

The Impact of Structure of Shielding Textiles on the Attenuation of Electromagnetic Waves in the Microwave Range

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ABSTRACT The study aims to identify and compare the attenuation of electromagnetic waves at 1.161 GHz and 2.45 GHz frequencies between uncoated and coated woven fabric samples, wherein the metal-contained yarns were used in a weft direction with an increasing quantity per 10.5 mm long repeat of fabric length. Plain weave fabric samples were made of three different types of metal-containing yarns in the weft direction. The quantity of metal-contained yarns per centimeter was increased by every sample. In addition, samples were coated with polyurethane and graphite layers. The characteristics (thickness and surface density) of fabric samples were determined. The attenuation of electromagnetic (EM) waves was measured and compared for uncoated and coated samples. Two horn antennas and a network analyzer were used to measure at 1.161 GHz and 2.45 GHz, respectively. The graphite coating made the attenuation higher for the samples with a lower content of metal-contained yarns. Still, this improvement was irrelevant for the samples with a more extensive content of metal-contained weft yarns.

KEYWORDS Attenuation, fabric, graphite coating, metal contained yarns.

I. INTRODUCTION

ITH the fast development and continuous use of communication technologies, the environment gets more polluted with electromagnetic (EM) fields (nonionizing radiation) that affect human health negatively. Day by day, people are exposed to radiation from the wireless internet and smartphones. Medical scientists created such a disease designation as electromagnetic sensitivity. People with this problem mention such unpleasant symptoms as sleep disturbances, headache, nervousness, tiredness, inability to concentrate, heart disease, redness of the skin, eye disease, depression, back pain, circulatory problems, and tremors [1, 2]. The reason for these problems is deeply found at the cellular level. Since the 1970s, many experiments have been conducted to prove the adverse effect of EM fields on live creatures, such as animals and human cells. In publications for the last decade, specialists and scientists have summarized enough research to review topics, such as the effects of radiofrequency EM field exposure on male fertility, pregnancy, and birth outcomes [3], oxidative stress [4], cellular DNA damage, changes in non-steroid hormone levels, heat shock protein induction, and neurological and neuropsychiatric effects [5].

The causes of human health disorders have been studied at the cellular level. For example, in research [6], the rats were exposed to 2.1 GHz for 6 and 12 hours to investigate oxidative stress and apoptosis. The results showed that exposure induced oxidative stress-mediated acute renal injury, depending on the length of exposure and dosage.

There are several preventive actions to reduce the negative impact of EM fields on the human body. It can be realized by shortening the exposure time to the source of radiation, e.g., by using the equipment or device as needed and increasing the distance from the equipment or device during usage. Another way people can be protected is by using special EM shields and screens [7]. The shields can be made from a metal mesh of planes and textile materials, e.g., woven or knitted fabrics and non-woven materials, with metal-contained coatings for shielding. As well these textile materials may consist of various structures' yarns or threads - synthetic yarns (polyester, polyamide), natural polymers (viscose, bamboo cellulose), or natural (cotton, silk) fibers blended or twisted with metal (copper, stainless steel, silver, gold), metalized (metal-plated filaments), and carbon filaments [8-13].

For example, woven fabrics (plain weave) from flax incorporating coated yarns with different content and distribution of silver have been developed and researched. The samples consisted of metalized yarns incorporated only in the weft direction, the warp direction, and both weaving

systems, making a grid of conductive yarns. The distances between the conductive yarns were 10 mm and 20 mm. Samples were exposed to 0.02–0.05 MHz and 2.4 GHz frequency radiation. The results showed that the more metalized yarns the fabric had, the better shielding effectiveness (SE) was observed [14].

Another study [15] was carried out on fabrics made from blended stainless steel and polyester yarns in combination with cotton yarns. Fabrics were made with different densities of metal-contained weft yarns, varying distances of metal-contained weft yarns, and fabrics with varying grid-size openings of stainless steel or polyester yarns. Samples were irradiated with electromagnetic waves that had frequencies ranging from 300 kHz to 1.5 GHz. High SE was observed at a frequency of 0.68 GHz for samples with an increased density of metal-contained weft yarns, with an increased proportion of these weft yarns, and for samples with a metal-contained yarn grid. The highest shielding value of 53 dB was obtained for the fabric with the maximum stainless content at the same frequency.

In Z. Liu's study, SE was measured depending on the fabric weave pattern (plain, twill, and satin) and the density of warps and wefts. Samples consisted of stainless steel and polyester/cotton fiber blended yarns and were irradiated with 2.2–2.65 GHz frequencies. The highest SE was observed for plain weave pattern fabric, followed by twill weave fabric. Satin weave fabric had the lowest SE. Concerning the density of the fabric, as it increased, SE also increased [16]. In turn, research [17] was carried out on the carbon filaments embedded in the weft and warp directions of glass fiber fabric, thus making a carbon grid with a cell opening of 1 cm × 1 cm. The samples were exposed from 18 GHz to 30 GHz, and it was observed that with increasing frequency, the shielding properties decreased.

Regarding the SE determination equipment and methods, an anechoic chamber [19], a waveguide and network analyzer [20] are used. SE is also measured by completely shielding textile bags in which the radiating device is deposited, and afterward, the difference is measured [21]. The principle of determination of SE is the same, while the measuring equipment and sample size may differ depending on the radiated wavelength [18].

In a previous study [22], we examined the shielding effectiveness of woven and graphite-coated samples, where the quantity of metal-contained weft yarns was doubled for every next sample, and measurements were done at a frequency of 870 MHz and 1.161 GHz. The goal of the current study is to identify and compare the attenuation of electromagnetic waves at 1.161 GHz and 2.45 GHz frequencies between uncoated and coated plain weave fabric samples made of polyester yarns (in the warp direction) and metal-contained yarns (in the weft direction) with increasing quantity per 10.5 mm long repeat of fabric length. As the developed fabric is intended to be integrated

into clothing, it is useful to clarify the attenuation properties at a frequency of 2.45 GHz to which people are exposed daily using smart devices. 1.161 GHz is used for aviation navigation and aviation mobile.

II. MATERIALS

In this section, the characteristics of the metal-contained yarns are given, and the incorporation of them in the fabric and the application process of graphite coating are described.

A. PREPARATION OF WOVEN SAMPLES

For woven sample preparation, there were three types of metal-contained yarns and multifilament polyester (PES) yarns in the weft direction, but for all the warps, polyester multifilaments were used. Different textures of metal-contained yarns were selected, considering factors such as the closest conformity to traditional textile yarns, the structure and chemical consistency of the yarns, and the possibility of using the yarns in automatic weaving looms. The composition and parameters of selected yarns are shown in the Table.

TABLE Metal-contained Yarns for Woven Samples Preparation

Code of the yarn	A	В		С	
Туре	Single spun yarn	Two-plied yarn formed from metal monofilament and PES multifilament yarn		Three-plied yarn formed from metal monofilament and 2 cotton yarns	
Composition	PES (82 %), steel (18 %)	PES (67 %)	Steel filament (33 %)	Cu filament coated with Ag (50 %)	Cotton (50 %)
Single yarn linear density, tex	30	20	10	10	10
Total linear density of plied yarn, tex	30	33		20	
Yarn thickness, mm	0,13	0,12		0,09	
Fiber diameter (d, µm)	-PES fiber, d=20; -steel staple fiber, d=10	-PES fiber, d=20; -steel fiber, d=30		-cotton fibers; -Cu fiber coated with Ag, d=30	
Resistance per 10 cm	2 kΩ	3,8 Ω		84,9 Ω	

The steel staple fiber of yarn A is the finest (0.01 mm) among the other metal filaments (0.03 mm) of the yarns. The highest resistance is observed in yarn A, which is explained

by its not-uniform structure of metal components. The steel staple fibers are short and connect to each other only by twisting, increasing the resistance. The resistance of yarns B and C is much smaller than that of yarn A, because these yarns have continuous metal filaments in their composition. Fabric samples were made in a plain weave pattern using an industrial pneumatic loom, Omni-4-R. The density of the weft was 140 yarns per 10 cm, and the density of the warp was 400 yarns per 10 cm. Figure 1 shows eight pattern repeat schemes of arranging 15 weft yarns per 10.5 mm length of the fabric. The numbers define the quantity of metal-contained weft yarns (black stripes), but other grey stripes are multifilament polyester yarn. Based on these patterns, 200 mm +/- 5mm long and 1400 mm flat woven samples of each metal-contained yarn (listed in the Table) were made.

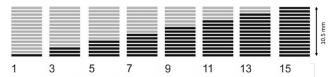


FIGURE 1. Quantity of metal contained (yarn A, B, or C, black stripes) and multifilament polyester (grey stripes) weft yarns per 10.5 mm length of sample

B. PREPARATION OF COATED SAMPLES

The developed fabric samples were coated with two layers. To achieve a more even and non-porous surface, woven samples were coated with the first basic polyurethane paste layer of *Tubicoat Mea CHT Bezema* of 60±3 μm thickness and dried at 100°C for two minutes. Afterward, the second layer of graphite paste of 60±3 µm thickness was applied and also dried at the same conditions as the polyurethane layer. Acrylic paste Print Perfekt 226 was mixed with graphite powder particles (fineness ~5 μm) at a 25% concentration to obtain a graphite coating paste. The samples were coated using the blade method and dried for layer fixation in Mathis Labdryer (see Fig. 2 a). The sample was fixed in the needled frame (Fig. 1 a) and embedded into the dryer mechanism. A paste layer was applied to the sample after setting the blade and putting the paste along it. Then, the frame with the sample was automatically inserted into the dryer and kept for two minutes for complete fixation. As a result, coated samples were obtained (see Fig. 3).

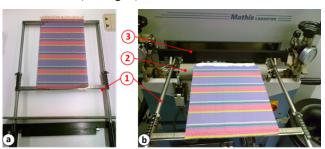


FIGURE 2. Sample fixed in needled frame (a); frame embedded into dryer mechanism (b): 1 – needled frame, 2 – rubber pad with two inner rolls, 3 – metal blade



FIGURE 3. Sample coated with graphite layer, magnification x100

III. MEASUREMENT METHODS

In this section, the standard methods for measuring textile parameters, like thickness and mass per square meter, are listed. The equipment and the method of measuring the attenuation level of EM radiation are described.

A. DETERMINATION OF CHARACTERISTICS OF SAMPLES

The thickness of woven samples was measured according to the standard LVS EN ISO 5084:2001 "Textiles - Determination of thickness of textiles and textile products". The mass of one square meter was estimated according to the standard LVS EN 12127:2001 "Textiles - Fabrics - Determination of mass per unit area using small samples" standard [23].

B. DETERMINATION OF WAVE ATTENUATION

A test set of two horn antennas, *Rohde & Schwarz HF* 906 and vector network analyzer (VNA) *Anritsu MS2024B*, was used. The distance between the source of signal radiation and the signal receiver was 150 cm (Fig. 4). The selected antennas and the VNA device cover different frequency ranges; therefore, measurements were performed in the range of 1 GHz to 4 GHz. The scattering parameters s11 (input port reflection) and s12 (reverse gain) were measured from antenna 1 to antenna receiver 2. Initially, the reference measurement was done without the sample; then, the sample was put between the antennas but closer to antenna 1. VNA reported the attenuation of the s12 parameter in dB, and the difference between the s12 parameter value with and without a sample was calculated in relative values.

Shielding efficiency (SE) is characterized as a ratio of transmitted wave intensity (I_{TR}) to incident intensity (I_{INC}), referring to (1).

$$SE = \frac{I_{TR}}{I_{INC}} \tag{1}$$

Attenuation (A) of transmitted electromagnetic waves is calculated as

$$A(\%) = (1 - SE) *100$$
 (2)



The advantages of the method include selecting the best samples of the developed set from the obtained results and properly measuring them with high-precision equipment afterward. Arranging the equipment in an anechoic chamber or manufacturing finished products like bags is time-consuming and financially expensive.

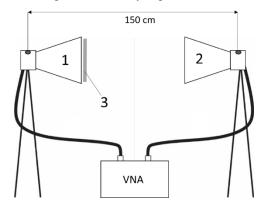


FIGURE 4. Test set of two horn antennas (1 and 2), VNA, and sample (3)

IV. RESULTS AND DISCUSSION

This section includes the obtained results of the fabric samples' characteristics, such as mass per square meter and thickness, and as well as the measurement results of attenuation level in 2.45 GHz and 1.161 GHz frequency of uncoated and graphite coated samples, and their compassion.

A. CHARACTERISTICS OF WOVEN SAMPLES

The mass values per square meter of developed woven samples are shown in Fig. 5. Samples with yarn C have less weight than other samples because the linear density of yarns A and B is 10 tex thicker than yarn C. The weight of yarn C samples is quite similar, 68 ± 1 g/m², despite the different proportions of metal contained and polyester yarn. This can be explained by the fact that yarn C has a similar linear density to polyester yarn and that diverse proportions have less influence on the weight of the fabric.

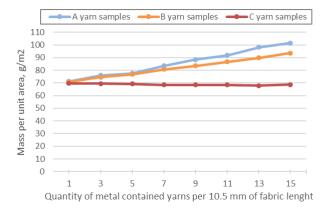


FIGURE 5. Mass per unit area of woven fabrics containing metal-contained yarns A, B, and C

A similar weight tendency is observed for samples of yarns A and B. The weight tends to increase as the quantity of polyester yarns decreases and the quantity of metal-contained yarns increases.

Although the linear density of yarns A and B is equal (see Table), the samples with yarn A are heavier than those with yarn B. The heaviest samples among the woven samples are where yarn A is used for all wefts (101 g/m²) and with a weft proportion of 13 metal-contained and 2 polyester yarns (98 g/m²). A similar weight for all yarn samples is observed with the weft yarn proportion: one metal-contained yarn and fourteen polyester yarns.

A similar thickness (\sim 0.3 mm) is observed for all yarn samples with one, three, and five metal-contained yarns per 10.5 mm of fabric length (see Fig. 6). The thickest samples are with yarn A (0.32 \pm 0.019 mm), but the thinnest are samples with yarn C (0.29 \pm 0.016 mm), because it is thinner than A and B yarn (see Table). By increasing the quantity of metal contained yarns, the thickness of yarn A and B samples tends to grow, but the thickness of yarn C samples tends to decrease. It can be explained by the different structures of the yarns. The resulting linear density of plied yarn C (see Table) is 20 tex, but it is 30 tex and 33 tex for yarns A and B, respectively. So, as the number of finer yarns increases in repeat, the fabric thickness reduces.

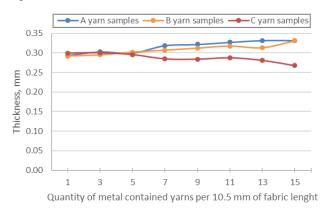


FIGURE 6. The thickness of woven fabrics containing metal-contained yarns A, B, and C

B. RESULTS OF WAVE ATTENUATION IN TEXTILE SAMPLES

The transmittance of EM waves was characterized by the calculation of its attenuation, according to Eq (2). In Fig. 7 and Fig. 8, the attenuation values are given for uncoated woven samples positioned vertically to the radiation source at 2.45 GHz and 1.161 GHz, respectively. A common tendency can be seen for yarns B and C (Fig. 7). The more metal-contained yarns in the samples are, the less radiation passes through them. All the fabric samples with nine metal-contained yarns per 10.5 mm have the highest attenuation. As for assumptions, yarn C, which contains Cu filament coated with Ag, and yarn B, which contains steel filament, should have higher attenuation because the resistance (see Table) per



10 cm length of these yarns is less than for yarn A, which contains steel staple fibers, but the results are opposite.

At 1.161 GHz frequency (Fig. 8), another situation is observed: yarns B and C have the highest attenuation (99.3%–99.9%) for the samples, which contain 1 and 3 metal contained yarns per 10.5 mm. However, yarn A samples have a lower (82.4%–96.5%) attenuation according to the composition of weft yarns. Such a case can be explained by the fact that the wavelength of 1.161 GHz is longer than the wavelength of 2.45 GHz, which is why the attenuation of samples at 1.161 GHz (Fig. 8) is higher than for samples at 2.45 GHz (Fig. 7). Very similar tendency of results is seen for the samples of steel-contained yarns (A and B), beginning from five to all metal-contained weft yarns per 10.5 mm.

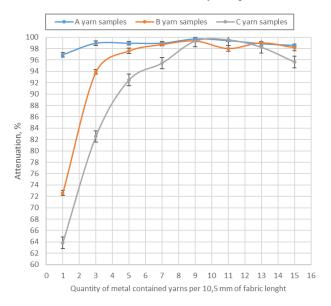


FIGURE 7. The attenuation of the EM waves as a function of the number of metal-contained yarns A, B, and C in woven samples oriented vertically at 2.45 GHz

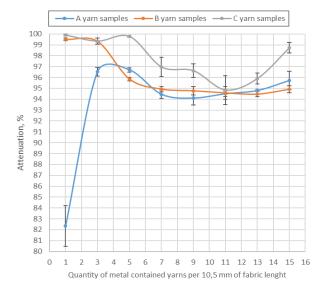


FIGURE 8. The attenuation of the EM waves as a function of the number of metal-contained yarns A, B, and C in woven samples oriented vertically at 1.161 GHz

Comparing the uncoated (Fig. 7) and coated (Fig. 9) samples at 2.45 GHz, we can observe a similar tendency in the curves of the results, but with the improvement of attenuation properties by the graphite layer for some samples. A more obvious scene is presented in Fig. 11. The graphite layer makes the attenuation properties worse for a sample of nine B weft yarns per 10.5 mm. As for B and C yarn samples, the improvement is visible, especially for the samples with 1, 3, and 5 metal-contained yarns per 10.5 mm. The difference in attenuation decreases when the number of metal-contained yarns increases in these samples. For a sample of nine B weft yarns per 10.5 mm, the graphite layer makes the attenuation properties worse.

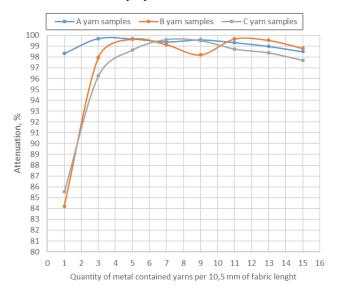


FIGURE 9. The attenuation as a function of the number of metal-contained yarns A, B, and C in woven samples with graphite coating oriented vertically at 2.45 GHz

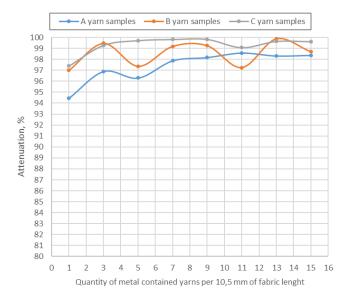
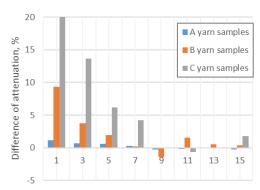


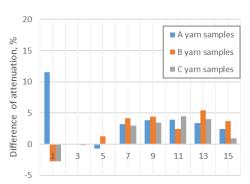
FIGURE 10. The attenuation of the EM waves as a function of the number of metal-contained yarns A, B, and C in woven samples with graphite coating oriented vertically at 1.161 GHz

As for measurement results at the frequency of 1.161 GHz (Fig. 10), the graphite layer also increases the samples' attenuation. The average improvement in attenuation is approximately 3.5% for three types of yarns in almost all samples containing 7, 9, 11, 13, and 15 metal yarns per 10.5 mm (see Fig. 12). For samples of one B and one C yarn per 10.5 mm, the graphite coating decreases attenuation for 2.3%. Still, for stainless steel staple yarn (A), the attenuation increases by 11.5%.



Quantity of metal contained yarns per 10,5 mm of fabric lenght

FIGURE 11. The evaluation of improvement of attenuation with graphite coating, samples oriented vertically at 2.45 GHz



Quantity of metal contained yarns per 10,5 mm of fabric lenght

FIGURE 12. The evaluation of improvement of attenuation with graphite coating, samples oriented vertically at 1.161 GHz

The obtained results can hardly be compared with the reviewed publications because in this research an extraordinary combination of materials is used: fabric samples of proportionally increased metal-contained weft yarns and additionally coated with graphite layer. If we compare the shielding results only of fabric samples with metal-contained yarns at the 2.45 GHz frequency, then a common tendency can be observed with the research [14]: as the amount of metal-contained yarns increases, the shielding level increases.

V. CONCLUSIONS

This study analyzed the dependence of the attenuation of EM waves by samples on the amount of metal-contained yarns and graphite coating application. It determined that increasing the number of metal-contained yarns rapidly increases the attenuation, reaching values of more than 92% at concentrations of 5 metal-contained yarns and 10 polyester

The graphite coating makes the attenuation of EM waves higher for the samples with a lower composition of metal-contained weft yarns (one, three, and five per 10.5 mm). This improvement is non-essential for the samples with an increased amount of metal-contained weft yarns.

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