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Microwave Electrodynamic Characteristics of Ceramic Materials

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The results of experimental studies of the developed veneering ceramics with electrically conductive SiC admixtures of 10 and 20 wt. % are presented. The main electrodynamic characteristics of ceramics such as microwave permittivity, dielectric loss tangent, attenuation and reflection coefficients were measured by PNA N5227A Keysight Technologies vector network analyzer in the frequency range of 1-67 GHz. The instrument software automates measurements of complex permittivity and permeability of materials. The results can be presented in S-parameter format, ε', ε'', tanδ, μ' and μ''. The effective permittivity of the composite depends on the filling factor of the composite matrix with particles (the ratio of the total volume of particles to the entire volume of the medium). In the case of low concentrations of nanoparticles, the approach based on the Maxwell-Garnett effective medium theory provides fairly accurate results. The characteristics of the developed ceramics are shown, which allow its use in construction engineering and electronic devices in order to effectively shield harmful electromagnetic radiation. According to the classification, ceramics themselves can be attributed to radio-absorbing ceramics.

Keywords: Ceramic tile, Electrically conductive admixtures, Attenuation and reflection coefficients, Complex permittivity and permeability, Dielectric loss tangent.

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1. INTRODUCTION

At present, a person's life, both at work and at home, takes place in conditions of an increased concentration of adverse factors, including electromagnetic radiation: broadcasting television; navigation systems; energy and electric transport; computers; office and household appliances; analog, digital, military and special communications and amateur radio; industrial and medical equipment, and many others [1, 2]. The frequency range, in which radiating equipment mainly operates, extends from 1 to 5 GHz (microwave ovens, 3G/4G mobile communication, etc.). Next in line is 5G mobile communication, the Internet of Things, which requires an increase in data exchange speed by 1-2 orders. This is provided by increasing the operating frequency to 20-70 GHz.

It is known that high-power electromagnetic radiation exceeding the permissible levels can cause certain functional disorders in the human body, in some cases irreversible. Failure to observe precautions and lack of proper protection under electromagnetic radiation can lead to increased fatigue, disorders of the central nervous system, clouding of the eye lens, etc. [3, 4]. In addition, electromagnetic radiation adversely affects the technical state of electronic systems right up to failure, which is extremely dangerous in modern conditions of the spread of automated control systems for technological processes and medical aid [5, 6].

Traditionally, metals and their alloys, ferrites are used to protect against the effects of electromagnetic radiation [7, 8]. The use of such materials in their pure form is impractical both from economic and technological points of view. Therefore, it makes sense to use them as ingredients of composite radioprotective materials. Namely, the introduction of electrically conductive admixtures into the dielectric matrix provides a decrease in volume resistivity and an increase in magnetic permeability of ceramic materials. The main disadvantages of the most commonly used composite materials are low strength, flammability, toxicity associated with various organic substances as matrices (resins, rubbers, paints, varnishes, etc.) [9]. The use of ceramic matrices can eliminate these shortcomings.

The class of electrically conductive admixtures includes mainly metals and their alloys, graphite, etc. But prevalent admixtures used in electromagnetic protective materials are generally unstable during heat treatment (they burn out, react with the formation of new products possessing high resistivity values), which is unacceptable when creating protective ceramic composite materials [10].

Therefore, the proper choice of electrically conductive admixtures for ceramic composite materials protecting biological and technical objects from negative effects of electromagnetic radiation is an urgent problem in Ukraine and EU countries as well as throughout the world.

Based on the above, the goal of our work is to experimentally study the electrodynamic characteristics of electrically conductive composite veneering ceramics with SiC admixture in the frequency range from 1 to 67 GHz.

2. DEFINITIONS

When an electromagnetic wave passes through a material, the material-radiation interaction is determined by the parameters of transmission T, reflection R and absorption A [1]:

$$T + R + A = 1,$$

where $T = 10^{S21}$, $R = 10^{S11} = \left|\frac{\mathrm{VSWR}-1}{\mathrm{VSWR}+1}\right|^2$, S_{21} is the power transmission coefficient in dB, S_{11} is the power reflection coefficient in dB, VSWR is the voltage standing wave ratio, S_{21} and S_{11} are standard scattering parameters measured by microwave network analyzers, reflectometers, etc.

For a planar material layer of thickness l, the transmission and reflection are determined by the following relations [1]: $T = |t|^2$, $R = |r|^2$,

$$r = (r_{12} - r_{12} \cdot e^{-2\gamma \cdot l}) \,/\, (1 - r_{12} \cdot e^{-2\gamma \cdot l}),$$
$$t = ((1 - r_{12}^2) \cdot e^{-\gamma \cdot l}) \,/\, (1 - r_{12}^2\, e^{-2\gamma \cdot l}),$$

where $r_{12} = (1 - n)/(1 + n)$ is the reflection index at the space-material interface, n is the complex index of refraction, γ is the complex propagation constant in the material. All stated terms are dependent on material permittivity and permeability.

3. EXPERIMENT

The choice of the ceramic mass was based on the condition of the lowest temperature and annealing time, taking into account the possible oxidization and burning out of the admixture or its interaction with the dielectric (ceramic) matrix. In this work, the material for the production of veneering ceramics was considered.

A promising approach in the design of effective composite shielding materials is based on the use of a dielectric matrix with an electrically conductive admixture (electrode coke, technical carbon, carbon nanotubes, graphite, carbonyl iron, silicon carbide, silicon, aluminum, iron, copper, nickel, iron (III) oxide, copper oxide (II)) [8-10].

Taking into account the requirements [10-15] imposed on electrically conductive admixtures used in electromagnetic protective ceramic composite materials, SiC was chosen (ρ_v: 0.001-0.3·10^{-6} Ohm·m, TCLE: 5-7·10^{-6} deg^{-1}, T_m: 2.700 °C). With regard to manufacturability of the mass, the amount of introduced admixtures was determined from 10 to 20 wt. %.

To obtain press powder, raw materials were weighed in a predetermined amount, 10 and 20 % silicon carbide was added, and wet grinding in ball mills was carried out. The resulting slip was dried in an oven, crushed and passed through a No 05 sieve. The ready-made press powder for veneering ceramics with SiC was moistened to 8 %, weighed and poured into a mold for pressing. The pressure force was 18-20 MPa. The resulting crude was dried in an oven. The semi-finished product was annealed in a silite furnace at a temperature of 1120-1140 °C with holding at the maximum temperature for 5-10 min.

The chemical composition of ceramic masses with silicon carbide for the subsequent fabrication of facing ceramics specimens is shown in Table 1.

Table 1 – Chemical composition of ceramic masses

Name	The content of components, wt. %								
	Al_2O_3	SiO_2	Fe_2O_3	K_2O	Na_2O	CaO	TiO_2	SiC	PPP
OK 1	14.9	51.69	1.26	4.57	1.47	6.3	0.72	9.09	14.9
OK 2	13.24	45.95	1.12	4.07	1.3	5.6	0.64	8.08	13.24

The electrodynamic characteristics of the ceramics were measured by PNA N5227A Keysight Technologies vector network analyzer. In our research, we focused on measuring these characteristics precisely in the microwave range, and the actual frequency range was 1-67 GHz. The instrument software automates measurements of complex permittivity and permeability of materials. The results can be presented in S-parameter format, ε', ε'', tanδ, μ' and μ''.

Ceramic samples of cylindrical shape with a central hole were placed in the coaxial waveguide of the measuring device. Sample sizes: diameter 1.85 mm, hole diameter 0.82 mm, length varied from 2.4 mm for a sample with 10 wt. % SiC (OK 1) up to 3.6 mm for a sample with 20 wt. % SiC (OK 2).

Fig. 1 shows the spectra of transmission and reflection coefficients for a sample of veneering ceramics OK 1. The spectra demonstrate rather high values of transmission and relatively low reflection, but certain resonances appear in the dependence. It is known that the permittivity of dielectric mixtures is determined by their composition as well as particle size and can be approximately calculated using the Maxwell-Garnett effective medium theory [2]. It predicts the appearance of resonant absorption bands depending on the constituent components of the composite.

Fig. 2 shows the dielectric spectra of OK 1 composite. Resonances are observed at frequencies of approximately 45 GHz and 60 GHz.

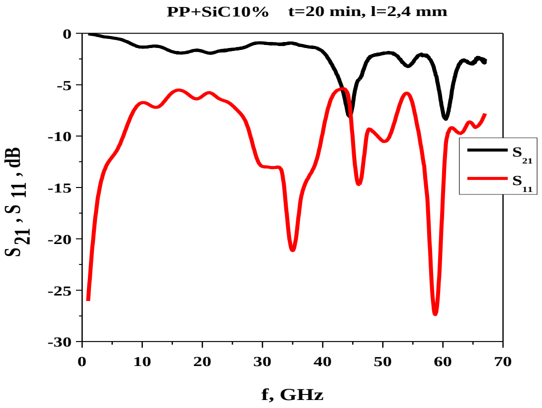

Fig. 1 – Spectra of transmission and reflection coefficients of ceramic sample OK 1

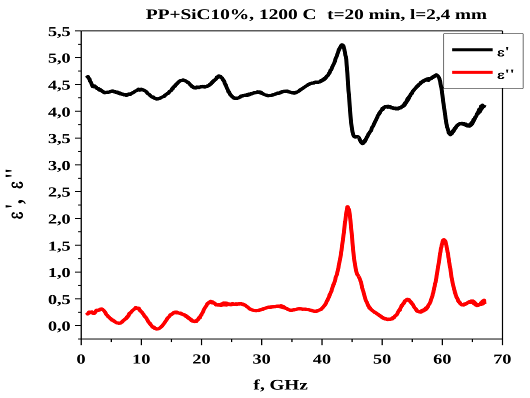

Fig. 2 – Dielectric spectra of composite OK 1

As it was mentioned, the presence of two components in a composite can lead to resonant interaction of a material with microwave radiation. The range of resonance amplitudes and frequencies is determined by the permittivities and particle sizes of admixtures. In this case, the effective permittivity of the composite depends on the filling factor of the composite matrix with particles (the ratio of the total volume of particles to the entire volume of the medium). In the case of low concentrations of nanoparticles, the approach based on the Maxwell-Garnett effective medium theory provides fairly accurate results.

Accordingly, the dielectric loss tangent (Fig. 3) has resonant regions where losses increase sharply.

Increasing the concentration of SiC in the composite up to 20 wt. % (OK 2) completely restructures the frequency dependences and increases the losses (Fig. 4-Fig. 6). With an increase in conductive admixtures, the permittivity also increases. In addition, the dielectric loss tangent increases significantly.

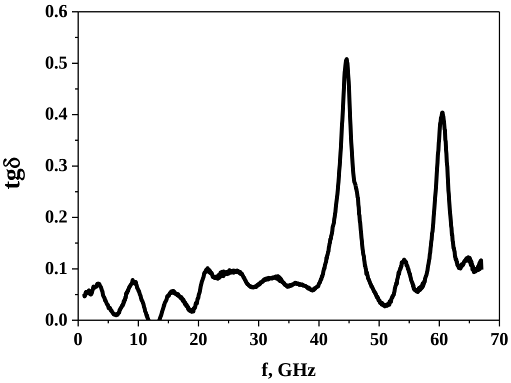

Fig. 3 – Dielectric loss tangent of sample OK 1

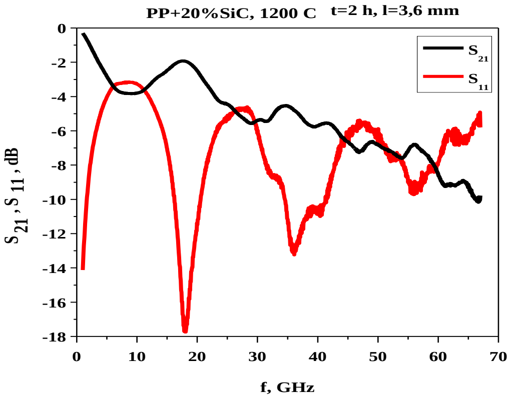

Fig. 4 – Spectra of the transmission and reflection coefficients of ceramic sample OK 2

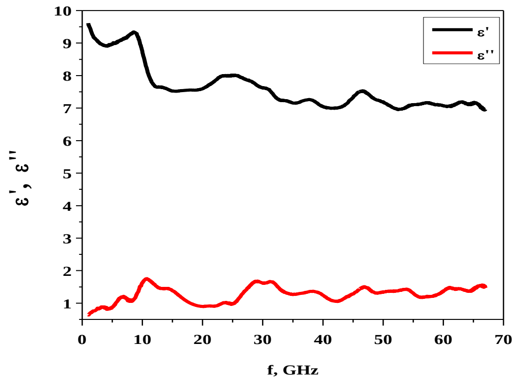

Fig. 5 – Dielectric spectra of composite OK 2

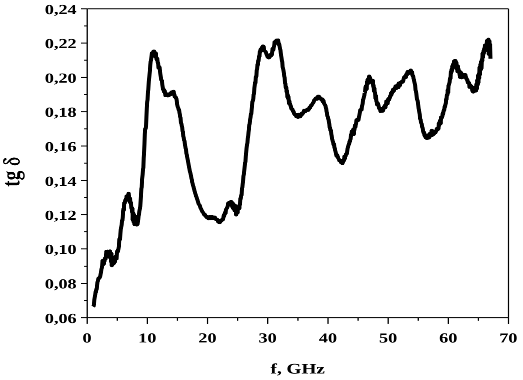

Fig. 6 – Dielectric loss tangent of sample OK 2

4. CONCLUSIONS

The electrodynamic characteristics of electrically conductive composite veneering ceramics with the addition of SiC were studied in the microwave range from 1 to 67 GHz. The following findings can be drawn:

– It is experimentally shown that the transmission and reflection coefficients of the test samples in the range of 1-67 GHz increase with increasing conductive admixture concentration from 10 to 20 wt. % SiC. At the same time, the absorption of microwave radiation increases, and ceramics can be considered as a radio-absorbing material.

– The developed and fabricated composite ceramic materials with the appropriate concentration of admixtures meet the basic requirements for the operation of such materials. They can be suitable for electromagnetic protection inside premises exposed to radio wave radiation and for environmental purposes to reduce the electromagnetic field intensity.

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Мікрохвильові електродинамічні характеристики керамічних матеріалів

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Наведено результати експериментальних досліджень розробленої облицювальної керамічної плитки з електропровідними добавками SiC 10 і 20 мас. %. За допомогою векторного аналізатора мережі Keysight Technologies PNA N5227A вимірювалися основні електродинамічні характеристики кераміки: мікрохвильова діелектрична проникність, тангенс кута діелектричних втрат, коефіцієнти загасання і відбиття в діапазоні частот 1-67 ГГц. Програмне забезпечення приладу автоматизує вимірювання комплексної діелектричної проникності і магнітної проникності матеріалів. Результати можуть бути представлені в форматі S-параметрів, ε', ε'', $\tan\delta$, μ' і μ''. Ефективна діелектрична проникність композиту залежить від коефіцієнта заповнення композитної матриці частинками (відношення загального об'єму частинок до всього об'єму середовища). У разі низьких концентрацій наночастинок підхід, заснований на теорії ефективного середовища Максвелла-Гарнетта, дає досить точні результати. Показано характеристики розробленої кераміки, які дозволяють використовувати її в конструкційній техніці та електронних пристроях з метою ефективного екранування шкідливого електромагнітного випромінювання. Саму кераміку за класифікацією можна віднести до радіопоглинаючої.

Ключові слова: Керамічна плитка, Електропровідні домішки, Коефіцієнти загасання та відбиття, Комплексна діелектрична та магнітна проникність, Тангенс діелектричних втрат.