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MICROWAVE ABSORBERS BASED ON MÖBIUS STRIP RESONATORS

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Abstract

The paper deals with technology of manufacturing of microwave absorbers with ordered and structured surface layer. This layer contains Möbius strip resonators, located on the fixed distance from each other. The technology was developed by the authors on the base of the following data: 1) results of theoretical study of microwaves interaction with Möbius strip resonator; 2) results of experimental study of electromagnetic radiation reflection, transmission and absorption coefficients in the microwave frequency range of the experimental samples of microwave absorbers based on Möbius strip resonators, which differ by the distance between these resonators. It was established on the base to the listed results that the microwave absorbers manufactured in accordance to the technology proposed by the authors are wide-band ones. Electromagnetic radiation absorption coefficient values of these absorbers changes from 0.5 to 0.97 in frequency range 2.0–17.0 GHz if the distance between the Möbius strip resonators containing in their surface layer, is 15.0 mm. If the distance between the Möbius strip resonators containing in the surface layer of the considered absorbers is less than 15.0 mm their electromagnetic radiation absorption coefficient in the indicated frequency bands is lower than presented values. The considered absorbers are promising for use in shielded rooms and anechoic chambers.

Keywords*:* *aluminum foil, microwave absorber, Möbius strip resonator, reflection, transmission*

Introduction

According to the Google Scholar database ~ 30.0 % of the modern research works in the sphere of electromagnetic materials science deals with the branch, connected with development and study of metamaterials or materials with frequency selective surface. This proportion increases every year (Fig. 1).

It follows from the presented data, that the branch connected with development and study of metamaterials is urgent. The objects of ~ 95.0 % of the research works conducted within the framework of this branch are microwave metamaterials, i.e. metamaterials, reducing the energy of electromagnetic radiation in microwave range. The objects of the remaining 5.0 % of such research works are optical metamaterials.

The urgency of the indicated branch is due to the following advantages of the metamaterials:

1) the possibility to predict by the theoretical modelling the operating frequency bands of the metamaterials [1];

2) the reproducibility of the results of implementing technologies for manufacturing of metamaterials is higher than, for example, technologies for manufacturing of electromagnetic

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radiation absorbers based on powdered or fibrous materials and binders (this is due to the fact that the results of implementation the second of indicated technologies depend on the uniform distribution of powdered or fibrous materials in the volume of binders) [2].

As a rule, microwave metamaterials are characterized by ordered and structured surface, containing the similar plane or volume elements made from electroconductive or dielectric materials [3]. These elements are called resonators. Electromagnetic radiation energy absorption provided by microwave metamaterials is due to the mechanisms of this radiation interaction with the resonators. Such mechanisms are connected with the electrical charge forcing on the resonator surface or with the dielectric (polarization) losses [4].

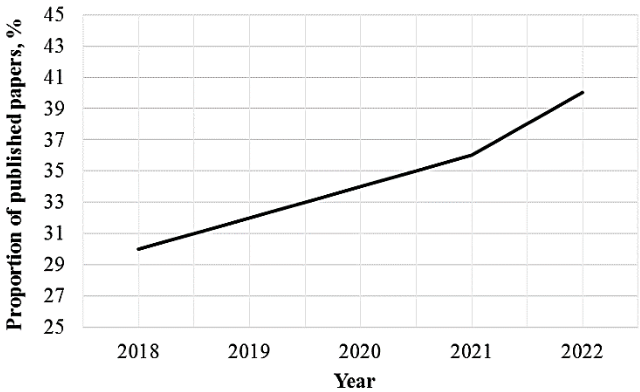

Fig. 1. Proportion of the published papers dealing with microwave absorbers with ordered and structured surface from the published papers dealing with electromagnetic radiation absorbers in 2018–2022

Resonators of modern microwave metamaterials could be characterized by regular (ring, circle, triangle, square et al.) or irregular (fractals, loops et al.) geometric shape [5]. The values of the boundaries of operating frequency bands of the microwave metamaterials are defined by the shape and geometrical parameters of their resonators. These shape and parameters and distance between the resonators define the degree of indicated values dependence from the incidence angle of electromagnetic radiation [6]. Due to this fact the research works conducted within the framework of the branch connected with development and study of microwave metamaterials deal with theoretical or / and experimental substantiation of new shape of the resonators for these materials. Such shape should be the reason of wide operating frequency band and low degree of this band dependence from the incident angle of electromagnetic radiation.

In course of the presented paper preparing the authors have been conducted the research work based on the results of theoretical substantiation of prospectivity of use resonators with Möbius strip shape in different branches, connected with materials and antennas systems development. These results are presented in papers [7, 8]. The aim of the research work conducted by the authors was experimental substantiation of new technology of manufacturing of microwave absorbers with ordered and structured surface layer, containing Möbius strip resonators. To achieve the aim, the following scientific and engineering tasks were solved:

1) the geometrical sizes of the Möbius strip resonators for microwave absorbers manufacturing have been substantiated;

2) the experimental samples of microwave absorbers with ordered and structured surface layer, containing Möbius strip resonators with substantiated geometrical sizes have been made;

3) electromagnetic radiation reflection (S_{11}), transmission (S_{21}) and absorption (A) coefficients in the microwave frequency range of the made experimental samples have been obtained and analyzed;

4) the technology of manufacturing of microwave absorbers based on Möbius strip resonators have been described taking into account the results of the conducted analysis.

Materials and Methods

Möbius strip resonators for the experimental samples making have been formed on the base of foiled polymer film fragments. This film was chosen due to its flexibility and increased strength compared to foil. In course of the foiled polymer film fragments obtaining the following requirements were taken account:

1) the length of each fragment should not exceed one third of wave length at the middle value of frequency range in which it was planned to measure S_{11} and S_{21} values of the manufactured samples;

2) the width of each fragment should not exceed five hundredths of wave length at the middle value of frequency range in which it was planned to measure S_{11} and S_{21} values of the manufactured samples.

The first requirement was based on the results presented in paper [9]. This requirement was taken account in order to provide extended operating frequency band of the absorber compared with its analogs.

The second requirement was based on the results presented in paper [6]. This requirement was taken account in order to minimize the degree of dependence of the values of the boundaries of operating frequency band of the absorber from the incidence angle and polarization of electromagnetic radiation.

The appearance on the Möbius strip resonator formed on the base of foiled polymer film is presented on Fig. 2.

Fig. 2. The appearance on the Möbius strip resonator formed on the base of foiled polymer film

There were two groups of the experimental samples manufactured on the base of Möbius strip resonators formed on the base of foiled polymer film. Experimental samples of every group differed by the number and content of layers. Experimental samples of the first group contained one layer. Experimental samples of the second group contained two layer. The experimental samples of the first group was made by the fixing the Möbius strip resonators formed on the base of foiled polymer film on the cellulose substrate. The first (outer) layer of the experimental samples of the second group was made by the fixing the Möbius strip resonators formed on the base of foiled polymer film on the cellulose substrate. The second layer of the experimental samples of the second group was the fragment of foiled polymer film with the size and width similar to the size and width of cellulose substrate, containing in their first layer. The first and the second layers of the experimental samples of the second group were connected to each other with adhesive tape.

There were there kinds of experimental samples within the framework of every group. Experimental samples of every kind within the framework of defined group differed by the distance between Möbius strip resonators fixed on the cellulose substrate. The distance between Möbius strip resonators fixed on the cellulose substrate was no more than four tenths of wave length at the middle value of frequency range in which it was planned to measure S_{11} and S_{21} values of the manufactured samples. This condition was taken account in order to minimize the degree of dependence of the values of the boundaries of operating frequency band of the sample from the incidence angle and polarization of electromagnetic radiation [6].

Möbius strip resonators fixed on the cellulose substrate were located at an angle of 45° with respect to it. It was shown in paper [8], if Möbius strip resonator is oriented by such way the scattering and absorption losses of the energy of electromagnetic waves, interacting with the resonator, are maximum possible.

The characteristics of the manufactured experimental samples are presented in Table 1.

Table 1. The characteristics of the manufactured experimental samples

The experimental sample designation	The group to which the sample belongs to	Distance between the Möbius strip resonators, mm
Sample 1.1		5.0
Sample 1.2	The first	10.0
Sample 1.3		15.0
Sample 2.1		5.0
Sample 2.2	The second	10.0
Sample 2.3		15.0

Top view of the sample 1.3 is presented on Fig. 3.

S_{11} and S_{21} values of the manufactured experimental samples were measured with use of scalar network analyzer. The measurements were conducted according to method, presented in paper [10]. The measurements were conducted in frequency range 2.0–17.0 GHz. The measurements were conducted in specified frequency range due to the set of the following reasons:

1) spectrum of electromagnetic radiation of the most part of modern radioelectronic devices is associated with this frequency range [11];

2) one of the ways of microwave absorbers use is providing of electromagnetic compatibility of radioelectronic devices;

3) the studied absorbers were considered by the authors from the point of view of the possibility of their use for providing of electromagnetic compatibility of radioelectronic devices.

Fig. 3. Top view of the sample 1.3

Values of the manufactured experimental samples were calculated on the base of measured S_{11} and S_{21} values. The method presented in paper [10] was used for it.

Results and Discussion

Frequency dependences of S_{11} in the range 2.0–17.0 GHz of the samples 1.1, 1.2, 1.3 are presented on Fig. 4.

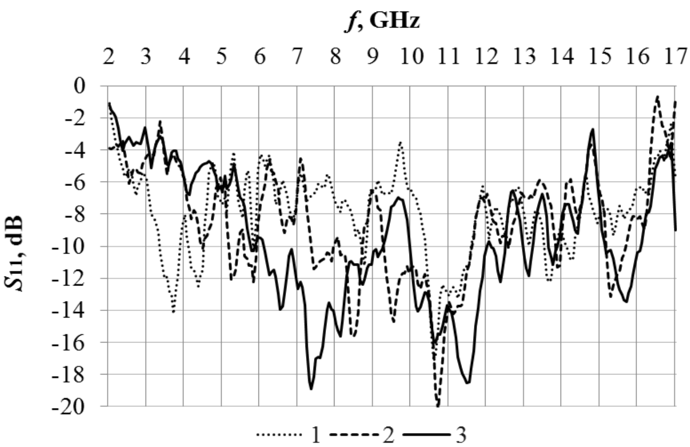

Fig. 4. Frequency dependences of S_{11} values in the range 2.0–17.0 GHz of the samples 1.1 (curve 1), 1.2 (curve 2), 1.3 (curve 3)

As it seen from Fig. 4, S11 values in the frequency range 2.0–17.0 GHz of the sample 1.1 change from –2.0 till –16.0 dB. The values of the considered parameter in the specified frequency range of the sample 1.2 and sample 1.3 change from –2.0 till –20.0 dB.

Table 2 presents the frequency bands of the range 2.0–17.0 GHz, where every from considered samples is characterized by lowest S11 values compared with other studied samples.

Table 2. The frequency bands of the range 2.0–17.0 GHz, where every studied sample (1.1, 1.2 or 1.3) is characterized by lowest S_{11} values compared with other studied ones

Sample name	Frequency band	Frequency band width
Sample 1.1	2.0–5.0 GHz	3.0 GHz
Sample 1.2	5.0–6.0 GHz	1.0 GHz
	8.2–8.6 GHz	0.4 GHz
	9.5–10.0 GHz	0.5 GHz
	10.5–11.0 GHz	0.5 GHz
Sample 1.3	6.0–8.2 GHz	2.2 GHz
	8.6–9.5 GHz	0.9 GHz
	11.0–13.5 GHz	2.5 GHz
	15.0–17.0 GHz	2.0 GHz

As it seen from Table 2, the width of frequency bands, where sample 1.3 is characterized by the lowest S_{11} values compared with sample 1.1 and sample 1.2 is more than the width of frequency bands, where sample 1.1 or sample 1.2 is characterized by the lowest S_{11} values compared respectively with sample 1.2 and sample 1.3 or sample 1.1 and sample 1.3. Moreover the average S_{11} value in the frequency range 2.0–17.0 GHz of the sample 1.3 is equaled to 9.5 dB. This is lower compared with average S_{11} values in the frequency range 2.0–17.0 GHz of the sample 1.1 and sample 1.2 (7.9 dB and 8.5 dB respectively). It might be connected with the set of the following features [12]:

1) sample 1.3 contains the lower quantity of Möbius strip resonators compared with sample 1.1 and sample 1.2;

2) due to the first feature the total amount of “scattering points”(i. e. surface areas scattering the electromagnetic waves) on the surface of the sample 1.3 is lower compared with total amount of “scattering points” on the surface of the sample 1.1 and sample 1.2;

3) due to the second feature the total amount of electromagnetic waves scattered by the sample 1.3 surface is lower compared with the total amount of electromagnetic waves scattered by the sample 1.1 surface and sample 1.2 surface;

4) due to the third feature the superposition of the electromagnetic waves scattered by the sample 1.3 surface and characterized by the similar phase affects to a lesser extent the increase in the energy of the electromagnetic wave reflected from its surface compared with superposition of the electromagnetic waves scattered by the sample 1.1 surface and by sample 1.2 surface and characterized by the similar phase.

Frequency dependences of S_{21} values in the range 2.0–17.0 GHz of the samples 1.1, 1.2, 1.3 are presented on Fig. 5.

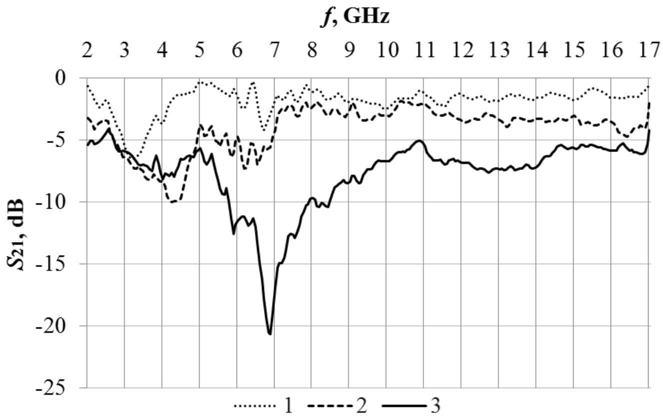

Fig. 5. Frequency dependences of S_{21} values in the range 2.0–17.0 GHz of the samples 1.1 (curve 1), 1.2 (curve 2), 1.3 (curve 3)

As it seen from Fig. 5, S_{21} values of the samples 1.1, 1.2, 1.3 in the frequency range 2.0–17.0 GHz change by the following way respectively: from –1.0 till –7.0 dB, from –3.0 till –10.0 dB, from –5.0 till –20.0 dB. As it also seen from Fig. 5 frequency dependence of S_{21} values in the range 2.0–17.0 GHz of the studied samples are resonant curves. The resonant point of frequency dependence of S_{21} values in the range 2.0–17.0 GHz of the sample 1.1 is 3.2 GHz. The resonant points of frequency dependences of S_{21} values in the range 2.0–17.0 GHz of the sample 1.2 and the sample 1.3 are 4.5 GHz and 7.0 GHz respectively. Frequency dependence of S_{21} values in the range 2.0–17.0 GHz of the sample 1.3 has more bright character compared with frequency dependences of S_{21} values in the range 2.0–17.0 GHz of the sample 1.1 and the sample 1.2. Generally, S_{21} values in the frequency range 2.0–17.0 GHz of the sample 1.3 are lower compared with S_{21} values of the sample 1.1 and the sample 1.2. It could be connected with the fact, that the sample 1.3 absorbs in greater degree the electromagnetic radiation interacting with it that the sample 1.1 and the sample 1.2.

Frequency dependences of S_{11} values in the range 2.0–17.0 GHz of the samples 1.1, 1.2, 1.3 are presented on Fig. 6.

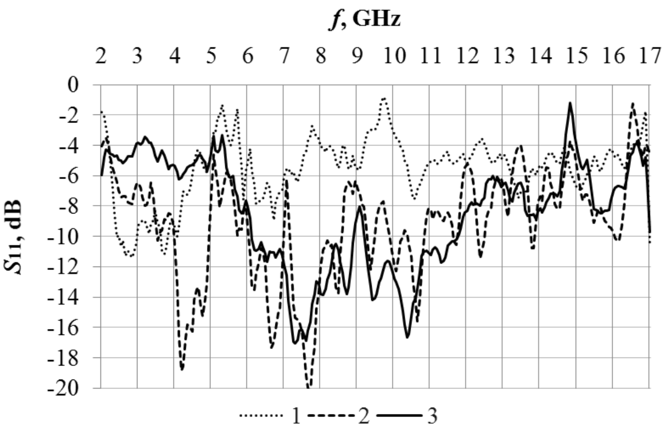

Fig. 6. Frequency dependences of S_{11} values in the range 2.0–17.0 GHz of the samples 2.1 (curve 1), 2.2 (curve 2), 2.3 (curve 3)

As it seen from Fig. 6, S_{11} values in the frequency range 2.0–17.0 GHz of the sample 1.1 change from –2.0 till –11.0 dB. The values of the considered parameter in the specified frequency range of the sample 1.2 and sample 1.3 change from –4.0 till –20.0 dB and from –4.0 till –17.0 GHz. Table 3 presents the frequency bands of the range 2.0–17.0 GHz, where every from considered samples is characterized by lowest S_{11} values compared with other studied samples.

Table 3. The frequency bands of the range 2.0–17.0 GHz, where every studied sample (2.1, 2.2 or 2.3) is characterized by lowest S_{11} values compared with other studied ones

Sample name	Frequency band	Frequency band width
Sample 2.1	2.3–3.5 GHz	1.2 GHz
Sample 2.2	3.5–7.0 GHz	3.5 GHz
	7.5–8.0 GHz	0.5 GHz
Sample 2.3	8.5–12.0 GHz	3.5 GHz

As it seen from Table 2, the width and quantity of frequency bands, where sample 2.2 is characterized by the lowest S_{11} values compared with sample 2.1 and sample 2.3 is more than the width and quantity of frequency bands, where sample 2.1 or sample 2.3 is characterized by the lowest S_{11} values compared respectively with sample 2.2 and sample 2.3 or sample 2.1 and sample 2.2. Moreover the average S_{11} value in the frequency range 2.0–17.0 GHz of the sample 2.2 is equaled to 9.1 dB. This is lower compared with average S_{11} values in the frequency range 2.0–17.0 GHz of the sample 2.1 and sample 1.3 (5.5 dB and 8.5 dB respectively). It might be connected with the fact, that the phase difference between the electromagnetic wave reflected by the surface of the first layer of the sample 2.2 and electromagnetic wave reflected by the surface of its second layers is more than phase difference between the specified electromagnetic waves associated with sample 2.1 and sample 2.3 [13].

Frequency dependences of A values in the range 2.0–17.0 GHz of the samples 1.1, 1.2, 1.3 are presented on Fig. 7.

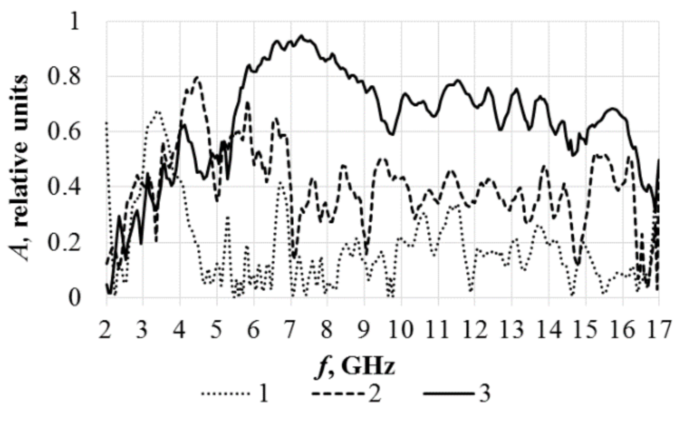

Fig. 7. Frequency dependences of A values in the range 2.0–17.0 GHz of the samples 1.1 (curve 1), 1.2 (curve 2), 1.3 (curve 3)

As it seen from Fig. 7, *A* values in the frequency range 2.0–17.0 GHz of sample 1.1 change from 0.01 till 0.65. The values of the considered parameter in the specified frequency range of sample 1.2 and sample 1.3 change respectively from 0.01 till 0.8 and from 0.01 till 0.9.

Table 4 presents the information about parameters of effective absorption bands of the considered samples.

Table 4. Effective absorption bands parameters of the samples 1.1, 1.2, 1.3

Sample name	Effective absorption band	Effective absorption band width
Sample 1.1	3.0–3.5 GHz	0.5 GHz
Sample 1.2	4.0–4.5 GHz	0.5 GHz
	6.5–7.0 GHz	0.5 GHz
Sample 1.3	4.0–16.0 GHz	12.0 GHz

As it seen from Table 4, sample 1.1 and sample 1.2 are narrow bands microwave absorbers, sample 1.3 is wide band microwave absorber.

Frequency dependences of *A* values in the range 2.0–17.0 GHz of the samples 2.1, 2.2, 2.3 are presented on Fig. 8.

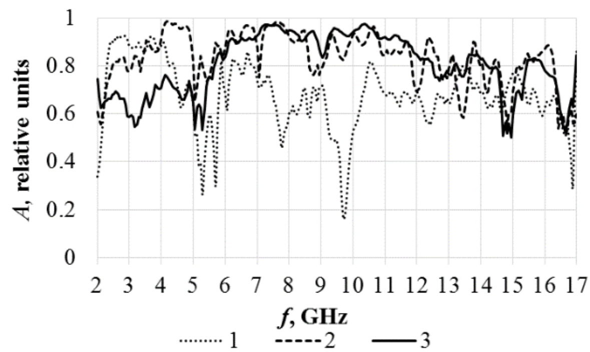

Fig. 8. Frequency dependences of *A* values in the range 2.0–17.0 GHz of the samples 2.1 (curve 1), 2.2 (curve 2), 2.3 (curve 3)

As it seen from Fig. 8, *A* values in the frequency range 2.0–17.0 GHz of sample 2.1 change from 0.25 till 0.9. The values of the considered parameter in the specified frequency range of sample 2.2 and sample 2.3 change respectively from 0.01 till 0.8 and from 0.5 till 0.95.

Table 5 presents the information about parameters of effective absorption bands of the considered samples.

Table 5. Effective absorption bands parameters of the samples 2.1, 2.2, 2.3

Sample name	Effective absorption band	Effective absorption band width
Sample 2.1	2.0–5.0 GHz	3.0 GHz
	5.8–9.5 GHz	3.7 GHz
	10.0–16.5 GHz	6.5 GHz
Sample 2.2	2.0–16.5 GHz	14.5 GHz
Sample 2.3	2.0–17.0 GHz	15.0 GHz

As it seen from Table 5, sample 2.1 is narrow bands microwave absorber, sample 2.2 and 2.3 are wide band microwave absorbers.

The authors propose the following technology of manufacturing of 2.0–17 GHz microwave absorbers based on Möbius strip resonators taking into account the obtained research results.

Step 1. Forming the cellulose substrate the shape and size of which correspond to the shape and size of the manufactured absorber.

Step 2. Obtaining the foiled polymer film fragments taking into account the following requirements:

– the length of each fragment should not exceed one third of wave length at the middle value of operating frequency band of the manufactured electromagnetic radiation absorber;

– the width of each fragment should not exceed five hundredths of wave length at the middle value of operating frequency band of the manufactured electromagnetic radiation absorber.

Step 3. Forming the Möbius strip resonators on the base of the obtained fragments (Step 2).

Step 4. Fixing the formed Möbius strip resonators (Step 3) on the one surface of the formed cellulose substrate (Step 1) taking into account the following requirement:

– step of Möbius strip resonators fixing should be 15.0 mm.

Step 5. Forming the foiled polymer film fragment the shape and size of which correspond to the shape and size of the manufactured absorber.

Step 6. Fixed formed foiled polymer film fragment (Step 5) on the surface of cellulose substrate, where Möbius strip resonators were not fixed in course of Step 4 implementation.

Microwave absorbers manufactured in accordance to the presented technology are characterized by wider effective absorption band compared with analogs (see Table 6).

Table 6. Effective absorption band parameters of the absorber manufactured in accordance to the proposed technology and its analogs

Absorber name	Effective absorption band	Effective absorption band width
Absorber manufactured in accordance to the presented technology	2.0–17.0 GHz	15.0 GHz
Metamaterial based on split ring resonator [14]	1.0–10.0 GHz	9.0 GHz
Metamaterial based on square split-ring resonator [15]	1.4–1.6 GHz	0.2 GHz
	4.8–5.2 GHz	0.4 GHz
	5.8–6.2 GHz	0.4 GHz
Metamaterial with symmetric square shaped structure [16]	3.5–4.0 GHz	0.5 GHz
	5.6–6.0 GHz	0.4 GHz
	6.8–7.2 GHz	0.4 GHz
	11.6–12.0 GHz	0.4 GHz
	17.6–18.0 GHz	0.4 GHz
Metamaterial with symmetric left-handed square shaped structure [17]	5.5–7.3 GHz	1.8 GHz
	9.0–11.4 GHz	2.4 GHz
	13.5–13.6 GHz	0.1 GHz

Conclusion

Microwave absorbers in the form of Möbius strip resonators fixed on the cellulose substrate are characterized by the best absorption properties (the widest effective absorption band

(12.0 GHz), the highest maximum value of electromagnetic radiation absorption coefficient in the effective absorption band (0.95)) when the distance between these resonators is 15.0 mm.

Two-layer microwave absorbers in the form of Möbius strip resonators fixed on the cellulose substrate (outer layer) and containing fragment of foiled polymer film (inner layer) are also characterized by the best absorption properties when the distance between the indicated resonators is 15.0 mm. It's necessary to stress that effective absorption band of these absorbers is wider on 3.0 GHz than effective absorption band of the absorbers in the form of Möbius strip resonators fixed on the cellulose substrate. The maximum value of electromagnetic radiation absorption coefficient in the effective absorption band of the first ones are greater on 0.02 than maximum value of electromagnetic radiation absorption coefficient in the effective absorption band of the second ones. Due to this fact the proposed technology is targeted for manufacturing of two-layer microwave absorbers.

Microwave absorbers manufactured in accordance to the proposed technology are promising for use in shielded rooms and anechoic chambers to solve the problems of radioelectronic equipment protection from electromagnetic radiation impact (including the problems of electromagnetic compatibility).

References

[1] Z. Hou, T. Tang, J. Shen, F. Li, F. Li, *Prediction Network of Metamaterial with Split Ring Resonator Based on Deep Learning,* **Nanoscale Res Let, 15**, 2020, p. 83, https://doi.org/10.1186/s11671-020-03319-8

[2] K. Bi, Q. Wang, J. Xu, L. Chen, C. Lan, M. Lei, *All-Dielectric Metamaterial Fabrication Techniques*, **Advanced Optical Materials, 9(1)**, 2021, p. 2001474

[3] T.J.Cui, *Microwave metamaterials*, **National Science Review**, **5(2),** 2018, pp. 134–136, https://doi.org/10.1093/nsr/nwx133

[4] A.D. Boardman, K. Marinov. *Electromagnetic energy in a dispersive metamaterial*, **Phys. Rev. B**, **73**, 2006, p. 165110, https://doi.org/10.1103/PhysRevB.73.165110

[5] P. Kaushik, *Review on Design of Frequency Selective Surfaces*, **International Journal of All Research Education and Scientific Methods**, **8(5)**, 2020, pp. 75–85

[6] A. Singh, *Quad-Band FSS for Electromagnetic Shielding***, International Journal of Computer Communication and Informatics**, **3(1)**, 2021, pp. 1–14

[7] U.L. Rohde, *Mobius Strips and Metamaterial Symmetry: Theory and Applications*, **Microwave Journal**, **57(11)**, 2014, pp. 76–88

[8] J.K. Hamilton, *Absorption modes of Möbius strip,* **Scientific Reports, 11,** 2021, p. 9045, https://doi.org/10.1038/s41598-021-88280-x

[9] Y. Liu, L. Shafai, D. Isleifson, C. Shafai, *Split Ring Antennas and Their Application for Antenna Miniaturization,* **Sensors, 23**, 2023, p. 846, https://doi.org/10.3390/s23020846

[10] O. Boiprav, H. Ayad, S.A. Abdaljlil, L. Lynkou, M. Abdulmawlay, *Charcoal- and Foil-Containing Materials for Radio Electronic Control Systems Protection from Electromagnetic Interferences*, **IEEE 21st international Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA)**, Sousse, Tunisia, 19–21 December 2022, pp. 299–304, https://doi.org/10.1109/STA56120.2022.10019059

[11] H. Urbancokova, S. Kovar, O. Halaska, J. Valouch, *Immunity of electronic devices against radio-frequency electromagnetic fields*, **MATEC Web of Conferences CSCC**, **125**, 2017 p. 02039. https://doi.org/10.1051/matecconf/201712502039

[12] L. Zheng, C. Wang, J. Lu, A. Sun, *Application of the Reciprocity Theorem to Scattering of Surface Waves by a Surface Crack in Viscoelastic Material,* **Appl. Sci., 12,** 2022, p. 10785, https://doi.org/10.3390/app122110785

[13] J. Baker-Jarvis, S. Kim *The Interaction of Radio-Frequency Fields With Dielectric Materials at Macroscopic to Mesoscopic Scales*, **J Res Natl Inst Stand Technol, 117,** 2012, pp. 1-60

[14] V. Sharma, S.S. Pattnaik, T. Garg, S. Devi. *A microstrip metamaterial split ring resonator*, **International Journal of the Physical Sciences, 6(4)**, 2011, pp. 660-663, https://doi.org/10.5897/IJPS10.572

[15] M.L. Hakim, M.T. Islam, T. Alam, S.K. Abdul Rahim, B. Bais, M.S. Islam, M.S. Soliman, *Triple-Band Square Split-Ring Resonator Metamaterial Absorber Design with High Effective Medium Ratio for 5G Sub-6 GHz Applications*, **Nanomaterials (Basel), 13(2)**, 2023, p. 222

[16] T. Ramachandran, M.R.I. Faruque, M.T. Islam, *Symmetric square shaped metamaterial structure with quintuple resonance frequencies for S, C, X and Ku band applications,* **Scientific Reports**, **11**, 2011, p. 4270, https://doi.org/10.1038/s41598-021-83715-x

[17] T. Ramachandran, M.R.I. Faruque, M.T. Islam. *A compact square-shaped left-handed passive metamaterial with optimized quintuple resonance frequencies for satellite applications*, **Chinese Journal of Physics, 67,** 2020, pp. 360–375, https://doi.org/10.1016/j.cjph.2020.06.024.

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