Conductive textile structures and their contribution to electromagnetic shielding effectiveness

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ABSTRACT – REZUMAT

Conductive textile structures and their contribution to electromagnetic shielding effectiveness

Fabrics for electromagnetic shielding are especially relevant in nowadays context, contributing to human's protection and wellbeing and to proper functioning of electronic equipment, in relation to electromagnetic compatibility. Fabrics with electromagnetic shielding properties employ two main technologies, namely insertion of conductive yarns and application of conductive coatings. Magnetron sputtering is a modern technology to enable conductive coatings with thickness in the range of nanometers onto fabrics. This paper aims to analyze contribution of various conductive textile structures out of both fabrics with inserted conductive yarns and coatings to Electromagnetic shielding effectiveness (EMSE). EMSE was measured in the frequency range of 0.1–1000 MHz by using a TEM cell according to standard ASTM ES-07. Results show a gain of 10–25 dB when introducing silver yarns in warp/ weft direction, a variation of 5–35 dB between conductive yarns out of silver and stainless steel and an up to 12 dB gain out of thin copper coating by magnetron plasma onto the fabrics with inserted conductive yarns.

Keywords: *stainless steel yarns, silver yarns, thin copper coating, fabrics, electromagnetic shielding*

Contribuția la atenuarea electromagnetică a unor structuri textile cu proprietăți conductive

Materialele textile pentru ecranare electromagnetică sunt deosebit de importante în contextul actual, având în vedere aplicațiile destinate protecției sănătății umane și funcționării adecvate a echipamentelor electronice, în conformitate cu legile comptabilității electromagnetice. Materialele textile cu proprietăți de ecranare electromagnetică pot fi obținute prin două principii tehnologice: inserarea de fire conductive și aplicarea de acoperiri conductive. Plasma de tip magnetron sputtering reprezintă o tehnologie modernă, care permite acoperiri conductive de ordinul nanometrilor pe materialele textile plane. Acest articol analizează contribuția la atenuarea electromagnetică pentru diferite structuri textile, obținute atât prin inserare de fire conductive cât și prin acoperire în plasmă. Atenuarea a fost determinată în domeniul de frecvență 0,1–1000 MHz, prin utilizarea sistemului de măsuare cu celulă TEM, în conformitate cu standardul ASTM ES-07. Rezultatele arată o creștere a atenuării de 10–25 dB la inserarea firelor de argint în direcția urzelii/bătăturii, o variație de 5–35 dB între firele conductive de argint și inox și o creștere de până la 12 dB datorată acoperirii în plasmă magnetron de cupru pe materialele textile plane cu fire conductive inserate.

Cuvinte-cheie*: fire de inox, fire de argint, acoperire de cupru, materiale textile, ecranare electromagnetică*

INTRODUCTION

Electromagnetic shielding achieved by flexible conductive fabrics represents a valuable solution in nowadays radiation polluted environment. Its application range reaches shielding of various frequencies out of various radiation sources, such as: PPE for working on broadcasting antennas, curtains for protection against GSM or WiFi signals, tents for ensuring data privacy in outdoor environment etc. The provisioned applications are related on one hand towards protection of human's health against the non-ionizing radiation, and on the other hand towards proper functioning of electronic equipment by ensuring electromagnetic compatibility principles [1, 2].

Main topic on electromagnetic shielding is the modality of achieving electrically conductive structures on fabrics, therefore most of the papers are oriented towards the description of new manufacturing methods for achieving such materials, reporting the measured values of the shielding effectiveness. The scientific literature distinguishes two main modalities: insertion of conductive yarns and coating with conductive layers [3]. Each of them involves specific technologies, such as insertion of conductive yarns by weaving or knitting for the first case and application of conductive layers on the fabric surface for the second case. The conductive yarns may be achieved by blending extremely thin metal fibers with various textile fibers like polypropylene [4] or polyester fibers [5], as well as by covering an internal metallic wire with a natural or synthetic yarn [6]. Various technologies are available for achieving the coating of fabrics, among which are: painting with metallic particles, vacuum metallization, spraying, electro less plating, conductive adhesive tapes etc. [7]. Also, the utilization of novel materials for coating the fabrics is reported, among them being those based on carbon nanotubes [8], low pressure plasma treatment followed by soaking in amine-treated multiwall carbon nanotubes [9] or coating by combinations of carbon nanotubes, conductive polymers and metal nanoparticles [10]. One modern technology to impart conductive layers to fabrics is plasma coating by magnetron sputtering, using mostly metallic targets [11].

Another topic of special interest related to electromagnetic shielding of fabrics is related to the modelling of shielding effectiveness for a certain frequency range for fabrics with electrically conductive structures, both by insertion of conductive yarns [12–15] and by coating with conductive layers [3], while other papers deal with new methods of experimental determination of shielding effectiveness for fabrics [16]. Finally, a few works discuss on the clothing comfort behaviour and influence of washing/drying cycles on values of EMSE of fabrics [17–20].

In this context, the present paper deals with the development of a new type of manufacturing method and considers a combined approach based on the production of fabrics with inserted conductive yarns which are coated by magnetron sputtering by a metal layer. The main aim of our work is to analyze how combined modalities for achieving electrically conductive structures on fabrics (insertion of conductive yarn and magnetron plasma coating) contribute to electromagnetic shielding effectiveness (EMSE) in the frequency range of 0.1–1000 MHz.

MATERIALS AND METHODS

Materials

Five samples of woven fabrics with inserted conductive yarns out of silver (Ag) and stainless steel (SS) and copper plasma coating were manufactured and analyzed regarding EMSE. Figure 1 shows the experimental concept of the five fabric samples used in this research, evidencing how the materials were consecutively increasing their complexity to allow the evaluation of the shielding in each step of the processing.

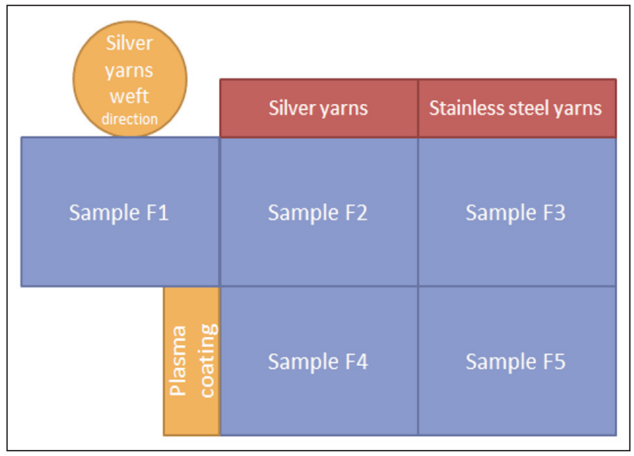


Fig. 1. Scheme of fabrics with electric conductive structures

The designed and manufactured woven fabric samples had the structures described in table 1.

The grid of the fabrics with silver and stainless steel yarns in warp and weft direction was set on 4 mm. Copper coating was achieved by magnetron plasma coating on both fabrics with inserted silver (1200 nm) and stailess steel yarns (400 nm).

Table 2 presents some of the physical-mechanical properties of the 5 fabric samples, such as mass, density and thickness.

Table 1

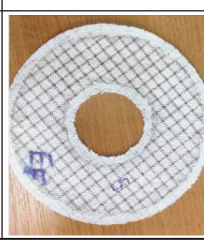
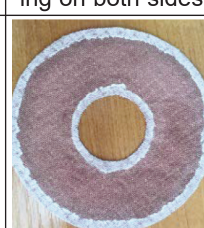
FABRIC STRUCTURES WITH CONDUCTIVE ELEMENTS (CONDUCTIVE YARNS AND COATINGS)					
Sample code	**F1**	**F2**	**F3**	**F4**	**F5**
Main yarns	Cotton yarn (Nm 50/2)	Cotton yarn (Nm 50/2)	Cotton yarn (Nm 50/2)	Cotton yarn (Nm 50/2)	Cotton yarn (Nm 50/2)
Conductive yarns	Silver yarn (Statex 117/17 dtex 2 PLYHC+B)	Silver yarn (Statex 117/17 dtex 2 PLYHC+B)	Stainless steel yarn (Bekinox BK50/2)	Silver yarn (Statex 117/17 dtex 2 PLYHC+B)	Stainless steel yarn (Bekinox BK50/2)
Warp	NA	Ag in warp float repeat 6:2	SS in Warp, float repeat 6:2	Ag in warp float repeat 6:2	SS in Warp, float repeat 6:2
Weft	Ag in weft float repeat 6:1	Ag in weft float repeat 5:2	SS in Weft, float repeat 6:2	Ag in weft float repeat 5:2	SS in Weft, float repeat 6:2
Weaving type	plain weave	plain weave	plain weave	plain weave	plain weave
Plasma coating details	NA	NA	NA	1200 nm Cu coating on both sides	400 nm Cu coating on both sides
Sample prepared for EM shielding measurements					

Table 2

PHYSICAL-MECHANICAL PROPERTIES OF ACHIEVED TEXTILE STRUCTURES				
Fabric code	**Specific mass (g/m^2)**	**Fabric density (no. yarns/10 cm)**		**Thickness (mm)**
		Warp	Weft	
F1	329	650	340	0.490
F2	118	168	150	0.495
F3	143	180	170	0.550
F4	144	170	154	0.564
F5	155	180	170	0.580

Methods

Plasma coating technique

The Cu coating of the textile fabrics was performed into a dedicated spherical stainless steel vacuum chamber (K.J. Lesker), pumped out by an assembly of a fore pump and turbomolecular pump (Pfeiffer), which allowed the obtaining of a base pressure down to 3×10^{-5} mbar. The chamber is provisioned with a magnetron sputtering gun from K.J. Lesker, accommodating a high purity Cu target (99.999%). Enhanced deposition uniformity was achieved by rotating the samples during the deposition process (200 rotations/min). A constant Ar (6.0) flow of 50 sccm was continuously introduced into the chamber by means of a Bronkhorst mass flow controller, so that the pressure established during the process was 5.3×10^{-3} mbar. The discharge was ignited with an RF generator (13.56 MHz) – model CesarR provisioned with an automatic matching box for adapting the impedance. The deposition time was set to insure a coating thickness of 400 nm and 1200 nm on both sides of the textile fabrics.

A sketch of the experimental set-up was provided elsewhere [20]. Figure 2 presents the magnetron plasma equipment of INFLPR, evidencing the copper discharge above the textile surface.

Insertion of conductive yarns

The achieved woven fabrics with inserted conductive yarns were manufactured at SC Majutex SRL, Barnova Iasi. Stainless steel yarns (Bekinox BK 50/2) and silver yarns (Statex 117/17 dtex) were inserted both in warp and weft system, after a weaving preparation process. Figures 3 and 4 present the warping machine and the weaving loom of type SOMET width 1.90 m.

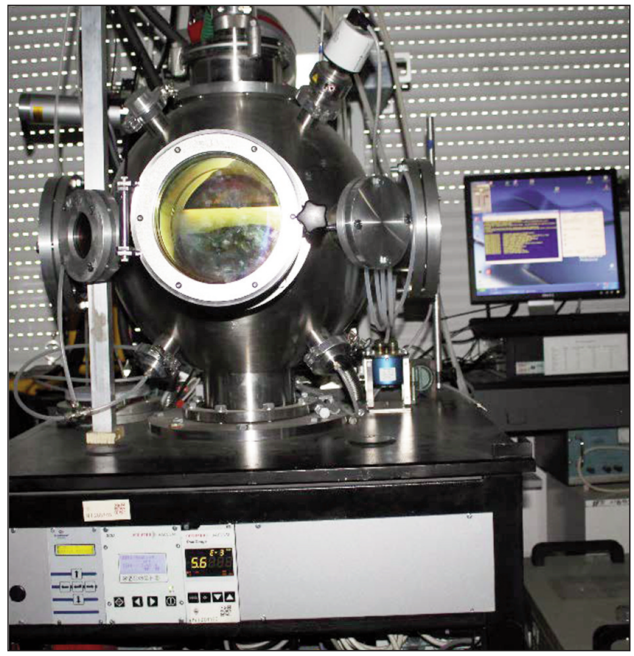


Fig. 2. Magnetron plasma equipment of INFLPR

Shielding effectiveness measurement

Electromagnetic shielding effectiveness (EMSE) is defined as:

$$EMSE = 10 \log_{10}\left(\frac{\textit{power of incident signal}}{\textit{power of transmitted signal}}\right) \quad (1)$$

Shielding effectiveness of fabric samples was measured via a coaxial TEM cell, according to standard ASTM ES-07. A scheme of coaxial TEM cell and a load fabric sample is presented in figure 5.

Tested fabric samples were tailored in annular shape having an outer diameter of 100 mm and an inner diameter of 30 mm and fixed onto the cell by means of colloidal Ag paste. The measurement system included a signal generator E8257D, a Power amplifier model SMX5, the Coaxial TEM cell model 2000 and an Oscilloscope Tektronix model MDO3102.

Fig. 3. Warping machine at SC Majutex SRL

Fig. 4. SOMET Weaving loom at SC Majutex SRL

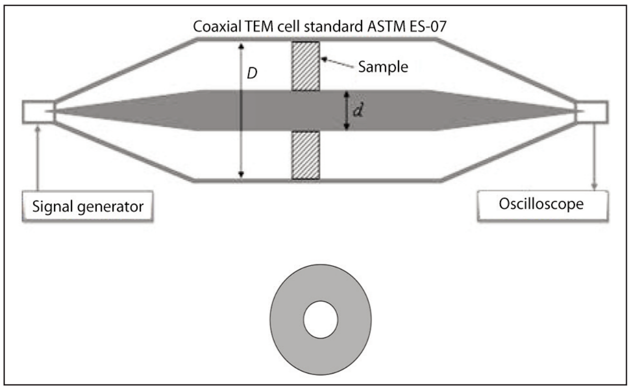


Fig. 5. Scheme of TEM cell and load sample according to standard ASTM ES-07

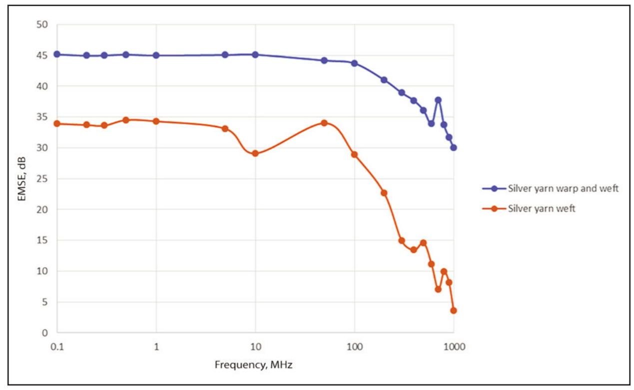


Fig. 6. Contribution to EMSE of inserting silver yarns both in warp and weft direction

EXPERIMENTAL

Woven fabrics with conductive yarns out of silver and stainless steel were manufactured by insertion in warp and weft direction, in order to obtain a conductive grid at the distance of 4 mm (Samples F2 and F3). 100% cotton was selected for the support textile material, due to its good dielectric properties and easy process ability. Sample F1 has silver yarns only in weft direction and was included in the experimental scheme, in order to underline the contribution to EMSE of the sample F2, having silver yarns both in warp and weft direction (figure 1). Samples F2 and F3 were processed by magnetron plasma deposition with a thin Copper coating of 1200 nm, respectively 400 nm, yielding samples F4 and F5. All five samples were measured by same electromagnetic shielding effectiveness (EMSE) investigation system, namely via TEM cell standard ASTM ES-07. The results of EMSE were comparatively assessed by underlining following aspects regarding fabric structures and raw materials:

- The contribution to EMSE of inserting silver yarns both in warp and weft direction when compared to inserting yarns only in weft direction (figure 6);
- The contribution to EMSE of the raw materials (silver and stainless steel), forming the grid of conductive yarns (warp and weft direction) with a distance of 4 mm (figure 7);
- The contribution to EMSE of the copper plasma coating for the fabric with inserted silver yarns (figure 8);
- The contribution to EMSE of the copper plasma coating for the fabric with inserted stainless steel yarns (figure 9).

RESULTS AND DISCUSSION

Figures 6–9 show the experimental results of electromagnetic shielding effectiveness for the five studied woven fabrics samples.

Figure 6 presents comparatively the results recorded during the test of woven fabric denoted F1 (with silver yarns only in weft direction) and F2 (with silver yarns in both warp and weft directions). The superiority of F2 is proved in the whole range of frequencies. At low frequency (0.1...100 MHz) the difference is in the range of 10...12 dB while at higher frequency (100...1000 MHz) the difference lays in the range of 12 to 25 dB. The decrease of attenuation at high frequency is justified by the fact that, generally, the reflection term is the main one for electric thin (but compact, not meshed) shields having good conductivity properties.

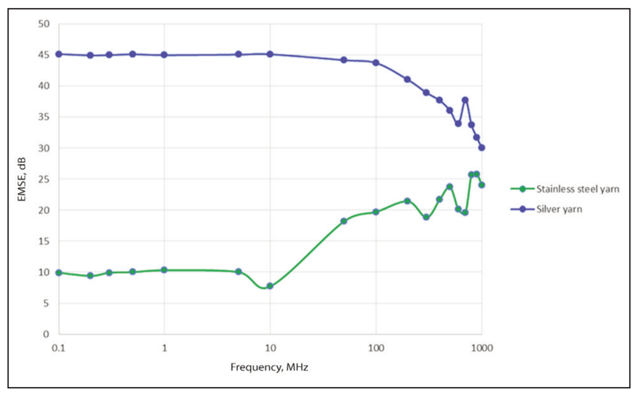


Fig. 7. Contribution to EMSE related to raw materials of inserted yarns (silver and stainless steel)

Figure 7 compares the results obtained during the tests of woven fabrics with silver and stainless yarns in warp/weft directions, the metallic meshgrid with square eyes with side of 4 mm. The graph shows the superiority, regarding the attenuation level, of the grid with good conductive wires (silver) vs. the grid with magnetic properties (steel) of about 25–35 dB in the range of 0.1–100 MHz, this one being reduced at 5–25 dB for the frequency range of 100–1000 MHz. This behaviour is explained by the properties of the two types of materials, knowing that in low frequency range the good conductive ones present better attenuation of reflection term, this one decreasing with frequency. On the other hand, at high frequencies the obtained values for both samples are in accordance with the known relation of attenuation, valid for metallic meshgrids [21]:

$$EMSE = 20 \log \frac{\lambda}{2g} \ [\text{dB}] \qquad (2)$$

where λ is the plane wave electromagnetic radiation wavelength and g – the side of meshgrid.

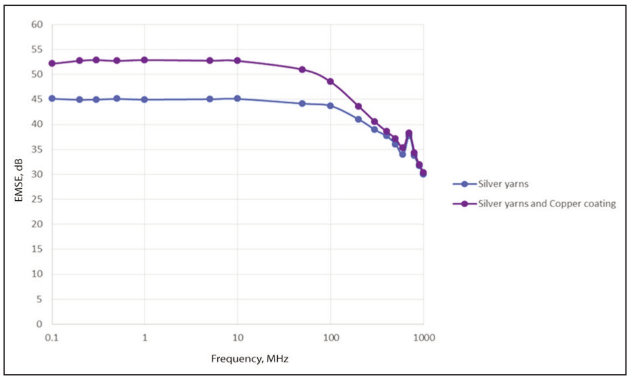


Fig. 8. Contribution to EMSE of copper plasma coating on fabrics with inserted silver yarns

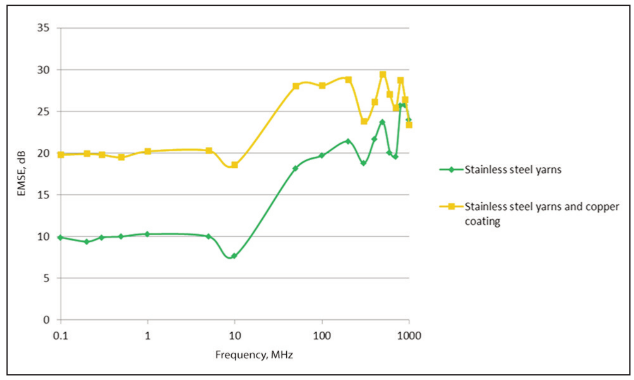


Fig. 9. Contribution to EMSE of copper plasma coating on fabrics with inserted stainless steel yarns

The values are independent of the own electric/magnetic properties of metals involved. As example, for 1000 MHz, λ = 0.3 m and because g = 0.004 m, the $EMSE$ = 31.5 dB, value close to those measured.

In order to enhance the shielding properties of woven fabrics tested up to now, these samples containing metallic meshgrids were covered with a thin layer of copper, as described in the section 2. Figure 8 shows, by comparison, the attenuation of fabric with silver yarns with and without copper coating. The copper coating ensures a higher attenuation of about 3–8 dB on the entire frequency domain explored.

Similarly, the coating with copper of woven fabrics containing stainless steel yarns improves the EMSE with about 5–12 dB on the entire explored frequency range. The results were shown in the figure 9.

CONCLUSIONS

This paper describes novel manufacturing methods to achieve flexible electromagnetic shields, out of woven fabrics. Both main technologies to impart conductivity to fabrics, namely insertion of conductive yarns in the woven structure and coating with conductive layers were applied and comparatively assessed. Electromagnetic shielding effectiveness was determined according to standard ASTM ES07, via TEM cell. Electromagnetic shielding properties of woven fabrics with metallic yarns, with conductive or magnetic properties, disposed in warp or warp/weft directions and also the effect of copper coating of these fabrics was studied. The superiority of metallic mesh grids comparing to ones having simple parallel yarns was proven. Concerning the addition of copper as coating layer, a weak enhancement of shielding effectiveness was observed for sample containing silver meshgrid and a more effect was recorded in the case of material with stainless steel yarns insertion. These results allow the proper choice of woven fabrics with metallic yarns in accordance to the imposed electromagnetic attenuation for different applications.

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