Improving the shielding efficiency and weight reducing of the radio-absorbing coating by adding a matching layer

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Abstract. The spectra of complex permittivity of the composites consisting of rubber silicone compound and electroconductive fine-dispersed silver-coated copper powder were investigated. To enhance the effectiveness of the composite interaction with microwaves and reduction of its weight and dimensions characteristics two and three-layer constructions were produced. Matching layers were made of foam glass material with addition SiC and Fe₂O₃.

1. Introduction
Materials effectively shielding diverse objects are widely used in various sectors: radioelectronics, ecology, medicine, counter-terrorism systems and security [1–4]. The increased use of radioelectronic equipment in science and production, for improvement of living conditions [5] poses a number of problems. First, it pollutes the environment and contributes to increased incidence. In this regard, shielding devices are necessary for biological objects protection and separate blocks of radioelectronic equipment interference suppression. The screens are constantly being developed, but new challenges appear and the old methods become outdated. The use of well-established metal (steel, copper, aluminium etc.) screens is limited now due to miniaturization, when weight and size are of primary importance. One of the possible ways of weight reduction is production of composite materials made of conductive polymers [6] or usage of dielectric polymer matrices filling with conductive particles. If the filling exceeds the percolation threshold, the screen reflects electromagnetic energy, i.e. it becomes analogous to a metal screen but lighter by weight. If the filling is below the percolation threshold, non-reflecting screens where electromagnetic energy transforms to thermal can be produced. Polymer screens are flexible, elastic, inexpensive and producible. Nowadays polymer materials with fillings are used in 3D printer filaments production allowing to produce protective screens of the most complicated shapes [7,8]. In particular, 3D printing makes it possible to design metasurfaces, that allow matching the wave impedances of free space and a shielding device. [9,10]. Creation of new materials based on foaming [11,12] and carbonic aerogel synthesis [13, 14] leads to weight reduction.
2. Materials and methods

The composite consisting of rubber silicone compound IRP-1401 (technical specifications (TS) 38.103372-77) and electroconductive fine-dispersed silver-coated copper powder PMI-certified (TS 24.44.21-001-32946049-2018) was used as main shielding material. Compounding was performed on cold gap-mill with 1:1.15 friction coefficient. PMS-100 - certified silicone oil was used as an adjuvant improving metal powder incorporated into matrix. The amount of electroconductive powder in the compound is 85 wt %. By controlling the conductivity of the compound, the mixing quality was achieved. Further, electroconductive silicone compound was loaded into rubber vulcanizing press at clamping force 100 kg/cm. The time of vulcanization was 10 min, vulcanization temperature was 190°C. Plate was cooled at room temperature for 24 hours after extraction from the pressform. Finally, the composite (TSC) of 4,06 g/cm³ density was obtained.

A foam glass material with addition of silicon carbide and ferrous oxide [15] was used as a matching layer having lowest real and imaginary component of permittivity, which provides reduction of characteristic impedance jump. Porous foam glass was produced by low-temperature method described in [15]. Sodium liquid glass of 2.5 acidity index was used as a matrix, where cullet powder of 6000 cm²/g specific surface was incorporated. Hydrophilic aluminum powder was used as a gasifier. To improve bond performance SiC was added in liquid glass composite in the amount of 20 and 40 wt % instead of cullet powder. Silicon carbide was chosen due to large width of its forbidden gap (3.26 eV), permittivity (6.5-7.5 rel. un.) and covalent type of chemical bond, which influences on material strength properties.

During foam glass material synthesis, it was observed that the increase of SiC content the value of expansion coefficient increases. The reaction of additional gasification in the system results in porosity increase and composite density decrease (table 1). This effect is corroborated by scanning electron microscopy (SEM) pictures (figure 1).

| Composite | Amount of SiC in the composite, mass percent | Physical-mechanical properties |
|-----------|--------------------------------------------|--------------------------------|
|           |                                            | density, kg/m³ | compression strength, MPa |
| PSSiC-20  | 20                                         | 388             | 1.43                        |
| PSSiC-40  | 40                                         | 354             | 0.50                        |

When the cullet powder was used as a filler between liquid glass and glass particles as similar components, the surface interaction was observed. When initial materials were replaced by powders, greatly differed by its properties (density, strength, wettability), the cohesion between matrix and filler was decreased. If the concentration is rather low, silicon carbide particles strengthen the composite. Silicon carbide content above 40 wt % leads to a decrease in the strength of the final sample due to the formation of an uneven porous structure and an increase in the average pore size (figure 1 b). According to obtained experimental data the criteria for formation of even, finely porous structure in liquid glass composition were determined: the ratio of the mass of the liquid phase to the solid filler should be 0.35; dynamical viscosity of the composition must be at 1.5 Pa×s rate.

To increase the electromagnetic effectiveness of foam glass material, GaAs semiconductor material was incorporated in the structure of the filler. In doing so, the problem of recycling in order to decrease anthropogenic burden on the environment was solved. To estimate the possibility of this use of the technology 40 wt %. SiC was replaced by the waste of semiconductor industry (marking of the sample – PSSiC-GaAs). In attempt to use magnetic properties of the composites, ferrous oxide (marking – PSSiC-Fe₃O₄) was incorporated instead of silicon carbide in the same proportion as semiconductor material.
Complex permittivity and electromagnetic response components (reflection, transmission and absorption factors) of the composites were measured by STD-21 terahertz spectrometer [16]. Calculation of complex permittivity spectra was made for normal incidence of flat electromagnetic wave on flat material surface.

![SEM pictures of composites](image1)

Figure 1. SEM pictures of composites with 20 wt % of SiC (a) and 40 wt % of SiC (b).

3. Results and discussion
Composite complex permittivity spectra of silver-coated copper powder in silicone matrix have weak decreasing dependence on frequency increase, while imaginary component have no dispersion (figure 2).

![Complex permittivity spectrum](image2)

Figure 2. Complex permittivity spectrum of silicon composite TSC. 
\( \varepsilon' \) is real part of permittivity, \( \varepsilon'' \) is imaginary part of the permittivity.

Foam glass material without additive (PS) has \( \varepsilon^* = 2.2 - i0.42 \) without dispersion in 120-250 GHz bandwidth. Frequency dependence of permittivity complex values of foam glass composites with additives are shown on figure 3.

![Complex permittivity spectra](image3)

Figure 3. Complex values spectra of permittivity complex values of foam glass composites: 1 – PSSiC-20, 2 – PSSiC-40, 3 – PSSiC-GaAs, 4 – PSSiC-Fe\textsubscript{3}O\textsubscript{4}.
The change of silicon carbide concentration in the investigated bandwidth influenced on imaginary component and had no significant influence on real component. The addition of gallium arsenide to the foam glass led to an increase in both components of the permittivity. In this case, the imaginary part of the permittivity increases in the frequency range from 120 to 180 GHz with subsequent stabilization of the value in the region of 1.2 relative units in the frequency range from 180 to 250 GHz. The addition of ferrous oxide also raised the value of permittivity. All the examined materials have much weaker interaction with electromagnetic field than TSC composite and have closer values to the parameters of free space.

The frequency dependences of the electromagnetic response (transmission, reflection and absorption), obtained by solving the direct electrodynamic task, are shown in figure 4–6. Figure 4 demonstrates the characteristics of two-layer construction, where remote layer is 1 mm thick made of silicon composite with copper powder. Near to the front of incident wave layer was replaced by foam glass samples where silicon carbide concentration was 20 and 40 wt %, then by silicon carbide, gallium arsenide and ferrous oxide combinations. The thickness of matching layers was 2 mm. Electromagnetic characteristics of one-layer TSC composite are shown on the same figure for comparison.

![Figure 4](image1.png)

**Figure 4.** Two-layer coating electromagnetic response components.

As it is shown, a construction reflectance decreased significantly. Transmission also decreased due to the growth of construction absorbance.

![Figure 5](image2.png)

**Figure 5.** Three-layer coating electromagnetic response components.
The replacement of half-thickness of matching layers in the construction by foam glass material without additives 1 mm thick didn’t change the whole thickness but significantly decreased reflectance ratio due to contrast decay between medium impedance bringing electromagnetic energy and three-layer structure.

Figure 6 shows electromagnetic response spectra of the construction, where remote layer thickness was reduced by half and the thickness and control positions of matching layers remain the same as on Figure 5.

![Figure 6. Three-layer coating electromagnetic response components with reduced thickness of first layer.](image)

As can be seen (black line in figure 5 and figure 6), the reflectance remained approximately the same as for 1mm thick sample of TSC, transmission increased and absorption decreased. The problem was solved by addition of matching layers. Although absorption decreased, other characteristics of electromagnetic response enabled to use the construction for effective shielding.

4. Summary
The research has shown that electrophysical characteristics of foam glass material are alterable depending on filler composition. The construction made of main absorber (silver-coated copper powder in silicon matrix) and foam glass matching layer enables to decrease reflectance from −5 dB to −16 dB. The usage of matching layers reduced the weight of the construction by half, as the remote layer with the density of 4,06 g/cm$^3$ has the main weight, foam glass material being 10 times lighter.

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