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Review Article

Electromagnetic shielding behaviour of conductive filler composites and conductive fabrics – A review

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In this study, theory of EMI shielding and research conducted on textile fabrics to impart conductivity for attenuating the electromagnetic (EM) radiation by means of different techniques have been reviewed in detail. Shielding of the EM waves can be done by means of reflection, multiple reflection and absorption by the shield. Different metals with their alloys and polymeric materials are initially used as shielding materials with some limitations. However, the recent developments in conductive fabrics and composites replace the conventional shielding materials. The composites with better conductivity and light weight could be a promising barrier material for protecting electronic circuits from the EM radiation and mechanical damage. Materials with high absorption co-efficient could impart shielding effectiveness of 80 dB for the frequency of 18 GHz. This paper mainly focuses on the necessity of conductive textile fabric and composites used as hybrid electromagnetic shields.

Keywords: Electromagnetic shielding, Conductive filler composites, Conductive fabrics, Vector network analyzer

1 Introduction

As the technology grows, use of electrical and electronic systems has increased enormously in all the engineering and technology fields. The advances in electronics reduces the component size and placing more number of electrical parts in limited space reduces the system size and increases the mobility. Placing the more number of components in a very confined space builds the problem of keeping the electromagnetic interference (EMI) of these systems from interfering with other systems through radiation. Most of the time, these systems are radiating EM waves which intentionally or unintentionally affect the activity of the other systems, resulting in reduced performance or damage of the exposed systems. If human beings are exposed to the EM waves, the network of veins in high risk organs such as eyes might be affected. This is due to heat build-up in the eyes by the EM waves which could not be easily dissipated[1]. In order to avoid these hazards to human beings and to protect the sensitive circuits from undesired EM radiation, EMI shielding is essential. In order to block the undesired EM radiation, one has to understand the properties and behavior of EM waves. The EM wave consists of electric field (E) and magnetic field (H) which are oscillating phase perpendicular to each other and also perpendicular to the direction of energy propagation. These electric and magnetic fields can be arrested by means of reflection or absorption. Many research work has been carried out on shielding material starting from metals to conductive fabrics and composites with required shielding and mechanical properties. The low frequency signals can be arrested by means of reflection whereas high frequency signals should be arrested by means of absorption which needs much attention. Much research has been conducted to develop high frequency EM absorbers by means of coating fillers with magnetic materials or incorporation of magnetic materials in the polymer matrix. This study mainly elaborates various shielding materials developed for different frequency range and different way of shielding such as reflection and absorption.

2 Hazards of EM Radiation on Human Health

The human body is daily exposed to EM radiation of varying intensity at different places. The EM radiation causes damage to human cells which depends on frequency, intensity of electric and magnetic field, direction and polarization of the waves. When these waves fall on human tissues, partially it gets transmitted[2]. Most of the waves are

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absorbed by the body tissues which raise the body core temperature[3]. Kumar and Pathak[4] studied EM field strength and specific absorption rate in close proximity to mobile phone base stations and found that transmission power near populated area causes ill to the human beings. The study also advised not to reside near transmission tower at least for 4m distance. Some studies stated that heavy use of mobile and cordless telephone causes brain cancer (most pronounced for glioma)[4]. Many standards have been developed by international bodies for the safe use of RF/Microwave radiations such as the National council on Radiation Protection and Measurement (NCRP, 1986), and the Australian Radiation Protection and Nuclear Safety Agency Standard (ARPANSA, 2002). All the protection standards set the safety limit for specific absorption rate which is 1.6 W kg^{-1}.

3 Mechanism for Shielding of EM Radiation

When the EM waves impinge on surface of an object, it undergoes four different mechanisms, namely reflection, multiple reflection, absorption, and transmission. In order to arrest the EM wave, it should be reflected (multiple reflection) or absorbed by the shielding materials. Figure 1 shows the mechanism of shielding of the EM waves which depends on the nature of the wave and material characteristics.

Reflection

Reflection of the EM waves takes place when the shielding material is made of highly conductive materials. If the shield has limited conductivity, some signal may penetrate through it. When it reaches the opposite face of the shield, it encounters another boundary (Fig. 1) and gets reflected back into the shield. The reflection of the EM waves by shield is decided by the frequency of incident wave, conductivity and magnetic permeability of the material[5].

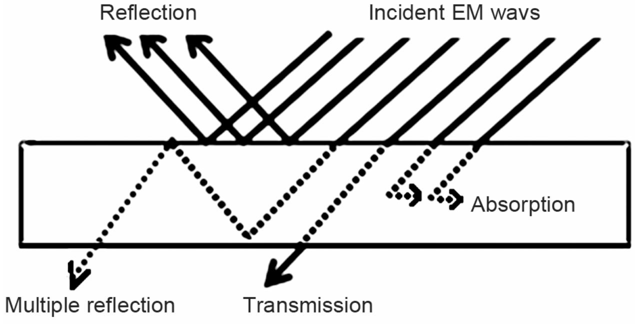

Fig. 1—Shielding mechanism of homogenous electromagnetic absorber

Multiple Reflection

Multiple reflections of EM waves occur due to various surfaces or phases present inside the shield. Materials with large specific surface (internal surface) like foamed materials and composite with filler show internal reflections of the EM waves[6].

Absorption

For absorption of the EM waves to occur, shield should contain electric and/or magnetic dipoles to interact with the EM field. Material with high dielectric constant (Barium titanate -$BaTiO_3$) provides electric dipoles and the material with high magnetic permeability (Ferrous-ferric oxide - Fe_3O_4) provides magnetic dipoles for the absorption of the EM waves[7]. Electric dipoles present in the shield destroy the electric field of the EM waves by converting it as heat[8]. Along with all these criteria, a good shielding material should also possess better absorption loss (insertion loss), lower volume and surface resistivity.

Transmission

When the EM waves pass through the shielding material without any attenuation, then high transmission of EM waves was observed. The non-conductive materials like glass, polyester and polypropylene show less or zero transmission loss to the EM waves.

4 Measurement of EMI Shielding

When the EM wave passes through a shielding material (which has higher thickness than the skin depth), power of wave (incident power) is divided into three parts, namely reflection (P_{ref}), transmission (P_{trans}) and absorption (P_{abs}). This is usually measured in decibel (dB). Therefore, we can define the incident power as given below:

$$P_{in} = P_{ref} + P_{trans} + P_{abs} \quad \ldots (1)$$

If the shield is thicker than the skin depth, the effect of multiple refection will be included[9] in Eq. (1). Shielding effectiveness (SE) of any barrier can be defined as the ratio of power transmitted (P_{trans}) to power incident (P_{inc}), as provided in following equation:

$$SE(dB) = 10 \log \frac{P_{trans}}{P_{inc}} \quad \ldots (2)$$

Electromagnetic shielding effectiveness (EMSE) of materials is assessed using coaxial transmission line method. The planar materials like woven fabric can be assessed using coaxial transmission holder according to ASTM D4935. Figure 2 shows the test set up used for assessing the EM behavior of conductive fabrics[10]. The signal generator inside the vector network analyzer creates different frequencies of microwave and carried by coaxial cable to the top sample holder. The fabric sample is placed between the top and bottom sample holders. The received signal is processed through reflection port. Finally, the SE of fabric can be assessed using the Eq. (2). This method is suitable for measuring the SE of materials in far-field condition.

5 Commercially available EMI Shielding Materials

5.1 Metal Coated Carbon Fibre

To fabricate conductive composites, metal coated carbon fibre is commercially supplied by Electro Fibre Technologies LLC, Stratford. Newburgh. Continuous fibre tow plated with nickel, copper or both, nonwoven veils/mats, woven fabric, continuous tow and chopped fibre are supplied for the purpose of EM shielding. Composites made from these fibres are highly suitable for aerospace, defense, electronics, construction and medical markets. But the cost of the fibre is 3 - 10 times higher than plain carbon fibre. In 1996, especially when hand held radio frequency devices were in practice, researchers at the state university of New York at Buffalo developed micro thin nickel coated carbon filaments (2 microns diameter) and it was embedded in a polymer matrix for shielding high frequency range[11]. At higher frequencies, only the outer region contributes for shielding and hence the composite with micron filament effectively contributes for arresting the EM waves. The filaments are fabricated by electroplating nickel on the carbon filament, resulting in only 6 % by volume of carbon exist in the fibre.

5.2 Metallized Cloth (3M fabrics)

Apart from 3M™ EMI absorber with shielding, many other conductive fabrics were developed by 3M technologists such as nickel on copper-plated PET ripstop fabric, silver-coated PET fabric, gold-coated PET fabric, copper-plated PET ripstop fabric, copper-plated PET ripstop fabric with nickel coating, glass fibre braids overwound with tin-plated copper foil and PET fibres braided with tin-plated copper foil. These products mainly provide electromagnetic compatibility, shielding or absorbing the radio frequency interference from ground sensitive electronic components and boards, protecting cables and providing conductive properties to the materials, etc. Especially for laptop, 3M™ EMI shielding foil and fabric tape are used for display grounding and EMI shielding. For this purpose, conductive fabric coated with acrylic adhesive containing Ni filler on one side of the fabric is used. This has the feature of XYZ electrical conductivity, conformable-soft, single sided and provides EMI shielding and grounding, better adhesion to all substrates and lower thickness (0.2 – 0.75mm). Two side coated conductive fabric is also available for this purpose.

Seal Science Inc. designed metalized fabrics as shielding material for aerospace/military, electronics and medical equipment. They have tried variety of fillers for the use as shielding materials. Carbon can be used where lower conductivity is required especially in ESD application. Nickel coated graphite can provide good EMI/ESD performance where the environment requires low corrosive reactivity. Silver coated nickel and silver coated copper can be used in high performance shields in non-corrosive environment. Pure silver particles could be the best filler where highest shielding and conductivity are required in a non-corrosive or reactive environment.

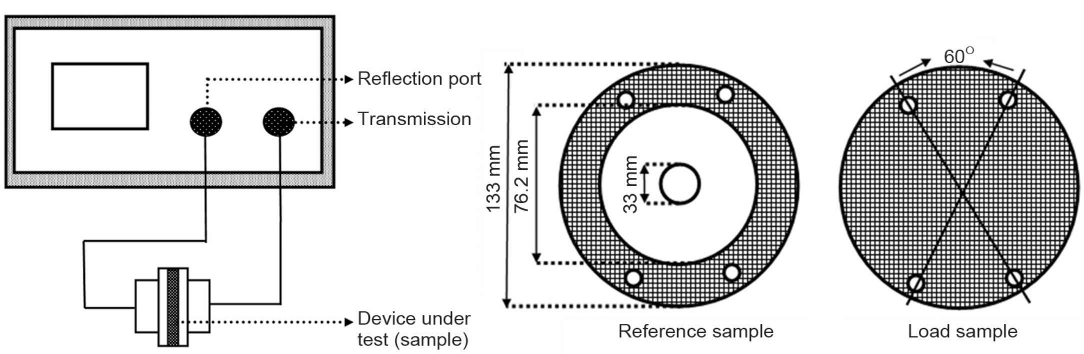

Fig. 2—A typical coaxial transmitter and sample holder for EMSE testing.

5.3 Shielding Through Spray Coating on Substrate

CHO-SHIELD® 608 is a high performance silver filler PET conductive coating to provide better shielding for 1-10 GHz. Coating of material is done by spraying silver filler PET polymer which gives very flexible and thin coating. The supplied CS 608 (at 51 % by weight solids) is thinned using methyl ethyl ketone to a suitable viscosity for application. It gives surface conductivity of 0.015 ohms/square for 0.5 mils thickness. A dry film thickness of 0.0005 inches (1 mils) is used to obtain 70 dB SE for 80 MHz to 10 GHz. However, the thinner or thicker coat may be made according to the shielding requirements of the device.

5.4 Shielding Tents

Shielding tents are used to protect the army weapons or cover any material from EM radiation. Mostly double or single layer conductive fabric is used for this purpose. Conductive PET fabric is plated with Cu/Ni to provide 30-50 dB SE and used as shielding tents. Usually the access point is made out of magnetic strips which is covered by electrically conductive layers of textile. The magnetic closure confirms the better electrical contact after the tent is closed. This can be fitted over aluminum mounting frame with varying size and shape.

6 Coated Shielding Materials

Traditionally, metals and their alloys were used as shielding materials. With the help of free electrons of metals and their shallow skin depth, shielding of the EM waves is occurred through surface reflection. Table 1 shows the conductivity of different metals used for EM shielding. Common metal used for shielding was mumetal which consists of 14% iron, 5% copper, 1.5% chromium and 79.5% nickel. However, most of the metals have certain limitations, e.g. aluminum based materials have low impact resistance and steel have higher density,[12] which restricts their usage as EM barrier materials. Also, metals are usually heavy, costly, rigid and easily prone to metal oxidation/corrosion[13]. These drawbacks and limitations made researchers to use metal coated materials as shields instead of using metals directly. The metal coating of materials can be done by means of different metallization methods. In recent years, textile fabrics are coated with metals and used as shielding material. The reason for choosing textile fabrics as shielding materials is their flexibility, good formability[14], mechanical properties, EM discharge, EMI protection[15], RF interference protection[16], light weight and thermal expansion matching[17]. For metal coating of the fabric, electroless plating is preferred by many researchers due to its homogeneous metal deposition, uniform electrical conductivity and suitability for non-conductors and complex shaped materials[18].

Table 1—Electrical conductivity of metals[7]

Metals	Conductivity S/cm
Silver	6.8×10^5
Copper	6.4×10^5
Aluminum	4.0×10^5
Nickel	9.7×10^4
Steel	6.3×10^4
Stainless steel	1.8×10^4

Initially, electroless plating of copper (Cu) and nickel (Ni) was tried on cellulosic material (paper) and synthetic pulp by Shinagawa *et al.*[19] They could make conductive paper (80 g/m^2) with 40% Ni-Cu-PET and 60% synthetic polyethylene pulp. The metal coated paper showed over 40 dB SE between 10 MHz and 1 GHz. The electroless plating of copper on fabric was also done by Han *et al.*[18], who prepared conductive PET by coating with copper. They found that SE of copper coated fabric was 50 dB in the frequency range of 0.20 - 1.8 GHz. The physical properties of coated fabric such as fracture behavior and tensile strength were negatively affected due to ductility and brittleness of deposited copper film. In order to improve the properties of coated fabric, thickness and uniformity of copper film should be controlled. This can be done by modifying the base substrate used for electroless plating. Štefečka *et al.*[20] modified the base substrate by means of plasma treatment to form an active surface for the electroless plating. As a result, hydrophilic groups are formed on fibres which enhances the catalyst absorption that results in controlled deposition of copper. The adhesion of copper layer with plasma treated fabric is found to be much high which showed good peeled off resistance. The plasma treatment also increased the fabric shielding up to 80 dB in the frequency of 200 - 1600 MHz. However, copper coated fabric is easily susceptible to oxidation and has lower corrosive resistance than other metals like Ni and Ag. Hence, in order to improve the corrosive resistance of copper, Perumalraj and Dasaradhan[21] tried nickel coating on the surface of copper wire. They prepared nickel plated copper core conductive yarn and then woven into fabric. They observed that fabric has good SE of 25-45 dB in the frequency range 200-1000 MHz. These fabrics can be used to shield FM/AM radio, wireless phone, cellular phone and computer which operates up to 1000 MHz frequency. Despite of better shielding performance of metal coated fabric, the main drawbacks of coated fabrics are poor wear and scratch resistance, low mechanical properties and high rigidity which limit their application as the shielding materials in many areas[15]. Therefore, instead of metals, conductive polymers are examined for their shielding efficiency by several researchers. The next section discusses about research carried out on intrinsically conductive polymers and application of such polymers on textile fabrics.

7 Use of Intrinsically Conductive Polymers as Shielding Material

Intrinsically conductive polymers (ICPs) are light weight, corrosion resistant and easily made electrically conductive comparable to typical metals[22]. ICPs have string interdependence between chemical structural and electronic properties. Small changes in morphology of polymers by adding solvents could raise the electrical conductivity. Hence, ICPs are most suitable materials for arresting EM radiation[23]. EMI shielding in electrically conducting polymers takes place through both reflection and absorption and can be improved by tailoring electrical conductivities or dielectric constants. Hence, ICPs can be a suitable material for EM shielding because of their conductivity, better electrostatic discharge (ESD), shielding behavior and chemical resistance[24]. The ICPs such as polypyrrole and polyaniline are used for this purpose. Among ICPs, polyaniline (PANi) could be easily tailored for conductivity and dielectric constant through chemical modification such as stretch ratio and molecular weight. Despite better shielding provided by the conductive polymers, the rigid characteristics of ICP caused by chemical conformation of benzene rings restrict its application in the field of microwave absorbers[25]. And also poor long term stability and lack of processing methods limit the commercial success. Instead of coating of polymers on the surface of materials, usage of conductive fillers such as carbon, stainless steel etc. as reinforcement materials in polymer matrix can resolve these problems.

8 Blending with Conductive Fibres (or) Particles

The ease of processability and low density of conductive fibres and particles make them highly suitable to use as conductive fillers in the composite materials[26]. Conductive fillers such as stainless steel (SS) fibres, aluminum and aluminum alloy flakes, silver coated fillers, copper coated glass fibres, brass fibres and nickel coated graphite fibres with a small unit size have been blended with polymers to form electrically conductive polymers. While blending, the distribution, dispersion and L/D (length-to-diameter) ratio of fillers play a vital role in deciding the conductivity of polymers. At a particular concentration of conductive fillers, the polymer starts conducting electricity. This critical concentration of conductive filler is called percolation threshold point. At this concentration or above, 3D conductive network is formed by the fillers, which enhances the shielding behavior of materials[27]. The skin depth of the filler composites can be enhanced by decreasing the size of the fillers which decides the shielding level of composites[26]. Next section discusses about research carried out on conductive filler added polymer composites and their shielding efficiency in different frequency range.

8.1 Carbon Fibre Reinforced Polymer Composites

Compared to metal based shields, carbon based shielding materials are widely used due to their light weight, flexibility, corrosion resistance and formability[28]. Many forms of carbon fillers such as graphite, CB and carbon fibres were incorporated in polymer matrix. Since carbon fibre has better electrical conductivity and tensile strength, it was widely used as conducting fillers in EM shields[29]. Jana *et al.*[30] studied carbon fibres with different aspect ratio for their shielding efficiency in the frequency range 8-12 GHz. They found that composites with higher fibre aspect ratio (L/D = 100) form better conducting network which improves the EMI shielding. It was also observed that the composite with higher fibre concentration and sample thickness has good absorption loss and maximum SE value. To improve the conductivity of carbon composite further, Luo and Chung[31] developed carbon-carbon composite using carbon as a filler as well as a matrix. In order to assess the shielding effect, impedance measurement of different carbon composite was carried out. Figure 3 shows the impedance value of different carbon fibre composites for varying frequency. They found that carbon–carbon composite has high impedance which increases most abruptly with increasing frequency. The impedance values of epoxy-matrix composites also increased with frequency, but the abrupt change was observed only at higher frequencies (Fig. 3). However, the carbon-carbon composite has the highest shielding of 124 dB at 0.3 MHz to 1.5 GHz than other composites. They also found that composite with continuous carbon fillers showed better shielding than the composite with discontinuous carbon fillers. This might be due to the formation of better conducting network by continuous fillers than discontinuous fillers. The developed composites may be used to shield the radio frequency devices such as wireless communication devices.

Despite composite's better shielding, its flexibility is not as good as of other shielding materials. Therefore, in order to develop flexible composite, Das *et al.*[32] tried CB and short carbon fibre (SCF) filled ethylene vinyl acetate (EVA) and natural rubber (NR) ISNR-5 composites. Figure 4 shows the shielding behavior of CB and SCF filled EVA and NR composites. It was found that SCF/EVA composite shows higher shielding of 34 dB than SCF/NR composite with 30 dB. This could be due to the better dispersion of carbon fibre in EVA composite. But, the SCF filled NR composite exhibited prominent shielding effect compared to CB loaded NR composites. In the case of carbon fibre/EVA composite, it showed much higher shielding (34.1 dB) than CB/NR composite (8.4 dB) at 12 GHz frequency range. Moreover, the effect of fibre loading on shielding behavior was also studied by them. It was found that SCF composite has higher shielding than CB filled composite. This could be due to longer conductive path of carbon fibre than shorter conductive network of CB. Also, the increase in filler loading increased the SE for both SCF and CB based composites. The lower SE of CB filled composite was also confirmed by Wang[33] who found the SE of 8-10 dB for nanostructural carbon black/acrylonitrile butadiene styrene composite for 35 wt% CB loading.

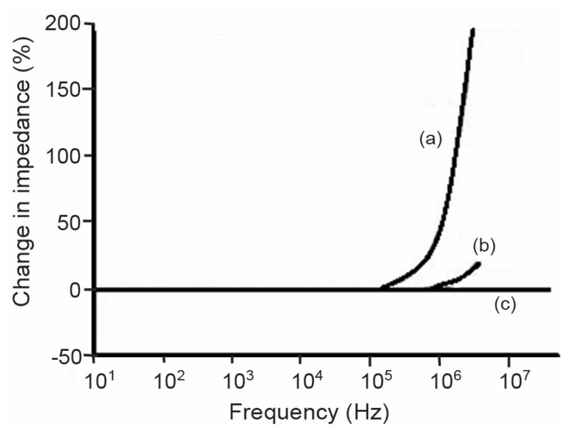

Fig. 3—Impedance of different carbon fibre composites for varying frequency; (a) carbon-carbon composite, (b) epoxy-matrix carbon-fiber composite, and (c) epoxy-matrix carbon fibre carbon filament composite[31]

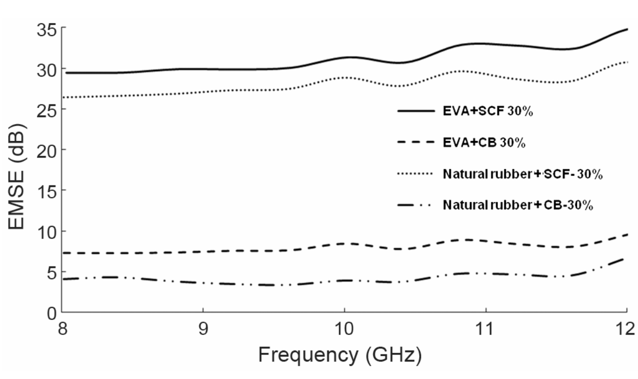

Fig. 4—Shielding behaviour of CB and SCF filled EVA and NR composites[32]

While processing the carbon fibre/rubber composite, it is reported that high fibre fraction leads to reduced mechanical properties. Therefore, in order to reduce the consumption of filler, Das *et al.*[27] did partial replacement of SCF with conductive CB in EVA polymer to enhance the reinforcement properties. The 20 phr SCF and 30 phr CB blended composite showed higher SE than 30 phr SCF and 50 phr CB filled composite. They found that added CB aggregate bridged the gap between two short carbon fibres, thus improved the SE up to 50-55 dB. This composite can be used for shielding electronic devices from microwave frequencies. They[34] also studied the effect of rubber blends in carbon/rubber composites on the EMI shielding. They observed that EVA-EPDM (ethylene propylene diene monomer rubber) blends (50/50) loaded with CB and SCF showed higher SE than pure EVA or pure EPDM. This could be due to the fact that EVA is polar and EPDM is non-polar which resulted in well-defined interface in the rubber blend. Hence, the filler deposited in one phase in the blend matrix forms heterogeneous dispersion which improved the electrical conductivity. The EVA-EPDM blends loaded with 50 phr SCF showed higher SE than EVA-EPDM blends loaded with 50 phr CB. In general, higher filler loading leads to better conductivity. But the mechanical properties of polymer are affected due to poor filler matrix interactions[29]. For example, CB based composite requires 30-40% filler loading to get better conductivity which deteriorates the mechanical properties of polymer composites. Hence, the amount of filler should be reduced to get optimized shielding and mechanical properties. Earlier, Das *et al.*[27] put some effort to reduce the filler content which was discussed in previous section. The use of carbon nanotubes may reduce filler concentration and can increase the shielding efficiency of filler composites.

8.2 Use of Carbon Nanotubes as Shielding Materials

Nanotechnology is becoming as emerging field in many areas of applications including EM shielding. With the help of nanotechnology, CNTs have attained great demand from their innovation by Iijima[35]. The CNTs are nanoscale structures formed by carbon atoms with C-C bonding. The CNTs including single-walled and multi-walled have unique structures and properties such as smaller diameter, high aspect ratio, high conductivity and good mechanical properties which make them highly suitable for shielding material[36]. These nanotubes are usually incorporated in a polymer matrix as a filler to impart conductivity and good SE[37]. Compared to CB and carbon fibre, CNTs have better conductivity and SE. Yang *et al.*[38] analyzed the shielding behavior of CNTs and CNF. Fig. 5 represents the shielding behavior of CNF and CNTs incorporated polymer composites. It was found that SE of CNT was much higher than CNF. To achieve shielding above 20 dB, more amount of CNF was required than CNT. The filler concentration of 20% by weight of CNF provided only 20 dB, whereas 5% by weight of CNT delivered SE of 24 dB in the frequency range 8-12 GHz. The major advantage of using CNT is that the conductivity can be brought with minimum fibre loading due to low percolation threshold, very high L/D ratio and high electrical conductivity. Studies have been carried out on single-walled and multi-walled carbon nanotubes filled polymer composite for EMI shielding which is given in next section.

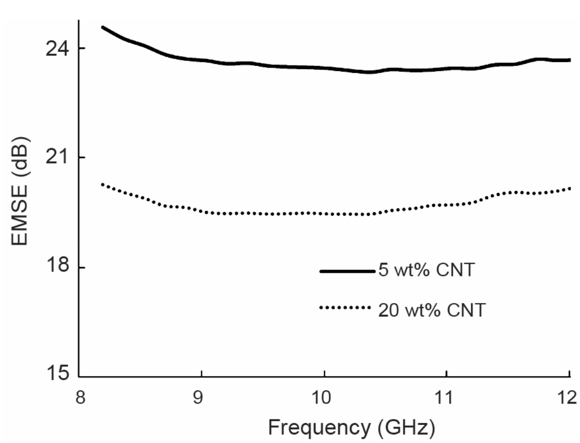

Fig. 5—SE of CNF and CNTs based polymer composites[38]

8.2.1 Single-walled Carbon Nanotubes (SWCNTs) Reinforced Polymer Composites

Li *et al.*[39] prepared SWCNT-epoxy composite for EMI shielding in the frequency range 500 MHz to 1.5 GHz. They found the shielding of 15-20 dB for 15% by weight of SWCNTs. It was also found that higher SWCNT bundle ratio and wall integrity enhanced the EMI shielding. On the other hand, Liu *et al.*[28] tried to disperse the SWCNT (L/D ratio 240) in polyurethane (PU) to make conductive composite. They reported the SE of 17 dB for 20% by weight of SWCNTs in the X band region. This study was further continued by Huang *et al.*[40]. He studied the type of SWCNTs such as long, short and annealed SWCNT in polymer composite on shielding efficiency. Figure 6 shows shielding behavior of different SWCNT in the frequency range 8-12 GHz. It was found that long SWCNTs show better shielding (27 dB) than short and annealed SWCNTs composites (21 dB and 16 dB respectively) at 15% fibre loading. The percolation threshold value of long SWCNTs (0.062%) was also lower than short (0.318%) and annealed (0.342%) SWCNTs in which better conductive network was formed at lower filler concentration of long SWCNTs. These composites can be used in civil and military electrical applications as effective light-weight EMI shielding materials. From this study, it was observed that SE of

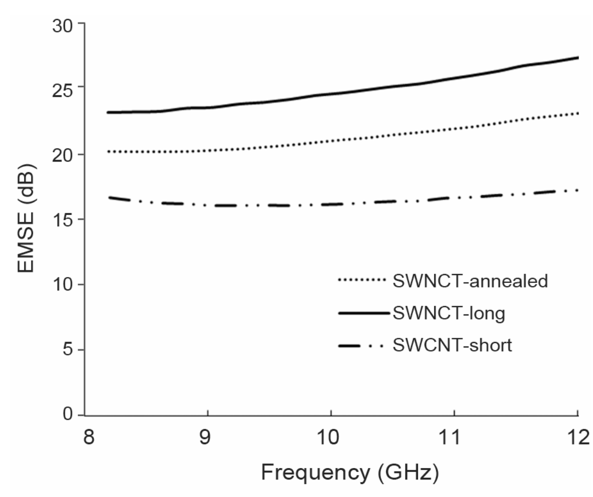

Fig. 6—SE of different SWCNTs incorporated polymer composite[40]

SWCNT is comparable with many MWCNTs polymer composites[41]. Another researcher Das and Maiti[42] developed SWCNT/EVA composite through melt mixing technique and found percolation threshold point for 3% by weight of SWCNTs and the SE of 23 dB for 15% by weight of SWCNTs in the polymer matrix. They also found that thickness of composite plays a major role in deciding the SE. Figure 7 shows the effect of composite thickness on SE. They found that as the thickness of the composite increased, the SE was also increased. The thickness of composite plays a major role in deciding shielding of composite especially at higher frequencies (12 GHz). The developed composites can be applied as shield in military electrical applications. Nevertheless, their compatibility with polymers and shielding efficiency are lower than MWCNTs incorporated composite. So the direction of research is shifted to MWCNTs incorporated polymer matrix.

8.2.2 Multi-walled Carbon Nanotubes (MWCNTs) Incorporated Polymer Composites

Compared to SWCNTs, MWCNTs are cheaper and more suitable for electromagnetic applications[43]. Apart from high shielding effect, strength of MWCNTs is also eight times greater than SS fibre[44]. Yang *et al.*[45] compared the SE of MWCNTs and Ag nanoparticles incorporated in PS. It was found that MWCNT/PS composite shows higher shielding of 22 dB than metal composite of 0.46 dB with 5% by weight of filler in the frequency of 12.4-18 GHz. It could be due to the better L/D ratio, dispersion of MWCNT and formation of conductive network inside the PS composite. Al-saleh and Sundararaj[46] studied the MWCNTs and structural nanosize carbon black incorporated PP composite. They found that the SE of 1 mm plate made of 7.5 vol% MWCNT/PP composite was higher (35 dB) than the plate made of 7.5 vol% high structural carbon black /PP composite (18 dB). To support this study, Sohi *et al.*[47] analyzed CB, SCF and MWCNT-filled EVA composites and found that MWCNTs exhibit better EM shielding than CB and SCF for lower filler loading.

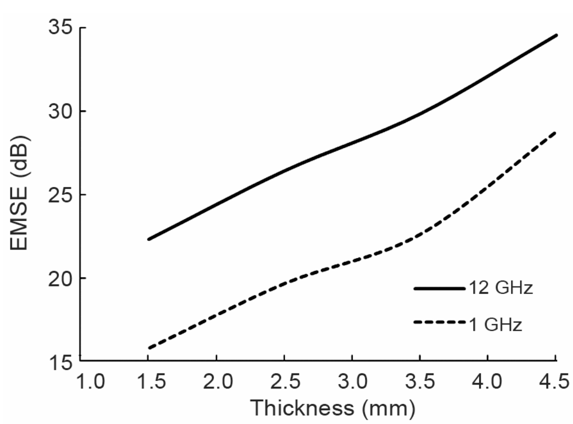

Fig. 7—Effect of composite thickness on SE[42]

Despite MWCNT's better conductivity and SE, Skotheim *et al.*[48] and Kim *et al.*[49] stated that problem of MWCNTs lies with the dispersibility due to strong Van der Walls interactions between MWCNTs and polymers. In order to overcome the problem, MWCNTs were modified[50] with acids such as HNO_3 or HNO_3/H_2SO_4. However, the acid modification also increased the defects of MWCNTs and shortened them, which resulted in reduced electrical conductivity. Therefore, the researchers tried out other methods such as *in situ* and *ex situ* polymerization for dissolving MWCNTs in polymer matrix. Yuen *et al.*[51] prepared MWCNT-PMMA composites by *in situ* and *ex situ* fabrication methods and studied the effect of processing conditions on shielding properties of MWCNT-PMMA composites. They reported that the composite prepared by *in situ* polymerization showed good SE. Also, the composite prepared by stacking 10 layers of 0.1 mm MWCNT-PMMA films showed higher SE (58.73 dB) than single 1 mm thick piece of bulk 4.76 wt% MWCNT-PMMA composites showing 32.06 dB at 2.18 GHz.

On the other hand, Mathur *et al.*[52] prepared MWCNT-PMMA composite films by solvent casting method. The solvent casting is a solution-based method in which a good mixing and dispersion of CNTs in PMMA can be possible. The developed composite films showed SE of 18 dB for 10 vol% MWCNT dispersed in PMMA matrix. The study was further continued by Pande *et al.*[53] who enhanced the shielding of MWCNTs composite by means of stack layering technique. The composite was prepared by stacking 7 layers of 0.3 mm thick MWCNT-PMMA composite films demonstrating higher shielding efficiency of 40 dB than 1.1 mm thick MWCNT-PMMA bulk composite prepared by stacking of two layers demonstrating only 30 dB. This might be due to increase in number of stacked layers, resulted in more multiple reflection loss and absorption of the EM waves. On the other hand, Nam *et al.*[54] approached new fabrication process to develop MWCNTs composite through three roll milling and lamination process. Using this method, multilayered

CNT-epoxy composites were fabricated by stacking B-stage CNT films layer by layer to enhance the electrical properties. The shielding efficiency of MWCNTs can be further enhanced by coating it with different ferrite materials or different layer of metals using organometallic compound as metal precursor. The uniformity and dispersibility of MWCNTs is a major issue to exploit the SE of MWCNTs effectively. An innovative dispersing method should be developed or modification of CNTs can be done with affecting its wall structure and conductivity to enhance the shielding effectiveness of carbon nanotubes.

9 Addition of Conductive Fibres or Yarns into Fabric

The textile fabric can be made conductive by introducing conductive fibres such as carbon, stainless steel and copper in yarn stage or in fabric stage. Different fabric parameters and amount of metal content decide the shielding efficiency of fabrics. Much work has been done on conductive filaments incorporated textile fabric for their shielding effectiveness. The type of fabric structure, density of threads and number of fabric layers are the key factors which needs to be tailored for better shielding effectiveness.

9.1 Carbon Filament Incorporated Shielding Fabrics

Carbon filaments have better electrical conductivity, chemical resistance and low density than most of textile fibres[55] and hence they can be used with textile material to make shielding fabric. Moreover, compared to carbon fibre, carbon filaments have higher L/D ratio which improves electrical conductive network. Much research has been conducted on carbon filament incorporated woven fabric for the purpose of EM shielding. Jou[56] prepared woven continuous carbon fabrics by weaving carbon filaments in a particular fashion. They studied the effect of weave [plain, balanced twill and unidirectional (UD) fabric] and angle of overlapping on shielding of EM waves. From the study it was observed that woven fabric has better SE of 50 dB than UD fabrics. This might be due to arresting of both horizontal and vertical waves, resulting in formation of better conductive network by woven structures. However, the overlapping angle has no significant effect on the SE of plain and balance twill weave structures. In the case of UD composites, on increasing the overlapping angle, greater SE was found. This could be due to the change in fibre orientation with respect to different overlapping angle(s). This carbon fabric in composite form can be used in optoelectronic applications, such as a low-cost, plastic laser-diode modulus. On the other hand, Lee *et al.*[57] analyzed different patterns like square and dipole pattern on the SE of fabric (Fig. 8). It was observed that fabric with square pattern shows high shielding with lower aperture ratio. The gap between carbon fibre roving acted as a dipole and defined the EM property of the fabric composites. The carbon filament based fabric can be a promising material for EM shielding. The carbon fabric provides shielding by means of reflection at low to medium range frequencies which also offers better mechanical strength to the shields. In future these filaments can be given metal coating with the help of electroless deposition in order to improve its electrical conductivity and corrosion resistance. Then the metal coated filaments can be woven into fabric for use as shielding materials in outdoor applications. Like carbon fillers, multilayer coating of carbon filaments also leads to a new research direction, where we can tailor the shielding performance of carbon fabric. Various metal coated carbon fabrics can be plied together to get collective properties for shielding wide range of frequencies.

9.2 Copper Filament Incorporated Shielding Fabrics

Many researchers suggested copper as a good shielding material due to its superior electrical conductivity compared to other metals[58]. Das *et al.*[59] studied shielding behavior of copper, brass and different textile material(s) such as cellulose and PET fibre. They showed that copper has better SE than brass, cellulose and PET materials. Hoeft and Tokarsky[60] prepared metal clad aramid yarn and made woven fabric along with the copper wire. The developed fabric has flexibility and better mechanical and EM properties with high SE of 70 dB. The surface transfer impedance or surface resistivity of

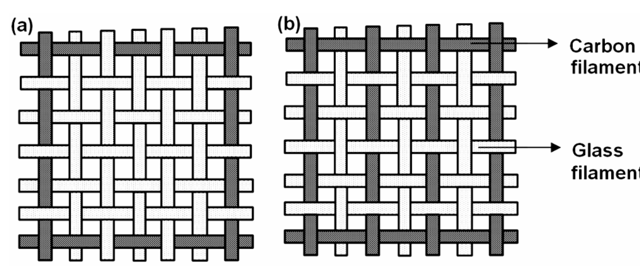

Fig. 8—FSFC with different weave patterns[57]

fabric is found to be 0.5 - 1.3 mΩ/square at low frequencies. Hence, this fabric is highly suitable for shielding low frequency EM waves ranging from 1 kHz to 100 MHz. In general, film type shield shows consistent shielding effect throughout the specimen, whereas mesh type shields show different resonance peaks at different frequencies[61]. All shielding fabrics belong to mesh type shield, and hence the factors like mesh size, geometry and aspect ratio of fabric define the SE. Roh *et al.*[5] developed conductive fabrics using insulated copper (coated with polyesterimide), bare copper and SS with different open grid structures. It was found that fabric with less open grid and aspect ratio provides better SE. It was also observed that insulated copper based fabric shows lower shielding of 25-30 dB from 30 - 800 MHz due to prevention of conduction by insulated coating. However, at higher frequencies (800-1500 MHz), the fabric showed higher shielding of 40-50 dB. This could be due to the formation of conductive mesh network by capacitive coupling, resulting in better shielding. The copper and SS filament based composite showed lower shielding than insulated copper fabric at higher frequencies.

While developing the conductive sheath-core yarn, it was observed that the ratio of core- to-sheath mainly affects the shielding and mechanical behavior of the yarn. Ramachandran and Vigneswaran[62] developed different sheath core copper yarn with different sheath core ratio. It was found that 67/33 copper core-to-cotton sheath conductive yarn has higher tenacity of 3.27 cN/tex and elongation-to-break of 5.27% as compared to other core–sheath ratios like 80/20 and 90/10. This might be due to good core sheath interaction factor (21.22%) which provides a better yarn structure. The core–sheath yarns has very low resistance of about 3–28 MΩ. Therefore, the SE of the fabric with 67/33 core sheath ratio provided good shielding of 32 dB in the frequency range of 760-860 MHz. This copper core conductive fabrics can be used to shield television, computers and also shield gadgets like cellular phones, etc. The study was further continued by Perumalraj *et al.*[63] to observe the effect of fabric parameters such as weave, ends per inch (EPI), picks per inch (PPI), number of fabric layers and copper wire diameter on SE. Increase in EPI, PPI and cover factor of fabric increases the SE from 350 –18,000 MHz. The twill fabric revealed better SE than plain fabric at medium to higher frequency range (600–18,000 MHz). This could be due to the fact that float length of twill weave results in grouping of yarn, thereby reduces porosity of fabric. However, plain fabric displayed higher shielding at low frequencies (20–200 MHz) than twill fabric. The fabric with 0.09 mm copper showed better shielding than fabric with 0.1 mm copper. For high copper diameter the bending resistance is high and this results in more open spaces in the fabric, hence SE is lower. These fabrics can be applied to shield the household appliances, FM/AM radio broadcast sets, wireless phones, cellular phones, computers, buildings, secret rooms and various electronic gadgets which operate up to 4000 MHz frequency. On the other hand, knitted fabric made from copper core yarn was studied by Perumalraj and Dasaradhan[64]. They analyzed effect of different fabric parameters such as fabric weave, thickness and tightness factor on shielding behavior of the fabric. They found that the increase in wale density, course density and tightness factor which increases the shielding efficiency of fabric. Perumalraj and Dasaradhan[64] also found that interlock structures show better shielding of 60 dB than plain and rib structures (40-45 dB) in the frequency of 20-18000 MHz. This could be due to interlocking of two copper core yarns which offered grouping of yarn, thereby reduction in porosity of the fabric. This knitted fabric is mainly designed for shielding industrial appliances such as mobile, electronic gadgets, automotive electronic parts, power lines, etc. Soyaslan *et al.*[65] analyzed the different fabric structures like plain knitting, weft in-laid plain knitting, 1×1 rib and weft in-laid 1×1 rib structures for their shielding behavior. The knitted fabric was made using folded yarns produced from Ne 20/2 cotton and copper wire with diameter of 0.1, 0.15, and 2×0.15mm. In the frequency range 800 -3000 MHz, the fabric structure is not effective on the shielding behaviour. But for the frequency range 27 – 400 MHz, weft-inlaid plain knitted fabric showed good shielding effect, whereas the weft in-laid 1×1 rib structure was found to be most effective structure in the range 600 – 800 MHz. They also found similar SE for weft in-laid plain knitted and plain knitted samples in the frequency range 400 – 3000 MHz. The plain knitted fabric with two 0.15 mm copper content showed better shielding effect than the plain knitted fabric with one 0.15 mm copper content for the frequency range 27 – 350 MHz. But both the samples show similar SE in the frequency range 800 – 3000 MHz. Overall the knitted fabric showed SE of 20–50 dB at 27–1000 MHz.

Mostly copper based fabric does shielding by means of reflection for low to medium range frequencies. In high frequencies, shielding efficiency of copper material is found to be very low and reflective shielding is not advisable in such high frequencies. Hence, coating of ferrite magnetic material on copper may improve the shielding level. This can be a future research where magnetic coating of copper will be helpful in shielding the wide range of frequencies.

9.3 Use of Stainless Steel as a Shielding Material

Clayton[66] stated that any barrier material with high absorption and low reflection loss is highly suitable for shielding the EM energy. In comparison with other metals, SS has good magnetic permeability and better EM wave absorption. Therefore, SS based shielding materials could be an effective absorbers due to their better absorption loss and low reflection loss to the EM waves[67]. The stainless steel is incorporated in two forms inside the shielding fabrics i.e SS fibre and SS filament. The following section discuss about SS fibre and SS filament in shielding fabrics.

9.3.1 Stainless Steel Fibre Incorporated Shielding Fabrics

The SS fibre can be blended with textile fibre to make conductive hybrid yarn. Cheng[68] prepared SS and polyester fibres blended (SS/PET) hybrid yarn using ring and open-end friction spinning systems and made knitted fabric. He found that knitted fabric made of 30/70 proportion of SS/PET open-end friction core-spun yarn showed good shielding. The conductivity of fabric could be tailored by fabric structure, stitch density, and the amount of conductive filler material. This SS based conductive fabric may be suitable for EM shielding of home electrical and electronic appliances. Although, the SS based PET or PP fabric provides better shielding, strength of the conductive fabric is low. In order to improve the strength and to enhance shielding efficiency, Cheng[69] developed conductive open end friction core-spun yarn using SS wire (or core copper), inner sheath SS stable fibre and outer sheath rayon (or kevlar) fibre for EMI shielding. This sheath-core yarn was produced using DREF-III spinning machine. The fabric made of SS wire showed better EMSE of 49 dB than fabric made of the copper wire due to better permeability of the SS. It was also observed that rayon based fabric showed higher EMSE than kevlar based fabric due to the presence of higher moisture content which improved the electrical conductivity of rayon fabric. For increasing incident frequency, from 300 kHz to 3000 MHz, all the fabric showed increasing trend for shielding behavior. The composite component manufactured from these fabric prepregs are suitable for shielding electrical appliances from EM fields. Compared to SS fibre, stainless steel in filament form has high strength along with better conductivity. The work done on SS filament based fabric is discussed in next section.

9.3.2 Stainless Steel Filament Incorporated Shielding Fabrics

Su and Chern[70] developed the conductive fabric made of three different yarns namely cover, core and plied yarns which consist of the SS as core and PET filament as sheath material. Figure 9 shows the effect of yarn geometry on EMSE. It was observed that EMSE of fabric increases initially as the frequency increases, and then decreases for further increase in the frequency. While comparing the three types of yarns, core and plied yarns show higher shielding than cover yarns. In the cover yarn, the SS filaments has a helical path which increases the filament path length, hence it has a higher electric resistance, resulting in lower SE. In the plied yarn, the SS filament was twisted with the spun yarn, therefore the distance was shorter resulting in lower resistance and higher SE. In the core yarn, the SS filaments lie in the central region of the spun yarn and hence it offers lowest resistance among all. Therefore, the conductive core yarn has better EMSE value (41.25 dB) among all yarns in the frequency range from 9 kHz to 3 GHz. On the other hand, Ortlek *et al.*[71] developed conductive fabric using PET covered SS yarn (hybrid yarn) with the help of hollow spindle covering machine. The fabric with different weave patterns like plain, twill, rib and panama was studied for shielding effect. It was found that rib structures show better SE than other weaves for horizontally polarized waves and no change was observed for vertically polarized waves. But, the EMSE of woven fabrics for vertical polarization increased with the increase in weft density. This could

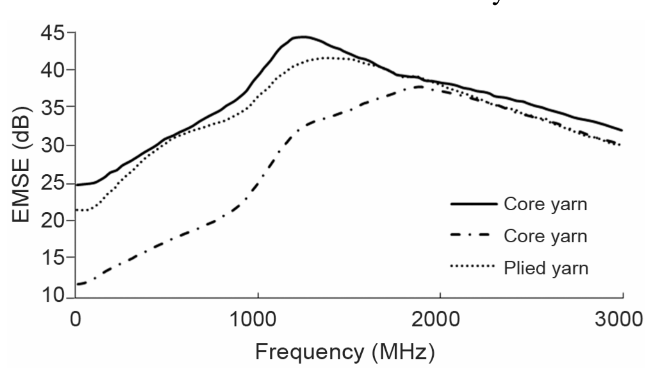

Fig. 9—Effect of yarn geometry on EMSE[70]

be due to high intercept of vertical polarized waves by weft way yarns present in the fabrics. This fabric may be suitable for strengthening the walls and windows, in order to prevent the emission of EM energy which contains secret information. It can also be used in house and office buildings for protection against EM radiation. From these studies, it is observed that the shielding by copper based conductive fabric is based on reflection not on absorption which is not fulfilling the demands in many areas such as defense. In case of military areas, the waves coming from radar should be absorbed and not get reflected back by the shielding material. Hence, in order to reduce the reflection and to improve the absorption of the EM waves, many researchers developed copper (Cu) and SS blended composite yarns for improving absorption coefficient of the shielding materials.

9.4 Copper and Stainless Steel Blended Hybrid Yarn Incorporated Shielding Fabrics

Lou *et al.*[72] prepared conductive sheath core yarn using rotor twister which has core of polypropylene nonwoven selvedge (PPNS), copper and SS wire and sheath of SS wire. It was found that fabric produced with such hybrid yarn has the SE of 40-50 dB at 300 kHz to 3GHz. In particular, six-layer fabric woven from sheath core yarns with 0º/90º/0º/90º/0º/90º lamination angles, has an EMSE of 56.1dB. The surface and volume resistivity of this fabric was very low and hence higher shielding was obtained. In another study, Huang *et al.*[40] prepared SS/PET, Cu/PET and SS/Cu/PET composite ply yarns using rotor twister and a knitted fabric was made. The developed fabric blocked the EM waves by either reflection or the multihop mechanism, which leads to different levels of decay of the EM waves. The SE of Cu/PET (12.36 dB) was higher than SS/PET (10.62 dB) fabrics in the frequency range below 1.1 GHz. This could be due to copper wires which are hardly influenced by the quarter wavelength of incident frequency. They observed that knitting needle density does not have any significant effect on EMSE of the metal/PET fabrics. For increasing the lamination layer, greater EMSE of the fabrics was found (26.6 dB for Cu/PET and 34 dB for SS/PET) at 0.44 GHz. However, no significant difference was observed for the frequency above 0.9 GHz. This might be due to high penetrability of high frequency range, which could not be shielded by increasing the metallic coverage area by means of higher lamination layers. However, by changing the lamination angle of the fabrics, more shielding was obtained due to higher attenuation of EM waves. They also found that fabric with SS/Cu/PET showed higher SE of 21.8 dB than Cu/PET (12.36 dB) and SS/PET fabrics (10.62 dB) in the frequency range 1.1 - 1.4 GHz. This study clears that combined shielding effect of copper and SS wires can be effectively utilized to attenuate the EM waves. Since, different shielding materials have different skin effect, their interaction with the EM waves is also different. Therefore, blending of such materials results in enhanced shielding at different frequencies.

To support this, Çeken *et al.*[73] prepared conductive core yarn in which copper and SS wires were wrapped on acrylic yarns and then knitted fabric was made. It was found that fabric with lacoste knits showed higher SE than 1×1 plain knit structure due to cross-wise orientation of tuck stitches in the knit structure. Especially significant improvement in EMSE of lacoste knit was found in the low frequency bands. For double pique fabrics, higher EMSE was found than interlock fabrics in the medium frequency range. This might be due to cross-wise miss stitches in the double pique knit structure. Ciesielska-Wróbel and Grabowska[74] used Swiss shield yarn (made up of cotton and copper), steel filaments and hybrid yarn (composed of stainless filament braided by Swiss shield yarn) for weaving different knitted fabric. They found that fabric made from hybrid yarn showed better shielding than Swiss shield yarn due to the formation of better conducting network by copper and SS filaments. Hence, the fabric made from Cu/SS hybrid yarn could be able to show better shielding of micro-waves from lower to higher frequency range. However, it could not be suggested for shielding the EM waves in outdoor applications. The use of copper is easily prone to oxidation, resulting in formation oxide film over the surface of copper. Therefore, the EMSE can be easily reduced tremendously. This problem can be avoided by coating copper with nickel (as mentioned in Section **6**) before start weaving the fabric. This can be a future research on Cu/SS woven shielding fabric and by optimizing the coating thickness of nickel as well as filler content, SE of nickel coated copper fabric can be decided.

10 Gaps in the Research and Future Scope

In recent years, the research mainly focuses on the use of different conductive fillers along with magnetic fillers in polymer matrix to improve the magnetic shielding without compromising other properties. It also focuses the magnetic coating of fillers in micro and nano level in order to reduce the filler loadings in polymer matrix. The future research can concentrate on metal coating of conducive fabrics for enhanced shielding of magnetic and electric interference of varying frequency. The fabric can also be developed with different proportions of microwave absorbing materials. Much research has been conducted for developing shield with high shielding efficiency and mechanical stability. Incorporation of high performance fibres such as kevlar, boron and basalt fibres while making fabric, will help in improved mechanical properties. The improvement in shielding can be done by adding micron layer of copper and nickel film as reinforcement in composite making stage. For the use of high performance microwave absorbers, development of multilayer conductive fabric can be a future research area to enhance the conductivity in 3 dimensional networks. Development of conductive fibre composite with the thickness of 1-2 mm having superior mechanical and shielding properties can be very useful. Further research on MWCNTs with modified conductive properties would help in reduction of composite thickness and could improve the electrical and magnetic properties of hybrid composite.

11 Summary

In general, shielding enclosures are used to protect the inner electronic device from EM radiation and mechanical damage. It is usually made of conductive materials such as metals and conductive composites, which has complex shapes with various apertures and slots for cable passage, air ventilation, etc. Designing of an enclosure depends on properties of material, geometric size and thickness, position and number of apertures, electronic characteristics of inner device, etc. Metal based enclosures like mumetal was initially used as the EM shielding material. Nevertheless it has some limitations like metal oxidation, fabrication of complex shapes, etc. which restrict the usage as shielding materials. In order to overcome this problem, conductive textile fabric and polymer composites have been tried. Conductive fabrics are used in various technical areas such as smart clothing, destaticizing people (or) equipment, RF protective suits, covers for sensitive electrical equipment, tents, curtains, tapestry, etc. Fabrics woven from conductive hybrid yarns are used for wall and windows for preventing emission of the EM energy which contain secret information. Fabrics with multi-conductive threads were developed for shielding wide range of frequencies starting from low to very high frequencies.

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