Original papers
Materials for energy and environment, next-generation photovoltaics, and green technologies

УДК 537.87:620.22 DOI: 10.17277/jamt.2023.04.pp.294-303

Multifunctional composite charcoal-containing microwave and X-ray radiation absorbers

© Olga V. Boiprav[a]✉, Vadim A. Bogush[a], Nikolay N. Grinchik[b]

[a] *Belarusian State University of Informatics and Radioelectronics, 6, P. Brovki St., Minsk, 220013, Belarus,*
[b] *Institute of Heat and Mass Transfer named after A.V. Lykov National Academy of Sciences of Belarus, 15, P. Brovki St., Minsk, 220072, Belarus*

✉ smu@bsuir.by

Abstract: The article presents multifunctional composite absorbers of microwave and X-ray electromagnetic radiation proposed and developed by authors. Compared with the analogs, these absorbers contain powdered activated charcoal as the component absorbing microwave electromagnetic radiation energy and powdered barium sulfate as the component absorbing X-ray electromagnetic radiation energy. The absorbers are three-layer ones. It was established that microwave electromagnetic radiation absorption coefficient values of the absorbers containing the powdered activated birch charcoal vary from 0.5 rel. units up to 0.92 rel. units in the frequency bands 3.5–7.0 GHz, 10.8–14.2 GHz, and microwave electromagnetic radiation absorption coefficient values of the absorbers containing the powdered activated coconut charcoal vary within the specified limits in the frequency bands 5.0–7.5 GHz, 10.2–17.0 GHz. The values of X-ray attenuation coefficient provided by the absorbers vary from 2.0 to 8.7 rel. units. These absorbers can be used to cover the walls of rooms where X-ray machines are located. This will ensure a reduction in the degree of influence on these devices, as well as computer equipment connected to them, of microwave electromagnetic radiation from external sources, as well as a reduction in the degree of influence of X-ray radiation generated by these devices on electronic devices and on people who are outside the specified rooms.

Keywords: absorption coefficient; powdered activated charcoal; microwave electromagnetic radiation; X-ray electromagnetic radiation; barium sulfate.

For citation: Boiprav OV, Bogush VA, Grinchik NN. Multifunctional composite charcoal-containing microwave and X-ray radiation absorbers. *Journal of Advanced Materials and Technologies*. 2023;8(4):294-303. DOI: 10.17277/jamt.2023.04.pp.294-303

Многофункциональные композиционные углесодержащие поглотители микроволнового и рентгеновского электромагнитного излучения

© О. В. Бойправ[a]✉, В. А. Богуш[a], Н. Н. Гринчик[b]

[a] *Белорусский государственный университет информатики и радиоэлектроники, ул. П. Бровки, 6, Минск, 220013, Республика Беларусь,*
[b] *Институт тепло- и массообмена имени А. В. Лыкова Национальной академии наук Беларуси, ул. П. Бровки, 15, Минск, 220072, Республика Беларусь*

✉ smu@bsuir.by

Аннотация: Представлены многофункциональные композиционные поглотители микроволнового и рентгеновского электромагнитного излучения, предложенные и разработанные авторами. По сравнению с аналогами данные поглотители содержат порошкообразный активированный уголь в качестве компонента, обеспечивающего поглощение энергии микроволнового электромагнитного излучения, и порошкообразный сульфат бария в качестве компонента, обеспечивающего поглощение энергии рентгеновского электромагнитного излучения. Такие поглотители являются трехслойными. Установлено, что значения коэффициента поглощения микроволнового электромагнитного излучения поглотителей, содержащих порошкообразный активированный березовый уголь, изменяются в пределах от 0,5 до 0,92 отн. ед. в полосах частот 3,5…7,0 ГГц, 10,8…14,2 ГГц, а значения коэффициента поглощения микроволнового электромагнитного излучения поглотителей, содержащих порошкообразный активированный кокосовый уголь, изменяются в указанных пределах в полосах частот 5,0…7,5 ГГц, 10,2…17,0 ГГц. Значения коэффициента ослабления рентгеновского излучения, обеспечиваемого поглотителями, изготовленными в соответствии с разработанной технологией, изменяются в пределах от 2,0 до 8,7 отн. ед. Данные поглотители могут быть использованы для покрытия стен помещений, где располагаются рентгеновские аппараты. При этом обеспечивается снижение степени влияния на эти аппараты и подключенные к ним средства вычислительной техники микроволнового электромагнитного излучения от внешних источников, а также снижение степени влияния рентгеновского излучения, генерируемого данными аппаратами, на приборы электронной техники и людей, которые находятся за пределами указанных помещений.

Ключевые слова: коэффициент поглощения; порошкообразный активированный уголь; микроволновое электромагнитное излучение; рентгеновское электромагнитное излучение; сульфат бария.

Для цитирования: Boiprav OV, Bogush VA, Grinchik NN. Multifunctional composite charcoal-containing microwave and X-ray radiation absorbers. *Journal of Advanced Materials and Technologies*. 2023;8(4):294-303. DOI: 10.17277/jamt.2023.04.pp.294-303

1. Introduction

Modern multifunctional materials that provide microwave electromagnetic radiation energy attenuation are characterized by the following properties: 1) thermal insulation [1–4]; 2) thermal conductivity [5, 6]; 3) sound insulation [3, 7]; 4) fire resistance [8, 9]; 5) optical transparency [3, 10]; 6) controllability of the electromagnetic radiation absorption coefficient (ERAC) value during absorber use [11]; 7) self-cleaning [1]; 8) self-healing [12].

Research interest in the development of multifunctional microwave electromagnetic radiation absorbers is increasing every year. This statement is based on information about the dynamics of changes in the share of scientific publications devoted to these absorbers from the number of scientific publications devoted to microwave electromagnetic radiation absorbers in general (Fig. 1).

We made the contribution to the research field devoted to the development of multifunctional microwave electromagnetic radiation absorbers based on porous carbon-containing materials. This contribution consists in conducting the research aimed at the development and experimental validation of microwave and X-ray electromagnetic radiation absorbers. These absorbers were proposed and developed given the research results presented in [13, 14]. In particular, paper [13] presents composite building materials based on powdered charcoal and gypsum. It was shown that these materials provide 10.0–1000.0 times reduction of microwave electromagnetic radiation power. In [14] composite coatings based on powdered barium sulfate and sodium silicate aqueous alkaline solution were presented. It is shown that if the thickness of such coatings is 0.2 cm, then they are characterized by values of the X-ray attenuation coefficient of 2.0–8.7 rel. units (if X-ray electromagnetic radiation voltage values vary from 50.0 to 150.0 kV).

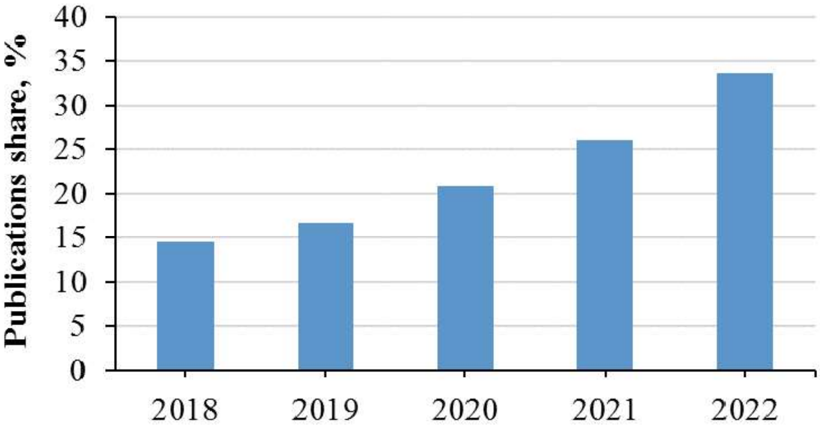

Fig. 1. Dynamics of changes in the share of scientific publications on multifunctional microwave electromagnetic radiation absorbers from the total number of those on microwave electromagnetic radiation absorbers

The urgency of the development of the indicated absorbers is due to the need to simultaneously solve two problems related to improving the conditions for the operation of X-ray machines: 1) reducing the impact of microwave electromagnetic radiation from external sources on X-ray machines, as well as computer equipment connected to them; 2) reducing the impact of radiation generated by X-ray machines on electronic devices and people who are outside the rooms where these devices are installed.

Thus, in this article, we developed and studied three-layer multifunctional composite absorbers of microwave and X-ray electromagnetic radiation. To achieve the set goal, the microwave electromagnetic radiation reflection coefficient (ERRC) and electromagnetic radiation transmission coefficient (ERTC) values of the made samples were measured; microwave ERAC values of the made samples were calculated; an analysis of the patterns of changes in the values of microwave ERAC of the made samples was carried out depending on the type of powdered activated charcoal that was used during their making.

2. Materials and Methods

2.1. Absorber production technology

The proposed absorbers were developed using the technology, comprising the following stages:

1. Cutting the (50.0 ± 5.0) microns thick foiled polymer film (KOTAR Ltd., Poland) into the fragments. Geometrical shape and size of the fragments should be relevant to the geometrical shape and size of the made absorber.

2. Cutting (0.2 ± 0.05) cm thick cellulose sheets (Spektr upakovki" factory, Belarus) into fragments. Geometrical shape and size of the fragments should relevant to the geometrical shape and size of the made absorber.

3. Preparing the mixture with following composition: powdered activated birch or coconut charcoal (trade mark BAU-A, standard 6217-74, Russia) or trade mark KAU-A (India), respectively – 20.0 vol. %, building gypsum (OJSC "BELGIPS", Belarus) – 30.0 vol. %, water – the rest.

4. Applying the (0.5 ± 0.1) cm thick layer of the mixture prepared during stage 3 to the one of the surfaces of the fragment of foiled polymer film cut during stage 4.

5. Preparing the mixture with the following composition: barium sulfate (OJSC "Chemical Plant named after L.Ya. Karpov", Russia) – 30.0 vol. %, sodium silicate aqueous alkaline solution (JSC "DEKART", Belarus) – the rest.

6. Applying the (0.2 ± 0.05) cm thick layer of mixture prepared during stage 5 to the one of the surfaces of the cellulose sheet fragment obtained during stage 2.

7. Fixing the cellulose sheet fragment with applied to it layer of mixture (stage 6) on the surface of the mixture applied during stage 4.

7. Drying the resulting absorber under standard conditions.

Thus, in this study, four groups of the samples were made in accordance with the presented technology.

The characteristics of the made samples are presented in Table 1. Schematic images of the made samples are presented in Fig. 2.

Table 1. Characteristics of the made samples

Name of the samples group	Composition of the sample first layer	Composition of the sample second layer	Composition of the sample third layer
Samples of group 1	Mixture of powdered activated birch charcoal, building gypsum and water	Foiled polymer film	No
Samples of group 2	Mixture of barium sulfate and sodium silicate aqueous alkaline solution	Mixture of powdered activated birch charcoal, building gypsum and water	Foiled polymer film
Samples of group 3	Mixture of powdered activated coconut charcoal, building gypsum and water	Foiled polymer film	No
Samples of group 4	Mixture of barium sulfate and sodium silicate aqueous alkaline solution	Mixture of powdered activated coconut charcoal, building gypsum and water	Foiled polymer film

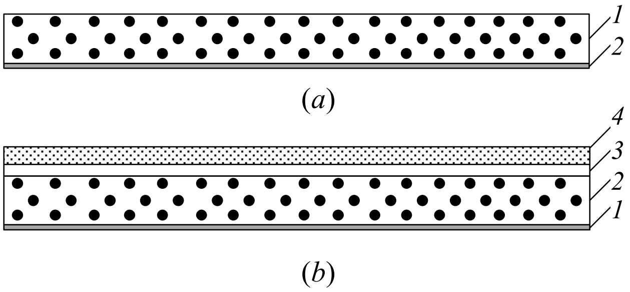

Fig. 2. Schematic images of the samples of groups 1 and 3 (*a*) and the samples of groups 2 and 4 (*b*):
1 – foiled polymer film; *2* – layer based on the mixture of powdered activated charcoal, building gypsum and water; *3* – cellulose sheet fragment; *4* – layer based on the mixture of barium sulfate and sodium silicate aqueous alkaline solution

As can be seen from Table 1 and Fig. 2, the made samples of groups 1 and 3 were two-layer ones, and the made samples of groups 2 and 4 were three-layer ones. Stages 1 and 3 of the proposed technology were used to make samples of groups 1 and 3, and 4. All stages of the proposed technology were used to make samples of groups 2 and 4. Samples of groups 1 and 3 were made to assess the degree of impact of adding the layer based on barium sulfate and sodium silicate aqueous alkaline solution to the structure of absorbers based on powdered activated charcoal on the microwave electromagnetic radiation reflection, transmission and absorption characteristics of such absorbers.

Ten samples of each group were made. The samples of each group were made in the specified quantity to create conditions for assessing the reproducibility of the results of implementing the presented technology (i.e., to assess the reproducibility of microwave ERRC, ERTC and ERAC characteristics of the absorbers made in accordance with the presented technology).

2.2. Determination of microwave ERRC, ERTC and X-ray attenuation coefficient

The microwave ERRC and ERTC of the made samples were studied using the measuring system including panoramic meter of electromagnetic radiation reflection and transmission coefficients SNA 0.01–18 (manufactured by Belarusian State University of Informatics and Radioelectronics), two horn antennas P6-23M, personal computer with special software for the measuring process management. The description of the method used in the course of the research was presented in [15]. The ERACs of the samples were calculated through the ERRC and ERTC. The calculation algorithm was described in detail in [15].

These measurements and calculations were carried out in the frequency range 2.0–17.0 GHz. This range was chosen because [16, 17]: frequencies of unwanted emissions of many modern radio-electronic devices belong to the specified range; modern devices for transmitting signals over wireless media operate in the specified range.

The X-ray attenuation coefficient of the made samples was studied using the measuring system including the X-ray calibration installation UPR-AT300 (“ATOMTECH” OJSC “MNIPI”, Belarus), the precision dosimeter DKS-AT5350 (“ATOMTECH” OJSC “MNIPI”, Belarus), the ionization chamber TM23361 (PTW Freiburg, Germany). The research methodology was described in detail in [14].

3. Results and Discussion

The ERAC frequency dependences in the range of 2.0–17.0 GHz for samples of groups 1 and 2 are presented in Fig. 3.

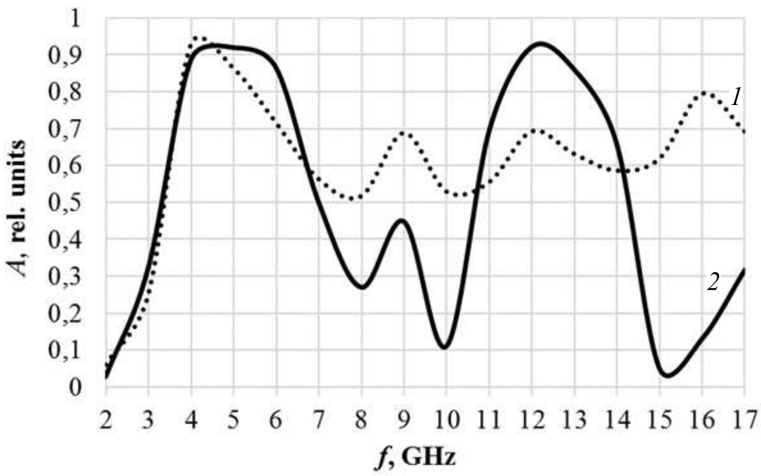

Fig. 3. ERAC frequency dependences in the range of 2.0–17.0 GHz of group 1 samples (curve *1*) and group 2 samples (curve *2*)

As can be seen from Fig. 3, the ERAC values in the frequency range 2.0–17.0 GHz for samples of groups 1 and 2 vary from 0.05 rel. units up to 0.92 rel. units These samples are essentially frequency-selective microwave absorbers in the frequency range 2.0–17.0 GHz. Effective absorption band of samples of group 1 is 3.5–17.0 GHz. Effective absorption bands of samples of group 2 are 3.5–7.0 GHz, 10.8–14.2 GHz. That is, samples of group 1 are broadband microwave absorbers in the frequency range 2.0–17.0 GHz, and samples of group 2 are multiband microwave absorbers in the specified frequency range. ERAC values in the frequency bands 7.0–10.8 GHz and 14.2–17.0 GHz for samples of group 2 are lower by 0.1–0.55 rel. units than ERAC values in the indicated frequency bands of samples of group 1. This feature is due to the following:

– the ERRC values in the specified frequency bands of group 2 samples were higher by 2.0–8.0 dB than those of group 1samples (see Fig. 4);

– the ERTC values in the specified frequency bands of groups 1 and 2 samples were practically equivalent (from –15.0 to –35.0 dB), which is due to the fact that this parameter value of the listed groups samples was influenced to the greatest extent by the foiled polymer film included in their structure.

The ERAC values in the frequency band 10.8–14.2 GHz for samples of group 2 were higher by 0.15–0.22 rel. units than the ERAC values in the specified frequency band of group 1samples. This is due to the fact that the ERRC values in the specified frequency band of group 2 samples were lower by 1.0–7.0 dB than those of group 1 samples (see Fig. 4), provided that the ERTC values in the specified frequency band of these samples were almost completely equivalent.

The ERAC frequency dependences in the frequency range 2.0–17.0 GHz of groups 3 and 4 samples are presented in Fig. 5.

It is seen from Fig. 5 that the ERAC values in the frequency range 2.0–17.0 GHz for groups 3 and 4 samples vary from 0.1 rel. units up to 0.95 rel. units.

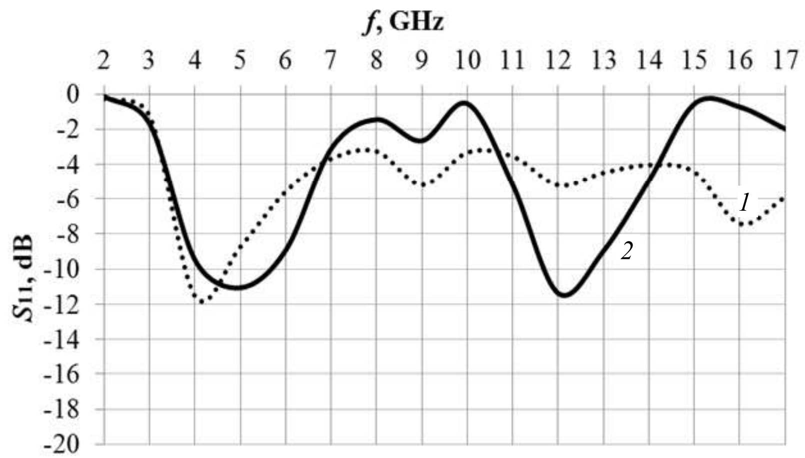

Fig. 4. ERRC frequency dependences in the range of 2.0–17.0 GHz of group 1 samples (curve *1*) and group 2 samples (curve *2*)

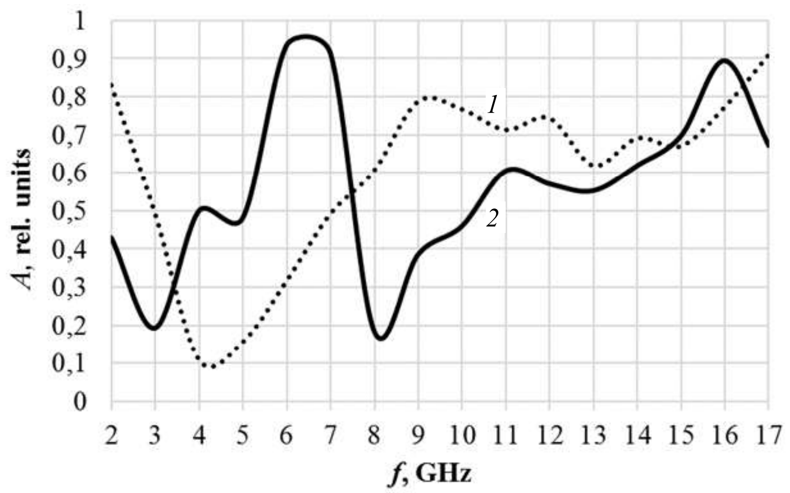

Fig. 5. ERAC frequency dependences in the range of 2.0–17.0 GHz of group 3 samples (curve *1*) and group 4 samples (curve *2*)

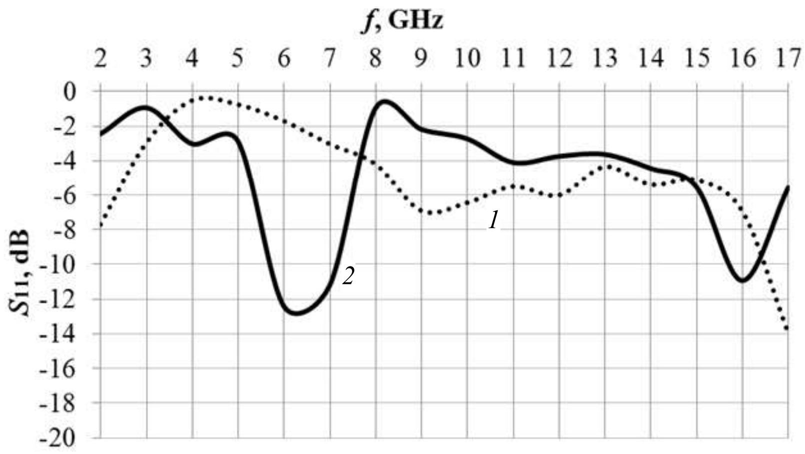

Fig. 6. ERRC frequency dependences in the range of 2.0–17.0 GHz of group 3 samples (curve *1*) and group 4 samples (curve *2*)

Effective absorption bands of group 3 samples are 2.0–3.0 GHz, 7.0–17.0 GHz. Effective absorption bands of group 4 samples are 5.0–7.5 GHz, 10.2–17.0 GHz. Groups 3 and 4 samples, like group 2 samples, are multiband microwave absorbers in the range of 2.0–17.0 GHz. The ERAC values in the frequency bands 2.0–3.0 GHz and 7.5–10.2 GHz for group 4 samples of are lower by 0.1–0.4 rel. units than the ERAC values in the specified frequency bands of group 3 samples. This is due to the fact that the ERRC values in the specified frequency bands of group 4samples are higher by 1.0–5.0 dB than the ERRC values in the specified frequency bands of group 3 samples (see Fig. 6), provided that the ERTC values in the specified frequency bands of these samples are almost completely equivalent. The ERAC values in the frequency bands 3.0–7.5 GHz and 15.0–16.5 GHz of samples of group 4 are higher by 0.1–0.55 rel. units than the ERAC values in the specified frequency bands of group 3 samples. This is due to the fact that the ERRC values in the specified frequency bands of group 4 samples are lower by 1.0–10.0 dB than the ERRC values in the specified frequency bands of group 3 samples (see Fig. 6), provided that the ERTC values in the specified frequency bands of these samples are almost completely equivalent.

The higher ERRC values of group 2 samples compared to those of group 1 samples in the frequency bands 7.0–10.8 GHz and 14.2–17.0 GHz and the higher ERRC values of group 4 samples compared to those of group 3 samples in frequency bands 2.0–3.0 GHz and 7.5–10.2 GHz are due to the following features of electromagnetic waves interaction with these samples:

1) electromagnetic waves reflected from the surfaces of the sample layers interact with each other;

2) the ERRC values of the samples depend on the value of energy of electromagnetic waves resulting from the interaction of electromagnetic waves reflected from the samples layers surfaces (if this energy is higher, electromagnetic radiation reflection coefficient values are higher; if this energy is lower, electromagnetic radiation reflection coefficient values are lower);

3) in the above frequency bands, the difference between the phases of electromagnetic waves reflected from the surfaces of the layers of groups 2 and 4 samples is smaller than the difference between the phases of electromagnetic waves reflected from the layer surface of groups 1 and 3 samples.

The lower ERRC values in the frequency band 10.8–14.2 GHz of group 2 samples compared to those of group 1samples, and the lower ERRC values in the frequency bands 3.0–7.5 GHz and 15.0–16.5 GHz of group 4 samples compared to group 3 samples is due to features 1 and 2 described above, as well as the following feature:

– in the listed frequency bands, the difference between the phases of electromagnetic waves reflected from the layer surfaces of groups 2 and 4 samples is greater than the difference between the phases of electromagnetic waves reflected from the layer surface of groups 1 and 3 samples.

Table 2 presents the results of the study of X-ray attenuation coefficient of the made samples.

The proposed electromagnetic radiation absorbers are characterized by the ERAC values (*A*) and the width of the effective absorption band (Δf) similar to the ERAC values and the width of the effective absorption band of the analogs (microwave absorbers based on porous carbon-containing materials [18–23]) (see Table 3).

Table 2. Results of study of X-ray attenuation coefficient of the made samples

Average X-ray energy, keV	35.0	40.0	45.0	50.0	55.0	60.0	65.0	70.0	75.0	80.0
X-ray attenuation coefficient, rel. units	8.7	6.5	5.0	4.0	3.5	3.0	2.8	2.5	2.2	2.0

Table 3. Characteristics of microwave absorbers based on porous carbon-containing materials

Absorber name	d^*, cm	A, rel. units	Δf, GHz	f_c^{**}, GHz
Proposed absorbers containing powdered birch charcoal	0.9	0.5–0.92	3.5; 3.4	5.2; 12.5
Proposed absorbers containing powdered coconut charcoal	0.9	0.5–0.95	2.5; 6.8	6.2; 13.6
Absorbers based on porous carbon and carbon nanotubes [18]	0.5	~ 0.9***	1.5	15.5
Absorbers based on carbon obtained from wood [19]	0.5	0.5–0.9***	6.0	9.0
Absorbers based on porous carbon obtained from biomass [20]	0.5	0.7–0.9***	4.0	6.0
Absorbers based on carbon hollow microspheres with a designed mesoporous shell [21]	0.4	≥ 0.9	4.8	8.2
Absorbers based on three-dimensional carbon foams obtained from fish skin [22]	0.3	0.5–0.9***	8.6	13.6
Absorbers based on nanoporous carbon obtained from walnut shells [23]	0.2	~ 0.9***	1.8	8.9

* d – absorber thickness value.
** f_c – value of the central frequency in the effective absorption band.
*** The values were estimated based on the energy losses of electromagnetic radiation due to its reflection.

In contrast to the analogs [18–23], the proposed absorbers provide the absorption of X-ray electromagnetic radiation energy along with the absorption of microwave electromagnetic radiation energy since their structure includes the composite coating based on barium sulfate and sodium silicate aqueous alkaline solution, which, as shown in [15], is characterized by the X-ray attenuation coefficient values of 2.0–8.7 rel. units (see Table 2). In addition, unlike carbon-containing absorbers [18–23], the proposed absorbers are multiband ones.

Thus, the main results for the experimental verification of the proposed absorbers are as follows.

1. Adding a (0.2 ± 0.05) cm thick layer based on the mixture of powdered barium sulfate and sodium silicate aqueous alkaline solution to the structure of microwave absorbers based on powdered activated birch charcoal, gypsum and water leads to:

– a decrease by 0.1–0.55 rel. units in the ERAC values in the frequency bands 7.0–10.8 GHz and 14.2–17.0 GHz of the indicated absorbers, which is due to an increase by 2.0–8.0 dB of their ERRC values in the specified frequency bands provided that their ERTC values almost do not change.

– an increase by 0.15–0.22 rel. units of the ERAC values in the frequency band 10.8–14.2 GHz of the indicated absorbers, which is due to a decrease by 1.0–7.0 dB of their ERRC values in the specified frequency band, provided that their ERTC values almost do not change.

2. Adding a (0.2 ± 0.05) cm thick layer based on the mixture of powdered barium sulfate and sodium silicate aqueous alkaline solution to the structure of microwave absorbers based on powdered activated coconut charcoal, gypsum and water leads to:

– a decrease by 0.1–0.4 rel. units of ERAC values in the frequency bands 2.0–3.0 GHz and 7.5–10.2 GHz of the indicated absorbers, which is due to an increase by 1.0–5.0 dB of their ERRC values in the specified frequency bands provided that their ERTC values almost do not change;

– an increase by 0.1–0.55 rel. units of ERAC values in the frequency bands 3.0–7.5 GHz and 15.0–16.5 GHz of the indicated absorbers, which is due to a decrease by 1.0–10.0 dB of their ERRC values in the specified frequency bands provided that their ERTC values almost do not change.

3. Effective absorption bands of the proposed absorbers containing powdered activated birch charcoal are 3.5–7.0 GHz and 10.8–14.2 GHz. Effective absorption bands of the absorbers containing powdered activated coconut charcoal are 5.0–7.5 GHz and 10.2–17.0 GHz. The average values of the ERACs in the effective absorption bands of the first of these absorbers are practically equivalent. The average value of ERAC in the band 5.0–7.5 GHz of the second of these absorbers is higher on 0.2 rel. units than their average value of ERAC in the band 10.2–17.0 GHz.

Based on the presented features, we can conclude that proposed absorbers containing powdered activated birch charcoal are advisable to use in cases where the frequency value of electromagnetic radiation, the energy of which must be attenuated to a greater extent due to its absorption than due to reflection, belongs to the S-band. Proposed absorbers containing powdered activated coconut charcoal are advisable to use in cases where the frequency value of electromagnetic radiation, the energy of which must be attenuated to a greater extent due to its absorption than due to reflection, belongs to the Ku-band.

4. Conclusion

The results of the experimental verification of the proposed absorbers are positive. They are multifunctional multiband ones in the frequency range of 2.0–17.0 GHz. They provide absorption of X-ray electromagnetic radiation along with absorption of electromagnetic radiation energy in the specified frequency range. These absorbers can be used to cover the walls of premises where X-ray machines are located. At the same time, these absorbers must be fixed in such a way that their layers based on foiled polymer film are adjacent to the premises wall. This will ensure: i) reflection of microwave electromagnetic radiation emitted by external sources (i.e. from sources located outside the specified premises), thus reducing the impact of this radiation on X-ray machines, as well as computer equipment connected to them; ii) absorption of X-ray electromagnetic radiation generated by X-ray machines, thus reducing the impact of this radiation on electronic devices and on people who are outside the specified premises; iii) absorption in a wide frequency band of microwave electromagnetic radiation emitted by computer equipment connected to X-ray machines, thus reducing the level of passive electromagnetic interference in the specified premises.

Based on the presented results, a patent application has been filed for methods for making microwave and X-ray electromagnetic radiation absorbers [24].

5. Funding

This study received no external funding.

6. Acknowledgments

The research was carried out within the framework of the scientific project “Development of Radio-Absorbing Composite Structures Based on Powdered Charcoal-Containing Materials” of the subprogram “Physics of Condensed Matter and the Creation of New Functional Materials and Technologies for Their Production” of the State scientific research program of the Republic of Belarus for 2021–2025 “Materials Science, New Materials and Technologies”.

7. Conflict of interests

The authors declare no conflict of interest.

References

1. Zhan B, Hao Y, Qia X, Qu Y, Ding J, Yang J-l, et al. Multifunctional cellular carbon foams derived from chitosan toward self-cleaning, thermal insulation, and highly efficient microwave absorption properties. *Nano Research*. 2023. DOI:10.1007/s12274-023-6236-7

2. Gu W, Sheng J, Huang Q, Wang G, Chen J, Ji G. Environmentally friendly and multifunctional shaddock

peel-based carbon aerogel for thermal-insulation and microwave absorption. *Nano-Micro Letters*. 2021;13(1). DOI:10.1007/s40820-021-00635-1

3. Yang C, Chen S, Niu S, Xiao L, Qu Y-c. Transparent broadband microwave metamaterial absorber with thermal insulating and soundproof. *Optoelectronic Letters*. 2021;17(2):85-89. DOI:10.1007/s11801-021-0023-8

4. Jiang C, Wang Y, Zhao Z, Ma Z, Liu Y. Multifunctional three-dimensional porous MOFs derived Fe/C/carbon foam for microwave absorption, thermal insulation and infrared stealth. *Ceramics International*. 2023;49(11):18861-18869. DOI:10.1016/j.ceramint.2023.03.008

5. Hong Z, Yu X, Xing Y, Xue M, Luo Y, Yin Z, et al. Tunable head-conducting microwave-absorbing multifunctional composites with excellent microwave absorption, thermal conductivity and mechanical properties. *Journal of Composite Science*. 2023;7(1):15. DOI:10.3390/jcs7010015

6. Fan B, Xing L, Yang K, Zhou F, He Q, Tong G, et al. Synergistically enhanced heat conductivity-microwave absorption capabilities of g-C_3N_4@Fe@C hollow micro-polyhedra via interface and composition modulation. *Chemical Engineering Journal*. 2023;451:138492. DOI:10.1016/j.cej.2022.138492

7. Qu S, Sheng P. Microwave and acoustic absorption metamaterials. *Physical Review Applied*. 2022;17(4):047001. DOI:10.1103/PhysRevApplied.17.047001

8. Wu S, Hou H, Xue X. Quad-band microwave absorbers based on MoO_{3-x}@MWCNT with tunable morphologies for multifunctional multiband absorption. *Carbon*. 2023;201:1160-1173. DOI:10.1016/j.carbon.2022.10.012

9. Sun H, Zhang Y, Wu Y, Zhao Y, Zhou M, Liu L, et al. Broadband absorption of macro pyramid structure based flame retardant absorbers. *Journal of Materials Science & Technology*. 2022;128:228-238. DOI:10.1016/j.jmst.2022.04.030

10. Li D, Hu X, Gao B, Yin W-Y, Chen H, Qian H. Highly transparent tunable microwave perfect absorption for broadband microwave shielding. *Progress in Electromagnetics Research*. 2023;176:35-44. DOI:10.2528/PIER22101901

11. Li X, Zhu L, Kasuga T, Nogi M, Koga H. Frequency-tunable and absorption/transmission-switchable microwave absorber based on a chitin-nanofiber-derived elastic carbon aerogel. *Chemical Engineering Journal*. 2023;469:144010. DOI:10.1016/j.cej.2023.144010

12. Kang S, Qiao S, Cao Y, Hu Z, Li N, Yu J, et al. Multifunctional tubular carbon nanofibers/polyurethane electromagnetic wave absorber with room-temperature self-healing and recyclable performance. *Nano Research*. 2023;16:33-44. DOI:10.1007/s12274-022-4743-2

13. Boiprav OV, Belousova ES, Ahmetdinova ES, Bogush NV. Charcoal-containing building materials for electromagnetic radiation shielding. *Magazine of Civil Engineering*. 2023;117(1):11709. DOI:10.34910/MCE.117.9

14. Boiprav OV, Grinchik NN, Guzov VD, Penialosa Ovalies DI. Study of the influence of the layer thickness of composite coatings based on barium sulphate on the attenuation of X-ray radiation. *Medicinskaya radiologiya i radiacionnaya bezopasnost*. 2022;67(2):69-72. DOI:10.33266/1024-6177-2022-67-2-69-72 (In Russ.)

15. Boiprav O, Ayad H, Abdaljlil SA, Lynkou L, Abdulmawlay M. Charcoal- and foil-containing materials for radio electronic control systems protection from electromagnetic interferences. *Institute of Electrical and Electronics Engineers (IEEE)*. 2023:299-304. DOI:10.1109/STA56120.2022.10019059

16. Shukla V. Review of electromagnetic interference shielding materials fabricated by iron ingredients. *Nanoscale Advances*. 2019;5:1640-1671. DOI:10.1039/c9na00108e

17. Pandey SP. Is it possible that the radiation emitted from electronic devices used in daily life can affect our DNA? *Iconic Research and Engineering Journals*. 2022;6(1):120-125.

18. de Medeiros LI, de Faria Lopes Medeiros NC, Lenz e Silva GFB, de Lima RGA, Amaral-Labat G, et al. Improved microwave absorption performance with sustainable porous carbon/carbon nanotube composites. *Materials Research*. 2022;25. DOI:10.1590/1980-5373-MR-2022-0169

19. Xi J, Zhou E, Liu Y, Gao W, Ying J, Chen Z, et al. Wood-based straightway channel structure for high performance microwave absorption. *Carbon*. 2017;124:492-498. DOI:10.1016/j.carbon.2017.07.088

20. Wu Z, Tian K, Huang T, Hu W, Xie F, Wang J, et al. Hierarchically porous carbons derived from biomasses with excellent microwave absorption performance. *ACS Applied Materials and Interfaces*. 2018;10(13):11108-11115. DOI:10.1021/acsami.7b17264

21. Xu H, Yin X, Zhu M, Han M, Hou Z, Li X, et al. Carbon hollow microspheres with a designable mesoporous shell for high-performance electromagnetic wave absorption. *ACS Applied Materials and Interfaces*. 2017;9(7):6332-6341. DOI:10.1021/acsami.6b15826

22. Zhou X, Jia Z, Feng A, Wang X, Liu J, Zhang M. Synthesis of fish skin-derived 3D carbon foams with broadened bandwidth and excellent electromagnetic wave absorption performance. *Carbon*. 2019;152:827-836. DOI:10.1016/j.carbon.2019.06.080

23. Qiu X, Wang L, Zhu H, Guana Y, Zhang Q. Lightweight and efficient microwave absorbing materials based on walnut shell-derived nanoporous carbon. *Nanoscale*. 2017;9:7408-7418. DOI:10.1039/C7NR02628E

24. Boiprav OV, Grinchik NN. *Methods for manufacturing absorbers of radio wave and X-ray radiation and absorbers of radio wave and X-ray radiation made in accordance with these methods*. Application for invention No. 20220063 (Republic of Belarus). 21 March 2022 (In Russ.)

Information about the authors / Информация об авторах

Olga V. Boiprav, Cand. Sc. (Eng.), Associate Professor, Associate Professor of Information Protection Department, Belarusian State University of Informatics and Radioelectronics (BSUIR), Minsk, Republic of Belarus; ORCID 0000-0002-9987-8109; e-mail: smu@bsuir.by

Vadim A. Bogush, D. Sc. (Phys. and Math.), Professor, Professor of Information Protection Department, BSUIR, Minsk, Republic of Belarus; ORCID 0000-0001-7516-4841; e-mail: bogush@bsuir.by

Nikolay N. Grinchik, D. Sc. (Phys. and Math.), Associate Professor, Leader Researcher, Institute of Heat and Mass Transfer named after A.V. Lykov National Academy of Sciences of Belarus, Minsk, Republic of Belarus; ORCID0000-0002-1369-4983; e-mail: nngrin@yandex.by

Бойправ Ольга Владимировна, кандидат технических наук, доцент, доцент кафедры защиты информации, Белорусский государственный университет информатики и радиоэлектроники (БГУИР), Минск, Республика Беларусь; ORCID 0000-0002-9987-8109; e-mail: smu@bsuir.by

Богуш Вадим Анатольевич, доктор физико-математических наук, профессор, профессор кафедры защиты информации, БГУИР, Минск, Республика Беларусь; ORCID 0000-0001-7516-4841; e-mail: bogush@bsuir.by

Гринчик Николай Николаевич, доктор физико-математических наук, доцент, ведущий научный сотрудник, Институт тепло- и массообмена имени А. В. Лыкова Национальной академии наук Беларуси, Минск, Республика Беларусь; ORCID 0000-0002-1369-4983; e-mail: nngrin@yandex.by

Received 29 September 2023; Accepted 03 November 2023; Published 15 December 2023