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EMI Shielding with Textile Fabrics: An Unadorned Review

N. V. Krishna Prasad[1] and N. Madhavi[2]

[1]*Department of Physics, G.S.S,*
GITAM University,
Bengaluru, India
[2]*Govt. College (Autonomous),*
Department of Statistics,
Rajhamundry, India

Electromagnetic radiation emitted from various sources need to be shielded. Especially, in case of human beings, this is of prime significance. EMI shielding can be done using various shields with more and more flexibility through stretchable, bendable, and droppable shields. In view of human health and its importance, lot of emphasis has been laid in developing textile fabrics, which can exhibit shielding properties along with mechanical strength, based on textile structure and material. The required characteristics such as electric and magnetic properties in normal textile fabrics are not up to the mark. Hence, these properties are to be added. This can be achieved by coating the layer, conductive yarn or magnetic fibre integration, *etc*. Based on the previous work done, an attempt was made to review the various materials and their use for this very purpose. This mainly includes fabrics with metal coating, MXene coating, carbon coating, *etc*. It is observed that high conductivity and effective EMI shielding make MXenes to be in the forefront in EMI shielded fabrics, while other coatings (magnetic and conductive) will be the next choice.

Електромагнетне випромінення, що випромінюється різними джерелами, потребує екранування. Це має першочергове значення, особливо для людей. Екранування від електромагнетних перешкод може бути здійснене за допомогою різних екранів з більшою гнучкістю завдяки розтяжним, гнучким і скидальним екранам. З огляду на важливість здоров'я людини, велику увагу приділяють розробці текстильних тканин, які можуть проявляти екранувальні властивості разом з механічною міцністю, залежно від структури текстилю та матеріялу. Потрібні характеристики, такі як електричні та магнетні властивості, у звичайних текстильних тканин не відповідають вимогам. Тому ці властивості необхідно додати. Цього можна досягти шляхом нанесення покриття, провідної нитки або інтеґрації магнетного волокна тощо. На основі попередньої роботи було зроблено спробу переглянути різні матеріяли та використання їх саме для цієї мети. Це головним чином включає тканини з металевим покриттям, покриттям максенами, вуглецевим покриттям тощо. Помічено, що висока провідність й ефективне екранування від електромагнетних перешкод висувають максени на передній план у тканинах, що екранують від електромагнетних перешкод, тоді як інші покриття (магнетні та провідні) будуть наступним вибором.

Key words: textile fabrics, EMI shielding, shielding effectiveness.

Ключові слова: текстильні тканини, екранування електромагнетних перешкод, ефективність екранування.

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1. INTRODUCTION

EMI (Electromagnetic Interference) is a phenomenon that takes place, when an electromagnetic field disturbs the operation of an electronic device close to it. Various EMI-shielding materials protect devices and human beings from this radiation by reflecting or absorbing it [1, 2]. In spite of huge increase in usage of electronic devices, shielding of human as well as equipment from EM waves is of prime importance. Since life without technology is not possible, electromagnetic irradiance even though dangerous for devices and human beings needs to be used in daily life. Many devices like switches, regulators, and circuit boards are likely to become defective due to EMI. These radiations also effect human cells and capable of altering DNA. Human cells subjected to EM radiation might lead to cancer. In addition, exposure to EM radiation leads to fatigue, stress and many other diseases. Earlier reports indicated biological impacts of EM radiation from various home appliances like TV, oven, *etc*. It was reported that exposure to microwaves impacts bone marrow and liver tissues [3, 4].

Figure 1 shows some of the non-cancerous effects of low frequency in the human beings.

Recent focus on developing EMI-shielding devices was towards usage of textile fabrics. Since textile fabrics are thin, lightweight, and flexible, they are preferred especially in view of cyber security. Reflection by conductive materials that lead to secondary electromagnetic radiation can be minimized through absorption [5, 6]. This mechanism in EMI shielding is widely used in medical electrical equipment. Generally, shielding materials are tested between 10^4–10^{12} Hz for computers, motors, and power lines [7, 8], while as other experiments like magnetic resonance tomography are tested for low frequencies [9, 10]. Various frequency ranges in a shielding

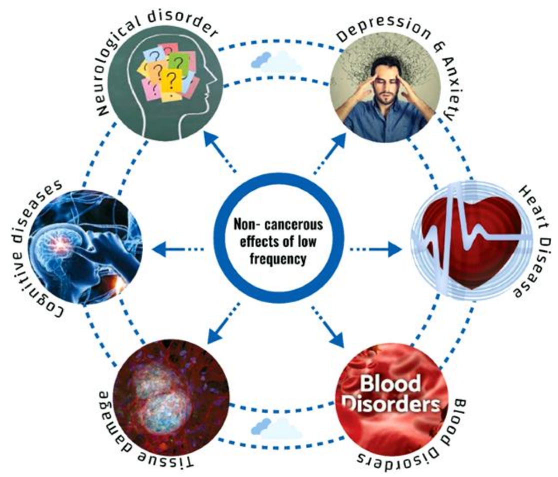

Fig. 1. Non-cancerous effects of low frequency in the human beings [4].

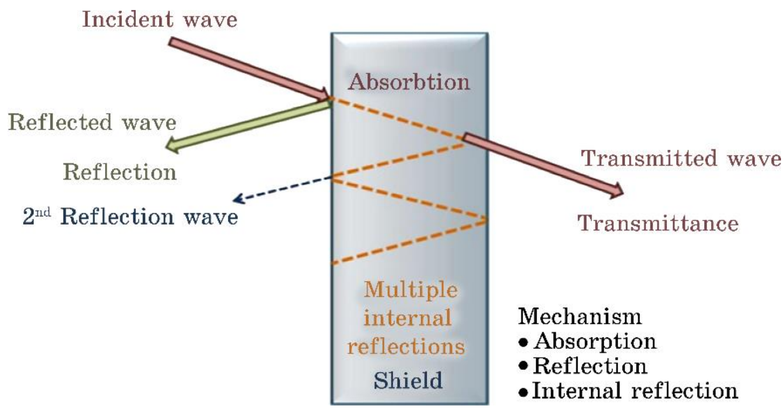

Fig. 2. Schematic representation of the EMI-shielding mechanism [4].

material demand various physical properties [11].

Figure 2 shows the mechanism of EMI shielding.

The effectiveness of shielding (SE) is given by:

$$SE = 20\log T^{-1} \text{ or as } SE = 10\log\left(\frac{P_0}{P_t}\right), \quad (1)$$

$$SE = SE_R + SE_A + SE_M, \quad (2)$$

where SE is a parameter comprises of shielding due to reflection (SE_R), absorption (SE_A), and multiple reflections (SE_M) inside the shielding material. T represents the transmission coefficient, P_0 and

P_t represent powers without and with shielding [12, 13]. Textile-based EMI shielding has gained more significance in recent times due to advent of novel materials such as MXenes. It is reported that EMI shielding depends on reflection and absorption inside the shielding fabric [12]. The thickness, porosity, conductivity, dielectric and magnetic properties influence shielding properties in textiles. If the thickness of the fabric is very small, multiple reflections need to be considered [14].

In general, electrical conductivity and thickness of a material determine high-frequency properties, while low-frequency properties are determined by magnetic properties [15–24]. Different methods are reported, while probing EMI shielding in materials. These include free space, shielded box, shielded room and coaxial transmission-line methods [25]. Coaxial transmission method is used between 10 kHz to 1 GHz. Free space method is preferred, if large distance exists between antenna and the device. Shielded-box method was confined to approximately 500 MHz with low reproducibility. Shielded room method uses an anechoic chamber, which is unsuitable for specimens in small size [26]. Various materials are used in EMI-shielding materials and some of them are discussed in the next subsequent sections.

2. ROLE OF MXenes IN EMI SHIELDING

Many techniques in preparation of EMI shielded fabrics are based on fibres, metal coating, and carbon coating. However, MXenes and their use in preparation of conductive coatings were widely reported. MXenes are 2*D* layered materials with nitrides [27]. Even though their preparation [28–30] is not mentioned in this review; sixty plus MXenes with different chemical composition and properties were reported [31].

2.1. MXene Coating

2*D* nature of MXenes makes them significant as coatings on textile fabrics. Electromagnetic interference shielding in combination with solar water evaporation as well as photothermal conversion was reported [32]. SiO_2 nanoparticles and PFOTES along with MXene were combined to yield shield effectiveness of 36 dB. Similarly, MXene textiles of bark shape demonstrated high effectiveness, good Joule heating and piezoresistive sensing [33]. It is reported that bark shape enhanced EMI-shielding effectiveness. Similarly efficient fabric shield with good electrical conductivity and low resistance with MXene loaded on cotton fabric that can be used as strain sensor to detect human motion was reported [34]. Basalt fibre fabrics are used as EMI shields [35]. Combination of Mxene with polymer network results in a textile fabric EMI shielding [36]. Samples without Mxene have almost zero EMI shielding in *X*-band [37]. Polyethylene terephthalate textiles applied with Ppy-modified Mxene sheets are coated with silicon. This yields 1000-S/m electrical conductivity and shielding efficiency of 90 dB [38]. Mxene combined with Pani nanowires on carbon-fibre fabric with PDMS coating reported a conductivity of 325 S/m and 35-dB effectiveness [39]. In a similar way, 3-dimensional nanoflower structure gives an effectiveness of 52 dB efficiency in *X*-band [40]; Mxene with metal reported 54 dB in *X*-band [41]; MXene with carbon-based conductive materials reported about 43 dB shielding [42].

2.2. MXene Fibres

Apart from MXenes, another possibility is to use MXene fibres. MXene fibres can be used as core in a coaxially spun fibre [43]. MXene fibres are reported to exhibit a shielding effectiveness of 27 to 33 dB for single layer with conductivity of 10^5 S/m. If 3 layers are considered, *SE* was up to 100 dB. Coaxial spinning of MXene core and aramid nanofibre shell has an efficiency of 83 dB [44]. Similarly, MXene fibres designed from MXene–glutaraldehyde (GA) solution with thermal drawing yield *SE* of 50–60 dB in *X*-band [45]. In continuation, short MXene fibres, which produce MXene nonwoven, yielded *SE* of 75 dB in *X*-band [46]. Similarly, a combination of reduced graphene oxide (*r*GO) and MXene to form a core shell aerogel reported to have *SE* value up to 83 dB, which could sustain 83% even after four months [47].

3. ROLE OF METALS IN EMI SHIELDING

Majority of the metals exhibits very high conductivity. However, low conductivity was seen in case of thin films and transition metals [48, 49]. Based on the magnetic properties, metals are used as coating to produce EMI shielding.

3.1. Metal Coatings & Metal Wires

Fabrics coated with metal (smart textiles) are used as strain sensors to detect human motion [50], as electrodes in ECG [51], textile batteries [52], textile solar cells [53], *etc*. In the same way, it was reported that EMI-shielding properties can be added to textile fabrics by metal coating. In this context, copper-coated polyester nonwoven was of importance [54]. As shown in Fig. 2, thick layer of copper was formed on the fibre, which reported a shielding effectiveness of 42 dB to 63 dB between 30 MHz to 1.5 GHz, depending on the coating thickness. In multilayer systems, 90 dB can be attained with three to five layers of copper-coated nonwoven fabrics.

Figure 3 shows a copper-coated PES fabric.

By using the above material, 30 to 55 dB can be attained between 0.5 GHz–1.5 GHz in a PES nonwoven fabric. This uses electroless plating of copper [55]. Apart from copper, silver is often selected to get high conductivity in coating. An oxidized-cellulose textile surface exhibited 47 dB and 69 dB for single and triple layers [56].

Combination of silver nanowires with Fe_3O_4 nanoparticles produced *SE* of 60 dB for single fabric layer and 100 dB for three fabric layers in *X*-band [58]. Silver nanowires combined with CNTs reached more than 51 dB EMI shielding [59]. A PES woven fabric,

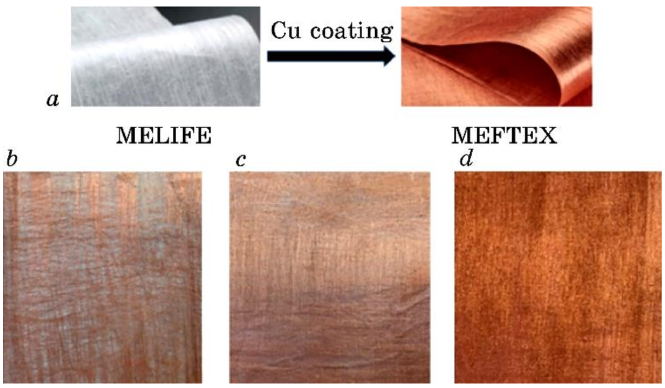

Fig 3. Copper-coated PES fabric [54].

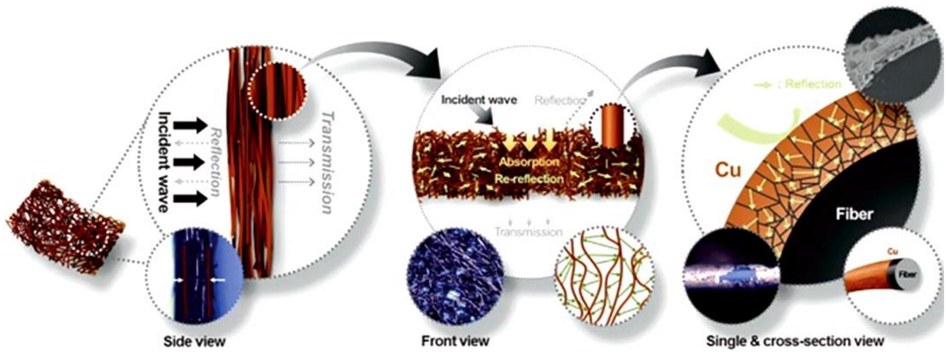

Fig. 4. EMI-shielding mechanism in copper-based activated carbon fibres [57].

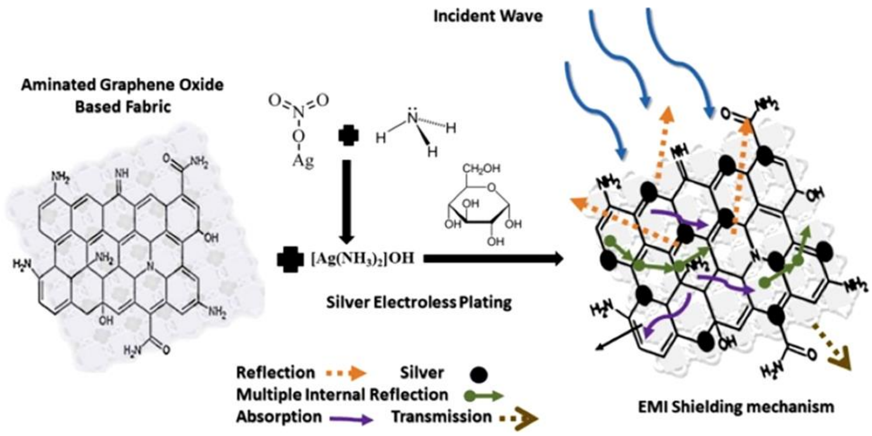

Fig. 5. Mechanism of Ag/aminated GO-based cotton fabrics [63].

when dipped in $Ni(CH_3CO_2)_2$ solution along with hydrazine hydrate, formed nickel nanoparticles on the surface of the fabric giving rise to 32-dB effectiveness. This is due to the ferromagnetic and conductive nature of nickel [60]. Keeping the mechanical, thermal, and chemical stability in view, various researchers opted for embedding of metal nanoparticles in polymeric coatings. A textile fabric immersed in PVB–ethanol solution embedded with silver nanowires yield an effectiveness of 59 dB between 5–18 GHz [61]. Silver nanowires with polyurethane layer exhibit *SE* of 64 dB that reduced by 11% after 20 washing cycles and to 18% after 5000 cycles. This fabric can be used as for various applications, where washing of fabric is essential [62].

Apart from these regular metals in nanoform, liquid metals are proposed. This include In, Pb, Ga, Bi, Sn, *etc.* with low melting points. A combination of liquid metal and PDMS coating yielded 73-dB efficiency [64, 65].

Apart from coating of textiles, metal wires can be inserted. Instead of polyamide filament yarns coated with silver, yarns with stainless-steel fibres are being used in smart textiles [66–69]. Since stainless-steel fibres exhibit magnetic properties, they are suitable for EMI shielding [70]. In place of stainless-steel yarns, self-spun yarns, which include stainless-steel wires, are widely used for EMI-shielding textile fabrics. A ring-spun composite yarn from stainless steel and polyester fibre reached EMI-shielding effectiveness of 31–35 dB in the range of 8.2–18.0 GHz [71–73]. A wrap yarn with same combination has *SE* around 5–28 dB for various wrapping densities in the frequency range of 4–8 GHz [74]. However, metal coatings are reported to have higher shielding effectiveness as compared to metal-wire approach [75, 76].

4. ROLE OF CARBON IN EMI SHIELDING

Designing of textile fabrics with carbon coating or carbon fibres was one of the techniques investigated. Carbon coated textiles are used in batteries, sensors [77], and electronic textiles [78–80]. Carbon has various forms like quantum dots, graphene, CNTs, carbon black and graphite [81]. Based on their dimension, carbon can have different conductivities [82]. Based on these conditions, they are well suited for EMI-shielding applications.

4.1. Carbon Coatings, Carbon Fibres, and Filaments

Carbon coatings with CNTs (carbon nanotubes) on fabrics enhance their EMI-shielding effectiveness. 1*D*-shape high anisotropic conductivity of carbon nanotubes influence EMI-shielding properties. Usage of CNTs along cotton fibres has *SE* of 21.5 dB in *X*-band and 20.8 dB in Ku-band [83].

By adding graphene, *SE* was enhanced [4]. EMI-shielding effectiveness was increased to 55 dB by adding ZnO nanoparticles and *r*GO in a textile coating [85] as desired in most of the shielding applications. Apart from copper, silver nanowires in combination with graphene reached *SE* of 72 dB at 8.2 GHz [90]. Usage of *r*GO sheets with silver nanoparticle coating on a fabric reach *SE* of 27 dB in *X*-band [86]. Combination of CNTs with nickel ferrite ($NiFe_2O_4$) coating on a textile fabric reached *SE* of 84 dB in *X*-band with enhanced structural stability and thermal conductivity [87]. Apart from carbon material and metal fillers' combination, conductive polymers are also used. It is reported that PANI polymerized on CNT improved distribution of CNT on cotton fabrics [88]. Usage of recycled carbon fibres reached *SE* of around 30–70 dB. In a similar way, 73 dB of *SE* with carbon fibre/TPU composite was reported [89].

These are some of the materials and methods reviewed in prepa-

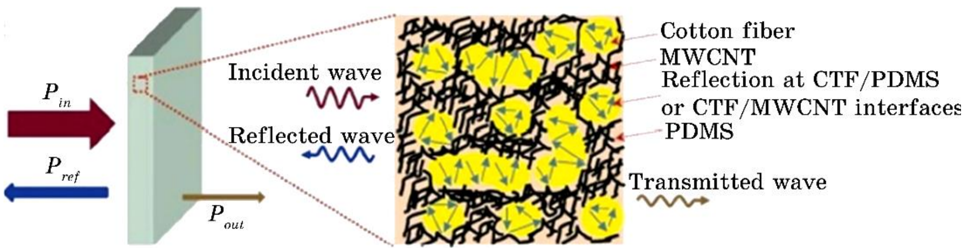

Fig. 6. EMI-shielding mechanism for PDMS/MWCNT-based cotton fabric [84].

ration of fabric textiles, which exhibit EMI shielding. Majority of the assessments were carried out in *X*-band, and a shielding effectiveness of about 30–90 dB was reported. The samples are of thickness below 1 mm. These values correlate with *SE* values of electro spun nanofibre mats [13]. Based on various factors, EMI-shielding fabrics, macroscopic textiles, and nanofibrous mats can be used in variety of applications.

5. CONCLUSIONS AND FUTURE PERSPECTIVES

Smart textiles and research in their area is widely enhancing in view of their EMI-shielding properties. Required physical properties, which include electrical and magnetic conductivity, may be added to regular fabrics by coating with conductive polymers, carbon- or metal-based coatings as well as MXenes. Apart from this, developing of yarns using metal wires or carbon fibres to produce EMI-shielding textile fabrics is of significance. In this review, some of the developments in this area of research were presented. In many cases, 30-dB to 100-dB EMI-shielding effectiveness based on various coatings was observed. Various approaches may be used to obtain high EMI-shielding effectiveness not limited to *X*-band, but also in other frequency ranges.

Future research is mainly focused on investigating more and more materials to dig their inherent properties and tailor them to act as a durable EMI shield. Emphasis should be laid on polymers

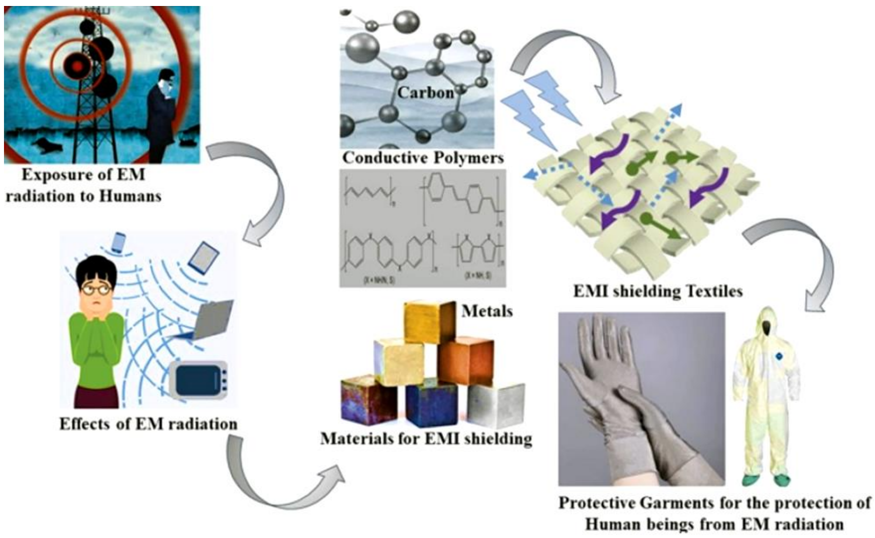

Fig. 7. Schematic representation of future perspectives [4].

and natural chemicals, which suit for EMI shielding. This would be economical and environment friendly. Fabrics should be reusable and could withstand various conditions like stress and strain. Since the effectiveness is reported to decrease with multiple washes, self-cleaning techniques need to be envisaged. In view of the significant potential for development of EMI-shielding fabrics at various work places with different conditions, emphasis need to be towards development of durable, flexible, and lightweight textiles for EMI-shielding applications.

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