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Measurement of Special Shielding Materials at S and C Band Using Improved Free-Space Transmission Technique

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***Abstract*—In this paper we discuss state of the art in the field of shielding materials investigation. Two types of newly manufactured shielding materials (nonwoven and fabric) were measured using improved free-space transmission technique at 2-5 GHz depending on electromagnetic wave (EM) polarization and antenna to specimen distance. Results of shielding effectiveness (SE) evaluation based on measured complex transmission coefficients (S_{21}) were presented and compared with SE measured using coaxial transmission line technique. Also results of surface resistance measurements with the four-probe technique for the test materials are shown.**

***Keywords*—Nonwoven, fabric, shielding effectiveness, free-space measurements, surface resistivity.**

I. Introduction

THE problem of protection from electromagnetic radiation (EMR) and electromagnetic interference (EMI) has been very actual during the last years [1], [2]. Current progress in electronics and telecommunications indicates that number of EMR, EMI sources will only increase with the course of time. Therefore protection of biological objects as well as electronic equipment has becomes the problem of paramount importance. Especially it concerns frequency ranges up to 1 kHz for EM sources of high intensity (heat stations, power transmission lines, transforming stations etc.) and of middle intensity (telecommunication equipment) – from 1 to 10 GHz. These factors in turn stimulate development of new protective means.

Electromagnetic shielding which is based on application of special shielding materials is the most used solution [3]. Lately thanks to nanotechnologies, new knowledge in physics, chemistry, material science, new testing possibilities shielding materials have evolved from simple metal sheets, foils, nets and composites to complex structures with desirable characteristics meeting various customers' requirements [4]–[6].

Among modern shielding material it is worth to mark conductive fabrics which are light, flexible, air-penetrable, inexpensive, have adequate shielding factor, can be used for protective clothing, covers, wall coating, curtains. Conductive nonwovens are less flexible and less air-penetrating, but also are promising. These types of materials are considered in the paper.

Shielding effectiveness is a key parameter which characterizes shielding properties of a material and indicates how quantitatively (in decibels) incident EM waves are attenuated by a shield. SE depends on a few factors such as material own parameters (conductivity, permittivity, permeability), its internal structure, shield geometry, frequency, distance from a source, EM wave polarization. Shielding effectiveness can be measured or predicted based on a theoretical model [7]–[10].

Direct measurement of shielding effectiveness is the simplest way to define it, besides, in some cases there is a possibility to choose a measurement technique which would simulate conditions close to real shield application, for example, shield sizes, construction, EM wave polarization and arbitrary direction of incidence. The most widespread techniques for shielding materials investigation are based on measurements using coaxial transmission line [11], [12], anechoic chamber [13]–[15] and reverberation chamber [16]–[19]. These methods have one common principle: SE is evaluated from measured S-parameters, and two measurements are performed – reference one without a test material and basic one with a test material. It is worth to say that mentioned methods are reflected more or less in standards and recommended for testing shielding gaskets, materials and enclosures [20]–[23]. But these standards (methods) do not take into account features of a material – its inner structure, inhomogeneity, anisotropy.

Coaxial transmission line techniques have limited operating frequency band depending on a system sizes, small specimens which require special preparation are used here, and there is no possibility to investigate parameters versus EM wave polarization. However the method exhibits the smoothest experimental curves, is practically free from resonance-like effects which appear in other methods [24].

Free-space techniques are realized in anechoic chamber, where large flat specimen is illuminated with normally or obliquely falling EM wave with vertical or horizontal polarization. Such measurement system's frequency range is not limited and depends only on antennas' and network analyzer's operating frequencies. But here experimental results can be interfered due to imperfect absorbers, mismatch of cable to antenna and antenna to load impedances, finite sizes of test specimen [25]. Time-domain reflectometry belongs to the free-space measurements as well. The technique enables

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to investigate materials with reflected probe pulse and then transfer results to frequency domain [26], [27].

Mode-stirred reverberation chamber (MSRC) is a large-size shielded room, type of resonant cavity, where generated EM field is statistically uniform inside the volume due to stirrer. Here it is possible to test very large shields having various configurations at frequencies from 1 GHz (for large-size MSRC) and depending on EM wave polarization. Nested reverberation chamber (NRC) or two connected NRC with opening where a test material is placed, shielded enclosure with opening are also used for SE testing. The main problem in such structures is multiple reflections and resonances impairing quality of experiments.

There is no one universal measurement technique which would be good fitted for testing of shielding materials of various types. Different techniques will produce different experimental SE. Choosing a technique is individual in every case and depends on desired frequency range, specimen sizes, available equipment, accuracy, material properties and structure.

Theoretical SE prediction is important at the stage of shields designing and investigation before mass manufacturing. Some models for nonwovens and fabrics have been proposed and are in good agreement with experimental data [8]–[10]. When modeling SE three basic mechanisms of interaction of EM wave and a material are separated: shielding due to reflection, multiple reflections within a material and absorption. Models are developed based on knowledge about own material parameters – permittivity $\dot{\epsilon}$, permeability $\dot{\mu}$, conductivity σ; its structure and composition; thickness d. Some parameters can be available from manufacturer; some of them can/should be measured. For example, permittivity and permeability can be evaluated for free-space or coaxial transmission line techniques from measured complex S-parameters using known algorithms [28], [29], also it is possible to find the parameters from reverberation chamber measurements [30]. Surface and bulk resistivity (conductivity) can be measured using four-probe or two-probe techniques [31]–[33]. Thickness can be measured with micrometer screw gauge or estimated using electron microscope.

In this work the free-space transmission technique have been chosen for investigation due to its features: it enables to model illumination of test material with a plane EM wave (far field) and depending on wave polarization, which is especially important for anisotropic materials (based on measurements of DC surface resistance); this technique is non-destructive, does not require a special sample preparation, uses large flat sheet for testing and is suitable for materials investigation in wide frequency range.

II. Subject of Investigation

Two types of special shielding materials of new generation were investigated. The materials are newly manufactured, so their shielding properties have to be estimated. The first material (A) is a nonwoven polypropylene-based with sputtered metal layer (Fig. 1a). The composite thickness is 0.7mm. The second material (B) is meshy metalized fabric with thickness about 0.45mm (Fig. 1b). Both materials due to manufacturing technology have irregular structure (Fig. 2).

a) *b)*

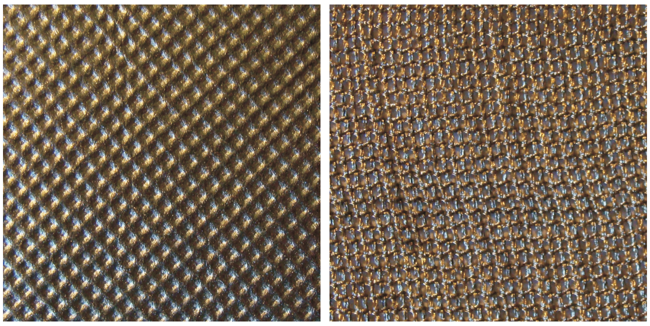

Fig. 1. Test materials: a) material A, b) material B.

a) *b)*

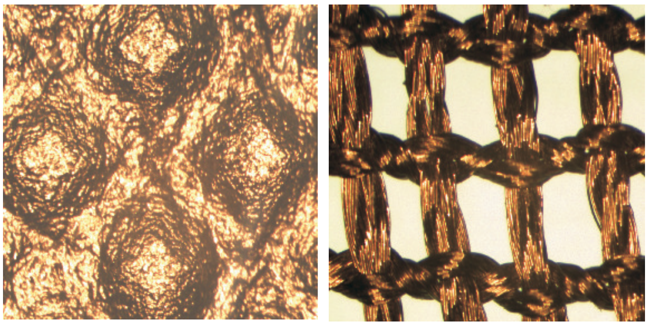

Fig. 2. Electron microscope pictures: a) material A, b) material B.

For the material A and B surface resistances R_S, Om/□ as a function of time (t=10 min.) were measured with DC four-probe technique in eight points. Self-made measurement set-up is shown in Fig. 3. In Fig. 4 lines along which electrodes were placed are presented. Experimental surface resistances (Fig. 5) show that current flowing in vertical, horizontal and diagonal directions is different. This may confirm the assumption that shielding fabrics are anisotropic. Besides, specimen A exhibited significant inhomogeneity depending on which points electrodes were applied in (Fig. 5a). Its surface resistances varied from 66 to 513 Om/□ in more conductive

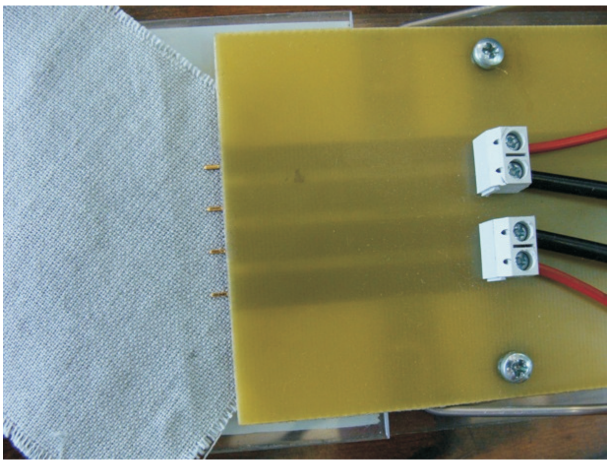

Fig. 3. Four-probe technique for measurement of surface resistance.

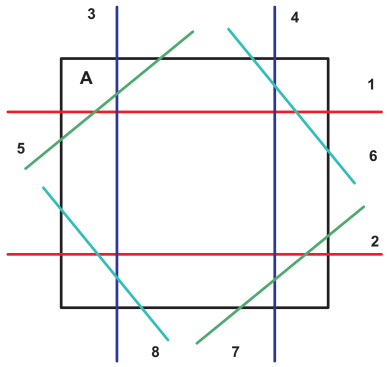

Fig. 4. Directions of electrodes apposition (8 points).

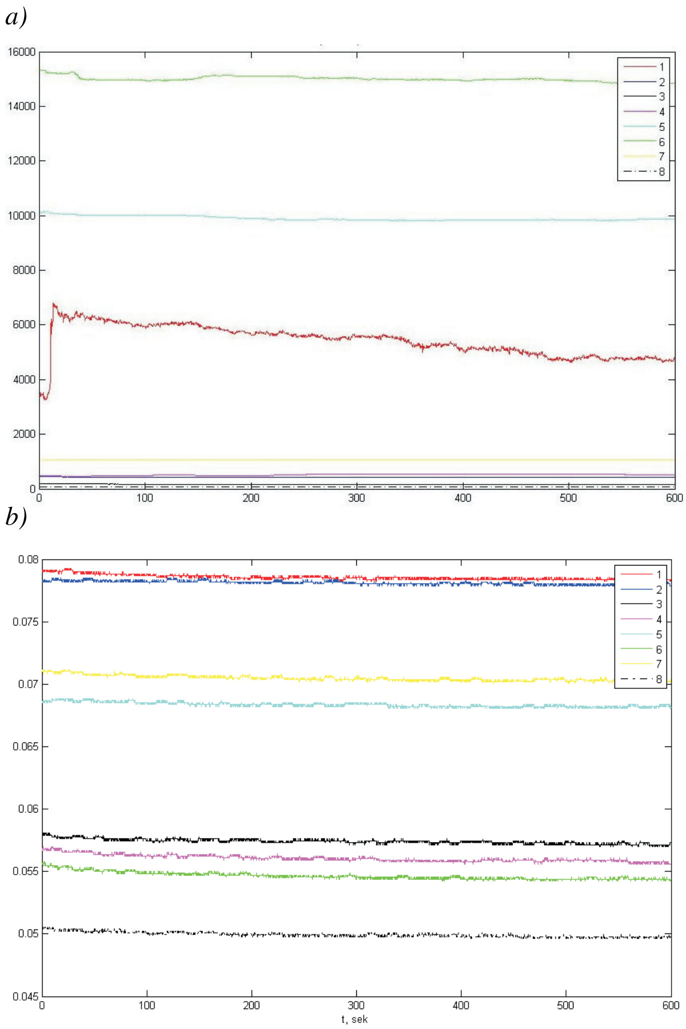

Fig. 5. Surface resistance vs time in eight test points: a) specimen A, b) specimen B.

places and from 1070 to 15000 Om/□ for less conductive ones. Surface resistance for specimen B (Fig. 5b) does not have such great deviations; the material can be considered practically as homogeneous, that is concerned with its manufacturing technology and structure.

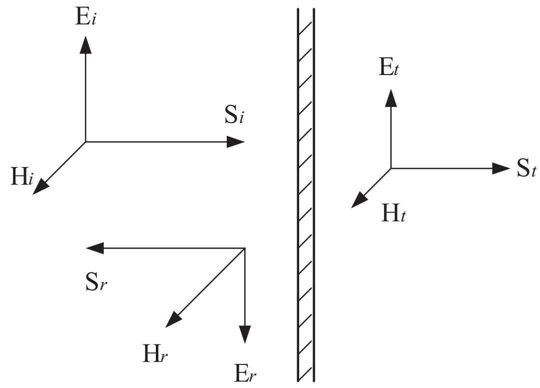

Fig. 6. Model of normal incidence of EM wave onto media boundary.

III. Measurement Technique

Free-space transmission method implements the model of EM wave propagation in free space with its normal incidence onto boundary between two media (Fig. 6) [34]. The model is described by reflection (R) and transmission (T) coefficients expressed through electrical and magnetic parameters of medium – complex permittivity $\dot{\epsilon}$ and complex permeability $\dot{\mu}$ (1).

$$\dot{R} = \frac{E_r}{E_i} = \frac{\dot{Z}_2 - \dot{Z}_1}{\dot{Z}_2 + \dot{Z}_1}; \quad \dot{T} = \frac{E_t}{E_i} = \frac{2 \cdot \dot{Z}_2}{\dot{Z}_2 + \dot{Z}_1}; \tag{1}$$

where E_i, E_r, E_t – electric field intensity for incident (i), reflected (r) and transmitted (t) wave; $\dot{Z}_{1,2} = \sqrt{\frac{\dot{\mu}_{1,2}}{\dot{\epsilon}_{1,2}}}$ – wave impedance in free space (1) and material (2).

The measurement technique based on the propagation model makes it possible to measure complex reflection and transmission coefficients and then find not only shielding effectiveness, but also using numerical methods estimate $\dot{\epsilon}$ and $\dot{\mu}$.

Performing experiments in free space in ideal case we have to fulfill exactly two basic requirements: 1) a specimen has to be in far field, i.e. antenna to sample distance $r > \frac{2 \cdot D^2 \cdot f}{c}$, where D – is an antenna maximal size, and 2) a specimen size has to be three times larger than 3dB antenna beam width to eliminate diffraction effect. At low gigahertz frequencies antennas have 3dB beam width wide enough ($\sim 60°$) and it diminishes with frequency growth. At frequencies above 30 GHz it is possible to apply focusing dielectric lenses resulting in plane wave, which solve the problem of far field [35]. Unfortunately at lower frequencies there is no such solution, and we need to find reasonable balance between two requirements provided that we have anechoic chamber and a specimen with fixed sizes and antennas with defined characteristics. Besides, we need to take into account that absorbers within a chamber are imperfect, so re-reflected waves will interfere with useful data. Standing wave appearing between an antenna and a sample as well as influence of a shielding material to antenna impedance also will reduce quality of experimental data.

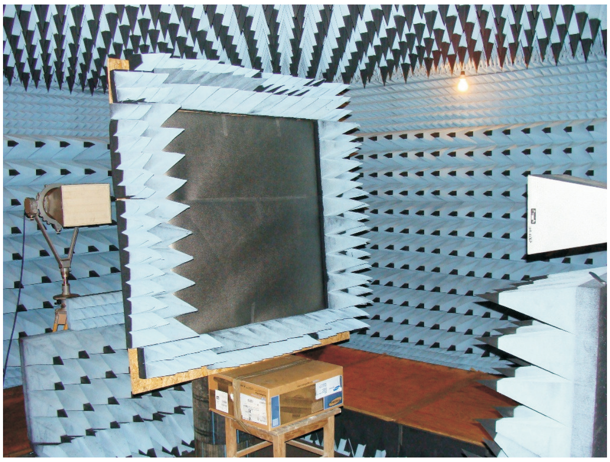

Fig. 7. Experimental set-up in anechoic chamber.

IV. Experimental Set-Up

Measurement set-up (Fig. 7) consists of the following units: transmitting and receiving antennas type П6-23A, vector network analyzer HP E5071C and a stand with tested materials. The specimens 1m $\times$ 1m were placed into special absorbing frame which served to reduce resonant effects due to interaction of incident EM wave with specimen edges (diffraction). Distances between an antenna and a material were 1,5m and 1m. Antennas polarization was changed to test its influence.

Connecting cables were calibrated with E-Cal. Instead of measurement set-up calibration a reference measurement "through" was made – transmission with no material in the absorbing frame.

S_{21} parameters were measured and then normalized:

$$S_{21} = S_{21through} - S_{21material}, \text{ dB} \qquad (2)$$

where $S_{21through}$ – reference value (dB); $S_{21material}$ – value for test material (dB).

These S_{21} parameters are shielding coefficients (SE).

V. Experimental Results

Shielding effectiveness has been estimated for material A and material B based on (2) without any additional data processing for two distances between an antenna and a material, for vertical (VP) and horizontal polarization (HP), without and with absorbing frame (Fig. 8 – Fig. 10).

As one can see from the diagrams, shielding effectiveness for material A with absorbing frame is more flat and has no pronounced peaks and slopes (Fig. 8). Shorter antenna to specimen distance for material A for vertical polarization produces flat enough curve, but for horizontal polarization there are several peaks (Fig. 9). For material B shielding effectiveness for horizontal polarization is more uniform (Fig. 10).

In general the results show relative uniformity, it is possible to denote trends. All curves have resonance-like effects that can be explained by multiple reflections due to imperfect absorbers inside anechoic chamber, diffraction effect, standing wave appearance and influence of shielding specimen to antenna impedance.

In Fig. 11 shielding effectiveness measured with coaxial transmission line technique at 0.1-1.5 GHz for materials A and B is presented for comparison. Other specimens of the materials A and B were used for measurements with the technique. Experimental set-up has been implemented according to ASTM D4935-99 standard at our department by MSc. eng. J. Janukiewicz (Fig. 11a). As we can see from Fig. 11c for material B at 1.5 GHz SE is about 45 dB. For free-space transmission technique SE is in the range of 40-45 dB at 2-5 GHz. Here the techniques show good conformity. For specimen A for the coaxial transmission line method SE at 1.5 GHz varied from 7 to 18 dB (Fig. 11b, the worse and the best cases for series of experiments are presented). During the experiments the material showed high inhomogeneity, SE significantly changed depending on test region. These results and observations have direct correlation with our measurements of surface resistance for the material (Fig. 5a). SE obtained for the material A with the free-space transmission technique is about 35 dB at 2-5 GHz. Such great difference in SE values for the two techniques can be explained only with the material inhomogeneity. Besides, it should be taken into consideration that in the free-space transmission technique large specimen are illuminated, that makes it possible to obtain some averaging, effective SE for all illuminated region, while the coaxial transmission line method allows testing only small regions and with no regard to EM wave polarization.

Conclusions

Improved free-space transmission technique has been presented. Shielding effectiveness for nonwoven and textile shielding materials has been measured depending on EM wave polarization, antenna to specimen distance. Presented results demonstrate relative uniformity with visible trends and some resonance effects possibly connected with multiple reflections inside anechoic chamber, diffraction effect, presence of standing wave and influence of shielding material to antenna impedance. The results have been compared with ones measured with the coaxial transmission line technique and showed good conformity for the material B, which is more homogeneous. But for highly inhomogeneous material A shielding effectiveness differ in about 15-20 dB. Also results of surface resistance measurement with the four-probe technique have been presented.

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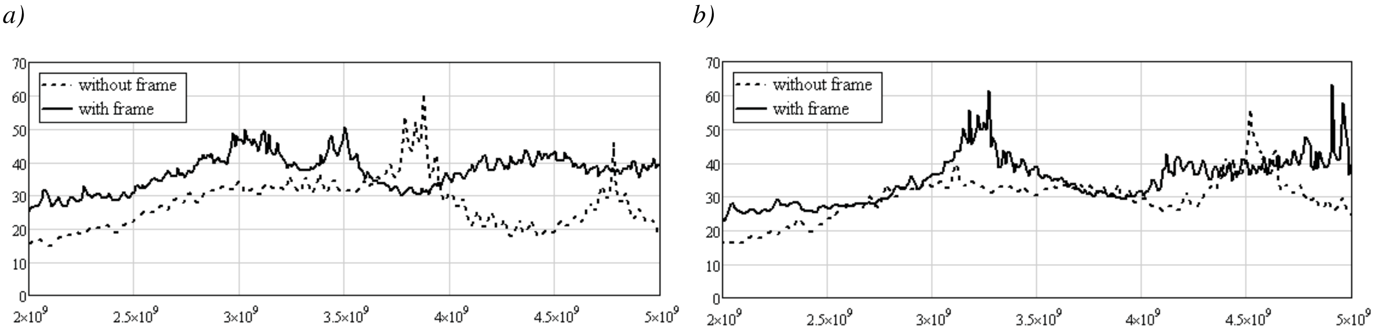

Fig. 8. Shielding effectiveness vs frequency, without and with absorbing fame, specimen A; a) VP, b) HP.

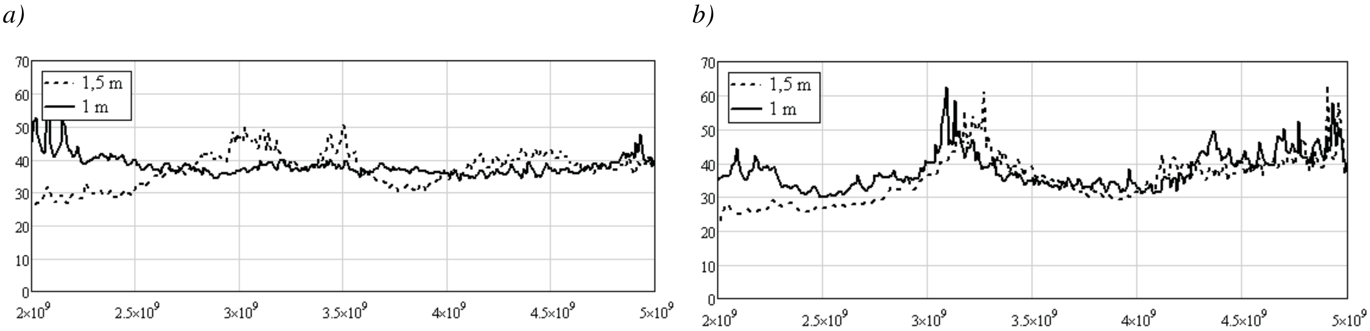

Fig. 9. Shielding effectiveness vs frequency, absorbing frame, two “antenna to specimen” distances, specimen A; a) VP, b) HP.

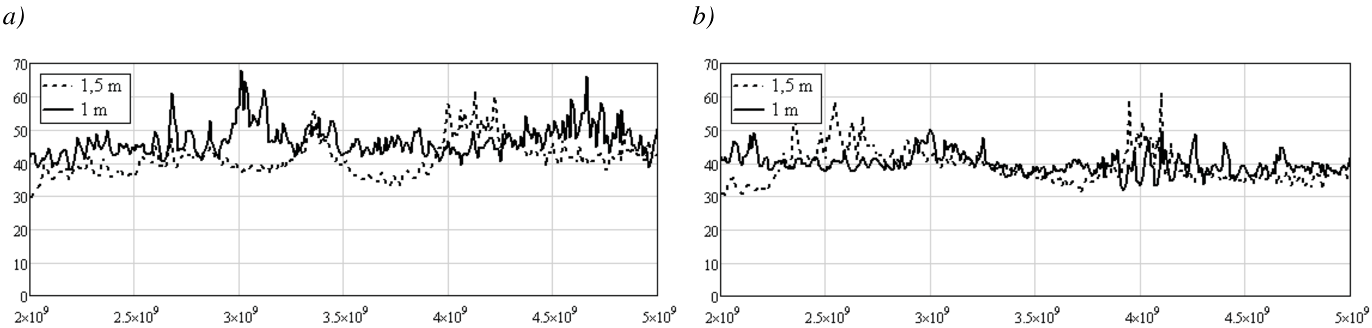

Fig. 10. Shielding effectiveness vs frequency, absorbing frame, two “antenna to specimen” distances, specimen B; a) VP, b) HP.

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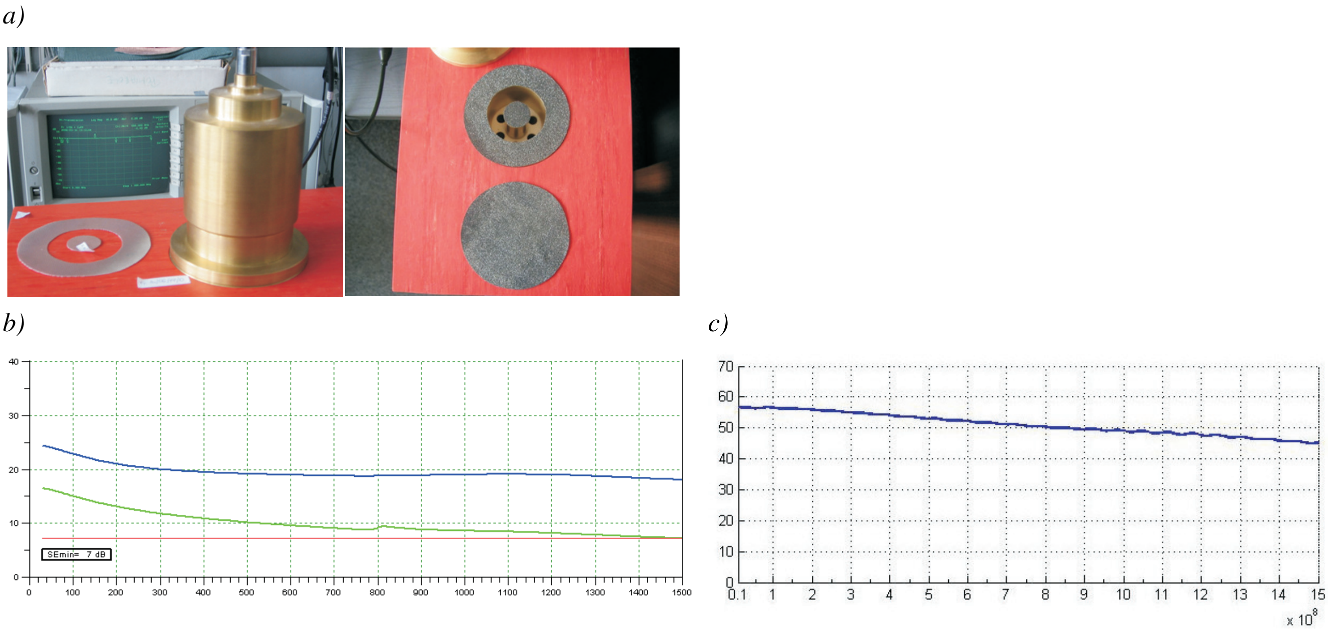

Fig. 11. Coaxial transmission line technique: a) experimental set-up; b) SE vs frequency [MHz], specimen A; c) SE vs frequency [Hz], specimen B.

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