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Electromagnetic Shielding Characterization of Conductive Knitted Fabrics

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Abstract—This paper examines the electromagnetic shielding characteristics of milano, cardigan and lacoste with respect to weft and rib type composite knitted fabrics. All of these fabrics, made of hybrid yarns containing 50 μm diameter metal fibres such as copper, silver and stainless steel, were produced for electromagnetic shielding purposes. The shielding effectiveness (SE) of the fabrics was measured by reading S parameters from the signal when the sample was placed in the path of signal at the frequency range 1.7 to 2.6 GHz inside the WR430 waveguide system. After which S parameters was converted to SE values. The variation in electromagnetic shielding effectiveness (EMSE) with the factors, such as radiant frequency, metal type, wales density and geometry, were discussed. Experimental results show that all factors, especially the geometry of the fabric, have significant effect on SE. The best EMSE values were obtained by milano type knitted fabrics which was above 20 dB. It was found that milano, cardigan and lacoste composite fabrics, uncommon in EMSE experiments found in literature, give better shielding performances than rib and weft composite fabrics, under the same conditions.

1. INTRODUCTION

The use of electrical and electronic devices has been increased rapidly in recent years. Electromagnetic waves emitted from such sources are considered to have harmful effects to human health. They may also interfere with electronic equipments and damage them. It has become an essential issue to reduce electromagnetic exposure [1–4]. In order to succeed, shielding, one of the popular methods in preventing EM waves, is conducted. Shielding protects human beings, electronic and electrical equipments against radiated electromagnetic energy by providing electromagnetic compatibility [5].

Metal is considered the best electromagnetic shielding material due to its high conductivity and permeability [6], but it is expensive, heavy and not flexible at all. Coating the fabric with conductive polymers is an alternative way of getting adequate shielding [7]. However, coated fabrics may be affected by environmental factors and easily wear off. Besides, coated fabrics prevent electromagnetic waves mainly by reflecting the radiation through their surfaces. On the other hand, composite fabrics not only reflect but also absorb the incident wave [7–9]. This property, along with advantages of low density, good flexibility, good shielding effect, convenient processing, ensures conductive fabrics to get more widely used [10].

An ordinary fabric is transparent to EM radiation [5]. However, conductive fabrics are composed of yarns and metal fibres that are knitted directly into the fabric providing blockage from EM frequencies. They are used in many types of EM protection products such as protective clothing, shielding tents, and shielding curtain [2, 11–13].

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Most of the researchers [1, 9, 14–16] have mainly focused on the frequency range of 0–3 GHz. This is the range which includes the operating frequencies of the majority of electrical devices used in living areas, such as GSM communicating devices, microwaves, and bluetooth featured devices. Besides, there are some researchers who also examine SE of composite fabrics in a wider frequency ranges such as 30 MHz–9.93 GHz [17], 20–18000 MHz [5], 8 GHz–12.4 GHz and 50–110 GHz [10]. These examples overlap with idea that conductive fabrics can be regarded as a shield barrier along the large frequency range.

This paper covers the shielding properties of composite knitted fabrics. The influences of different factors on the experimental results of composite fabrics are revealed for the 1.7–2.6 GHz frequency range via figures and explained in detail.

For this research, conductive fabrics are produced by using metal core yarns. These yarns are formed by twisting the conductive metal fibre and cotton yarn by core spun yarn spinning machine. Afterwards, denseness of stitches are properly arranged on knitting machines so that the knitted fabrics are manufactured. The metal types are copper, silver and stainless steel.

The fabric geometry has important effect on the SE, but it is very difficult to determine or predict the EM shielding behaviour of composite fabrics [7, 18]. Hence, the researchers find the SE performance of fabrics by conducting experiments for each geometry. However, the studied geometries found in the literature are mainly related with rib-type knitted fabrics and thier derivatives. This is a matter of necessity to work out alternative geometries. For this reason, in the present study apart from rib and weft-knitted fabrics, new fabric types are introduced and compared to those found in the literature. These are milano, cardigan and lacoste.

Oxley [10] developed a setup that made measuring the SE of small area sections of conductive fabrics easy in the laboratory. A similar system has been used in our work. The present setup consists of WR430 waveguide with flanges, a network analyzer and coaxial transmission lines. The frequency range in this system is 1.7–2.6 GHz.

2. MATERIAL METHOD

2.1. Production of the Knitted Fabrics

Composite yarns composed of a metal fibres and cotton yarns was produced by a process known as plating. Fig. 1 reveals the process scheme. First, metal fibre and the cotton yarn were fed into two separate rollers so that their tension was properly arranged. Later, the front roller pulls both filaments in such a way to feed the same needle hook [19].

Hybrid yarns containing 50 µm diameter metal fibres, such as copper, silver and stainless steel, were produced with core spun yarn spinning machine. Afterwards, to obtain conductive fabrics, yarns were fed to the knitting machines Faycon CKM-01-S and Passap Duomatic 80.

The course density of all fabrics is 3 loops/cm. The other characteristics of obtained knitted fabrics are illustrated in Table 1.

In Table 1, hybrid yarn abbreviations Co/Cu, Co/Ag and Co/SS stand for cotton/copper, cotton/silver and cotton/stainless steel, respectively. Fabric geometries and samples are illustrated in the Fig. 2.

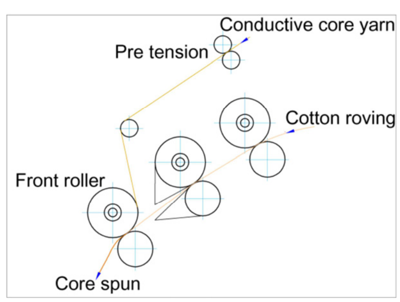
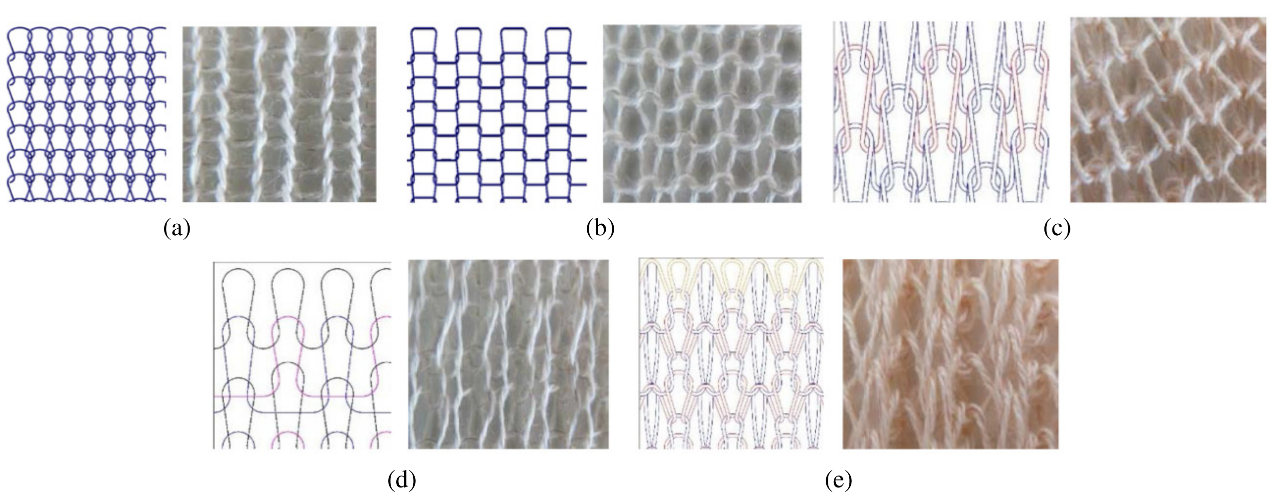


Figure 1. Schematic core spinning process.

Table 1. Fabric properties.

Knitted Fabric	Hybrid Yarn	Metal Content (%)	Yarn (Nm)	Wales Density (1/10 cm)
Rib	Co/Cu	11	7,06	50
	Co/Cu	11	7,06	25
	Co/Cu	11	7,06	16.5
	Co/Ag	13	7,19	50
	Co/SS	14	7,67	50
	Co/SS	14	7,67	16.5
Weft-knitted	Co/Cu	11	7,06	50
	Co/Cu	11	7,06	25
	Co/Cu	11	7,06	16.5
	Co/Ag	13	7,19	50
	Co/SS	14	7,67	50
	Co/SS	14	7,67	16.5
Lacoste	Co/Cu	11	7,06	25
	Co/Cu	11	7,06	16.5
Cardigan	Co/Cu	11	7,06	25
	Co/Cu	11	7,06	16.5
	Co/SS	14	7,67	16.5
	Co/SS	14	7,67	12.5
Milano	Co/Cu	11	7,06	25
	Co/Cu	11	7,06	16.5
	Co/SS	14	7,67	16.5
	Co/SS	14	7,67	12.5



(a) (b) (c) (d) (e)

Figure 2. Fabrics' geometries and samples respectively for (a) rib, (b) weft-knitted, (c) lacoste, (d) milano, (e) cardigan.

2.2. Experimental Setup

The experimental setup consists of WR430 waveguide system with flanges and a network analyzer Anritsu MS4624B. The present waveguide operates in the frequency range from 1.7 to 2.6 GHz. The dimension of tested sample is 54.61 × 109.22 mm which is the size of aperture of flanges. The coaxial transmission lines connect identical input and output sections of waveguide to network analyzer. The whole scheme is shown in Fig. 3.

A photograph of measurement setup is shown as in Fig. 4.

The test sample is placed between flanges, and then the flanges are fastened. The procedure is carried out carefully to ensure that no EM leakage occurs. The scheme of flange is shown in Fig. 5.

The flange's aperture is enclosed by a sample, after which the input signal is transmitted through waveguide. Fabric sample on the path will either let pass through the signal or reject. The network analyzer reads scattering parameters with respect to the input and output port terminations. Afterwards, the data are sent to computer for further operations. Hence, scattering parameters, transmitted (S_{21}) and reflected (S_{11}) parameters are obtained.

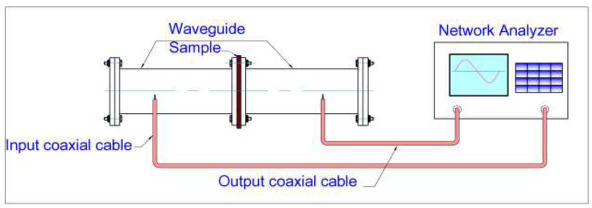


Figure 3. Experimental setup scheme.

Figure 4. Photograph of experimental setup.

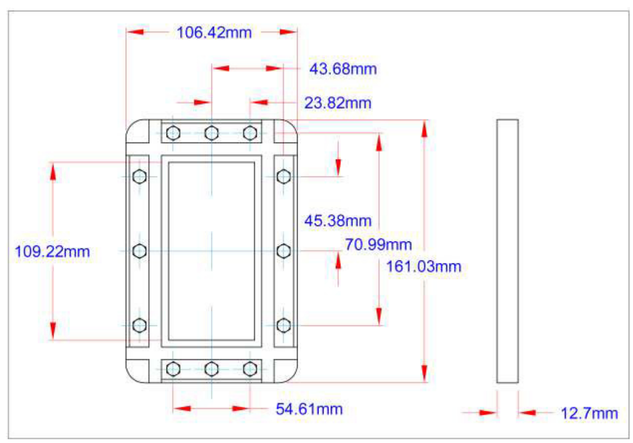


Figure 5. WR430-CPRG ange.

2.3. TRL Calibration

In order to get accurate result, a good enough calibration is inherently necessary. The TRL calibration technique, which is mostly used in literature, is illustrated in Fig. 6.

It has 3 steps, which are thru, reflect and line standard, for determining the error coefficients. Thru standard step is a straight transmission measurement and two of the waveguide adaptors are connected without fabric. Reflect standard step is reflection measurement, and two of the waveguide adaptors are shorted using metal plate respectively. Finally, line standard step is line transmission measurement, and two of the waveguide adaptors are connected by using length of $\lambda/4$ of the long midband frequency merged. After calibration, S parameters were obtained from network analyzer.

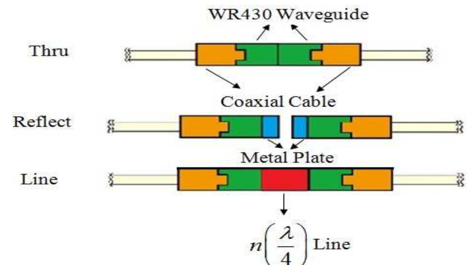


Figure 6. TRL calibration technique.

2.4. Shielding Effectiveness

The shielding can be divided into reflection loss, absorption and multiple reflections. The SE of a material is given by the equation [20]

$$SE = R + A + B \text{ (dB)} \tag{1}$$

where R represents the reflection loss, A the absorption loss, and B the correction factor due to multiple reflections within the shielding material. The term B is often neglected due to its negligible small value. Thus, shielding generally relies on reflection and absorption loss.

The scattering (S) parameters expressed in terms of dB, were obtained from the two-port measuring system. Afterwards, S_{11} (reflection) and S_{21} (transmission) were transformed into SE values by using the formulas below [21, 22]

$$R = 10 \log \left(1 - 10^{\frac{S_{11}}{10}}\right) \tag{2}$$

and,

$$A = 10 \log \left(\frac{10^{\frac{S_{21}}{10}}}{1 - 10^{\frac{S_{11}}{10}}}\right) \tag{3}$$

where R is the reflection loss and A the absorption loss. The total shielding effectiveness is obtained by substituting reflection and absorption loss values into Equation (1). In order to achieve better shielding, higher value of SE is needed.

3. EXPERIMENTAL RESULTS

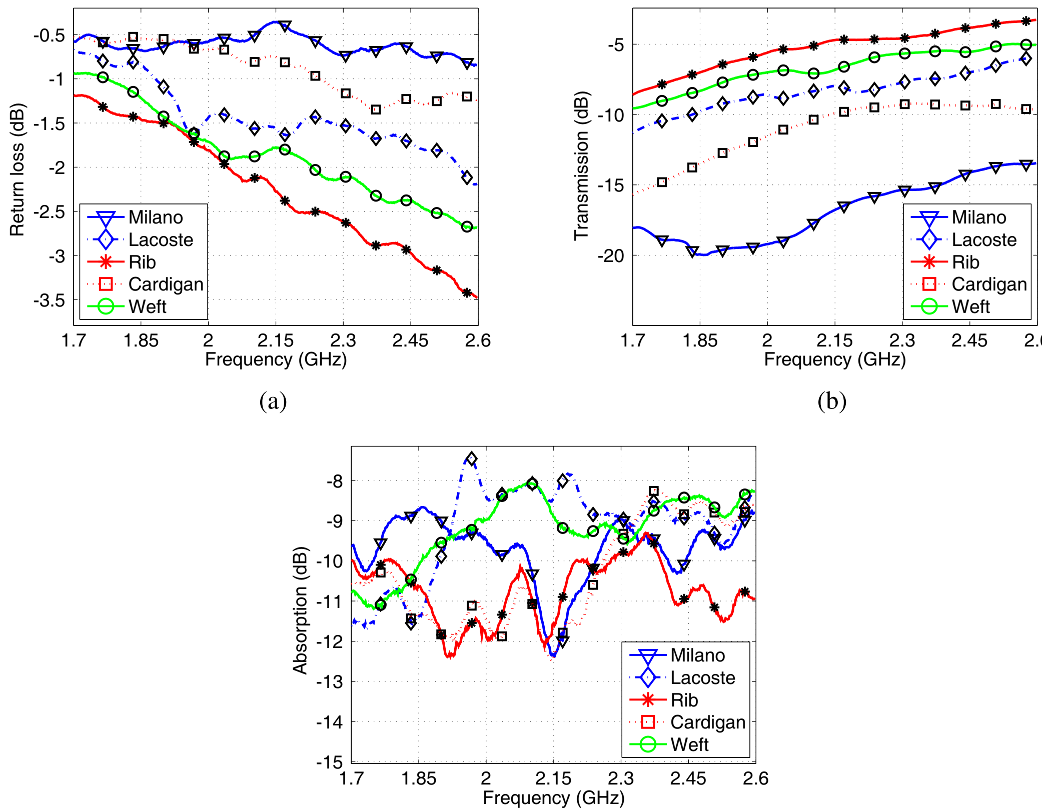
The return loss, transmission and absorption properties of fabrics containing copper metal wire have been derived by using S_{11} and S_{21} parameters. The common property of these fabric is wales density which is 25/10 cm. Figs. 7(a) to 7(c) show that the best reflecting fabric is milano. Milano also transmits far less than any other fabric. In absorption term, there exist some frequency ranges where some fabrics have sensible advantages over another, but still it is hard to detect the best absorbing fabric.

Following Fig. 7, one can calculate the SE values which are illustrated in Fig. 8. It can be seen from the figure that the best SE value is obtained by the Milano fabric. Rib fabric has the worst SE value. All SE values seem to decrease as the frequency increases.

To reveal the influence of the wales density, the same settings similar to Fig. 8 is established in Fig. 9. The only difference between figures is a decrease in wales density of the samples. The wales density in Fig. 8 is 16.5WD. By comparing the SE results between the same fabrics with different stitch sizes, it is obvious that the SE decreases with the decrease in wales density.

The SE of the fabric containing stainless steel with 16.5WD is shown in Fig. 10. It is obvious from the figure that the highest SE value is obtained from the milano type fabric.

The physical properties of the fabrics are identical in both Figs. 9 and 10 except the metal fibre type that fabrics contain. After comparing Figs. 9 and 10, it can be said that stainless steel is the best material for shielding in the given frequency range.



(a) (b)

(c)

Figure 7. (a) Return loss, (b) transmission, (c) absorption behaviour of copper core fabrics having 25WD.

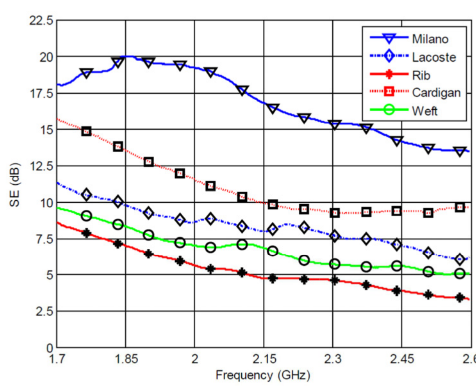


Figure 8. SE of copper core fabrics having 25WD.

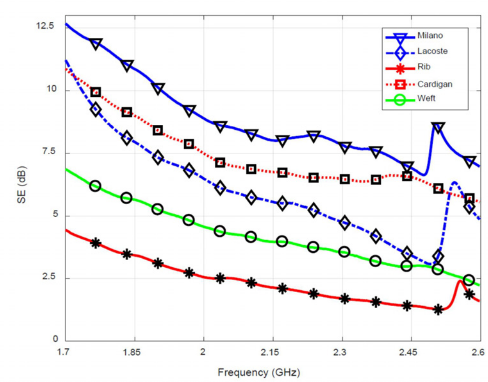


Figure 9. SE of copper core fabrics having 16.5WD.

To reveal the influence of all metal types on the SE, the copper, silver and stainless steel core rib and weft-knitted type fabrics which have 50WD each, are examined, and SEs of these fabrics are illustrated in Fig. 11.

In Fig. 11, the SEs of two distinct fabrics are compared to each other. It is obvious that in terms of SE values obtained, there is not much difference between rib and weft knitted fabrics. However, compared to other metal types, both fabrics containing stainless steel have better shielding.

All figures in the paper show that SE decreases for all samples as the frequency increases. The slope of tendency towards decreasing is obtained by fitting single term exponential model. The SE values in Fig. 8 is exposed to fitting. Fig. 12 shows the fitting results of total SE values for all samples within the frequency range 1.7–2.6 GHz.

The single term exponential model is given by

$$fitSE = a \times e^{b \times freq} \tag{4}$$

where $fitSE$ is the new fitted SE value along the frequency range frequency from 1.7 to 2.6 GHz, a the coefficient and b the slope. Obtained coefficients are shown in Table 2.

Table 2. Comparison between the perfusion coefficient (B) for the different tissues.

Sample	a	b
Milano	44.56	−0.4552
Lacoste	29.55	−0.5944
Rib	48.93	−1.054
Cardigan	46.3	−0.6753
Weft	33.2	−0.7522

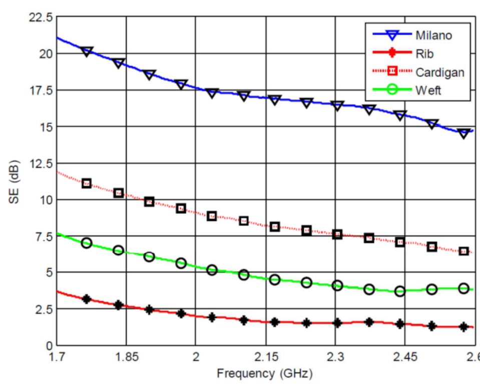


Figure 10. SE of stainless steel core fabrics having 16.5WD.

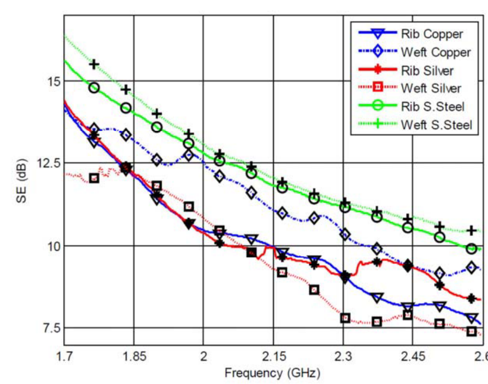


Figure 11. SE of copper, silver and stainless steel core rib and weft-knitted type fabrics.

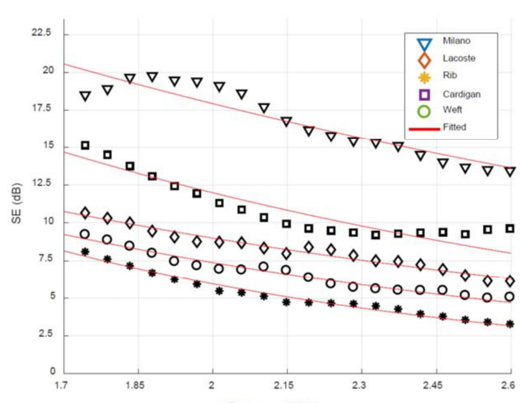


Figure 12. Exponential fitting the SE of the fabric.

Total SE is reflection and absorption dependent. Unlike reflection, absorption behaviour of all fabrics seems to continue irregularly along the frequency range. Hence, the slopes were evaluated for only total SE values of fabrics. From Table 2, it can be concluded that milano type fabric has the lowest slope which makes it more stable than other fabric types in the given frequency range.

4. CONCLUSION

The results obtained in this paper can be concluded as the following aspects. First, the geometries of milano, cardigan and lacoste were introduced. These are the fabric types that were not investigated together for shielding experiments previously. In the light of data gathered from the experiments, it was obvious that milano type fabric has better EMSE which is 20 dB in 1.7–2.6 GHz. The texture of milano type fabric is such that the yarn forms a loop on the front and a line dividing this loop in the mid of its legs, on the back surface of the fabric. Therefore, the apertures on the surface get smaller, and the fabric becomes thicker in particular sections on the back. This contributes to better absorption and reflection. But still, unlike our study, the SE of knitted fabrics obtained by the experiments in the literature can be found as high. This is explained by the fact that researchers generally prefer denser composite fabrics resembling metal sheets of which high SE performance is well known. Nevertheless, the proposed composite fabrics, i.e., shielding materials, indeed gave meaningful results though low wales densities. In order to get required shielding performance, it is enough to test denser fabrics which are producible.

Second, the effect rate on the SE of each metal type is compared. Though values are close in some cases, from observations it can be said that stainless steel core fabrics have better EMSE. Since stainless steel has high magnetic permeability which yields high shielding performance in microwave frequencies, fabrics having stainless steel fibres give better EMSE results.

Third, wales density affects the SE performance. Identical conductive fabrics except for wales density are compared, and denser fabrics give better EMSE results for all metal types.

Finally, all figures reveal that SE decreases as the frequency increases. SE values of fabrics are fitted into the single term exponential model. It was found that within the range 1.7–2.6 GHz milano type fabrics SE has tendency to decrease slower than any other fabric type. This makes milano more stable among samples which develop foresight in predicting shielding performances for wider frequency ranges.

In this paper, a conceptually simple and effective technique to measure the SE of composite fabrics is accomplished. The authors believe that the workflow and findings will contribute to further researches on the subject.

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