**Original article**
**EDN: AWJAQN**
**DOI: 10.21285/2686-9993-2026-49-2-5**

# Investigation of electromagnetic properties of ceramic material based on white-burning clay from Kornilovskoye deposit with non-ferrous metal additives at varying concentrations: analysis of electromagnetic radiation absorption and reflection

**Aleksey N. Sigaev[a], Arthur E. Fedorov[b], Nikita I. Chekh[c], Daniil E. Kulikov[d]✉, Afanasiy S. Apkarian[e]**

[a–e]*Tomsk State University of Control Systems and Radio Electronics, Tomsk, Russian Federation*
[e]*Panin Institute of Strength Physics and Materials Science, Siberian Branch of the Russian Academy of Sciences, Tomsk, Russian Federation*

***Abstract.*** The paper reports the results of an experimental investigation into the electromagnetic properties of a ceramic material obtained from white-burning clay from the Kornilovskoye deposit with the addition of non-ferrous metals (lead and copper) at varying concentrations. The relevance of the study is driven by the need to develop effective radar-absorbing materials for protection against electromagnetic radiation across a wide frequency range. The purpose of the study is to investigate the relationship between the reflection and absorption coefficients of electromagnetic waves and the metallic phase content within the ceramic matrix, as well as to identify the optimal composition of the material for radar-absorbing coatings formation. The study employs the following research methods: S-parameter analysis in the 0–18 GHz frequency range and time domain reflectometry (TDR), which allows for the estimation of the reflected signal level. It has been found that the addition of lead and copper significantly affects the electrophysical properties of the material, altering its dielectric permittivity and electrical conductivity. It has been shown that at the metal concentration of 20% an insufficient degree of electromagnetic radiation absorption is observed, whereas at 40%, the reflectivity increases due to the rise in conductivity and surface effects. The most effective radar absorption properties are achieved at the metallic phase content of approximately 30%, which corresponds to the formation of an optimal material structure that ensures a balance between dielectric and conductive losses. The obtained results indicate the promise of using the developed ceramic material as a basis for radar-absorbing coatings, shielding structures, and protective elements against electromagnetic exposure.

***Keywords:*** white-burning clay from the Kornilovskoye deposit, non-ferrous metals, radar-absorbing material, electromagnetic radiation, absorption coefficient, reflection coefficient

***For citation:*** Sigaev A.N., Fedorov A.E., Chekh N.I., Kulikov D.E., Apkarian A.S. Investigation of electromagnetic properties of ceramic material based on white-burning clay from Kornilovskoye deposit with non-ferrous metal additives at varying concentrations: analysis of electromagnetic radiation absorption and reflection. *Earth sciences and subsoil use*. 2026;49(2):?-?. https://doi.org/10.21285/2686-9993-2026-49-2-5.

**Научная статья**
**УДК 504.064.3**

# Исследование электромагнитных характеристик керамического материала на основе беложгущейся глины Корниловского месторождения с добавлением цветных металлов при различных концентрациях: анализ поглощения и отражения электромагнитного излучения

**А.Н. Сигаев[a], А.Е. Федоров[b], Н.И. Чех[c], Д.Е. Куликов[d]✉, А.С. Апкарьян[e]**

[a–e]*Томский государственный университет систем управления и радиоэлектроники, Томск, Российская Федерация*
[e]*Институт физики прочности и материаловедения им. В.Е. Панина СО РАН, Томск, Российская Федерация*

***Аннотация.*** В работе представлены результаты экспериментального исследования электромагнитных характеристик керамического материала, полученного на основе беложгущейся глины Корниловского месторождения с добавлением цветных металлов (свинца и меди) в различных концентрациях. Актуальность исследования обусловлена необходимостью разработки эффективных радиопоглощающих материалов для защиты от электромагнитного излучения в широком диапазоне частот. Целью работы является установление зависимости коэффициентов отражения и поглощения электромагнитных волн от содержания металлической фазы в керамической матрице, а также определение оптимального состава материала для формирования радиопоглощающих покрытий. В качестве методов исследования использованы анализ S-параметров в диапазоне частот 0–18 ГГц и метод временной доменной рефлектометрии (TDR), позволяющий оценить уровень отраженного сигнала. Установлено, что введение свинца и меди существенно влияет на электрофизические свойства материала, изменяя его диэлектрическую проницаемость и электрическую проводимость. Показано, что при концентрации металлов 20 % наблюдается недостаточная степень поглощения электромагнитного излучения, тогда как при 40 % усиливается отражательная способность вследствие роста проводимости и поверхностных эффектов. Наиболее эффективные радиопоглощающие свойства достигаются при содержании металлической фазы около 30 %, что соответствует формированию оптимальной структуры материала, обеспечивающей баланс между диэлектрическими и проводящими потерями. Полученные результаты свидетельствуют о перспективности использования разработанного керамического материала в качестве основы для радиопоглощающих покрытий, экранирующих конструкций и элементов защиты от электромагнитного воздействия.

***Ключевые слова:*** беложгущаяся глина Корниловского месторождения, цветные металлы, радиопоглощающий материал, электромагнитное излучение, коэффициент поглощения, коэффициент отражения

***Для цитирования:*** Сигаев А.Н., Федоров А.Е., Чех Н.И., Куликов Д.Е., Апкарьян А.С. Исследование электромагнитных характеристик керамического материала на основе беложгущейся глины Корниловского месторождения с добавлением цветных металлов при различных концентрациях: анализ поглощения и отражения электромагнитного излучения // Науки о Земле и недропользование. 2026. Т. 49. № 2. С. ?–?. https://doi.org/10.21285/2686-9993-2026-49-2-5.

## Introduction

Ceramic materials based on clay raw materials are actively used in radio-shielding coatings, protective structures, systems for reducing electromagnetic pollution, and shielding composites [1–6]. The introduction of non-ferrous metals (lead and copper) into the ceramic structure makes it possible to modify its dielectric characteristics, electrical conductivity, and, consequently, its ability to reflect and absorb electromagnetic waves[1,2] [7, 8].

The aim of the conducted study was to investigate the relationship between the reflection and absorption coefficients of electromagnetic radiation and the concentration of non-ferrous metals (lead and copper) in the ceramic material based on white-burning clay from the Kornilovskoye deposit, as well as to determine the optimal concentration for forming an effective radar-absorbing layer.

Special attention in the work is paid to the principles of electromagnetic radiation measurement and the interpretation of its interaction with the studied materials. Within the framework of the study, the physical fundamentals of recording reflected and absorbed signals are examined, as well as the specific features of applying spectral filtering methods (S-parameters) and time domain reflectometry (TDR) for analyzing the properties of the medium.

The research objectives include:

– developing a ceramic material based on white-burning clay from the Kornilovskoye deposit with the addition of non-ferrous metals for protection against electromagnetic waves;

– determining the potential applications of the material;

– investigating the clay materials from the Kornilovskoye deposit;

– studying the impact of electromagnetic radiation on humans;

– developing the batch composition and temperature regime for the production of a material for protection against electromagnetic waves based on white-burning clay and non-ferrous metals.

## Materials and methods

For the study, three samples of clay from the Kornilovskoye deposit with lead and three samples with copper were used. The material specimens are designated as OSV-1, OSV-2, OSV-3, OM-1, OM-2, and OM-3. The following methods were employed in the investigation:

– spectral filtering method (S-parameter analysis) – to determine the absorption coef-

[1] Tretyakov Yu.D. *Inorganic chemistry: a textbook for students. Vol. 2: Chemistry of non-transition elements.* Moscow: Akademiya; 2011, 365 p.

[2] Landau L.D., Lifshitz E.M. *Course of theoretical physics: a textbook for universities. Vol. 8: Electrodynamics of continuous media.* Moscow: Fizmatlit; 2005, 656 p.

ficient of the material in the frequency range of 0–18 GHz[2] [9, 10];

– time domain reflectometry (TDR) – to record the reflected signal for estimating the reflection coefficient [11].

The measurement of electromagnetic radiation characteristics in this work is based on the analysis of the interaction of the incident wave with the interface between media. The main measured parameters are the reflection coefficient *R* and transmission coefficient *T*, which are derived from the S-parameters (S11, S21) recorded using a vector network analyzer.

The reflection coefficient S11 characterises the fraction of energy reflected from the sample surface and is defined as the ratio of the reflected wave amplitude to the incident wave amplitude. The transmission coefficient S21 reflects the ability of the wave to pass through the material. Based on these parameters, the absorption coefficients, which are associated with energy losses in the material volume, are calculated [12, 13].

The TDR method is based on recording the response of the medium to a short pulse. Analysis of the waveform and amplitude of the reflected signal makes it possible to determine the distribution of inhomogeneities and to evaluate the dielectric properties of the material. The time resolution of the method provides the ability to localise regions with different electrophysical characteristics.

An important aspect is the consideration of signal attenuation, multiple reflections, and dispersion effects, which is especially significant when studying composite materials with conductive phase inclusions.

## Results and discussion

The batch composition is based on white-burning clay from the Kornilovskoye deposit. Various concentrations of non-ferrous metals were introduced into it, %: lead – 20, 30, 40; copper – 20, 30, 40. The same preparation procedure was applied to all specimens: mixing, shaping, drying, and firing at 1,250°C [14, 15].

For the investigation, the results of refractoriness determination of the clay material with non-ferrous metal additions were used, with the aim of employing the material under high-temperature conditions (Table). Firing was performed in an electric furnace “Nakal” (Nakal – Industrial Furnaces JSC, Russia).

The obtained experimental data are considered not only from the standpoint of the material properties, but also as a result of the implemented measurement procedure based on the analysis of the reflection and absorption parameters of electromagnetic radiation. The features of the resonance curve shapes and the amplitudes of the TDR signals make it possible to assess the sensitivity of the methods to changes in the medium structure and the concentration of the conductive phase.

In the filtering plot (S-parameter graph) at the lead content of 20%, comparatively shallow resonance dips are observed in the 9–11 GHz and 15–16 GHz ranges, which corresponds to a moderate degree of absorption. The TDR graphs confirm this – the amplitude of the reflected pulse is elevated, which is characteristic of materials with a low level of internal losses [16].

An increase in the lead concentration to 30% results in the deepest resonance minima, a broadening of the absorption frequency band, and a decrease in the reflection level on the TDR diagram. This indicates that an optimal balance between conductivity and dielectric losses has been achieved [17].

When the lead content is increased to 40%, the absorption intensity is partially preserved; how-

**Results of refractoriness determination of the clay material with non-ferrous metal additives**
**Результаты определения огнеупорности глинистого материала с добавлением цветных металлов**

| Sample number | Heavy metal | Heavy metal content, % | Refractoriness temperature, °C | Refractoriness classification |
|---|---|---|---|---|
| ОСВ-1 | Свинец | 20 | 1250 | Refractory |
| ОСВ-2 | Свинец | 30 | 1250 | Refractory |
| ОСВ-3 | Свинец | 40 | 1250 | Refractory |
| ОМ-1 | Медь | 20 | 1250 | Refractory |
| ОМ-2 | Медь | 30 | 1250 | Refractory |
| ОМ-3 | Медь | 40 | 1250 | Refractory |

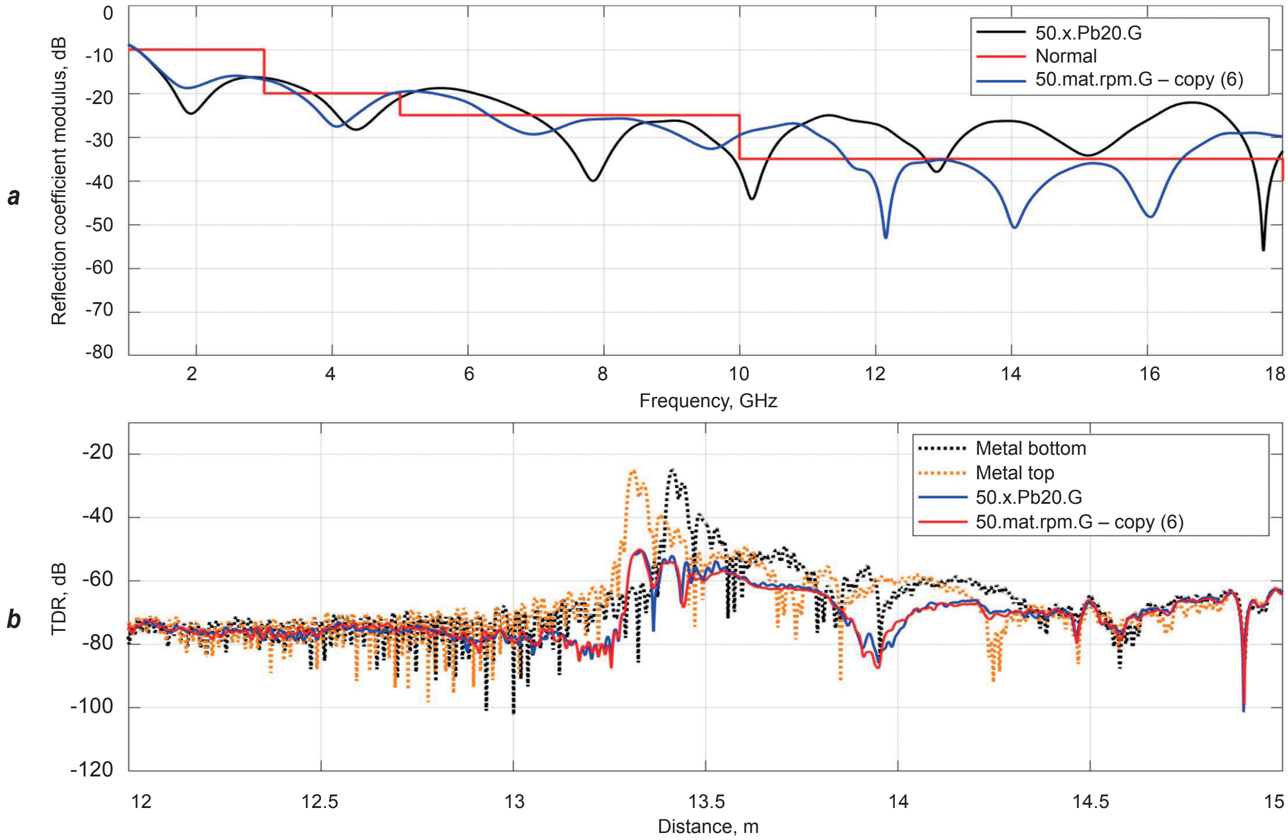



*Fig. 1. Filtration (a) and time domain reflectometry (b) graphs at the lead concentration of 20%*
*Рис. 1. Графики фильтрации (a) и временной доменной рефлектометрии (b) при концентрации свинца 20 %*

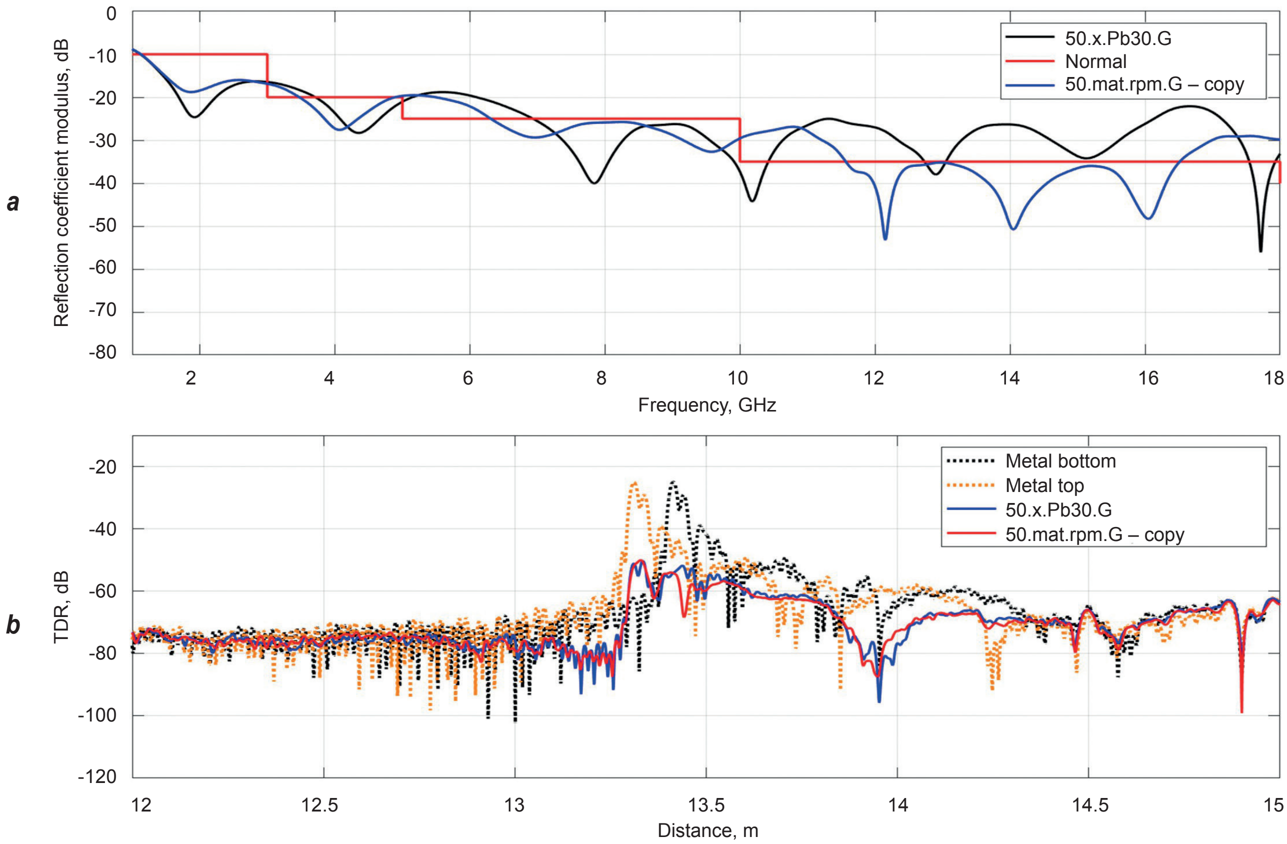



*Fig. 2. Filtration (a) and time domain reflectometry (b) graphs at the lead concentration of 30%*
*Рис. 2. Графики фильтрации (a) и временной доменной рефлектометрии (b) при концентрации свинца 30 %*

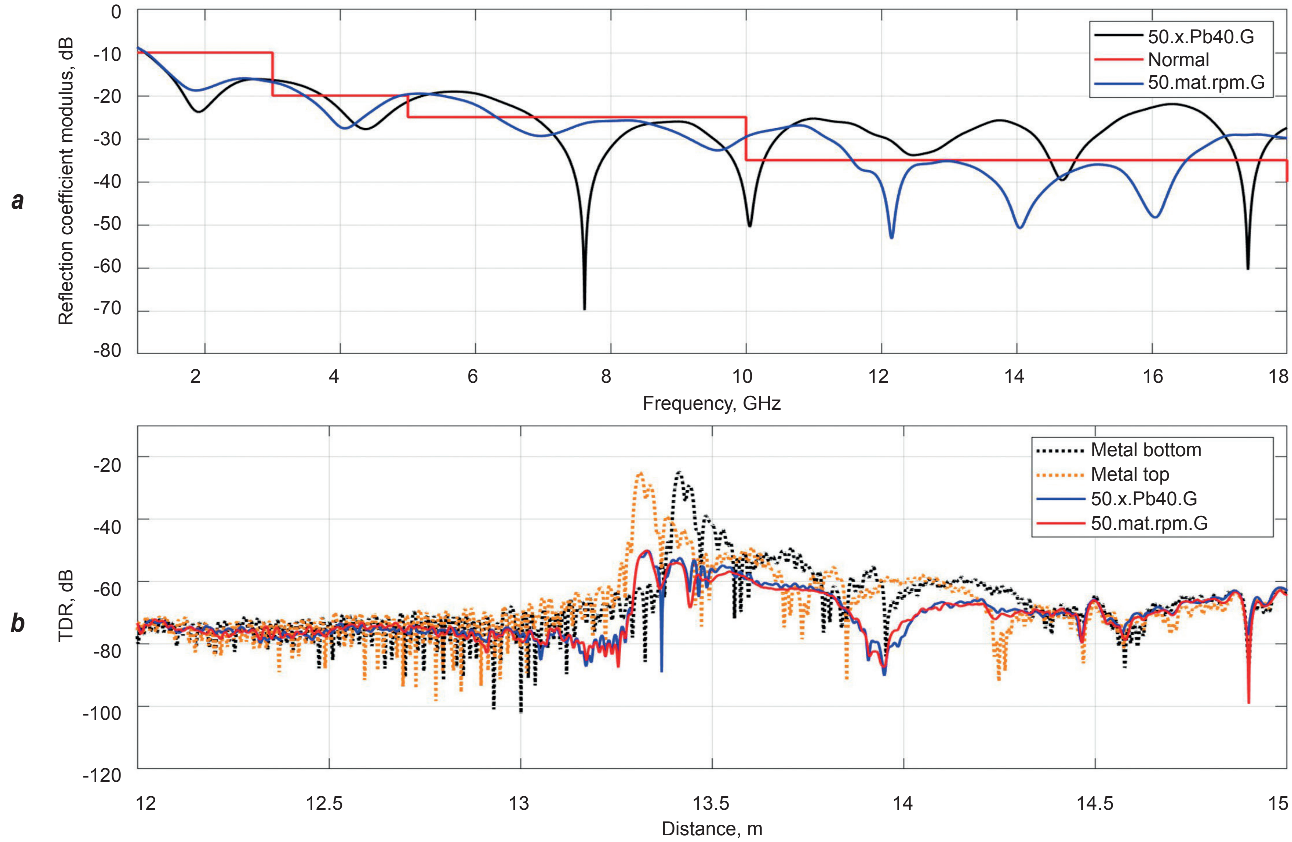



***Fig. 3. Filtration (a) and time domain reflectometry (b) graphs at the lead concentration of 40%***
***Рис. 3. Графики фильтрации (a) и временной доменной рефлектометрии (b) при концентрации свинца 40 %***

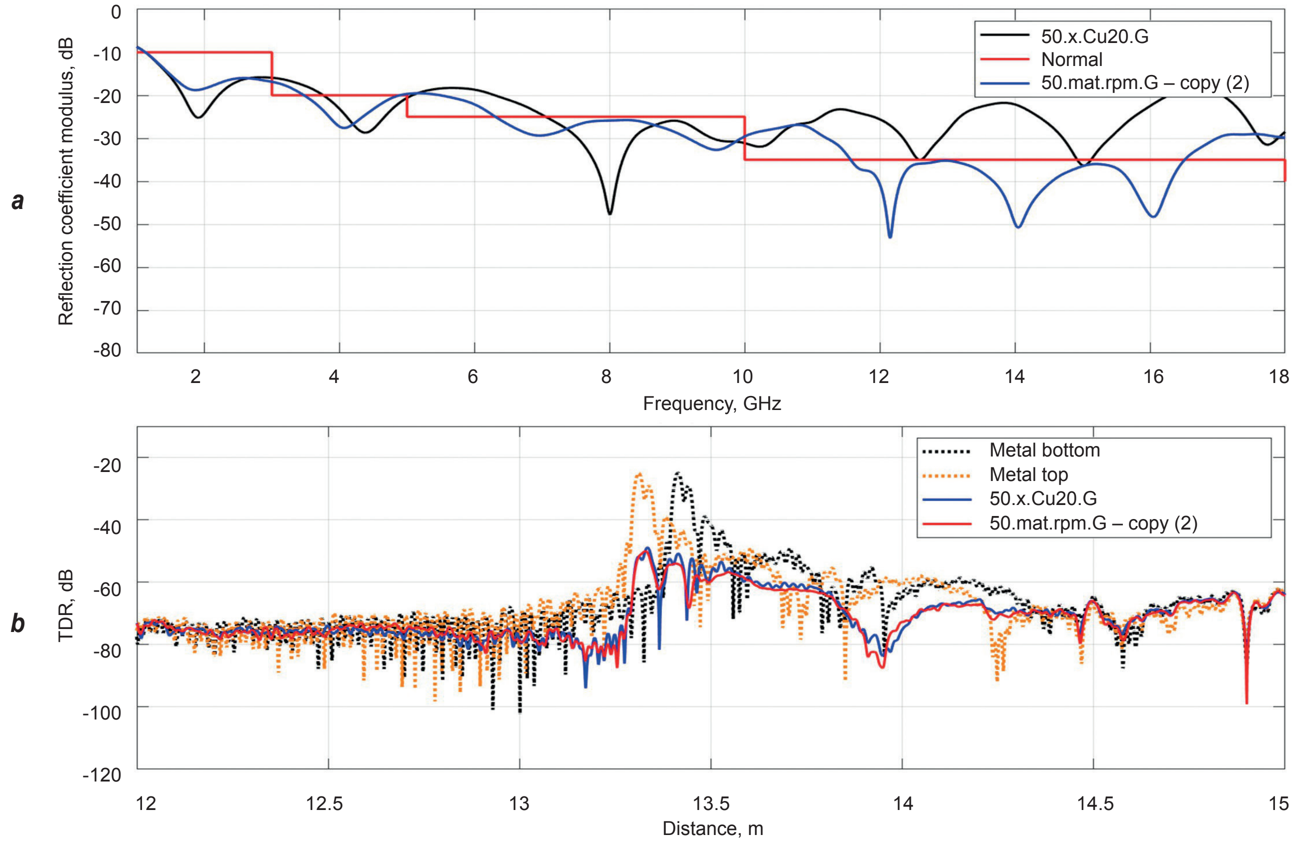



***Fig. 4. Filtration (a) and time domain reflectometry (b) graphs at the copper concentration of 20%***
***Рис. 4. Графики фильтрации (a) и временной доменной рефлектометрии (b) при концентрации меди 20 %***

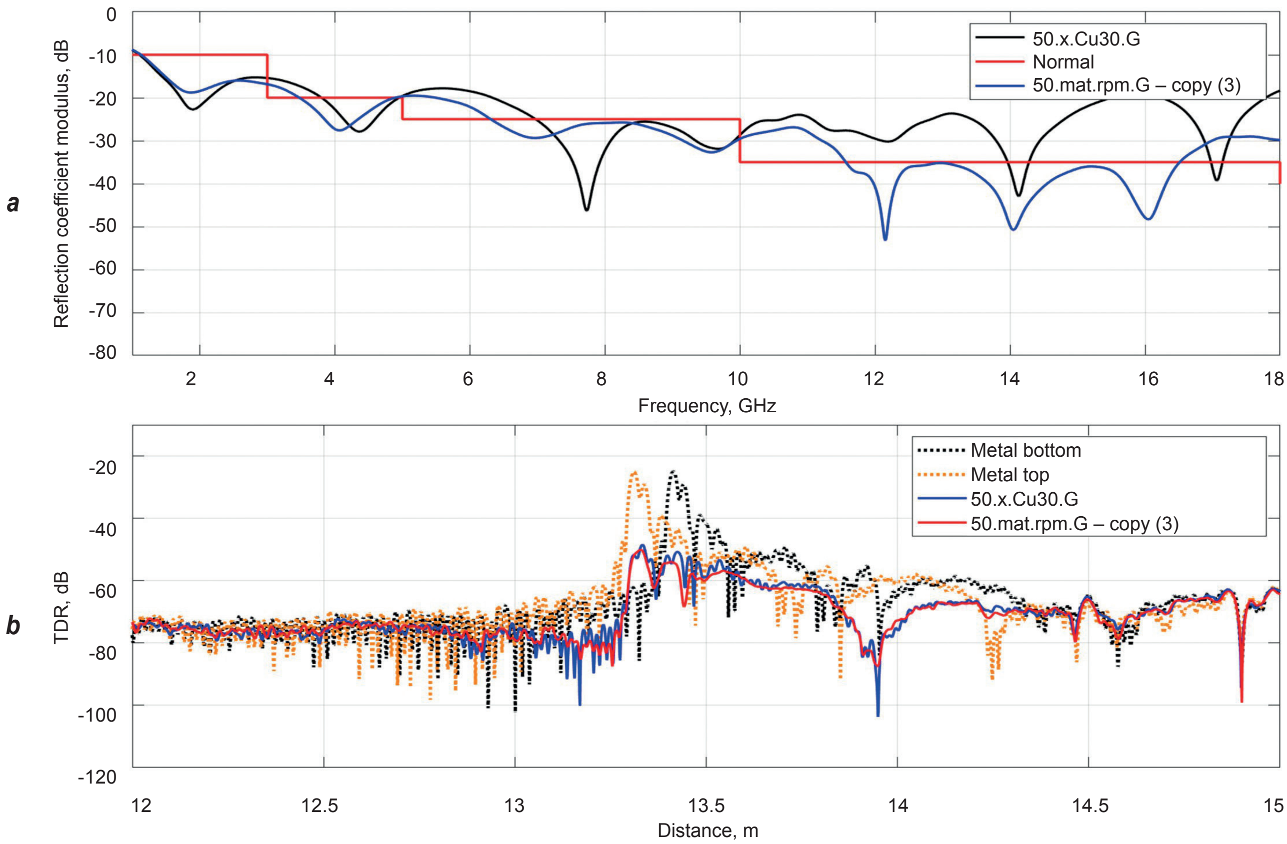



*Fig. 5. Filtration (a) and time domain reflectometry (b) graphs at the copper concentration of 30%*
*Рис. 5. Графики фильтрации (a) и временной доменной рефлектометрии (b) при концентрации меди 30 %*

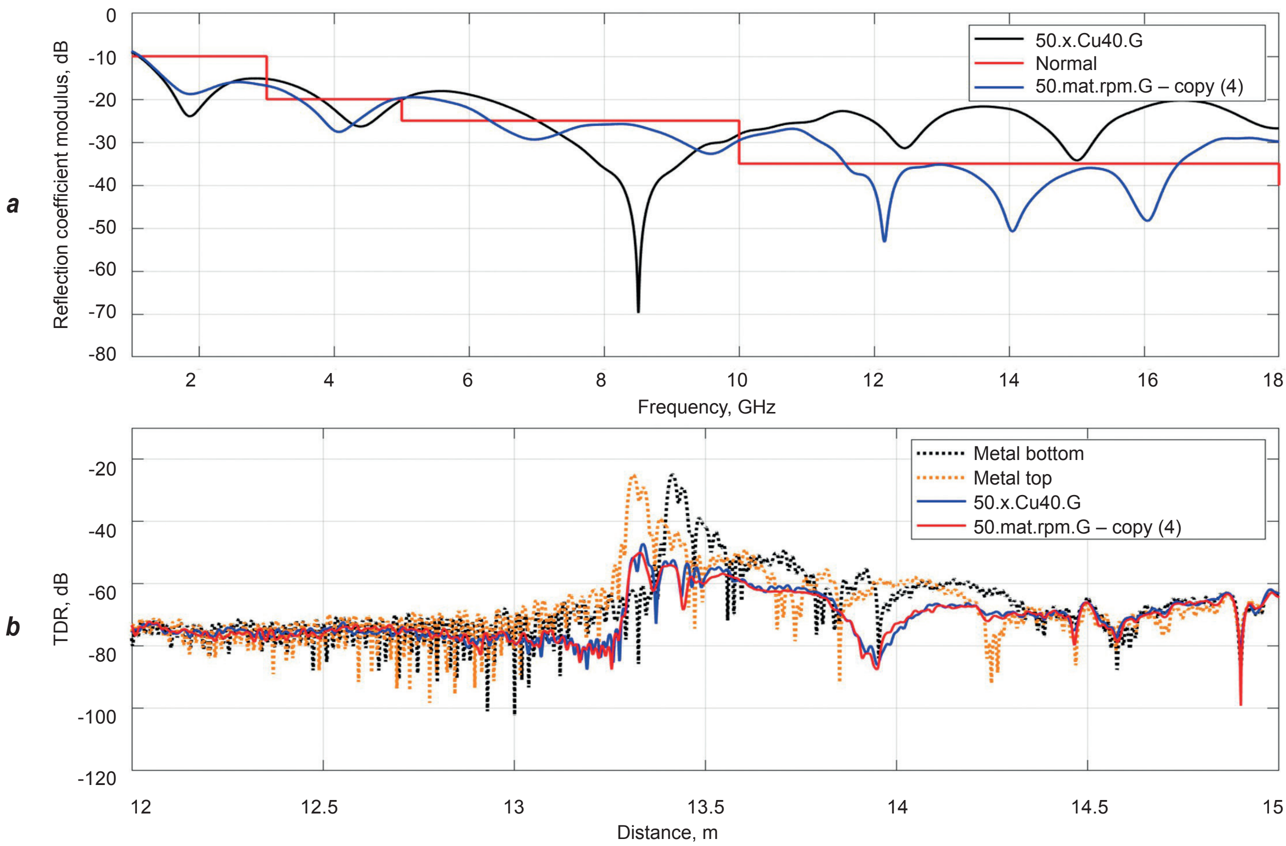



*Fig. 6. Filtration (a) and time domain reflectometry (b) graphs at the copper concentration of 40%*
*Рис. 6. Графики фильтрации (a) и временной доменной рефлектометрии (b) при концентрации меди 40 %*

ever, the spectrum becomes less uniform, and the amount of reflected energy increases. This is attributed to excessive conductivity and enhanced surface reflection [18].

The studies of copper samples with concentrations of 20, 30, and 40% are presented in Figs 4–6.

At the copper concentration of 20%, only initial resonance features of absorption are formed, and the TDR graphs confirm a high amplitude of the reflected signal, indicating weak attenuation of the electromagnetic wave within the material volume [13, 14].

At the copper concentration of 30%, the most developed absorption band with deep resonance dips and a substantial reduction in reflection is recorded.

When the copper fraction is increased to 40%, the spectra again become less uniform, the dip depth decreases, and the reflected pulse intensifies. This effect is attributed to the increase in conductivity and the reduction in wave penetration depth, which leads to enhanced surface reflection [19].

For both lead and copper, a common trend is observed: the best absorbing properties are achieved at the concentration of 30%, whereas at 20% the material is insufficiently effective, and at 40% it begins to exhibit excessive reflectivity. This confirms the critical role of the percolation threshold of the metallic phase in the formation of the electromagnetic properties of ceramic materials [20].

## Conclusion

The study has demonstrated the effectiveness of applying S-parameter analysis and TDR for the quantitative assessment of electromagnetic radiation characteristics upon interaction with composite materials. It has been shown that these methods are highly sensitive to changes in the medium structure and can be used in problems of geophysical monitoring, remote sensing, and materials diagnostics.

Based on the analysis results, it should be noted that products manufactured from white-burning clay from the Kornilovskoye deposit with non-ferrous metals represent a promising basis for radar-absorbing panels and shielding elements. The introduction of heavy metals into the clay matrix significantly affects the electromagnetic properties of the material. At concentrations below 30%, the material exhibits insufficient absorbing capacity; at concentrations above 30%, reflection increases due to excessive conductivity.

### *References*

1. Osipov V.I., Sokolov V.N. *Clays and their properties. Composition, structure and property formation*. Moscow: GEOS; 2013, 576 p. (In Russ.).

2. Apkar'yan A.S., Sablina T.Yu. Physical and technical properties of clays from the Kornilovskoye deposit of the Tomsk Region. *Russian Physics Journal*. 2022;65(7):1102-1108. https://doi.org/10.1007/s11182-022-02737-8.

3. Yakovleva A.A., Nemchinova N.V. Local clay prospects to be used in metallurgical practice. *Proceedings of Irkutsk State Technical University*. 2019;23(2):415-425. (In Russ.). https://doi.org/10.21285/1814-3520-2019-2-415-425.

4. Balinova Yu.A., Grashchenkov D.V., Shavnev A.A., Babashov V.G., Chainikova A.S., Kurbatkina E.I., Bolshakova A.N. High-temperature heat-shielding, ceramic and ceramic-metal composite materials for new-generation aviation equipment. *Vestnik Kontserna VKO "Almaz – Antey"*. 2020;(2):83-92. (In Russ.). https://doi.org/10.38013/2542-0542-2020-2-83-92.

5. Kuvaldin A.B., Lepeshkin A.R., Fedin M.A., Kuleshov A.O., Ilyinskaya O.I. Modeling the thermal state of parts with ceramic coatings in a high-frequency electromagnetic field. *Bulletin of the Russian Academy of Sciences: Physics*. 2021;85(12):1507-1509. https://doi.org/10.3103/S1062873821120212.

6. Barabanova E.V., Ospelnikov N.M., Ivanova A.I., Karpenkov A.Yu. Effect of acceptor doping on the dielectric properties of sodium niobate ceramics. *Fizika tverdogo tela*. 2025;67(4):639-647. (In Russ.). https://doi.org/10.61011/FTT.2025.04.60545.342.

7. Buzko V.Yu., Goryachko A.I., Ivanin S.N., Shutkin I.Yu. Development of a flexible thin-film radio-absorbing structure for UHF and SHF microwave range. *Technical Physics*. 2023;68(3):365. https://doi.org/10.21883/tp.2023.03.55811.185-22.

8. Samukhina Yu.V., Glushko A.N., Buryak A.K. Comparative analysis of chromatograph mass spectrometric ways of detecting impurities in a concentrated hydrogen peroxide–rocket fuel oxidizer. *Russian Journal of Physical Chemistry A*. 2025;99(2):292-299. https://doi.org/10.1134/S0036024424703321.

9. Astafyev P.A., Pavelko A.A., Andryushin K.P., Borzykh A.R., Reisenkind Y.A., Lerer A.M., et al. Radio-absorbing properties of ferroelectric piezoceramic materials. *Pis'ma v Zhurnal tekhnicheskoi fiziki*. 2024;50(16):43-46. (In Russ.). https://doi.org/10.61011/PJTF.2024.16.58538.19892.

10. Isaev I.M., Kostishin V.G., Korovushkin V.V., Salogub D.V., Shakirzyanov R.I., Timofeev A.V., and Mironovich A.Yu. Magnetic and radar absorbing properties of polycrystalline spinel ferrite $Li_{0,33}Fe_{2,29}Zn_{0,21}Mn_{0,17}O_4$. *Zhurnal tekhnicheskoi fiziki*. 2021;91(9):1376-1380. (In Russ.). https://doi.org/10.21883/JTF.2021.09.51217.74-21.

11. Pevneva N.A., Kondrashov D.A., Gursky A.L., Gusinsky A.V. Estimation of S-parameters and dielectric permittivity of quartz ceramics samples in millimeter waveband. *Doklady BGUIR*. 2021;19(7):65-71. (In Russ.). https://doi.org/10.35596/1729-7648-2021-19-7-65-71.

12. Tarasov S.P., Kutsenko A.N., Belous Yu.V. Reflection coefficient as an informative parameter for environmental studies. *Izvestiya Taganrogskogo gosudarstvennogo radiotekhnicheskogo universiteta*. 2002;6:87-91. (In Russ.).

13. Krasniakova I.O., Sidorenko E.N., Galatova A.O., Rudsky D.I., Glazunova E.V., Kuprina Yu.A., et al. Features of the structure, microstructure, radio-emitting and radio-absorbing properties of mechanically and non-mechanically activated $BiFeO_3$ ceramics. *Physics of the Solid State*. 2023;65(4):537. https://doi.org/10.21883/pss.2023.04.55992.560.

14. Apkarian A.S., Kulikov D.E. Physical and technical properties of composite high-temperature thermal insulation material based on white-burning clay from Kornilovsky deposit in the Tomsk Region. *Journal of Construction and Architecture*. 2025;27(2):198-205. (In Russ.). https://doi.org/10.31675/1607-1859-2025-27-2-198-205.

15. Kijko V.S., Pavlov A.V. The composite BeO + $TiO_2$-ceramics for the electronic engineering and other technical applications. *New Refractories*. 2017;12:64-70. (In Russ.). https://doi.org/10.17073/1683-4518-2017-12-64-70.

16. Skirdin K.V., Dorozhkin K.V., Kazmina O.V. Magnetite's influence on the radio-absorbing properties of a porous glass composite at high-frequencies. *Glass and Ceramics*. 2022;79(5-6):175-179. https://doi.org/10.1007/s10717-022-00479-0.

17. Samukhina Yu.V., Nikoladze G.M., Kulkova T.A., Buryak A.K. Radar-shielding and microwave-absorbing properties of composite materials based on shungite. *Russian Journal of Physical Chemistry A*. 2023;97(2):373-376. https://doi.org/10.1134/s0036024423020231.

18. Terukov E.I., Babaev A.A., Zhilina D.V., Tkachev A.G. Radio-wave absorbing properties of polymer composites on the basis of shungite and carbon nanomaterial Taunit-M. *Technical Physics*. 2018;63(7):1044-1048. https://doi.org/10.1134/S1063784218070289.

19. Shakirzyanov R.I., Isaev I.M., Kostishin V.G., Kayumova A.R., Olitsky V.K., Salogub D.V. Radar absorbing and shielding characteristics in ferrite-polymer composites Mn-Zn ferrite/P (TFE-VDF). *Zhurnal tekhnicheskoi fiziki*. 2022;92(3):462-471. (In Russ.). https://doi.org/10.21883/JTF.2022.03.52142.242-21.

20. Cherkasov V.D., Shcherbak Yu.P., Cherkasov D.V. Radar absorbing materials based on sealant "Abris". *Construction Materials and Products*. 2023;6(4):30-41. (In Russ.). https://doi.org/10.58224/2618-7183-2023-6-4-30-41.

***Список источников***

1. Осипов В.И., Соколов В.Н. Глины и их свойства. Состав, строение и формирование свойств. М.: ГЕОС, 2013. 576 с.

2. Apkar'yan A.S., Sablina T.Yu. Physical and technical properties of clays from the Kornilovskoye deposit of the Tomsk Region // Russian Physics Journal. 2022. Vol. 65. Iss. 7. P. 1102–1108. https://doi.org/10.1007/s11182-022-02737-8.

3. Яковлева А.А., Немчинова Н.В. Перспективы использования глин локального проявления в металлургической практике // Вестник Иркутского государственного технического университета. 2019. Т. 23. № 2. С. 415–425. https://doi.org/10.21285/1814-3520-2019-2-415-425.

4. Балинова Ю.А., Гращенков Д.В., Шавнев А.А., Бабашов В.Г., Чайникова А.С., Курбаткина Е.И. [и др.]. Высокотемпературные теплозащитные, керамические и металлокерамические композиционные материалы для авиационной техники нового поколения // Вестник Концерна ВКО «Алмаз – Антей». 2020. № 2. С. 83–92. https://doi.org/10.38013/2542-0542-2020-2-83-92.

5. Kuvaldin A.B., Lepeshkin A.R., Fedin M.A., Kuleshov A.O., Ilyinskaya O.I. Modeling the thermal state of parts with ceramic coatings in a high-frequency electromagnetic field // Bulletin of the Russian Academy of Sciences: Physics. 2021. Vol. 85. Iss. 12. P. 1507–1509. https://doi.org/10.3103/S1062873821120212.

6. Барабанова Е.В., Оспельников Н.М., Иванова А.И., Карпенков А.Ю. Влияние легирования акцепторными примесями на диэлектрические свойства керамики ниобата натрия // Физика твердого тела. 2025. Т. 67. № 4. С. 639–647. https://doi.org/10.61011/FTT.2025.04.60545.342.

7. Buzko V.Yu., Goryachko A.I., Ivanin S.N., Shutkin I.Yu. Development of a flexible thin-film radio-absorbing structure for UHF and SHF microwave range // Technical Physics. 2023. Vol. 68. Iss. 3. P. 365. https://doi.org/10.21883/tp.2023.03.55811.185-22.

8. Samukhina Yu.V., Glushko A.N., Buryak A.K. Comparative analysis of chromatograph mass spectrometric ways of detecting impurities in a concentrated hydrogen peroxide–rocket fuel oxidizer // Russian Journal of Physical Chemistry A. 2025. Vol. 99. Iss. 2. P. 292–299. https://doi.org/10.1134/S0036024424703321.

9. Астафьев П.А., Павелко А.А., Андрюшин К.П., Борзых А.Р., Рейзенкинд Я.А., Лерер А.М. [и др.]. Радиопоглощающие свойства сегнетопьезокерамических материалов // Письма в Журнал технической физики. 2024. Т. 50. № 16. С. 43–46. https://doi.org/10.61011/PJTF.2024.16.58538.19892.

10. Исаев И.М., Костишин В.Г., Коровушкин В.В., Салогуб Д.В., Шакирзянов Р.И., Тимофеев А.В., Миронович А.Ю. Магнитные и радиопоглощающие свойства поликристаллического феррита-шпинели $Li_{0,33}Fe_{2,29}Zn_{0,21}Mn_{0,17}O_4$ // Журнал

технической физики. 2021. Т. 91. № 9. С. 1376–1380. https://doi.org/10.21883/JTF.2021.09.51217.74-21.

11. Певнева Н.А., Кондрашов Д.А., Гурский А.Л., Гусинский А.В. Определение S-параметров и диэлектрической проницаемости образцов кварцевой керамики в миллиметровом диапазоне длин волн // Доклады Белорусского государственного университета информатики и радиоэлектроники. 2021. Т. 19. № 7. С. 65–71. https://doi.org/10.35596/1729-7648-2021-19-7-65-71.

12. Тарасов С.П., Куценко А.Н., Белоус Ю.В. Коэффициент отражения как информативный параметр для экологических исследований // Известия Таганрогского государственного радиотехнического университета. 2002. № 6. С. 87–91.

13. Krasniakova I.O., Sidorenko E.N., Galatova A.O., Rudsky D.I., Glazunova E.V., Kuprina Yu.A., et al. Features of the structure, microstructure, radio-emitting and radio-absorbing properties of mechanically and non-mechanically activated $BiFeO_3$ ceramics // Physics of the Solid State. 2023. Vol. 65. Iss. 4. P. 537. https://doi.org/10.21883/pss.2023.04.55992.560.

14. Апкарьян А.С., Куликов Д.Е. Исследование физико-технических свойств композиционного высокотемпературного теплоизоляционного материала на основе беложгущейся глины Корниловского месторождения Томской области // Вестник Томского государственного архитектурно-строительного университета. 2025. Т. 27. № 2. С. 198–205. https://doi.org/10.31675/1607-1859-2025-27-2-198-205.

15. Кийко В.М. Композиционная ($BeO$ + $TiO_2$)-керамика для электронной и других областей техники // Новые огнеупоры. 2017. № 12. С. 64–70. https://doi.org/10.17073/1683-4518-2017-12-64-70.

16. Skirdin K.V., Dorozhkin K.V., Kazmina O.V. Magnetite’s influence on the radio-absorbing properties of a porous glass composite at high-frequencies // Glass and Ceramics. 2022. Vol. 79. Iss. 5–6. P. 175–179. https://doi.org/10.1007/s10717-022-00479-0.

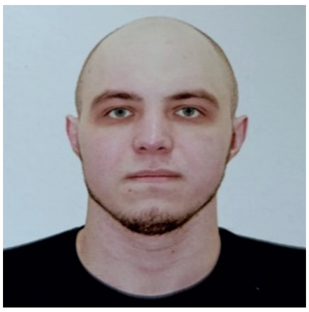
17. Samukhina Yu.V., Nikoladze G.M., Kulkova T.A., Buryak A.K. Radar-shielding and microwave-absorbing properties of composite materials based on shungite // Russian Journal of Physical Chemistry A. 2023. Vol. 97. Iss. 2. P. 373–376. https://doi.org/10.1134/s0036024423020231.

18. Terukov E.I., Babaev A.A., Zhilina D.V., Tkachev A.G. Radio-wave absorbing properties of polymer composites on the basis of shungite and carbon nanomaterial Taunit-M // Technical Physics. 2018. Vol. 63. Iss. 7. P. 1044–1048. https://doi.org/10.1134/S1063784218070289.

19. Шакирзянов Р.И., Исаев И.М., Костишин В.Г., Каюмова А.Р., Олицкий В.К., Салогуб Д.В. Радиопоглощающие и радиоэкранирующие характеристики феррит-полимерных композитов Mn-Zn феррит/П (ТФЭ-ВДФ) // Журнал технической физики. 2022. Т. 92. № 3. С. 462–471. https://doi.org/10.21883/JTF.2022.03.52142.242-21.

20. Черкасов В.Д., Щербак Ю.П., Черкасов Д.В. Радиопоглощающие материалы на основе герметика «Абрис» // Строительные материалы и изделия. 2023. Т. 6. № 4. С. 30–41. https://doi.org/10.58224/2618-7183-2023-6-4-30-41.

**Information about the authors / Информация об авторах**



**Aleksey N. Sigaev,**
Student,
Tomsk State University of Control Systems and Radio Electronics,
Tomsk, Russian Federation,
lexa.s.05@mail.ru
https://orcid.org/0009-0007-3163-7046
**Сигаев Алексей Николаевич,**
студент,
Томский государственный университет систем управления и радиоэлектроники,
г. Томск, Российская Федерация,
lexa.s.05@mail.ru
https://orcid.org/0009-0007-3163-7046

**Arthur E. Fedorov,**
Student,
Tomsk State University of Control Systems and Radio Electronics,
Tomsk, Russian Federation,
arturfeodoroff@yandex.ru
https://orcid.org/0009-0008-8433-4564
**Федоров Артур Евгеньевич,**
студент,
Томский государственный университет систем управления и радиоэлектроники,
г. Томск, Российская Федерация,
arturfeodoroff@yandex.ru
https://orcid.org/0009-0008-8433-4564

**Nikita I. Chekh,**
Student,
Tomsk State University of Control Systems and Radio Electronics,
Tomsk, Russian Federation,
wbquit@gmail.com
https://orcid.org/0009-0002-2926-2496
**Чех Никита Иванович,**
студент,
Томский государственный университет систем управления и радиоэлектроники,
г. Томск, Российская Федерация,
wbquit@gmail.com
https://orcid.org/0009-0002-2926-2496

**Daniil E. Kulikov,**
Postgraduate Student,
Tomsk State University of Control Systems and Radio Electronics,
Tomsk, Russian Federation,
✉ daniil1870@mail.ru
https://orcid.org/0009-0002-4524-495X
**Куликов Даниил Евгеньевич,**
аспирант,
Томский государственный университет систем управления и радиоэлектроники,
г. Томск, Российская Федерация,
✉ daniil1870@mail.ru
https://orcid.org/0009-0002-4524-495X

**Afanasiy S. Apkarian,**
Dr. Sci. (Eng.),
Professor of the Department of Radioelectronic Technologies
and Environmental Monitoring,
Tomsk State University of Control Systems and Radio Electronics,
Tomsk, Russian Federation,
Head of the Research and Education Center
of Tomsk State University at the Institute of Strength Physics
and Materials Science, Siberian Branch of the Russian Academy of Sciences,
Panin Institute of Strength Physics and Materials Science,
Siberian Branch of the Russian Academy of Sciences,
Tomsk, Russian Federation,
asa490@mail.ru
https://orcid.org/0009-0000-9107-5232
**Апкарьян Афанасий Саакович,**
доктор технических наук,
профессор кафедры радиоэлектронных технологий
и экологического мониторинга,
Томский государственный университет систем управления и радиоэлектроники,
г. Томск, Российская Федерация,
руководитель Научно-образовательного центра
Томского государственного университета
при Институте физики прочности и материаловедения СО РАН,
Институт физики прочности и материаловедения им. В.Е. Панина СО РАН,
г. Томск, Российская Федерация,
asa490@mail.ru
https://orcid.org/0009-0000-9107-5232

**Contribution of the authors / Вклад авторов**

Aleksey N. Sigaev – writing – original draft.
Arthur E. Fedorov – investigation.
Nikita I. Chekh – investigation.
Daniil E. Kulikov – formal analysis, writing – editing.
Afanasiy S. Apkarian – conceptualization, supervision.

А.Н. Сигаев – написание черновика рукописи.
А.Е. Федоров – проведение исследования.
Н.И. Чех – проведение исследования.
Д.Е. Куликов – формальный анализ, редактирование рукописи.
А.С. Апкарьян – разработка концепции, научное руководство.

**Conflict of interests / Конфликт интересов**

The authors declare no conflict of interests.
Авторы заявляют об отсутствии конфликта интересов.

*The final manuscript has been read and approved by all the co-authors.*
*Все авторы прочитали и одобрили окончательный вариант рукописи.*

**Information about the article / Информация о статье**

The article was submitted 22.05.2026; approved after reviewing 04.06.2026; accepted for publication 15.06.2026.
Статья поступила в редакцию 22.05.2026; одобрена после рецензирования 04.06.2026; принята к публикации 15.06.2026.