Effect of Reflection Property on Microwave Absorbing Materials - A Review

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Abstract: *This review is based essentially on the results in the field of microwave absorbing materials (MAMs) taking different parameters into account like permittivity permeability, impedance matching of absorbing material with free space ,thickness, type of material used highlighting the reflection properties of the material. As the name implies, microwave-absorbing materials are coatings whose electrical and/or magnetic properties have been altered to allow absorption of microwave energy at discrete or broadband frequencies. Microwave absorbers have been traditionally used for EMI reduction, antenna pattern shaping and radar cross section reduction. Particularly in military applications they are used externally to reduce the reflection from or transmission to particular objects as in case of radar.*

Keywords: MAMs, RMAMs, Microwave absorption, Radar, Reflection

1. Introduction

Microwave is the 300MHz-300GHz frequency electromagnetic waves, that are radio waves in a limited band of short wavelength. The basic nature of microwave is usually presented by its three basic properties penetration, reflection and absorption. For glass, plastic and ceramics, microwave is almost through without being absorbed. For water and food it performs self-heating and for metals it will be a reflected microwave. Microwave absorbing materials have been attracting greater attention due to the increasing electromagnetic (EM) interference problems and because they are essential parts of stealth defence in all military platforms. By making it possible to minimise the reflectivity of MAMs, they can be used for number of applications like detection avoidance through radar cross section reduction, for safe microwave ovens , for designing microwave circuits

Reflectivity Minimization: Here several important points for reflectivity minimization are considered [1]. In order to minimize the reflection from a surface it is useful to consider the following physical Eq.s that represents the reflection process. There are three conditions that result in a minimum reflectivity.

1. The first Eq. of interest is that describing the reflection coefficient at an interface.

$$r = \frac{\eta_M - \eta_o}{\eta_{M+\eta_o}} = \frac{Z_M - z_O}{Z_M + z_O} \qquad \text{Eq. 1[1]}$$

where r is the reflection coefficient and η is the admittance of the propagating medium (subscript 'o' for incident medium or air and 'M' for the substrate). The admittance in this Eq. can be replaced with the intrinsic impedance ($Z = 1/\eta$). The reflection coefficient falls to zero when η_M η_o, or in other words the material in the layer is impedance matched to the incident medium. The intrinsic impedance of free space is effectively given by

$$Z_O = \frac{E}{H} = \sqrt{\frac{\mu_O}{\varepsilon_O}} \approx 377 ohms \qquad \text{Eq. 2 [1]}$$

Where **E** and **H** are the electric and magnetic field vectors and μ_o and ε_o are the permeability and permittivity of free space. Thus a material with an impedance of 377ohms will not reflect microwaves if the incident medium is free space.

2. Perfect impedance matching can also be realized if the electric permittivity and the magnetic permeability are equal. This gives the second condition that results in a minimum reflection coefficient. In this case first Eq. can be written as

$$r = \frac{\frac{Z_M}{Z_0}-1}{\frac{Z_M}{Z_0}+1} \qquad \text{Eq. 3[1]}$$

The normalized intrinsic impedance is

$$\frac{Z_M}{Z_O} = \sqrt{\frac{\mu_r^*}{\varepsilon_r^*}} \qquad \text{Eq. 4[1]}$$

where $\varepsilon_r^* = \frac{\varepsilon' - i\,\varepsilon''}{\varepsilon_o}$ and $\mu_r^* = \frac{\mu' - i\mu''}{\mu_o}$,the prime and double prime superscripts represent the real and imaginary components of the complex numbers, respectively. If the incident medium is free space and the reflectivity is zero, then it follows that $\mu_r^* = \varepsilon_r^*$ .The implication is if both the real and imaginary parts of the permittivity and permeability are equal, then the reflectivity coefficient is zero.

3. The third consideration is the attenuation of the wave as it propagates into the absorbing medium. The power of the wave decays exponentially with distance x, by the factor $e^{-\alpha x}$. α is the attenuation constant of the material and can be expressed as $\alpha = \sqrt{\varepsilon_o}\sqrt{\mu_o}\,\omega\,(a^2 + b^2)^{\frac{1}{4}}\sin(\frac{1}{2}\tan^{-1}(-\frac{a}{b}))$ where $\alpha = (\varepsilon_r'\mu_r' - \varepsilon_r''\mu_r'')$
and

$$b = (\varepsilon_r'\mu_r' + \varepsilon_r''\mu_r'') \qquad \text{Eq. 5[1]}$$

To get a large amount of attenuation in a small thickness, α must be large, which implies that ε_r' ,ε_r'', μ_r' and μ_r'' must be large.

Absorber Types [11]: Free space absorbers come in two broad types, reflectivity absorbers and insertion loss absorbers. Reflectivity absorbers reduce the reflection level compared to a perfect reflector (metal plate). They are classified as:

1. Reflectivity – Narrowband

Any single layer homogeneous material will resonate when its thickness is equal to ¼ wavelength. It is seen that in the microwave engineering world, absorber design is an impedance matching problem, in this case matching the impedance of a metal surface (Z=0) to the impedance of free space (Z=377 ohms). If the impedance seen by the wave at the surface of the material is equal to 377 ohms, the wave will be completely absorbed by the material. One of the earliest absorber types which is inherently narrowband is known as the Salisbury screen. The impedance at a metal surface is equal to zero. At one quarter wavelength in front of the surface the impedance will be infinite and the admittance will be zero. If a resistive sheet with surface resistivity equal to 377 ohms is placed here, the impedance will be equal to 377 ohms. Since this only works when the substrate material is ¼ wavelength a Salisbury screen is inherently narrowband

2. Reflectivity – Broadband

Several absorber types exhibit broadband reflectivity performance. Multiple discrete layers can be stacked which will enable the 377 ohm input impedance condition over a broader range of frequencies. The design of this class of a material is same as design of a quarter- wave transformer. A second class of broadband absorbers uses an impedance gradient. The reduction of RCS increases the survivability and decreases the target detection of military aircraft.

Sankarsan Padhy et al.[2] have successfully prepared a new U-type hexaferrite microwave absorbing material (Ba_4 Mg_{2-x} Mn_x Fe_{36} O_{60}) and has reported the complex permittivity and permeability measurement for different value of x in range $0 \leq x \leq 2$ using vector network analyser (VNA) in X-band. The reflection loss of the materials is computed for different values of x and thickness using the measured permittivity and permeability values. The optimum reflection loss is found to be −43 dB for hexaferrite pellet (x = 0.5) at a thickness of t = 1.7 mm. Microwave absorbing paint pellets are prepared by mixing hexaferrite powder with polyimide solution . Using these measured values, radar cross-section reduction simulation for artillery shells has been carried out using electromagnetic simulation software in the 8–10 GHz frequency range. A maximum radar cross-section reduction of 15 dB has been observed for a 30 mm artillery shell at 9 GHz. The reflection loss (RL) in decibels (dB) is determined as

$$R_L = -20 \log_{10}[(Z-Z_0)/(Z+Z_0)] \qquad \text{Eq. 6 [2]}$$

Where Z is the wave impedance at air-absorber interface and Z_0 is wave impedance in free space. The reflection loss is based on a model of single-layered plane wave absorber proposed by Naito and Suetake. Figure 1 shows that the minimum value of reflection loss R_L (or absorption is maximum) is −43 dB with a matched thickness of 1.7 mm in sample x = 0.5.The absorption is decreased in sample x = 1.0 and 1.5 because of lower impedance matching.
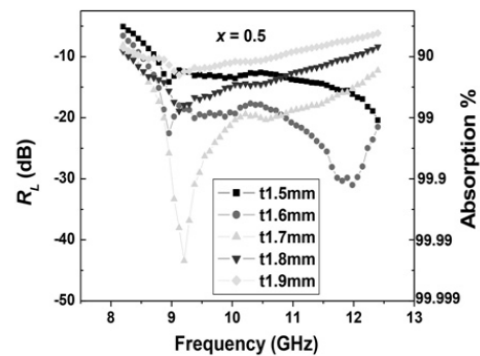

Figure 1: Reflection loss as a function of frequency for x=0.5[2]

From results, it is concluded that the optimum reflection loss is found to be −43 dB for hexaferrite pellet (x = 0.5) at a thickness of t = 1.7 mm.

Y.S.Lee et al.[3] presented the effect of different thickness of rice husk microwave absorber material on its absorption performance in Ku-band frequency. The complex permittivity is measured using an Agilent dielectric probe. The reflection loss and absorption performance of rice husk microwave absorbers (pyramidal shape) is investigated. The technique and software used are rectangular waveguide simulation technique and CST Microwave Studio Wave respectively. Rice husk contains 35.77% of carbon. Carbon is an important element for a microwave absorber to absorb the microwave signal and can help to attenuate the microwaves that pass through the rice husks. The length and width of the sample are 15.799 mm and 7.899 mm and the different thickness used is 1 mm, 2 mm, 3 mm, 4mm, and 5 mm. In this simulation, the rice husk samples were simulated together with a metal back-plate. Without the sample all microwave signals are reflected back to port 1. When a metal back plate puts it at behind the absorber sample, some part of microwave signal was reflected and absorbed. Figure 2 shows the reflection loss result of the rice husk microwave absorber from simulation. The "empty" in fig is the measurement without sample. Without the sample, the entire signal will be reflected back to port 1 by the metal back- plate. Hence, the reflection loss is equal to 0 dB. From the results it is evaluated that, the reflection loss decreases while increasing the thickness of the sample. Other than that, it also decreases while increasing the frequency. The reflection loss of sample with 5 mm thickness at 12 GHz is -3.8 dB. When at 18 GHz, the reflection loss of sample with 5mm thickness is -6.03 dB. The difference of reflection between 1mm and 5mm thickness is -2.23dB. It is concluded that the thickness of the rice husk sample with 5 mm thickness has the highest absorption 75.08 %. More the thickness, more the absorption.
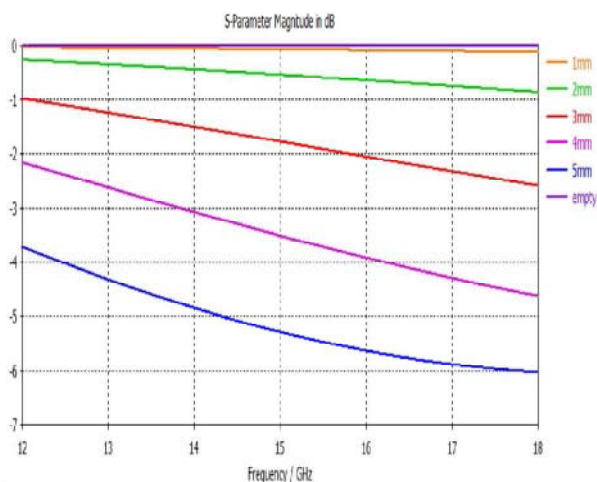
Figure 2: Reflection Loss result from 1-5mm and without sample [3]

Xiangxuan Liu et al.[4] concluded the absorption properties of Single-layer absorbers, having silicon carbide (SiC) and nanosize carbon black (CB) as the absorbent, with a thickness of 2 mm exhibiting excellent microwave absorption properties in the frequency range 2–18 GHz. Excellent electrical conductivity, light weight but small absorption peak of CB blended with SiC having adjustable electrical conductivity increases the absorption capacity. The microstructure, conductivity, dielectric property, and microwave absorption of the material are studied by means of field emission scanning electron microscopy, trielectrode method, and vector network analyzer (HP 8510B) respectively. The morphologies of the SiC and CB particles are obtained by field emission scanning electron microscopy (FESEM, JSM-6700F).
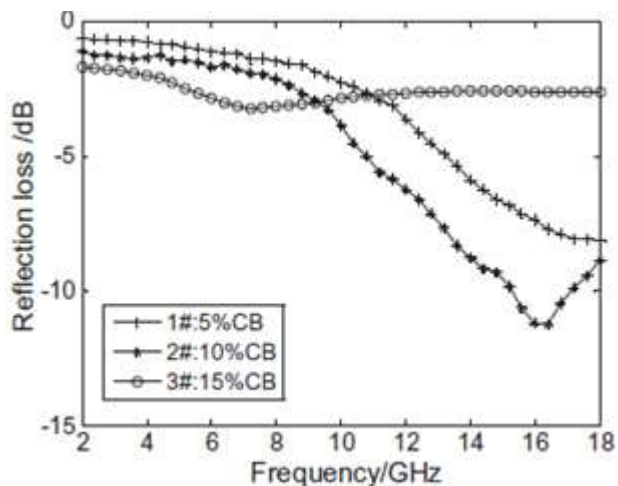

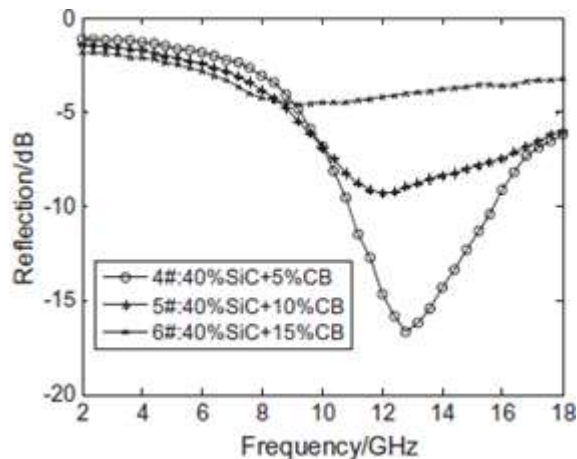**Figure 3:** Effect of the CB mass fraction on the microwave reflection loss [4].

Figure 4: Effect of the CB mass fraction on the microwave reflection loss of SiC/EP Composites [4].
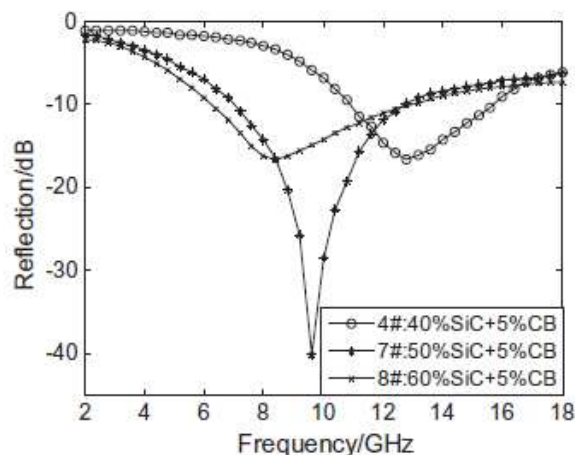

Figure 5: Effect of the SiC mass fraction on the microwave reflection loss of the CB/EP composites [4].

The reflection loss is evaluated corresponding to various CB mass fraction and SiC composites. Figure 3 shows the microwave absorption curves of samples 1-3, which indicates the influence of CB mass fraction. The peak for the reflection loss shifts to a low frequency with an increase of the CB mass fraction. The peak value initially increases and then decreases. Sample 2 with a filling of 10 wt. % has a higher reflection loss than samples 1 and 3 with the same thickness. The reflection loss of sample 2 is below -10 dB at 15.6–16.8 GHz, and minimum value is -11.2 dB at 16.4 GHz.
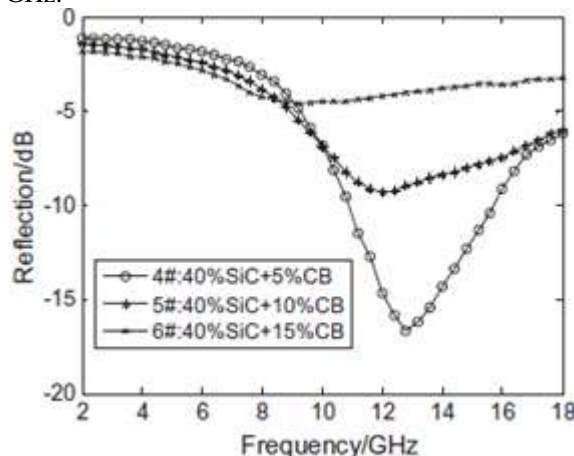
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Figure 4 shows the microwave absorption properties of 40 wt.% SiC composites with different CB content in the range of 2–18 GHz. As the content of CB increases, the peaks of the reflection loss curves move to a lower frequency, and the value becomes lower. Sample 4 with 5 wt.% CB has an better reflection loss than samples 5 and 6. Figure 5 shows that the position of the reflection loss peak moves to a lower frequency with an increasing SiC mass fraction. The absorption properties increases with the SiC content and reaches a maximum 50 wt.% SiC, while the reflection loss dramatically decreases when the mass fraction of SiC exceeds 50 wt.%. The lowest reflection loss is -41.5 dB at 9 GHz, and the-10 dB absorption bandwidth reaches 6 GHz. It is concluded that when 5 wt. % carbon black is blended with 50 wt.% SiC to fabricate a composite with a 2 mm thickness the maximum reflection loss becomes -41 dB at 9 GHz, and the -10 dB bandwidth reaches 6 GHz. Thus, the prepared composite has the potential for use in electromagnetic absorption [14].

Electronic Microwave Circuits: Electromagnetic compatibility of an electronic circuit at microwave frequencies is of prime concern in the design of microwave circuits. External electromagnetic radiations should not interfere with the basic circuit performance and as well the circuit should not radiate electromagnetic energy to interfere with other neighbouring circuits. The best method of achieving such an electromagnetic compatibility is to house the circuit in an enclosure made with a laminate which attenuates the radiations from the circuit and stops the external radiations interfering with the circuit. A laminate of microwave absorbing material is considered to improve the electromagnetic compatibility capability of the circuit.

Cheruku D. Raj et al.[5] have evaluated results for microwave absorbing materials like Ca-NiTi hexaferrite composites $(Ca(NiTi)_x Fe_{12-2x} O_{19})$ for x = 0.4,M-Type Barium ferrites $(BaFe_{12-2x} A_x Co_x O_{19}$ for the tetravalent A ions, Ru^{4+} is chosen) , MnZn ferrite-Rubber composites with volume fraction vf = 0.4 and Carbonyl-Iron particle composites with volume fraction vf = 40% along with conducting materials like copper, stainless steel are considered to form the interface in the laminate. A laminate of MAM-metallic conductor having different thickness of layers is considered to improve the electromagnetic compatibility capability of the circuit which is designed such that the radiation from the microwave circuit is attenuated to a very large extent before it propagates out of the circuit housing and simultaneously, also shields the microwave circuit from external radiation inferences. The thickness of the material layers in the laminate are so designed such that the reflectivity and shielding effectiveness of the laminate are achieved as per the requirement of the circuit compatibility considerations.

Reflectivity is nothing but the total reflection coefficient of the laminate looked from absorbing material layer direction. *Figure 6* and *Figure 7* shows the variations of reflectivity with frequency for different absorbing materials at a thickness of 5 and 10 mm respectively.
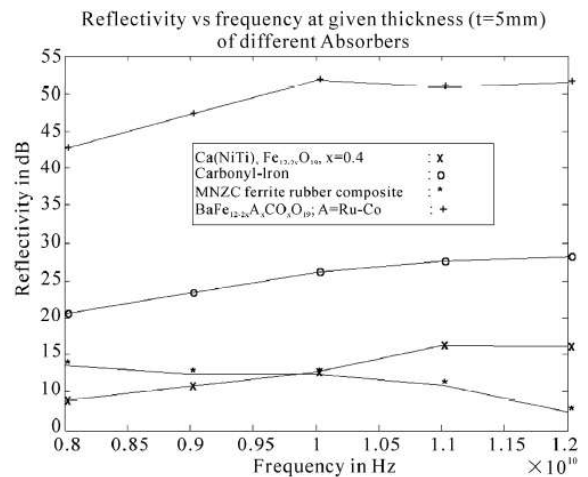

Figure 6: The variation of the reflectivity as a function of frequency for different microwave absorbers at absorber thickness of 5mm [5].
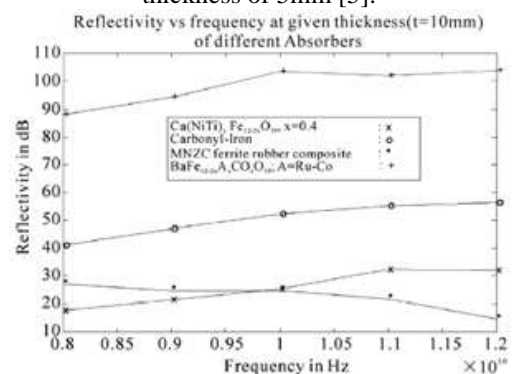

Figure 7: The variation of the reflectivity as a function of Frequency for different microwave absorbers at absorber Thickness of 10 mm [5].

Figure 8 and Figure 9 shows the plots for variations of reflectivity with thickness of layer of absorbing materials $(Ba_4 Fe_{12-2x} A_x Co_x O_{19}$ for the tetravalent A ions, Ru^{4+} is chosen and ferrite-Rubber composites with volume fraction vf = 0.4) at different frequencies. Reflectivity of the laminate mainly depends upon the absorption properties of the microwave absorbing material and its thickness. Thus, the microwave absorbing material, M-Type Barium ferrites exhibits excellent reflectivity (around 20 dB better than Carbonyl-Iron particle composites with volume fraction vf = 40%) over the entire frequency range compared to other types of absorbing materials.
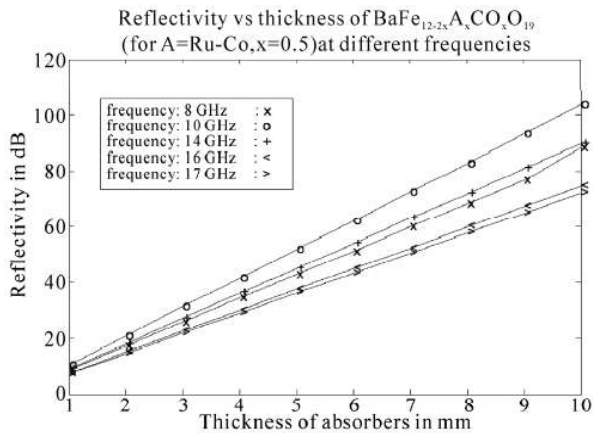
Figure 8: The variation of the reflectivity as a function of thickness for the $BaFe_{12-2x} A_x Co_x O_{19}$–copper laminate at different frequencies [5].
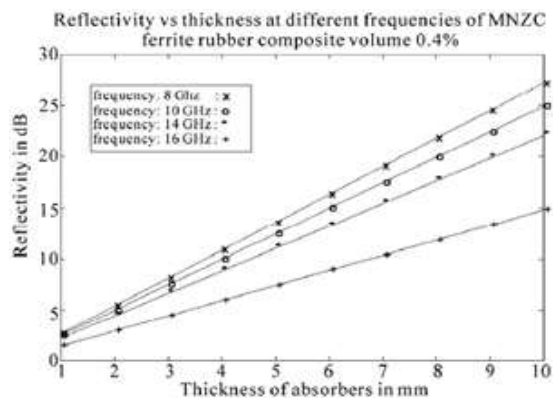

Figure 9: The variation of the reflectivity as a function of thickness for the MnZn ferrite-Rubber composite-copper laminate at different frequencies [5]

It is concluded that the reflectivity laminate comprising of M-Type Barium ferrites as absorbing material layer and stainless steel as conducting material layer exhibits very good reflectivity [15].

Hua Zou et al.[6] have investigated the determining factors for the complex permittivity, complex permeability, and reflectivity of rubber microwave absorbing materials (RMAM) with various samples including different crystal structures of Ba-ferrite (M-type, W-type, and Y-type), the ferrite with doped elements (Ba, Sr), the materials' thickness, the combination ratio of ferrite and carbonyl iron. The effects of surface modification and loading amount of ferrite on the mechanical properties, processing performance, and absorbing property of RMAM were also assessed. RMAM consisting of methyl vinyl silicone rubber as matrix and ferrite as major absorbent was prepared by mechanical blending method. The crystal structure was observed by X-ray powder diffraction (XRD) and the electromagnetic parameters were measured with the coaxial method using a vector network analyzers with an aluminium plate used as under boarding and an APC-7mm coaxial line in the frequency range of 2-18 Ghz. The test sample has a toroidal shape with an outer and inner diameter of 7.0 mm and 3.0mm respectively. Figure 10 shows that RMAM based on Ba-M almost has no absorption ability in the whole frequency range of 2-18 Ghz, and all the electromagnetic waves are reflected. The Ba-Y based RMAM has poor microwave absorption, and its minimum reflectivity is

higher than -5dB. Ba-W based RMAM has a reflectivity of less than -9dB in the absorption in a wide frequency bandwidth. *Figure 11* shows the reflectivity of Ba-ferrite filled and Sr-ferrite-filled absorbing silicon rubber. Both materials have good absorbing performance in the frequency of 8-18 GHz, suitable for microwave absorption at X-wave and Ku-wave band. On the other hand Sr-W based RMAM has better absorbing performance because its reflectivity is lower than -10dB in the frequency of 9-18 Ghz, and the peak value is lower than -30dB.
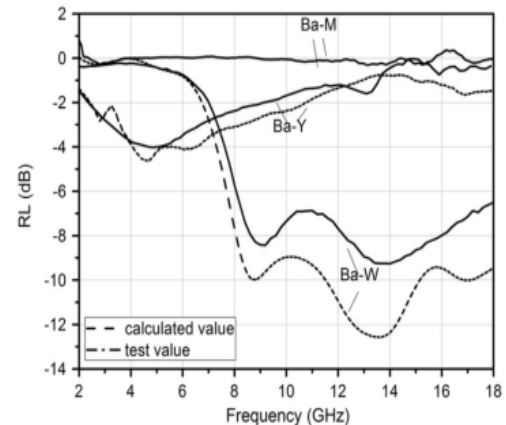

Figure 10: Reflectivity of Ba-ferrite based silicon rubber with different crystal structures [6]
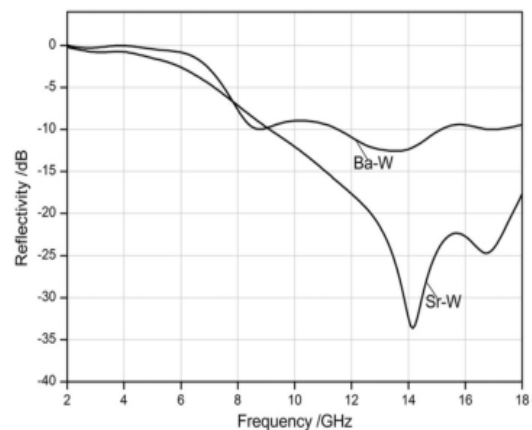

Figure 11: Reflectivity of silicon rubber filled with Ba-ferrite and Sr-ferrite (ferrite loading 450 phr) [6]

The results show that W-type Ba-ferrite based RMAM exhibits better absorbing property at high frequencies (8–18 GHz) than the other two barium ferrites (M-type and Y-type) based ones, and the absorbing property of RMAM based on Sr-ferrite is best. As the thickness of RMAM and the amount of absorbents increase, the absorption peak moves toward low frequency, the absorption frequency bandwidth is narrowed, and the reflectivity first decreases and later increases. The optimum thickness is 1.5–1.7 mm, and the amount of ferrite is 450 parts per hundreds of rubber (phr).[10]

Pallab Bhattacharya et al.[7] have compared the microwave absorption ability of Graphene/Multiwall carbon nanotubes (MWCNT) in thermoplastic polyurethane(TPU) matrix. The RAMs should capable of cancelling out both the magnetic and electrical components of the electromagnetic radiation

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for an effective absorption. The material is prepared with 10% loading and sample thickness is kept at 2 mm. Field Emission Scanning electron microscopy (FESEM) and Transmission Electron Microscopy (TEM) is used for morphological study and scattering parameters were measured in X-band region (8.2-12.4 Ghz) by using a Agilent Vector Network Analyzer (ENA E5071C). Graphene has flat sheet-like structure whereas CNT has tubular structure. According to transmission line theory, when the electromagnetic wave transmits through a medium, the reflectivity is affected by many factors such as permittivity, permeability, sample thickness, and electromagnetic wave frequency. Here the frequency of radiation and thickness of sample is same for all samples. From the scattering parameters S11 & S21, the reflection coefficient (τ) with the help of the following Eq.s:

$$\tau = x \pm \sqrt{(x^2 - 1)}; |\tau| \leq 1$$

where $x = (S_{11}^2 - S_{21}^2 + 1)/2S_{11}$
Eq. 7[7]
Reflection loss (in dB) = -20 log [τ]

Figure 12 represented the return loss Vs frequency plot for Graphene and MWCNT present in TPU matrix. The prepared RAMs showed the absorbing properties in a wide frequency range in the X-band region. Graphene and MWCNT in TPU showed the maximum return loss of -12.56 dB at 10.43 GHz and -7.6 dB at 10.73 GHz respectively. Both were showing their maximum return loss peak almost in the same frequency range but Graphene showed better absorption capacity than MWCNT [12].
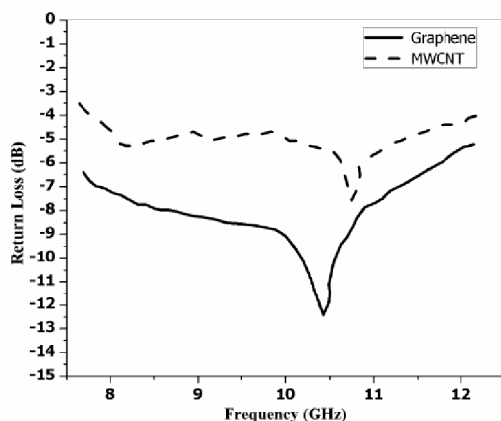

Figure 12: Return loss v/s frequency of graphene and MWCNT [7]

Xinwei Ji et al.[8] determined the electromagnetic and microwave absorbing properties of material composed of Co-Ferrite particles and carbonyl iron particles (CIP) as absorbent and aliphatic polyurethane resin as matrix which can be tuned by changing the weight fraction of Co-ferrite at 4–18 GHz. The morphology of material is studied by Field Emission Scanning electron microscopy (FE-SEM), electromagnetic parameters by S-Parameter Network Analyzer 8722ES and the microwave absorbing characteristics were studied by Agilent PNA-X Network analyzer N5244A. The CIP are spherical particles of around 2–5μm in diameter. The Co-ferrite particles embody variable

shapes like rod, flake and sphericity. The specimens of 1#, 2#, 3#, and 4# contained concentration of 0 wt%, 20 wt%, 40 wt%, and 60 wt% Co-ferrite particles, and 60 wt%, 40 wt%, 20 wt%, and 0 wt% CIP, respectively.

The reflection loss (electromagnetic absorption) of the specimens was measured with NRL arch method and the results are shown in Figure 13 . It expresses the relationship between reflection loss and frequency for the coatings with different CIP and Co-ferrite content.
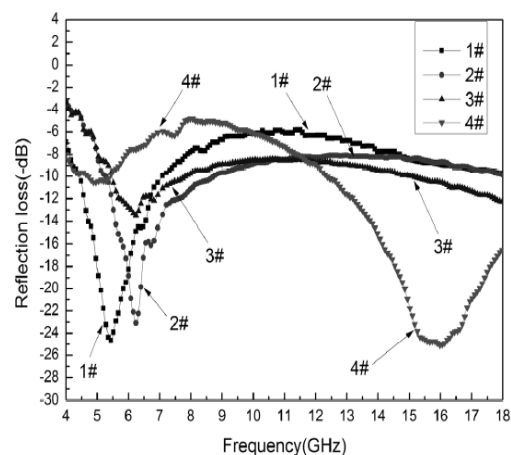

Figure 13: Reflection loss of the coatings with different content of CIP and Co-ferrite particles [8]

Here, the specimens of 1# and 4# contained concentration of 60 wt% CIP and 60 wt% Co-ferrite particles, have RL values below -8 dB in the range of 4–8 GHz and 12–18 GHz, respectively. The minimum RL value of specimen 1# reaches -24.77 dB at the frequency 5.42 GHz, and that of 4# reaches -25.14 dB at 16.04 GHz. The effective bandwidths (RL < -8 dB) of 1# and 4# are 7.1 GHz and 8.5 GHz. The ratio of CIP and Co-ferrite particles in the specimens 2# and 3# is 2:1 and 1:2 respectively. And the effective bandwidths of 2# and 3# are 12.9 GHz and 13.0 GHz. It is concluded from the reflectivity results that the maximum absorption of the coating with hybrid particles is less than that containing only one kind particle. But the effective bandwidths (< -8 dB) increases to 13 GHz [12].

Luiza de Castro Folgueras et al.[9] have characterised the electromagnetic properties (absorption, transmission and reflection of electromagnetic energy; and electric permittivity and magnetic permeability) of sheets of microwave absorbing materials using conductive polyaniline dispersed in a silicone rubber matrix in X-band (8-12 Ghz). The polyaniline is taken in powdered form and was added to a matrix composed of either one of two types of silicone rubber, L9000 and RTV630 (GE Silicones). Two different sheets were obtained; the sheet produced with L9000 silicone rubber had a thickness of 2.80 mm, and the one produced with RTV630 silicone rubber was 4.39 mm thick. The electromagnetic properties of the sheets were analyzed using the waveguide technique which was coupled to a vector network analyzed connected to an S-parameter test and a synthesized frequency generator (45 MHz – 26 GHz).The reference material taken is aluminium plate. Figure 14 shows the results derived from S-parameters measurements (reflected, transmitted and absorbed

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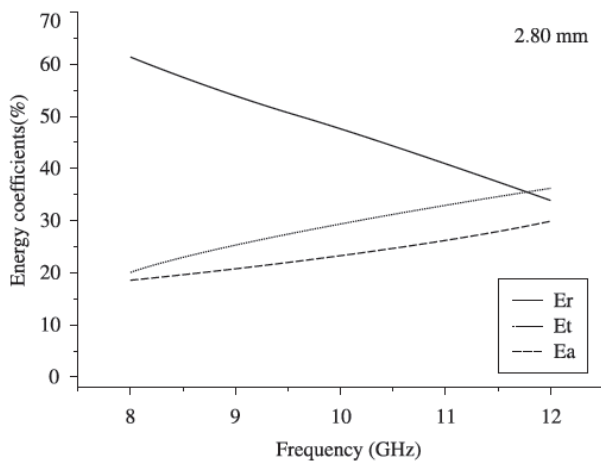electromagnetic energy) as a function of frequency for the two single-layer RAM's.

Figure 14: Curves of coefficients (in percentages) absorbed (Ea), transmitted (Et) and reflected (Er) energies: RAM thickness 2.80mm L9000 [9]
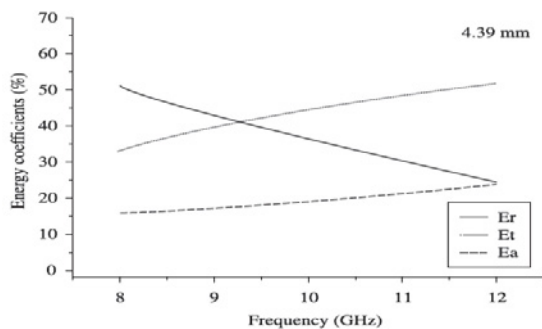

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Figure 15: Curves of coefficients (in percentages) absorbed (Ea), transmitted (Et) and reflected (Er) energies: RAM thickness 4.39mm RTV630 [9]

For Figure 14 and Figure 15 it is observed that for both materials, the value of absorbed energy is increased by about 10% with frequency in the frequency range of the measurements. The maximum energy absorption, which was measured at 8 GHz, was 18.5 and 16.2% for the materials with 2.80 and 4.39 mm respectively, showing that the thinner material had better absorbing properties. When the reflectivity of these materials were measured using an aluminum back plate, the 2.80 mm thick material absorbed 88% of the incident energy at 8 GHz whereas the 4.39 mm thick material absorbed 71% of the incident energy. The single-layer materials developed in this study can be combined into multi-layer materials to produce RAM's with different absorbing properties but the order in which these materials are stacked plays an important role in determining the final properties of the RAM. It is concluded that the materials produced with conductive polyaniline dispersed in a silicone matrix attenuated the incident radiation up to about 88%, implying that these materials can be used as absorbers of electromagnetic radiation having advantage of being less dense, flexible and inexpensive to produce in comparison to conventional absorbers [13].

2. Conclusion

Different microwave absorbing materials are taken into consideration as shown in the table. Each material has its own variation in properties having its own usefulness and limitations. The type of material can be chosen depending upon the particular application for which it is to be used and the purpose of its need.

Table 1: Comparison of different materials on the basis of its type, thickness, frequency and reflection loss [2] – [4], [6]-[8]

S.No	Type of material	Frequency Range(GHz)	Thickness (mm)	Reflection loss(dB)
1.	$(Ba_4 Mg_{2-x} Mn_x Fe_{36} O_{60})$	8-10	1.7	- 43
2.	Rice husk	12-18	5	-6.03
3.	SiC and nano size carbon black	2-18	2	-41
4.	Sr-based RMAM	9-18	1.5-1.7	< -10
5.	Graphene in tpu matrix	8.2-12.4	2	-12.56
6.	CIP and Co ferrite particles	8-12	1.2	< -8

From the above table it is concluded that , U-type hexaferrite microwave absorbing material $(Ba_4 Mg_{2-x} Mn_x Fe_{36} O_{60})$ shows strong microwave absorbing ability with reflection loss equal to -43 dB in the frequency range 8-10 Ghz and thickness of the material being 1.7 mm in rust free environment. Further for higher frequency range from 2-18 GHz ,SiC and nano size carbon black particles with slightly higher thickness of 2mm exhibiting reflection loss of -41 dB can be considered.

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