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S_{11} and S_{21} characteristics of carbon fiber fabric fixed in the polyurethane based matrixes

O.V. Boiprav ✉, **E.S. Belousova**, **V.S. Mokerov**

Belarusian State University of Informatics and Radioelectronics, Minsk, Republic of Belarus

✉ smu@bsuir.by

ABSTRACT

The aim of the research presented in the paper was the establishment of the regularities of change of electromagnetic radiation reflection (S_{11}) and transmission (S_{21}) characteristics values in the frequency range 2.0 – 17.0 GHz of carbon fiber fabric fixed in the polyurethane mastic based matrices depending on these matrixes composition. Such research is urgent due to the following reasons: (1) carbon fiber materials are characterized low stability of S_{11} and S_{21} characteristics due to their hydroscopicity; (2) to increase stability of S_{11} and S_{21} characteristics and strength of carbon fiber materials it's necessary to perform their additional processing (for example, to fix them in matrices or substrates). It's demonstrated in the paper that values of S_{11} characteristics in the frequency range 2.0 – 17.0 GHz of carbon fiber fabric fixed in the matrix from polyurethane without fillers are from −0.1 till −3.5 dB. S_{11} characteristic values in the frequency range 2.0 – 17.0 GHz of carbon fiber fabric fixed in the matrix from polyurethane with aluminum oxide, titanium oxide and zinc oxide fillers are from −0.1 till −11.0 dB, from −0.1 till −3.0 dB, from −0.1 till −5.0 dB respectively. S_{21} characteristic values in the frequency range 2.0 – 17.0 Hz of the listed materials are from −20.0 till −40.0 dB. The studied materials are suitable for use for making special boxes for storing equipment sensitive to microwave interference.

KEYWORDS

electromagnetic radiation • carbon fiber fabric • microwave absorber • polyurethane matrix • S_{11} characteristic S_{21} characteristic

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Introduction

Carbon fiber materials are currently widely used for the manufacture of microwave absorbers [1–10]. This is due to the following advantages of these materials [11]:

1. high electrical conductivity, due to which microwave absorbers based on these materials are characterized by high efficiency;
2. the possibility of providing the required electrical conductivity values for these materials by changing the percentage of carbon fibers in their composition (due to the indicated advantage, the required operating frequency range, as well as the S_{11} and S_{21} characteristics values can be provided for electromagnetic radiation absorbers based on the indicated materials);
3. flexibility, due to which products of complex shape (special clothing, covers for electronic devices, modules for cladding the walls of shielded rooms) can be manufactured from the microwave absorbers based on the indicated materials;

4. high corrosion resistance compared to metals with comparable values of specific electrical conductivity.

The indicated absorbers are used to solve the following problems [12–17]: protection of electronic devices from electromagnetic interference, protection of humans from electromagnetic radiation; ensuring the security of information processed using computing equipment. Since the introduction of 5G technologies, the urgency of solving the first and the second of the indicated problems has increased significantly [18–22]. However, microwave absorbers based on carbon fiber materials are characterized by such disadvantage as instability of the values of S_{11} and S_{21} characteristics values, due to the fact that:

1. carbon fibers are weakly fixed in the volume of the indicated materials and, as a result of mechanical action (bending, stretching, etc.), can change their mutual arrangement;
2. carbon fibers are hygroscopic.

To exclude the indicated disadvantage of the microwave absorbers based on carbon fiber materials it's necessary to perform their additional processing by fixing them in the matrices or substrates. The aim of the presented study was to establish the patterns of change of S_{11} and S_{21} characteristics values of carbon fiber fabric depending on the composition of the matrix in which they are fixed. To achieve the stated aim, the following tasks were solved:

1. selection and justification of the material for forming the matrix in which it is advisable to fix carbon fiber fabric;
2. selection and justification of the types of fillers to be added to the selected material for forming the matrix;
3. making of experimental samples using the selected matrix and fillers;
4. measurement and analysis of S_{11} and S_{21} characteristics values in the frequency range of 2.0–17.0 GHz of the manufactured experimental samples;

5 development of recommendations for the practical application of the studied materials.

Material and Methods

Polyurethane mastic was chosen as the material for forming the matrix in which it is advisable to fix carbon fiber fabric. The choice of such a material is due to the following advantages:

1. flexibility, which, together with the flexibility of carbon fiber fabric, allows for providing a similar property for microwave absorbers based on such components;
2. availability and low cost (the cost of the selected material in the volume required to form 1.0–3.0 mm thick matrices for the manufacture of 1.0 m^2 of microwave absorbers based on carbon fiber fabric is 10.0–30.0 times lower than the cost of 1.0 m^2 of such fiber material);
3. controlled viscosity (the viscosity of the selected material is reduced by adding a petroleum solvent to it [23], which improves the adhesive properties of the matrix formed on the basis of such material, and also reduces the time required to include fillers in it [24–26]).

Finely dispersed materials characterized by dielectric properties were chosen as fillers for addition to the polyurethane mastic. This choice is due to the fact that by adding these materials to the composition of microwave absorbers containing conductive components, it is possible to reduce their wave resistance, and, as a consequence, reduce their S_{11} characteristics values and increase electromagnetic radiation absorption characteristics values [27,28]. The following finely dispersed materials characterized by dielectric properties were chosen for addition to the polyurethane mastic: aluminum oxide, titanium dioxide; zinc oxide.

The cost of the listed materials in the volume required to form 1.0 – 3.0 mm thick matrices for the production of 1.0 m^2 of microwave absorbers based on carbon fiber fabric is lower than the cost of polyurethane mastic for forming such matrices in the specified volume. The particle size of the listed materials is 0.1 – 1.0 μm. It has been experimentally established that the optimal volume ratio of the mixture of polyurethane mastic and aluminum oxide, titanium dioxide or zinc oxide is 70.0 : 30.0 %. Using the selected materials, experimental samples were made for the study. Table 1 presents the characteristics of these samples.

Table 1. The characteristics of the made samples for the study

Sample	**The composition of matrix used for the sample preparing**
Sample 1	–
Sample 2	Polyurethane mastic
Sample 3	Polyurethane mastic (70.0 vol. %), aluminum oxide (30.0 vol. %)
Sample 4	Polyurethane mastic (70.0 vol. %), titanium oxide (30.0 vol. %)
Sample 5	Polyurethane mastic (70.0 vol. %), zinc oxide (30.0 vol. %)

Sample 1 was a carbon fiber fabric fragment, the length and width of which were not less than the length and width of the antenna aperture included in the setup for measuring S_{11} and S_{21} characteristics values in the frequency range 2.0 – 17.0 GHz. Samples 2–5 were made in the following way:

1. cutting off a fragment from a roll of carbon fiber fabric with use of scissors. The length and width of the fragment were not less than the length and width of the antenna aperture included in the setup for measuring S_{11} and S_{21} characteristics values in the frequency range 2.0 – 17.0 GHz;
2. during the manufacture of sample 2, uniform mechanical application of a 2.0 ± 1.0 mm thick layer of polyurethane mastic to both surfaces of the fragment cut as a result of implementing stage 1 with use of spatula;
3. during the manufacture of samples 3–5:

3.1. uniform mechanical application of a 2.0 ± 1.0 mm thick layer of polyurethane mastic to one surface of the fragment cut off on the stage 1 with use of spatula;

3.2. preparation of a mixture of polyurethane mastic and finely dispersed aluminum oxide (when making sample 3), titanium dioxide (when making sample 4), zinc oxide (when making sample 5), taking into account that the volume ratio of the components in such mixture should be 70.0 : 30.0 %. The building mixer was used in course of the mixture preparation;

3.3. uniform mechanical application of a 2.0 ± 1.0 mm thick layer of the mixture prepared on the stage 3.2 to the second surface of the fragment cut off on the stage 1 with use of spatula.

Optic microscopy image of the surface fragment of the carbon fiber fabric used for the sample making is presented on Fig. 1. The carbon material used for the samples making is characterized by the following properties: density is 200.0 g/m^2; weave type is twill; equal strength (has the same number of threads in the warp and weft). 70.0 : 30.0 % volume ratio of the components of the mixture preparing in stage 3.2 is optimal one. This is because that increasing of the aluminum oxide, titanium dioxide or zinc oxide content in the mixture leads to the decreasing of the mechanical straight of the layers formed on the base of it and applied in the stage 3.3. Decreasing of the aluminum oxide, titanium dioxide or zinc oxide content in the mixture leads to the increasing of the wave resistance of the layers formed on the base of it and applied in the stage 3.3.

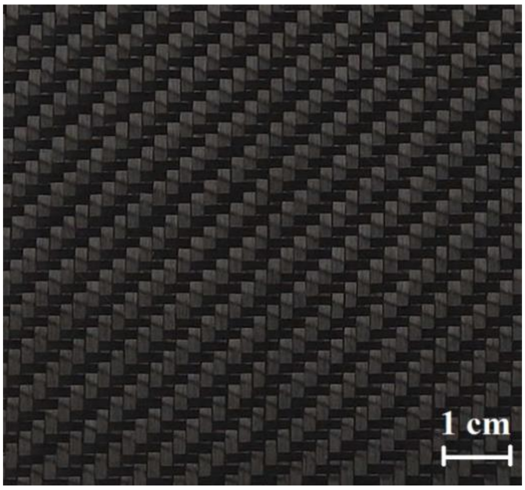


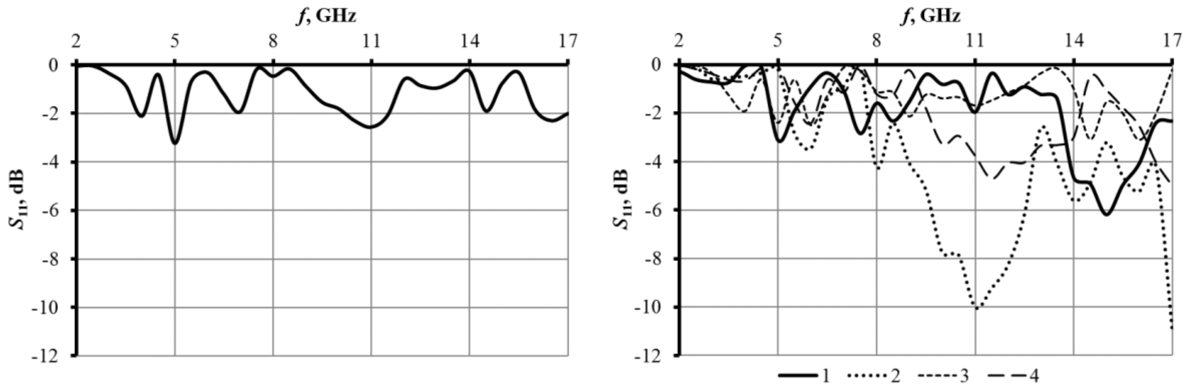
Fig. 1. Optic microscopy image of the surface fragment of the carbon fiber fabric used for the samples making

2.0 ± 1.0 mm thickness of layer of the mixture prepared on the stage 3.2 is the optimal one. This is because such thickness is minimum possible one which could be applied on the surface of the carbon fiber fabric. The increasing of this thickness leads to the increasing the mass of such fabric and worsens its performance properties. There were made 5 units of every sample. The measurements of S_{11} and S_{21} characteristics values in the frequency range 2.0 – 17.0 GHz were carried out with use of setup included: panoramic meter of transmission and reflection coefficients SNA 0.01–18; two horn antennas P6-23M with aperture size 351.0 × 265.0 mm.

The measurements of the indicated values were carried out in accordance with method described in [29]. The relative error module of measurements of S_{11} and S_{21} characteristics values using the panoramic meter of transmission and reflection coefficients SNA 0.01–18 doesn't exceed 10.0 %.

Results and Discussion

S_{11} characteristics in the frequency range 2.0–17.0 GHz of samples 1–5 are presented on Fig. 2. As it seen on Fig. 2, S_{11} characteristic values in the frequency range 2.0–17.0 GHz of the sample 1 vary from −0.1 till −3.0 dB, of the samples 2–5 – from −0.1 till −6.0 dB, from −0.1 till −11.0 dB, from −0.1 till −3.0 dB, from −0.1 till −5.0 dB respectively.



(a) (b)

Fig. 2. S_{11} characteristic in the frequency range 2.0–17.0 GHz of samples 1 (a), and 2–5 (b, curves 1–4 respectively)

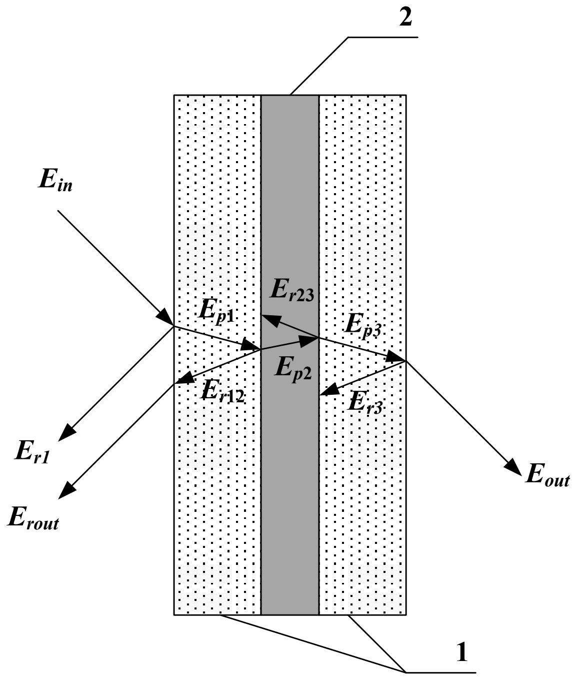


Fig. 3. The scheme of interaction of electromagnetic waves with the samples: 1 – matrix; 2 – carbon fiber fabric; E_{in} – incident waves; E_{r1} – the waves reflected from the surface of matrix part covering carbon fiber fabric outer surface (surface oriented to the electromagnetic waves source); E_{rout} – the waves reflected from the boundary between surface of matrix part covering carbon fiber fabric outer surface and carbon fiber fabric outer surface and passed through this part of matrix back to the electromagnetic waves source; E_{p1} – the waves passed through the matrix part covering carbon fiber fabric outer surface; E_{r12} – the waves reflected from the boundary between surface of matrix part covering carbon fiber fabric outer surface and carbon fiber fabric outer surface; E_{p2} – the waves passed through the carbon fiber fabric; E_{r23} – the waves reflected from the boundary between surface of matrix part covering carbon fiber fabric inner surface and carbon fiber fabric inner surface; E_{p2} – the waves passed through the matrix part covering carbon fiber fabric inner surface; E_{out} – the waves passed through the sample

S_{11} characteristics in the frequency range 2.0 – 17.0 GHz of the samples 2, 3 and 5 have resonant points. These points are 15.0, 11.0 and 11.5 GHz respectively. These points are the result of antiphase interaction on the listed frequencies of electromagnetic waves reflected from the matrix surface and electromagnetic waves reflected from the carbon fiber fabric surface [30]. The scheme of such interaction is presented on Fig. 3.

It was established, the studied samples are characterized by the similar S_{21} characteristic in the frequency range 2.0–17.0 GHz. These characteristics are presented on Fig. 4. As it seen from Fig. 4, S_{21} characteristic values in the frequency range 2.0 – 17.0 GHz of the studied samples vary from −20.0 till −40.0 dB. Thus, fixing of the carbon fiber fabric in the polyurethane mastic based matrices doesn't impact on it S_{21} characteristic values in the frequency range 2.0 – 17.0 GHz. This is because the carbon fibers provide significantly greater losses of electromagnetic radiation energy in the indicated frequency range compared with the polyurethane mastic and finely dispersed aluminum oxide, titanium dioxide and zinc oxide [31,32].

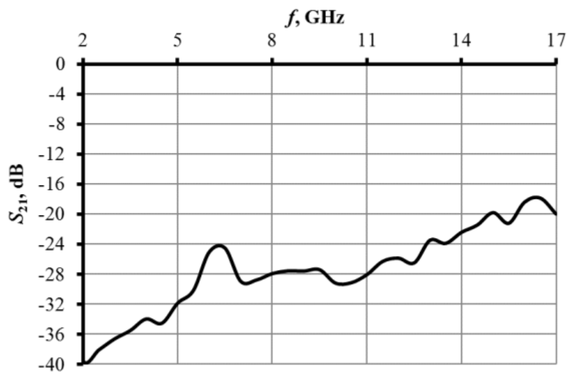


Fig. 4. S_{21} characteristic in the frequency range 2.0–17.0 GHz of samples 1–5

Conclusions

Thus, it's possible to reduce on 0.5 – 3.0 dB S_{11} characteristic values in the frequency range 2.0 – 17.0 GHz of carbon fiber fabric by fixing it in the polyurethane mastic-based matrix. If add to this matrix filler in the form of finely dispersed aluminum oxide or zinc oxide it's possible to increase on 0.5–5.0 dB the indicated reduction. In general, S_{11} characteristic values of the carbon fiber fabric are reduced after it fixing in the polyurethane mastic due to reducing of the wave resistance of this fabric surface. S_{21} characteristic values in the frequency range 2.0 – 17.0 GHz carbon fiber fabric vary from −20.0 till −40.0 dB and don't depend significantly form the content of matrix where it's fixed. The studied materials are suitable for use for making special boxes for storing equipment sensitive to microwave interferences.

CRediT authorship contribution statement

Olga V. Boiprav: supervision, conceptualization, investigation, writing – original draft; **Elena S. Belousova**: conceptualization, investigation; **Vyacheslav S. Mokerov**: investigation, data curation.

Conflict of interest

The authors declare that they have no conflict of interest.

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