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Multilayer microwave absorbers with an ordered structured layer based on powdered activated charcoal containing magnetic particles

ABSTRACT

The technique of manufacturing four-layer microwave absorbers with an ordered structured layer is presented. This technology consists of heat pressing of a structure in the form of two fragments of synthetic non-woven fibrous material (the first and third layers), between which elements formed from powdered activated charcoal impregnated with a mixture of isopropyl alcohol and finely dispersed magnetic material (the second layer) are orderedly distributed, and then fixing a fragment of an aluminum-containing foiled polymer film (the fourth layer) on the surface of the third layer. It was found that the width of the effective absorption band of the absorbers manufactured accordingto the presented technique is 13.2 GHz and exceeds the width of the effective absorption band of their analogs by 4.7–11.2 GHz. Electromagnetic radiation absorption coefficient values of such absorbers are from 0.5 rel. units to 0.92 rel. units.
Keywords: *Charcoal,isopropyl alcohol,microwave absorber,iron (III) oxide, titanomagnetite.*

1. INTRODUCTION

Microwave absorbers are a type of protective materials. This is due to the fact that they are used to solve the following practical problems:

– protection of electronic devices and humans from exposure to microwave electromagnetic radiation [1–3];
– information protection [4–6].

The number of published scientific papers devoted to the results of development and research of microwave absorbers increases every year (Table 1). This is due to the increase in practical interest in such absorbers, which is primarily due to the development of wireless information transmission technologies [7–9].

Thus, studies devoted to the substantiation of materials and improvement oftechnologies for the manufacture of microwave absorbers are relevant. For the manufacture of microwave absorbers, it is advisable to use composite materials that include electrically conductive and magnetic components (see, for example, works [10–20]).

Table 1. Proportion of published papers about microwave absorbers from total amount of published material science papers in period 2020–2024 (according to Google Scholar Database)

Year	2020	2021	2022	2023	2024*
Proportion of published papers, %	1.6	1.9	3	7.3	11.3

*From January till September

This is due to the fact that by adding magnetic components to the composition of microwave absorbers, it is possible to reduce the reflection losses (S_{ER}) and increase the absorption losses (S_{EA}) of the energy of electromagnetic radiation interacting with such absorbers. This is confirmed by the following equations [21]:

$$SE_R = 39.5 + 10\lg\frac{\sigma}{2f\pi\mu}, \quad (1)$$

$$SE_A = 8.7 \cdot d \cdot \sqrt{f \cdot \pi \cdot \sigma \cdot \mu}, \quad (2)$$

where

f – electromagnetic radiation frequency; μ – relative magnetic permeability of an absorber magnetic components; d – an absorber thickness; σ – specific electrical conductivity of an absorber electrically conductive components.

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The paper [22] presents the experimental substantiation of the prospects of using the dispersed composite containing powdered activated charcoal and iron (III) oxide forthe production of effective microwave absorbers. The paper also presents the technology developed by the authors for producing two-layer microwave absorbers based on such dispersed composite. This technology consists of fixing a 0.3±0.1 cm thick layer ofdispersed composite containing powdered activated charcoal and iron (III) oxide between two fragments of a polymer self-adhesive film. The advantage of this technology compared to technologies that require the use of binders is the low time costs for its implementation. The disadvantage of this technology is the impossibility of increasing the thickness of microwave absorbers manufactured accordingto it. The indicated disadvantage is due to the fact that the fixing of particles of dispersed composite containing powdered activated charcoal and iron (III) oxide in the volume of the microwave absorber is ensured by a thin adhesive layer in the polymer self-adhesive film (in fact, the particles of the specified composite cover this layer). This paper presents the results of a study aimed at substantiating another technology for the manufacture ofmicrowave absorbers based on dispersed composite containing powdered activated charcoal and magnetic (iron (III) oxide or titanomagnetite) particles, which is characterized by an advantage and doesn't have the disadvantage of the technology [22].

2. EXPERIMENTAL

The developed technology includes the following operations.

1. Formation of the first (outer) and third layers of the microwave absorber by cutting two identical fragments from a roll of synthetic non-woven fibrous material, the overall dimensions and shape of which are determined by the requirements for the overall dimensions and shape of the absorber being manufactured.
2. Formation of the second layer of the microwave absorber.

2.1. Obtaining the dispersed composite containing powdered activated charcoal and magnetic (iron (III) oxide or titanomagnetite) particles.

1.2.1. Preparation of a mixture of isopropyl alcohol (90.0 vol. %) and magnetic particles (the rest).

1.2.2. Immersion of powdered activated charcoal particles into an empty container.

1.2.3. Pouring the prepared mixture of isopropyl alcohol and magnetic particles into a container in which particles of powdered activated charcoal are immersed (the volume of the said mixture should be 2.0 times greater than the volume of powdered activated charcoal particles).

1.2.4. Mixing of powdered activated charcoal particles with the poured mixture of isopropyl alcohol and magnetic particles.

1.2.5. Drying the mixture obtained as a result of operation 1.2.4 implementation in the oven at a temperature of 50.0 °C for 1.5 hours.

2.2. Placing a stencil characterized by the following properties on the surface of one of the fragments obtained as a result of step 1:

– the stencil cells are characterized by the same size and shape and are distributed with the same step;
– the step of distribution of the stencil cells (S) satisfies the condition:

$$S \le 0{,}4 \cdot \lambda_r,\ m, \qquad (3)$$

Whereλ_r – wavelength on the resonant frequency (middle value of the operating frequency range) of a microwave absorber;

– the stencil cells are characterized by a round or square shape;
– the width of the stencil cells (W) satisfies the condition:

$$W = \frac{\lambda_r}{3},\ m. \qquad (4)$$

The conditions described by Eqs. (3) and (4) must be taken into account in order to minimize the degree of dependence of an absorber's resonant frequency value on the electromagnetic radiation incidence angle and polarization degree.

2.3. Filling each cell of the stencil with volume-standardized portions of the dispersed composite obtained as a result of operation 2.1 implemention.

2.4. Removing the stencil from the surface of a fragment of synthetic non-woven fibrous material (Figure 1).

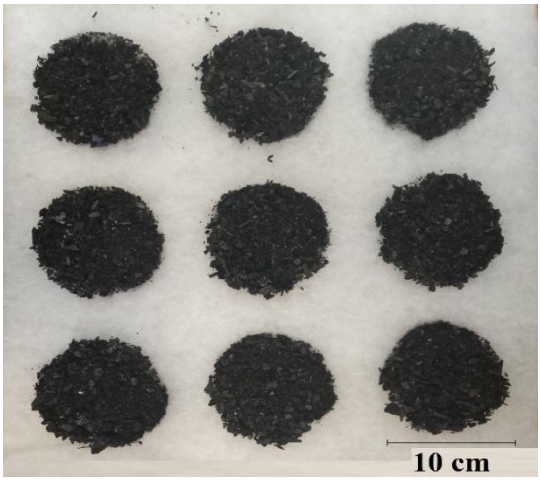

Figure 1.Top view of elements formed from dispersed composite and placed on the surface of a fragment of synthetic non-woven fibrous material

3. Placing the second of the fragments obtained as a result of operation 1 implementation on top of the elements formed as a result of operations 2.1–2.3implementation.
4. Heat pressing the structure obtained as a result of operations 1–3 implementation at a temperature of ~ 250.0 °C (i.e. at a temperature corresponding to the melting point of the synthetic non-woven fibrous material) for 10.0 min.
5. Forming the fourth (inner) layer of the microwave absorber by cutting off a fragment from a roll of aluminum-containing foiled polymer film, the overall dimensions and shape ofwhich are determined by the requirements for the overall dimensions and shape ofthe microwave absorber being manufactured.
6. Fastening the cut fragment of the aluminum-containing foiled polymer film to one of the surfaces of the structure obtained as a result of operations 1–4 implementation, using spray adhesive.

In the course of experimental substantiation of the efficiency of microwave absorbers manufactured according to the developed technique, the following was performed:

– three groups of experimental samples of microwave absorbers were manufactured according to thedevelopedtechnique (Table 2);
– electromagnetic radiation absorption characteristics in the frequency range of 2.0–17.0 GHz of the manufactured experimental samples were studied;
– relative magnetic permeability of the dispersed composite containing powdered activated charcoal and iron (III) oxide or titanomagnetite particles was evaluated.

Table 2. Brief characteristic of the manufactured samples

Samples names	Material used for samples manufacturing
Samples of group 1	Powderedactivatedcharcoal
Samples of group 2	Dispersedcompositecontainingpowderedactivatedcharcoalandiron (III) oxideparticles
Samples of group 3	Dispersedcompositecontainingpowderedactivatedcharcoalandtitanomagnetite particles

To obtain the electromagnetic radiation absorption characteristics in the frequency range of 2.0–17.0 GHz of the manufactured experimental samples, the measuring system was used consisting of:

– panoramic meter of transmission and reflection coefficients SNA 0.01–18 (manufacturer – BSUIR, Republic of Belarus), including a sweep frequency generator and a measuring signal processing unit;
– personal computer;
– video display terminal;
– two horn antennas;
– directional coupler units (units B and A/R) designed to isolate and detect incident, reflected and transmitted electromagnetic waves through the sample;
– special software for setting the measurement parameters (frequency range, type of measured value), processing and systematizing their results.

The procedure for obtaining the electromagnetic radiation absorption characteristics in the frequency range of 2.0–17.0 GHz of the manufactured experimental samples was as follows.

1. Obtaining electromagnetic radiation reflection coefficient values of the sample. The following actions were performed within the framework of this step.

1.1 Calibration of the measuring system in accordance with the diagram shown in Fig. 2, to establish the optimal level of electromagnetic radiation power for the operation of the detectors of the measurementsignal processing unit.

1.2 Carrying out measurements of the electromagnetic radiation reflection coefficient values in accordance with the diagram shown in Fig. 2 (a microwave absorber sample should be installed instead of the metal plate in front of the transmitting antenna).

1.3 Sequential repetition of steps 1.1 and 1.2 at least 4 times.

1.4 Calculation of the electromagnetic radiation reflection coefficient average values ($\langle S_{11} \rangle$) according to the following equation:

$$\langle S_{11} \rangle = \frac{\sum_{i=1}^{n} S_{11i}}{n}, \; dB, \qquad (5)$$

Where S_{11i}isthe electromagnetic radiation reflection coefficient value of the sample measured in the *i*-th time; *n* is the number of times that the electromagnetic radiationreflection coefficient value of the sample was measured ($n \geq 5$).

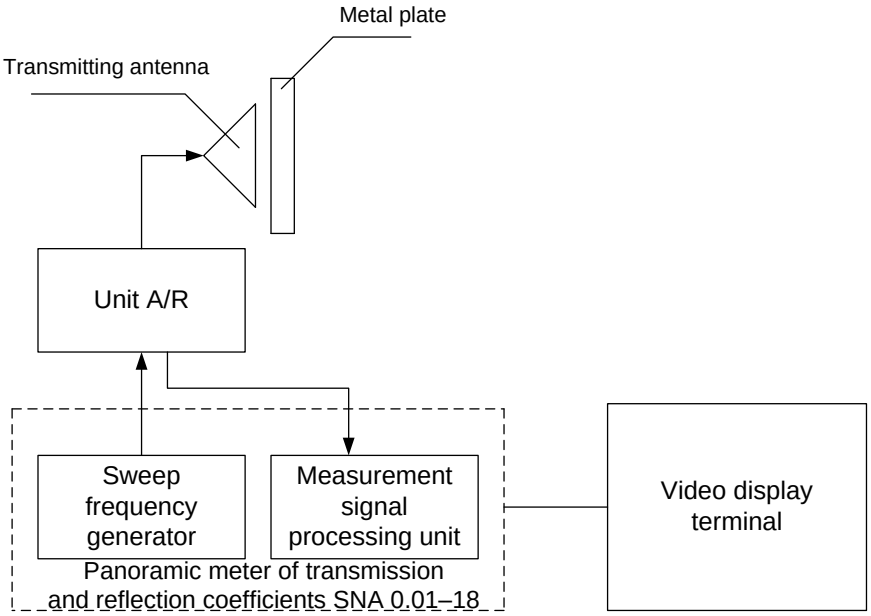

Figure 2. Connection diagram of the measuring system devices during its calibration before measuring S_{11i}values

2. Obtaining the electromagnetic radiation transmission coefficient values. The following actions were performed within the framework of this step.

2.1. Calibration of the measuring system in accordance with the diagram shown in Fig. 3, to establish the optimal electromagnetic radiationpower level for the operation of the detectors of the measurement signal processing unit.

2.2. Carrying out measurements of the electromagnetic radiationtransmission coefficient values in accordance with the diagram shown in Figure 3 (a microwave absorber sample must be installed between the transmitting and receiving antennas).

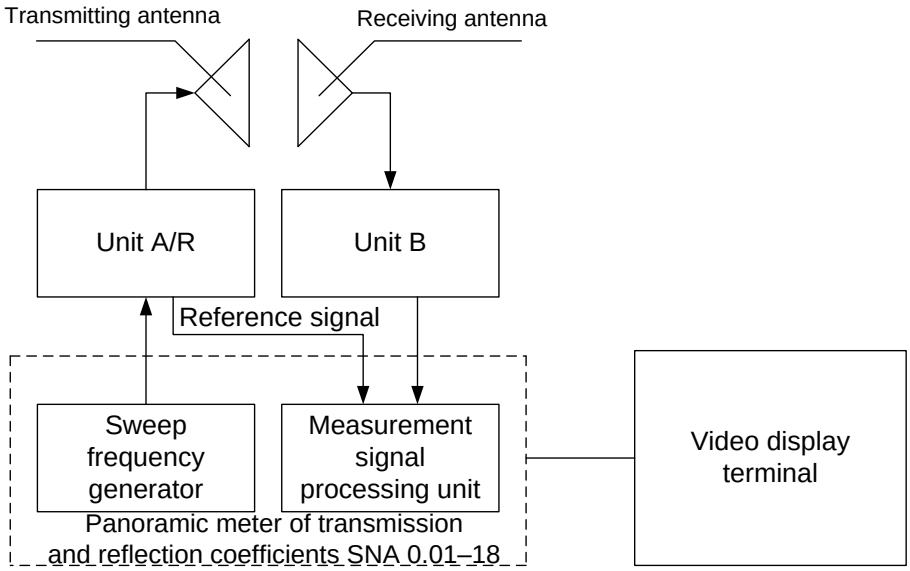

Figure 3. Connection diagram of the measuring system devices during its calibration before measuring S_{21i} values

2.3. Sequential repetition of steps 2.1 and 2.2 at least 4 times.

2.4. Calculation of the electromagnetic radiation transmission coefficient average values (S_{21})according to the following equation:

$$\langle S_{21} \rangle = \frac{\sum_{i=1}^{m} S_{21i}}{m}, \; dB, \qquad (6)$$

S_{21i} is the electromagnetic radiationtransmission coefficient value of the sample measured in the *i*-th time; *m*is the number of times that the electromagnetic radiationtransmission coefficient value of the sample was measured (*m*≥ 5).

3. Calculation of the electromagnetic radiation absorption coefficient values (*A*) of the sample, according to the following equation:

$$A = 1 - 10^{\frac{\langle S_{11} \rangle}{10}} - 10^{\frac{\langle S_{21} \rangle}{10}}, \text{rel. units} \qquad (7)$$

The relative error module of measurements of the electromagnetic radiation reflection and transmission coefficients values carried out using the panoramic meter of transmission and reflection coefficients SNA 0.01–18 is no more than 10.0 %.

The relative magnetic permeability of dispersed composite containing powdered activated charcoal and magnetic particles was estimated using an automated vibration magnetometer Liquid Helium Free High Field Measurement System (manufacturer – Cryogenic LTD, Great Britain). The operating principle of this magnetometer is based on the induction method. The procedure for carrying out measurements using this magnetometer was as follows.

1. Filling the magnetometer measuring cell with the material to be studied. The measuring cell consists of two combined coils wound in opposite directions and spaced apart along one conventional axis.
2. Starting the magnetometer, which sets the measuring cell into a state of oscillation, the source of the external magnetic field begins to function and, under its influence, magnetization of the material to be studied is realized.
3. Recording the induction values of the external magnetic field (*B*).
4. Registration of the electromotive force of induction (*E*) induced by the magnetized material being studied in the coils included in the measuring cell, using a phase-sensitive voltmeter connected to the control personal computer and the special software VSM Software-v081018 installed on this computer.
5. Calculation of the magnetization (*M*) of the material being studiedaccording to the following equation:

$$E \sim \frac{\partial M}{\partial z} \upsilon_z, \text{V}, \qquad (8)$$

wherezisthe direction of the conventional axis along which the coils of the measuring cell are spaced and along which it oscillates; υ_z – the frequency of oscillation along the *z*-axis of the measuring cell filled with the material being studied (during the studies it was 19.4 Hz).

6. Calculation of the values of the function of dependence of the relative magnetic permeability of the material being studied on the induction of an external magnetic field (μ (*B*)) according to the following equation:

$$\mu(B) = \frac{\partial M}{\partial B}, \text{rel. units} \qquad (9)$$

The relative error module of measurements carried out using the automated vibration magnetometer Liquid Helium Free High Field Measurement System does not exceed 1.5 %.

3. RESULTS AND DISCUSSION

The frequency dependences of the electromagnetic radiation absorption coefficient in the range of 2.0–17.0 GHz of the studied samples of the microwave absorbers is shown in Fig. 4.

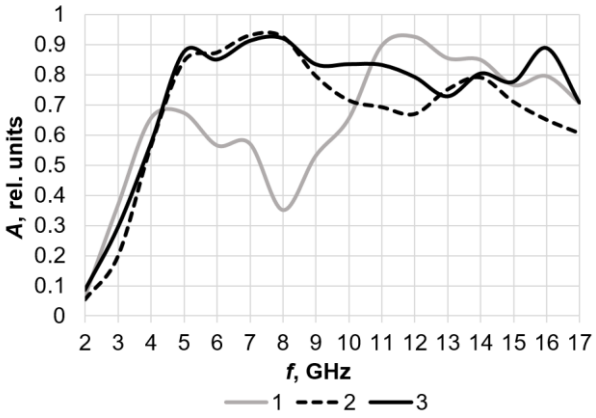

Figure 4. Frequency dependences of the electromagnetic radiation absorption coefficient in the range of 2.0–17.0 GHz of the samples of groups 1, 2 and 3 (curves 1, 2 and 3 respectively)

It is seen from Figure 4,the electromagnetic radiation absorption coefficient values in the frequency range of 5.0–10.0 GHz of the samples of groups 2 and 3 are higher by 0.05–0.6 relative units than the electromagnetic radiation absorption coefficient values in the specified frequency range of the samples of group 1. This is due to the fact that theelectromagnetic radiation reflection coefficient values in the specified frequency range of the first and second of the specified samples are

lower by 0.01–0.55 relative units than those of the third of the specified samples (Figure 5).

This is due to the fact that the samples of groups 2 and 3 are manufactured of the dispersed composite containing magnetic particles (see Eq. (1)). It was found that μ value of the dispersed composite used to manufacture the samples of group 2 is 3.0, and μ value of the dispersed composite used to manufacture the samples of group 3 is 20.0.

It's established, that microwave absorbers manufactured according to the developed technique are characterized by the wider effective absorption band (EAB) compared with the analogs (Table 3).

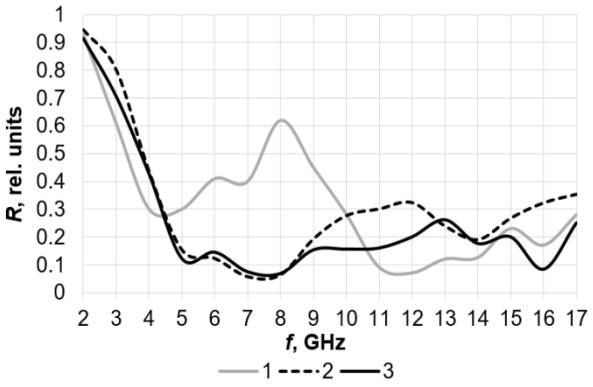

Figure 5. Frequency dependences of the electromagnetic radiation reflection coefficient in the range of 2.0–17.0 GHz of the samples of groups 1, 2 and 3 (curves 1, 2 and 3 respectively)

Table3. Characteristics of microwave absorbers based on carbon-containing and magnetic materials

Brief description ofmicrowave absorbers	Thickness, cm	EAB	EAB width, GHz
Microwave absorbers manufactured according to the developed technique	0.5±0.1	3.8–17.0 GHz	13.2
Two-layer microwave absorbers based on dispersed composite containing powdered activated charcoal and iron (III) oxide [22]	0.3±0.1	2.8–6.5 GHz 8.5–17.0 GHz	3.7 8.5
Microwave absorbers based on porous carbon obtained from rice husks and containing iron particles [11]	0.14	12.2–17.8 GHz	5.6
Microwave absorbers based on porous carbon obtained from jute biomass and containing iron (II, III) oxide nanoparticles [14]	0.16	13.8–17.8 GHz	5.0
Microwave absorbers based on porous carbon and iron carbide [15]	0.35	6.0–14.2 GHz	8.2
Microwave absorbers based on porous carbon obtained from cotton biomass and containing iron nanoparticles [16]	0.25	11.0–16.2 GHz	5.2
Microwave absorbers based on carbon obtained from metal-organic frameworks and iron oxide (II, III) [17]	0.2	6.5–14.0 GHz	7.5
Microwave absorbers based on carbon doped with diiron nitride [18]	0.19	12.0–16.3 GHz	4.3
Multilayer microwave absorbers based on MXene and iron (II, III) oxide [19]	0.19	8.0–12.0 GHz	4.0
Microwave absorbers based on graphite containing iron (II, III) oxide particles [20]	0.3	7.0–9.0 GHz	2.0

4. CONCLUSION

Thus, the width of EAB absorbers manufactured accordingto the developed technique exceeds the width of EAB of two-layer microwave absorbers based on dispersed composite containing powdered activated charcoal and iron (III) oxide by 4.7 GHz [22]. Microwave absorbers manufactured in accordance with the developed technology can be used to create shields for isolating shielded zones in rooms containing electronic devices sensitive to the effects of microwave radiation and/or being sources of such radiation.

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IZVOD

VIŠESLOJNI MIKROTALASNI APSORBERI SA UREĐENIM STRUKTURIRANIM SLOJEM NA BAZI AKTIVNOG UGLJA U PRAHU KOJI SADRŽI MAGNETNE ČESTICE

Prikazana je tehnika izrade četvoroslojnih mikrotalasnih apsorbera sa uređenim strukturiranim slojem. Ova tehnologija se sastoji od toplotnog presovanja konstrukcije u vidu dva fragmenta sintetičkog netkanog vlaknastog materijala (prvi i treći sloj), između kojih se raspoređeni elementi formirani od praškastog aktivnog uglja impregniranog mešavinom izopropil alkohola i fino dispergovanog magnetnog materijala (drugi sloj), a zatim fiksiranje fragmenta od četiri sloja folije (4. površine trećeg sloja . Utvrđeno je da širina efektivnog apsorpcionog opsega apsorbera proizvedenih prema predstavljenoj tehnici iznosi 13,2 GHz i da premašuje širinu efektivnog opsega apsorpcije njihovih analoga za 4,7–11,2 GHz. Vrednosti koeficijenta apsorpcije elektromagnetnog zračenja ovakvih apsorbera su od 0,5 rel. jedinica do 0,92 rel. jedinice.
Ključne reči: *ugalj, izopropil alkohol, mikrotalasni apsorber, gvožđe (III) oksid, titanomagnetit.*

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