Electromagnetic Shielding and Reflection Loss of Conductive Yarn Incorporated Woven Fabrics at the S and X Radar Bands

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This study provides comparison of different types of conductive yarns stitched on top of the plain woven fabric via two different structures (parallel and mesh form) for electromagnetic shielding applications. Different types of structures with conductive yarns were investigated for electromagnetic shielding and reflection loss features within the S and X Radar bands. Conductive yarns; namely stainless steel, copper and silver plated polyamide yarns, having different linear resistance values were arranged evenly throughout the woven structure in parallel lines and in mesh form. The S-parameters (S_{11} and S_{21}) of the woven fabrics were measured using a vector network analyzer in conjunction with a waveguide system incorporating the woven fabric samples. More specifically, the transmission line techniques with waveguides of type WR430 (WG9) and WR90 (WG16) were used; as such, the frequencies between 2.2–3.3 and 8.2–12.0 GHz were tested, respectively. Test results revealed that there is a highly varying shielding effectiveness among samples while there is also a remarkable difference with respect to shielding effectiveness between samples having mesh and parallel structure at horizontal polarizations.

Key words: Conductive woven fabrics, electromagnetic shielding, waveguide transmission line technique, radar band, reflection loss

INTRODUCTION

Due to the advances in electronic systems and excessive use of electronic and electrical equipment containing digital devices/circuits in the field of industry, military and consumer sections, the problem of the radio-frequency interference or electromagnetic wave interference (EMI) has increased. Leakage of information, cross talk and generation of noise, etc., resulting from electronic and electrical equipments/devices/circuits radiating electromagnetic (EM) waves intentionally or unintentionally

affect the functioning of exposed systems. Moreover, miniaturization in electronics and advances in wireless systems over the past decades have increased the problem of electromagnetic interference, which results in reduced performance or damage of the exposed systems.^{1,2} Many devices such as digital computers, mobile phones, the cell phone, radar signals, FM/AM radio broadcasting waves, etc., are sources of emitting electromagnetic waves. EMI may affect the proper operation of the exposed systems and also cause serious health problems like leukemia, brain tumours, Alzheimer's disease, allergies, stress and sleep problems, etc.^{3–5} For these reasons, EM shielding is essential in order to prevent those hazards to human beings and to protect the sensitive circuits from undesired EM

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radiation; herein, we consider that EM shielding describes the prevention of electromagnetic waves passing from one region to another using conductive or magnetic materials.^{6,7}

Much research work has been carried out to develop EM wave absorbing and shielding materials using conductive fabrics. Vacuum deposition and electroless metal deposition methods are used to coat polymeric fabric surfaces with nano-metals such as nickel on copper plated polyester (PET) and polyamide (PA) ripstop fabric, silver and gold coated polyester fabric, glass fiber, PET fiber braids overwound with tin-plated copper foil and polypyrrole (PPy) coated regular poly(acrylonitrile) (PANi) and PET fiber mats.^{8–11} These products mainly ensure electromagnetic shielding or absorbing EM waves from ground sensitive electronic boards. On the other hand, a variety of fillers are also used inside polymeric coatings to be used as shielding materials. Carbon is chosen in cases where the lower conductivity is critical, particularly for electrostatic discharge (ESD) application. Nickel-coated graphite can be a good option for EMI/ESD compatibility where the environment requires low corrosive reactivity. For non-corrosive environments, silver coated nickel or copper can be suitable especially where high performance shields are necessary. Pure silver particles can be incorporated into fillers in cases where the highest shielding and conductivity are required. Common metals used for shielding are silver, copper, nickel, chromium, stainless steel and aluminum. However, most of the metals have certain limitations such that aluminum based materials present low impact resistance, stainless steel based materials have higher density which makes the structure heavy and rigid, silver based materials require non-corrosive environment, etc.¹² On the other hand, Dijith et al. studied screen printing silver line patterns (vertical or horizontal) on the surface of LSCO loaded epoxy composite (having shielding effectiveness (SE) of around 6 dB at X band and around 5 at 15 GHz) in order to achieve high SE, and they reported SE values of around 7 dB for vertical and around 20 dB for horizontal printed samples in the X Radar band (8–12 GHz), and around 7 dB for vertical and 13 dB for horizontal patterns at 15 GHz, respectively. Furthermore, they mentioned that printing a mesh pattern further increased SE, up to 22 dB at 10 GHz and 18 dB at 15 GHz. Maximum SE of 31.3 dB at 8.2 GHz was achieved after full coating with silver.¹³

Apart from plating, coating and printing, textile fabrics can be even made conductive by incorporating directly conductive fibers such as carbon, stainless steel, copper and silver plated ones into yarn stage or in the fabric stage. Considerable research efforts have been conducted in the literature on shielding effectiveness of the fabrics containing conductive fibers.^{14,15} The type of fabric structure (woven, knitted), density of the threads, distribution of the threads and the number of plies of fabrics

were examined for shielding effectiveness.^{16–26} Stainless steel, copper, silver, carbon yarn and their combinations, the effect of fabric parameters such as weave, ends per inch (EPI), picks per inch (PPI), number of fabric layers and diameter of copper yarns were also investigated by many researches for EM shielding effectiveness.²⁷ It was generally observed that increase in EPI, PPI and cover factor of fabric increase the SE from 350 up to 18,000 MHz.¹² Su and Chern¹⁶ studied shielding behavior of conductive fabrics containing three different yarns namely cover, core, and plied yarns which consist of stainless steel as core and polyester as sheath. It was reported that the conductive core yarn has better shielding effectiveness due to a high conductivity level since the stainless steel filaments lie in the central region of the yarn hence creating lowest resistance among all. In another study, SE of different conductive fabric patterns like plain, twill, rib and panama, using polyester covered with stainless steel yarns was studied.²⁸ It was found that rib structures showed better SE than other fabric types. Literature review also reveals that the shielding effectiveness particularly for copper based conductive fabrics is based on reflection rather than on absorption, and this phenomenon is not fulfilling the demands of protection against radar.¹² For this reason, copper (Cu) and stainless steel (SS) blended composite yarns were also tested for shielding effectiveness. For instance, Huang et al. developed SS/PET, Cu/PET, SS/Cu/PET composite yarn structures for having conductive knitted fabrics. It was observed that fabric with SS/Cu/PET showed higher SE among all others. It is suggested that a combination of materials might be useful for their interactions with EM waves to present better performance.²⁹ Carbon filament incorporated woven fabrics or PANi coated conductive yarns were also studied by many researchers and proposed for the EM shielding purposes.^{30,31} The carbon based fabrics were also found to be promising for EM shielding applications by means of reflection at low to medium range frequencies.

However, in none of the studies, the shielding behavior of different types of conductive yarns incorporated onto woven structures is considered for investigation in the S-band and X-bands of the spectrum. In this paper, the S-parameters of the woven fabrics containing different types of conductive yarns (stainless steel, copper and silver plated polyamides) positioned with different intervals on top of the woven fabric structure were measured in the S and X bands using a vector network analyzer (VNA) in conjunction with a waveguide system incorporating fabric samples.

FABRICATION AND MEASUREMENT

Fabrication of Conductive Samples

In order to implement the proposed study, different types of conductive yarns, namely stainless

steel, copper and silver plated polyamides, were stitched on top of 65% polyester/35% cotton blend woven fabric samples having a plain weave pattern. Conductive threads were placed in parallel lines and in mesh form on top of the woven fabrics in order to observe the effectiveness of the design on shielding efficiency and reflection loss (RL). The characteristics of conductive yarns used in the study are summarized in Table I. The linear resistances of conductive yarns were measured using a Keithley® multimeter based on 4-probe measurement technique as described in Ref. ³², and they were calculated in ohm per meter (ohm/m) by taking measurement along yarn sample length.

The individual variants of the woven fabrics were different in their distribution of conductive threads, as shown in Fig. 1. The conductive threads were arranged evenly throughout the woven fabrics, in some samples they are forming symmetric mesh structure, while in other samples the same conductive threads were arranged in visible stripes running along the length of the woven fabric like in parallel form.

Electromagnetic Interference Shielding Efficiency

Electromagnetic interference shielding efficiency (or shielding effectiveness) is expressed in decibels (dB) and defined as the ratio of the incident to transmitted power of the electromagnetic wave³³:

$$SE(\text{dB}) = 10 \log \left| \frac{P_i}{P_t} \right| = 20 \log \left| \frac{E_i}{E_t} \right|, \quad (1)$$

where $P_i(E_i)$ and $P_t(E_t)$ are the incident electromagnetic power in W/m^2 (incident electric field) and the transmitted electromagnetic power in W/m^2 (-transmitted electric field), respectively.

The reflectance (R_e) and the transmittance (T_r) of the material, are the square of the ratio of reflected (E_r) and transmitted (E_t) electric fields to the incident electric field (E_i), respectively, and can be calculated as follows:

$$R_e = \left| \frac{E_r}{E_i} \right|^2 = |S_{11} \text{ or } (S_{22})|^2, \quad (2)$$

$$T_r = \left| \frac{E_t}{E_i} \right|^2 = |S_{21} \text{ or } (S_{12})|^2. \quad (3)$$

Here, the physical meaning of S_{11} describes the input reflection coefficient with the output of the network terminated by a matched load, whereas S_{21} describes the forward transmission (from port 1 to port 2), S_{12} the reverse transmission (from port 2 to port 1) and S_{22} the output reflection coefficient. These S -parameters indeed represent the scattering function of the waves and this is a convenient way to describe a given network behavior in terms of waves rather than voltages or currents—particularly for high frequencies. For practical reasons, in this paper the description in terms of in- and outgoing waves are presented in S -parameters. The lower S_{11} value indicates low reflection and, similarly, the lower S_{21} value corresponds to low transmission and means that there is more EMI shielding.³⁴

Experimental Methods and Measurement System

The transmission line technique (with a waveguide) was used to measure the reflection loss (RL) and SE of the woven fabric samples containing different types of conductive yarns in the frequency ranges of 2.2–3.3 GHz (S-band) and 8.2–12.0 GHz (X-band). A waveguide transmission line was connected via

Fig. 1. Woven fabrics with various shapes of conductive yarns (parallel and mesh forms).

coaxial-to-waveguide adaptors to a VNA (namely Rohde & Schwarz, model ZVA24). The technique consists in introducing the samples under measurement in a section of the waveguide and measuring the two-port complex scattering parameters with the VNA. The schematic view of the waveguide measurements system together with the experimental setup including the sample holders are depicted in Figs. 2 and 3. Two different waveguides were used in the study to measure the shielding behavior at different frequencies in the S and X bands. In particular, waveguides of the type WR430 (WG9), dimensions (86.36×43.18) mm, were used for the frequencies between 2.2 GHz and 3.3 GHz; also, waveguides of the type WR90 (WG16), dimensions (22.86×10.16) mm, were used for the frequencies between 8.2 GHz and 12.0 GHz. The research was conducted for eleven samples settings in vertical and horizontal orientation with respect to the transmitted E-field that was vertically polarized.

Calibration should be done without the sample holder holding any woven fabric sample before making measurements. The material must be tightly placed in the sample holder in order to reduce the measurement uncertainty caused by air gaps inside the holder. In order to avoid air interface after placement of the sample between the shim of the waveguide, squeezing clamps are used to fix the sample. After calibration was carried out, all samples were put into the holder and S-parameters (S_{11} and S_{21}) were measured by using the graphical user interface on the network analyzer. This setup measured the S-parameters of the material, the transmission and reflection coefficients S_{12}/S_{21} and S_{11}/S_{22} , respectively, thus effectively measuring the SE and RL of each sample. The results are discussed in the following section.

RESULTS AND DISCUSSION

The SE measurements were made for the samples considered in this work at frequencies in the range of the S-band (2.2–3.3 GHz) and X-band (8–12 GHz) of the radar band. Figure 4 shows the variation of SE and RL in horizontal and vertical polarization in function of frequency on the domain 2.2–3.3 GHz for conductive textile samples having mesh structure with copper yarn (yarn 1), stainless steel yarns (yarn 2 and yarn 3) and silver plated polyamide yarns (yarn 4, yarn 5 and yarn 6), details of which are given in Table I. From Fig. 4, it is seen that all the samples have shown a consistent SE in the entire S-band both in vertical and horizontal polarization. As it is observed, the SE of the conductive textile samples is similar for each conductive yarn even in both vertical and horizontal polarization. Yarn 4 (silver coated) with a linear resistance of $50 \Omega/\text{m}$ offered maximum SE of ~ -14 dB, while yarn 1 (copper) with a linear resistance of $1.5 \Omega/\text{m}$ presented minimum SE of ~ -5 dB in vertical polarization. On the contrary, the highest RL (~ -10 dB) was obtained with yarn 1 (copper) with a linear resistance of $1.5 \Omega/\text{m}$.

As it is known, conductive textile threads are not homogeneous materials. Some conductive yarns are made of a bundle of very fine metallic wires having the voids between their threads which make them inhomogeneous. For instance; stainless steel yarn 2 and yarn 3 are the examples of this kind. On the other hand, some of the conductive yarns are made of a central non-conducting polymer core, e.g., polyamide, polyester; with one or more thin metallic exterior layers deposited by plating, e.g., silver, copper. Those metallic exterior layers are quite thin with respect to the conductive material's skin depth even at fairly high frequencies.³⁵ In our study, skin depths effects of the silver plated polyamide

Fig. 2. Waveguide measurements system.

Fig. 3. The transmission line technique setup for (a) WR430 (WG9) waveguides for frequencies between 2.2 GHz and 3.3 GHz, and (b) WR90 (WG16) waveguides for frequencies between 8.2 GHz and 12.0 GHz.

Fig. 4. Mesh structures containing conductive yarns at the S Radar band (2.2–3.3 GHz) (a) Shielding effectiveness in vertical polarization and (b) Shielding effectiveness in horizontal polarization, and (c) Reflection loss in vertical polarization and (d) Reflection loss in horizontal polarization.

conductive yarns are also seen apparently. With reference to Figs. 4 and 5, Yarn 4 (silver coated) with a linear resistance of $50 \Omega/\text{m}$ offered the highest shielding effect among the silver plated yarns due to the highest conductivity level. However, for the frequencies above 8 GHz (see Figs. 6 and 7), silver plated polyamide yarns' interaction with the EM waves is different. This might be due to high penetrability of the high frequency range, which could not

be shielded by increasing the conductivity level of silver plated yarns, in other words, by increasing the exterior metallic coverage area.¹²

Figure 5 depicts the variation of SE and RL in horizontal and vertical polarization as a function of frequency for frequencies within 2.2–3.3 GHz for conductive textile samples having parallel structure. From the figure, it is obvious that SE is obtained at vertical polarization with parallel

Table I. The characteristics of the conductive yarns

Conductive yarn ID	Material type	Yarn diameter (μm)	Tensile strength (cN)	Extension (%)	Linear resistance (Ω/m)
Y1	Insulated Copper	150	440	24.57	1.50
Y2	100% Stainless steel	612	2556	0.52	20
Y3	100% Stainless steel	464	2593	0.74	32
Y4	Silver plated PA	764	1512	14.02	50
Y5	Silver plated PA	420	319	18.79	300
Y6	Silver plated PA	380	282	22.15	400

Fig. 5. Parallel structures containing conductive yarns at the S Radar band (2.2–3.3 GHz) (a) Shielding effectiveness in vertical polarization and (b) Shielding effectiveness in horizontal polarization, and (c) Reflection loss in vertical polarization and (d) Reflection loss in horizontal polarization.

structure. This can be explained by the parallel orientation of E-field and sample yarns. The SE of yarn 6 was found highest among all samples in the S-frequency band. It can be further said that the measured RL is also highest with yarn 6 (silver plated) in the entire measured frequency band. Yarn 6 has offered peak RL of -50.094 dB at 2.8 GHz and RL is lower than -15 dB in the whole

operating frequency band at horizontal polarization (2.2–3.3 GHz).

Unlike the 2.2–3.3 GHz, at 8–12 GHz similar aspects were observed for both types of vertical and horizontal polarization (Fig. 6). Yarn 6 with a highest linear resistance value of $400 \Omega/\text{m}$ among all samples presented highest SE for both types of polarization and gave peaks of -15 dB at 9.7 GHz

Fig. 6. Mesh structures containing conductive yarns at the X Radar band (8–12 GHz) (a) Shielding effectiveness in vertical polarization and (b) Shielding effectiveness in horizontal polarization, and (c) Reflection loss in vertical polarization and (d) Reflection loss in horizontal polarization.

and -48 dB at 10.6 GHz, in vertical and horizontal polarizations, respectively. As it is expected, RL again becomes apparent and highest with yarn having highest conductivity (yarn 1; copper with a linear resistance of $1.5 \Omega/\text{m}$) while it is least with yarn having lowest conductivity (yarn 6; silver plated with a linear resistance of $400 \Omega/\text{m}$) in the whole measured frequency range and for both types of polarizations.

Compared with that of the mesh structure case in Fig. 6, similar aspects are also observed for both types of vertical and horizontal polarization for the parallel structure, as presented in Fig. 7. However, RL values are more similar compared to the SE values. One can see that all samples show a broadband relatively high SE at the sub-range of $8.2\text{--}10.0$ GHz than the sub-range of $10.0\text{--}12.0$ GHz

for both types of polarization. The fluctuations observed in the resultant SE by far exceeded 10 dBs. The RL again is found highest (~ -40 dB) with yarn having the highest conductivity (yarn 1; copper with a linear resistance of $1.5 \Omega/\text{m}$). Remarkable difference was also observed as the surface became more reflective in mesh structure compared to parallel structure due to its high amount of positioned conductive yarns nature on woven fabric. It is therefore concluded that RL increases due to an increase in conductivity level and reflecting nature of conductive surfaces as also reported in the literature.³⁶ It is apparent that the SE values achieved at X band by stitching conductive yarns were superior to those reached after screen printing of silver via similar linear or mesh patterns.¹³

Fig. 7. Parallel structures containing conductive yarns at the X Radar band (8–12 GHz) (a) Shielding effectiveness in vertical polarization and (b) Shielding effectiveness in horizontal polarization, and (c) Reflection loss in vertical polarization and (d) Reflection loss in horizontal polarization.

CONCLUSIONS

In this study, conductive woven structures containing different types of conductive yarns, namely stainless steel, copper and silver plated polyamides, having different linear resistance values have been investigated regarding their electromagnetic SE and RL features within the S and X bands (2.2–3.3 GHz and 8.2–12 GHz, respectively). It is shown that there is a remarkable difference between samples having mesh and parallel structures in SE for horizontal polarization in the S frequency range. The fabrics having mesh structure exhibited better SE since they contain higher amounts of conductive yarns. Moreover, fluctuations observed in the resultant SE measurements far exceeded 40 dBs. On the other hand, it was generally observed that RL is high especially in the X-band with woven fabric sample including yarn having high conductivity (copper yarn) due to the fact that when surface becomes more conductive the reflection increases. Our study provided comparison of different types of conductive yarns stitched on top of woven structures via two different forms (parallel and mesh form) in two popular bands for shielding applications. It was shown that stitching conductive yarns on woven fabrics offer

superior shielding effectiveness when compared with screen printing conductive lines or mesh patterns. As a future study, increasing the stitch frequency or picks/ends per cm is suggested since the results would be promising for radar band applications.

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