ADVANCES IN FERRITE MATERIALS FOR ELECTROMAGNETIC INTERFERENCE SHIELDING RESPONSE

Abstract

In today's world, electromagnetic interference (EMI) is a modern kind of environmental pollution. With the growing technology, the excessive usage of electronic devices making it more dangerous. EMI not only degrade the working performance of electronic gadgets, but also harmful for living creatures also. There is lots of work present on the significant EMI materials in broad bandwidth frequency like X-band and Ku-band. Among them, ferrites are the advanced materials for many applications including the EMI shielding with exceptional magnetic, dielectric, optical and mechanical properties. Various nanocomposites of ferrites with different materials like conducting polymers, carbon materials or metallic particles etc. represent a different class of promising shielding materials. The present chapter exploring the EMI theory and shielding materials related to ferrites.

Keywords: Electromagnetic Interference, EMI materials, Ferrites, Composites

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I. INTRODUCTION

These days advancement in technology of electronic gadgets has increased the probability of electromagnetic disturbances that can interrupt the working of nearby electronic devices in the form of malfunctioning and deterioration of their life span. This can be called as electromagnetic interference (EMI) [1-3]. EMI not only cause the unacceptable degradation of system performance but also can do severe damage to electronic gadgets and their safety operation. These unwanted EM radiations have also ill-effects on human health such as languidness, insomnia, nervousness, headache and long exposure to these radiations result in acute disease like skin burns, cancer and cardiovascular etc [4, 5]. Also, EMI is a topic of concern in military equipments like radars and antenna systems. So, development of standard Shielding materials is imperative to mitigate the EMI problems in broad category of applications varying from the electronic to biological systems in various frequency bands.

II. EMI Shielding Theory

The attenuation capacity of a shielding object is defined as shielding effectiveness (SE). In other words, mathematically it can be described in logarithmic quantities as [6]:

$$\text{SE (dB)} = 10\ \log_{10}\frac{P_T}{P_I} = 10\ \log_{10}\frac{E_T}{E_I} = 10\ \log_{10}\frac{H_T}{H_I} \qquad (1)$$

where $P_I = E_I = H_I =$ power of incident wave, incident electromagnetic power (electric or magnetic field)

&

$P_T = E_T = H_T =$ power of transmitted wave transmitted (electric or magnetic field)

For an EMI shielding material, when an EM waves strike to its surface, then overall EMI shielding is subjected to three different fundamental mechanisms, namely, reflection from the surface (R), absorption within the shield (A), and multiple reflections between the interfaces of the material (MIR) as shown in figure 1. A reflection phenomenon is governed by the impedance divergence between the material and EM wave. It generally takes place in electrically conducting materials which usually have mobile charge carriers for the interaction with the EM wave like metallic materials. For absorption, materials are expected to have interacting electric and/or magnetic dipole, for eg., conducting or magnetic materials. In case of multiple reflections in a shield, reflections occur between its two reflecting surfaces, for eg., foam or porous materials, which have large surface area. The MIR loss is not so much reason of concern if the distance between reflecting surface is larger as compare to the skin depth. The distance at which intensity of an incident EM radiations drops to 1/e or 37 % of its initial value is known as skin depth (δ).

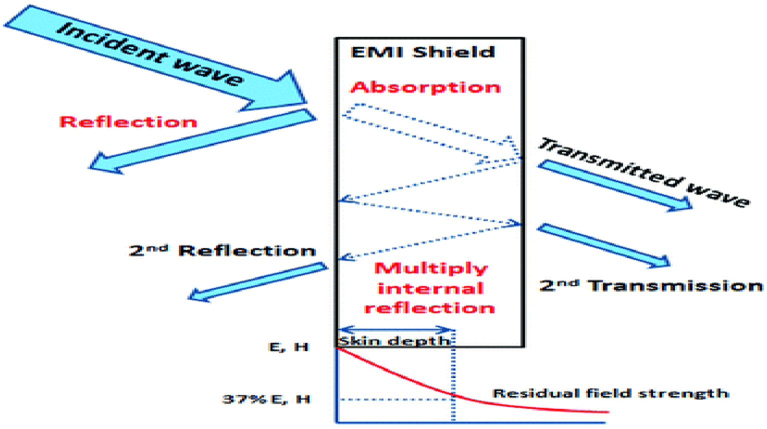

Figure 1: Schematic Model of Emi Shielding Mechanism for the Thin Plate Shield. J. Kruzelak Et Al.[7]

The skin depth of a good conductor can be represented as:

$$\delta = \sqrt{\frac{1}{\pi\omega\mu\sigma}} \qquad (2)$$

where ω is frequency, μ is magnetic permeability, σ is electric conductance of EM shield [8,9].

From above equation, one can observe that the skin depth depend upon frequency, conducting and magnetic properties. With the increase of these factors, there will be increase in reflection instead of absorption.

Thus, the total shielding effectiveness (SE_T) of an EMI shielding obejct can be depicted through below equation [10,11]:

$$SE_T\,(dB) = SE_R + SE_A + SE_M \qquad (3)$$

Here, SE_R= SE due to reflection loss, SE_A= SE due to absorption loss, and SE_M=SE caused by the multiple reflection loss respectively. In practical, when SE_A is $\geq$ 10 dB, multiple reflection factor (SE_M) can be discarded [12].

III. PROPERTIES AFFECTING THE EMI PERFORMANCE

There are various parameters that impact the EMI shielding performance of an EMI shielding material as described below:

1. **Dielectric properties:** The dipole, electronic, and interfacial polarization are the main factors behind the dielectric loss attributes. The ionic, and electronic polarization is governed by the bound charges in the materials and mainly exists at the high frequency, therefore these phenomena are not so prominent in small frequency ranges. Dipole polarization occurs due to the present of defects and residual group in the material during their fabrication process and also temperature dependent. Interfacial polarization attributed to the gathering of space charge at an interface between two materials or

regions due to the variation in their electrical conduction or dielectric constant [13]. Materials have high value of permittivity generally good for shielding properties.

2. **Magnetic properties:** The magnetic loss is mainly caused by domain wall motion, ferromagnetic resonance, eddy current and hysteresis loss in the microwave frequency region [14]. The hysteresis loss can be described in the form of energy loss due to the hysteresis curve of the materials. Eddy current loss is in the form of power loss produced by eddy currents that is generated due to induced EMF in magnetic material with the applied magnetic field. The eddy current loss is not considerable in case of highly conducting materials. Domain wall motion generally exists in MHz frequency region and negligible at higher frequency. The natural ferromagnetic resonance also usually originates at a lower frequency [15, 16]. A conservative value of magnetic permeability favors the effective microwave absorption in the shielding materials.

3. **Thickness:** For an appreciable EM shielding, thickness also plays an important role [17-18]. Generally, absorption properties increase with the material's thickness due to enhanced EM wave dimensional resonance, which in turn improving the overall shielding effectiveness of the material.

IV. FERRITES

Basically, Ferrites are oldest magnetic materials composed of oxides with ferric ions like hematite (Fe2O3) or magnetite (Fe3O4) as the principal constituent [19-23]. Due to their unique properties such as higher saturation magnetization, high electrical resistivity, low current losses and good chemical stability, they are ideal materials for numerous applications as shown in fig 2. 4. Ferrites can be prepared by several methods like ceramic methods, chemical co-precipitation, hydrothermal, sol-gel etc. Different interesting properties are obtained through these synthesis routes.

1. **Types of ferrites**: Depending upon the crystallography geometry, Ferrites can be divided into various categories such as:

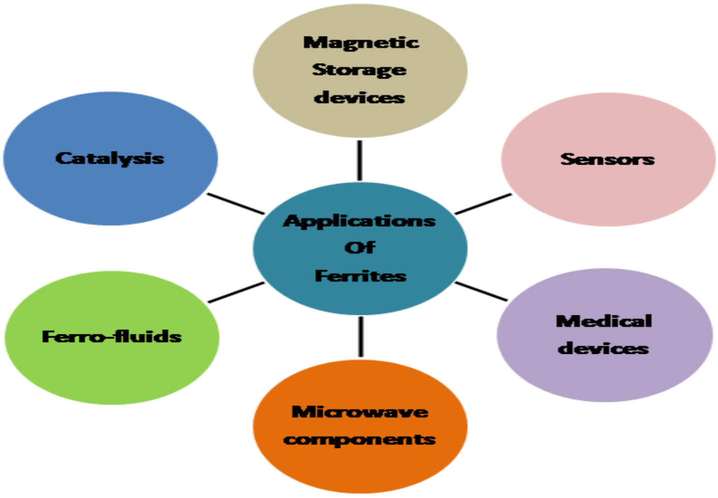

Figure 2: Application of Ferrites

- **Spinel Ferrite:** Spinel ferrite are homogenous materials possessing the spinel structure and having the formula MFe_2O_4, where M is divalent metal ions like $Co^{2+,}$ Ni^{2+}, Cu^{2+}, Zn^{2+}etc.An ideal spinel ferrite consist of two kind of interstitial sites namely tetrahedral (A)andoctahedral[B]. A remarkable characteristic of this structure is that a large range of cationic distribution fulfills these sites giving the huge variation in the functional properties like optical, electrical and catalytic activity. These properties are useful in potential application in the field of magnetic bulk cores, biomedicine, magnetic recording, magnetic separable catalysts, sensors, magnetic fluids, batteries and microwave absorbers.

- **Garnet ferrites:** The crystal structure of ferrimagnetic garnet material is described by is $Me_3Fe_5O_{12}$ where, Me stands for trivalent ion such as rare earth elements. These types of ferrites are generally hard, chemically stable with significant magnetic and optical properties usable in various fields like microwave, optical or maneto-optical application.

- **Hexaferrite:** All ferrimagnetic materials that crystallize in hexagonal geometry can be referred as hexaferrite. Their magnetic properties are interlinked to different, though related crystalline structure with hexagonal and rhombohedral symmetry. These have become considerable important materials in all commercial and technological fields. These ferrites are synthetic and have usage in numerous applications like magnetic storage devices permanent magnets, microwave absorbers and electrical devices.

V. FERRITE AS SHIELDING MATERIAL

From the above study it is clear that ferrites material have many advantages like large saturation magnetization, good chemical stability, high remanace and tunable magnetic properties that are useful for various applications. Although, ferrites are able to achieve the considerable value of shielding effectiveness in comparison to other materials. Very few literatures are available for pure ferrite materials as EMI shielding materials. Iqbal et al. prepared the barium ferrite (BaFe12O19) using sol-gel method as EMI shielding material. A total shielding effectiveness of −17.57 dB was showed with ferrite nanoparticles in X-band frequency [24].

Naidu et al. fabricated of bulk and nano Ni1-xMgxFe2O4 (x = 0–1) materials through microwave double sintering and hydrothermal techniques respectively. The authors have done a comparison of EMI shielding properties of current bulk and nanomaterials in 8.4–12 GHz frequency and concluded that bulk Ni0.6Mg0.4Fe2O4 sample demonstrated the highest SET of ∼17 dB attributed to their larger bulk densities [25].

Gaiorla et al. studied the electromagnetic wave absorbing properties of the Co–Mn–Ti substituted barium ferrites synthesized through solid-state method. A maximum reflection loss upto -14.7 dB was showed for the the x=0.4 composition in the X-band [26]. Mosleh et al. fabricated Ba1−*x*Ce*x*Fe12O19 (*x*=0.0, 0.05, 0.1, 0.15, and 0.2) using the sol–gel route. For *x*=0.15 and *x*=0.2 composition, a maximum reflection loss of −16.74 dB at 10.3 GHz and of −20.47 dB at 16.22 GHz was observed respectively in 2–18 microwave frequency range.[27] Yusoff et al. showed the electromagnetic and absorption attributes of (Li0.5Fe0.5)0.7Zn0.3Fe2O4 (LiZn) ferrite in the 0.3–13.51 GHz frequency . At a matching thickness of 8.0 mm, they achieved a maximum reflection loss of -46.13 dB at frequency of 0.32 GHz [28]. Alam et al. reported the microwave absorption properties of Zn, Co and Zr cations barium hexaferrite/PVA samples prepared via co-precipitation technique. A reflection loss upto -14 dB was achieved for BaZn0.5Co0.5ZrFe10O19 composition in the frequency region of 8–12 GHz [29].

From EMI shielding point of view ferrites alone are not capable for providing significant attenuation of EM waves especially at high frequency because of several drawbacks like heavy weight, lack of flexibility, poor processability, narrow absorption bandwidth etc. However, ferrites composites with other materials like conducting polymers or carbonaceous materials are able to achieve tremendous shielding effectiveness from application purposes. Ferrite is most commonly used filler for the preparation of composite materials in shielding application. The forthcoming sections have been discussing various ferrites reinforced composites as shielding materials.

1. **Ferrite/Carbonaceous materials composites:** During the past few years, carbonaceous materials such as carbon fiber, carbon black, grapheme, CNTs, MWNTs have kindled up the entire field of shielding materials. They are the most widely used as advanced materials for various commercial applications from biomedicine to memory devices due to their fascinating properties like low density, high surface area, good thermal stability, high conductivity and permittivity etc. They are not only having well electrically conductivity, but also can be used as good absorbers materials of EM wave over a wide frequency rang. Further the addition of ferrite materials into these carbon materials provide the synergistic tuning of permeability and permittivity of both the materials, which are beneficial for getting effective shielding effectiveness.

   Various reports have been published on different type of ferrites with different type of carbon materials. Wang et al. reported CoFe2O4/CNTs nanocomposites as EMI shielding materials prepared by a facile hydrothermal approach at 200°C with the solvent (benzyl alcohol). EMI shielding performances of synthesized materials were investigated at Ku band frequency (12–18 GHz). The prepared nanocomposite of 2 mm sample thickness has shown the excellent SE values upto 22-25 dB. The absorption phenomenon was dominant in overall shielding performance due to excellent electrical conductivity of carbon nanotubes. However, the inclusion of cobalt ferrite provides the numerous polarization and magnetic active sites to improve the EMI performance at high frequency region [30]. Zhao et al. prepared the sandwich micro structured expand graphite (EG)/BaFe12O19 (BF) composite samples at nanoscale connected with carbon nano tubes successfully via in-situ sol-gel auto-combustion rote. A maximum reflection loss up to −45.8 dB was demonstrated with 1mm sample thickness in the region of 2-18 GHz frequency. The experimental results show that CNT/EG/BF nanocomposites exhibit good impedance mismatch and the synergistic tuning between dielectric and magnetic properties [31].

   “Datt et al. fabricated the composite thin films of carbon black with nickel ferrite composites through dispersion of the functionalized carbon black (NCF NPs) in a poly (vinyl alcohol) matrix Shielding analysis of these nanocomposite films have shown the significant SE value of 27 dB at frequency bandwidth of 8-18 GHz with a specimen thickness of 1.5 mm. The shielding phenomenon is mainly dominant by the contribution of absorption [32].

Mansa et al. reported the synthesis of Nickel Spinal Ferrites (NiFe) and thermally reducing graphene oxide (TRGO) (NiFe-TRGO) NiFe nanoparticles, and PVC/NiFe-TRGO, nanocomposites film. The fabricated materials have shown the Improved EMI shielding efficiency in the 0.1–20 GHz frequency range.[Fig3] The EMI shielding was investigated through the inclusion of different filler quantities (5 wt.% to 40 wt.%) in three frequency range (microwave (0.1 to 20 GHz), near-infrared (700–2500 nm), and ultraviolet (200–400 nm). A highest attenuation of 65 dB was obtained with a filler amount of 40% of NiFe/TRGO composite film [33].

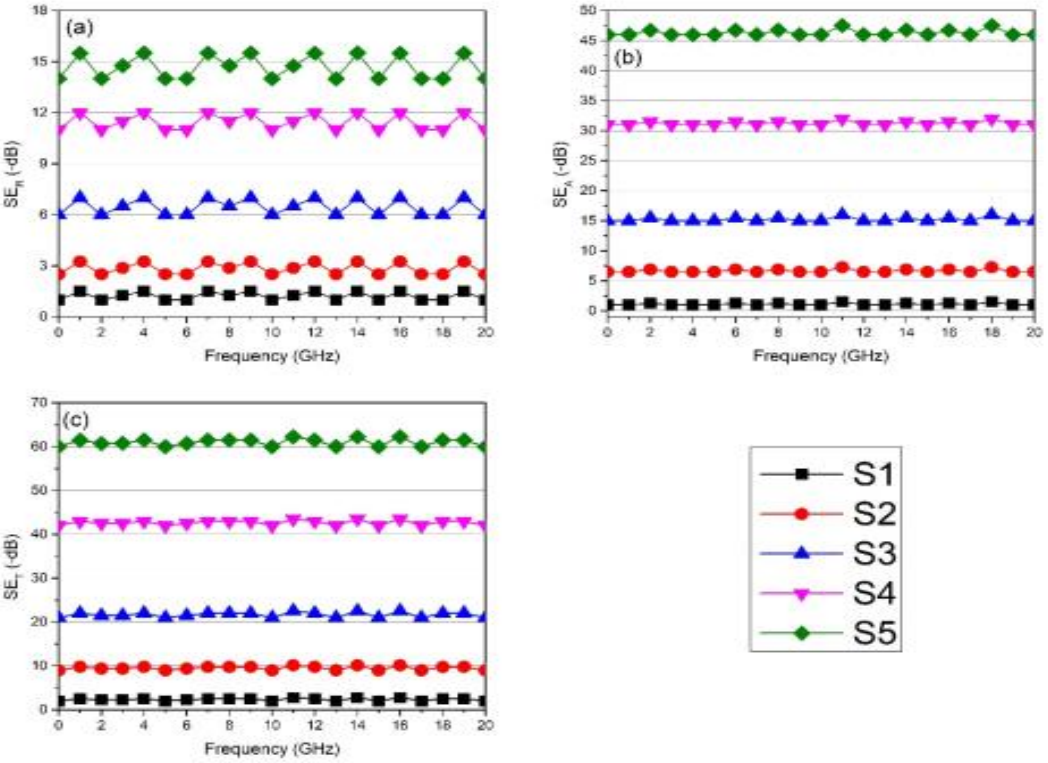

Figure 3: (A) Reflection (B) Absorption And (C) Total Shielding Effectiveness of PVC/Nife-TRGO Composites, Mansa Et Al. [33]

Shu et al. prepared the hybrid composites of nitrogen-doped MWCNTs / Co0·5Zn0·5Fe2O4 via a facile one-step solvothermal approach. 3D conducting network was formed due to attachment of microsphere structured Co0·5Zn0·5Fe2O4 on the surface of NMWCNTs, that influenced the microwave absorption properties of these hybrid materials. These composite materials achieved the minimum reflection loss of −64.7 dB at the sample thickness of 2.1 mm in the X-band frequency [34]. Wu et. al investigated the EM absorption properties RGO/MWCNTs/NiFe2O4 ternary nanomaterials prepared via a facile one-pot hydrothermal approach. Experimental results demonstrated that the minimum reflection loss of −50.2 dB was shown with a matching thickness of 1.4 mm and effective absorption bandwidth can be achieved upto 14.64 GHz (91.5% of 2–18 GHz) by varying the sample coatings from 1 to 5 mm [35].

Verma et al. Investigated the EM properties of BaFe12O19@RGO nanocomposite prepared via energy ball milling technique in the Ku band frequency. A high EMI SE value up to 32 dB (~99.9% attenuation was achieved at a sample thickness of 3 mm in the range of 12.4–18 GHz frequency [36]. Shu et al. developed the nitrogen-doped reduced graphene oxide/Ni0.5Zn0.5Fe2O4 samples as high-performance microwave absorbers. A minimum reflection loss of −63.2 dB with a sample thickness of 2.91 mm of samples in the X-band and also effective absorption bandwidth of 5.4 GHz at the Ku-bandwidth with a thin sample thickness of 2.0 mm was demonstrated [37]". Gupta et al. investigated the EMI shielding properties of 3D interconnected graphene aerogels decorated with cobalt ferrite nanoparticles and ZnO nanorods hybrid materials. Due to idealistic properties like low density, high porosity and large surface area, the graphene aerogel demonstrated the total EMI SE value of 25.07 dB at a matching thickness of 5 mm. After the incorporation of ferrite particles, SE value enhanced upto 42.10 dB in the X-band frequency [38]. Rao et al. prepared Fe3O4 nanoparticles decorated single-layer graphene-assembled porous carbon (SLGAPC) with polyvinyl alcohol (PVA) via solution casting method for the shielding application. The synthesized composites achieved a SET value ∼15 dB with a matching thickness of 0.3 mm in the X-band. The high dielectric permittivity of composite material caused by enhanced interfacial polarization because of the inclusion of ferrite nanoparticles that helped in improving the shielding efficiency of the fabricated materials [39]

As discussed above carbon materials are capable to provide superior EMI properties in broad band width owing to their fascinating properties such as low density, electrical and mechanical. Despite all these, carbon materials suffer from various drawbacks like complex fabrication, high cost, poor processability etc. Moreover, as these materials possess the high conductivity, it is difficult to reduce reflection mechanism in them, which create hindrance to use them as absorbing materials in application like stealth technology.

2. **Conducting polymer /ferrite composites:**As compare to carbon materials, conductive polymers have gained worldwide popularity as the EMI shielding material due to their unique properties like low density, ease of synthesis, corrosion resistant, good processability and tunable conductivity. However, they also suffer from several drawbacks such as poor mechanical properties and poor thermal stability etc. But in order to remove these problems, addition of fillers like magnetic materials can prove more strategistic. These organic and inorganic hybrid materials can offer the properties of both materials that can be useful for various applications. So conducting polymer matrix with ferrite filler are highly effective from EMI shielding application.

   For example, Ohlan et al. prepared the conducting polymer polyphenyl amine/ barium ferrite nanocomposites as shielding materials in 12.4–18 GHz frequency. These materials (monomer/ferrite weight ratio 1:3) obtained the maximum shielding effectiveness of 28.9 dB due to absorption (SEA) caused by improved permittivity and permeability because of inclusion of ferrite nanoparticles [40]. Ismail et al. reported the PANI-PTSA/cobalt ferrite composites prepared using the chemical oxidative and sol–gel method. A highest reflection loss was obtained of − 28.4 dB at 8.1 GHz frequency

[41]. Iqbal et al. synthesized the strontium ferrite encapsulated polythiophene via emulsion polymerization approach. The prepared composite (SrF:PT weight ratio = 2:1) showed higher SE value of −31.64 dB at 15.73 GHz for the sample thickness 1 mm in the Ku-band as compared to other composites and pure SrFe12O19. The inclusion of mesoporous structures ferrite nanoparticles in conducting polymer matrix provide the conductive network for better electron transportation, that offer the superior impedance match for EM wave.[42].

Tang et al. prepared the core–shell structured nickel ferrite @polypyrrole micro-rod composites as capable EM wave absorbing materials. This study reflects the significance of optimize synergistic effects between dielectric and magnetic loss for the NFO/PPy composites C, X, and Ku frequencies [43]. Lei et al. synthesized the Co-doped NiZn ferrite/polyaniline on Ti3C2TX MXene composite through exfoliation, hydrothermal process, and interfacial polymerization. These multiple-layer composite material exhibit excellent microwave absorption with a maximum reflection loss (RL) of −37.1 dB at sample thickness of 2.2 mm only [44]. Hosseini et al. fabricated the conductive polyaniline/manganese ferrite. The synthesized composites achieved a minimum RL of –15.3 dB at the frequency of 10.4 GHz at the sample thickness of 1.4 mm [45]. A similar core–shell structured pyrrole /ZnFe2O4 composites were reported that showed a minimum reflection loss of - 28.9 dB in the X-band frequency was reported by Li et al. [46]. Tung et. al. fabricated the Fe3O4 decorated rGO/PEDOT hybrid materials. The EMI SE of multifunctional hybrid composites (with 1 wt % of Fe3O4-RGO content) was 22 dB in the 20 to 1000 MHz frequency [47].

3. **Ferrite based hybrid /composite materials:** In addition to above discussed materials, a large number of literature is also available on several composite or hybrid materials based on ferrite fillers with other second phase metallic particles, ceramics, metal oxide or conventional polymers, which can be utilized as EMI shielding materials.

Wang et al. developed ferrite/Co/porous carbon microwave absorbers through in situ pyrolysis method. At a thickness of 1.5mm, composite materials showed a maximum reflection of −31.05 dB at 14.32 GHz. A highest reflection loss reached upto −47.31 dB at 8.4 GHz frequency. The absorption characteristics were improved due to impedance match, interfacial polarization and scattering loss phenomena in synthesized materials [48]. Gupta et al. used the 3D graphene aerogels/ cobalt ferrite/ZnO nanorods as EMI shielding material.Total EM absorption was increased upto 48.56 dB with the synthesized composite materials [49]

Qing et al. studied the shielding properties of the $BaTiO_3/NiFe_2O_4$ nanomaterials. At a sample thickness of 1.2 mm, the composite material with 30 wt% filler demonstrated an EMI SE of 34 dB in the X-band [50]. Li et al. reported the EMI properties of Ni/hexagonal ferrite/polymer composites. These three phase composites showed the superior SE value of 67 dB with 2 mm thick sample. The EMI shielding mechanism in these materials was absorption dominant [51]. Ahemed et al. reported the hybrid polymer composite of PVDF with few layered graphene nanosheets (FLG) and Nickel spinel ferrite (NSF) as shielding material. The maximum SE was measured up to ∼45 dB and ∼53 dB for PVDF/FLG-3 and PVDF/FLG-3/NSF-15 composites respectively in 1-12 GHz region. The synthesized materials have a promising application prospect due to enhanced SE attributed to absorption-dominant mechanism associated with the magnetic property of spinel nickel ferrite [52].

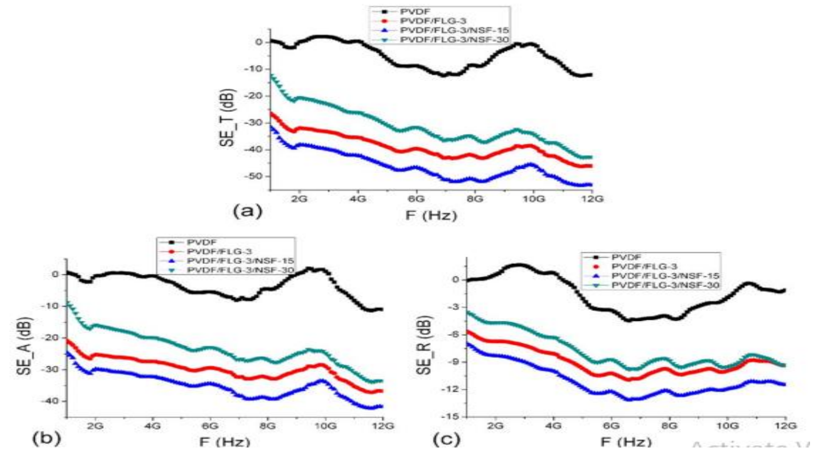

Figure 4: Schematic Representation of the Shielding Mechanism. Ahmed Et Al. [52]

Annadurai et al. prepared barium ferrite and carbon black filler composites with EPDM rubber matrix for microwave application. Authors measured the insertion and return loss in X-band frequency [53]. Phan et al. developed the MnZn ferrite/ MWCNTs/ epoxy composites as shielding material. At 2.0 mm thickness, 4.0 vol% filler concentration in composites achieved an SET of 44 dB at 10 GHz with the inclusion of conductive silver particles mixing. The authors concluded that shielding performance of hybrid fillers composites is comparable with the commercial EMI absorber [54]. EMI shielding composite materials made of Mg-Zn ferrite, carbon black and acrylonitrile-butadiene rubber (NBR) were investigated by kruzelak et al in the frequency range of 1MHz-3GHz [Fig 5].

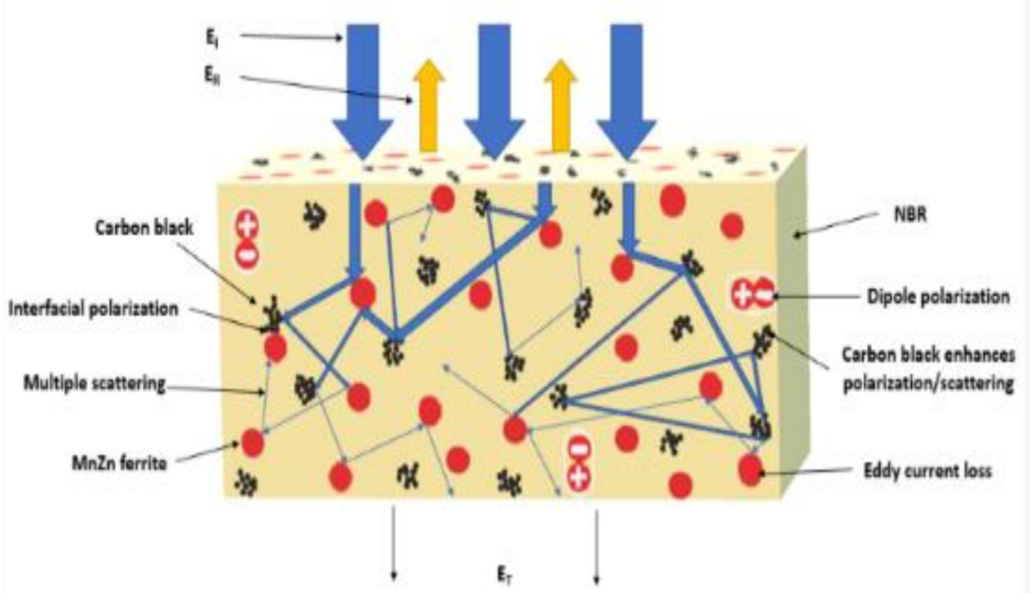

Figure 5: Schematic Illustration of EMI Shielding Mechanisms for Hybrid CB/Ferrite Composites. J. Kruželák, et al.[55]

The resultant composite containing 200 phr of Mg-Zn ferrite showed a return loss at −10 dB and −20 dB in broad frequency region. In hybrid CB/ferrite/ rubber composites, ferrite particles provided the polarized center in the existence of EM wave, which improved their better absorption behavior [55].

Yadav et al. fabricated the NiFe2O4/RGO/Polypropylene composites at nano scale as the EMI shielding material. At 2 mm thickness, these nanocomposites exhibited EMI SE of 29.4 dB in the frequency region of 5.8-8.2 GHz [56]. Wang et al. presented the microwave absorption properties of NiFe2O4@SiO2@RGO composites. The fabricated materials demonstrated the superior microwave absorption properties (−42.9 dB) as compare to pure NiFe2O4 (−11.3 dB) and NiFe2O4@SiO2 (−25.9 dB) composite [57].

VI. CONCLUSION

This chapter provides a comprehensive study of fundamentals about electromagnetic interference shielding based upon different ferrite materials. Ferrite have received much attention as the microwave absorbers. But they effective for microwave absorption in narrow bandwidth only. In this context, ferrite hybrid and composites with other materials are the prominent avenues for commercial shielding applications. As compare to traditional ceramics, metallic particles or conventional polymers, ferrite composites with carbon materials or conducting polymer have received wide popularity for enhancing the shielding effectiveness due to their synergistic effect of magnetic and conducting properties. A deep study of published reports in this chapter significantly favors this fact.

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