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Metrol. Meas. Syst., Vol. XX (2013), No. 2, pp. 217–228.

METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.pg.gda.pl

MEASUREMENTS OF SHIELDING EFFECTIVENESS OF TEXTILE MATERIALS CONTAINING METAL BY THE FREE-SPACE TRANSMISSION TECHNIQUE WITH DATA PROCESSING IN THE TIME DOMAIN

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Abstract

The results of shielding effectiveness (SE) measurements of textile materials containing metal by the free-space transmission technique (FSTT) in the 1-26.5 GHz frequency range are presented in the paper. It is shown that experimental data processing using time-domain gating (TDG) makes it possible to effectively remove diffracted and reflected components from the desired signal. The comparison with the results obtained by other techniques, namely modified FSTT with TDG and coaxial line probe technique (ASTM D4935-99) is given. The comparison shows that the proposed technique gives more reasonable results while the measurement set-up is simpler in realization.

Keywords: textiles, shielding effectiveness, free-space transmission technique, time-domain gating

1. Introduction

Nowadays the protection from electromagnetic radiation (EMR) is a challenging engineering problem. Most EMR sources (mobile and satellite communications, wireless access networks, TV broadcasting, radars etc.) are concentrated from near L through K band (1-26.5 GHz) and situated in densely populated urban areas. Moreover, their number is growing steadily. Radiation from these sources may be dangerous for humans and the environment depending on exposure intensity and duration, frequency range, organism or system immunity [1]. Therefore, at present the development and application of effective methods of protection against radiation is still of great importance.

There are various types of electromagnetic shields, or shielding materials, having reflective or absorbing properties depending on, e.g. their electrical parameters (permittivity, permeability, and conductivity), inner structure, and shield geometry as well [2, 3]. Variety of existing shielding materials is able to meet various customers' requirements relating to their application: operating frequency range, shielding effectiveness, mechanical, and thermal properties, size etc. [4, 5, 6, 7].

The shielding materials produced using technologies of light industry are of special interest. These materials are usually made with woven or knitted technology from artificial and metal threads or from metal-containing composite fibers. In the literature, they are referred to as shielding (or conductive) textiles, fabrics or woven materials. The raw materials for the fabrics can be for example silver, copper, steel, aluminum, polyester, polyamide or nylon. It is worth to mention that due to their composite nature such materials are always inhomogeneous. The typical applications of the materials are curtains, canopies, and clothing.

Article history: received on Nov. 16, 2012; accepted on Feb. 25, 2013; available online on Jun. 03, 2013; DOI: 10.2478/mms-2013-0019.

The woven and knitted materials are light, flexible, air-penetrating, and simultaneously resistant enough to moderate mechanical actions including washing. Also, some additional properties such as incombustibility and optical transparency can be accomplished. Furthermore, their price is reasonable due to low fabrication cost.

The main physical quantity characterizing the shielding materials is *shielding effectiveness* (SE). Conventional definition states that SE is the ratio of electromagnetic field strength measured before (E_0) and after (E_{shield}) the shielding material is installed:

$$SE\ [\text{dB}] = 20 \cdot \log_{10} \frac{E_0}{E_{\text{shield}}}, \tag{1}$$

on the assumption that the material is an infinite plane, and that it is located between the source of electromagnetic radiation and the measuring device [3, 8].

The SE of shielding textiles usually takes on values from 20 to 80 dB, depending on the structure of the composite and the type of conductive reinforcements. However, this dependence is sophisticated [9, 10, 11]. The investigation of shielding textiles may also include: measurement of the permittivity, the permeability, and the conductivity of the components; study of the structure and internal relations between fibers; and designing materials with desired shielding properties. The electrical conductivity can also be measured with methods on direct current [12, 13] supplementing the RF measurements.

2. Techniques of shielding effectiveness measurement

2.1. State of the art

Currently several techniques used for SE measurement of shielding materials at frequencies above 1 GHz can be marked out as main trends.

The coaxial line probe technique based on the ASTM D4935 standard [14] is commonly used due to its relative simplicity and good accuracy of measurement results. It is often applied for commercial materials and it is suitable for comparison with other methods. However, the method is not broadband (for each frequency range it is required to use a coaxial line probe of appropriate size), and furthermore it does not allow to distinguish the results for various polarizations, because a sample is tested with an incident wave having radial polarization [15].

Another group of measurement techniques consists in broadband measurements in a reverberation chamber, a nested reverberation chamber [16] or a vibrating intrinsic reverberation chamber [17]. Separation of the source of radiation and the receiver is provided with the exception of a special opening in which the measured sample is situated. Rich scattering environment of the reverberation chamber simulates a scenario in which the material under test will be typically used, with arbitrary polarized waves arriving from arbitrary directions. Nevertheless, multiple reflections in the chamber reduce the accuracy of the method. Moreover, the reverberation chamber is not available in every research institution.

An alternative technique assumes measurements within anechoic or semi-anechoic chamber divided into two parts [18]. A sample of the material under test is situated in a hole between these parts. The sample is illuminated by normally incident waves only and the polarization of the waves is well determined. It is also a broadband technique.

It should be noticed that there is a variety of techniques for testing the shielding properties of various types of enclosures. These techniques are beyond the scope of this article, because they do not directly relate to microwave measurements of planar materials.

As opposed to those techniques, this paper is focused on the broadband technique which can be applied in an arbitrary environment.

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2.2. Free-Space Transmission Technique with Time-Domain Gating

In the *free-space transmission technique* (FSTT) [19, 20, 21] two broadband horn antennas and a vector network analyzer (VNA) are needed for measurements. The antennas form a radio link. The sample of material under test (MUT) is located between the antennas, breaking the line of sight of the radio link, but there is no additional isolation between the antennas. In such arrangement the no-diffraction criterion is not fulfilled due to limited sample size.

The transmission coefficient of the radio link measured by the VNA is a sum of three terms, related to the following phenomena:

- transmission caused by the wave propagating directly through the MUT; this is the desirable part of measured quantity, on the basis of which SE might be determined; hereinafter signal component related to this phenomenon is referred to as *straight line component*;
- transmission caused by diffraction effects occurring at all edges of the sample;
- transmission caused by reflections from the environment or any reflection from the measurement set-up.

The two latter parts are very likely to be dominant and consequently plain FSTT cannot give accurate results. This drawback is usually overcome by the measurement set-up configuration [22] in combination with data averaging, though that does not give satisfactory results. Therefore, the FSTT is not popular, particularly in the characterization of shielding textiles.

Nevertheless, a feasible and efficient solution for the aforementioned disadvantage is to combine the FSTT with time domain data processing. In this approach the measured transmission coefficient S_{21} is transformed to the time domain and treated as a signal in the time domain. Then known *time-domain gating* (TDG) algorithm [19, 23, 24] is applied for separation of the straight line component from all other components delayed in time due to longer propagation paths (diffracted, reflected). The separated component is used for further analysis.

The FSTT-TDG is relatively simple in realization because it does not require a specially prepared environment, such as anechoic or reverberation chamber. However, due to specific properties of the transformation between the frequency and time domains, special care must be paid to satisfy the following requirements:

- The measurement must be broadband in order to obtain suitable resolution in time. According to the performed investigation, the frequency range from 1 GHz to 18 GHz or more is preferable.
- The antennas should be broadband and should have short pulse response [25] in order to avoid stretching of data in the time domain. In particular, broadband log-periodic antennas are inapplicable due to long pulse response.
- The number of measurement frequency points must be large enough in order to avoid aliasing effects in the time domain.
- A sample of MUT has to be flat and as large as possible. In the case of microwave measurements preferably it should have dimensions not less than 1 m × 1 m in order to provide appropriate delay between straight line component and diffracted components of the signal in time domain. Textiles have limited width due to the manufacturing process, but fortunately usually not less than one meter.
- The technique is not suitable for measurement of materials having narrow-band resonances due to the reduction of frequency resolution resulting from time domain gating.

The sample is illuminated by normally incident waves having well specified polarization. The FSTT-TDG technique is non-destructive for a MUT.

3. Materials under test

Three kinds of textile materials made of metal-containing yarns were tested. Fig. 1 shows microscopic images of these materials. Vertical and horizontal directions are marked by means of arrows (V and H, respectively). Material denoted by A has one warp and two wefts with double interweaving. Its yarns consist of synthetic fibres coated with a conducting metal. On the contrary, yarns of materials denoted by B and C are made of two types of fibres – among synthetic fibres there is also a number of metallic conducting fibres. Both materials, B and C, have one warp and one weft with simple interweaving, so called 'plain weave'.

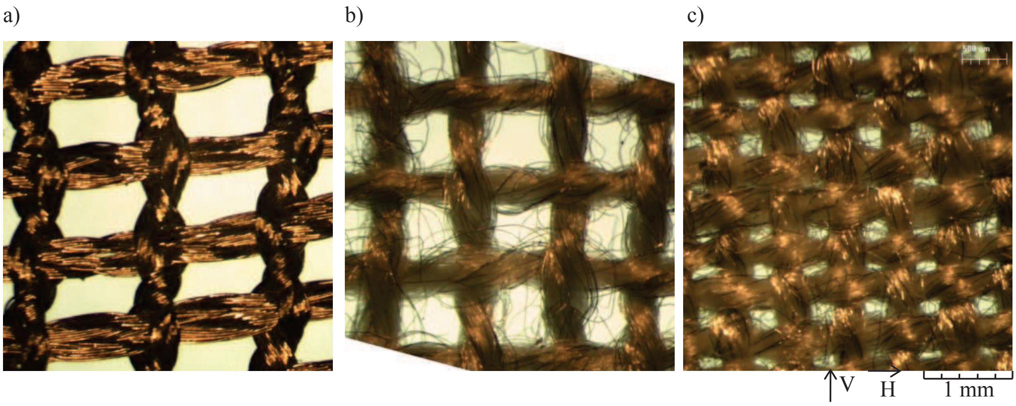

Fig. 1. Optical microscope images of: a) material A, b) material B, c) material C.

The densities of yarns as well as approximate thicknesses of the three materials are presented in Table 1. Conductivities of the samples have been measured using four-probe technique with pin electrodes for various directions of current flow [12]. Typical results are presented in Tab. 2. Measured sheet resistances are the lowest for the material A due to the yarn construction (all fibres are conducting). "Diagonal" resistances for materials B and C are much higher than the ones measured along the yarns. It is caused by sparse distribution of conducting fibres in vertical and horizontal yarns. The conducting fibres rarely contact each other and thus the materials B and C are strongly anisotropic. This fact leads to the conclusion that the four probe technique from [12] is inadequate for the measured materials, because it assumes isotropy of the sheet under test. Consequently, data in Tab. 2 should not be treated as definitive. Furthermore, measurement results were unstable due to unrepeatable contact to the conducting fibres in the yarns.

Table 1. The density of yarns and the approximate thickness of the textiles.

	Material A	Material B	Material C
Vertical fibres	8.4 per cm	10.4 per cm	18 per cm
Horizontal fibres	12.0 per cm	11.0 per cm	21 per cm
Thickness (approx.)	0.45 mm	0.34 mm	0.41 mm

Table 2. Sheet resistance of tested materials measured with the four probe technique.

Current flow	Material A	Material B	Material C
Vertical	0.362 Ω/□	22.1 Ω/□	5.00 Ω/□
Horizontal	0.265 Ω/□	10.8 Ω/□	6.65 Ω/□
Diagonal	0.315 Ω/□	34.7 Ω/□	41.1 Ω/□
Diagonal (ortog.)	0.325 Ω/□	61.8 Ω/□	32.4 Ω/□

4. Measurement set-up for FSTT-TDG and principles of data processing

A diagram of the measurement set-up for FSTT-TDG is presented in Fig. 2 a). According to the FSTT principles (see Section 2.2) two broadband horn antennas form a radio link and the sample of MUT is placed centrally in the line of sight. The VNA is used to determine S-parameters of the set-up, particularly the transmission coefficient (S_{21}). The set-up operates in a certain environment, in general reflecting electromagnetic waves. The MUT has limited dimensions; in the considered set-up it is a square of dimensions $2h \times 2h$.

Although the technique has the potential to be implemented in free to choose environment, an anechoic chamber was used in preliminary measurements (Fig. 2 b). In such case the reflected components of the transmission coefficient are suppressed, but the most troublesome diffracted components are not affected. Therefore the measurements presented in the paper prove the usefulness of the technique regardless of the environment.

In order to apply the TDG algorithm [19, 23], the measurement data is transformed into the time domain by means of inverse discrete Fourier transform (IDFT):

$$\{s_{21}(t)\} = \mathrm{IDFT}\{W(f) \cdot S_{21}(f)\}, \quad (2)$$

where $W(f)$ is a frequency window. The frequency window $W(f)$ is used in order to suppress side lobes of pulses observed in the time domain [23, chap. 5.2.2]. In the paper the Hamming window is applied.

The $S_{21}(f)$ data might be put into formula (2) in a *bandpass mode*, beginning from frequency $f > 0$, or in a *lowpass mode* with a center frequency $f = 0$ [23]. The lowpass mode is reasonable when the start measurement frequency is equal to 0 Hz or is much lower than the width of the measurement frequency band. This mode is used in the paper.

Afterwards, the time domain representation of the data $s_{21}(t)$ is windowed in the time domain and transformed back to the frequency domain by means of discrete Fourier transform (DFT):

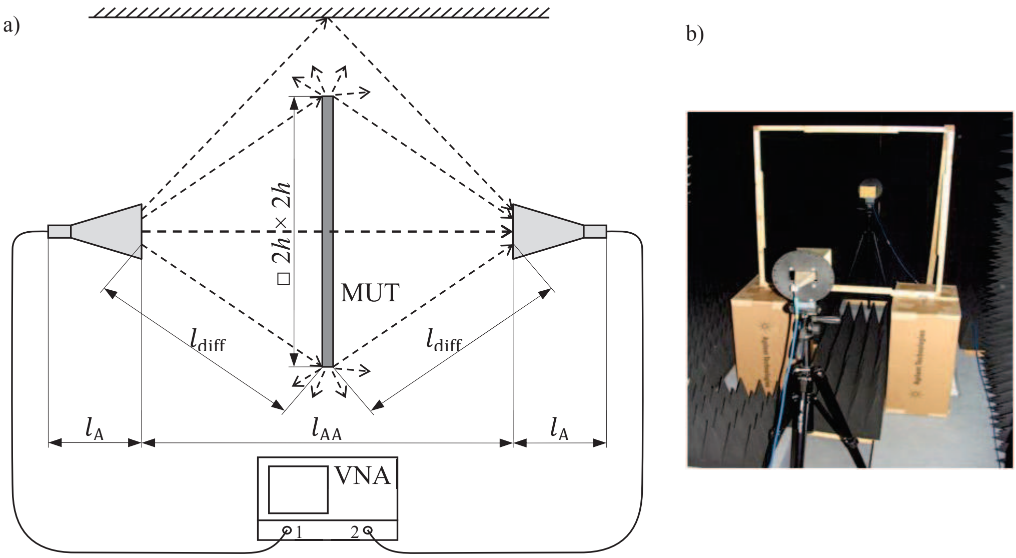

Fig. 2. a) A diagram of the measurement set-up for the FSTT-TDG.
b) Measurement set-up in the laboratory, where $2h \times 2h = 1$ m × 1 m, $l_{AA} = 2.06$ m, $l_A = 0.3$ m.

$$\{S_{21,\mathrm{TDG}}(f)\} = \mathrm{DFT}\{w(t) \cdot s_{21}(t)\}, \tag{3}$$

where $w(t)$ is a time gating window. The $w(t)$ is a square window, chosen so to select the part of $s_{21}(t)$ waveform related to the straight line component and to reject the part related to diffracted and reflected components. This is possible on condition that these parts are separable in time. Most of requirements for FSTT-TDG specified in Section 2.2 are given in order to fulfill this condition.

Finally, the shielding effectiveness is calculated with the following formula:

$$SE(f)\ [\mathrm{dB}] = 20 \cdot \log_{10} \frac{|S_{21,\mathrm{TDG,ref}}(f)|}{|S_{21,\mathrm{TDG}}(f)|}, \tag{4}$$

where $S_{21,\mathrm{TDG,ref}}(f)$ is the reference data (subjected to frequency and time windowing, too) for measurement performed with no sample, hereinafter referred to as *reference measurement*. Normalization to the reference measurement is applied in formula (4) in order to eliminate the attenuation of the radio link, in which the MUT is measured.

Fig. 2 b) presents the measurement set-up in the laboratory. PNA-X N5242A made by Agilent Technologies has been used as the VNA, and two GZ0126ATP made by Geozondas as antennas. Antennas' operating frequency band covers 1 – 26.5 GHz range. However, the measurements were carried out in the whole operating frequency band of the VNA, i.e. 10 MHz – 26.5 GHz. This reduces cutting effects at frequencies near to 1 GHz. 26491 frequency points have been used with 1 MHz spacing. It results in 1000 ns of time response, which is sufficient to determine the pulse response and to avoid aliasing effects. The VNA has been calibrated to the input ports of the antennas.

During the measurements the samples of MUT have been stretched on a wooden frame of dimensions 1 m × 1 m (i.e. h = 0.5 m). The frame is visible in Fig. 2 b). The distance between antennas l_{AA} was 2.06 m, measured between the fronts of the horns. The MUT was situated in the middle of this distance. The physical length l_{A} of each antenna from the feeding point to the front of the horn was approximately 0.3 m. The antennas' centers were at a height of 1.28 m from the floor.

5. Measurement results

The $S_{21}(f)$ parameter of the radio link has been measured for various scenarios: in the absence of a sample (reference measurement) and in the presence of the samples of materials A, B, and C for both polarizations (VP and HP). Time domain representation of measurement data determined according to the formula (2) is presented in Fig. 3. Figures 3 a) and b) present waveforms for reference measurement calculated with a square frequency window $W(f) = 1$ and with Hamming window, respectively. Reduction of side lobes is obtained for a Hamming frequency window. It can be observed in Fig. 3 a) and b) for $t < 9.1$ ns. Further plots in Fig. 3 present waveforms for particular samples of MUTs, for both polarizations, VP and HP, all processed with Hamming frequency window.

The waveform for reference measurement (Fig. 3 b) has one dominant component, which can be identified as the straight line component. It starts at $t = 9.1$ ns, which corresponds to the distance 2.73 m and agrees with the physical distance: $l_{\mathrm{AA}} + 2l_{\mathrm{A}} \approx 2.06\ \mathrm{m} + 2 \cdot 0.3\ \mathrm{m} = 2.66\ \mathrm{m}$.

The diffraction component is visible in Fig. 3 c), d), and e) and starts at $t = 9.8$ ns. It is explicitly separated from the straight line component. Its delay to the straight line component is approximately 0.7 ns, which corresponds to 0.21 m difference in distance. This also agrees with the difference of physical path lengths, calculated on the basis of geometrical rules:

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$$2l_{\text{diff}} - l_{\text{AA}} = 2\sqrt{\left(\frac{l_{\text{AA}}}{2}\right)^2 + h^2} - l_{\text{AA}} \approx 2.29\ \text{m} - 2.06\ \text{m} = 0.23\ \text{m}. \quad (5)$$

The delay inside the MUT is neglected, because it is relatively small.

The time gating window $w(t)$ has been selected to start at 9.0 ns and to end at 9.6 ns. White regions indicate the time gating window in Fig. 3.

Examples of frequency domain representation of the processed data in successive stages of processing are presented in Fig. 4 and 5. Raw measurement data $S_{21}(f)$, frequency windowed data $W(f) \cdot S_{21}(f)$ and time gated data $S_{21,\text{TDG}}(f)$ are presented for the reference measurement (Fig. 4) and for the measurement of sample of material A, vertical polarization (Fig. 5).

As it can be seen, the diffraction components from the edges of the sample significantly contribute to the total signal and cause large distortions. Particularly, diffraction components are dominant for the frequencies below 5 GHz (Fig. 5). The diffraction effect at low frequencies is related to the wide antenna half-power beam width and the limited sample size.

As the final result of the measurement, values of the shielding effectiveness (SE) are determined accordingly to the formula (4). The SE for three samples and both polarizations is presented in Fig. 6. The SE for material A and B decreases with the frequency in most of the frequency range. That is known as the "grid" effect for materials of such structure. The material C has such large density of yarns (Tab. 1), that it can be assumed "solid" for a given frequency band.

The differences between results for particular polarizations are strongly related to the density of yarns in the textiles in respective direction (given in Tab. 1). For the material A, SE for vertical and horizontal polarization differs about 5 dB. It is connected with the relatively high difference of densities of vertical and horizontal yarns (Tab. 1) and with visible difference of weaving in wefts and warps (Fig. 1 a). The SE for material B has nearly the same values for both polarizations. It corresponds with the fact that material B has an almost identical structure of vertical and horizontal yarns. The densities differ less than 6% (Tab. 1). And subsequently, for the material C, the SE has slightly higher values for horizontal polarization (2-5 dB), which corresponds with slightly higher density of horizontal yarns (approximately 17%). This is also a good example that for measurements of textile materials the methods sensitive to electromagnetic wave polarization should be used.

6. Comparison of different measurement techniques

In order to verify the obtained results three reference measurement techniques have been employed: 1) modified FSTT-TDG technique implemented in a shielded room with the maximum frequency reduced to 11 GHz; 2) modified FSTT-TDG technique implemented in an anechoic chamber equipped with a metal barrier separating transmitting and receiving antennas, the MUT is installed in a hole in the barrier and the maximum frequency is reduced to 5.5 GHz; 3) the coaxial line probe technique ASTM D4935-99 operating up to 8.5 GHz, without time-domain gating. Results obtained by techniques 1), 2), and 3) are marked in Figures 7-9 as 'ShRoom', 'MetBar' and 'ASTM'[1], respectively. Results marked as 'FSTT-TDG'[2] are cited from Section 5.

In Fig. 7, the comparison of SE measured for material A by means of various techniques is presented. The results show very good conformity. The curves obtained in the shielded room (ShRoom) and in the anechoic chamber with metal barrier (MetBar) have some artifacts due to insufficient time resolution and accompanying difficulties with the window size selection,

[1] Measurements were conducted at the EMC premises of the Wroclaw University of Technology.
[2] Measurements were conducted at the Institute of Radioelectronics of the Warsaw University of Technology.

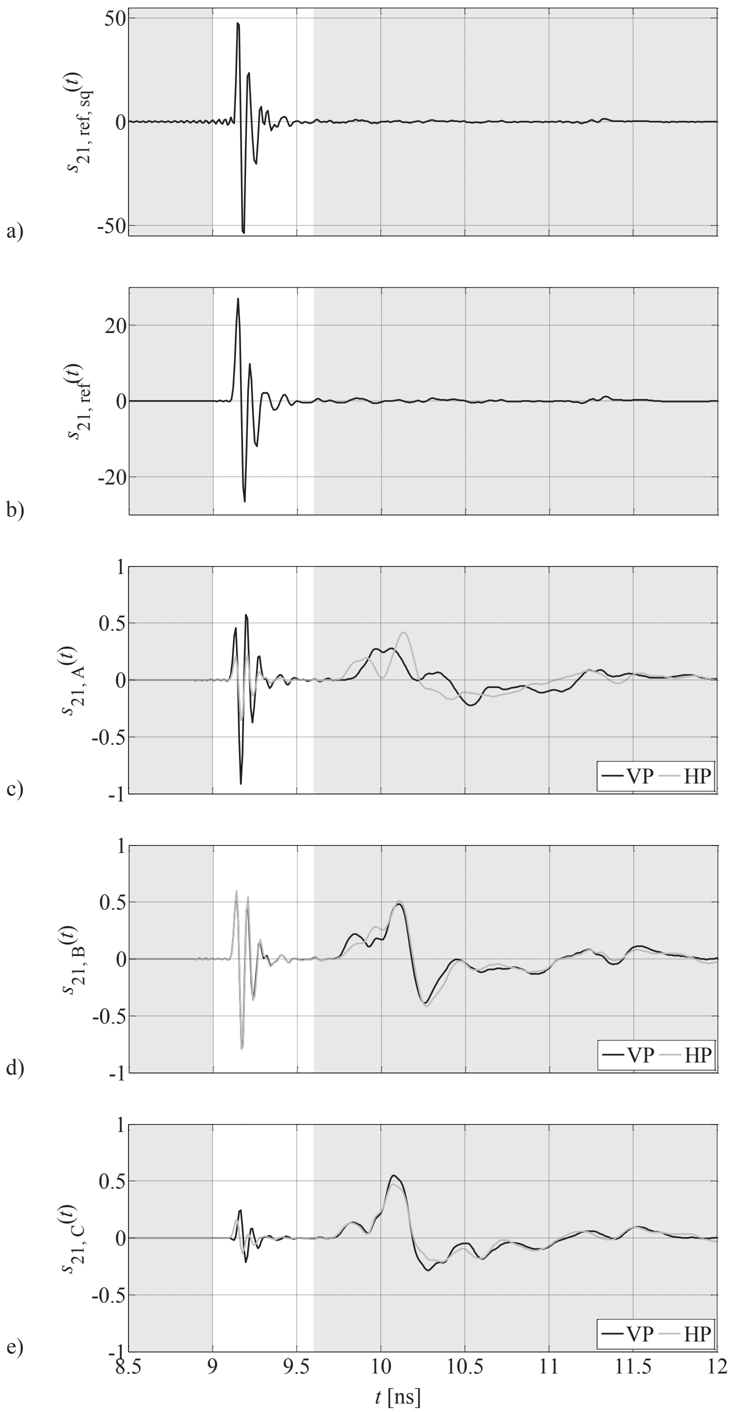

Fig. 3. Time-domain representation of the measurement data: a) reference data taken with square frequency window; b) reference data taken with Hamming frequency window; c), d), and e) data for sample A, B, and C, respectively, both polarizations. White region indicates the time gating window. Relative values are presented for all cases.

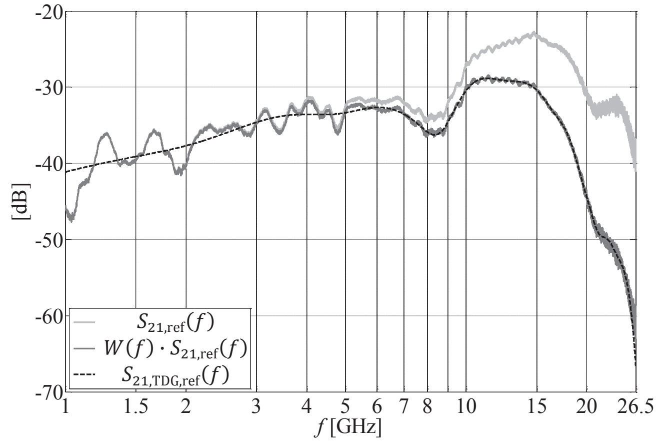

Fig. 4. Successive stages of data processing for the reference measurement.

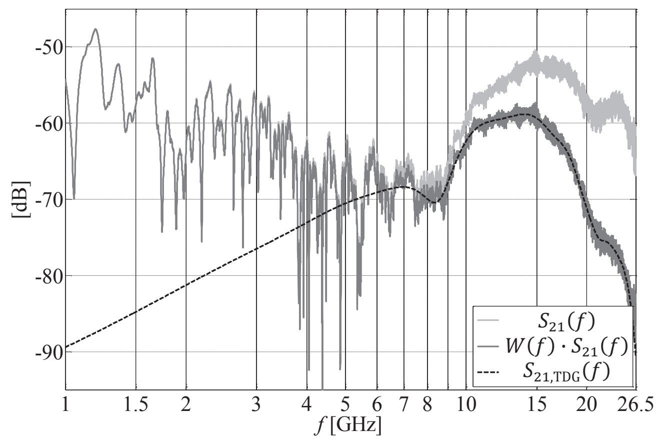

Fig. 5. Successive stages of data processing for sample of material A, vertical polarization.

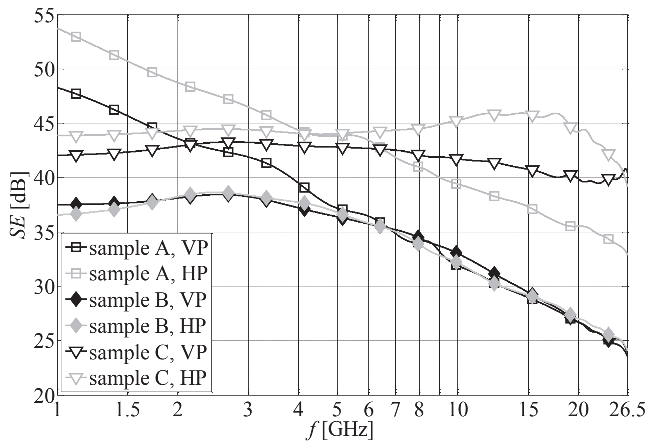

Fig. 6. Shielding effectiveness (*SE*) measured for three samples (A, B, C) and for both polarizations (VP, HP).

both of them resulting from too narrow frequency band of measurements. These results show the importance of careful determination of measurement conditions for further TDG data processing. The SE in the anechoic chamber with metal barrier was measured only for horizontal polarization. The SE measured with the ASTM technique is not polarization sensitive. It lies below other results. However, it excellently replicates the shape of other plots.

In Fig. 8 and 9, the comparisons of SE measured for materials B and C are shown. The SE plots for all techniques demonstrate good agreement except for the ASTM-based measurement. The SE taken in the anechoic chamber with metal barrier again exhibits some artifacts related to the narrow frequency band of measurements. The SE measured in coaxial transmission line (ASTM) differs very much in values and shape from other results. The ASTM D4935-99 is a contact measurement technique and probably the inaccuracy is due to the structure of materials B and C, preventing proper contact. Similar problems in measurements of sheet resistance of materials B and C are reported in Section 3.

The results presented in this section show that the frequency band should be properly chosen in order to get results without artifacts in the FSTT-TDG technique.

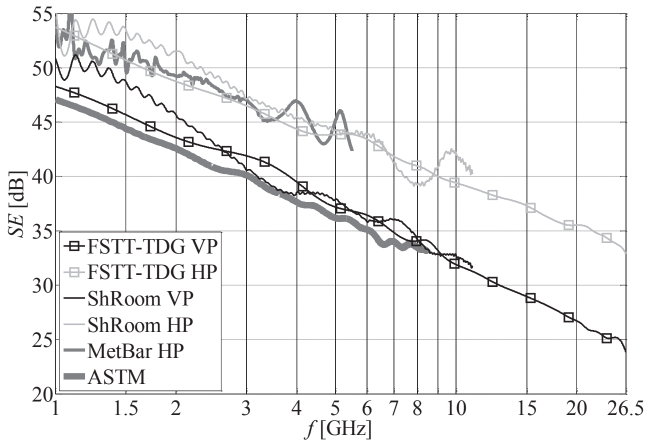

Fig. 7. Shielding effectiveness (*SE*) of sample A measured by means of various techniques.

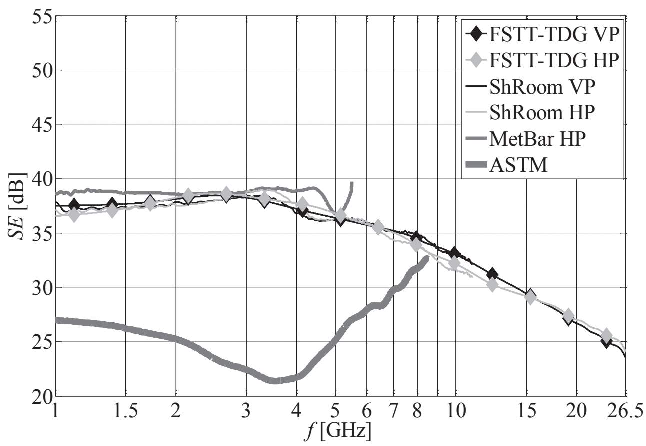

Fig. 8. Shielding effectiveness (*SE*) of sample B measured by means of various techniques.

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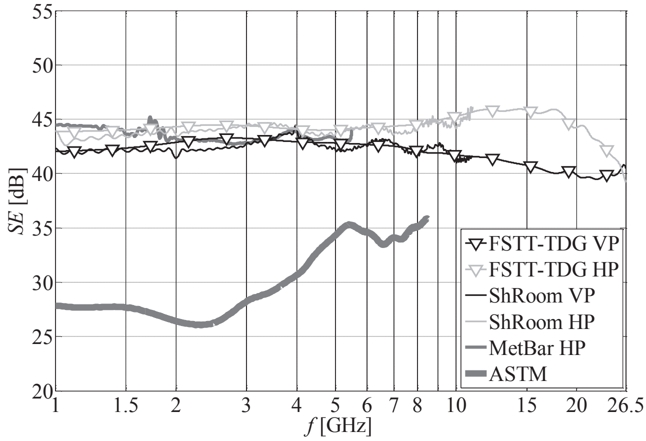

Fig. 9. Shielding effectiveness (*SE*) of sample C measured by means of various techniques.

Conclusions

Free-space transmission technique with time-domain gating (FSTT-TDG) has been proposed and validated for the measurement of shielding effectiveness (SE) of three textile materials containing metal in the 1 GHz – 26.5 GHz frequency range. It has been shown that although the no-diffraction criterion is not fulfilled in the measurement scenario, data processing in the time domain can provide efficient removal of the diffracted and reflected components from the measured quantities. Consequently, the measurement of SE of the materials might be conducted without extraordinary environments providing separation between transmitting and receiving antennas.

It has also been shown that common contact measurement methods, at DC and at RF frequencies, are not suitable for the textile materials containing metal, due to their complex structure.

Since the FSTT-TDG technique has demonstrated high quality results, is very simple in realization and provides capability of elimination of reflected and diffracted multipath components, it is proposed as a good alternative to other techniques of SE measurement of both woven and non-woven materials.

Acknowledgement

The experimental part of this work was carried out under support of the Erasmus Mundus External Co-operation Window Programme of the European Union (Feb. 2009 – Nov. 2011).

References

[1] Schwan, H.P. (1971). Interaction of microwave and radio frequency radiation with biological systems. *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, no. 2, pp. 146-152.

[2] Schulz, R.B., Plantz, V.C., Brush, D.R. (Aug 1988). Shielding theory and practice. *Electromagnetic Compatibility, IEEE Transactions on*, vol. 30, no. 3, pp. 187-201.

[3] Joyner, K.H., Copeland, P.R., MacFarlane, I.P. (May 1989). An evaluation of a radiofrequency protective suit and electrically conductive fabrics. *Electromagnetic Compatibility, IEEE Transactions on*, vol. 31, no. 2, pp. 129-137.

[4] *http://www.yshield.eu* (April 2012).

[5] *http://www.solianiemc.com* (April 2012).

[6] *http://www.ferrishield.com* (April 2012).

[7] *http://www.shieldingsystems.eu* (April 2012).

[8] Więckowski, T. W., Janukiewicz, J. M. (2006). Methods for Evaluating the Shielding Effectiveness of Textiles. *Fibres & Textiles in Eastern Europe*, Vol. 14, No. 5 (59), pp. 18-22.

[9] Henn, A., Cribb, R. (1992). Modeling the shielding effectiveness of metallized fabrics. In *Proc. IEEE 1992 International Symposium on Electromagnetic Compatibility,* Anaheim, CA, USA, pp. 283-286.

[10] Chen, H., Lee, K., Lin, J., Koch, M. (2007). Fabrication of conductive woven fabric and analysis of electromagnetic shielding via measurement and empirical equation. *Journal of Materials Processing Technology,* vol. 184, pp. 124-30.

[11] Yang, S., Lozano, K., Lomeli, A., Foltz, H.D., Jones, R. (2005). Electromagnetic interference shielding effectiveness of carbon nanofiber/LCP composites. *Composites*, Part A 36 (2005), pp. 691-697.

[12] Smits, F.M. (1958). Measurement of sheet resistivities with the four-point probe. *The Bell System Technical Jornal*, pp. 711-718, May 1958.

[13] PN-EN 1149-1, "Odzież ochronna. Właściwości elektrostatyczne. Cześć 1: Metoda badania rezystywności powierzchniowej," Warszawa 2008.

[14] American Society for Testing and Materials, Standard Test Method for Measuring the Electromagnetic Shielding Effectiveness of Planar Materials, Standard D4935-99, 1999.

[15] Wilson, P.F., Ma, M.T., Adams, J.W. (Aug 1988). Techniques for measuring the electromagnetic shielding effectiveness of materials. I. Far-field source simulation. *Electromagnetic Compatibility, IEEE Transactions on*, vol. 30, no. 3, pp. 239-250.

[16] Holloway, C.L., Hill, D.A., Ladbury, J., Koepke, G., Garzia, R. (2003). Shielding effectiveness measurements of materials using nested reverberation chambers. *IEEE Trans. Electromag. Compatib.*, vol. 45, no. 2, pp. 350-356.

[17] Skrzypczynski, J. (2011). Dual vibrating intrinsic reverberation chamber used for shielding effectiveness measurements. In Proc. *EMC Europe 2011,* York, pp. 133-136.

[18] Atkins, D.J., Miller, J.A., Sanders, J.D. (1992). Shielding effectiveness of spacecraft (European Polar Platform) CFRP panels. In Proc. *Electromagnetic Compatibility, 1992., Eighth International Conference on*, pp. 100-107.

[19] Chen, L.F., Ong, C.K., Neo, C.P., Varadan, V.V., Varadan, V.K. (2004). *Microwave electronics. Measurement and materials characterization*, John Wiley & Sons Ltd.

[20] Dvurechenskaya, N., Zielinski, R. (2011). Measurement of special shielding materials at S and C band using improved free-space transmission technique. *International Journal of Electronics and Telecommunication PAN*, vol. 57, no. 3, pp. 329-334.

[21] Dvurechenskaya, N., Zielinski, R. J. (2011). Advantages and disadvantages of the free-space arch method used for investigation of shielding materials at low gigahertz frequencies. In Proc. *EMC Europe 2011*, York, UK.

[22] Marvin, A.C., Dawson, L., Flintoft, I.D., Dawson, J.F. (2009). A method for the measurement of shielding effectiveness of planar samples requiring no sample edge preparation or contact. *IEEE Trans. Electromag. Compatib.*, vol. 51, no. 2, pp. 255-262.

[23] Hiebel, M. (2008). *Fundamentals of vector network analysis*, 4th ed., Munchen: Rohde&Schwarz.

[24] Wilson, P.F., Ma, M.T., Adams, J.W. (1988). Techniques for measuring the electromagnetic shielding effectiveness of materials. I. Far-field source simulation. *Electromagnetic Compatibility, IEEE Transactions on*, vol.30, no.3, pp.239-250.

[25] Bury, M., Yashchyshyn, Y. (2007). Pulse Response of UWB Antenna: Meaning and Simple Measurement Procedure. In Proc. *Antennas and Propagation, 2007. EuCAP 2007. The Second European Conference on*, pp.1-6.