A comparative study of EMI shielding effectiveness of metals, metal coatings and carbon-based materials

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Abstract. The increased use of electronic gadgets across almost all fields in the fast progressing 21st century has resulted in a new type of pollution. This pollution can be fatal for animals, humans as well as electronic gadgets. This new form of pollution is nothing but the electromagnetic interference or radio-frequency interference. When these harmful electromagnetic waves come in contact with the electronic devices, it causes them to malfunction thus resulting into damage of the costly equipment. Hence comes the need to protect the electronic gadgets and systems of commercial as well as defence fields from these harmful waves by providing a shielding effect. The review is a study of materials used for shielding like coated nano-fibers, nano-composites, metals, conducting polymers and carbon nanotubes (CNTs).

1. Introduction
With increase in electronic devices there is a rise in electromagnetic interference. Electrostatic discharge is one of the biggest reasons for EMI[1][2][3]. The signal radiations caused due to EMI can damage the electronic systems upto a great extent[4][5][6]. The distortions in audio or video signals on radio/ TV when an aircraft is flying at a low altitude, or the noise on microphones are the effects of these EMI. This on large exposure can cause the devices to malfunction and also affect human health. The only solution to prevent damage through these harmful radiations and protect electronic devices is to provide a shield which filters interferences[7][8]. There is a high demand of Strong and light weight Shielding Materials nowadays [9][10][11]. The materials used to manufacture these shields are being studied closely in this review.

1.1 Shielding of EMI
An electromagnetic wave has two major components- magnetic field and electric field, both perpendicular to each other. Forces are produced on the charge carriers under the influence of electric field. When the ideal surface of conductor comes in contact with electric field, the current will be induced which results in causing charge displacement in conductor that further cancels the applied electric field thereby stopping the current. In the similar way the applied magnetic field gets cancelled due to the presence of generated varying magnetic field. The conductor only responds to the static magnetic fields when it is undergoing relative motion with respect to the magnetic field [12]. The outcome is the reflection of EM radiation from conductor’s surface, internal fields stay inside and external fields stay outside. Absorption and reflection occurs when an EMI wave is passed through a
shield [13][14]. The energy which is left after the phenomenon of absorption and reflection is termed as residual energy which emerges out of the shield. The ratio of this residual energy to impinging energy can be termed as Shielding Effectiveness (SE) [3]. Conductive or magnetic materials are used as barriers to reduce the electromagnetic field in space by blocking the fields this process is called electromagnetic shielding. In order to isolate the electronic device from outside world the shielding is applied to enclosures. Similarly, it is also done to keep wires isolate from environment through which the cable runs. [2][15]. Radio frequency shielding is typically the process of blocking radio frequency and electromagnetic radiation,[16] Shielding mainly reduces the coupling of electromagnetic fields, electrostatic fields and waves. This phenomenon is dependent on the material used, thickness of the shield, volume, and frequency of fields of interest, shape and orientation of apertures in a field to an incident EM field. [17][18][19].

\[
SE = 20 \log \left( \frac{Et}{Ei} \right) \quad (i) \\
SE = 20 \log \left( \frac{Ht}{Hi} \right) \quad (ii)
\]

where \( Et \) is electric field of transmitted wave  
\( Ei \) is electric field of incident wave  
\( Ht \) is magnetic field of transmitted wave  
\( Hi \) is magnetic field of incident wave.  

The units of Electric field and magnetic field are volts/m and amps/m respectively. Three mechanisms are responsible for attenuation of an EM wave, namely absorption (A), reflection (R) and multiple reflections (M) Fig. 1.

Thus, \( SE = A + R + M \)

**Figure 1.** Attenuation of EM wave [20]

The shielding effectiveness is quantified using fours of the following methods. It’s detail description can be obtained from [20].

- Open Field or Free Space Method
- Shielded Room Method
- Shielded Box Method
- Coaxial Transmission Line Method

In the subsequent sections, studies on materials used for EMI shielding are presented with a focus on their comparative effectiveness.

### 2. Metals used for shielding purposes
Sheet Metal, metal foam and metal screen are typically used as shielding materials. The size of irregularity or holes in the material or mesh should be lesser than wavelength of the radiation which is to be kept out. Thus these irregularities in the shield should be considered minor than the radiation wavelength [21]. Coating with metal ink or similar material inside the enclosure is another variant of shielding method. The ink has very small particulates of carrier material that is loaded with suitable metal such as copper or nickel. It is then deposited on the enclosure, which produces a layer of continuous conductive material which further can be electrically connected to a chassis ground of the equipment thus providing effective shielding [22]. Radio Frequency shielding enclosures filter a range of frequency for specific conditions. Copper is usually used as RF shielding material because the absorption capacity of radio and magnetic waves of copper is considerably high if design is made properly and constructed well [23]. From the field of computers and electrical switches to the city scans and MRI scans used in hospitals the copper is used as RF Shielding material which is found satisfactorily effective [24][25].

Dou et al. [26] reported the production of shielding material by using aluminium composites i.e. aluminium 2024 along with CFA, and Aluminium 2024 along with PFA provided excellent shielding effectiveness till frequency of 100.0 MHz but declined at 600 MHz and further degraded exponentially at the frequency of 1.0 GHz in comparison with 2024 Al. Thus, it was inferred that the 2024 aluminium’s shielding effectiveness was much better than CFA/2024 Al at 1.0 GHz.

EMI shielding effectiveness and electrical properties of GCu nanoparticles reinforced in PVC nano composites developed by Alghamdi et al.[5] were examined. The composites having a higher volume of GCu did show an excellent Shielding Effectiveness of 70 db in at a frequency of 20 GHz.

Yao et al. [19] concluded that electromagnetic shielding effectiveness of materials based on cement is affected significantly by adding nickel fiber. An increase in the nickel fiber content has a direct effect on increase in SE of the Nanocomposites with cement as base. The maximum shielding effectiveness reported was 24.48 dB at 120 MHz for a composite with doped nickel fiber.

To significantly improve the shielding effectiveness of the composite, the cement matrix reinforced with nickel fiber must be treated with silica fume. Here the maximum SE achieved was 35.50 dB at frequency of 30 MHz.

3. Metals used as coatings for shielding

Materials with metals as base component are used on large scale for the protection of devices from EMI shielding [27]. But the bulkiness, and their nature to corrode act as one of the main reasons to limit their use [28]. Hence to overcome the limitations, metals are used in plated form on fibres and other carbonaceous materials.

Jiang and Guo [29] investigated the electro-less plating of nickel, phosphorous and nickel, copper multilayers on polyester fabrics gave good results of EMI shielding along with corrosion free results unlike other metal conductors. The Cu-Ni coat gave better EMI shielding effectiveness than Ni-P coating. Kim and Kyong [30] reported the Emi shielding behaviours of MWCNTs filled epoxy matrix nanocomposites coated with Ni. The higher the percentage of nickel in the composite, the better the EMI shielding effectiveness. He reported the shielding effectiveness of the 17.65 % nickel composite had the best results.

Kim [31] further reported the SE results of carbon fibre reinforced composite coated with Co alloy and Ni. Since Co also has magnetic properties like Ni, he experimented with addition of Co in his next research. Hence coating with addition of cobalt can cause a massive change in conduction, i.e., absorption of EMI will be strong. Ni- Co electroplating method resulted in excellent electromagnetic interference shielding efficiency of the CF- reinforced composites. The resistivity decreased and thus the conductivity increased. The composite with 69.39% Co and 18.85 % Ni proved to be the best material.
Yuan et al. [9] reported that the low effectiveness materials are less used, copper has high shielding effectiveness value among other available metals. Also, the weight of these metals is a major concern for its application in fields of aviation and aerospace. One way to reduce the weight constraint is by coating the surfaces of light weight porous materials with metallic materials using vacuum deposition. But still these materials can cause problems such as less chemical resistance, high prone to oxidation, highly corrosive, etc.

Hence polymer composites come into picture. Yuan et al prepared Samples of CH- rGO ie. Carbon honeycomb reduced graphene oxides of varying thickness were experimented for achieving SE.

4. Carbon-based shielding material

The metal coated or metal plated are conventional materials for shielding. Stainless steel fibers, copper and nickel coated fibers are mostly used. But there are limitations in these metal based shielding materials like bulkiness[32], low corrosion resistance, and lack of structural flexibility [33][34][35][36]. Hence, it is better to design a material which can overcome a few of these disadvantages. Therefore, carbon based are given preference as a better option for shielding materials [37]. In comparison with the metals or metal based electro-magnetic shielding materials, nano-carbon based shielding materials such as graphene, CNTs (carbon nano-tubes), graphene oxide, etc. are used [20]. These materials have exceptional structural flexibility, Strength and Electrical conductivity [38][39].

Arjmand et al. [21] compared the electrical conductivity of nitrogen doped and undoped CNTs in their experiment. The presence of extra electron in Nitrogen has been a topic for research to change the electrical conductivity of Carbon. According to him the synthesis conditions are important in deciding the electrical percolation behaviour of CNTs. On experimentation, the results proved that undoped CNTs have greater electrical conductivity, improved dispersion, less percolation ratio and thus better EMI shielding. It further states that nitrogen doping hampers crystallinity and shielding behaviour of CNTs. Thus it is better to use undoped CNTs. These are carbon and its various forms are used as conductive fillers. EMI shielding materials possesses shielding as a primary function and reflection as secondary function [36].

Al-Saleh et al. [36] conducted experiments on shielding by making composites of MWCNTs and polypropylene of varying MWCNTs concentration and different thicknesses. According to the theoretical studies and experimental results of experiments conducted by him the shielding effectiveness of the material improved with the increase in MWCNTs in composite along with its thickness. Thus, shielding effectiveness of material increases with increase in the the amount of Carbon Nano tubes present in the composite along with thickness.

Zhou et al. [40] experimented and studied the synergistic effect of GF (Graphene Films) and GCF (Graphene – Carbon nanotube Films). The Electrical conductivity and thus shielding effectiveness performance of graphene films can be increased to a good extent by introducing CNTs into them. Just by addition of CNTs by 20% can improve the shielding from ~50db to ~60db [40]. The SE of samples with CNTs content from 0% to 20% gradually increased with peak SE shown by sample GCF- 20, but the SE started to decrease as soon as the CNT content increased from 20%. Thus GCF- 20 was found to be the best material for shielding with the maximum shielding effectiveness. Also, the mechanical reliability of GCF- 20 was found to be excellent as it had good flexibility and structure integrity during bending.

Verma et al. [41] prepared samples of Polyurethane based composite materials with varying amounts of CNT pillared Graphene nanostructures (GCNTs). The GCNTs were mixed in amounts of 0%, 0.5%, 1%, 2%, 3%, 5%, 10% wt in thermoplastic polyurethane matrix. The hybrid filler was tested against frequency range of 12.4 to 18 GHz. It was noted that the shielding effectiveness increased with the increase in GCNTs. On the 10% wt GCNT composite, the shielding obtained was -47db, thus blocking more than 99.99% of the incident EMI radiations.

Because of skin effect, conductive fillers of smaller diameters are preferred than those of higher diameter [42].
To enhance the EM SE of composite fibers, electrical conductive fillers of various types were added to it. These conductive fillers included continuous metal mesh and discontinuous silver coated micro balloons. Silver was used as its electrical conductivity is better than that of copper. According to Liang et al. [10] the SE for EM in through absorption is better than the SE due to reflection. The EM of absorption was observed to be sensitive with regards to areal density. Absorption proved to be more dominant mechanism for shielding EMI.

Fletcher et al. [22] reported the nano composites formed of carbon Nano Tubes with the polymer of fluorocarbon in the form of foamed elastomers were potential materials for being a Shielding element. Although no significant change in the Shielding Effectiveness was noted but a major decrease in the weight of 25%-30% was recorded. In the study conducted by Wu et al. [1] Graphene Carbon Fibers (GCF) and magnetic Graphene (MG) were filled in Epoxy resin based composites. The SE of the nano composite material improved largely on adding MG (Magnetic Graphene). According to the study, if the surface of Magnetic Graphene is modified, the SE will be better. This can be a major take away for future references. Another reason for better SE was the interpenetrating 3 dimensional structure of the composite.

Table 1. The SE and electrical conductivity of EP/MG /GCF composites

| Sample   | Content% | Shielding Effectiveness(SET)/db |
|----------|----------|---------------------------------|
|          |          | X-Band | Kn-Band | K-Band      |
| GCF/EP   | 0.5      | 28.9-29.7 | 29.6-30.3 | 31.9-38.8   |
| GCF/MG/EP| 0.5      | 30.8-32.8 | 32.7-34.1 | 37.0-39.2   |
| GCF/NMG/EP| 0.5   | 31.3-33.6 | 33.2-37.7 | 36.6-41.7   |
| GCF/MG2/EP| 0.5   | 31.9-34.3 | 34.5-38.3 | 41.7-41.2   |
| GCF/MG3/EP| 0.5   | 34.0-37.1 | 37.8-38.8 | 44.6-51.1   |

Xing et al [43] reported that a composite reinforced with ultra-thin multilayer carbon fiber of thickness less than 1 mm was prepared for Electro Magnetic Interference absorption dominated applications for frequency range of 30–1500 MHz. The Shielding Effectiveness of the UTM-CFRC increased with increase in number of shielding layers.

Table 2. The Shielding Effectiveness of the UTM-CFRC

| Sample Designation | Thickness(mm) | Frequency(GHz) | SET(db) | A     |
|--------------------|---------------|----------------|---------|-------|
| MWCNT/PANI/PEO     | 3.0           | 0.85-4         | 42.0    | 0.15  |
| PDMS               | 1.0           | 8-12           | 23.0    | 0.39  |
| MCMB/MWCNT         | 0.6           | 8.2-12.4       | 56.0    | 0.16  |
| CNFRSF             | 3.0           | 0.03-1.2       | 25.0    | 0.27  |
| UTM-CFRC           | 0.81          | 0.03-1.5       | 30.1    | 0.53  |

Shielding Effectiveness of nickel-fiber reinforced cement based composite material is directly affected by compounded colloidal graphite. According to the study by Yao et al. [19] Composite with cement as base with doped 20% graphite colloid gave best SE results. The sample which gave best results of shielding effectiveness was a cement matrix with 5% vol Nickel fibre and 20% colloidal graphite. Mean
SE noted was 45.0 dB, the highest SE recorded was 51.19 dB at 1170 MHz, the least SE recorded was 35.18 dB at 1 MHz.

Li et al. [2] saw the need of requirement of materials to provide EMI shielding at higher temperatures. Hence they prepared samples of Graphene like Carbon silicon carbide composites. Better EMI shielding is delivered as graphene like carbon has higher degree of defects. The highest EMI shielding effectiveness recorded at room temperature was 36.8 db and at 600 degrees the SE was 33.8 db with the material sample being SiC100-0 of 7.6 wt % carbon mass.

Materials used by Pan et al.[7] were CNWs (Carbon Nano wires) and CNWs- CNTs(Carbon Nano Wires- Carbon Nano tubes) hybrid. CNWs have the Graphite nanosheets basal planes perpendicular to the wire axis, which is contrary to that of CNTs. 5%wt concentration proved optimal for improving the crystal structure of CNWs- CNTs hybrid. At 5.15 wt% carbon the shielding effectiveness due to absorption reaches 21.3 dB which alone accounts for 99.7% of shielding. Due to unique micro structure, CNWs did show better capability of attenuation and coefficient of absorption. These two composites are believed to give good results in harsh environments.

Nasouri et al[32] reported that the method of electrospinning was used to fabricate MWCNTs/ Polyvinyl Analin composite nanofibers which are electrically conductive. The increase in the diameter and electrical shielding of composite nanofibers was directly related with the increase in amount of MWCNTs. Composite Nanofibers’ reflection and absorption shielding effectiveness was optimized using Response Surface Methodology Technology. Sample of MWCNT's with content of 7.7 wt%, 0.3cm thickness and 12Ghz frequency was put under testing. The results showed Shielding effectiveness as 8.8 db in reflection and 31.5 db in absorption.

5. Conclusion
Metal based shielding materials are used conventionally. However, there are quite a few limitations such as large weight, poor corrosion resistance. Recently carbon based conducting polymer materials have been developed as suitable alternative to counter the limitations of the metal based shielding materials. It can be inferred from the review that there are some challenges with respect to the usage of polymeric shielding materials. These are lesser shielding effectiveness and poor mechanical flexibility. In addition, further research on for using nano materials to enhance shielding effectiveness.

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