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New possibilities for the measurements of shielding effectiveness using a flanged coaxial transmission line

Jarosław M. Janukiewicz, Tadeusz W. Więckowski

***Abstract*—This paper demonstrates the feasibility of increasing the measurement frequency range of material shielding effectiveness using the flanged coaxial transmission line. Furthermore, the authors presented their original solutions of measurement adapters and an analysis of the properties and measurement parameters of these adapters. A modification of the test stand was proposed, which will facilitate measuring samples in a wider frequency range and of much larger sizes. The authors also demonstrated modified methods for calibrating the test stands and measuring the shielding effectiveness of various materials, including thick materials.**

***Keywords*—shielding; measurement methods**

Introduction

THE extent to which societies depend on information transmission, storage and processing systems is rapidly growing and will undoubtedly continue to grow in the future. The above dependance is expected to be even greater with the increasing use of artificial intelligence algorithms. Therefore, issues related to the reliability and security of such systems are becoming particularly important, as they have an impact on the functioning of all societies. While issues related to cybersecurity are already prioritized in research, issues concerning the security and reliability of devices and installations that employ such solutions are not given similar attention. Although the EMC and RED directives help ensure that devices and installations do not interfere with each other, their requirements have proved to be insufficient in the case of deliberate actions.

Regarding such systems, the proper level of reliability and security is achieved not only through appropriate software solutions, with a particular emphasis on encryption techniques, but also through the protection of such systems, especially against intentionally generated electromagnetic disturbances (causing interference or damage) or against the undesirable electromagnetic emanations that allow the intercepting of processed or transmitted information. Such protection requires adequate hardware solutions, primarily shielding, as well as the implementation of appropriate filters and a well-designed earthing installation. The effectiveness of a shielding installation is the sum of a number of appropriate components and adjustments, such as design and assembly, filters and insulators, adapters, ventilation installation, and most important a material of adequate shielding effectiveness. The effectiveness of the shielding material depends not only on its electrical parameters (conductivity, electrical permittivity and magnetic permeability), but also on its thickness and structure. As shielding materials can have different structures (in the case of multi-layer shields each layer may have different electrical parameters), the most reliable, and on occasions the only method for identifying shielding effectiveness, is through measurements.

Measurements of shielding effectiveness can be defined as the ratio of the power received before shielding to the power received when an indefinitely large shielding barrier is introduced between the source of the electromagnetic field and the receiver. Practically all measurement methods are based on this definition. Measurements of shielding effectiveness were first performed by adapting methods used inter alia in the army for measuring the effectiveness of shielding chambers (MIL STD 285 [7]). The method has been significantly modified and described among others in the IEEE 299 standard [2]. These methods employ the definition of shielding effectiveness, with the shielding barrier here having finite dimensions and being installed most typically in the wall of the shielding chamber, the anechoic chamber or the reverberation chamber.

The effectiveness of the shield also depends on the angle of the electromagnetic field. For this reason, some measurement methods employ reverberation chambers positioned inside anechoic chambers, or reverberation chambers positioned one inside another [9].

The effectiveness of the above discussed methods was tested as part of research performed at Wrocław University of Science and Technology [4][8]. The authors of the study paid particular attention to the well-known method based on coaxial line (the ASTM D4935-18 method [1]). The research demonstrated that the method has additional measurement potential.

This article demonstrates the possibility of expanding the measurement frequency range and performing measurements for materials that have different structures, including thin and thick materials.

Flanged Coaxial Line Holder in Tests of Shielding Effectiveness

Fig. 1 shows the test stand used by the authors in the shielding effectiveness tests performed for different types of shielding materials [3].

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The test stand made by the authors differs from that described in the latest ASTM D4935-18 standard [1]. A vector network analyzer was used to measure the S-parameters of the system. New measurement adapters were designed and made.

The measured specimens were mounted in a modified way. The test stand calibration process was extended to include measuring the correctness of the connections and determining the range of the measurement system dynamics.

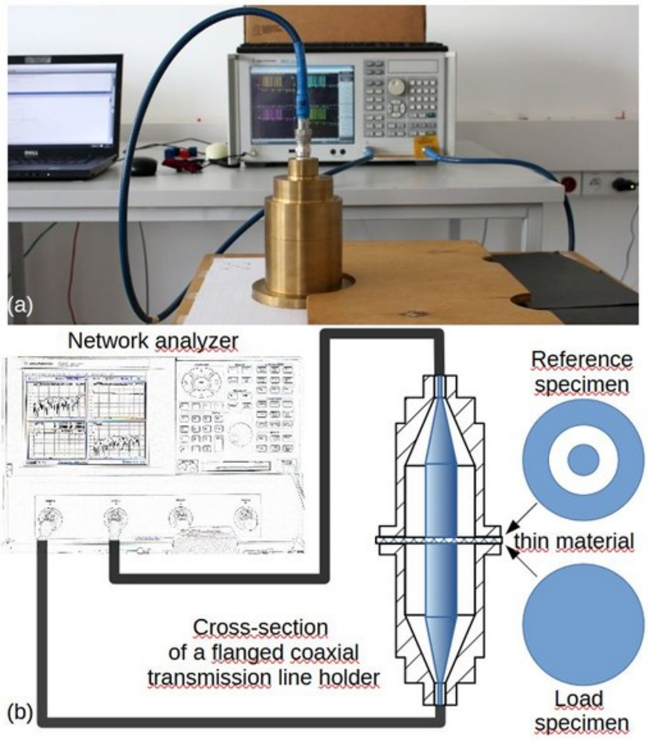
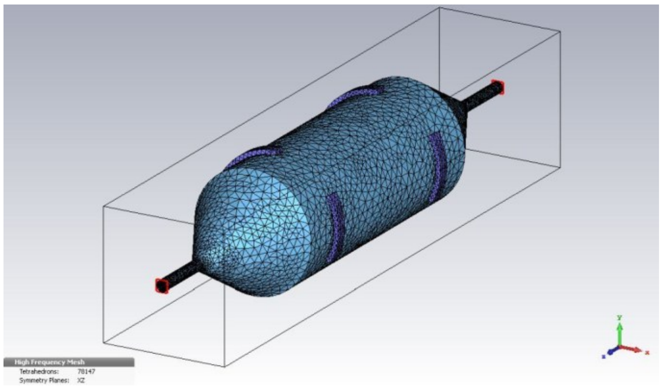


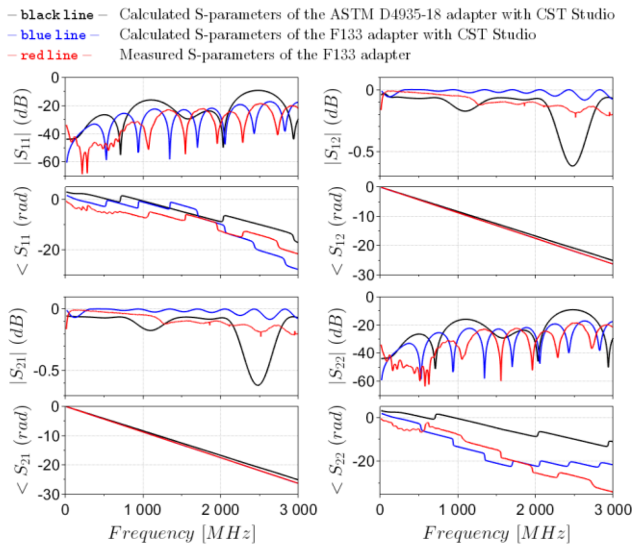
Fig. 1. The test stand for measuring shielding effectiveness of thin materials with a new adapter solution proposed by the authors (a); measurement method using calibration and test sample (b)

The use of vector network analyzers as a source of signal inducing and the measuring of the signal level on the load allows the measurements of the S-parameters to be performed in a short, broad frequency band and with a limited step. Information about these parameters in a wide frequency band and with a small frequency step allows a significant improvement in the precision and repeatability of the measurements. Moreover, the obtained information may enable numerical models of the investigated samples to be developed, and for their electromagnetic properties to be defined. Most of the shielding materials that are currently used have a non-uniform structure. Measurements performed for individual points, or for samples of limited surface areas may result in significant errors. This problem is solved by using adapters that allow measurements of samples with greater surface areas. However, as a consequence, the upper limit of the measurement frequency is lowered. If the cross-section surface area of the adapter is greater, higher order modes are induced at lower frequencies, which in turn lower the upper measurement frequency. Information on the S-parameters within a wide frequency range and with a small frequency step allows the use of appropriate algorithms in order to eliminate the influence of the higher modes, and thus increase the upper measurement frequency relative to the frequency resulting from the dimensions of the coaxial line.

The ASTM D4935-18 standard [1] precisely describes such an adapter and provides its dimensions, enabling it to be modeled in the Microwave Studio simulator, which was used to calculate its S-parameters as a function of frequency. The simulation results presented in Fig. 2 show that the standard adapter poorly fits the transmission line, and as a consequence the measurement results are significantly distorted.



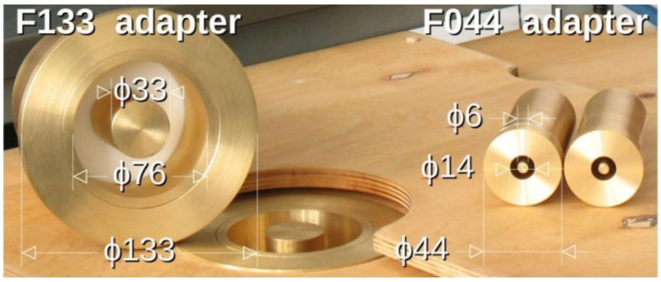
(a)



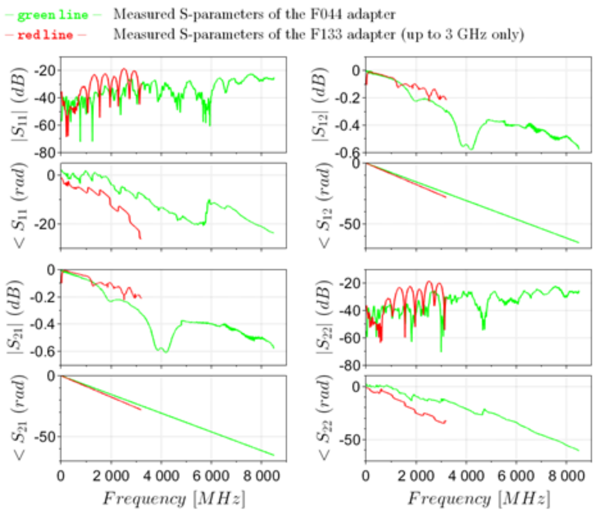
(b)

Fig. 2. CST Studio model of the ASTM D4935-18 adapter (a); representative results of the S parameter calculations for the adapter described in the ASTM D4935-18 standard; results of calculations and the S parameter measurements for the F133 adapter developed by the authors (b)

Therefore, a decision was made to develop an original adapter with an optimized fitting of the characteristic impedance of the VNA test port. The measurement result is also significantly influenced by the uniformity of the contact surface between the two parts of the adapter and between the two parts of its central electrode (septum). An identical and constant pressure across the entire contact surface between the two parts of the adapter is also important. The holding screws and the flanges were removed and the required pressure was effected by using the weight (gravity) of one of the adapter parts. Figure 3a shows the F133 adapter with a measurement surface and frequency range conforming to the ASTM D4935-18 standard, and the F044 adapter with a small measurement surface and frequency range extended to 9 GHz. Figure 3b shows the measured S-parameters of these adapters. Shielding materials have different structures (various size meshes, unwoven or woven fabrics with different plait types, as well as multi-layer and composite materials).



(a)



(b)

Fig. 3. Adapter developed by the authors (a), and the S-parameters of the adapters (b)

Fig. 4 Locations of the measurement points used in the verification of the method for the shielding effectiveness tests by means of surface scanning, together with the measurement results

The measurement surface of the adapters should be sufficiently large to include such a surface area that is representative of the structure of the shielding material. Such a solution, however, is not always possible due to the measurement surface of the adapters. The proposed design of the adapters allows an uncomplicated movement of the specimen between the measurements (scanning).

As a result, the tests may be performed for significantly larger specimens than in the case of the standard method (Fig. 4). In particular, this makes it possible to compare results obtained with adapters of different cross sections. As shown in Figure 4, a 52-point measurement with the F044 adapter covers the same surface as a single measurement with the F133 adapter.

Regardless of the surface of the shielding material, shielding effectiveness is frequently influenced by small (occasionally point-size) non-uniformities, and therefore it is necessary to use adapters that have a limited measurement surface and thus – a high upper measurement frequency. The reason for the above is that at smaller cross-sections, higher-order modes are induced at higher frequencies.

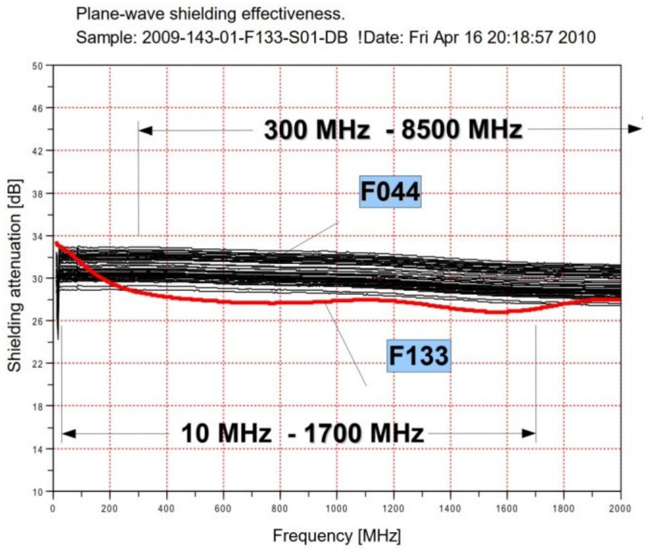
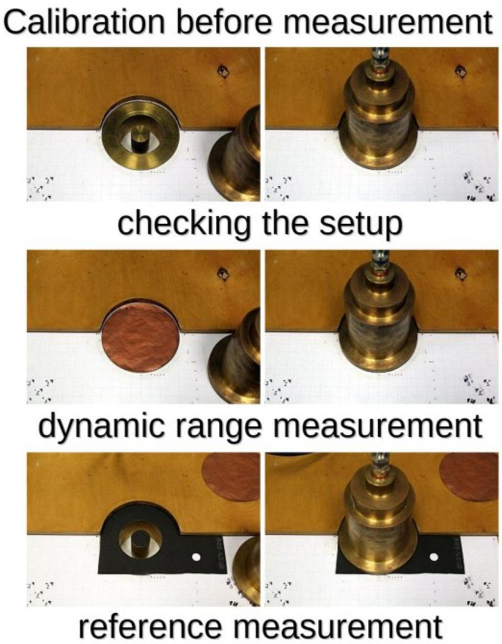


Fig. 5. Comparison of the shielding effectiveness determined by a single measurement with the F133 adapter (red line) and 52 measurements with the F044 adapter (black lines).

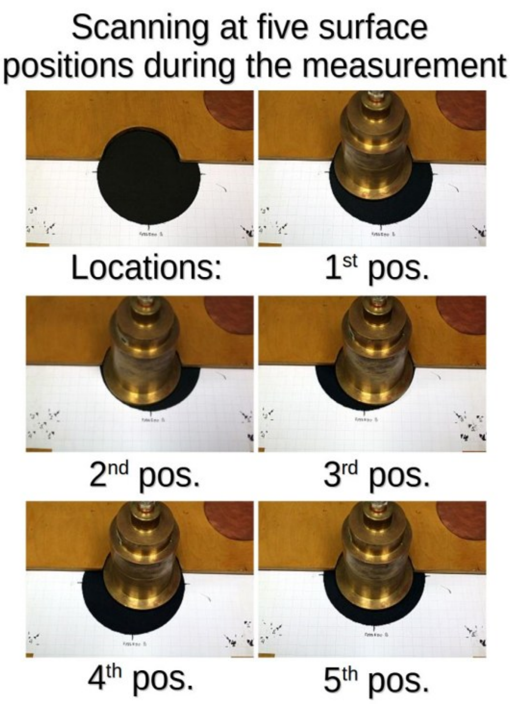
Fig. 5 shows the results of shielding effectiveness measurements of the same sample obtained with the F133 and F044 adaptors. The red line represents the result of a single measurement with the F133 adapter with a cross-section conforming to ASTM D4935-18. The black lines represent the results of measurements with the F044 adapter with a small cross-section measured at 52 points covering the same surface as the F133 adapter. The comparison was performed for the measurement range that was shared by both adapters - from 300 MHz to 1700 MHz. The local shielding effectiveness measured with the adapter with a small cross-section surface area varies within a 4 dB range for individual frequencies. The shielding effectiveness values measured with the adapter with a large cross-sectional surface area are approximately 2 dB lower than in the worst case using the adapter with a small cross-section surface area. The proposed procedure for the tests of shielding effectiveness is practically identical to the recommended procedure [1]. It introduces modifications that accelerate the measurement and allows control of the measurement correctness.

MEASUREMENT PROCEDURE

The measurements were performed on a setup shown in Fig. 6a. In order to enable the measurements of the S-parameters,



(a)



(b)

Fig. 6. Calibration is performed in three different configurations (a); measurement is performed from five adapter positions (b)

a vector network analyzer was employed, whose transmitting-receiving inputs are connected with the adapter using 1.5-metre coaxial cables with stable transmission parameters and high shielding effectiveness. In the presented case, the measurements were performed within the 10 MHz to 2 GHz range. Importantly, measurements above 1.7 GHz may be biased with an additional error due to the operation of the adapter above the cutoff frequency (upper usable frequency). A calibration based on reference specimens (mechanical or electronic) is recommended prior to the test in order to eliminate the influence of cables on the measurement results.

The measurement is carried out in two stages. First, the installation of the cables and the operation of the adapter is checked by measuring the transmission and reflectance parameters of an empty adapter at the lowest VNA frequencies. The dynamics of the system are determined by measuring a calibration specimen with a very high screening efficiency and comparing the result with the result for the reference specimen. The reference specimen is then measured, the results of which are used to compensate for losses due to capacitive coupling at frequencies below 300MHz. (Fig.6a). The actual measurement is performed in the second stage. If non-uniformities are to be included, the measurements should be performed in numerous locations on the specimen (Fig. 6b).

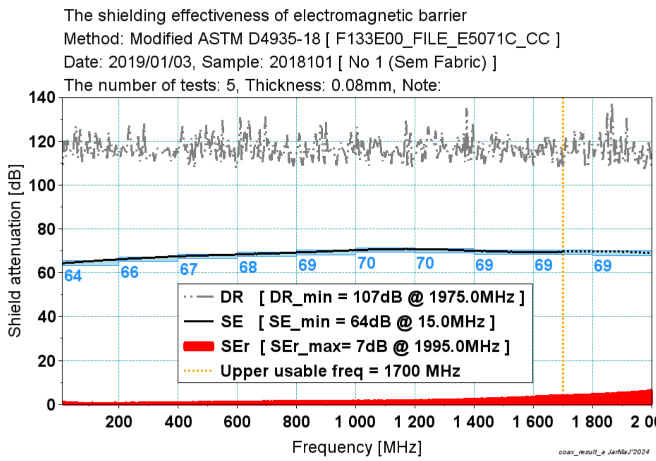


Fig. 7. Representative test results for a thin barrier material

The shielding effectiveness (SE) is defined as the difference of the S21 modules converted to dB in the system with the reference specimen (reference measurement) and in the system with the tested specimen (actual measurement) (1).

$$SE = 20 \cdot log_{10}\left(s_{21_{ref}}\right) - 20 \cdot log_{10}\left(s_{21_{test}}\right) \qquad (1)$$

In this case, the measurement result is assumed to be the minimum value for each frequency. The non-uniformity indicator of the barrier material (*SEr*) was defined as the difference between the maximum and minimum shielding effectiveness as a function of frequency (2).

$$SEr(f) = SE_{max}(f) - SE_{min}(f) \qquad (2)$$

Fig. 7 shows representative measurement results for a thin material. The effectiveness and usefulness of both the developed adapters and the modified measurement procedure have been confirmed not only in numerous tests of various flat barrier materials, but also in comparative tests performed by independent laboratories. These are described in detail in [5] and [6].

TEST OF THICK BARRIER MATERIALS

The presented adapter solutions may be adjusted to measurements of materials with greater thicknesses, e.g. to concrete or composite specimens. In this case, shielding effectiveness is significantly influenced by the absorption of electromagnetic energy.

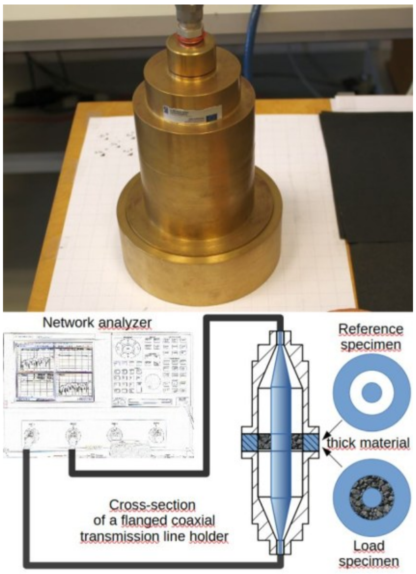


Fig. 8. Representative implementation of the module for the tests of the thick barrier materials

The adapters presented in this article are additionally provided with an original module shown in Fig. 8

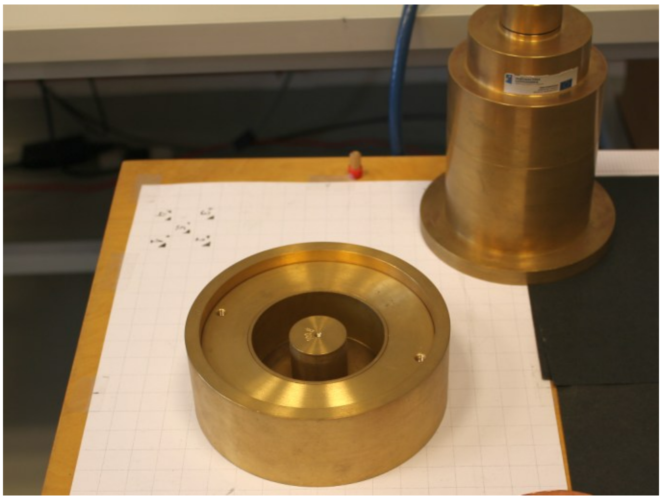


Fig. 9. Reference specimen for the verification of the test setup for the measurements of the thick barrier materials

Such modules can be arranged in stacks, allowing measurements of barrier materials with even greater thicknesses or structures with layers of different parameters.

The principle behind the measurement is practically identical to the procedure described above (except the stage with the reference specimen). However, an additional original calibration module is required (as shown in Fig. 9).

The measurement and calibration modules need to be adjusted to the dimensions of the measurement surface area of the adapter. As in the case of thin barrier materials (1), the shielding effectiveness is determined as the difference in S_{21} modules converted to dB measured in a system with a calibration module and with a measuring module filled with the absorption material. Modules with such a design also allow measurements of bulk materials. Fig. 10 shows representative measurement results for a material with increased thickness.

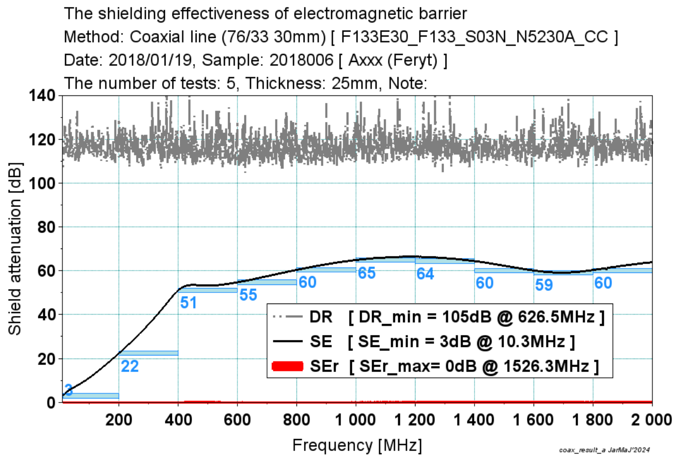


Fig. 10. Representative test results for a ferrites thick barrier material

MEASUREMENT OF ELECTRICAL PARAMETERS

The proposed test stand (Fig. 8 and Fig. 9), together with the adapters modified by the authors, also enables the measurement of electrical permittivity and magnetic permeability of materials.

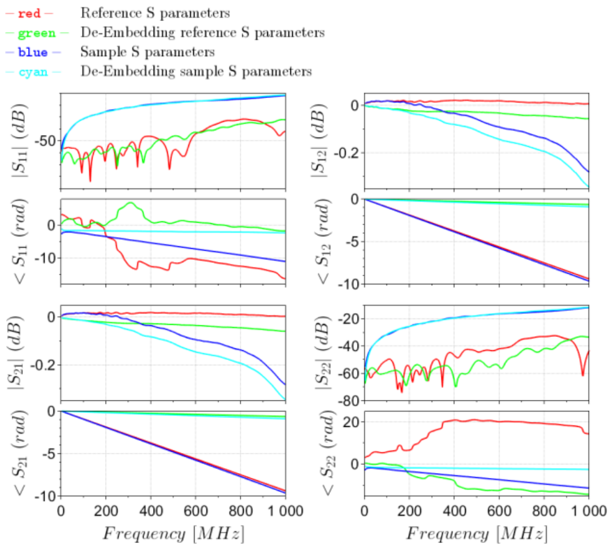


Fig. 11. S-parameters of the adapter and the Teflon reference sample.

The standardized measurement method [10] makes it possible to measure small-size samples, usually matched to a 7 mm coaxial airline. In practice, the structure of the materials is heterogeneous.

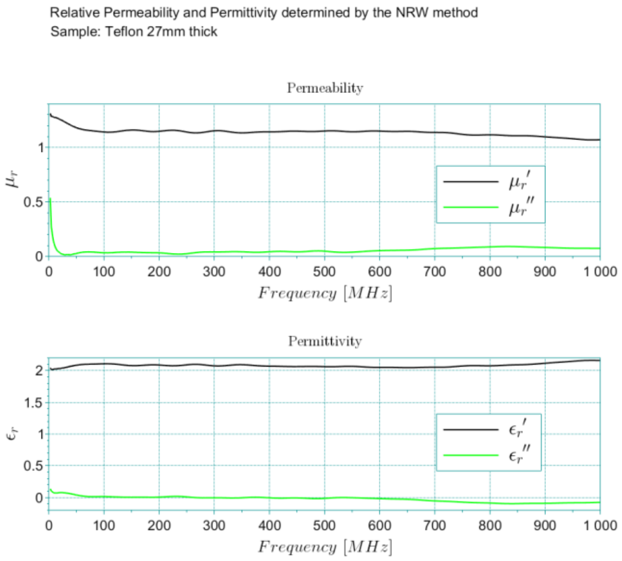


Fig. 12. Relative electrical and magnetic permeability of Teflon sample determined by NRW method.

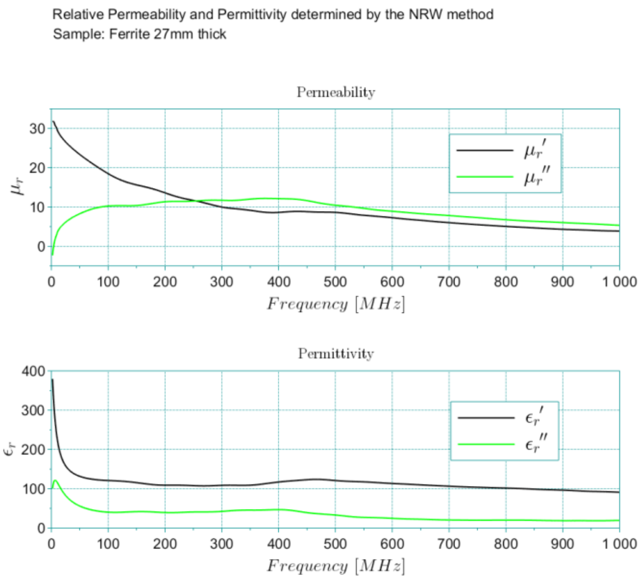


Fig. 13. Relative electrical and magnetic permeability of ferrite sample determined by NRW method.

Thus, the measurement, practically at one point, using the standardized method is insufficient, for example, in the case of composite shielding materials. The measurement of samples of larger sizes makes it possible to determine the substitute electrical permittivity and substitute magnetic permeability of the entire measured sample. However, this requires measurement of all S-parameters. Tin order to test the effectiveness of this method, the electrical parameters were measured, using the test stand described in the article, of a reference sample made of homogeneous Teflon and known electrical parameters.

The results of the measurement of S-parameters are shown in Fig. 11, and the values of electrical permittivity and magnetic permeability determined by the NRW method are shown in Fig. 12. Thus, it can be seen the full suitability of the developed test stand, together with modified adapters, for measuring the electrical parameters of materials. The electrical parameters of a shielding heterogeneous material were also measured, and the results are illustrated in Figure 13.

Conclusion

The novel adapter solutions presented with the proposed modifications to the measurement procedures facilitate an increase in the measurement frequency above the cutoff frequency that results from the cross-sectional dimensions of the coaxial line. The smaller the cross-sectional dimensions of the measurement space in the adapter, the higher the cutoff frequency. The proposed adapter design allows measurements of barrier materials that have substantial dimensions by means of surface scanning. The proposed adapter can additionally be expanded with modules that enable the measurements of thick materials for which shielding effectiveness is significantly affected by the absorption of electromagnetic energy.

The implementation of both the vector network analyzers in the test setup and the modified test procedure allows measurements of the S parameters, and thus the calculation of the electrical parameters of the tested materials.

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