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Broadband shielding screens for microwave range: measurement of characteristics

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Abstract

Radio-electronic devices are used in all areas of our life. Many of these emit energy, and this radiation can adversely affect human. In warfare, a critical challenge is the protection of personnel and equipment from detection by radar systems and range finders. Therefore, the issue of shielding screens against electromagnetic radiation is of utter importance.

For this purpose, materials that absorb and reflect electromagnetic radiation are used. This paper describes microwave-range shielding screens that are based on the effect of strong absorption of radiation in conductors, the diameters of which are much smaller than the wavelength. The absorption efficiency factor of conductors with diameters of several micrometres in the centimetre and millimetre wavelength ranges can reach hundreds or thousands. It has also been found that the absorption of these conductors remains constant across a wide frequency range – from several hertz to tens of gigahertz. Measurements of the characteristics of such screens were performed in the frequency from 2 to 40 GHz. The screens included segments of graphite fibres with 12–15 μm in diameter, randomly distributed on the film. The complex impedance of the screens in the frequency range of 9–12 GHz was also determined. The experiments confirmed the effectiveness of using thin conductors in shielding screens and demonstrated their broadband performance.

Keywords: electromagnetic radiation; shielding screens; thin conductors; absorption; transmission; reflection; measurement.

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Introduction

We are surrounded by electromagnetic fields – both natural (lightning, solar radiation, stellar and cosmic emissions) and artificial (radio stations, radar systems, industrial facilities, computers, and household devices). In many of the cases, it becomes necessary to introduce barriers to the electromagnetic radiation to protect human life and health, to conceal personnel and equipment, and to address numerous other practical needs.

When working with transmitting devices, wearing of protective clothing is sometimes required. As RF technologies continue to advance in the areas such as mobile communications, computer networks, and military applications, the number of personnel to be protected is steadily increasing.

Military equipment shall be protected from detection by radio engineering systems. In many of the cases, it is desirable for radiation to be strongly absorbed, since reflected waves may negatively affect the environment and human health. However, in concealing applications, it is sometimes necessary for a portion of the radiation to be reflected, creating a natural background consistent with the surrounding environment. Otherwise, the concealed object would appear as a “dark spot”. Therefore, a critical challenge is the development of shielding screens with predetermined reflection and absorption characteristics.

Absorbing screens are generally divided into two types – volumetric and surface screens. Volumetric screens use media with relatively low electrical conductivity, often based on carbon or graphite. By selecting an appropriate screen thickness – typically several centimetres – it is possible to achieve strong absorption and low reflection over a wide frequency range. However, the substantial thickness of such screens is a major disadvantage. They are mainly used for shielding large objects that can be enclosed with absorber blocks several centimetres thick.

Surface screens are produced in the form of films or fabrics containing radiation-absorbing fibres or small conductive particles. Such surfaces can be used to protect people or equipment of relatively small size, which is significantly advantageous over volumetric screens. However, it is much more difficult to ensure uniform absorption across a wide frequency range in such structures. Their frequency response is almost always non-uniform.

In [1, 2], an absorber that extends the operational bandwidth of the well-known microwave Salisbury Screen (SS) is described. Fig. 1 shows the variation of the screen reflection over the frequency range from 2 to 18 GHz.

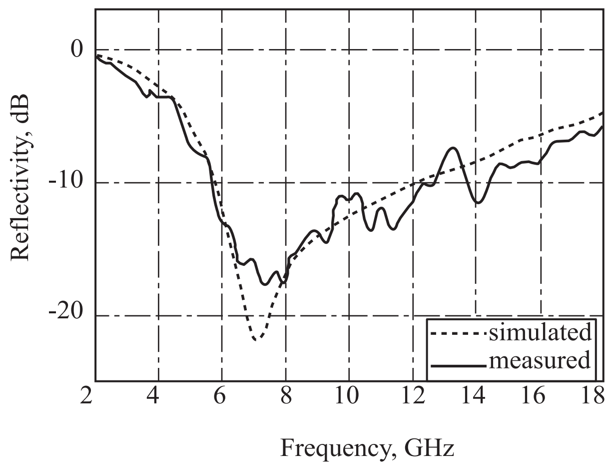


Fig. 1. Reflection from a screen with a microwave absorber SS [1]

A well-known device is the resonant microwave absorber, the Salisbury Screen (SS) [3]. It includes a resistive screen positioned a quarter wavelength above a conductive surface, separated by a dielectric spacer. Several structures have been proposed to overcome the main drawback of the Salisbury Screen – the strong frequency dependence of its attenuation [4–6]. These methods involve using periodic structures, such as a frequency-selective surface (FSS) [4] or an electromagnetic bandgap (EBG) [5]. However, these approaches do not significantly improve the screen performance.

In [6], various methods for microwave shielding at mobile communication frequencies – 950, 1850, 2150, and 2650 MHz – were tested. Saltwater was applied to a paper layer, and the paper layers were separated from each other by films. The sample consisted of 10 layers.

The measurement results implied that the salt solution imparts the paper with fairly good radio-frequency shielding properties (Fig. 2). Reflection losses decrease with each additional layer of salt-treated paper, reaching 4–6.5 dB in the ten-layer sample. Paper impregnated with salt solution demonstrated its ability to provide effective shielding at frequencies used in mobile communications. The drawback of this method is the use of materials that require constant moisture maintenance.

In [7], a system for measuring microwave absorption in the frequency range from 700 MHz to 13 GHz was developed. The tested materials included conductive paints on fabrics, conductive fabrics, and metallic meshes. Both conductive paints and conductive fabrics exhibited high absorption. Conductive paints can be applied directly to the surface of an object to create effective shielding. However, the paint is heavy and increases the overall weight of the object. Moreover, paints make flexible materials rigid. Metallic meshes and screens are also effective, albeit heavy and difficult to deploy on an object. Several of the lighter meshes are easier to handle, yet they still require a supporting structure to hold the screen material in place. Conductive fabrics are preferable, as they are lightweight and easy to deploy. They can also be easily removed for transportation to another location.

In all the above cases, the frequency response of the screens is non-uniform, which is a significant drawback.

Thus, the task of developing shielding screens for the microwave range of electromagnetic waves, particularly for military applications, remains relevant.

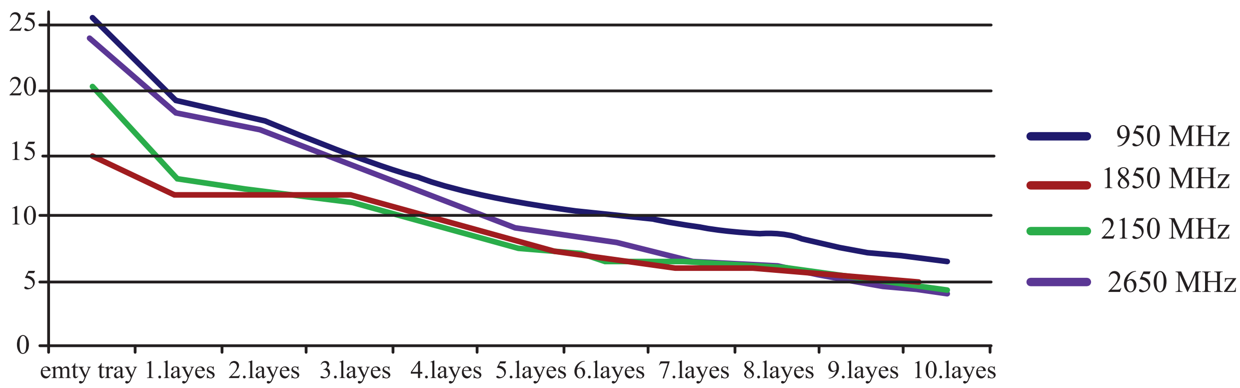


Fig. 2. Reflection losses in paper treated with salt solution [6]

At the same time, the complexity of this problem is evident. Achieving a uniform attenuation characteristic over a wide frequency range is challenging, as illustrated by the examples discussed above.

In this paper, a novel approach to addressing this challenge is presented. Shielding screens based on thin conductors – metallic or graphite fibres with diameters ranging from a few micrometres to several tens of micrometres – are proposed. In the metre, centimetre, and millimetre wavelength ranges, these fibres exhibit strong absorption of electromagnetic radiation.

1. Theory

The efficiency of radiation absorption and scattering by objects depends on the ratio between their characteristic size D and the wavelength λ of the incident radiation. Typically, the maximum interaction of radiation with a fibre occurs at $D/\lambda \approx 1$ [8, 9]. However, studies describe the phenomenon of uncommonly strong absorption and scattering of microwave radiation by thin conductors, the diameters of which are several hundred times smaller than the wavelength of the incident radiation. The absorption efficiency factor for such microconductors can reach values of several hundreds or even thousands. Fig. 3 shows the dependence of the absorption efficiency factor of a graphite fibre on its diameter for different wavelengths.

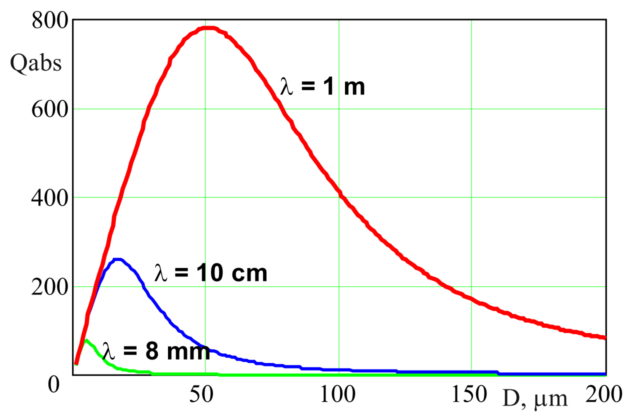


Fig. 3. Absorption efficiency factor of a graphite fiber

The absorption efficiency factor $Qabs = Pabs / P$ is defined as the ratio of the radiation power $Pabs$ absorbed by the fibre to the incident power P falling on it. The absorbed power $Pabs$ can be much greater than the incident power P because, close to the fibre, the energy flow lines are distorted, resulting in more radiation incident on the fibre than determined by geometric optics (Fig. 4).

For certain values of D/λ, a maximum in absorption occurs. The conditions for this maximum are considered in [10, 11]. It was found that the absorption reaches its peak when

$$D/\lambda_i \approx 0.1,$$

where λ_i is the wavelength in the material, that is, when the diameter of the conductor is much smaller than the wavelength.

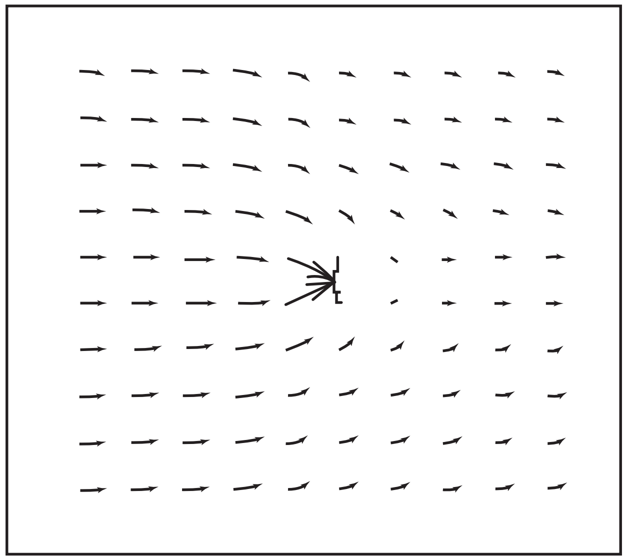


Fig. 4. Energy flux lines near a thin fiber

The effect occurs when the electric field vector of the incident wave is parallel to the fibre axis (E-wave). In the case of an H-wave, the absorption efficiency factor is minimal.

The maximum absorption in metals occurs at tiny wire diameters – fractions of a micrometre. This poses challenges when using metallic fibres. Therefore, it is more practical to use graphite fibres. Although their peak absorption is lower than that of metallic fibres, at diameters of several tens of micrometres, their absorption is significantly higher than that of metallic conductors.

Another factor demonstrating the effectiveness of using thin conductive fibres in microwave-range shielding is the uniformity of their absorption across a wide frequency range.

Fig. 5 shows the frequency dependence of the absorption efficiency factor of a graphite fibre. From extremely low frequencies up to a certain cut-off frequency, the absorption remains nearly constant, after which it decreases. The cut-off frequency depends on the fibre diameter: it shifts toward higher frequencies as the diameter decreases, but at the same time, the overall absorption decreases. Thicker fibres exhibit stronger absorption, but the flat region of the frequency response is smaller compared to thinner fibres.

2. Measurements of screen parameters and characteristics

Three screen samples were studied. Their photographs are shown in Fig. 6. The base of each screen is cardboard of 0.5 mm thick. On this base, segments of graphite fibre with diameters of 12–15 μm and lengths of 1–3 mm are randomly arranged.

The surface density of fibres on the screens is lowest for Screen 1 and highest for Screen 3.

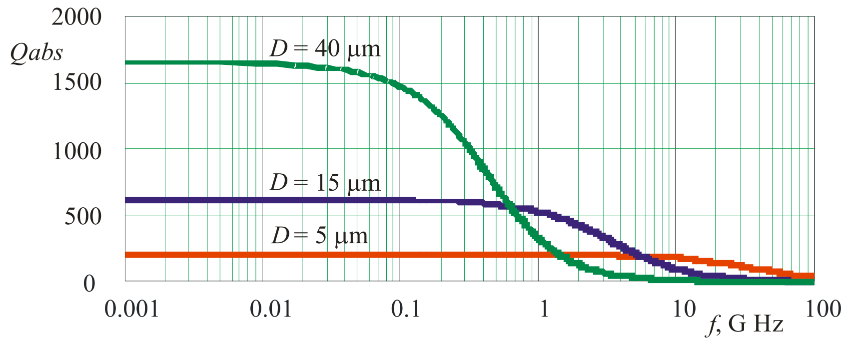
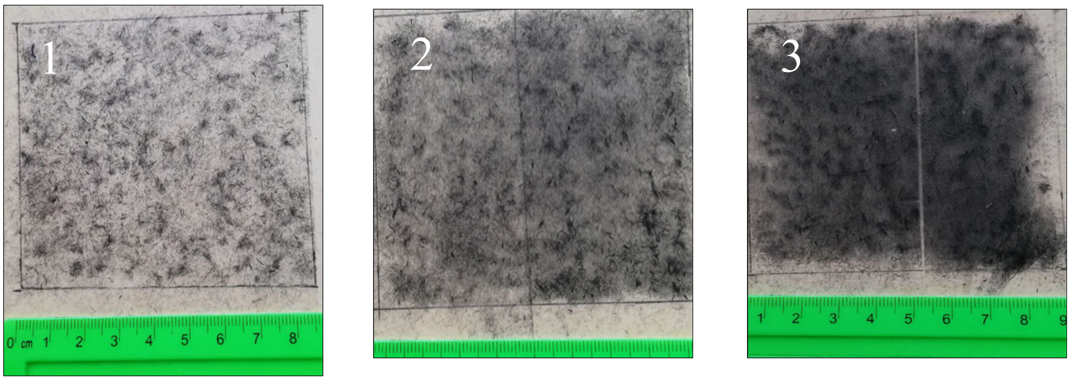


Fig. 5. Absorption in graphite fibers of different diameters



Screen 1 — Screen 2 — Screen 3

Fig. 6. Shielding screens

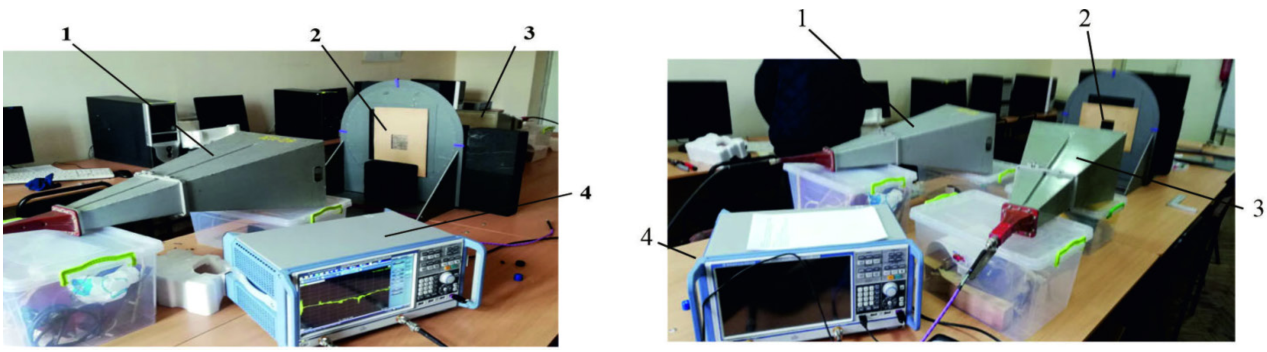


Fig. 7. Measuring of transmission and reflection: 1 – transmitting horn, 2 – screen, 3 – receiving horn, 4 – control unit

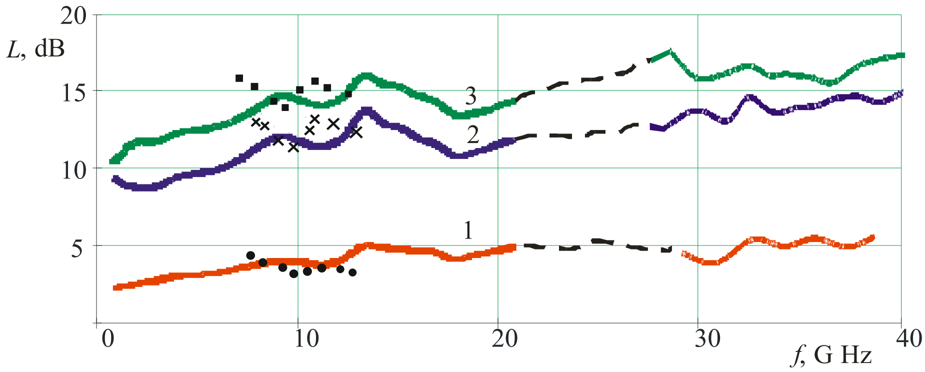


Fig. 8. Attenuation of radiation by the screens, 1, 2, 3 are screen numbers

2.1. Transmission and reflection

Transmission and reflection measurements of the screens were performed using three experimental setups:

- In the frequency range from 2 to 40 GHz on a broadband setup “Vector Network Analyzer ZMB-40”, Rohde & Schwarz (Fig. 7).
- In the frequency range from 9 to 12 GHz on a setup with a klystron generator.

The results of the attenuation measurements are shown in Fig. 8.

One can see that attenuation across the entire frequency range from 2 to 40 GHz varies only slightly, which confirms the suggestion of uniform screen characteristics. The oscillations observed in the graphs are caused by wave interference in the gaps between the screen and the transmitting and receiving horns. One discrepancy between theory and experiment is that the attenuation of radiation by the screens increases with frequency, whereas theoretically, as shown in Fig. 5, it should decrease. A possible reason for this is that the calculations were performed for infinitely long fibres, whereas in the experiment their length was comparable to the wavelength of the radiation. This leads to certain resonant effects, modifying the interaction of the radiation with the object [12, 13]. This issue is to be further studied.

The results of the reflection measurements are shown in Fig. 9. One can see that, across the frequency range from 2 to 40 GHz, the reflection for each screen varies only slightly.

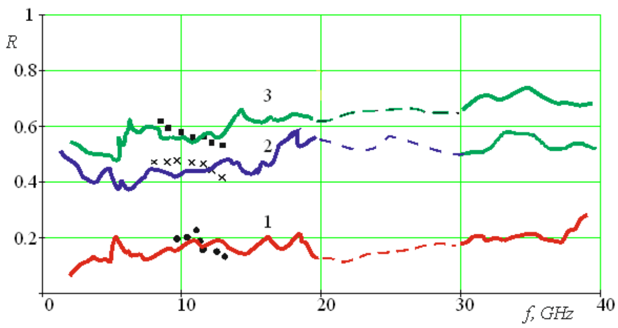


Fig. 9. Reflection of radiation by the screens, 1, 2, 3 are screen numbers

Average attenuation values across the entire frequency range are

$$L_1 = 3.9 \text{ dB}, \quad L_2 = 10.0 \text{ dB}, \quad L_3 = 11 \text{ dB}.$$

Average values of the transmission coefficients are

$$T_1 = 0.41, \quad T_2 = 0.10, \quad T_3 = 0.08.$$

Average values of the reflection coefficients are

$$R_1 = 0.18, \quad R_2 = 0.37, \quad R_3 = 0.45.$$

The formula for the transmission coefficient can be expressed as follows:

$$T = (1-R)(1-K),$$

where K is the absorption coefficient.

From this, it follows that the absorption coefficient of the screen for the incident radiation power can be determined using the formula

$$K = 1 - \frac{T}{1-R}.$$

Substituting the values of transmission and reflection into this formula, one has:

$$K_1 = 0.59, \quad K_2 = 0.90, \quad K_3 = 0.95.$$

It can be seen that a thin screen can absorb a large amount of incident radiation power.

The setup for measuring the characteristics of the screens in the frequency range from 9 to 12 GHz is shown in Fig. 10.

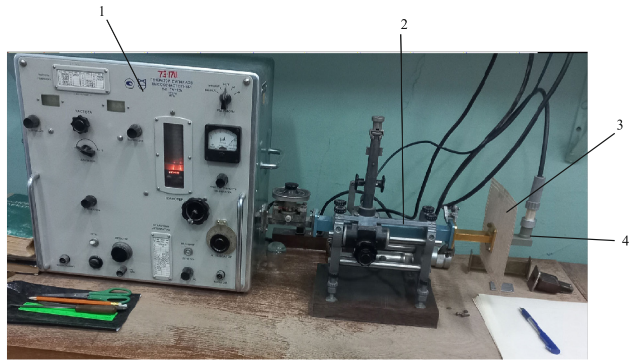


Fig. 10. Experimental setup (9–12 GHz)
1 – generator, 2 – measurement line, 3 – screen, 4 – detector section

The radiation source is the klystron-based generator 1. The generator operates in the frequency range of 8.85–12.09 GHz, with an output power of 10–30 mW. The generator output is a waveguide with cross-sectional dimensions of 23×10 mm. The radiation passes through the measurement line 2, the test screen 3, and is absorbed by a matched load or the detector section 4.

The signal P_0 was measured from the detector section in the absence of the screen, the signal P in the presence of the screen, and the standing wave ratio r in the path with the screen adjusted. Using these data, the screen transmission coefficient $T = P / P_0$ and reflection coefficient $R = \left(\frac{r-1}{r+1}\right)^2$ were determined.

The measurement results are shown as points in Figs. 8 and 9. They are in good agreement with previously obtained data. Some discrepancies can be explained by the fact that some measurements belong to free space, while others relate to the waveguide volume.

2.2. Dependence of the screen transmission on the angle of the radiation incidence

This characteristic is essential because in real conditions, radiation can fall on the screen from different sides.

Measurements were performed in the frequency range of 28–40 GHz.

Fig. 11 shows the dependence of attenuation in screens 1 and 2 on the angle of incidence of the radiation. The characteristic for screen 3 is close to that of screen 2. Measurement errors are indicated. One can see that the increase in absorption with increasing angle of incidence exceeds the measurement errors and represents a real physical phenomenon.

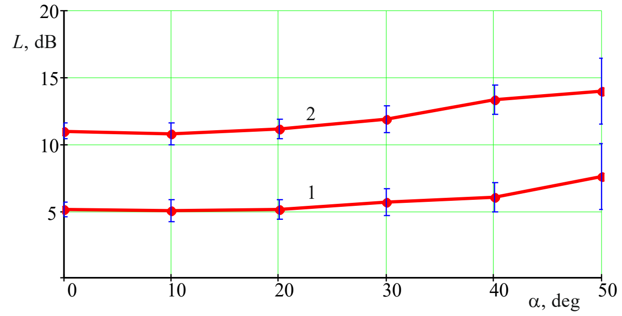


Fig. 11. Dependence of attenuation on the angle of incidence of radiation 1, 2 – screen numbers

A slight increase in absorption with an increasing angle of incidence can be explained by the fact that, at oblique incidence, some segments of the screen are aligned along the propagation direction of the radiation. The absorption efficiency factor of these segments increases as does the angle of incidence, which is demonstrated in [14]. The increase is small because a sharp rise in absorption occurs only when the radiation strikes the segment at a grazing angle (incidence angles greater than 85°).

2.3. Complex impedance of screens

The complex impedance of microwave devices is an essential parameter. It determines the ability of the devices to match with energy transmission lines or with free space.

The scheme of the measurement setup is shown in Fig. 12.

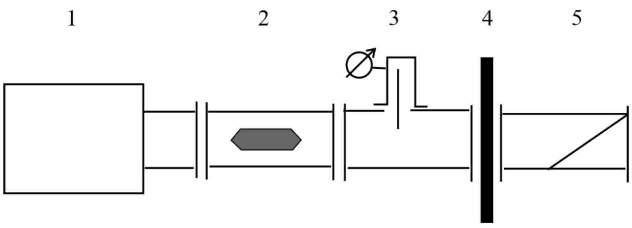


Fig. 12. Block-scheme of complex impedance measurement of the screen, 1 – generator, 2 – matching attenuator, 3 – measurement line, 4 – screen, 5 – load

During the measurements, the output of the measurement line was initially terminated with a metal short-circuit plate. The wavelength in the waveguide λ_w was determined as double distance between adjacent standing wave nodes. The position of one minimum was recorded as the reference end of the measurement line. Then, the screen (4) and the load (5) were adjusted in the place of the plate, and the minimum displacement $d_{\min}$ and the standing wave ratio r were measured. The displacement toward the generator was considered positive.

The complex impedance Z is determined using the formula

$$Z = \frac{r + i\left(r^2 - 1\right)\sin\left(\beta d_{\min}\right)\cos\left(\beta d_{\min}\right)}{\sin^2\left(\beta d_{\min}\right) + r^2\cos^2\left(\beta d_{\min}\right)},$$

where $\beta = 2\pi/\lambda_w$, $i = \sqrt{-1}$.

The complex impedance Z is normalized to the characteristic impedance of the waveguide,

$$Z_w = 120\pi \Big/ \sqrt{1 - \left(\frac{\lambda_0}{\lambda_{kp}}\right)^2},$$

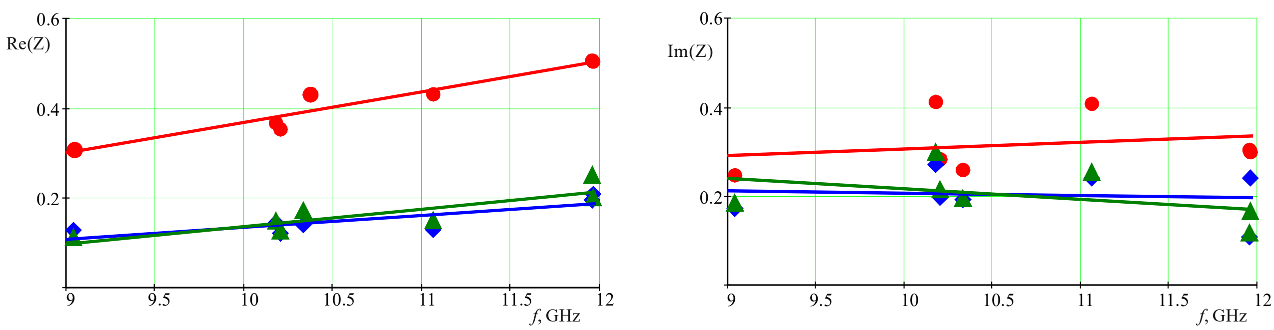
where λ_0 is a wavelength in free space, λ_{kp} is a cut-off wavelength in the waveguide.

Measurements of the complex impedance of the screens were performed in the frequency range from 9 to 12 GHz. Fig. 13*a* shows the dependence of the screen resistive impedance on frequency. The upper curve corresponds to Screen 1, while the lower curves correspond to Screens 2 and 3. Screens 2 and 3 have a higher density of graphite segments than Screen 1, resulting in lower surface resistance. In all three screens, the resistive component increases with the frequency.

The reactive impedance of Screen 1 is also higher than that of Screens 2 and 3 (Fig. 13*b*). However, its frequency dependence falls within the measurement error, so no definitive conclusion about this trend can be made.

Conclusions

1. A relevant task is the development of screens to protect people and equipment from the effects of electromagnetic radiation.



a *b*

Fig. 13. Resistive (*a*) and reactive (*b*) components of the screen complex impedance

2. Microwave-range shielding screens are proposed, which account for the effect of strong radiation absorption in thin conductive fibres.

3. The advantage of such screens is a uniform absorption characteristic across a rather wide frequency range.

4. Measurements of the shielding screen characteristics were performed in the frequency range from 2 to 40 GHz.

5. The measurement results confirmed the feasibility of creating broadband screens with the specified parameters.

Широкосмугові захисні екрани мікрохвильового діапазону. Вимірювання характеристик

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Анотація

Радіоелектронні пристрої застосовуються у всіх галузях нашого життя – науці, техніці, зв’язку, освіті та ін. Багато з них (мобільні телефони та ретранслятори для них, комп’ютери, радіомовні та радіолокаційні станції тощо) випромінюють електромагнітну енергію в навколишнє середовище. Це випромінювання може погано впливати на здоров’я людей, перешкоджати правильній роботі інших електронних приладів. У військовій справі актуальною є проблема захисту людей і техніки від виявлення їх радіолокаційними станціями, радіопеленгаторами, далекомірами. Тому існує проблема захисту від електромагнітного випромінювання. Для цього використовуються різні захисні екрани. Вони поглинають або відбивають електромагнітне випромінювання. У статті описуються захисні екрани мікрохвильового діапазону, які використовують ефект сильного поглинання випромінювання в провідниках, діаметр яких значно менший від довжини хвилі. Фактор ефективності поглинання провідників діаметром кілька мікрометрів у сантиметровому й міліметровому діапазонах досягає сотень і тисяч. Встановлено також факт, що поглинання таких провідників однакове в діапазоні частот від одиниць герц до десятків гігагерц.

Описано вимірювання характеристик таких екранів у діапазоні частот від 2 до 40 ГГц. В екранах застосовувались відрізки графітових волокон діаметром 12–15 мкм, хаотично розташованих на папері або поліетиленовій плівці. Вимірювалось пропускання і відбивання випромінювання при різних кутах падіння хвилі на екран. У діапазоні частот від 9 до 12 ГГц проведені вимірювання комплексного опору екранів. Експерименти підтвердили ефективність застосування в екранах тонких провідників і широкосмуговість таких пристроїв. Важливим є також те, що такі екрани мають малу товщину і можуть бути гнучкими, вони легкі, технологічні та недорогі. Їхні характеристики можуть бути задані до виготовлення.

Ключові слова: електромагнітне випромінювання; захисні екрани; тонкі провідники; поглинання; пропускання; відбивання; вимірювання.

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