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# Electromagnetic Shielding Effectiveness of Doubled Copper-Cotton Yarn Woven Materials

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## Abstract

*This paper describes a study on the development of 2-ply and 3-ply of cotton copper yarns and fabrics for electromagnetic shielding applications. 2-ply and 3-ply of cotton-copper yarns were produced on ring doubling machines and their woven fabrics made on a power loom. The shielding effectiveness of the 2-ply and 3-ply of cotton copper yarn fabrics was measured using the Network Analyser electromagnetic shielding test (ASTM D4935-99) in the frequency range from 20 to 18,000 MHz. The variation in EMSE with the woven fabric structures, ends per cm, picks per cm, cover factor, yarn type, and copper wire diameter are discussed. The results indicate that the woven fabric of higher EMSE proposed can be used for the purpose of EMI shielding, as well as for some electronic and electrical applications.*

**Key words:** electromagnetic wave, electromagnetic inference, conductive material, network analyser, woven copper fabric.

## Introduction

With the rapid growth of electrical and electronic devices and accessories, which emit electromagnetic energy in the different frequency bands used in the markets, it has become essential to limit and shield electronic equipment against all sources of interference due to all these types of electromagnetic energy [1 - 4]. Electromagnetic interference (EMI) is electromagnetic energy that adversely affects the performance of electrical/electronic equipment by creating undesirable responses or complete operational failure. There is a growing need for setting limits on the electromagnetic emissions from these devices in order to minimise the possibilities of interfering with radio and wire communications. In order to avoid EMI, shielding is required. Shielding is a very popular method of ensuring electromagnetic compactability and protecting electronic and electrical equipment as well as human beings against radiated electromagnetic energy.

Shields are used either to isolate a space (a room, apparatus, a circuit etc.) from outside sources of electromagnetic radiation, or to prevent the unwanted emission of electromagnetic energy radiated by internal sources. Many countries have introduced new regulations so that the manufacturers of electrical and electronic equipment comply with the electromagnetic compatible (EMC) requirement. In the USA, the Federal Communications Commission (FCC) is entrusted with the responsibility of controlling the interference from and to wire and radio communications. The FCC Rules and Regulations contained in Title 47 of the Code

of Federal Regulations state that a radio frequency device is any device that is capable of emitting radiofrequency energy by radiation, conduction or other means whether intentionally or not. Nomenclature and the ranges of the sub-frequency bands is given below:

- The radio frequency extends from 9 kHz to 3000 MHz.
- The frequency range for conducted emission - 450 kHz to 30 MHz.
- The frequency range for radiated emissions - 30 MHz to 40 GHz.

The purpose of Part 15 of Title 47 is to control the interference from these emitters. The FCC further categorises digital devices into Class A and Class B. Class A digital devices are those that are used in a commercial, industrial, or business environment. Class B digital devices are those that are in a residential environment, notwithstanding their use in a commercial, industrial, or business environment [5, 6].

With the advent of electrical and electronic devices worldwide, electromagnetic interference (EMI) among appliances is one of the major problems to be resolved. Various researchers and industrial companies have shown keen interest in providing solutions to overcome this problem. Traditionally, sheet metal is considered to be the best material for electromagnetic shielding, but it is expensive, heavy, inflexible and undergoes thermal expansion. However, the use of textile products for protecting electronic and electrical devices is suitable due to the fact that they are lightweight, flexible and less expensive. In general, textile products electrically insulating and

transparent to electromagnetic radiation i.e., their inherent electromagnetic shielding effectiveness (EMSE) is practically zeroed. Many of the synthetic fibers used in textile fabrics are insulating materials with a resistivity of the order of  $10^{15} \Omega/\text{cm}^2$ . This is much higher than the resistivity desired for electromagnetic shielding applications. For example, the resistivity of an anti-electrostatic material desired is in the range of  $10^9 \Omega/\text{cm}^2$  and  $10^{13} \Omega/\text{cm}^2$ . The value desired for a statically dissipate material is between  $10^2 \Omega/\text{cm}^2$  and  $10^6 \Omega/\text{cm}^2$ , and for shielding material it is lower than  $10^2 \Omega/\text{cm}^2$  [7, 8]. Among the various solutions offered, textile products and textile-based composite materials have caught the attention of researchers due to the versatility and conformability these textile structures provide [9 - 14]. The basic source of EMI is due to unwanted electromagnetic emission coupled with electrical signals from the source being radiated or conducted into the surrounding electrical device. Such emissions might be due to electromagnets, coil components, digital devices, and cables carrying large DC or AC current at power frequencies that are capable of emitting radio frequency energy. There is a pressing need to control and shield electrical components from these kinds of emissions [15]. The increased awareness of EMI has led to the formulation of new regulations around the globe for manufacturers of electrical and electronic equipment to comply with the electromagnetic compatibility requirements. Several methods are available for shielding electromagnetic radiation, such as ionic plating, electroless plating, cathode sputtering, conductive paints, vacuum

metallisation, zinc paints, zinc flame spraying, zinc arc spraying, and conductive fillers, such as copper, stainless steel, and aluminum. The above methods can be categorised under two headings: surface treatments and fillers. Surface treatments are often time-consuming, labour intensive, and costly. Conductive fillers in the form of particulates, filament, and woven fabrics are increasingly being used for shielding electromagnetic radiation. Attempts by researchers [16 - 19] using woven fabric indicate that the shielding effectiveness of fabrics depends on the content of the conductive filler. Various conductive fillers are selected based on their values of electromagnetic shielding effectiveness (EMSE) at different electromagnetic frequencies [20 - 28].

Woven metal cloth along with base textile material are being increasingly utilised in shielding EMI and for anti-electrostatic purposes in various applications in the defence, electrical and electronic industries. This is mainly due to their desirable properties in terms of flexibility, good formability, mechanical properties, electrostatic discharge, EMI protection, and radio frequency interference protection. The reduction of EMI depends upon the signal amplitude and frequency in relation to fabric parameters such as ends per cm, picks per cm, the wire diameter and fabric structure. In this study, copper was selected as the shielding material mainly because of its superior electrical properties compared to other metals. Moreover, copper exhibits high absorption and low reflection to electromagnetic energy. Absorption loss is defined as the product of conductivity and permeability. It has been cited in literature that materials with a high absorption loss and low reflection loss are highly effective in shielding electromagnetic energy. Copper is also less expensive compared to other materials. Hence, copper was chosen as the conductive filament [29 - 32]. The level of the EMSE desired for use in high end applications such as military applications, electronic enclosures and others is around 50 – 70 dB. The development of fabrics with such shielding effectiveness would be a handy tool for safeguarding electronic appliances from EMI. In this research, studies were carried out to study the electromagnetic shielding effectiveness of conductive fabrics made of 2-ply and 3-ply of cotton copper yarns with varying ends per cm, picks per cm, cover factor, fabric struc-

ture, yarn types and diameter of the copper wire.

### The shielding mechanism

The purpose of shielding is to confine radiated energy to the bounds of a specific region, or to prevent radiated energy from entering a specific region.

Shields may be in the form of partitions and boxes as well as in the form of cable and connector shields. Shield types include solid, non solid (e.g., screen), and braid, as is used on cables. In all cases, a shield can be characterised by its shielding effectiveness, which is the number of decibels by which the shield reduces the field strength as the result of it being in place. Shielding effectiveness seems to be dependent not only on the material from which the shield is made and its thickness but also upon the frequency, the distance from the source to the shield, and the quantity and shape of any shield discontinuities (22). The first step in the design of a shield is to determine what undesired field level may exist at a point with no shielding and what the tolerable field level is. The difference between the two is the shielding effectiveness required.

### Attenuation provided by shield results from three mechanisms:

- (1) Incident energy is reflected by the surface of the shield because of the impedance discontinuity of the air-metal boundary. This mechanism does not require a particular material thickness, but simply an impedance discontinuity.
- (2) Energy that does cross the shield surface, i.e., is not reflected but is attenuated when passing through the shield.
- (3) The energy that reaches the opposite face of the shield encounters another air-metal boundary, and thus some of it is reflected back into the shield.

### Analysis of the shielding effectiveness of plain woven fabric performances (apertures)

The following analysis of leakage through openings in copper core yarn fabric shields is based upon transmission line theory. The shielding effectiveness is given by the equation

$$S = A_a + R_a + B_a + K_1 + K_2 + K_3 \quad (1)$$

where:

$A_a$  - attenuation introduced by a particular discontinuity in dB

$R_a$  - fabric aperture. Single reflection loss in dB

$B_a$  - multiple reflection correction term in dB

$K_1$  - correction term to account for the number of like discontinuities in dB

$K_2$  - low-frequency correction term to account for skin depth, dB in and

$K_3$  - correction term to account for coupling between adjacent holes in dB.

**Term  $A_a$ .** Assume that the incident wave is below the cut-off frequency,

$f_c = c/\lambda_c$ . The cut-off wavelength is 2.0 times the maximum dimension of a rectangular opening.

$$A_a = 27.3 (d/W) \text{ dB} \quad (2)$$

where:

$d$  - depth of fabric opening in cm,

$W$  - width of fabric opening perpendicular to the E-field in cm,

**Term  $R_a$ .** The aperture single reflection loss term depends upon both the impedance of the incident wave and the shape of the fabric aperture. This term is given by Equation (3):

$$R_a = 20 \log_{10} [(1 + 4K^2) / 4K] \text{ dB} \quad (3)$$

where:

$K = j 6.69 \times 10^{-5} f W$  for plane waves and rectangular apertures

$f$  - frequency in MHz.

**Term  $B_a$ .** The multiple reflection correction term is given by Equation (4):

$$B_a = 20 \log_{10} [1 - (K - 1)^2 / (K + 1)^2] \times 10^{-A_a/10} \text{ dB, for } A_a < 15 \text{ dB} \quad (4)$$

**Term  $K_1$ .** For a source distance from the shield that is large compared with the aperture spacing; the correction term for the number of discontinuities is given by Equation (5):

$$K_1 = -10 \log_{10} n \text{ dB, } r \gg W, r \gg D \quad (5)$$

where:

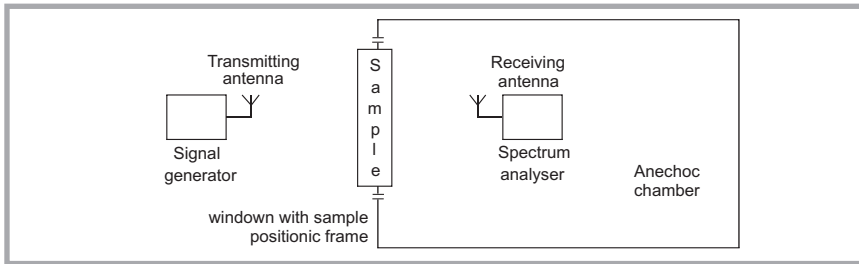
$a$  - area of each fabric hole (sq cm), and

$n$  - number of fabric holes/sq cm.

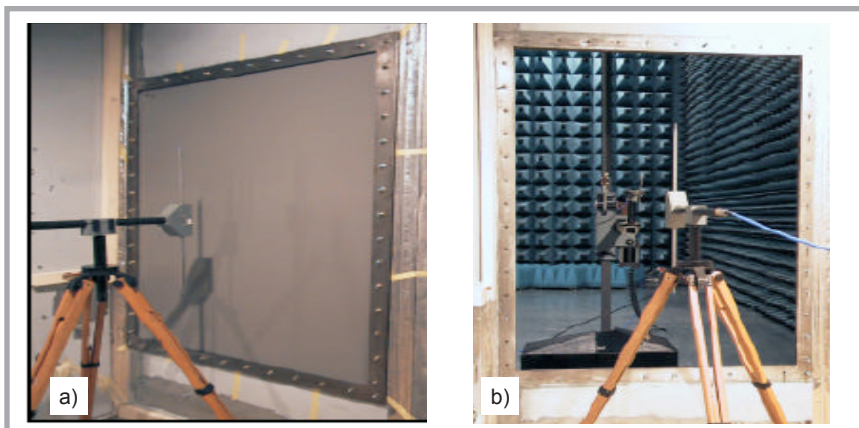
**Term  $K_2$ .** The skin depth correction term accounts for the reduction in shielding effectiveness when the skin depth becomes comparable to the copper wire diameter or the dimension between the apertures, which occurs at low frequencies. An empirical relationship has been developed for the skin depth correction term, which is represented by Equation (6):

**Table 1.** Specification of 2-ply and 3-ply of copper-cotton yarns and woven fabric

Sample	Yarn	Linear density, tex	Copper wire diameter, mm	Ends per cm	Picks per cm	Cover factor	Weave
S1	3-ply yarn	188	0.12	79	69	23.0	Twill
S2	3-ply yarn	188	0.12	79	66	22.7	Plain
S3	3-ply yarn	83	0.11	79	69	17.4	Twill
S4	3-ply yarn	83	0.11	79	69	17.4	Plain
S5	2-ply yarn	51	0.10	97	79	16.7	Twill
S6	2-ply yarn	51	0.10	79	66	14.5	Plain
S7	3-ply yarn	83	0.11	71	66	16.7	Plain
S8	3-ply yarn	83	0.11	79	81	18.5	plain



**Figure 1.** Test setup.



**Figure 2.** Arrangement of testing stand; a) transmitting antenna, b) anechoic chamber with receiving antenna.

$$K_2 = -20 \log_{10} (1 + 35p^{-2.3}) \text{ dB} \quad (6)$$

where:

p - copper wire diameter/skin depth (fabric), and

p - conductor width between holes/skin depth (perforated sheets).

**Term  $K_3$ .** Shielding effectiveness is relatively high when the fabric apertures in the shield are closely spaced, and the depth of the fabric openings is small compared to the fabric aperture width. This is the result of coupling between adjacent holes, which is especially important for small openings. The correction term for adjacent fabric hole coupling is given by Equation (7)

$$K_3 = 20 \log_{10} (\coth [A_a/8.686]) \text{ dB}. \quad (7)$$

## Experimental details

### Productions of 2-ply and 3-ply of copper / cotton yarns

For the production of 2-ply and 3-ply of cotton copper yarns, a ring doubling machine was used in the present research work. The 30 tex cotton yarn and copper filament (of 0.1 mm, 0.11 mm, and 0.12 mm wire diameter) were used to produce double and 3 ply of cotton copper yarn on the ring doubling machine. The yarns produced were 188 tex, 83 tex and 51 tex (resulting count). Details of the yarn procedure are given in **Table 1**.

### Production of woven fabric with 2-ply and 3-ply of copper/cotton yarns

The 2-ply and 3-ply of cotton copper yarns were transformed into woven fabric

using a weaving machine. From the 2-ply and 3-ply cotton copper yarn produced, different types of plain and twill weave fabrics were manufactured by varying the fabric parameters listed in **Table 1**. It was observed that making woven fabric from the 2-ply and 3-ply of copper-cotton yarn is not much easier than ordinary woven fabric production.

### The electromagnetic shielding effectiveness test

The EMSE of the conductive fabric was calculated by following ASTM D4935-99 Test methods for measuring the electromagnetic shielding effectiveness of planar materials with the given setup [33 - 35]. The shielding effectiveness (SE) of EM enclosures has been well defined and is easily understood. It is the ratio of the signal received from a transmitter without the shield to the signal received with the shield; or in terms of the insertion loss when a shield is placed between the transmitting antenna and the receiving one, as shown in **Figure 1**.

The basic characteristic of the conductive fabric is its attenuation property. Attenuation of the electromagnetic energy is a result of reflection, absorption and multi-reflection losses caused by a specific material inserted between the source and receptor of the electromagnetic energy radiated.

Attenuation caused by a material is characterised, depending on the measuring method used, by two quantities:

- Screening effectiveness (SE)
- Insertion loss (A)

### Screening effectiveness (SE)

Screening effectiveness (SE) is defined as the ratio of the electromagnetic field strength ( $E_0$ ) measured with and without the material tested ( $E_1$ ) when it separates the field source and the receptor.

$$SE = E_0/E_1$$

or, in decibels,

$$SE_{dB} = 20 \log E_0/E_1$$

This depends on the distance between the source and receptor of electromagnetic energy. In the far field zone, it characterises the attenuation of an electromagnetic wave. The measurement carried out in the near field zone characterises the attenuation effectiveness for the electric or magnetic field component only.

### Insertion loss (A)

Insertion loss (A) is a measure of the losses (or attenuation) of a transmitted signal from the test material being inserted into the measuring channel [16].

$$A = U_0/U_1$$

or, expressed in dB,

$$A_{dB} = 20 \log (U_0/U_1)$$

where:

$U_0$  – the channel output voltage without the test material.

$U_1$  – the same voltage with the test material.

We used a spectrum analyser with coaxial transmission equipment to measure the EMSE of the copper core conductive fabric at frequency ranges from:

- 20 MHz – 200MHz,
- 200 MHz – 1GHz and
- 1GHz –18GHz.

### Test procedure

**Figure 2** shows the window with the transmitting antenna on the outside of the hall and the receiving antenna within the hall. Tests are carried out in an anechoic chamber. An anechoic chamber is a room in which no acoustical reflections or echoes exist. The floor, walls and ceilings of these rooms are lined with a metallic substance to prevent the passage of electromagnetic waves.

An RF Signal is generated by a signal generator and transmitted through an antenna outside the chamber. The signal from the signal generator is measured using a spectrum analyser with an antenna inside the chamber. The first measurement (calibration) is carried out without the test fabric. Tests in the different frequency ranges are conducted. This method eliminates the problems of test procedure ambiguity, measurement error, resonance in a shielded room and the dependence of test results on the measurement set-up.

### Test results of electromagnetic shielding effectiveness

From the EMSE test results, by drawing a line chart for all three frequency levels with the frequency in the x-axis and shielding effectiveness in the y-axis, the variation in fabric characteristics and their effect on EMSE was carefully studied and discussed. They are,

- Effect of the copper wire diameter,
- Effect of the weave,
- Effect of the number of ply of the yarn
- Effect of the ends per cm (EPCM),
- Effect of the picks per cm (PPCM),
- Effect of the cover factor,

### Effect of the copper wire diameter on EMSE

To study the effect of the copper wire diameter on the EMSE, two samples, S1 and S3, are considered. Sample S1 is made of 3-ply yarn with copper filament of 0.12 mm diameter, whereas sample S3 is made of 3-ply yarn with copper filament of 0.11 mm diameter. Both these samples are made of twill weave of different yarn count. The wire diameter has a significant influence on the shielding effectiveness of the fabric. In order to study the effect of the wire diameter, fabrics designated as Sample S1 and Sample S3 were analysed. **Figure 3** show the effect of the diameter of wire with constant warp and weft densities of 3-ply cotton copper woven fabric. With an increase in the wire diameter, a general decrease in shielding effectiveness was shown by samples S1 and S3. Since copper is a rigid material compared to polymeric textile material, it offers resistance to bending when woven into fabrics. With an increase in the diameter, the bending of copper thread became more difficult, resulting in openness in the fabric structure, thereby providing less shielding effectiveness compared to the other samples. It was also observed that the maximum EMSE of 44 dB - 74 dB was obtained in the frequency range from 800 MHz to 2000 MHz for samples S1

and S3. **Figure 3** show that the EMSE of the two fabrics increases with an increase in the incident frequency and then declines after the maximum value is obtained.

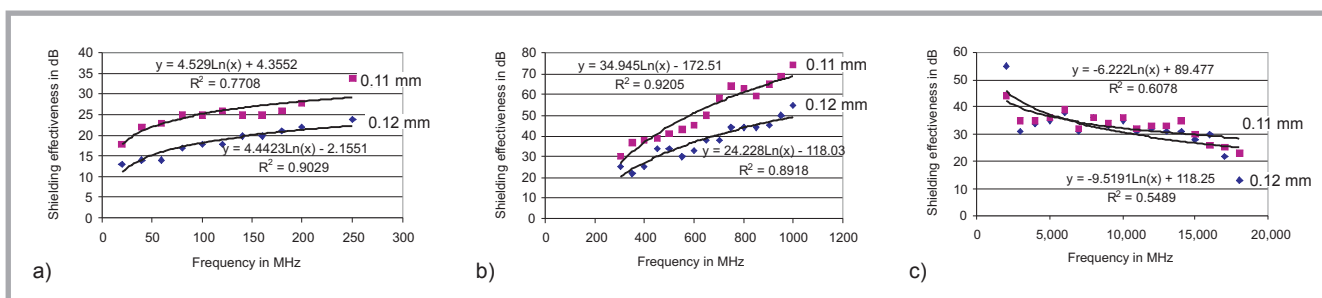
### Effect of weave on EMSE

To study the effect of weave on EMSE, samples S4 (plain weave) and S3 (twill weave) are considered. Both these samples are made of yarn with the same count and copper of 0.11 mm diameter.

**Figures 4** (see page 78) show the effect of the weave on the EMSE of fabric samples S3 and S4 with an incident frequency from 20 MHz to 18,000 MHz. From **Figure 4** (see page 78), it can be understood that sample S3 (twill weave) displayed better EMSE at a low to higher frequency range (20 MHz - 18000 MHz) than sample S4 (plain weave) due to the float length; there is a grouping of yarn, thereby reducing the porosity of the fabric. Samples S3 and S4 have good shielding effectiveness (61 dB - 74 dB) between the frequency ranges (750 MHz to 1000 MHz). From **Figure 4**, it can be seen that the EMSE of the two fabrics increases with an increase in the incident frequency and declines after the maximum value is obtained.

### Effect of the number of ply yarns

To study the effect of the number of ply yarns on EMSE, samples S4 and S6 are considered. From **Figure 5** (see page 78), it can be observed that sample S4 (3-ply cotton copper yarn) displayed good EMSE at a low to higher frequency range (20 MHz – 18,000 MHz) compared to sample S6 (doubled cotton copper yarn) due to the yarn constitution and the fact that sample S4 was produced with 3 ply copper yarn. Samples S4 and S6 have good shielding effectiveness (47 to 63 dB) between the frequency ranges (700 MHz to 1000 MHz). The EMSE of the fabric increases with an increasing in-



**Figure 3.** Effect of copper wire diameter on EMSE at: a) low frequency, b) medium frequency, c) high frequency.

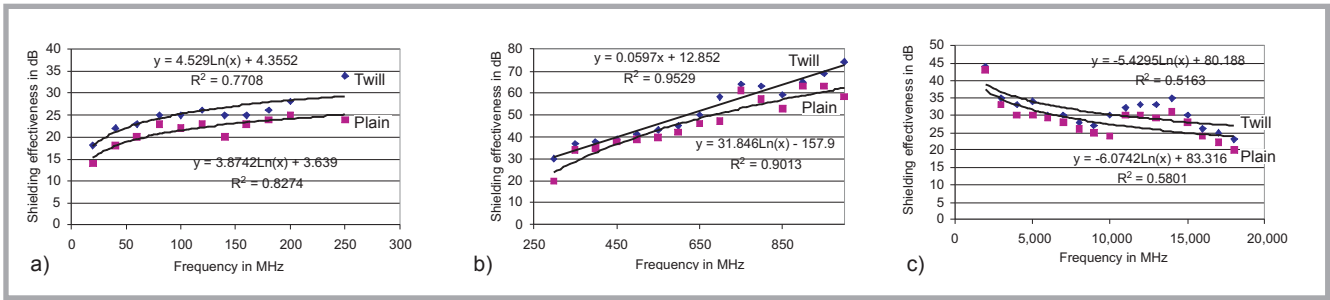


Figure 4. Effect of the weave on EMSE at: a) low frequency, b) medium frequency, c) high frequency.

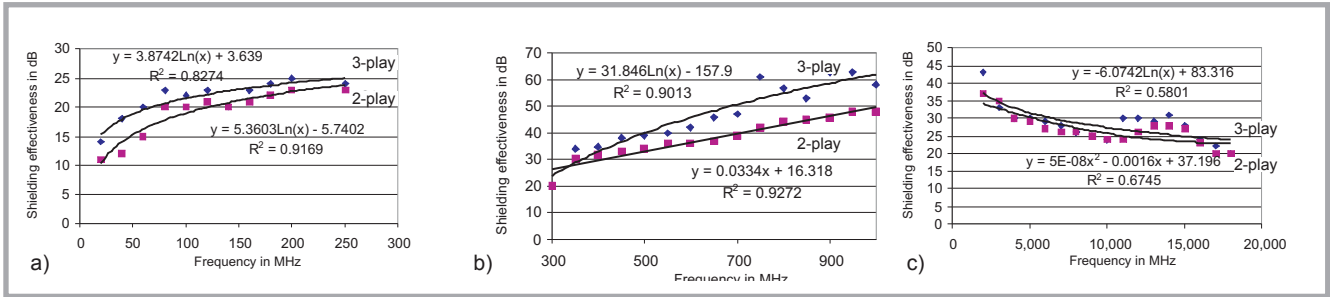


Figure 5. Effect of ply yarn on EMSE at: a) low frequency, b) medium frequency, c) high frequency.

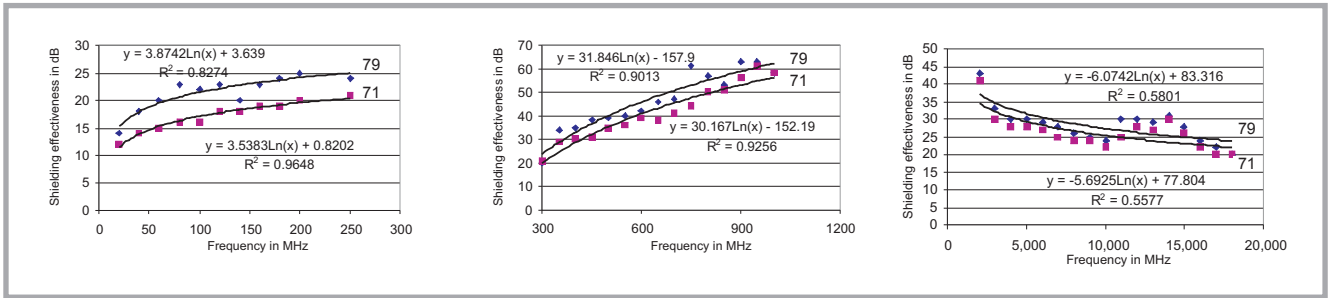


Figure 6. Effect of ends per cm on EMSE at: a) low frequency, b) medium frequency, c) high frequency.

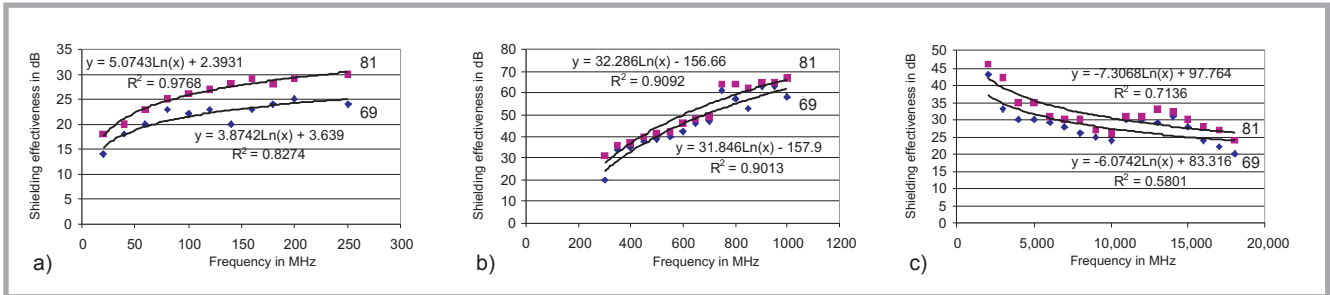


Figure 7. Effect of picks per cm on EMSE at: a) low frequency, b) medium frequency, c) high frequency.

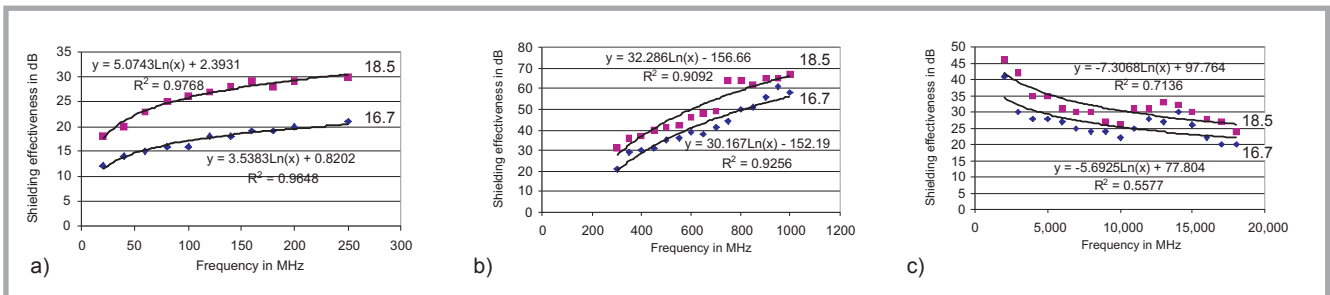


Figure 8. Effect of the cover factor on EMSE at: a) low frequency, b) medium frequency, c) high frequency.

cident frequency and then decreases at a higher frequency range.

#### Effect of ends per cm on EMSE

To study the effect of the ends per cm on EMSE, samples S4 and S6 are considered, for which three line charts were drawn for different frequency ranges.

**Figure 6** show the effects of EPI on the EMSE of samples S4 and S7. The EMSE of the two fabrics increases with an increase in the incident frequency and then decreases after the peak of the frequency range i.e. above 1000 MHz. From **Figure 6**, it can be understood that sample S4 displays better EMSE at a low to higher frequency range than sample S7. The increase in the shielding effectiveness of the woven fabric with an increase in warp densities is due to the presence of an increased copper content per square meter of the fabric. Samples S4 and S7 have better EMSE (41 to 63 dB) within a frequency range of 700 to 1,000 MHz.

#### Effect of picks per cm on EMSE

To study the effect of picks per cm on EMSE, samples S4 and S8 are considered, for which three line charts were drawn for different frequency ranges.

**Figure 7** show the effects of picks per cm on the EMSE of samples S4 and S8. The EMSE of the two fabrics increases with an increase in the incident frequency and then declines after the peak of the frequency range i.e. above 1000 MHz. From **Figure 7**, it can be observed that sample S8 has better EMSE at low to higher frequency ranges than S4 sample. The increase in the shielding effectiveness of the woven fabric with an increase in weft density was due to the presence of an increased copper content per square meter of the fabric.

#### Effect of cover factor on EMSE

To study the effect of the cover factor on EMSE, samples S2 and S4 are considered, for which a line chart was drawn for different frequency ranges. **Figure 8** show the effect of the cover factor of fabric on the EMSE of samples S7 and S8. The EMSE of sample S8 has a higher shielding effectiveness than sample S7 at a low to higher frequency level. This is due to the higher number of threads per unit area in the fabric sample. It was also observed that maximum shielding effectiveness was obtained in the frequency range 650 MHz - 1000 MHz.

## Conclusion

Conductive fabric produced from 2-ply and 3-ply of cotton copper yarns provides an attenuation of 40 dB to 74 dB at a medium frequency range of 700 MHz to 5,000 MHz. Hence these fabrics can be used to shield household appliance, FM/AM radio broadcasts, wireless phones, cellular phones, computers, buildings, secret rooms and various electronic gadgets that operate at a frequency of up to 5,000 MHz.

The following conclusions can also be drawn:

- With an increase in the warp density, weft density and cover factor, an increase in shielding effectiveness is observed for a low to higher frequency range (20 to 18,000 MHz) due to the higher number of copper threads per unit area.
- 3-ply of cotton copper yarn has higher EMSE at a low to higher frequency range.
- Fabric with a twill weave structure has higher EMSE at a low to higher frequency range (20 to 18,000 MHz) due to their float length. They have a grouping of yarns, thereby reducing the porosity of the fabric.
- With an increase in the copper wire diameter, there is a general decrease in electromagnetic shielding effectiveness. Since copper is a rigid material compared to polymeric textile material, it offers resistance to bending when woven into fabrics. With an increase in diameter, the bending of copper thread became more difficult, resulting in openness in the fabric structure, thereby providing less shielding effectiveness.

Variation in the shielding effectiveness of the fabric can be attributed to the fact that the electrical property of the material varies depending upon the frequency. Hence, it is suggested to use the fabric at frequencies where higher attenuation is obtained.

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