

Development of Coatings for Radar Absorbing Materials at X-band

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Abstract. The present review gives a brief account on some of the technical features of radar absorbing materials (RAMs). The paper has been presented with a concentrated approach towards the material aspects for achieving enhanced radar absorption characteristics for its application as a promising candidate in stealth technology and electromagnetic interference (EMI) minimization problems. The effect of metal particles doping/dispersion in the ferrites and dielectrics has been discussed for obtaining tunable radar absorbing characteristics. A short theoretical overview on the development of absorber materials, implementation of genetic algorithm (GA) in multi-layering and frequency selective surfaces (FSSs) based multi-layer has also been presented for the development of radar absorbing coatings for achieving better absorption augmented with broadband features in order to counter the radar detection systems.

1. Introduction

Nowadays, radar absorption has become an important issue with rapid technological development in the radar detection systems which arises the need to develop techniques for achieving better radar absorption. Main challenge in defence is how to hide various targets like aircraft, ships, missiles and other defence vehicles and this challenge can be achieved by a substantial reduction in the radar cross section of the target. With the reduction in RCS, the targets can be better escaped from radar detection, whether it is a vehicle or a guided weapon. Several techniques have been used for reducing the RCS like (i) shaping, (ii) active cancellation, (iii) passive cancellation and (iv) radar absorbing materials (RAMs). Shaping involves the design of surface profiles or modifying the external features so that no energy or little energy is scattered or reflected back to the radar and is one of the most effective techniques to control RCS [1]. However, due to certain design limitation, complete RCS control through shaping is not possible. Normally reduction is achieved only in a limited angular region and at the expense of increased RCS in other regions. Furthermore, shaping is effective only at higher frequencies; in fact, at lower frequencies, it is almost ineffective [1]. The best examples of shaping are B-2 Spirit stealth bomber, F-22 Raptor, F-35 Lightning II and F-117A nighthawk stealth fighters. Passive and active cancellation employ active/passive patches at the required locations on the target to reduce the scattering from hotspot regions (where the reflections are maximum). But these methods are related to narrow bandwidth and complexity of the system designs. Owing to the aerodynamics problem and complexity in the design of active and passive filters, the RAMs have found enormous importance for achieving radar absorbing characteristics. This review has also focused on RAMs owing to its extensive use for radar absorption.

Radar absorbing materials (RAMs) has attracted considerable attention, as these materials play a key role in defence organizations for imparting stealth features to the warheads and fighter aircrafts. The rapid development in microwave technology has greatly exploited electromagnetic spectrum and therefore, the demands for radar absorbing materials are increasing in a wide range of applications. RAM is a class of material which is coated on the surface of the structures to avoid radar detection i.e., invisibility to a radar. In stealth technology, RAMs are used to reduce radar cross section (RCS). A RAM actually absorbs the incident electromagnetic (EM) energy, thereby reducing the energy



reflected or scattered back to the radar [2]. This reduces the RCS signature of the coated object; thereby camouflaging it from the enemy eyes. Apart from defence related matters, RAMs also find considerable application in minimizing the problem of electromagnetic interference (EMI) pollution. The EMI problem has been on the rise; owing to the astronomical increase in the microwave operated electronic devices. The EMI pollution interferes with the circuitry of the device rendering its function unsatisfactory. Therefore, RAMs are developed which are seen as an answer to EMI related problems. Other than radar cross section reduction (RCSR), EMI reduction, RAMs also find application in areas such as wireless communication in mobile phones, protective sheet in microwave ovens, construction of anechoic chambers for scientific testing etc. The considerable use of RAMs for various applications has led to tremendous research in this field to develop RAMs with high reflection loss, broader bandwidth and thin absorber thickness.

2. Fundamentals of Microwave Absorption

There has been considerable research to understand the phenomenon behind radar absorption. The extensive research has given much insight into the absorption phenomenon and has also led to the formulation of well derived mathematical equations involved in the process. But still, all the mechanisms involved in radar absorption has not been clearly understood. This has occupied the minds of the researchers to develop a better understanding of the absorption mechanisms involved for the development of a better and efficient absorber. The complex permeability and permittivity is considerably affected by various parameters such as (a) type of materials used, its composition and phases involved, (b) process parameters involved in the synthesis method adopted and (c) layering which could be single layer, multi-layer and FSS based multi-layer coatings. The understanding of all these parameters aids in the development of an efficient absorber design. The correlation between various parameters affecting the radar absorption characteristics has been poignantly described in the fish-bone diagram shown in Fig. 1.

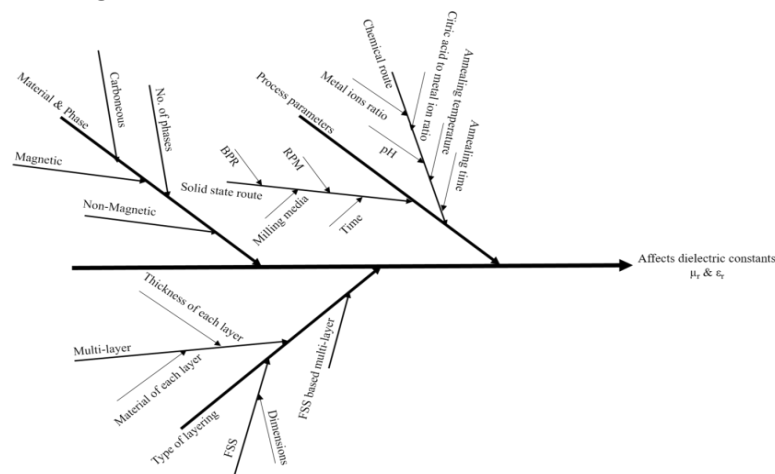


Figure 1. Fish-bone representation of various parameters affecting dielectric constants.

2.1. Mathematical formulation

Fig. 2 shows an infinite conducting plate coated with multi-layer microwave absorber having layers of different coating thickness with different complex permittivity and complex permeability. According to transmission line model, when an EM wave impinges on the surface of an absorber, it undergoes a combination of reflection, absorption and transmission.

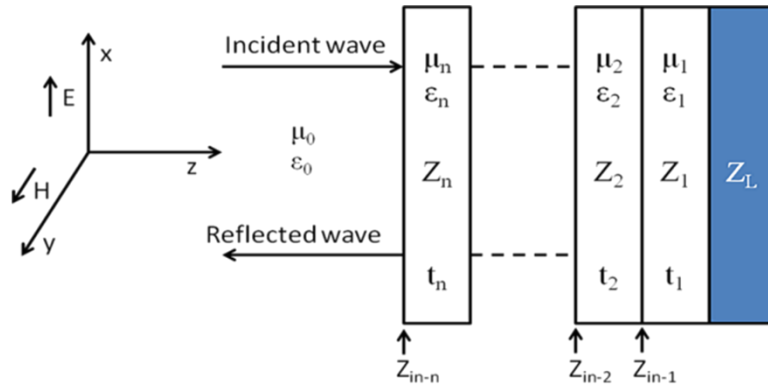


Figure 2. Schematic diagram of multi-layer microwave absorber [2].

Let t_i , ϵ_i , μ_i , z_i denote the thickness, complex permittivity, complex permeability and intrinsic impedance of the i^{th} layer respectively of n -layer absorber. The first layer is in contact with a perfectly conducting metal plate and n^{th} layer is terminated to free space. Let ϵ_0 and μ_0 are the permittivity and permeability of free space respectively. The wave impedance Z_n at the surface of outer most layer (i.e., $n = n$) is given by [3,4]

$$Z_{in,n} = \frac{Z_{in,n-1} + Z_n \tanh(\gamma_n t_n)}{(Z_{in,n-1}/Z_n) \tanh(\gamma_n t_n) + 1} \quad (1)$$

Similarly, the wave impedance Z_{n-1} at the surface of $(n-1)^{\text{th}}$ layer is given by

$$Z_{in,n-1} = \frac{Z_{in,n-2} + Z_{n-1} \tanh(\gamma_{n-1} t_{n-1})}{(Z_{in,n-2}/Z_{n-1}) \tanh(\gamma_{n-1} t_{n-1}) + 1} \quad (2)$$

Hence, the wave impedance Z_i at the surface of i^{th} layer is given by

$$Z_{in,i} = \frac{Z_{in,i-1} + Z_i \tanh(\gamma_i t_i)}{(Z_{in,i-1}/Z_i) \tanh(\gamma_i t_i) + 1} \quad (3)$$

The incident impedance at metal surface is zero as the impedance of the metal is zero (i.e., $Z_L = 0$). For a single layer absorber (i.e., $n = 1$), the incident impedance, Z_{in-1} , at free space and material interface may be written as

$$Z_{in,1} = Z_1 \tanh(\gamma_1 t_1) = Z_0 \sqrt{\mu_1/\epsilon_1} \tanh(\gamma_1 t_1) \quad (4)$$

where, Z_0 is the impedance of free space, γ is the complex propagation factor and is expressed as

$$\gamma = j \frac{2\pi f}{c} \sqrt{\mu\epsilon} \quad (5)$$

where, f is the working frequency, c is the propagation velocity of electromagnetic wave in free space. The reflection coefficient (Γ) for single layer absorber at the free space and material interface is given as

$$\Gamma = \frac{Z_{in,1} - Z_0}{Z_{in,1} + Z_0} = \frac{\sqrt{\frac{\mu_1}{\epsilon_1}} \tanh(\gamma_1 t_1) - 1}{\sqrt{\frac{\mu_1}{\epsilon_1}} \tanh(\gamma_1 t_1) + 1} \quad (6)$$

The reflection coefficient for two layer absorber (i.e., $n = 2$), where layer 1 is backed with perfect conductor and layer 2 is in contact with free space, is written as

$$\Gamma = \frac{Z_{in,2} - Z_0}{Z_{in,2} + Z_0} \quad (7)$$

where, $Z_{in,2}$ is the impedance at the free space and layer 2 interface, and can be expressed as

$$Z_{in,2} = \frac{Z_{in,1} + Z_2 \tanh(\gamma_2 t_2)}{(Z_{in,1}/Z_2) \tanh(\gamma_2 t_2) + 1} \quad (8)$$

where, Z_2 is the impedance of layer 2 and is given as

$$Z_2 = Z_0 \sqrt{\mu_2 / \epsilon_2} \quad (9)$$

Now, substitution of the above equations give reflection coefficient (Γ) for two layer absorber where layer 1 is backed with metal and layer 2 is opened to free space

$$\Gamma = \frac{\frac{\sqrt{\mu_1/\epsilon_1} \tanh(\gamma_1 t_1) + \sqrt{\mu_2/\epsilon_2} \tanh(\gamma_2 t_2)}{1 + \sqrt{\mu_1 \epsilon_2 / \epsilon_1 \mu_2} \tanh(\gamma_1 t_1) \tanh(\gamma_2 t_2)} - 1}{\frac{\sqrt{\mu_1/\epsilon_1} \tanh(\gamma_1 t_1) + \sqrt{\mu_2/\epsilon_2} \tanh(\gamma_2 t_2)}{1 + \sqrt{\mu_1 \epsilon_2 / \epsilon_1 \mu_2} \tanh(\gamma_1 t_1) \tanh(\gamma_2 t_2)} + 1} \quad (10)$$

The reflection loss (RL) of incident EM wave for single layer and multi-layer absorber in dB can be calculated as

$$\text{Reflection Loss (dB)} = -20 \log_{10} |\Gamma| \quad (11)$$

2.2. A Bird's Eye View on the Mechanisms Involved in Radar Absorption

When a radar signal impinges on the surface of an absorber, the wave undergoes a combination of reflection, absorption and transmission. At radar frequencies a reduction in reflection from an object can be achieved by one of two mechanisms: (1) absorption, and (2) cancellation. Coatings, also referred as resonant absorbers, reduce RCS by the cancellation of multiple reflections. Absorption is transfer of incident EM wave's energy into heat. The exact behaviour of the EM wave at the surface of the absorber critically depends on relative complex permittivity and permeability of the absorber. The loss mechanisms for a dielectric material are due to dielectric losses and conduction losses. Magnetic materials and metals having high electrical conductivity are governed by conduction losses. On the other hand dipolar losses dominate in dielectric materials. Magnetic materials also exhibit additional magnetic losses such as hysteresis, electron spin resonance and domain wall resonance. The skin depth of the particles is yet another factor which depends on the resistivity of the particles and hence plays a crucial role in radar absorption. Quarter wavelength destructive interference aids in microwave attenuation and this effect becomes more pronounced for multi-layer absorber. For multi-layer absorber, the multiple layer produces more attenuation. The impedance matching is another important factor which in conjunction with multiple internal reflections gives better radar absorption [28]. The impedance matching increases the depth of penetration of radar signals into the absorber which aids in more number of multiple internal reflections and hence increases the electrical length; thereby decreasing reflected radar signals.

3. Review of Development of Coatings for Radar Absorption

Considerable amount of research has been carried out to develop magnetic and non-magnetic RAM coatings for the enhancement of radar absorbing characteristics. This section focusses on the gradual development of ferrites and non-magnetic materials for achieving better radar absorbing behaviour.

3.1. Review of Ferrites as RAMs

Ferrites have been used as microwave absorber since World War II when German military scientists followed investigation of J.L. Snoek at Philips Eindhoven, Netherland [5]. Magnetic ferrites were developed by Japanese to make EM wave absorbers in 1970's. The Plessey Company UK, developed EM wave absorber for British Navy to satisfy the need to camouflage and also minimizing EMI [6]. In

the early 90's, the research was mostly focused on the effect of doping elements on the magnetic properties of ferrites. Surig et al. [7] in 1993 prepared Al-substituted Ba/Sr hexaferrite using sol gel method and calcined at 600 °C and 950 °C for 3 h. It is reported that saturation magnetization decreased with Al-substitution and correspondingly coercive field strength and anisotropy field strength increased by increasing Al content. Dishovski et al. [8] in 1994 showed that Co-Ti substitution in Ba-hexaferrite improves microwave absorption and reported the variation in the components' ratio which leads to change the optimal thickness of the absorber in 8-22 GHz frequency range. Abbas et al. [9] in 1998 developed (CoSi)-substituted Ba-hexaferrite by solid state reaction route and measured the microwave absorption of the paint coatings of different thicknesses in X-band. They reported a high value of absorption i.e., more than 10 dB at 9.5 GHz frequency level with 0.6 mm coating thickness and 57% fill factor.

In the early 2000's, the research concentrated on enhancing the bandwidth. Meshram et al. [10] in 2002 has developed single and double layer microwave absorbers using Mn-substituted Ba-hexagonal ferrites for Ku band. They compared both theoretical and experimental results and found that the single layer absorber has a reflection loss of -12.3 dB at 17.4 GHz for a thickness of 1.12 mm. On the other hand, the double layer absorber provided broadband characteristics corresponding to 6 dB level between 12-18 GHz frequencies. Meshram et al. [11] in 2004 has reported the design, development and characterization of $\text{BaCo}_{0.5}\text{dT}_{0.5}\text{dMn}_{0.1}\text{Fe}_{(11.87-d)}\text{O}_{19}$ and $\text{Ba}(\text{MnTi})_d\text{Fe}_{(12-2d)}\text{O}_{19}$ hexagonal ferrites ($d = 1.6$) as a microwave absorber in X-band. The ferrites were developed by dry attrition method and 60% by weight has been mixed in epoxy resin to observe microwave absorption for single- and two-layer microwave absorbers. It is found that the broadband characteristics with minimum absorption of -9 dB from 8.7 to 10.2 GHz for a coating thickness of 2 mm for two layer absorber.

Recently, the research trend has shifted from the use of metal ions as dopants to rare earth metals as the doping element in ferrites. Chang et al. [12] in 2012 substituted Ce in barium hexaferrite with chemical composition $\text{BaCe}_{0.05}\text{Fe}_{11.95}\text{O}_{19}$ using sol gel citrate method and measured the complex permittivity, permeability and microwave absorption properties in the frequency range of 8–13 GHz and at a thickness of 3.5 mm they observed better reflection loss. Li et al. [13] in 2012 fabricated $\text{Ba}_{(1-x)}\text{La}_x\text{Fe}_{12}\text{O}_{19}$ ($0.00 < x < 0.10$) nano fibers using electro-spinning method and measured the dielectric and absorption properties. It is reported by them that saturation magnetization and dielectric properties first increases and then decreases after $x = 0.05$; correspondingly, coercivity first decreases and then increases.

3.2. Review of Non-Magnetic RAMs

Dielectric absorbers are conventional absorbers with low dielectric permeability which exhibit high losses owing to relaxation dispersion [14]. Non-magnetic materials used as EM wave absorber are carbon black (CB), short carbon fiber (SCF), polymers, SiC and carbon nano tubes (CNT). Sun et al. [15] in 2002 and Zhang et al. [16] in 2002 investigated dielectric and infrared properties of pure, aluminum-doped and nitrogen-doped SiC using sol-gel process. Dielectric properties of pure SiC are much higher than doped one in the entire frequency range. Fan et al. [17] in 2006 stated that the microwave absorption of CNT composites is mainly attributed to the dielectric loss rather than magnetic loss. Wang et al. [18] in 2008 studied the electromagnetic properties of carbon black and BaTiO_3 nanocomposite synthesized by sol-gel method. This composite exhibits a minimum RL value of -23 dB at 13.4 GHz (30 wt.% nanocomposite with epoxy resin).

Zhao et al. [19] in 2010 measured complex permittivity and microwave absorbing properties of SiC particles doped with nitrogen in the frequency range of 8.2-18 GHz. The study revealed that the dielectric properties can be tailored by adding nano SiC particles. They achieved a maximum RL of -63.41 dB at 12.17 GHz with 2.96 mm thickness and a bandwidth of 9.8-15.8 GHz below -10 dB. Liu et al. [20] in 2011 investigated the effect of particle size of Fe-Si alloyed powder on the EM and microwave absorption properties in the 2-7 GHz frequency range. It is inferred that the particle size has great influence on the EM and microwave absorption properties of the composites and both the complex permittivity and permeability of the composites increase with decreasing the particle size to a

certain extent with an improvement in microwave absorption and shift in absorption peak towards lower frequency range.

4. Methods for Radar Absorption Enhancement

There are several techniques used for microwave absorption namely development of single layer RAM coatings, frequency selective surfaces (FSSs) and multi-layering of RAMs. In single layer RAM coatings various conventional and new materials are explored for achieving better absorption properties. The absorption characteristics are also improved by complimenting single layer RAMs with FSSs. FSSs are planar periodic structures of identical patches or apertures of conducting elements repeating periodically in either a one or two- dimensional array on a dielectric substrate [21]. Because of their frequency selective properties, FSSs are used as radar absorbing structures [22]. The absorption behavior of the FSS depends on the shape of the elements (apertures/patches), their size and spacing. Generally FSS are employed in front of a grounded dielectric slab (substrate) to synthesize high-impedance absorbing surfaces [23]. The ability of the microwave absorbing structures can also be enhanced with multi-layering of RAMs. In this method, thin absorbing coatings are designed with cascading layers of different materials such that the absorption properties of the coating are maximized over a specified frequency range [24]. To make multilayer with wide bandwidth out of available materials, it becomes necessary to apply an optimization technique [25]. The genetic algorithm (GA) has been briefed in this section for its implementation in the design parameters optimization.

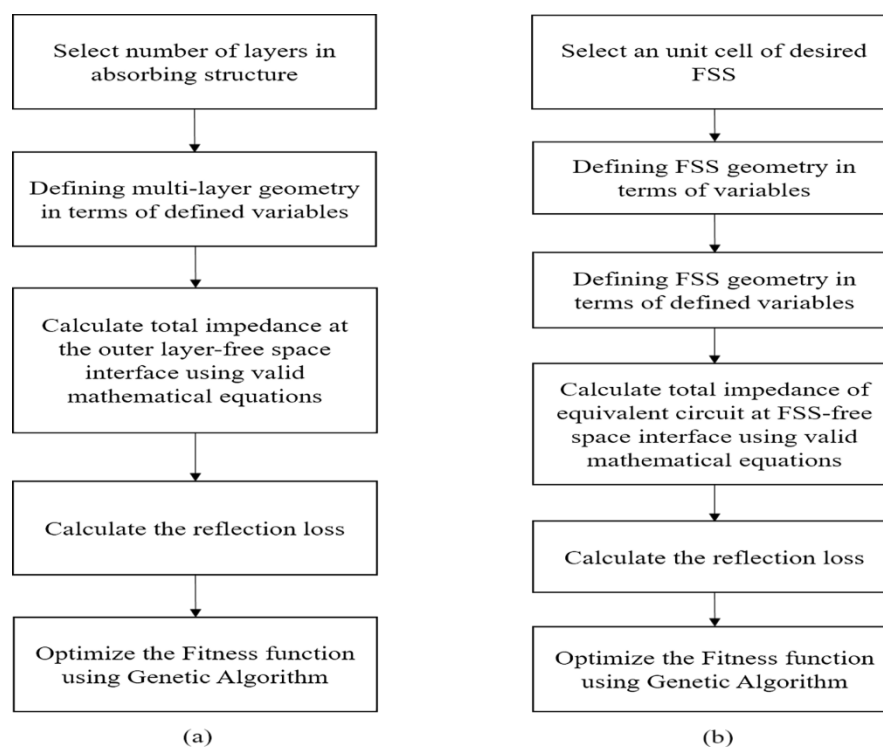


Figure 3. Steps followed to optimize parameters for multi-layered absorber (a) multi-layered microwave absorber and (b) multi-layered FSS based absorber.

The optimization of various multi-layer and FSS requires genetic algorithm (GA). There are many physical parameters needed to be determined, such as materials for coating (i.e., proper permittivity, permeability), their sequence and thickness in case of multilayer coating. In the case of FSS, coating materials, their sequence, thickness and the parameters defining shape (i.e. periodicity, gap and width) of FSS structure (which defines inductance and capacitance of the structure by which resultant impedance is calculated) needs to be determined. It is quite difficult and cumbersome to

compute these values by simplifying various equations. Therefore, there is a need to use the optimization technique, by which these parameters can be estimated. Genetic Algorithm (GA) is very powerful optimization tool for problems having a large number of variables [31]. The steps involved in GA optimization of multi-layer and FSS design parameters have been shown in Fig. 3.

4.1. Development of Single Layer Ferrites and Dielectrics Coatings for Enhanced Absorption Characteristics

This section focuses on the role of size, morphology and doping/dispersion of metal particles in the conventional ferrites and ceramics to obtain enhanced radar absorbing characteristics.

Kumar et.al. [26] in 2013 investigated the effect BaFe₁₂O₁₉ particles size on the radar absorption characteristics at X-band. It was found that the average particle size and standard deviation of BaFe₁₂O₁₉, both increase with the increase in annealing time and correspondingly the complex permittivity, complex permeability and loss tangents increase. As a result of the increase in complex dielectric properties the reflection loss and its bandwidth increases. A maximum RL of -20.21 dB (corresponding to 99% power attenuation) at 9.46 GHz was observed for an average particle size of 240 nm.

The effect of doping cobalt in BaFe₁₂O₁₉ with chemical formula BaCo_xFe_{12-x}O₁₉ (x = 0, 0.2, 0.4, 0.6, 0.8 and 1.0) on radar absorption was investigated by Kumar et.al. [27] in 2013. The results inferred that the formation of second phase starts when x exceeds 0.6, but morphology of the particles does not change much with doping. The real part of both permittivity and permeability decrease with Co-doping, on the other hand imaginary part of permittivity and permeability increase. A maximum RL of -39.22 dB at 10.88 GHz has been observed with 1.34 GHz bandwidth (-20 dB level). It is also observed that the maximum value of both absorption and bandwidth increase with Co-doping.

Kumar et.al. [28] in 2013 studied the effect of particle size of SiC on the complex dielectric and microwave absorption properties at X-band. The values of RL and bandwidth increase with the reduction in particle size, but after 6 h of milling the value of RL decreases as the iron atoms start entering into crystal structure of SiC. However, with prolonged milling, as more iron enters into the SiC structure, complex permeability of sample slightly increases and therefore, RL increases.

In 2012 Kumar et.al. [29] studied the effect of particle morphology on microwave absorption, 20 h milled SiC was calcined at 1400 °C in N₂ atmosphere. The irregular shaped morphology of as-received SiC particles change to spherical after milling and then, the spherical shaped particles change to micro wire like structure after heat treatment. The complex dielectric properties enhance with the change in the morphology from irregular to spherical and from spherical to micro-wire like structure. Hence, as a result the microwave absorption enhances from -16.23 dB at 11.47 GHz (with irregular morphology) to -26.62 dB at 10.88 GHz (with spherical morphology) and -36.87 dB at 10.89 GHz (with micro-wire like morphology). This infers that the morphology also plays a significant role in radar absorption enhancement.

Kumar et.al. [28] in 2013 studied the effect of Al, Ni, Co, Cr, Mn, Ni, Ti and Zn metals dispersion in SiC matrix using mechanical alloying process for 10 h at 300 rpm. With the dispersion of metallic elements in dielectric matrix, complex permittivity of composite improves. The free electrons from the metallic particles increase the charge at the metal dielectric interface and raise the space charge polarization which affects the conductivity. Therefore, the complex permittivity values of the composites increases due to improved conductivity. In case of SiC, values of RL improved with all metal dispersions but maximum improvement is observed with Cr and Mn metal dispersion. The maximum value of RL for milled SiC is -15.94 dB at 10.3 GHz, which improves to a maximum value of -37.08 dB at 10.888 GHz and -43.35 dB at 10.3 GHz with a bandwidth of 3.024 GHz for Cr and Mn dispersion, respectively.

4.2. Development of Multi-layer Coatings

The multi-layering concept is very useful to achieve broadband characteristics. Apart from dielectric and magnetic losses, the multi-layer exhibits more amount of quarter wavelength destructive interference owing to multiple layers and hence gives much better absorption characteristics. However, application of the multi-layering concept needs optimization of the parameters such as

sequence of each layer, thickness of each layer using evolutionary optimization techniques such as particle swarm optimization (PSO), genetic algorithm (GA), etc. The steps for multi-layer parameters optimization has been shown in Fig. 3(a)

Kumar [30] has successfully employed GA to optimize various design parameters of the multi-layer absorber. The optimized results was simulated using high frequency structure simulator (HFSS). The results showed a maximum RL of -23.37 dB with 2.27 GHz bandwidth (-10 dB level) for two layer absorber (1.5 mm total thickness) and for three layer absorber a maximum RL of -25.64 dB with 2.86 GHz (-10 dB level) has been observed with a total thickness of 1.7 mm using optimized parameters. It has been observed from the experimental RL results that designed absorber with multi-layering provides better absorption and its broadband characteristic improves in comparison to single layer absorber at X-band.

4.3. FSS based Multi-layer Coatings

The implementation of FSS of different structure at the front end of the absorber provides better absorption at certain frequencies depending on the structure. The implementation of FSSs also needs the aid of GA to optimize its' various dimensions. The steps involved in FSS parameters optimization has been shown in Fig. 3(b). In 2012 Singh et.al. [31] showed that broadband characteristic enhances with the implementation of FSS structures. GA was employed to optimize the dimensions of various FSS structures and selection of better alternative absorber materials. The results also showed that the radar absorption behaviour is strongly affected by the FSS structure.

5. Conclusions

The concept of RAMs is vastly interdisciplinary, demanding the in-depth knowledge of materials engineering combined with the understanding of electromagnetics and materials design. This paper depicts the usefulness of metal particles doping and dispersion for enhanced radar absorption characteristics in ferrites and dielectric materials. Multi-layering and FSS based absorbers has been demonstrated as an integral tool to achieve broadband characteristics. The paper also demonstrated the usefulness of GA for optimization of the various FSS and multi-layer design parameters for achieving enhanced absorption with broadband characteristics.

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