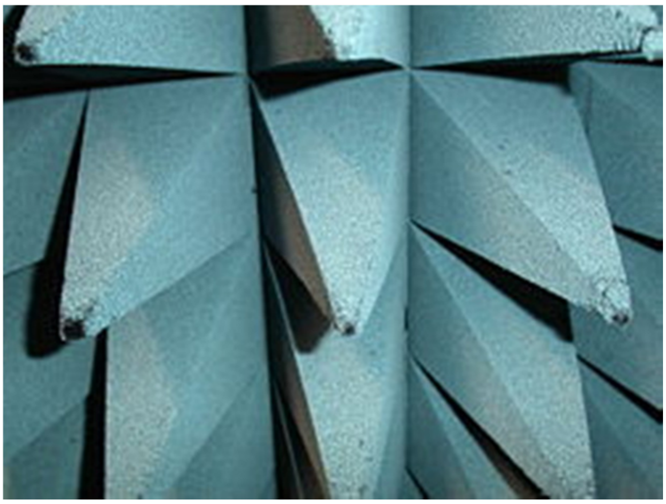

Fig. 1. RAM of the gradient type [8]

The drawbacks of the above-mentioned constructions are the complexity of manufacture and the requirement for using RAM with the height about a wavelength in the material, which becomes critical for the task of lowering reflections in the range of frequencies below 1 GHz, especially in case of restrictions on the general dimensional characteristics. Besides, for materials of this type it is often necessary to use impregnation ensuring fire safety.

Spurious reflection from the boundary surface caused by the mismatch of wave resistances can be suppressed by introducing in the material a component with a nonzero imaginary part of magnetic permeability μ''. And along with electroconductive fillers for creating RAM and RAC there are often used magnetic fillers (ferrite powders, carbonyl iron, etc.). In a number of works it is offered to use composite materials containing in a dielectric matrix (the foam polymeric composition) a fraction of a conductive filler in the form of extended inclusions (for example, of carbonic or metal fibers) together with fine-dispersed electroconductive and magnetic powders.

It is perspective to use ferrite fillers in radio absorbing materials, since the material has considerable magnetic losses and great values of magnetic conductivity μ'' make it possible to provide the best coordination of metal and strongly absorbing layers with free space [4].

A considerable number of publications in Russia and abroad deals with creation of new forms of ferrite fillers and shared use of ferrite powders, graphites and metal fibers. For example, in [5] it is offered to use RAM which contains in the capacity of polymeric binding synthetic glue on the basis of latex, and in the capacity of a magnetic filler – a powdery ferrite or carbonyl iron.

4. Due to the interference of reflections from the different coating layers, leading to reduction in reflection from the material (multi-layer coatings and coatings with a special-purpose form). Here complex wave resistance Z^* also decreases correspondingly with the depth of the coating. It allows avoiding sharp jumps of wave resistance and, therefore, unwanted reflections.

The simplest variety of such a structure is a two-layer coating from a material with non-uniform conductivity, where the top layer with smaller σ values is often called the coordinating one, and the bottom layer with big σ values is called the absorbing one. Formulas for calculating the absorption coefficient for multi-layer coatings contain a large number of interconnected frequency-dependent parameters and serve, as a rule, for the qualitative analysis of the factors influencing the absorption coefficient.

5. Due to the interference minimum of the waves reflected from the surfaces of ferrite RAC and the metal shield on which coating plates are pasted. The coating thickness is defined by the wavelength of the incident radiation. In RAM the wavelength decreases by $\sqrt{\varepsilon\mu}$ times. The interference minimum of reflection corresponds to the thickness of a plate which is equal to one fourth of the length of an electromagnetic wave in a ferrite:

$$d = \frac{\lambda}{4} = \frac{\lambda_0}{4\sqrt{\varepsilon\mu}}, \tag{3}$$

where λ_0 is the wavelength in vacuum, ε and μ are dielectric and magnetic permeability of RAM.

An increase in magnetic and dielectric permeability reduces the length of the electromagnetic wave and makes it possible to reduce the thickness of plates, which is especially important at low frequencies.

The attenuation coefficient of the reflected electromagnetic radiation depends to a great extent not only on the interference phenomena under the reflection of electromagnetic waves, but also on the processes of absorption of electromagnetic radiation as a result of the resonant phenomena.

Theoretical grounds for creating RAM

As electromagnetic absorption we understand electrical and magnetic losses in the material, occurring due to relaxation processes. The energy transferred to the system will be distributed between corresponding types of oscillation whose amplitudes will accept values corresponding to the thermodynamic equilibrium. Relaxation processes will determine the speed of the decay of oscillation amplitudes excited by external forces. If the system is under the influence of periodic external forces, relaxation processes exercise the continuous outflow of energy from the primary types of oscillation and provide the possibility of the continuous absorption of the energy from external forces by the system.

Relaxation processes in this case define the dissipative characteristics of the system. In [6] there are presented mathematical models of the spin-spin, spin-lattice, ionic relaxation, relaxation with involvement of current carriers, depending on the particles participating in the process of redistribution of energy. Isolation of several types of relaxation is conditional since all particles are connected by forces of interaction and participate in the process of energy redistribution at the same time. However such isolation appeared because of the complexity in the description of the relaxation process in a polycrystalline material as a whole.

The strongest absorption of energy is connected with the resonant phenomena in ferrites. Of the greatest interest are the resonance of domain boundaries (RDB) and a natural ferromagnetic resonance (NFMR) which are described by the equations of Dering and Landau-Lifshitz respectively [6]. These equations are almost postulated but for the solution of practical tasks it is expedient to use equations received empirically.

It is ascertained that processes of displacement of domain boundaries have a decisive impact on many physical properties of magnetic-ordered crystals. Non-linear processes of dynamic conversion of magnetization in the system of spins localized in a domain boundary define methods of dissipation of energy brought to the domain boundary from the outside [6].

It is known that magnetic losses of ferrite RAM in the range of frequencies 10 – 100 MHZ are to a considerable degree caused by the processes of the resonance of domain boundaries (RDB) leading to the outflow of external electromagnetic energy, due to energy redistribution between the electrons which form domain boundaries. For the phenomenological description of RDB the equation of Dering is used [7]:

$$m\,\frac{d^2x}{dt^2}+\rho\frac{dx}{dt}+\xi x=M_0H, \quad (4)$$

where m is the effective mass of the domain boundary, x is the boundary coordinate, ξ is the coefficient of "magnetic" elasticity depending on the initial magnetization and the sizes of domains; ρ is the generalized dissipative coefficient characterizing irreversible losses of energy in the system when it is acted upon by the generalized force of M_0H from an outside magnetic field; M_0 is the magnetization of saturation, H is the magnetic field intensity.

Drawing an analogy to the harmonic oscillator, it is possible to conclude that an increase in the effective mass of domain boundaries (and of an average grain size) will lead to lowering the frequency of RDB:

$$\omega_0=\sqrt{\xi/m}, \quad (5)$$

which is important for extension of the operating range of ferrite RAM.

The range of a magnetic susceptibility determined by the resonance of domain boundaries can be described by the expression:

$$\chi=\chi_0\left(1-\frac{\omega^2}{\omega_0^2}-j\frac{\omega}{\omega_{rel}}\right)^{-1}, \quad (6)$$

where χ_0 is the initial static susceptibility, ω_{rel} is the frequency of relaxation of boundary displacement; it is proportional to m^{-1} and can characterize mobility of the domain boundary. The level of absorption of electromagnetic radiation reaches its maximum near the frequency of their natural oscillations. The condition for initiation of the resonance is rigid fixation of domain boundaries on grain boundaries, pores or other defects, which provides reversible displacement of their sections relative to the equilibrium position. The frequency of natural oscillations of domain boundaries ω_0 is defined by the effective mass of the domain boundary m and the stiffness coefficient ζ, which characterizes the quasielastic force operating on the crystal wall.

From the formula (5) it follows that an increase in the mass of a domain boundary allows to reduce the resonance frequency and to expand in this way the frequency interval of absorption of a ferrite. As the mass of a domain boundary is to some extent a measure of its inertness and it is approximately proportional to the surface area of the boundary [8, 9], formation of coarse-grained structure shall lead to reduction in the resonance frequency of domain boundaries, whereas the spread of grains sizes shall lead to an increase in the width of the resonance curve (Fig. 2).

Formation (at grain boundaries) of dislocations, inclusions and atoms different in their sizes and electrochemical potential from cations which are a constituent part of a ferrite increases friction losses, that is the dissipative component ρ in the equation (4) (Fig. 3). The pictures on Fig. 2 and Fig. 3 are made on the scanning microscope from the company «Carl Zeiss Jena».

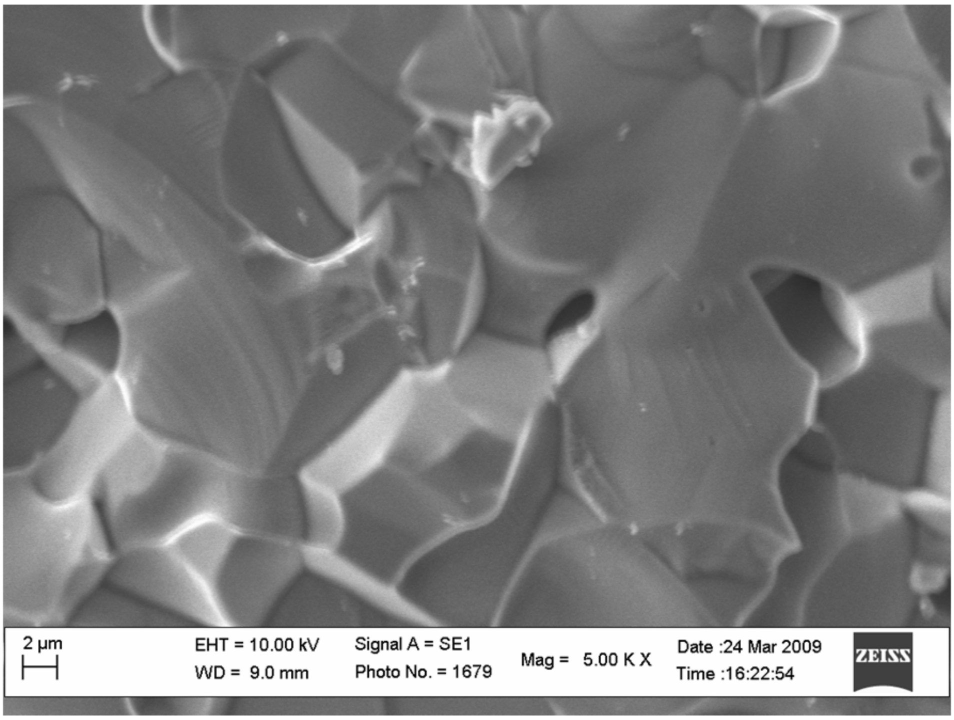

Fig. 2. An example of microstructure of a Ni-Zn ferrite with the spread of grains according to their sizes

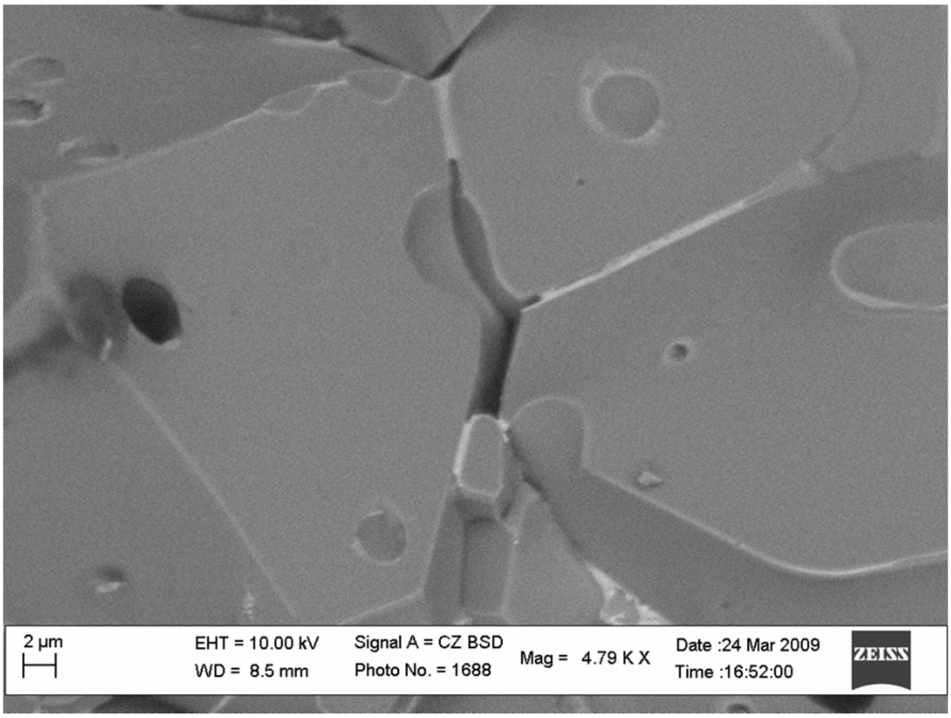

Fig. 3. Microstructure of a batch of Ni-Zn ferrites with addition of bismuth. Being larger than cations of Fe^{2+} and Ni^{2+}, ions of Bi^{3+} are ejected from the lattice and are located at grain boundaries (white inclusions)

Losses at higher frequencies (10^{10}–10^{11} Hz) are caused by the natural ferromagnetic resonance (NFMR) and connected with the internal field of the magnetic anisotropy. NFMR is initiated under coincidence of the frequency of an outside electromagnetic field with the precession frequency of rotational axes of electrons. The magnetic moment of an atom is developed from the spin and orbital magnetic moments, the spin moment considerably exceeding the orbital one. NFMR can be called the spin resonance and it can be treated as "tilting" of the magnetic spinning top. This "tilting" occurs when the frequency ω of an outside high-frequency field H, perpendicular to the precession axis (that is to the anisotropy field H_A), matches the resonance frequency ω_0. The resonance frequency is connected with the intensity of an internal field of anisotropy through a gyromagnetic ratio γ:

$$\omega_0 = \gamma H_A, \quad (7)$$

H_A – the intensity of the anisotropy field is defined by the formula:

$$H_\text{A} \approx \frac{K}{M_0}, \quad (8)$$

where K is the constant of crystallographic magnetic anisotropy. It depends on the composition of a ferrite and the nature of cationic distribution and defines the rigidity of domain boundaries. With an increase of K, the frequency of NFMR moves towards upper frequencies.

Next to the NFMR frequency there occurs dispersion – dependence of the magnetic susceptibility on the frequency of an outside field, as well as maximum of absorption of electromagnetic energy. In this case the power P of the absorbed energy of the alternating field is proportional to the imaginary component of magnetic susceptibility χ'':

$$\chi^* = \chi' + j\chi'', \quad (9)$$

$$P = \omega\chi'' H^2. \quad (10)$$

The occurrence of attenuation leads to some shift in the resonance frequency. Ferromagnetics show the biggest resonance absorption as they possess considerable spontaneous magnetization.

Anisotropy is connected with the finite sizes of the sample under research and its domain structure which is characterized by different directions of spontaneous magnetization. Thus, for estimation of the resonance frequency in a ferromagnetic it is necessary to take into account all its internal magnetic fields which can also be caused by mechanical stresses – because of the magnetostriction phenomenon. All the specified factors will promote broadening the band of the resonance frequency [10]:

$$\gamma H_A \le \omega \le \gamma H_A + 4\gamma\pi M_0, \quad (11)$$

where γ is the gyromagnetic ratio, M_0 is the magnetization of saturation;

The outflow of energy from an outside field also depends on relaxation processes. For example, in case of Ni-Zn ferrites substitution of bivalent ions of nickel with bivalent ions of iron in octahedral nodes leads to appearance of additional electrons, since Fe^{2+} ions have one "free electron" in comparison with Fe^{3+} ions. Such electrons, moving freely moved on the octahedral sublattice, will accelerate processes of energy redistribution. At the same time there occurs the broadening of the resonance line.

The width of the resonance line is influenced even by small amounts of impurity, porosity, magnetic anisotropy, the presence of two or more sorts of magnetic atoms in the lattice. On the contrary, the narrow line is peculiar for monocrystals and structures which are the most similar to the ideal ones.

Methods of measuring the reflection coefficient of RAM

The measurements of reflection coefficients in the short circuit mode in the samples of different width on the metallic plate in the range of frequencies from 0,3 to 1300 MHz are conducted on the laboratory bench, created on the base of the complex transmission measuring set «Obzor 103» in combination with the computer system of the signal registration and processing.

The samples are placed into the coaxial measuring cell with the net section in the sample positioning area 16/6.95 mm, matched with the coaxial measuring circuit.

The calculation of the complex magnetic permeability is carried out in accordance with the developed procedure, on the basis of the «short circuit – idle running» method [10].

Fig. 4 Measuring set «Obzor 103»

On the basis of mathematical processing of the measured reflection coefficient there are defined complex components of magnetic and dielectric permeability, that is, they are defined indirectly and their measurement has an evaluation character. The measurement method in a coaxial strip-line waveguide transmission line is acceptable for the low frequency range with a big wavelength.

For higher frequencies the horn-type method is used. In its section the horn has the form of a square whose side is proportionate to the wavelength with which the experimental sample of RAM or RAC is irradiated. For this reason it is difficult to measure the radio absorption coefficient at low frequencies by the horn-type method. For example, at 300MHz the length of the horn side is equal to 1m, and to make a horn for frequencies in digits and tens of MHz appears quite difficult.

In both methods the reflection coefficient is considered to be a decimal logarithm of the ratio of the power of the reflected wave to the power of the falling one.

Perspectives on creating new RAM

The tendency towards miniaturization of technical aids and transition to power supply units with SHF requires creation of RAC at the GHz range. As a rule, they are coatings from amorphous alloys containing Fe, Ni, Co whose thickness is several microns. These coatings are made by the evaporation method or by the application of melts onto fabric, film or other bases.

The technological process of manufacturing metalized tapes consists in pouring out the melt of the specified metals on the rotating barrel, from which there comes out a tape from an amorphous alloy 20 mm wide. The samples of tapes are cut in bands 50 to 250 cm long. From the bands (by placing bands with overlapping) a packet is formed 10 to 30 cm wide. The size of overlapping is 1 to 3 mm. After that the formed packet is laminated on the AR-320 laminator.

It should be noted that the suggested method makes it possible to obtain packages of any length.

The enterprise produces shields for power cables, vests for protection of welders and of the maintenance personnel for offshore structures and sea-going vessels.

Fabrics with sputtering of Ni and Co acquire metal brightness and become attractive for fashion designers.

If in the required range of absorption there appear megahertz frequencies, the thickness of RAM becomes quite considerable and sometimes can be commensurable with human height.

Such bulky materials used in anechoic chambers reduce the workspace. Besides, they are difficult to mount, contain toxic components and are costly.

The range from 10 to 400 MHz is the most problematic absorption region of electromagnetic energy in RAM and RAC. As this range corresponds to RDB (resonance of domain boundaries) frequencies in Ni-Zn and Mg-Zn ferrites, these specified materials are perspective for the megahertz range. For this reason the study of the resonant phenomena in ferrites, resonance of domain boundaries in particular, is quite urgent.

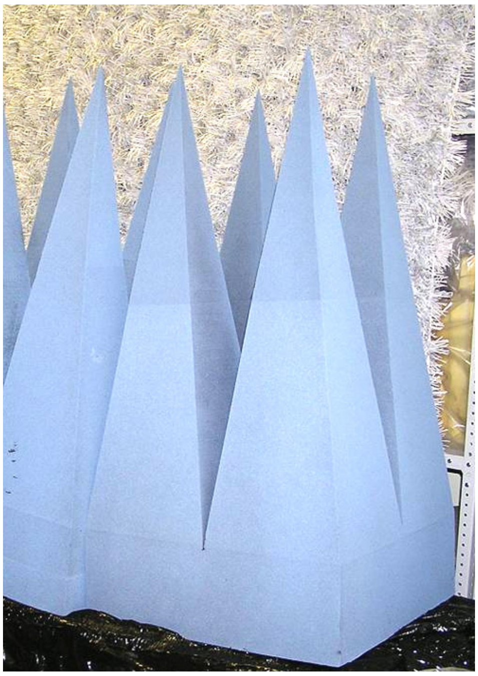

Fig. 6. Ultra wide-range absorber of the TDK company is as high as a pyramid of 1250 мм

To extend the absorption frequency range at frequencies less than 30 MHz it is necessary to develop new ferrite materials with a combination of high values of magnetic and dielectric permeability and with considerable manifestations of RDB. Along with Ni-Zn and Mg-Zn ferrites Mn-Zn ferrites are also rather perspective.

It is necessary to develop scientific bases for creation of broadband absorbers on the basis of ferrite materials, including powders on the basis of polymeric binding, as well as carry out mathematical simulation of the accumulated experimental data for the purpose of controlling radio-absorbing properties of RAM.

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Аннотация. *Актуальность и цели*. Согласно закону РФ «О государственном регулировании в области обеспечения электромагнитной совместимости технических средств» ужесточаются требования к уровню электромагнитного излучения выпускаемых электронных и электрических приборов. Испытания на соответствие требованиям проводятся в безэховых камерах, стены которых облицованы радиопоглощающими покрытиями (РПП) и радиопоглощающими материалами (РПМ), необходимыми для защиты персонала и измерительных приборов от переотраженного электромагнитного излучения (ЭМИ). *Материалы и методы*. В данной работе дан аналитический обзор назначения современных радиопоглощающих материалов (РПМ) и покрытий (РПП), теоретических основ и тенденций их создания. *Результаты*. Выявлены основные тенденции увеличения поглощения электромагнитной энергии: 1) за счет увеличения мнимой части диэлектрической проницаемости ε"; 2) за счет увеличения мнимой части магнитной проницаемости μ"; 3) за счет согласования волновых сопротивлений материала покрытия со средой распространения электромагнитной волны; 4) за счет интерференции отражений от разных слоев покрытия; 5) за счет интерференционного минимума волн, отраженных от поверхностей ферритового РПП и металлического экрана, на который наклеены пластины покрытия. Представлены способы измерения коэффициентов отражения РПМ, теоретические основы, а также перспективы создания РПМ и РПП. *Выводы*. Отмечено, что необходимо разрабатывать научные основы создания широкополосных поглотителей на основе ферритовых материалов.

Abstract. *Background*. According to the Act of the Russian Federation "About the state regulation in the field of ensuring electromagnetic compatibility of technical means", requirements for the level of electromagnetic radiation of available electronic and electrical appliances become tougher. Tests for compliance with the requirements are carried out in the anechoic chambers whose walls are coated with radio-absorbing materials (RAM) and radio-absorbing coatings (RAC) necessary for the protection of the personnel and measuring devices against the re-reflected electromagnetic radiation (EMR). *Matherials and methods*. This work deals with the analytical survey of the designation of contemporary RAM and RAC, theoretical principles of RAM electromagnetic losses. *Results*. There have been identified the major tendencies of increasing absorption of electromagnetic energy: 1. At the expense of increasing the imaginary part of dielectric permeability ε". 2. At the expense of increasing the imaginary part of magnetic permeability μ". 3. Due to coordination of wave resistances of a coating material with the propagation medium of electromagnetic waves. 4. Due to the interference of reflections from the different coating layers, leading to reduction in reflection from the material (multi-layer coatings and coatings with a special-purpose form). 5. Due to the interference minimum of the waves reflected from the surfaces of ferrite RAC and the metal shield on which coating plates are pasted. There have been set forth theoretical principles, as well as prospects of producing radio-absorbing materials and coatings. *Conclusions*. It is necessary to develop scientific bases for creation of broadband absorbers on the basis of ferrite materials, including powders on the basis of polymeric binding, as well as carry out mathematical simulation of the accumulated experimental data for the purpose of controlling radio-absorbing properties of RAM.

Ключевые слова: электромагнитное экранирование, мнимая часть диэлектрической и магнитной проницаемости, координация волнового сопротивления, минимальное вмешательство, резонанс доменных границ, естественный ферромагнитный резонанс, ферритовые радиопоглощающие материалы.

Key words: electromagnetic screening, imaginary part of dielectric and magnetic permeability, coordination of wave resistance, interference minimum, resonance of domain boundaries, natural ferromagnetic resonance, ferrite radio-absorbing materials.

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