CHAPTER I

Introduction

Content:

1.1 Introduction

Electromagnetic emissions are usually generated and transmitted during operation of wireless and electronic devices. Beyond a certain level, these emissions cause operational interferences and are classified as Electro-Magnetic Interferences (EMI). Growth in modern high speed electronic devices packaged alongside the electromagnetic wave emitting sources in devices such as cellular telephony, wi-fi, bluetooth, etc. are posing newer challenges for the designer. In addition, these multitude of applications have created an even more congested electromagnetic environment leading to operational challenges of systems in close proximity [1].

The electromagnetic vulnerability and radiation hazard have to be controlled for obtaining an electromagnetically compatible (EMC) environment by reducing EMI. Electromagnetic shields are generally used for sufficiently reducing EMI. Shielding can be done either by placing the device inside a metal enclosure which protects the device by reflecting the external electromagnetic waves (reflection type shields) or using absorbing materials on the device/surface which will absorb the electromagnetic wave (*em*) incident on it (absorption type shields) [2]. The reflection of electromagnetic waves from reflective shields may interfere with other devices in its vicinity, thus affecting devices both within the system enclosure and without. Due to the limitations of the reflection type of absorbers, the current work focusses on absorption type of shields and will be referred to as absorbers.

Research on electromagnetic wave absorbers dates back to the 1930's with the first patent appearing in 1936 in the Netherlands [3] which was a quarter-wave resonant type structure. Absorbers were first used during the World War II (1939-1945) where, Germany used the "Wesch" material [4, 5] for camouflaging of submarines and periscopes at 3 GHz. During 1941-1945, materials known as "HARP" (Halpern-anti-radar-paint) were used by the United States in airborne and shipborne environments in the X-band. Reflection loss of the absorbers used were in the range of 15-20 dB at resonance. During this period, another absorber commonly known as Salisbury screen absorber [6] was also developed in the Radiation Laboratory, MIT. It was a quarter-wavelength resonant absorber at 3 GHz with about 25% bandwidth. Since then, development in the field of microwave absorbers have progressed concentrating broadly on improving the absorption by restructuring, reducing weight and thickness, increasing absorption bandwidth to cater to specific applications [7-9].

A schematic representation of the various wave components involved in absorption is shown in figure 1.1. Design of microwave absorbers with enhanced absorption performance requires two important conditions to be satisfied: impedance matching characteristic and attenuation characteristic. When electromagnetic wave is incident on an absorber, reflection takes place at the free space-absorber interface due to mismatch in impedance. Reflections can be minimized if impedance of the absorber is matched to the free space impedance, resulting in penetration of the wave into the absorber, which is the first condition. Within the absorber, dissipation of radio frequency (RF) energy is maximized resulting in rapid attenuation of the amplitude as it propagates in the absorber structure. This is the second condition [10].

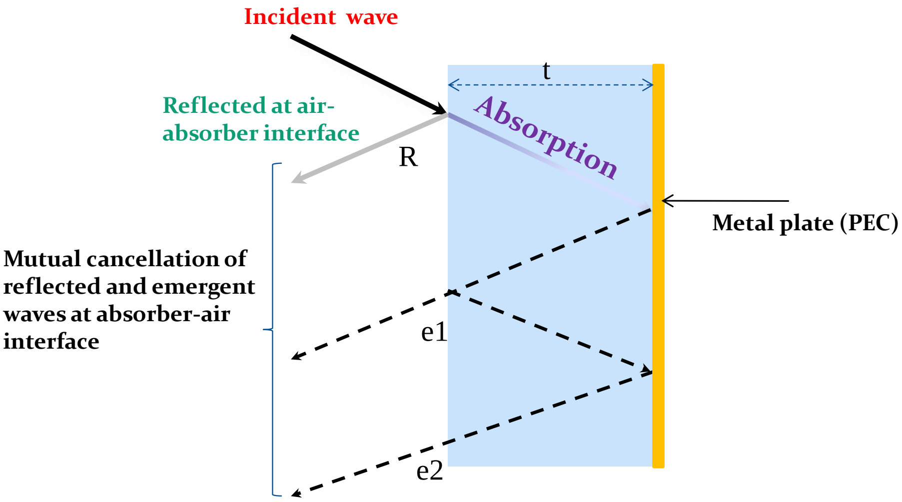

Figure 1.1: Schematic representation of absorbing type EMI shielding mechanism [11]

As seen from the schematic (figure 1.1) at the air-absorber interface two reflected waves reaches – one from the front surface of the absorber while the other from absorber-metal surface. For effective absorption there should be minimum reflection from the absorber's surface. When the two reflected waves are out of phase they cancel each other thus reducing reflection. This is possible if the two waves destructively interfere, i.e., having a path difference of $\lambda / 2$. Since, the wave travelling twice the thickness of the absorber (t) is equal to odd multiple of $\lambda_g/4$, where, $\lambda_g = \lambda_0 / (|\varepsilon_r||\mu_r|)^{1/2}$ where, $|\varepsilon_r|$ and $|\mu_r|$ are the moduli of complex permittivity (ε_r) and complex permeability (μ_r) respectively.

1.2 Absorption mechanism in microwave absorbers

When an electromagnetic wave penetrates any object, it interacts with different microscopic boundary conditions of the inclusions in the structure. The extent of absorption is generally dependent on the interaction. The mathematical formulation of this loss mechanism can be obtained using Maxwell's wave equations [12]. The general form of time varying Maxwell's equations in phasor form are;

$$\overline{\nabla} \times \overline{H} = \bar{J} + j\omega\overline{D} \tag{1.1}$$

$$\overline{\nabla} \times \bar{E} = -j\omega\bar{B} \tag{1.2}$$

where, $\overline{D} = \varepsilon\bar{E},\ \bar{B} = \mu\overline{H}, \bar{J} = \sigma_s\bar{E}$

$\overline{D}$ is the electric flux density (V/m), $\varepsilon = \varepsilon_0\varepsilon_r$ is the permittivity, $\bar{B}$ is the magnetic flux density (Wb/m^2) and $\mu = \mu_0\mu_r$ is the permeability. $\bar{J}$ is the electric current density (A/m^2), due to an external field and σ_s is the conductivity. A large majority of absorbers are based on non-conducting materials (insulators) where $\sigma_s \sim 0$ and hence, the conductivity term can be ignored in equation 1.1. Thus equations 1.1 and 1.2 becomes,

$$\overline{\nabla} \times \overline{H} = j\omega\varepsilon_0\varepsilon_r\bar{E} \tag{1.3}$$

$$\overline{\nabla} \times \bar{E} = -j\omega\mu_0\mu_r\overline{H} \tag{1.4}$$

The relative permittivity, ε_r and permeability, μ_r of the medium are complex in general and expressed as $\varepsilon_r = \varepsilon_r^{'} - j\varepsilon_r^{''}$ and $\mu_r = \mu_r^{'} - j\mu_r^{''}$, respectively. ε_r' and $\mu_r^{'}$ being the real parts while ε_r'' and $\mu_r^{''}$ are the imaginary parts.

When an oscillating electric field interacts with a dipole, the dipole rotates to align itself according to the polarity [13] resulting in energy loss through the generation of heat (friction). The degree to which the dipole is out of phase with the incident electric field, is a characteristic of the material and depends on the frequency of the oscillating electric field. This determines the magnitude of the imaginary part of the permittivity. The larger the imaginary part, the more is the energy dissipated. Thus, the imaginary part of the relative permittivity relates to loss in the system. Similarly, in case of magnetic materials, the field interacts with the magnetic dipoles. There are three main loss mechanisms for magnetic materials, viz. hysteresis, eddy current and residual loss. Residual losses include the resonance losses which dominate at high frequencies.

The equation 1.3 and 1.4 can be rewritten as

$$\overline{\nabla} \times \overline{H} = j\omega\varepsilon^{'}\left(1 - j\frac{\varepsilon^{''}}{\varepsilon^{'}}\right)\overline{E} \tag{1.5}$$

$$\overline{\nabla} \times \overline{E} = -j\omega\left(1 - j\frac{\mu^{''}}{\mu^{'}}\right)\overline{H} \tag{1.6}$$

The terms $tan\delta_e = \varepsilon^{''} / \varepsilon^{'}$ and $tan\delta_m = \mu^{''} / \mu^{'}$describe the amount of energy supplied by an external electric field that gets dissipated during dipole alignment. The phasor form (frequency domain) of wave equations are;

$$\nabla^2\overline{E} = \mu\,\varepsilon(j\omega)^2\overline{E} \tag{1.7}$$

$$\nabla^2\overline{H} = \mu\,\varepsilon(j\omega)^2\overline{H} = -\omega^2\varepsilon\mu\overline{H} \tag{1.8}$$

Let $-\omega^2\varepsilon\mu = \gamma^2$ (1.9)

The equations (1.7) and (1.8) reduce to

$$\nabla^2\overline{E} - \gamma^2\overline{E} = 0 \tag{1.10}$$

$$\nabla^2\overline{H} - \gamma^2\overline{H} = 0 \tag{1.11}$$

where, $\gamma = \sqrt{-\omega^2\varepsilon\mu} = j\omega\sqrt{\varepsilon_0\mu_0}\sqrt{\varepsilon_r\mu_r} = j\frac{2\pi f}{c}\sqrt{\varepsilon_r\mu_r} = \alpha + j\beta$ (1.12)

$\alpha,$ is the attenuation constant which defines the rate at which the fields of the electromagnetic wave attenuates and β is the phase constant representing the phase change as the wave propagates.

For a plane *em* wave propagating through the absorber in the x-direction, (figure 1.2) the electric field will be in the y-direction while the magnetic field will be in the z-direction. The electric and magnetic fields are given by;

$$\overline{E} = \overline{E}_y.\hat{a}_y = E_0 e^{-\gamma x}\hat{a}_y \tag{1.13}$$

$$\overline{H} = -\frac{1}{j\omega\mu}\overline{\nabla} \times \overline{E} = \frac{\gamma}{j\omega\mu}E_0 e^{-\gamma x}\hat{a}_z = \overline{H}_z.\hat{a}_z \tag{1.14}$$

The intrinsic impedance, η, of the wave is given as

$$\eta = \frac{\overline{E}_y}{\overline{H}_z} = \frac{E_0 e^{-\gamma x}}{\frac{\gamma}{j\omega\mu}E_0 e^{-\gamma x}} = \frac{j\omega\mu}{\gamma} = \frac{j\omega\mu_0\mu_r}{j\omega\sqrt{\varepsilon_0\mu_0}\sqrt{\varepsilon_r\mu_r}} = \sqrt{\frac{\mu_0}{\varepsilon_0}}\sqrt{\frac{\mu_r}{\varepsilon_r}} = Z_0\sqrt{\frac{\mu_r}{\varepsilon_r}} \tag{1.15}$$

where, Z_0 is the characteristic impedance of free space.

The extent of reflection as well as penetration of the *em* wave at the air-absorber interface is determined by the intrinsic impedance of the absorbing medium. Once the incident wave penetrates the absorbing material, the wave exponentially decays with distance, x, by the factor, $e^{-\alpha x}$ as shown in figure 1.2. This decay or absorption loss occurs because the currents induced in the medium produce ohmic losses; which manifest as heat in the material. The attenuation constant α can be expressed [14] as

$$\alpha = \frac{\sqrt{2}\pi f}{c} \times \sqrt{(\mu_r^{"}\varepsilon_r^{"} - \mu_r^{'}\varepsilon_r^{'}) + \sqrt{(\mu_r^{"}\varepsilon_r^{"} - \mu_r^{'}\varepsilon_r^{'})^2 + (\varepsilon_r^{'}\mu_r^{"} + \varepsilon_r^{"}\mu_r^{'})^2}} \quad (1.16)$$

It is seen from the above equation that larger the values of complex permittivity and permeability, larger will be the attenuation of the field amplitude. However, larger values of complex permittivity and permeability result in higher reflection due to impedance mismatch at the absorber interface thus impeding penetration of the wave into the material [16]. Choice of an absorbing material is therefore, a trade-off between these two conflicting conditions.

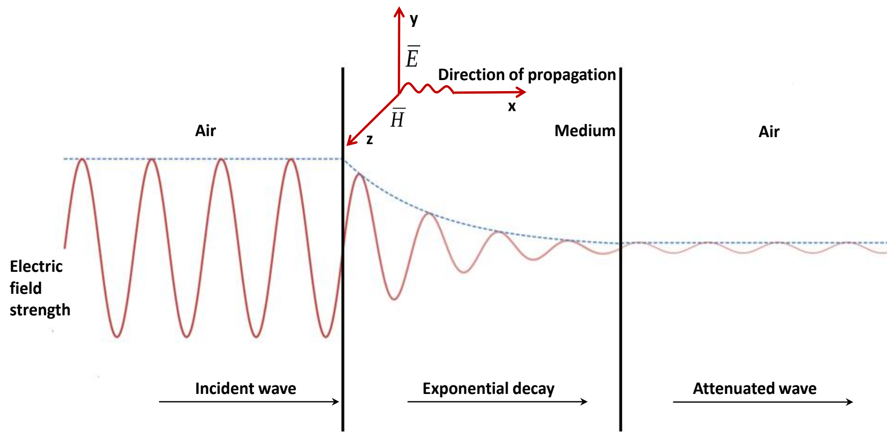

Figure 1.2: Attenuation of wave while travelling through a medium [15]

Since both electric and magnetic fields are involved in *em* wave propagation, permeability (μ) together with permittivity (ε) plays an important role in absorber performance. The magnetic component of absorber improves matching at the air-absorber interface ($Z^{'} = \sqrt{\mu/\varepsilon}$). Magnetic losses along with dielectric losses enhance attenuation of the incident wave resulting in reduced thickness of the absorber as the guide wavelength reduces by a factor of $1/\sqrt{\mu\varepsilon}$. Thus, the present work is focused on magnetic absorbers. A review of relevant literature is presented in the following section.

1.3 Literature survey on magnetic microwave absorbers

The work on customization of microwave properties of ferrites began proliferating towards the latter part of the 1960s with many patents on ferrite compositions for absorbers at different frequency ranges [7, 17-21]. In the year 1969, Suetake [22] patented thin microwave absorbing wall in the frequency range of 0-2 GHz using ferrites. The following year, Naito along with Suetake [23], showed performance superiority of ferrite or rubber ferrite absorber to that of lossy dielectric material absorber below the frequency range of 7.5 GHz with reduced thickness. Rado and his group from Naval Research Laboratory, USA [24] in the project "Newboy," initiated in 1976 developed thin radar absorbing materials using ferrites which was extensively used as stealth treatments for missile-like drones, aircraft and ships. In the year 1977, Wright [25] patented a ferrite pyramidal structure which was tapered ½ to 1 inch showing broadband absorption from 1 to 3 GHz. Till the end of the 1990s, absorbing structures were made using spinel ferrites [26-31], which limited their use to megahertz range as complex permeability drops at higher frequencies, given by Snoek's limit [32].

M-type hexagonal ferrites have high crystalline anisotropy, high saturation magnetization, high natural resonance, low density and high chemical stability. The anisotropy property of barium ferrite was exploited over the years to develop absorbers in gigahertz range [17-19, 33]. It was in the year 1998, when Sugimoto et al. [34] suggested that natural resonance of M-type barium ferrite can be used for absorption of microwaves. They reported that "this is the first study to show that it is possible to use natural resonance of M-type ferrite to absorb microwave radiation and minimum reflection loss occurred when the frequency matches with the natural resonance frequency". A reflection loss of better than -20 dB over the range of 1-20 GHz for matching thickness of 0.5 to 3.8 mm was reported, following which, absorption properties of M-type barium ferrite have been extensively studied with varying particle sizes and using various doping elements [33, 35-47].

Another hexagonal ferrite, M-type strontium ferrite ($SrFe_{12}O_{19}$) is reported to have high anisotropy (anisotropy constant of 3.5×10^6 erg cm^{-3}), high saturation magnetization (74.3 - 92.6 emu/g) and high chemical stability [48, 49] which makes it a suitable candidate for magnetic absorbers. In the early 2000's, Song [49] reported an electromagnetic absorber with strontium ferrite and carbon fused in silicon rubber which showed -29 dB reflection loss at 8.4 GHz and -23 dB at 5.5 GHz for a thicknesses of less than 3 mm in the frequency range from 5 to 10 GHz. A single layer microwave absorbers based on $SrCo_xTi_xFe_{12-2x}O_{19}$-epoxy composites in X-band was studied by Verma et al. [50]. Composites of 3 mm thickness showed a reflection loss of -36.5 dB for a composite with x = 0.3. In 2013, single layer microwave absorbers based on strontium ferrite–carbon black–nitrile rubber composites were fabricated for S and X-band by Vinaysree et al. [51]. They studied the influence of filler volume fraction, frequency, absorber thickness on the reflection loss characteristics. There were some reported work on use of substituted strontium ferrite as absorbers. In a few compositions, iron was replaced by Mn, Ti, Co or Zr [52] and in some other work strontium was replaced by Nd and rare earth elements [53, 54], using different synthesis method. The microstructure and microwave properties of $Sr_{0.9}Nd_{0.1}Fe_{12}O_{19}$ particles were investigated by Ebrahimi et al. in 2015 [54] where particle size reduced from 38.9 to 8.32 μm. Reflection loss of -39 dB & bandwidth 2.4 GHz was reported.

Nanoparticle based composites are reported to have relatively low density and high surface to volume ratio. Nano inclusions increase the interacting surface for *em* wave within the material and hence a small weight fraction, when fused into polymer matrix, gives the desired absorption characteristics thus reducing the overall weight of the absorber [55-58]. Carbon nanotubes (CNT) and expanded graphite nano flakes have been used by different groups [59-61] as nano inclusions for developing light weight *em* shields. Nanosized barium ferrites have been used as filler for developing light weight, thin and broadband absorbers [62-65]. However, there are relatively fewer reported works on use of nanosized strontium ferrites as fillers and in most of those works, the reflection loss was calculated. Ghasemi and his group experimentally studied nanosized substituted strontium ferrite [52] for microwave absorbers applications. They could reduce the thickness of the absorber down to 1.6 mm by controlling the substitution of Mn, Co and Zr elements in strontium ferrite. Recent computed reflection loss studies on using nanosized strontium ferrite based absorbers were carried out by Baniasadi et al. in 2014 [67] and Sadiq et al. in 2016 [53]. Baniasadi and his group reduced the size of synthesized $SrFe_{12x}Ti_{x/2}Zn_{x/2}O_{19}$ (x = 0-2.5) powders using high energy ball mill and obtained nanoparticle sizes of 15–40 nm. For x=2.5, the computed reflection loss of -36.13 dB was obtained. Sadiq and his group studied the effect of rare earth element substitution in $Sr_{1.96}RE_{0.04}Co_2Fe_{27.80}Mn_{0.2}O_{46}$ (RE=Ce, Gd, Nd, La and Sm) X-type hexagonal ferrites prepared by using sol gel autocombustion method. The Gd-substituted sample with particle size 54-100 nm showed a calculated reflection loss of -25.2 dB at 11.878 GHz.

Structural modifications using multiple layers were investigated to attain sufficiently good absorption over a broad range of frequencies so as to enhance the absorption bandwidth. Absorption bandwidth was enhanced by Hatakeyama [68] in 1984, by using a two layer absorber design with a ferrite layer at the air/absorber interface and a layer containing ferrite with short metal fibres as the absorber/metal interface. In 2003, Meshram and his group [69], developed double layer microwave absorber using barium ferrite in epoxy resin. Absorption in excess of -9 dB in the frequency range from 8.7 to 10.2 GHz for a thickness of 1.6 mm was reported. Few other computed studies on multilayering were reported in [70-73], where thickness of the layers were optimized to obtain maximum reflection loss and improvement in bandwidth.

In order to make the absorber light, polymeric composites are generally used to customize the electromagnetic properties of an aggregate of filler particles embedded in a polymer matrix. The matrix chosen should be easy to mould, of low cost, sufficiently inert to environmental conditions and be able to hold the filler particles. EPDM rubber, epoxy resin, natural rubber, NPR are some of the polymer matrix which are being used in recent years. Generally, long side branched polymers such as polyvinylidene fluoride, polystyrene, novalac phenolic resin, etc. can take less quantity of filler when used as matrix [74, 75]. Long linear chain and short side chain branched polymers, such as, linear low density polyethylene (LLDPE), disrupts the uniformity of the polymer thereby allowing higher filler concentration without sinkage [76-79], rendering such polymers suitable to be used as matrix.

1.4 Problem formulation and importance of the work

The following aspects are considered in development of microwave absorbers in this work:

- Absorption (≥ 90%)
- Thin and light weight
- Corrosion resistance
- Wide absorption bandwidth

- Ease of processing
- Cost

Due to the leakages from widely used sources in the X- band such as precision approach radar (PAR), military communication satellites, terrestrial communication and networking, motion detectors, traffic light crossing detectors, weather radars [80-85] and many other local area networking or wireless devices, there is a need for effective absorbers for the X-band. The thesis problem focuses on developing absorbers which can effectively reduce EMI in the X-band (8.2-12.4 GHz).

The influence of type and size of the ferromagnetic particles on *em* absorption are investigated in this work with an objective to develop absorbers with desirable absorption performance. The work is structured along the following lines:

- Synthesis and development of the nanosized ferrite and composite materials.
- Investigation of additional relevant characteristics of the developed composites such as homogeneity of filler in the base matrix, density, electrical and magnetic characteristics as well as environmental inertness.
- Investigating and analyzing the desirable microwave properties such as permittivity, permeability, dielectric and magnetic loss, to check the feasibility of using the material as an effective *em* shield.
- Design, thickness optimization and fabrication of single layer microwave absorber using developed magnetic composites.
- Enhancement of absorption performance using doping elements.
- Design, optimization and development of multilayer microwave structure for enhancement of absorption bandwidth.

1.5 Thesis outline

The thesis consists of five chapters and one appendix. Chapter I includes the mechanism of electromagnetic shielding against interferences. The process of absorption, reflection, and multiple reflections are presented along with survey of literature on magnetic absorbers. The theoretical background based on the Maxwell equations is presented.

Chapter II gives a theoretical background of the criterion for selection of the size and type of material to be used. The synthesis of strontium ferrite ($SrFe_{12}O_{19}$) nanoparticles as fillers and fabrication of nano-composites with LLDPE in different volume fraction is presented. The chapter includes microstructural investigation of nano-composites, (XRD, SEM, TEM) conducted for structure, size and homogeneity of fillers. This chapter also discusses *em* wave propagation through an absorber and the equivalent transmission line model. The chapter includes study of complex permittivity and complex permeability at microwave frequencies. Single layer conductor backed absorber using $SrFe_{12}O_{19}$-LLDPE composite is designed and fabricated and the thickness is optimized to achieve maximum reflection loss. The experimental results are compared with calculated values.

Chapter III illustrates enhancement of bandwidth by using nanosized strontium ferrite doped firstly with aluminium and then with cobalt. Nanosized $SrAl_xFe_{12-x}O_{19}$ for (x = 1.0-3.0) and $SrCo_xFe_{12-x}O_{19}$ are synthesized for different values of x (0.2-1.2). Composite samples are fabricated by blending LLDPE powder with ferrite powder. Microscopic details of the structure and homogeneity of the fabricated composites in the form of pellets are studied. Microwave characterizations are carried out and absorption performance is evaluated both theoretically and experimentally.

Chapter IV describes the multilayering technique for further enhancement of absorption bandwidth. A double layer structure using $SrFe_{12}O_{19}$-LLDPE and $SrCo_xFe_{12-x}O_{19}$-LLDPE composites as the constituent layers is studied where the thicknesses of the layers are optimized to achieve enhanced absorption bandwidth. A sandwiched absorber structure is designed with an expanded graphite (EG)-LLDPE layer sandwiched between two ferrite composite layers for bandwidth enhancement.

A summary of all the chapters, the results and the potential application of the developed composite as broadband X-band absorber are presented in Chapter V. Limitations and suggestions for future investigations are also included.

Appendix A contains the mathematical formulation for theoretical estimation on thickness restriction for broadband microwave absorption. MATLAB codes for optimizing parameters of single and multilayer microwave absorber are given in **Appendix B**.

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