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3D Conductive Textile Shields

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Abstract. The perturbing presence of electromagnetic fields is responsible for numerous malfunctions in equipment's operation. To eliminate these disturbances it is necessary both to reduce the electromagnetic radiation of electronic devices and to "immunize" them from the fields present in their operating environment. These requirements can be achieved by efficient shielding the source of the electromagnetic field and the receiver. The paper aims to develop new textile shield with spatial architecture, high shielding effectiveness, low manufacturing costs, shape diversity, mechanical elasticity and facile mounting. The shield were made by knitting and have a 3D spatial structure, with two external layers and an internal connection layer made with different combinations of conductive and non-conductive fibres.

Introduction

The disruptive presence of electromagnetic fields in the environment is the cause of many malfunctions of electrical and electronic equipments that ensure the security and accuracy of processes from various areas of activities. Given the exponential growth of the number of electrical and electronic equipments present in everyday life along with the increasing spread of wireless communications, the problem of electromagnetic pollution became a major concern. To eliminate these disturbances it is necessary both to reduce the electromagnetic radiation of electronic devices and to "immunize" them from the fields present in their operating environment. This can be obtained through an efficient shielding of the source and receiver of the electromagnetic field.

Electromagnetic shields can be divided in two main categories: *homogeneous* and *composite*. *Homogeneous shields* are generally made of metals and have the characteristic that all the mass contributes to the shielding effect. Although the shielding effectiveness (SE) is very good, disadvantages such as high production costs, high specific weight and propensity to corrosion have led to the emergence of a new category of shields: *composite electromagnetic shields* which possess high flexibility, reduced weight and low manufacturing costs. *Composite shields* are made by using at least two different materials: a support material (electromagnetic transparent) with role of mechanical support and an active material used for electromagnetic shielding. Support materials are mainly electrical insulators and are found in the form of plastics (polymer matrix) or textile materials made from natural or polymer fibres. There are also conductive support materials made from conductive polymers, such as polyaniline (PANI) and polypyrrole [1-2]. Active materials are mainly electrical conductors, which can be arranged on the surface of the support material as films or embedded, in the form of particles.

Coatings are made by different techniques and use a wide range of active materials. Copper is one of the most used metals used for coating; shielding effectiveness values of 54 dB for a coverage of 28.22 g/m^2 and a frequency range of 0.01 MHz – 18 GHz [3] and 55 dB for a frequency range of 0.2 – 1000 MHz [4] are reported. Another commonly used active material is silver, in [5] a SE between 32 – 45 dB for a frequency range of 0.01 – 18 GHz is reported. Multilayer coatings are used to obtain higher values of SE. In [6] the results of coating a set of textile fabrics with one or two layers of Cu-Ni/Ni-P are presented. A SE between 45 – 60 dB is reported for coverage of 50

g/m^2 in the 2 – 18 GHz range. In [7] textile fabrics were coated with polypyrrole and a SE of 37 dB was reported for the 100 MHz – 1.5 GHz range. Coated polymer matrix is also frequently encountered, a SE of 38 dB being reported in the 0.3 MHz – 1.5 GHz range for a polymer matrix coated with a 400 μm thick layer of graphite [8].

In [9] SE of fabrics made from twisted yarns of polymeric fibres (PET) and steel fibres, with various percentages of the conductive fibres, is presented. For a fabric with 10% of steel fibres, a SE of 15 – 25 dB is obtained, while for a fabric made from 100% steel fibres, the SE is 55 – 60 dB, both being reported for 200 – 1600 MHz frequency range. In [10] knitted fabrics made from copper core fibres with a 0.1 – 0.12 mm diameter and covered with a cotton sheath are investigated. Different knitting structures were tested and a shielding effectiveness of 30 – 63 dB was obtained for the 700 – 1000 MHz frequency range.

Since non-ferromagnetic metals, such as copper, provide a good reflection of incident radiation, and ferromagnetic metals ensure a good absorption, there are structures of textile shields developed by combining the two types of metals. In [11] a shield made from a combined yarn of copper and steel is presented, for which a 40 – 50 dB shielding effectiveness is reported for the 30 MHz – 3 GHz frequency range.

If the electromagnetic shields are used to make human operator protection equipment, then the comfort must also be considered, by using textile fibres inside the equipment. Thus, in [12] it is proposed that the 100% stainless steel fibres to be used only on the exterior of the knitted fabric. Similarly, in [13] a hybrid fibre, which ensures the comfort of the contact area with the human operator, is presented.

Increasing the SE is often achieved by using multilayered structures which involve joining multiple shields. An analysis of a wide range of textile shields in multilayer configuration is presented in [14]. For a structure made of two woven layers with steel fibres, a layer of textile fabric coated with aluminium and a knitted layer with steel and textile fibres coated with silver a shielding effectiveness of 50 dB was obtained for the 0.8 – 2.4 GHz range.

This paper aims to develop new textile shield with spatial architecture, high shielding effectiveness, low manufacturing costs, shape diversity, mechanical elasticity and facile mounting. The shields were made by knitting and have a 3D spatial structure, with two external layers and an internal connection layer made with different combinations of conductive and non-conductive fibres. Their shielding properties were investigated using the insertion loss method, able to give information about the shielding effectiveness of tested shields.

Test materials and method

The efficiency of the proposed shields will be assessed through shielding effectiveness (SE), expressed in decibels, which represents the logarithm of the ratio between the intensity of the incident field (E_i / H_i – incident electric/magnetic fields) and intensity of the transmitted field (E_t / H_t –transmitted electric/magnetic fields) or the ratio between the incident power (P_i) and the transmitted power (P_t). The field can be electric or magnetic and the shielding effectiveness is expressed as follows: $SE_E(dB) = 20\log(E_i/E_t)$, $SE_H(dB) = 20\log(H_i/H_t)$, and when considering the powers ratio: $SE_P(dB) = 10\log(P_i/P_t)$.

From the shielding mechanisms point of view, the shielding can be achieved by reflection (R), absorption (A) and multiple reflections (B), and the shielding effectiveness is defined as $SE(dB) = R+A+B$.

Reflection losses (R) refer to the impedance mismatch between the incident wave and electromagnetic shield. If the wave's impedance differs significantly from the shield's impedance, a large part of the energy will be reflected. However, if the wave's impedance is similar with the shield's impedance, then the wave passes through the shield with minimum reflection.

Absorption losses (A) depend on the shield's properties and are independent of the radiation source. As it passes through the shield, the amplitude of the radiation falls exponentially due to

Joule effect losses of the currents induced in shield's mass (heating the material). The distance required for the wave to be attenuated with 1/e is called penetration depth (δ).

Multiple reflections (B) occur at shield's interfaces (shield's limits with the environment) and depend on the impedance difference between the two adjacent materials.

The new structure of the electromagnetic shields, proposed in this paper, consists of three layers arranged in an "H" profile (Fig. 1). The external layers, manufactured of fibres arranged in two parallel plans, are reinforced by a third one, with orthogonally oriented fibres. Thus, the shield will be composed of three independent shields, electrically unconnected, which increases the shielding effectiveness as a consequence of the electrically unconnected multiple shields principle.

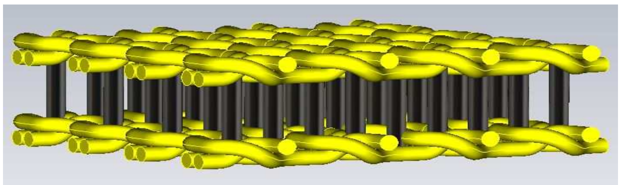

Fig. 1. Structure of the proposed electromagnetic shield

Through this new shield structure a synergy will be obtained between all the mechanisms involved in electromagnetic attenuation (reflection, absorption, multiple reflections). It will be achieved within a complex 3D structure, spatial knitting allowing the development of the entire system using a single low cost manufacturing operation.

Given the proposed structure, 18 configurations were obtained using different combinations of conductive and non-conductive fibres. Their description can be observed in Table 1.

Table 1. Description of tested shield configurations

Sample	External layers	Internal (connection) layer
S1	Thunderon_1 [1]	Cotton
S2	Thunderon_2 [2]	Cotton
S3	Carbon_1 [3]	Cotton
S4	Carbon_2 [4]	Cotton
S5	Cotton	Bekinox100% [5]
S6	Cotton	Bekinox20% [6]
S7	Cotton	Nickel coated polyester fibre
S8	Thunderon_1	Bekinox100%
S9	Thunderon_1	Bekinox20%
S10	Thunderon_2	Bekinox100%
S11	Thunderon_2	Bekinox20%
S12	Thunderon_2	Nickel coated polyester fibre
S13	Carbon_1	Bekinox100%
S14	Carbon_1	Bekinox20%
S15	Carbon_1	Nickel coated polyester fibre
S16	Carbon_2	Bekinox100%
S17	Carbon_2	Bekinox20%
S18	Carbon_2	Nickel coated polyester fibre

[1]Thunderon_1 – acrylic fibres coated with copper sulphide, [2]Thunderon_2 – cotton fibres + acrylic fibres coated with copper sulphide, [3]Carbon_1 – polyester fibre with trilobal carbon core, [4]Carbon_2 – Nylon fibres surface saturated with carbon particles, [5]Bekinox100% – 100% stainless steel fibres, [6]Bekinox20% – 20% stainless steel fibres + 80% polyester fibres

The measurements of shielding effectiveness were made via insertion loss method, able to give information related to reflection and absorption losses. The measuring stand, presented in Fig. 2, consists in a Radio Frequency (RF) Signal Generator (Keithley 2910), a shielding effectiveness test fixture (Electro-Metrics EM-2107A), a stand/holder for the test fixture (Electro-Metrics EM-6138), a spectrum analyzer (ifR 2398) and two coaxial cables. The signal generator transmits through the coaxial cable a test signal, which will pass through the shield sample mounted between the shielding effectiveness test fixtures. Next, the attenuated signal will be transmitted through the second coaxial cable and will be measured by the spectrum analyzer, which will give the shielding effectiveness. Since the test samples have different thicknesses, a calibration will be made for each type of shield. The measurements are made in the frequency range of 0.5 – 1.4 GHz. For each configuration of the electromagnetic shields, two measurements are made. The first measurement is made with the textile shields in an un-stretched state, while the second measurement in a stretched state. For the stretched state, one end of the fabric is held in place by a fixture while the other end is pulled by a mobile fixture to which a weight of 500 g is connected.

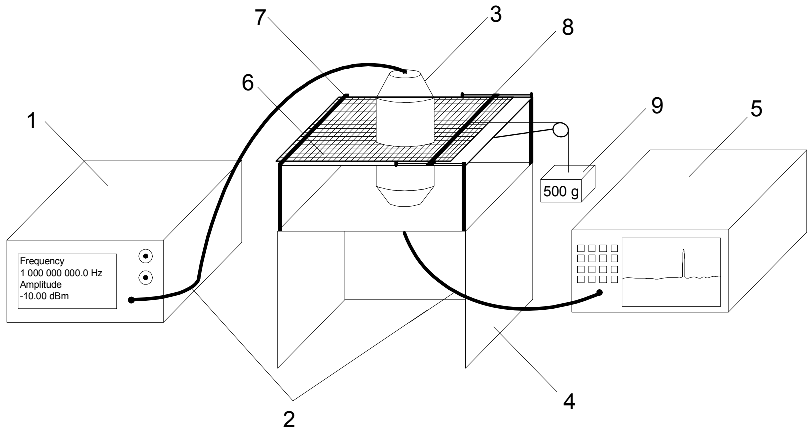

Fig. 2. SE measuring stand: 1. RF signal generator, 2. coaxial cables, 3. SE test fixture, 4. stand/holder for the test fixture, 5. spectrum analyzer, 6. tested fabric, 7. fixture, 8. mobile fixture, 9. weight.

Experimental data

With the measurements in the stretched and un-stretched states, it can be analysed how the shielding effectiveness is influenced by the increase of electrical connections between the conducting fibres, at knits level, in the stretched state. The shielding effectiveness measured for each sample, in the stretched (SE^*) and un-stretched state (SE), are presented in Table 2.

After analysing the results presented in Table 2, a first remark can be made, namely that the shielding effectiveness for shield's stretched state is higher than the shielding effectiveness for the un-stretched state. Thus, it can be said that the increase of electrical connections between the conducting fibres has a positive effect on shield's ability to attenuate the electromagnetic fields. It is believed that the increase of electrical connections determines a larger electrical path which determines higher eddy currents to be induced within the shield's conductive part. Since eddy currents determine a magnetic field that opposes to the original one, a higher shielding effectiveness is obtained.

Considering the materials from which the conductive part is made, the highest shielding effectiveness is determined by the shields that contain stainless steel fibres followed by the ones with copper sulphide, nickel and carbon. The shield with Thunderon_2 has a smaller shielding effectiveness than the one with nickel coated fibres, because it uses a mixture of fibres which determines a smaller percentage of copper sulphide coated fibres. Comparing the shields made with stainless steel fibres it can be observed that generally higher shielding effectiveness values are obtained for the shield with 100% of stainless steel. Thus, the higher the percentage of conductive material, the higher the shielding effectiveness is obtained.

The best overall shielding effectiveness values are obtained for the configuration made with Thunderon_1 and Bekinox100%, the two fibres that alone present the first and the third best shielding effectiveness. In terms of the electromagnetic field's frequency, it can be seen that the shielding effectiveness decreases as the frequency increases.

Table 2. Shielding effectiveness for different configurations of shields

Sample	SE	Frequency [GHz]									
		0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4
S1	SE [dB]	11.58	10.87	10.63	11.1	11.23	10.67	10.12	10.54	11.3	11.58
	SE* [dB]	16.4	15.15	14.8	15.15	15.11	14.11	13.33	13.66	14.4	14.6
S2	SE [dB]	2.47	2.54	2.14	2.36	2.65	2.74	2.36	2.25	2.76	3.34
	SE* [dB]	4	3.84	3.33	3.53	3.82	3.77	3.22	3.2	3.62	4.06
S3	SE [dB]	0.45	0.54	0.01	0.02	0.1	0.34	0.04	0.28	0.13	0.21
	SE* [dB]	1.04	1.04	0.33	0.2	0.35	0.64	0.22	0.14	0.07	0.24
S4	SE [dB]	1.58	1.65	1.05	1.07	1.14	1.34	0.92	0.7	0.94	1.34
	SE* [dB]	1.11	1.62	0.97	1.06	1.22	1.37	1	0.82	1	1.33
S5	SE [dB]	14.54	12.54	12.12	12.1	11.25	9.87	9.23	9.54	9.67	9.16
	SE* [dB]	16.31	14.15	13.73	13.73	12.82	11.04	10.04	10.44	10.55	9.97
S6	SE [dB]	11.5	10.76	9.9	9.74	9.16	8.01	7.03	7.12	7.45	7.27
	SE* [dB]	21.11	17.44	14.17	12.84	11.73	10.17	9.04	9.11	9.26	8.82
S7	SE [dB]	5.54	5.41	4.92	5.34	5.63	5.32	4.81	4.94	5.58	5.83
	SE* [dB]	11.2	10.57	9.77	10.17	10.28	9.22	8.04	8.13	8.6	8.55
S8	SE [dB]	18.05	16.47	16.27	16.7	16.47	15.43	14.74	15.43	16.03	16.12
	SE* [dB]	19.91	18	18.04	18.6	18.28	16.93	16.31	16.88	17.62	17.68
S9	SE [dB]	15.3	14.38	14.43	15.16	15.16	14.27	13.61	14.3	15.14	15.32
	SE* [dB]	18.42	16.77	16.57	17.11	16.88	15.68	14.88	15.46	16.2	16.35
S10	SE [dB]	14.7	12.34	11.81	11.67	10.92	9.38	8.78	9.3	9.7	9.43
	SE* [dB]	16.71	14.31	13.8	13.75	12.86	11	10.08	10.51	10.84	10.53
S11	SE [dB]	11.54	10.34	9.85	10.01	9.45	8.21	7.45	7.61	7.92	7.72
	SE* [dB]	15.42	13.51	12.84	12.77	11.84	9.91	8.84	9	9.2	8.86
S12	SE [dB]	5.83	5.65	5.83	6.54	6.87	6.32	5.78	6.18	6.74	6.85
	SE* [dB]	13.8	12.35	11.86	12.08	11.51	10.04	8.97	9.13	9.48	9.08
S13	SE [dB]	16.12	13.83	13.18	12.98	11.98	12.21	9.27	9.7	9.9	9.45
	SE* [dB]	17.06	14.66	14.11	14.04	13.02	11.08	9.86	10.15	10.28	9.77
S14	SE [dB]	10.56	9.65	9.7	9.94	9.43	8.18	7.3	7.47	7.67	7.25
	SE* [dB]	14.33	12.2	11.64	11.48	10.57	8.77	7.68	7.88	8.02	7.4
S15	SE [dB]	6.07	5.67	5.76	6.34	6.52	5.9	5.32	5.63	6.21	6.23
	SE* [dB]	9.71	8.95	8.86	9.33	9.2	7.95	7.04	7.28	7.62	7.42
S16	SE [dB]	16.11	13.73	13.04	12.88	12.02	10.42	9.71	10.06	10.46	10.11
	SE* [dB]	16.95	14.84	14.4	14.35	13.64	11.88	10.82	11.22	11.62	11.28
S17	SE [dB]	13.88	12.17	11.51	11.46	10.75	9.31	8.6	8.84	9.02	8.66
	SE* [dB]	13.77	11.91	11.62	11.82	11.04	9.26	7.97	8.31	8.71	8.57
S18	SE [dB]	10.06	9.48	9.42	9.86	9.84	8.95	8.31	8.66	9	8.77
	SE* [dB]	11.08	10.33	10.17	10.53	10.42	9.31	8.6	8.18	9.2	8.88

Conclusions

Within this paper a new structure for textile electromagnetic shields is proposed, consisting of three layers arranged in an "H" profile. The external layers are made with different fibres from the ones of the internal layer, therefore resulting three independent shields, which increase the shield's shielding effectiveness. Different configurations of shields were made and tested via insertion loss method, which gives results about the shielding effectiveness of the proposed shields.

Taken alone, the best shielding effectiveness is obtained by the shield with stainless steel fibres, followed by the ones with copper sulphide, nickel and lastly the one with carbon fibres. Also, the shielding effectiveness increases as the percentage of the conductive material increases, as it can be observed for the shields with 100% stainless steel fibres and 20% stainless steel fibres. In terms of frequency, the shielding effectiveness decreases as the electromagnetic shield's frequency increases.

For the shields made with different combinations of fibres, a better shielding effectiveness is observed than for the shields taken alone, which confirms the initial assumption that the three layers have a cumulative effect in terms of shielding effectiveness.

A better shielding effectiveness was observed in shield's stretched state, which opens a new research direction, to find a manufacturing technique so as to obtain a structure with a higher number of electrical connections between the fabric's knits.

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References

[1] Y.J. Chen, N.D. Dung, Y.A. Li, M.C. Yip, W.K. Hsu, N.H. Tai, Investigation of the electric conductivity and the electromagnetic interference shielding efficiency of SWCNTs/GNS/PAni nanocomposites, Diam. Relat. Mater. 20 (8) (2011) 1183-1187.

[2] Y.Y. Kim, J. Yun, H.I. Kim, Y.S. Lee, Effect of oxyfluorination on electromagnetic interference shielding of polypyrrole-coated multi-walled carbon nanotubes, J. Ind. Eng. Chem. 18 (1) (2012) 392-398.

[3] Y. Lu, Electroless copper plating on 3-mercaptopropyltriethoxysilane modified PET fabric challenged by ultrasonic washing, Appl. Surf. Sci. 255 (2009) 8430-8434

[4] Y. Lu, L. Xue, Electromagnetic interference shielding, mechanical proprieties and water absorbtion of copper/bamboo fabric (Cu/BF) composites, Compos. Sci. Technol. 72 (2012) 828-834.

[5] Y. Lu, S. Jiang, Y. Huang, Ultrasonic-assisted electroless deposition of Ag on PET fabric with low silver content for EMI shielding, Surf. Coat. Tech. 204 (2010) 2829-2833.

[6] S.X. Jiang, R.H. Guo, Electromagnetic shielding and corrosion resistance of electroless Ni-P/Cu-Ni multilayer plated polyester fabric, Surf. Coat. Tech. 205 (2011) 4274-4279.

[7] J. Avloni, L. Florio, A.R. Henn, R. Lau, M. Ouyang, A. Sparavigna, Electromagnetic Shielding with Polypyrrole-Coated Fabrics, J. Thermoplast. Compos. 20 (3) (2007) 241-254.

[8] T. Wang, G. Chen, C. Wu, D. Wu, Study on the graphite nanosheets/resin shielding coatings, Prog. Org. Coat. 59 (2) (2007) 101-105.

[9] T.W. Shir, J.W. Shie, Electromagnetic shielding mechanism using soft magnetic stainless steel fiber enabled polyester textiles, J. Magn. Magn. Mater. 324 (2012) 4127-4132

[10] R. Perumalraj, B.S. Dasaradan, Electromagnetic shielding effectiveness of copper core yarn knitted fabrics, Indian Journal of Fibre & Textile Research 34 (2009) 149-154.

[11] H.C. Chen, K.C. Lee, J.H. Lin, Electromagnetic and electrostatic shielding properties of co-weaving-knitting fabrics reinforced composites, Compos Part A-Appl. S. 35 (11) (2004) 1249-1256.

[12] F. Ceken, G. Pamuk, O. Kayacan, A. Ozkurt, Ş.S. Ugurlu, Electromagnetic shielding propreties of plain knitted fabrics containing conductive yarns, J. Eng. Fiber. Fabr. 7 (4) (2012) 81-87.

[13] I. Ciesielska-Wróbel, K. Grabowska, Estimation of the EMR Shielding Effectiveness of Knit Structures, Fibres Text. East. Eur. 20 (2-91) (2012) 53-60.

[14] S. Brzeziński, T. Rybicki, I. Karbownik, G. Malinowska, E. Rybicki, L. Szugajew, M. Lao, K. Śledzińska, Textile Multi-layer Systems for Protection Against Electromagnetic Radiation, Fibres Text. East. Eur. 17 (2-73) (2009) 66-71.