

**Development of Optimization Techniques
for
Multilayered Metamaterial Structures**

*A Dissertation Submitted in Partial Fulfillment of the Requirement for the Award of the
Degree of*

MASTER OF ENGINEERING In

Electronics and Communication Engineering

Submitted By

Paramveer Kaur

Reg. No. 801561021

Under Supervision of

Dr. Rajesh Khanna

Professor

Dr. Ravi Panwar

Assistant Professor



ELECTRONICS AND COMMUNICATION ENGINEERING DEPARTMENT

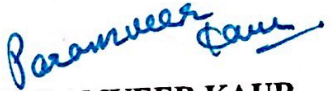
THAPAR UNIVERSITY, PATIALA, PUNJAB

JUNE, 2017

DECLARATION

I, **Paramveer Kaur**, hereby declare that the work presented in this thesis entitled "**Development of Optimization Techniques for Multilayered Metamaterial Structures**" in partial fulfillment of the requirement for the award of degree of Master of Engineering submitted at Electronics and Communication Engineering Department, Thapar University, Patiala is an authentic record of work carried out under the supervision of **Dr. Rajesh Khanna** (Professor, ECED, Thapar University, Patiala) and **Dr. Ravi Panwar** (Assistant Professor, ECED, Thapar University, Patiala). The present thesis has not been submitted either partially or fully to any other university or institute for the award of any other degree.

Date 13/07/2017


PARAMVEER KAUR
REG NO. 801561021

It is certified that the above statement made by the candidate is correct to the best of my knowledge and belief.



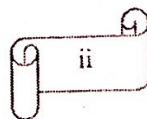
Dr. Rajesh Khanna
Professor
ECED, TU, Patiala

Date: 15/07/2017



Dr. Ravi Panwar
Assistant Professor
ECED, TU, Patiala

Date: 01/07/2017



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**PARAMVEER KAUR
(801561021)**

ABSTRACT

This thesis work aims to design and develop Optimisation Techniques for the development of Multilayered Metamaterial Structures. In the recent times, there have been a rise in the need of development of structures and materials which are able to provide Electromagnetic Shielding as these Electromagnetic devices not only interfere with communication devices, but have detrimental effects on the performance of many devices. Especially coming to the area of Stealth Technology, and improvement in the performance of various surveillance and communication devices, the Multilayered Metamaterial Structures are used and required not only to reduce interference between radar signals and surrounding structures like radar masts, but also to help reduce detection by hostile radars.

A number of approaches have been used for this traditionally such as Salisbury Screen, Jaumann Screen, Embedded single layer composite structures, however there is always an issue of trade-off between the reduced thickness of the absorber substance and the maximum absorption of incident EM wave. So multilayering of the composite substances in order to develop MMMS is one such effective technique which has recently been studied upon.

Optimisation Techniques are must for multilayering as number of parameters need to be optimally selected and modified for the development of a multilayered substance. These parameters include selection of materials from the database, their sequence on the conductive substance and the thickness of the layers.

This research aims to design such structures with the help of Genetic Algorithm and Particle Swarm Optimisation, which are thin enough to be practically implemented on the radars as well as should satisfy the requirement of high EM absorption in a wide range of frequencies, thus the design of a thin, cost-effective, broadband Multilayered Metamaterial Structure.

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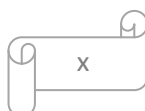
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LIST OF ABBREVIATIONS

MMMS	Multilayered Metamaterial Structures
EMI	Electromagnetic Interference
GHz	Gigahertz
RL	Reflection Loss
GA	Genetic Algorithm
PSO	Particle Swarm Optimisation
ANN	Artificial Neural Network
PEC	Perfect Electric Conductor
RCS	Radar Cross Section
FSS	Frequency Selective Surface
TE	Transverse Electric
TM	Transverse Magnetic
ATD	Absorber Testing Device
HFSS	High Frequency Structural Simulator
OF	Objective Function



CHAPTER 1

INTRODUCTION

In today's age of new Electromagnetic devices which require a high level electromagnetic compatibility (EMC) with all other devices in the electromagnetic environment, it has become highly imperative that the need is to develop and design EMI absorbing materials which should function reliably in all ranges of frequency, from kHz to GHz to micrometer and to millimetre waves range. The applications requiring microwave radiation reflection from surface are numerous. It can be microwave anechoic chambers, functioning in a confined space or surveillance radar systems at the sea. So the demands and requirements which are placed on MMMSs vary greatly according to the application, and there is no one structure and design for universal use.

Owing to the vast potential requirements and applications in Stealth Technology, MMMSs have been a topic of great interest among the researchers. According to the name, MMMSs are artificial man-made structures which are developed to have properties not found in natural materials[1]. They are developed from assemblies of number of elements made from composite materials which can be metals or plastics. These are arranged in repeating patterns, and the order of scales is smaller than the wavelengths of the processes they influence. These materials rather than deriving the properties from their base materials, derive them from the new designed and constructed structures. Some of the major applications of MMMS for EM Shielding include in the field of improvement of surveillance of radar systems, especially at the sea. It is often limited by return signals from nearby objects such as bridges. The improvement is made by coating these objects which results in such reflections with absorber materials. Another application is solving the issue of TV 'ghost images' in Japan, which occur due to multiple signal reflections from the buildings. Also, another important application is in the field of radar systems working in the X-band, i.e. in the frequency range from 8.2-12.4 GHz, are mainly considered as they have certain important advantages such as good resolution imaging and target identification with better precision. In this way, as this frequency range is focussed on in the stealth technology field, similarly the wider frequency range has its optimum use in the microwave shielding field.

1.1 MOTIVATION

The most important characteristics of a good absorber for stealth technology, along with being cost-effective, are minimum coating thickness ($\leq 1.5\text{mm}$) as well as wide bandwidth in the required frequency range, or that the reflection loss should be minimum ($RL \leq -10 \text{ dB}$). However it is a very challenging task to simultaneously achieve all these parameters together and often there is a trade-off between the coating thickness and bandwidth obtained [2]. As a solution to this problem, a lot of research has been conducted over Multilayered Metamaterial Structures [3], in which there are numerous numbers of layer boundaries and layer interfaces. The multi-layering phenomenon is a useful technique which is implemented by cascading multiple layers of various Metamaterial Structures, in order to minimise the reflections to a maximum extent. In such structures, multiple internal reflections take place at the multiple boundaries as well as there is increase in the number of interfaces due to which phase cancellation occurs, which increases the net absorption of the electromagnetic wave [4], which is demonstrated as follows that-

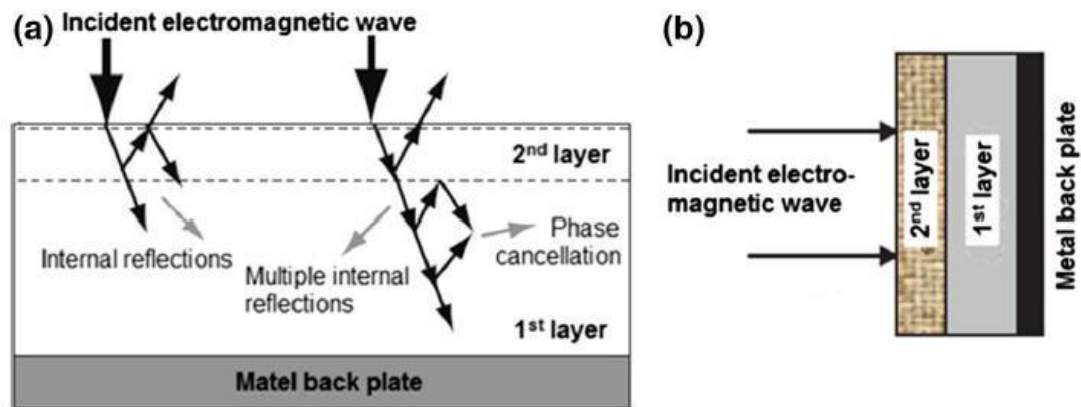


Fig. 1.1 a. Multi-layering phenomenon with double layers [5]

b. Schematic representation [5]

One of the most important requirements for multi-layering approach is to find Optimisation Techniques for solving multi-objective design problem like multi-layering. The optimization approach is needed for the selection of the best material(s) out of the database which is available, their sequential preferences and corresponding thicknesses. So multi-layering is a complex problem as all the various parameters play an equally important role in determining that the reflection of electromagnetic waves will be minimum, and that absorption will be maximum, over the desired bandwidth.

Over the years, a lot of different optimisation techniques have been studied and applied to the multi-layering of various forms of Metamaterial Structures. Majority of these being Genetic

Algorithm [2], [4], [6], Particle Swarm Optimisation [7]-[9], Central Force Optimisation [10], Self-adaptive Differential Evolution Algorithm [11] and Artificial Neural Networks [12], [13].

Also, another important consideration is the type of incidence of the EM wave on the absorbing structure. Owing to the properties and nature of EM waves, they behave differently depending on whether they strike the surface of Metamaterial Structures normally or in an oblique manner. While most of the research has been extensively done in the field of Normal Incidence, a lot of potential is tapped in oblique incidence as well.

1.2 KEY OBJECTIVES

The main aim of this research work is to design and optimise the structure for developing a multi-layered Metamaterial Structure which is cost effective, provides a wide bandwidth over the desired frequency range and also has minimum possible thickness of the coating structure. It aims to develop suitable optimisation techniques for normal as well as wide angle of incidences of EM wave, in order to simultaneously satisfy the conditions for a multi-layered absorbent structure to be used for practical purposes of stealth technology.

The outline of the thesis in order to study these challenges is as follows-

Chapter 2	Literature Review	Rigorous literature review for the research is presented. It shows the evolution of various methods used for RAM optimisation.
Chapter 3	Optimal Design Of Multilayered Structures For Normal Incidence	Detailed methodology and results of application of GA as well as PSO on multi-layered RAM is discussed and shown normal incidence, along with the detailed formulation of normal incidence.
Chapter 4	Optimal Design Of Multilayered Structures For Oblique Incidence	The detailed formulation and concept of oblique incidence and reflection is studied and optimisation using GA and PSO is studied. The results of both the techniques are compared and plotted.
Chapter 5	Future Scope	Summarising the entire research work, the future scope of the thesis study is presented.

Some of the important challenges inherent to developing a cost effective and broadband absorbent structure are as follows:

- Despite of the development and patent of a number of Metamaterial Structures, the development of a good absorption Metamaterial Structure, and still be cost effective, is a challenge.
- After multiple varieties of Metamaterial Structures developed by researchers, thickness-bandwidth trade-off still remains a challenge for developing a broadband Metamaterial Structure.
- In the employment of multi-layering techniques, issues such as number and sequence of layers of the structure, and their respective thicknesses pose a challenge to the research work.

1.3 EM THEORY FOR ABSORBER MATERIALS

Understanding the basic electromagnetic properties of metamaterial structures, which is based upon the multi-layering phenomenon, is the most basic requirements to design and develop novel metamaterial structures. Behavior of EM waves with such materials is related to the movement and propagation of free as well as bounded electrons, due to the Electric Field and also due to the changes in the orientation of atomic moments in space due to the effect of Magnetic Field. Now all these interactions are dominated and controlled by the following four Maxwell Equations, given as [14], [15]:

1. *Faraday's law of EM Induction:* It states that the electromotive force (emf) around a closed path is equal to the time derivative of the magnetic displacement through any surface bounded by the path:

$$\Delta \times E = -\frac{\partial B}{\partial t} \quad (1.1)$$

Writing in phasor notation-

$$\Delta \times E = -j\omega B \quad (1.2)$$

2. *Ampere's Law:* It states that magneto-motive force (mmf) around a closed path is equal to the conduction current plus the time derivative of the electric displacement through any surface bounded by the path:

$$\Delta \times H = J + \left(\frac{\partial D}{\partial t}\right) \quad (1.3)$$

Writing in phasor notation-

$$\Delta \times H = J + j\omega D \quad (1.4)$$

3. *Gauss law for electric field*: It states that the total electric displacement through the surface enclosing a volume is equal to the total charge within the volume:

$$\Delta \cdot D = \rho \quad (1.5)$$

4. *Gauss law for magnetic field*: The net magnetic flux emerging through any closed surface is zero:

$$\Delta \cdot B = 0 \quad (1.6)$$

Also, some other important relations are as follows [15]:

$$D = \epsilon E = (\epsilon' - j\epsilon'')E \quad (1.7)$$

$$B = \mu H = (\mu' - j\mu'')H \quad (1.8)$$

$$J = \sigma E \quad (1.9)$$

Here, E is the electric field strength vector, H is the magnetic field strength vector, D is the electric displacement vector, B is the magnetic flux density vector, J is the current density vector, ρ is the charge density, $\epsilon = \epsilon_0 \epsilon_r$ is the electric permittivity and $\mu = \mu_0 \mu_r$ is the magnetic permeability.

Here, ϵ_0 is the permittivity of the free space = 8.86×10^{-12} F/m. and μ_0 is the permeability of free space, whose value is $4\pi \times 10^{-7}$ H.

Now, as an oscillating electric field interacts with the dipole, the dipole rotates to align itself according to the polarity. During this process energy is lost through the generation of heat (friction) and the acceleration and deceleration of the rotational motion. The degree to which the dipole is out of phase with the incident electric field is a characteristic to the material and depends on frequency of the oscillating electric field, which determines the magnitude of the imaginary part of the permittivity. The larger the imaginary part, more the energy is being dissipated through the alignment motion and hence, less energy is available to propagate past the dipole. Thus, the imaginary part of the relative permittivity directly relates to loss in the system.

The Eq. (1.4) can be written as-

$$\Delta \times H = J + j\omega(\varepsilon' - j\varepsilon'')E \quad (1.10)$$

$$\Delta \times H = J + j\omega\varepsilon'(1 - j\frac{\varepsilon''}{\varepsilon'})E \quad (1.11)$$

Here the term $\tan\delta_E = \frac{\varepsilon''}{\varepsilon'}$ defines the electric loss tangent.

Now the two wave equations are [14]-

$$\Delta^2 E - \gamma^2 E = 0 \quad (1.12)$$

$$\Delta^2 H - \gamma^2 H = 0 \quad (1.13)$$

And,

$$\gamma = \sqrt{-\omega^2\varepsilon\mu} = j2\pi f/c\sqrt{\varepsilon\mu} = \alpha + j\beta \quad (1.14)$$

where γ is the propagation constant, α is the attenuation constant which defines the rate at which the fields of the electromagnetic wave attenuates as the wave propagates and β , is the phase constant defining the rate at which the phase changes as the wave propagates.

1.4 MATERIAL PROPERTIES

The most important parameters of the materials which credit for their absorbing features are the electric permittivity and the magnetic permeability. The permittivity is a measure of the material's effect on the electric field in the electromagnetic wave and the permeability is a measure of the material's effect on the magnetic component of the wave [16]. The permittivity is written as-

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \quad (1.15)$$

This arises from the dielectric polarization of the material. Here, ε' is called the Dielectric Constant of the material and ε'' measures the attenuation of the material. Also, greater is the electric loss tangent of the material, greater is the attenuation of the wave as it travels down the multiple layers of the MMMS.

In a similar fashion, we have the magnetic permeability of the material as-

$$\mu^* = \mu' - j\mu'' \quad (1.16)$$

Where the magnetic loss tangent is also defined in a similar way as-

$$\tan\delta_m = \frac{\mu''}{\mu'} \quad (1.17)$$

Here, the real part of the permeability defines the extent to which the material will be magnetised by the application of a magnetic field. The imaginary part is a measure of the energy losses incurred in re-arranging the alignment of the magnetic dipoles in that applied field. Now, the basic equation which is employed to evaluate how the absorption capability of the MMMS is affected by the dielectric parameters of the material is [17]-

$$A = \frac{1}{2}\sigma E^2 + \frac{1}{2}\omega\epsilon_o\epsilon_R E^2 + \frac{1}{2}\omega\mu_o\mu_R H^2 \quad (1.18)$$

Where,

- A (W/m³) is the electromagnetic energy absorbed per unit volume
- E (V/m) is the electric field strength of the incident electromagnetic radiation
- H (A/m) is the magnetic field strength of the incident electromagnetic radiation
- σ (S/m) is the conductivity of the material
- ω (sec⁻¹) is the angular speed of the electromagnetic wave

and the rest of the parameters have already been described previously.

Now this equation clearly shows that the attenuation and absorption of microwave energy in an MMMS is dependant on the conductivity, dielectric loss, and/or magnetic loss of the absorber material.

1.5 REFLECTIVITY MINIMIZATION

There are most importantly three conditions that can be satisfied in order to ensure that minimum reflection of the EM wave incident on the surface of the MMMS takes place. The reflection coefficient is written as[18]-

$$r = \frac{Z_M - Z_o}{Z_M + Z_o} \quad (1.19)$$

Now, these conditions are described briefly as follows [16]-

- *Impedance Matching:* The Reflection Coefficient which is used to calculate the Reflection Loss, falls to zero as $Z_o = Z_M$ i.e. as the impedance of the

multilayered structure becomes equal to the free space impedance. The free space impedance is equal to 377 ohms, so a material having an impedance of 377 ohms will not reflect the incident wave, if the incident medium is free space.

- *Electric Permittivity = Magnetic Permeability*: Rewriting Eqn. (1.19) as follows-

$$r = \frac{\frac{Z_M}{Z_o} - 1}{\frac{Z_M}{Z_o} + 1} \quad (1.19)$$

Now, normalised input impedance is equal to-

$$\frac{Z_M}{Z_o} = \sqrt{\frac{\mu^*}{\epsilon^*}} \quad (1.19)$$

The implication is if both the real and imaginary parts of the permittivity and permeability are equal, then the reflectivity coefficient is zero.

- *Attenuation of Wave*: For large values of attenuation, large values of permittivity and permeability would also be required, which would in turn result in a large value of reflection coefficient. So a trade-off must be made between the values of Reflection Coefficient and the Attenuation of the wave.

1.6 OPTIMIZATION OF MMMS

1.6.1 Heuristic Algorithms

Various heuristic algorithms have been developed for solving combinatorial and numerical optimization problems [19]. Further depending on the criteria which is considered, these algorithms are divided into separate groups like population based, stochastic based, iterative, random etc. Population based works on a set of solutions and tries to solve them, while the one that uses multiple iterations to reach to a single solution is called an iterative algorithm. Similarly an algorithm employing a probabilistic solution for improving a solution is called stochastic or probabilistic.

Another important distinction is made on the basis of phenomenon demonstrated by the algorithm, owing to which there are basically two types- Evolutionary and Swarm Intelligence.

1.6.2 Methodology and Database

The most basic requirement of any optimization algorithm is the material database, out of which the required number and types of materials will be selected according to the requirement of the application. In this case, out of the database the best suited composite materials will be selected for the microwave absorbing structure based on their EM properties. The database selected for this research work is described as follows-

Lossless Dielectric Materials ($\mu_r=1.+j0.$)		
#	ϵ_r	
1	10+j0.	
2	50+j0.	
Lossy Magnetic Materials ($\epsilon_r=15.+j0.$)		
$\mu=\mu_r-j\mu_i \quad \mu_r(f)=\frac{\mu_r(1GHz)}{f^\alpha} \quad \mu_i(f)=\frac{\mu_i(1GHz)}{f^\beta}$		
#	$\mu_r(1GHz), \alpha$	$\mu_i(1GHz), \beta$
3	5., 0.974	10., 0.961
4	3., 1.000	15., 0.957
5	7., 1.000	12., 1.000
Lossy Dielectric Materials ($\mu_r=1.+j0.$)		
$\epsilon=\epsilon_r-j\epsilon_i \quad \epsilon_r(f)=\frac{\epsilon_r(1GHz)}{f^\alpha} \quad \epsilon_i(f)=\frac{\epsilon_i(1GHz)}{f^\beta}$		
#	$\epsilon_r(1GHz), \alpha$	$\epsilon_i(1GHz), \beta$
6	5., 0.861	8., 0.569
7	8., 0.778	10., 0.682
8	10., 0.778	6., 0.861
Relaxation-type Magnetic Materials		
$\mu=\mu_r-j\mu_i \quad \mu_r=\frac{\mu_{rm}f_m^2}{f^2+f_m^2} \quad \mu_i=\frac{\mu_{rm}f_m f}{f^2+f_m^2} \quad (f \text{ and } f_m \text{ in GHz})$		
#	μ_{rm}	f_m
9	35.	0.8
10	35.	0.5
11	30.	1.0
12	18.	0.5
13	20.	1.5
14	30.	2.5
15	30.	2.0
16	25.	3.5

Fig. 1.2 Parameters of 16 different materials in the database [3]

The materials in this database are fictitious, but the study is useful as they represent a wide class of RAMs. There are three different types of materials in this database:

- Material 1-2: Lossless dielectrics with frequency-independent permittivity
- Material 3-5: Lossy magnetics, specified through their permittivity.
- Material 6-8: Lossy dielectrics, specified through their permeability.
- Material 9-16: Lossy magnetics with a relaxation type characteristic, defined through their real permeability at dc and permittivity is always equal to $15+j.0$

For instance, on plotting the graph of permittivity of Material 7, we get:

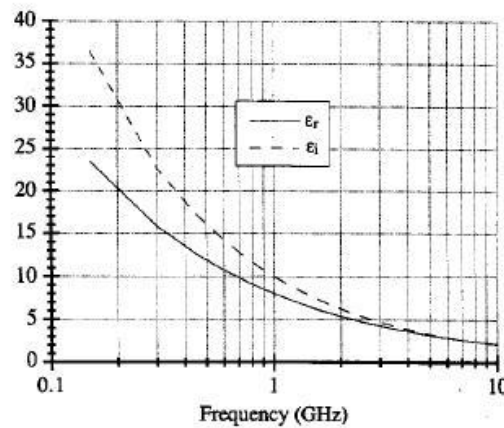


Fig. 1.3 Permittivity of Material 7 versus Frequency [3]

On plotting the permeability of material 11, we get:

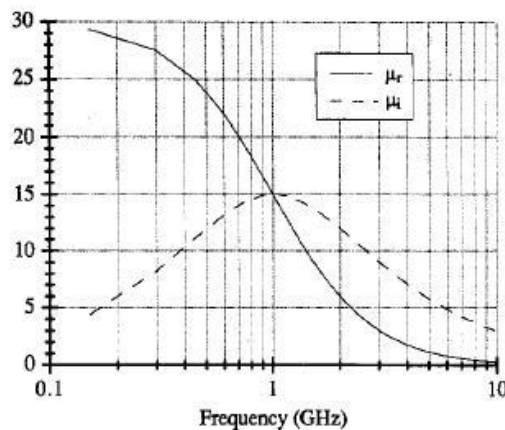


Fig. 1.4 Permeability of Material 11 versus Frequency [3]

1.7 GENETIC ALGORITHMS

1.7.1 Principles of GA

GA is an optimization technique which effectively searches for global maxima in a domain which consists of number of dimensions as well as is multimodal. Being an iterative

optimisation technique it begins with a random generation and selection of population of particles, which are potential solutions and slowly converge towards solutions which give better performance using genetic operators, such as selection, crossover and mutation. This optimisation method is different from others techniques because it uses coded parameters which are also discrete in nature. Also, operators which guide the potential solutions such as crossover and mutation, induce probabilistic rather than deterministic transitions. As a result of these features, the algorithm successfully converges to a global solution rather than getting stuck in local values which are also called local maxima.

The table showing the flow process of GA is as follows:

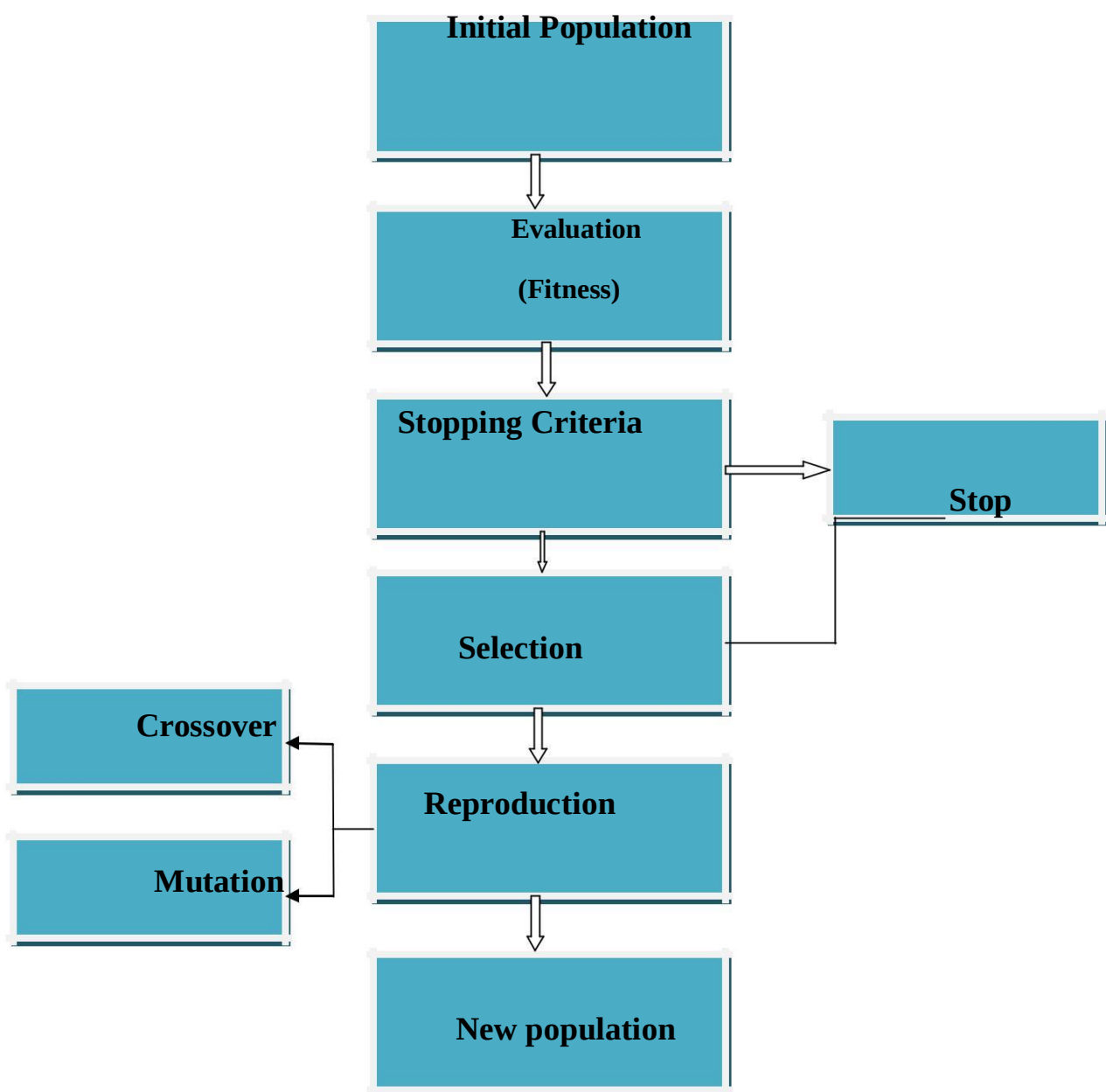


Fig. 1.5 Flow process of GA

1.7.2 MMMS Optimization using GA

GA greatly simplifies the multilayered absorber fabrication by simultaneously determining the optimal composite for each layer, layer preferences and corresponding thicknesses. The main aim of designing using this optimisation method is to evaluate the feasibility and use of developing and designing practical multilayered absorbing structures by combining heterogeneous composite RAMs having variable EM properties. Therefore, keeping in mind the practical implementation of the research work, a coating thickness constraint of 2.0 mm or less is employed. Also, the maximum number of layers have been studied for 2 and 3.

- Step 1: The database of a number of materials having different properties is prepared.
- Step 2: Upper and lower bounds to the thickness are applied.
- Step 3: The fitness function programs are written in MATLAB 12 and different parameters are optimized using the GA tool 'gatool' using 'gamultiobj'. The fitness function used is given as-

$$RL = |RL_{\text{calculated}} - RL_{\text{observed}}|^2$$

Here RL_{observed} is the required value of reflection loss which is ≤ -10 dB in this case.

1.8 PARTICLE SWARM OPTIMIZATION

1.7.1 Principles of PSO

PSO was originated and introduced by Edenhart and Kennedy in 1995. It is an evolutionary algorithm entirely based on the principle which defines how natural organisms like insect swarm, herds of animals and fishes look for their food [20]. Every member in the group changes the look pattern for food, on the basis of its own experience and also with the help of that of other members in the group or herd. While doing the mathematical modeling of this phenomenon, every member of the group is called a Particle, where it stand for a possible solution in the space consisting of D dimensions. The global optimum is taken to be the location of food. The fitness value of the particle as well as its velocity determine the direction of flying of the particle. The algorithm does so by determining it from the best experiences of the whole flock. The PSO algorithm [21] has easy execution and has performed well on a large number of optimization problems.

The fundamental steps and equations involved in the execution of PSO are explained as follows [21]:

- Step-1: The algorithm executes for N trials, which are independent of each other, also using an entirely different population each time. A random population ($P * D$) of P points and D dimensions is created at the beginning where each particle is constrained to some range.
- Step-2: Initial velocity and position are randomly generated for each particle in the beginning.
- Step-3: Next, for each particle a fitness value is also calculated using the objective function.
- Step-4: pbest of every particle is then compared to the present fitness value. In case the latter is better, it is assigned as the updated pbest of the particle. The coordinates of the particle pbest are also updated.
- Step-5: After this, determination of the most fit current value out of all the particles, along with the coordinates is done. Here also, if it is better than the gbest of the system, then again updation is done of gbest along with change of its coordinates.
- Step-6: The major equations used to update the Velocity (V_{id}) and position (X_{id}) of the i -th particle are:

$$V_{id}^t = w * V_{id}^{t-1} + c_1 * rand1_{id}^t * (pbest_{id}^{t-1} - X_{id}^{t-1}) + c_2 * rand2_{id}^t * (gbest_d^{t-1} - X_{id}^{t-1})$$

$$V_{id}^t = \min \left(V_{\max}^d, \max \left(V_{\min}^d, V_{id}^t \right) \right)$$

$$X_{id}^t = X_{id}^{t-1} + V_{id}^t$$

If $X_{id}^t > X_{\max}^d$, then,

$$X_{id}^t = X_{\min}^d + rand3_{id}^t * (X_{\max}^d - X_{\min}^d)$$

If $X_{id}^t < X_{\min}^d$, then,

$$X_{id}^t = X_{\min}^d + rand4_{id}^t * (X_{\max}^d - X_{\min}^d)$$

Fig. 1.6 Set of equations for implementation of PSO [21]

where c_1, c_2 = acceleration constants, w = inertia weight, $rand1, rand2, rand3$ and $rand4$ are used to express the uniform random numbers [58] between 0 and 1, which have different expressions in each dimension, and t represents the current iteration number.

- Step-7: The above steps are executed again till the system meets a predefined criteria to stop the execution. It also happens when all the iterations are completed.
- Step-8: Again, all the above steps are executed again till all the defined number of trials have been executed. At the last, out of all the gbest of each trial, the one with maximum value is taken as the final answer.

1.7.2 MMMS Optimization using PSO

For the application of PSO to our problem of multilayered RAM, an initial population of 30 particles is considered. The dimensions vary according to the number of layers in the multilayered structure. Both the acceleration constants c_1 and c_2 are set to a value of 1.4945, which remain constant in case of each iteration. The value of w is set to 0.8 which is also constant [21]. In the similar manner, the maximum particle velocity is also kept fixed for all runs. The constraint on maximum layer thickness is 1.5 mm. In every run, the number of trials are 20, and 700 iterations are executed.

As we know that the major aim of the research is to choose a given number of materials from a given material database, as explained in chapter 3, where the materials have different electrical properties, so as to obtain the goal of minimizing the total maximum reflection coefficient ($R_{0,1}$) of the absorber over the required set of frequencies, for normal incidence, and also the same for oblique incidence as well as all different polarizations. Along with this, the total thickness of the absorber should also be as low as possible. So keeping in mind these considerations, the objective function that is used for this research work is defined as follows:

$$\text{Minimum } f = \tau * 20 \log_{10}(\max |R_{0,1}|) \quad (1.20)$$

The goal of this fitness function is to minimize the weighted sum of overall maximum reflection coefficient of RAM over the required range of frequencies, for a given angle of incidence .

CHAPTER 2

LITERATURE REVIEW

This chapter is comprised of brief literature review carried out in the research area of radar wave absorption, with emphasis on composite multi-layered RAMs and the various optimisation techniques used for the designing of the same. All the results have been discussed pertaining to maximum RL values, -10 dB bandwidth and the total coating thickness.

2.1 HISTORY

RADAR stands for Radio Detection and Ranging, and they have numerous applications in engineering, especially considering the microwave band [22]. Exploitation of RAM began in the 1930s, soon after the invention of RADARs, the first patent appeared in 1936 in the Netherlands [23]. For reducing thickness, it used high permittivity Titanium dioxide and was structurally quarter-wave resonant type, which used carbon black as a lossy resistive material.

With the development of “Wesch” material by Germany, concerned with radar camouflage for submarines, the research started and they also produced a Jaumann absorber, which consisted of resistive sheets and rigid plastic. In the 1950s, commercial RAM called Spongex was produced, consisting of carbon coated animal hair. Resonant Salisbury Screen was also developed around the same time with about 25% bandwidth at resonance [24]. It consisted of resistive sheet which is kept at quarter wavelength distance from the scatterer, and a low dielectric constant material is kept in between. Also, dallenbach absorber based resonant absorber composed of a homogeneous lossy layer on a metal sheet has been reported [25].

The numerical analysis and optimization of anechoic chambers for EMI testing was also carried out [24]. The use of absorbent coating on the walls of anechoic chambers and on the exterior surfaces of military appliances can provide radar invisibility [25]. To increase the absorption over lower thickness of the absorbent, circuit analog absorbers, consisting of R, L and C were used [26]. The use of ferrites in 1960 turned out to be limited because of their large density. Later it was found that biotech products can provide broadband absorption characteristics, and so ferrite, carbon CNTs, graphene, SiC, Ti and other absorbers were studied. However, there is a strong need to concentrate over absorption enhancement approaches like multi-layering and fractal FSSs.

2.2 MULTI ELEMENT COMPOSITE RAMs

The theoretical design of a thin absorbent material over any required bandwidth range is easily possible to provide the desired absorption. However the practical implementation of it brings several difficulties. Ideally, there is strong need to have a control over the material EM parameters like ϵ , μ and $\tan\delta$ etc.

In **1979, Knott et al.** [29] showed that for single layer radar absorber which is dominantly magnetic in nature, there is no restriction of quarter wavelength thickness, and the required thickness may exceed a half-wavelength. It depends on the relative proportions of the dielectric and magnetic properties, and if magnetic properties are dominating, the thickness of the absorber can even exceed a half-wavelength.

In **1986, Varadan et al.** [30] showed that magnetite (Fe_3O_4) may act as good RAM owing to its high dielectric and magnetic loss tangent values. He discussed a reliable theoretical modeling of microwave absorption in a Fe_3O_4 -plastic composite, where Fe_3O_4 particles were randomly distributed in plastic (PVC). In the result, reflection coefficient has been found to decrease as a function of frequency, but showed high performance in lower frequency range due to high volume fraction of magnetite particles.

In **2000, Björkvall et al.** [31] presented the thermodynamic description of the three composites and showed that flash method can be appropriately used to measure their thermal diffusivities.

In **1996, Sang et al.** [32] showed a novel method for the computation of complex permittivity and permeability spectra of MnZn ferrite-rubber composite with different ferrite volume fractions in the range of 0.8 to 12 GHz. The absorption is found to improve from -5 dB to about -40 dB with a corresponding increase in the ferrite volume fraction for $v_f \leq 0.26$, and about -40 dB for $v_f \geq 0.26$.

In **2010, Cao et al.** [33] presented the effect of temperature and frequency electromagnetic coupling and shielding and absorption in microwave range of short carbon fiber/silica composites. Excellent RL characteristics of composites were observed, but the peak RL value has been noticed at approximately 4.5 mm coating thickness. Also, the strong RL value reaches -17.2 dB at 6.2 GHz with the optimal thickness of 5.5 mm for paraffin-based composites.

2.3 MULTILAYERED RAMs

The single-layered RAMs which were studied for a long time suffered heavily from the thickness-bandwidth trade-off. So multi-layered structures were studied and for that optimization algorithms are necessary. This optimization of multilayered structures requires a deep knowledge of the EM parameters like ϵ and μ etc. The EM properties of the composites in different layers and their thicknesses need to be selected to provide a minimum reflection of the incident power over a broad bandwidth and lower coating thickness.

In 1997, **Miyata et al.** [34] showed a 3 mm thickness absorber consisting of aligned thin magnetic metal particles. It possesses a strong RL of over -30 dB in the microwave region of frequency, which was 5% of the total volume.

In 1996, **Michielssen et al.** [35] applied the concept of Pareto optimality to the study of choice tradeoffs between reflectivity and thickness in the design of multilayer microwave absorbers. Three types of Pareto genetic algorithms for absorber synthesis are introduced and compared to each other. They are applied to construct Pareto fronts for RAM with five layers of materials selected from a representative database of available materials in the 0.2-2 GHz, 2-8 GHz, and 9-11 GHz bands.

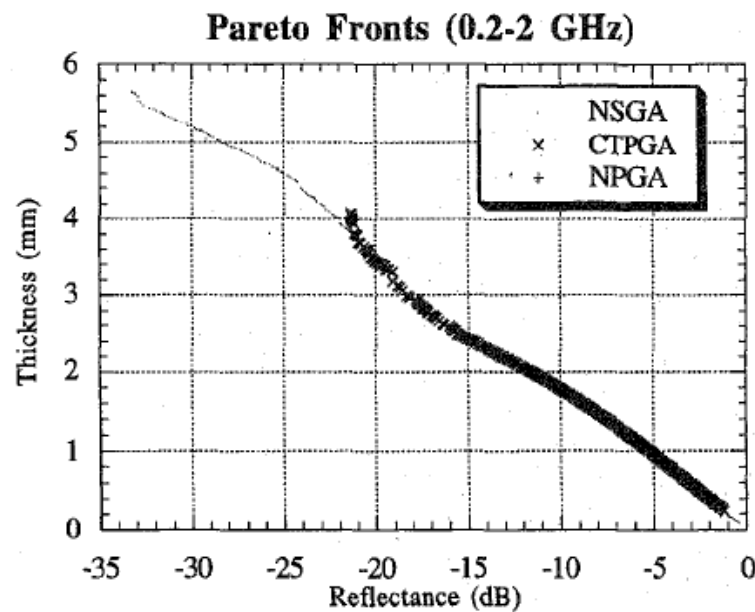


Fig. 2.1 Pareto fronts obtained in 0.2-2 GHz band [35]

In **1993, Michielssen et al.** [2] presented a novel procedure for the synthesis of Multilayered RAM. It selects the material choice and also the thickness out of N materials. It effectively absorbs TE and TM wave in a given frequency range and for prescribed angles of incidence. The technique is based on GA placing an upper bound on number of layers and their thickness as well. It was applied to structures working on frequency range from 0.2-2 GHz and 4-8 GHz.

In **1992, Pesque et al.** [3] developed an optimal control method to create an absorber with an not predefined number of layers. The results are compared with those designed by using the Simulated Annealing method. The results are proven to be superior than traditional methods, such as dallenbach and jaumann screens.

In **2004, Neo et al.** [36] composite microwave absorber using carbon fibers was presented and optimised. The designing was based on the modulus of permittivity, method obeying logarithmic law of mixtures while linear law of mixtures dominate the dielectric loss tangents. Data points are analysed using linear regression, a method which is used to predict effective permittivities at different frequencies.

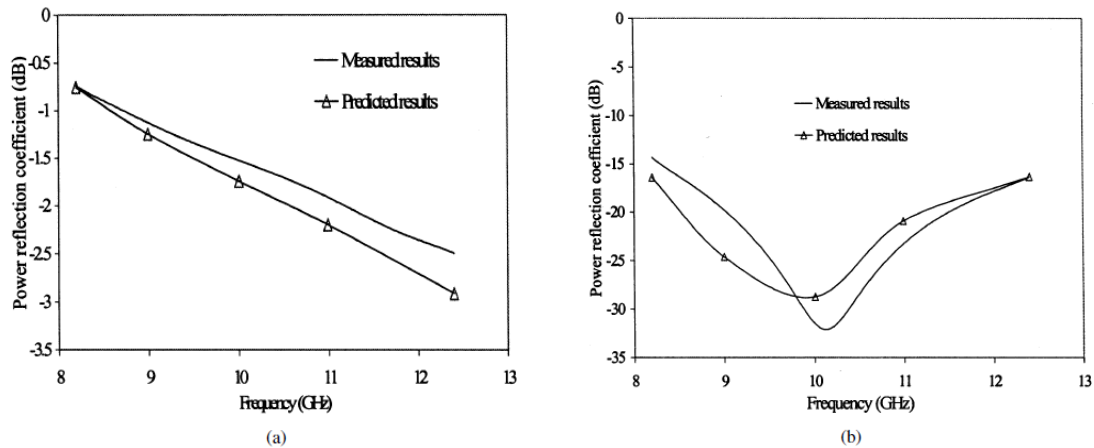


Fig. 2.2 a) τ of Single carbon composite layer absorber [36]

b) τ of Double layered absorber [36]

In **1993, Shin et al.** [37] studied the microwave absorbing characteristics of ferrite absorbers, and also the complex permeability dispersions. Plotting the measured complex permeability loci on the impedance matching solution map generates the theoretical matching frequencies. The results discussed show that 1st matching frequency of the ferrite

absorber strongly depends on its spin resonance frequency and the 2nd matching frequency is independent of the resonance frequency.

In **1989, Musal et al.** [36] presented a design of effective broad-band, thin layer, electromagnetic absorbers which shows the required results in the VHF/UHF frequencies. The design made ensures theoretically that there will be zero specular reflection.

In **2004, Park et al.** [37] presented a design technique which reduced the cross section of complex targets, so as to optimally design an absorber in wideband frequencies. GA and high frequency methods such as PO (physical optics), MEC (method of equivalent circuits) are combined for this. However as a form of pre processing, this high-frequency method needs a classification of shadow regions, for which A Z-buffer algorithm is used optimally.

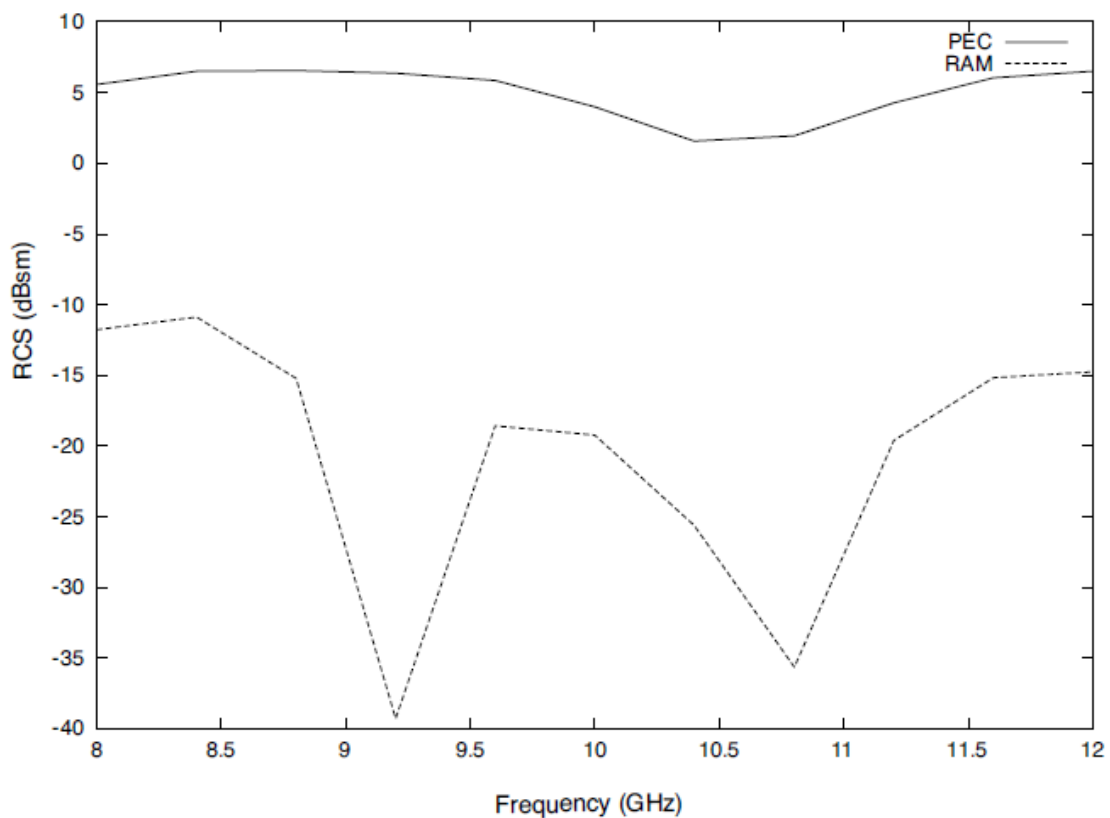


Fig. 2.3 Comparison of RCS between PEC and RAM, for angle=270 [37]

The results show a much higher absorption for multilayered RAM as compared to when a single conductor is used.

In **2006, Cui et al.** [38] presented a novel absorber made of lossy material by drilling holes in it. Next, GA is employed to reduce reflectivity to achieve maximum absorption over

wider bandwidth. The results using this method outperform the traditional absorbers made using embedded FSS.

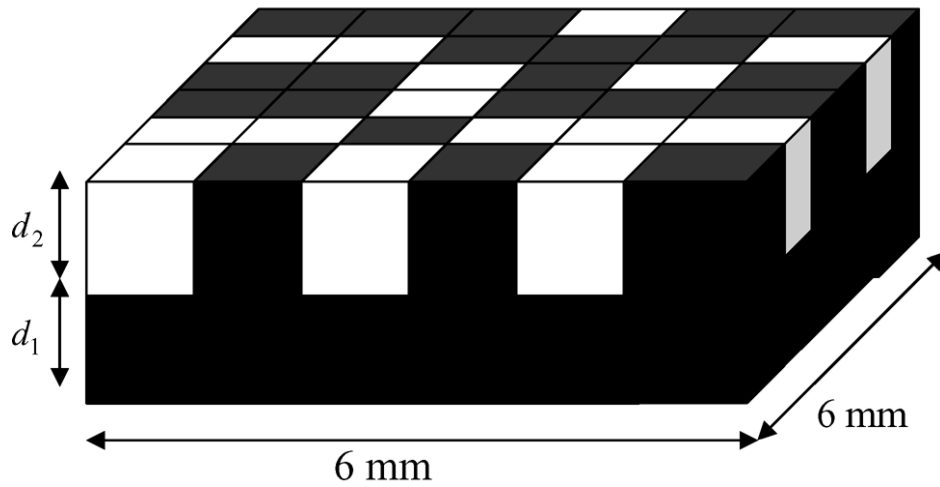


Fig. 2.4 Dual layer textured absorber model with holes partly drilled [38]

Even for wide angle of incidences, and both TE and TM mode, the drilled absorber shows much better values of absorbed power as compared to FSS absorber.

In 2006, **Guodos et al.** [7] employed multiobjective particle swarm optimization (MOPSO) for designing multi-layered planar multilayer coatings over vast range of frequencies and angles. It is pareto PSO algorithm whose results are also compared with multiobjective GA.

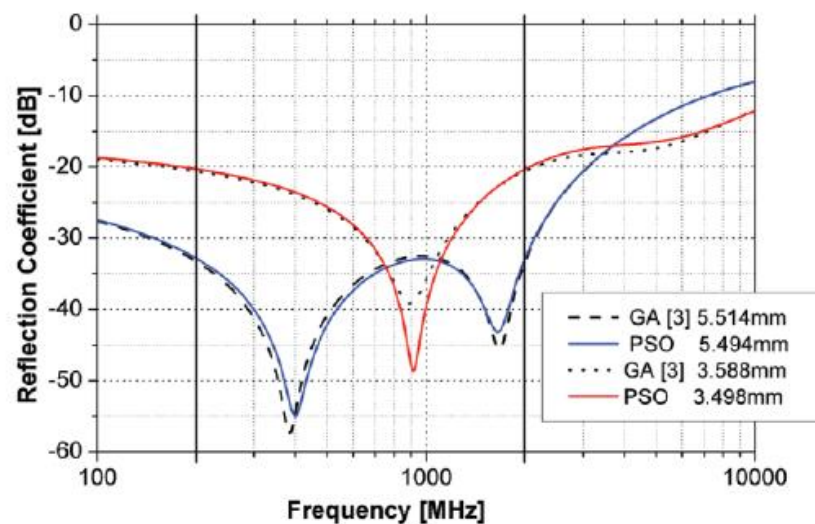


Fig. 2.5 Five layer absorber for normal incidence [7]

It can be seen that MOPSO performs than its GA counterpart, both in terms of thickness of the multi-layered RAM as well as the Reflection Coefficient.

In 2007, **Parida et al.** [39] employed GA to select the ferrite materials and choose the layer thicknesses to reduce RCS at X- band frequencies. A relationship is developed between μ and f , as well as ϵ and f , in order to better implement GA and maximise absorption and minimise reflectivity. An upper bound is placed on total thickness of the RAM as well as on the required number of layers, thus simplifying the process of optimisation. Also experimental validation has been done using ATD at X-band in an anechoic chamber.

In 2008, **Chamaani et al.** [8] demonstrated the effectiveness of the PSO algorithm by optimizing three different design cases. 4 variants of PSO are used, called global PSO (gbest), local PSO (lbest), comprehensive learning PSO (CLPSO), and modified local PSO (MLPSO).

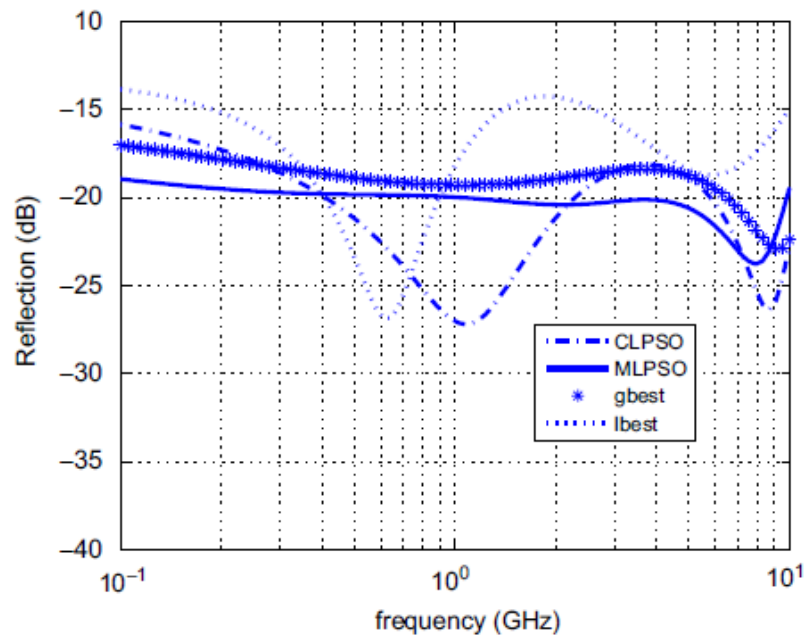


Fig 2.6 Five-layered RAM optimised using 4 variants of PSO [8]

Results show the best performance of MLPSO in a 5-layered structure, which has a reflection coefficient below 18.7 dB from VHF to 20 GHz.

In 2014, **Panwar et al.** [40] employed GA and validated the results with the help of ATD and Ansoft HFSS. For the composition, magnetic ceramic based nano-composites are used at X-band. The result is a peak value of reflection loss is -24.53 dB for 1.3 mm absorber layer coating thickness.

In 2016, **Mohd. et al.** [41] used Fe and Al metal powders to design a cost effective wideband multi-layered absorber. ANN was employed in order to optimise the design structure of the RAM.

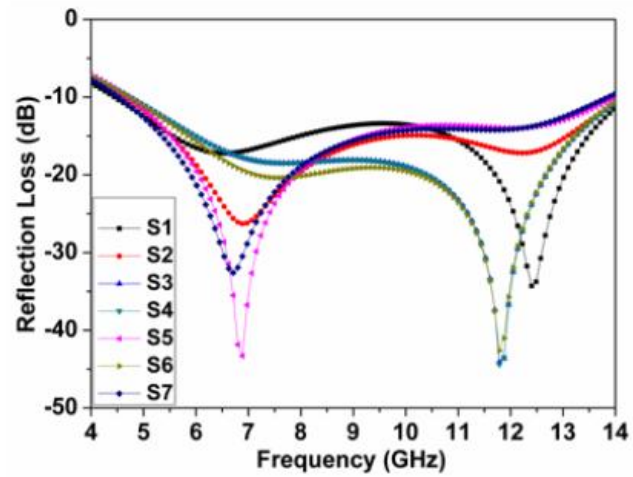


Fig. 2.7 Variation of frequency with RL for 2-layered absorbers using ANN [40]

The results show that with the use of ANN, the total coating thickness is reduced from 3 mm to 1.5 mm, which is very encouraging for its optimum use in stealth technology.

CHAPTER 3

OPTIMAL DESIGN OF MULTILAYERED STRUCTURES FOR NORMAL INCIDENCE

As it has been stated and explained that the major factors such as better impedance matching, numerous layer discontinuities coupled with more efficient loss mechanisms, play a much important role in establishing that multi-layered metamaterial structures provide much more efficient wave absorption characteristics as compared to single layered structures.

3.1 THEORETICAL BACKGROUND

The case of Normal Incidence of the EM wave on the MMMS surface is considered here. In this scenario, the incoming EM wave strikes the air-MMMS interface normally, and then according to the transmission line theory, the three of transmission, reflection and absorption of the EM wave take place[43]. In order to mathematically study the normal incidence of the wave on the MMMS surface, we consider the following figure where a schematic structure of k-layered MMMS is shown where the thickness of each i th layer is t_i , dielectric permittivity ϵ_i and magnetic permeability has value μ_i .

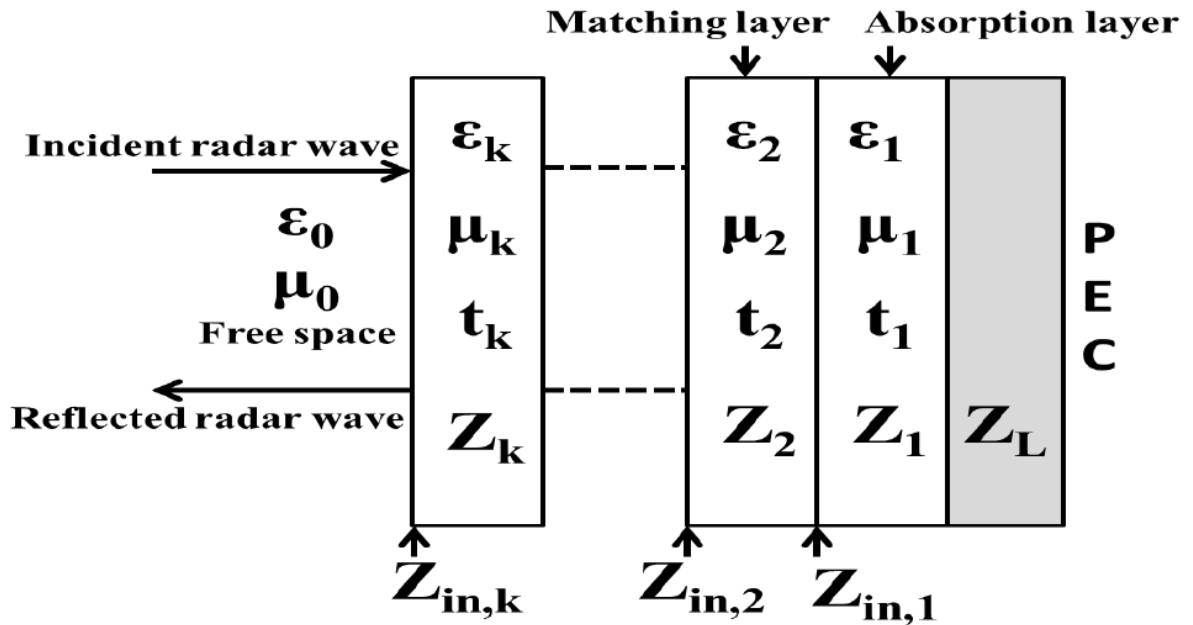


Fig. 3.1 Schematic of multilayered RAM backed by PEC [44]

In the case of incidence where the uniform plane wave, that is propagating along the Z axis with electric field is parallel to X-axis and the magnetic field is parallel to Y-axis, is normally incident on the air interface of the MMMS, then the EM wave and MMMS interaction leads

to a series of waves which are transmitted in +Z direction and also simultaneously reflected waves back in -Z direction. This reflection of the wave occurs within all the absorbing layers of the MMMS.

Also, the above figure shows that the absorption layer lies between the PEC and all the matching MMMS layers (k-1). Let ϵ_0 and μ_0 denote the permittivity and permeability of free space, respectively. Now, for normal incidence, the reflection coefficient (Γ) of this multilayered RAM backed by a PEC can be written as [15]-

$$\tau = \frac{Z_{in,k} - Z_0}{Z_{in,k} + Z_0} = \frac{\sqrt{\frac{\mu_k}{\epsilon_k}} \tanh(\gamma_k t_k) - 1}{\sqrt{\frac{\mu_k}{\epsilon_k}} \tanh(\gamma_k t_k) + 1} \quad (3.1)$$

The wave impedance $Z_{in,k}$ at the surface of k th layer is given by [9]-

$$Z_{in,k} = \frac{Z_{in,k-1} + Z_k \tanh(\gamma_k t_k)}{\left(Z_{in,k-1} / Z_k \right) + \tanh(\gamma_k t_k)} + 1 \quad (3.2)$$

Now, the impedance of the metal sheet is zero (i.e., $Z_L = 0$). So impedance at the interface of RAM and free space for single layer can be written as-

$$Z_{in,1} = Z \tanh(\gamma_1 t_1) = Z_0 \sqrt{\frac{\mu_1}{\epsilon_1}} \tanh(\gamma_1 t_1) \quad (3.3)$$

So, the reflection coefficient (Γ) for single layer absorber at the free space and a heterogeneous composite interface is [24]-

$$\tau = \frac{Z_{in,1} - Z_0}{Z_{in,1} + Z_0} = \frac{\sqrt{\frac{\mu_1}{\epsilon_1}} \tanh(\gamma_1 t_1) - 1}{\sqrt{\frac{\mu_1}{\epsilon_1}} \tanh(\gamma_1 t_1) + 1} \quad (3.4)$$

In the similar manner, the reflection coefficient (Γ) for two layer absorber (i.e., $k=2$), where layer 1 is backed with perfect conductor and second layer is in contact with free space can be given as [45]-

$$\tau = \frac{Z_{in,2} - Z_0}{Z_{in,2} + Z_0} = \frac{\frac{\sqrt{\frac{\mu_1}{\epsilon_1}} \tanh(\gamma_1 t_1) + \sqrt{\frac{\mu_2}{\epsilon_2}} \tanh(\gamma_2 t_2)}{1 + \sqrt{\frac{\mu_1}{\epsilon_1}} \tanh(\gamma_1 t_1) \sqrt{\frac{\mu_2}{\epsilon_2}} \tanh(\gamma_2 t_2)} - 1}{\frac{\sqrt{\frac{\mu_1}{\epsilon_1}} \tanh(\gamma_1 t_1) + \sqrt{\frac{\mu_2}{\epsilon_2}} \tanh(\gamma_2 t_2)}{1 + \sqrt{\frac{\mu_1}{\epsilon_1}} \tanh(\gamma_1 t_1) \sqrt{\frac{\mu_2}{\epsilon_2}} \tanh(\gamma_2 t_2)} + 1} \quad (3.5)$$

$$Z_{in,2} = \frac{Z_{in,1} + Z_2 \tanh(\gamma_2 t_2)}{\left(\frac{Z_{in,1}}{Z_2}\right) + \tanh(\gamma_2 t_2)} + 1 \quad (3.6)$$

$$Z_2 = Z_0 \sqrt{\frac{\mu_2}{\epsilon_2}} \quad (3.7)$$

where Z_2 is impedance of second layer for two layer absorber.

The same analogy can be easily extended to n number of layers of the MMMS. However in order to ensure that the research work is also valid and useful for the practical implementation, to real world materials, structures and atmospheric conditions, we limit our research to a maximum of three layers. It is done so as a MMMS consisting of 3 layers can be practically designed, developed and implemented in the required geometry and under the atmospheric conditions as well.

So, the reflection coefficient of three layer absorber (i.e., $k=3$), where the first layer is backed with PEC, second layer is backed with the first layer and the third layer is in contact with free space can be found in the similar manner.

In this case the impedance of the third layer is given as-

$$Z_{in,2} = \frac{Z_{in,2} + Z_3 \tanh(\gamma_3 t_3)}{\left(\frac{Z_{in,2}}{Z_3}\right) + \tanh(\gamma_3 t_3)} + 1 \quad (3.8)$$

$$Z_3 = Z_0 \sqrt{\frac{\mu_3}{\epsilon_3}} \quad (3.9)$$

$$\tau = \frac{Z_{in,3} - Z_0}{Z_{in,3} + Z_0} = \frac{\frac{\frac{\sqrt{\frac{\mu_1}{\varepsilon_1}} \tanh(\gamma_1 t_1) + \sqrt{\frac{\mu_2}{\varepsilon_2}} \tanh(\gamma_2 t_2)}{1 + \sqrt{\frac{\mu_1}{\varepsilon_1}} \tanh(\gamma_1 t_1) \sqrt{\frac{\mu_2}{\varepsilon_2}} \tanh(\gamma_2 t_2)} + Z_3 \tanh(\gamma_3 t_3)}{\frac{\sqrt{\frac{\mu_1}{\varepsilon_1}} \tanh(\gamma_1 t_1) + \sqrt{\frac{\mu_2}{\varepsilon_2}} \tanh(\gamma_2 t_2)}{1 + \sqrt{\frac{\mu_1}{\varepsilon_1}} \tanh(\gamma_1 t_1) \sqrt{\frac{\mu_2}{\varepsilon_2}} \tanh(\gamma_2 t_2)} - Z_0} \quad (3.10)$$

Now, based on these equations the *RL* for multilayered absorber can be expressed as [24]-

$$RL(dB) = -20 \log_{10} |\tau| \quad (3.11)$$

3.2 RL ANALYSIS OF DOUBLE LAYER STRUCTURES FOR NORMAL INCIDENCE

Having stated and understood the mathematical formulation of normal incidence of the EM wave on the MMMS, we now implement the previously explained optimization techniques to the database of different materials that we have considered. Both GA and PSO have been implemented on the database, under the required constraints of less than 2 mm thickness, bandwidth ≤ -10 dB over a wide range of frequencies.

In this section, the 2-layered MMMS is considered. So Eqn. 3.5-3.7 are used in order to calculate the Refection Loss for the MMMS under normal incidence of the EM wave. For a 2- layered MMMS, there will be 4 design parameters, i.e. two materials out of the 16 material database and their corresponding thicknesses.

The optimum results of both GA and PSO when applied to the database of materials are shown in the table below. Out of multiple solutions in GA, the optimum solution is chosen

under the required constraints of thickness restriction (≤ 2.0 mm), -10 dB bandwidth and peak RL.

Optimisation Technique	Material Sequence	Corresponding Thickness (mm)	Total thickness (mm)	Frequency of strongest RL (GHz)	Strongest RL (dB)	Bandwidth (≤ -10 dB)
PSO	10	0.7142	1.1892	6	-39.64	11.3
	16	0.4750				(2.6-13.9)
GA	14	0.8159	1.3217	4.3	-37.56	7.7
	7	0.5058				(2.2-9.9)

Table 3.1 Results obtained from PSO and GA for 2 layered MMMS

It can be seen that PSO technique selects materials 10 and 16 from the database with 0.7142 mm and 0.4750 mm thickness respectively while it is materials 14 and 7 for GA with 0.8159 mm and 0.5058 mm thickness. PSO provides a much better performance in terms of bandwidth as well as peak RL. Also the total thickness determined by PSO (1.1892 mm) is less than that determined by GA (1.3217 mm).

The particle swarm optimization not only provides a wider ≤ -10 dB bandwidth, which means the MMMS shows the required performance over the frequency range of 2.6 GHz to 13.9 GHz, but also provides a good peak RL value of -39.64 dB at 6 GHz frequency. Comparing this with GA, we can see that the required bandwidth criteria is satisfied over the frequency range from 2.2 GHz to 9.9 GHz, which is considerably less than that the structure design parameters provided by PSO. On the other hand, the strongest RL provided by GA, which is -37.56 dB at the frequency of 4.3 GHz is almost comparable to that of PSO.

The above results have been shown graphically as follows-

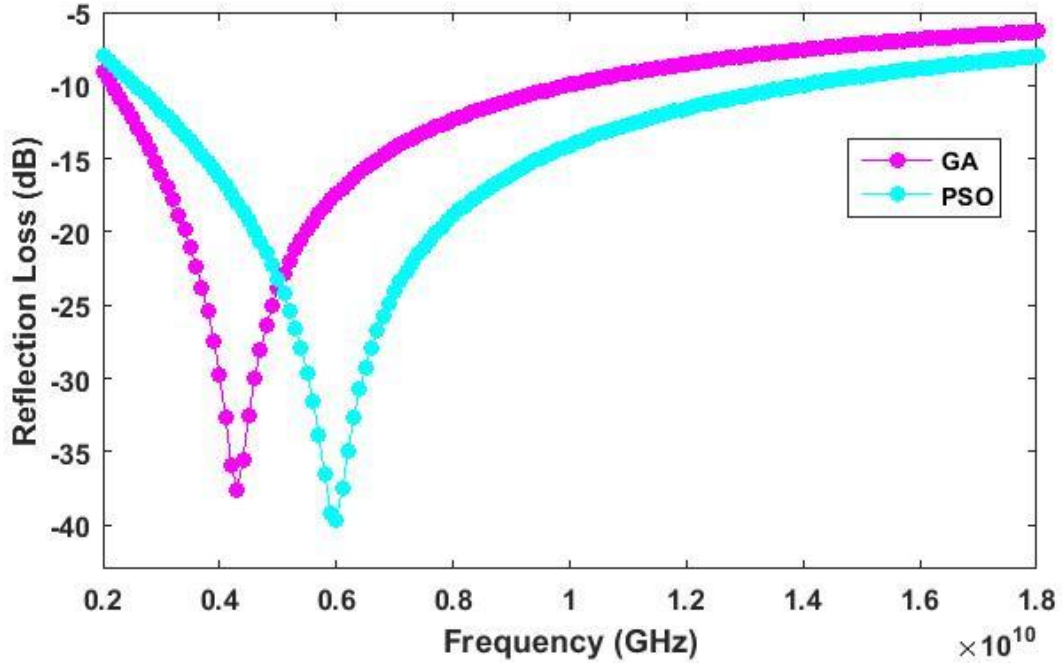


Fig. 3.2 Frequency dependant RL characteristics of 2-layered MMMS for Normal Incidence

3.2 RL ANALYSIS OF THREE LAYER STRUCTURES FOR NORMAL INCIDENCE

In order to study Reflection Loss characteristics of the 3-layered MMMS, Eqn. 3.9-3.11 are used to calculate the RL. In this case, we have a total of six design parameters, which are the 3 materials out of the database and their three corresponding thickness values.

In the similar manner for 2-layered MMMS, the optimal results for three layered structures are shown on the next page. It can be seen that while PSO selects materials 15,7 and 16 with a total thickness of 1.990 mm, GA chooses the materials 16, 8 and 8 with a total thickness of 1.925 mm. Also it is seen that PSO displays a peak RL value of -41.28 dB with a wide bandwidth of 16 GHz, i.e. it exhibits a ≤ -10 dB bandwidth over the entire frequency range of 2-18 GHz, which is very useful and better performance characteristics as compared to that shown by GA optimization technique in this case. In a stark comparison to this, the required bandwidth is provided by GA over the frequency range of 8.6 GHz. Also the strongest RL determined by GA is -38.58 dB at the frequency of 4.8 GHz.

All these design parameters are shown in a tabulated manner on the following page.

Optimisation Technique	Material Sequence	Corresponding Thickness (mm)	Total thickness (mm)	Frequency of strongest RL (GHz)	Strongest RL (dB)	Bandwidth (< -10 dB)
PSO	15	0.767	1.990	4.2	-41.28	16
	7	1				(2-18)
	16	0.223				
GA	16	0.652	1.925	4.8	-38.58	8.6
	8	0.559				(2.6-11.2)
	8	0.714				

Table 3.2 Results obtained from PSO and GA for 3 layered MMMS

These results are plotted as follows-

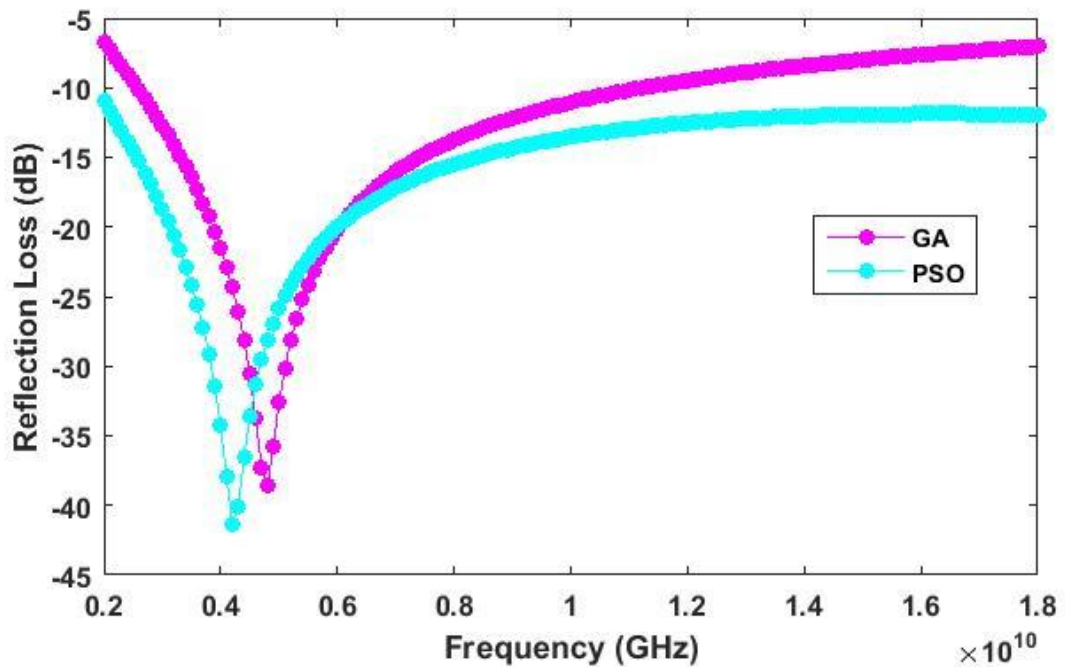


Fig. 3.3 Frequency dependant RL characteristics of 3-layered MMMS for Normal Incidence

CHAPTER 4

OPTIMAL DESIGN OF MULTILAYERED STRUCTURES FOR OBLIQUE INCIDENCE

After the formulation and implementation of Normal Incidence of the EM wave on the MMMS, we now study the case when the incident EM wave strikes the surface of the multilayered structure in an oblique manner.

4.1 THEORETICAL BACKGROUND

To understand the Oblique Incidence, let us consider a planer multilayered metamaterial structure with N layers on a substrate of a PEC. The EM wave, of a particular frequency incident on the MMMS, strikes the first layer at the interface (labelled,0) from air at an angle oblique θ with respect to the normal, at that point of incidence. After this, as the wave travels and moves through the successive layers of the MMMS, parts of the energy of the wave are absorbed in each layer of the structure. Finally the wave is reflected by the PEC (layer $N+1$), which ideally provides a perfect reflection. The structure is shown as follows-

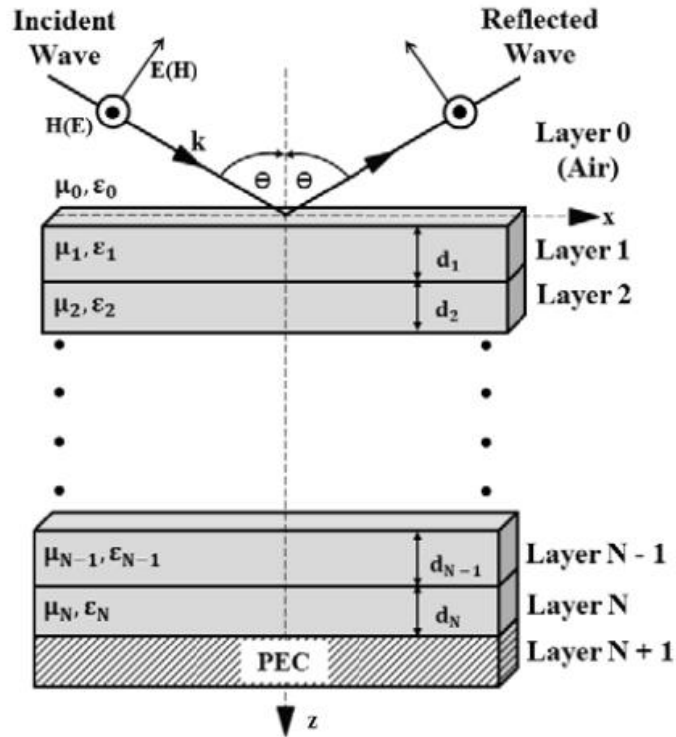


Fig. 4.1 Generalised model of absorber structure showing Oblique Incidence [46]

The generalized reflection coefficient [47,48] between two layers of the MMMS is given by the following recursive formula, which is given by the Transmission Line Theory [46], it is given as-

$$R_{i,i+1} = \frac{\rho_{i,i+1} + R_{i+1,i+2} \exp(-2jk_{i+1}d_{i+1})}{1 + \rho_{i,i+1} + R_{i+1,i+2} \exp(-2jk_{i+1}d_{i+1})} \quad (4.1)$$

Now in the **TM or Parallel mode** of polarization, in which the magnetic field is transverse to the propagation direction of the wave, while the electric field is normal to the this propagation direction:

$$\rho_{i,i+1} = \frac{\varepsilon_{i+1}k_i - \varepsilon_i k_{i+1}}{\varepsilon_{i+1}k_i + \varepsilon_i k_{i+1}}, i < N \quad (4.2)$$

While in the **TE or Perpendicular mode** of polarization, in which electric field is transverse to the propagation direction of the wave, while the magnetic field is normal to the this propagation direction:

$$\rho_{i,i+1} = \frac{\mu_{i+1}k_i - \mu_i k_{i+1}}{\mu_{i+1}k_i + \mu_i k_{i+1}}, i < N \quad (4.3)$$

Here, ε_i is the frequency dependant permittivity of the i th layer of the MMMS, μ_i is the frequency dependant permeability of the i th layer of the MMMS and k_i is the wave number of the i th layer, whose formulation is given by Snell's Law as follows-

$$k_i = \omega \sqrt{\mu_i \varepsilon_i - \mu_0 \varepsilon_0 \sin^2 \theta} \quad (4.4)$$

In this equation, ω is the frequency of the wave that is incident on the multilayered structure and μ_0 and ε_0 are the free space permeability and permittivity values.

Another important consideration is that the reflection coefficient of the last interface, i.e., between the last layer of the MMMS and the PEC ($R_{N,N+1}$), is set to +1 for TM polarization while it is set to -1 for TE polarization. In order to calculate the overall Reflection Loss of the MMMS, we need to calculate the reflection coefficient of the first interface. This is done so by recursively using the above mentioned equations from 4.1 to 4.4.

4.2 RL ANALYSIS OF DOUBLE LAYER STRUCTURES FOR OBLIQUE INCIDENCE

Since in the case of Oblique Incidence, the EM wave strikes the interface of the MMMS at a particular angle with the normal, we take two particular cases of the incidence angle, to implement the optimisation algorithms. So the cases of incident angle θ equal to 30 and 45 degrees are considered for both the polarizations discussed above.

- *TM Polarization*

Firstly, $\theta = 30^\circ$ is considered. Both GA as well as PSO are applied to the 16 material database explained previously. The results are tabulated as-

Optimisation Technique	Material Sequence	Corresponding Thickness (mm)	Total thickness (mm)	Frequency of strongest RL (GHz)	Strongest RL (dB)	Bandwidth (≤ -10 dB)
PSO	14	0.398	1.072	6.2	-29.842	14.1 (2.3-16.4)
	4	0.674				
GA	8	0.522	0.946	8.2	-16.031	15.3 (1.7-16)
	14	0.424				

Table 4.1 PSO and GA for 2 layered MMMS for an oblique incident wave (30° , TM)

It is seen that GA selects materials 8 (0.522 mm) and 14 (0.424 mm) with a total structure thickness of 0.946 mm and provides a ≤ -10 dB bandwidth of 15.3 GHz. As for particle swarm optimisation, the materials selected are 14 (0.398 mm) and 4 (0.674 mm) which provide a total thickness of 1.072 mm.

So even though GA provides with a lesser overall thickness value for the MMMS, which is one of the required characteristics of the absorbing structure, but PSO shows better and more desirable performance in terms of overall required bandwidth as well as the peak RL value. The peak RL value demonstrated by PSO is -29.842 GHz and that by GA is -16.031 GHz. Thus it is safe to say that PSO performs better than GA in this case of 2 layered MMMS for obliquely incident EM wave at 30 degrees angle of incidence.

The above results are graphically plotted as follows-

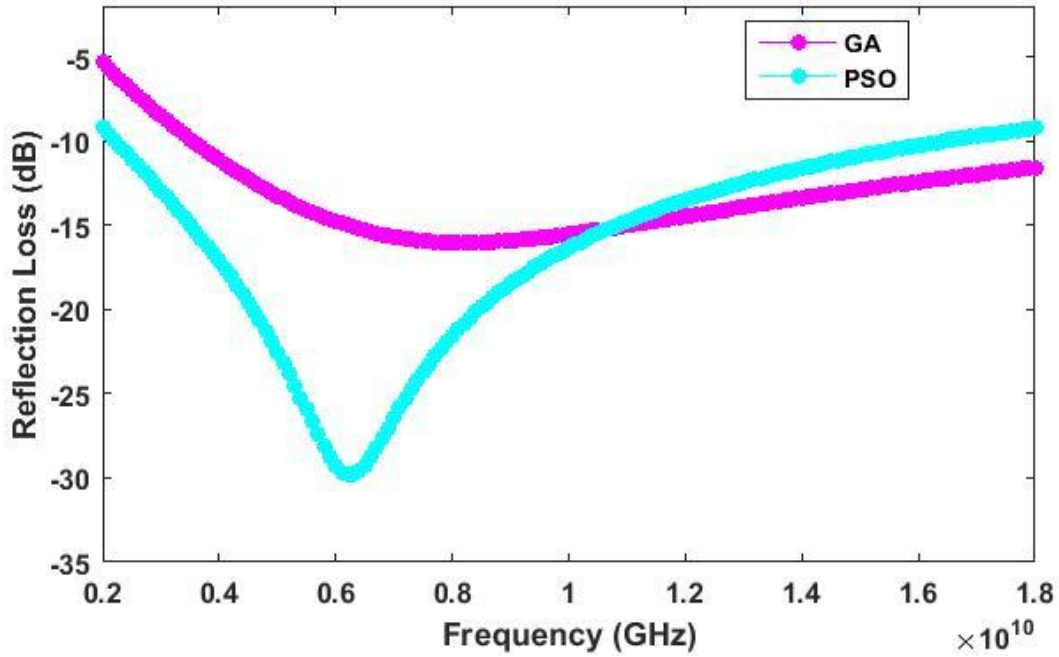


Fig. 4.2 Frequency dependant RL characteristics of 2-layered MMMS for Oblique Incidence (30°, TM mode)

Now, we consider the case of $\theta = 45^\circ$, for TM mode. Here, as PSO and GA are applied to the database, we obtain the following results-

Optimisation Technique	Material Sequence	Corresponding Thickness (mm)	Total thickness (mm)	Frequency of strongest RL (GHz)	Strongest RL (dB)	Bandwidth (< -10 dB)
PSO	7	1	1.739	4.7	-49.905	16
	15	0.739				(2-18)
GA	9	0.887	1.642	3.6	-46.496	7.1
	14	0.133				(2-9.1)

Table 4.2 PSO and GA for 2 layered MMMS for an oblique incident wave (45°, TM)

It can be observed that the bandwidth provided by the structure designed by PSO is much greater than that by GA. It covers the complete range of frequencies from 2 to 18 GHz, which is a massively desirable parameter. The same feature and other characteristics are graphically plotted as follows-

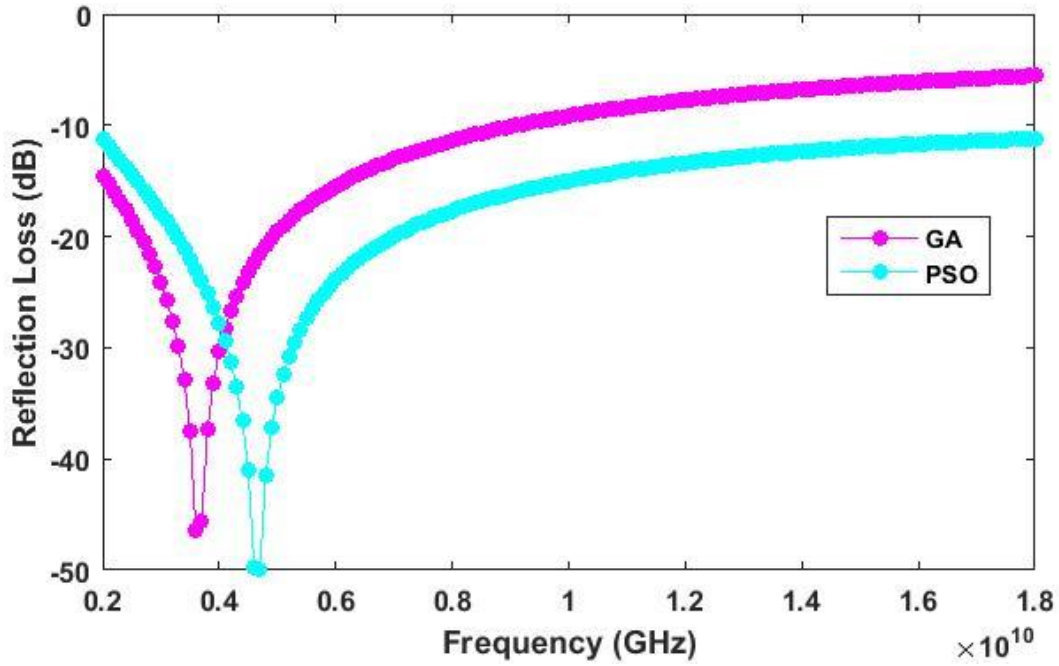


Fig. 4.3 Frequency dependant RL characteristics of 2-layered MMMS for Oblique Incidence (45°, TM mode)

- *TE Polarization*

In the similar manner as for TM mode, we first consider the case for $\theta = 30^\circ$. Using Eqn. (4.3) to calculate the Reflection Loss and then applying both the aforementioned optimisation techniques to the material database, we obtain the following results-

Optimisation Technique	Material Sequence	Corresponding Thickness (mm)	Total thickness (mm)	Frequency of strongest RL (GHz)	Strongest RL (dB)	Bandwidth (< -10 dB)
PSO	6	1	2	11.4	-18.154	15.7
	7	1				(2.3-18)
GA	14	0.944	1.398	5.7	-10.091	1.2
	5	0.454				(5.1-6.3)

Table 4.3 PSO and GA for 2 layered MMMS for an oblique incident wave (30°, TE)

The overall peak RL observed in the case of TM mode of polarization in oblique incidence is much less than that in the case of TM mode, but still the overall required bandwidth provided by PSO is desirable for practical uses. At the expense of a greater overall thickness as

compared to GA, PSO gives a good bandwidth range and and RL value. These results are shown in the following graph-

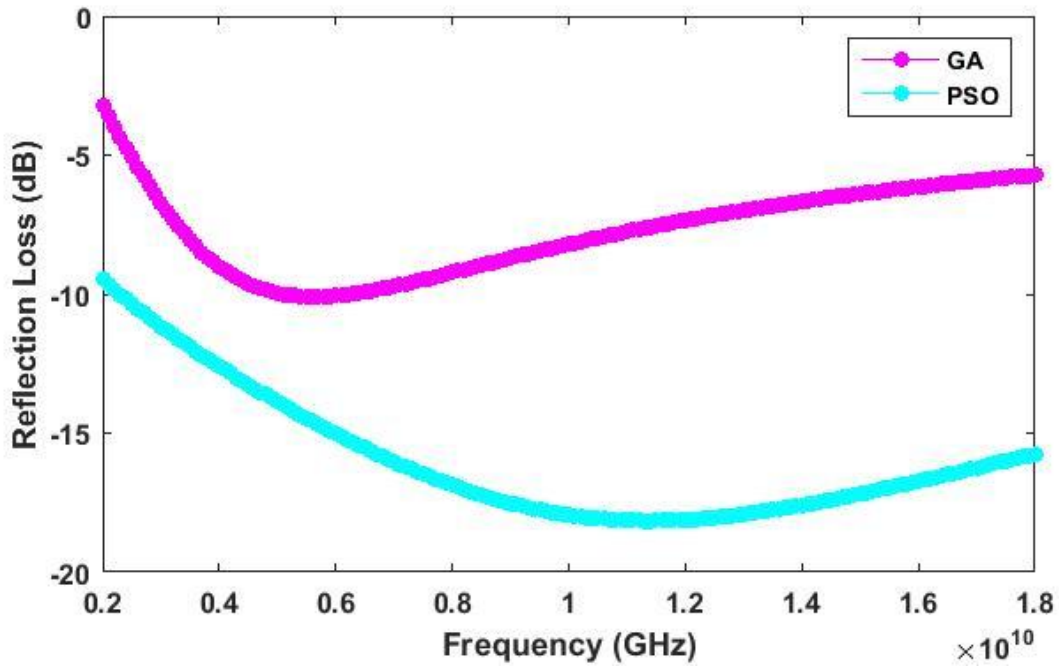


Fig. 4.4 Frequency dependant RL characteristics of 2-layered MMMS for Oblique Incidence (30°, TE mode)

Next if we consider the case of $\theta = 45^\circ$, the following results are obtained on applying the optimisation algorithms to the materials in the database-

Optimisation Technique	Material Sequence	Corresponding Thickness (mm)	Total thickness (mm)	Frequency of strongest RL (GHz)	Strongest RL (dB)	Bandwidth (< -10 dB)
PSO	6	1	1.987	6.6	-23.389	16
	6	0.987				(2-18)
GA	16	1	1.850	4.9	-13.260	3.8
	5	0.850				(3.5-7.3)

Table 4.4 PSO and GA for 2 layered MMMS for an oblique incident wave (45°, TE)

In this case it can be deduced that there is a minor change in the total thickness of the 2 layered MMMS designed by both the algorithms, however there is a huge difference in the overall desirable bandwidth range of both the design parameters. This occurs due to different

materials chosen by both the algorithms. PSO chooses material no. 6 for both the layers with individual thicknesses of 1 mm and 0.987 mm. And GA selects materials 16 and 5 with thickness of 1 mm and 0.850 mm respectively. The graph of the RL with respect to frequency is shown as below-

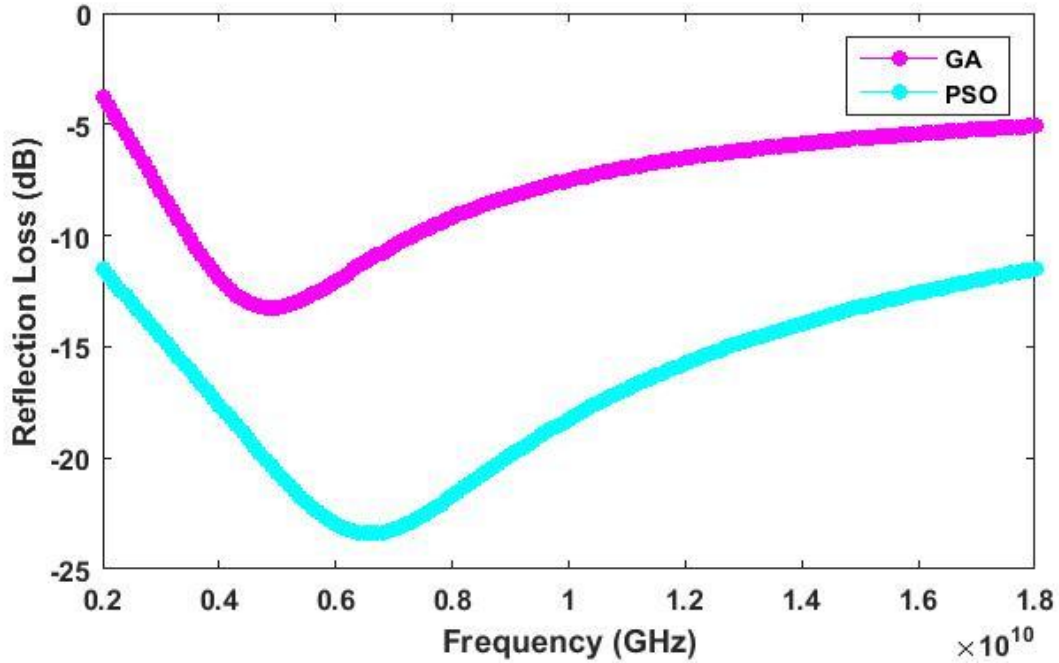


Fig. 4.5 Frequency dependant RL characteristics of 2-layered MMMS for Oblique Incidence (45°, TE mode)

4.3 RL ANALYSIS OF THREE LAYER STRUCTURES FOR OBLIQUE INCIDENCE

As in the case of double layered MMMS, here also we consider both the mose of polarizations and for two angles of incidences.

- *TM Polarization*

Firstly, $\theta = 30^\circ$ is implemented for TM mode and the optimisation algorithms are applied to it.

It can be seen that PSO selects materials 6,14 and 10 with the total thickness of 1.289 mm and a desired bandwidth of 14.1 GHz. The peak RL value is noted down to be -35.012 dB. Also, the materials chosen by GA are found to be 14, 12 and 8 with the total thickness of 1.457 mm and the bandwidth is found to be 12.7 GHz. So it is seen that PSO provides a better bandwidth range and also a better peak RL value, which is very beneficial for practical purposes like stealth technology.

The results of the algorithms are tabulated as follows-

Optimisation Technique	Material Sequence	Corresponding Thickness (mm)	Total thickness (mm)	Frequency of strongest RL (GHz)	Strongest RL (dB)	Bandwidth (< -10 dB)
PSO	6	0.280	1.289	5.6	-35.012	14.1
	14	0.505				(2.2-16.3)
	10	0.504				
GA	14	0.503	1.457	6.7	-31.775	12.4
	12	0.528				(2.8-15.2)
	8	0.426				

Table 4.5 PSO and GA for 3 layered MMMS for an oblique incident wave (30°, TM)

The graphical representation of the results is as below-

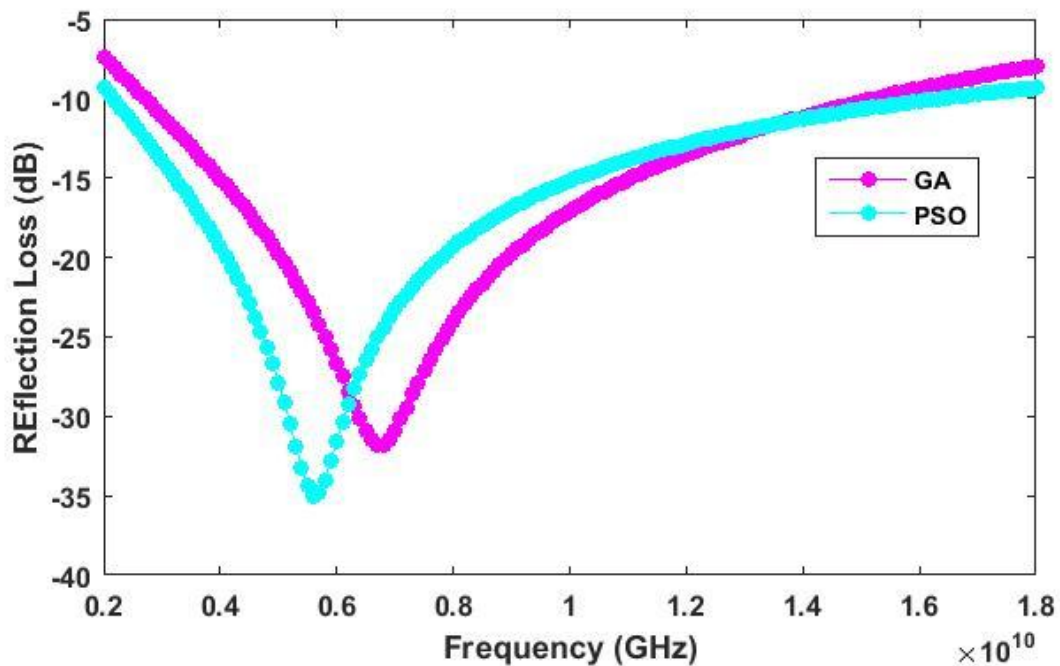


Fig. 4.6 Frequency dependant RL characteristics of 3-layered MMMS for Oblique Incidence (30°, TM mode)

Next we take the case of $\theta = 45^\circ$, and when the optimisation algorithms are applied to the database, following 6 parameters are obtained under the required constraints of thickness, Reflection Loss and bandwidth.

Optimisation Technique	Material Sequence	Corresponding Thickness (mm)	Total thickness (mm)	Frequency of strongest RL (GHz)	Strongest RL (dB)	Bandwidth (< -10 dB)
PSO	14	0.310	1.951	6.2	-51.408	16
	1	0.825				(2-18)
	10	0.816				
GA	11	0.522	1.642	3.9	-43.776	8.3
	11	0.549				(2-10.3)
	8	0.571				

Table 4.6 PSO and GA for 3 layered MMMS for an oblique incident wave (45° , TM)

The graphical representation of the above results is as follows-

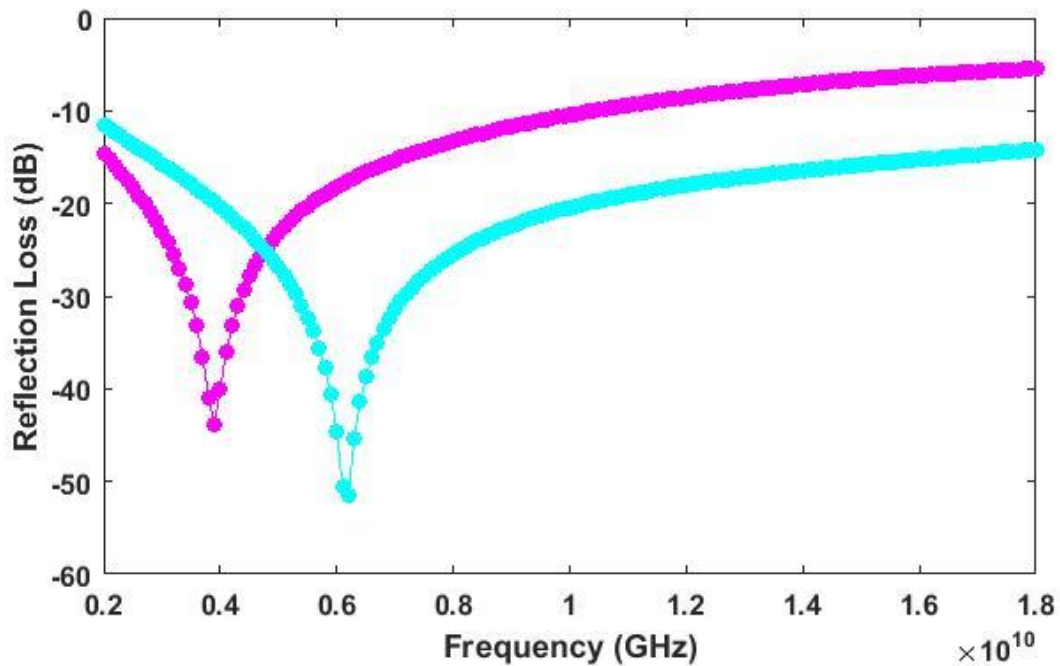


Fig. 4.7 Frequency dependant RL characteristics of 3-layered MMMS for Oblique Incidence (45° , TM mode)

It can be seen that the MMMS structure designed by PSO algorithm provides an excellent bandwidth of 16 GHz, i.e. it fulfils the desired requirement of having Reflection Loss below -10 dB over the complete range of frequency from 2 GHz to 18GHz. Also, the peak RL value is observed to be -51.40 dB at 6.2 GHz, when the materials selected are 14 (0.310 mm), 1 (0.825 mm) and finally the 10th material with a thickness of 0.816 mm.

In contrast to this the bandwidth provided by the structure designed by GA is 8.3 with peak RL value of -43.776 dB at the frequency of 3.9 GHz. Also the materials selected are 11, 11 and 8 with a total thickness of 1.642 mm.

- *TE Polarization*

The above explained procedure is again carried out for TE mode of polarization for a three layered MMMS. It is done for two angle of incidence of the incident EM wave on the interface of MMMS.

Firstly, we consider $\theta = 30^\circ$ in this polarization and then the two optimization techniques of GA and PSO are applied to the material database in order to design an optimum structure with respect to all the constraints provided according to the application required. The results obtained are tabulated as below-

Optimisation Technique	Material Sequence	Corresponding Thickness (mm)	Total thickness (mm)	Frequency of strongest RL (GHz)	Strongest RL (dB)	Bandwidth (< -10 dB)
PSO	14	0.579	1.882	6.3	-11.053	5.8 (4.1-9.9)
	2	0.377				
	7	0.926				
GA	6	0.366	1.472	7.2	-10.307	3.6 (5.8-9.4)
	14	0.550				
	2	0.556				

Table 4.7 PSO and GA for 3 layered MMMS for an oblique incident wave (30°, TE)

In this case it can be seen that the performance of both the techniques is almost comparable to each other in terms of all the constraints that are required. The total thickness of the

MMMS designed by GA is better than that of PSO, but the bandwidth and peak RL value designed by PSO is slightly better than GA. The materials selected by PSO are 14, 2 and 7 with total thickness of 1.882 mm and those selected by GA are 6, 14 and 2 with the total thickness of 1.472 mm. The Reflection Loss is plotted graphically for both the cases as below-

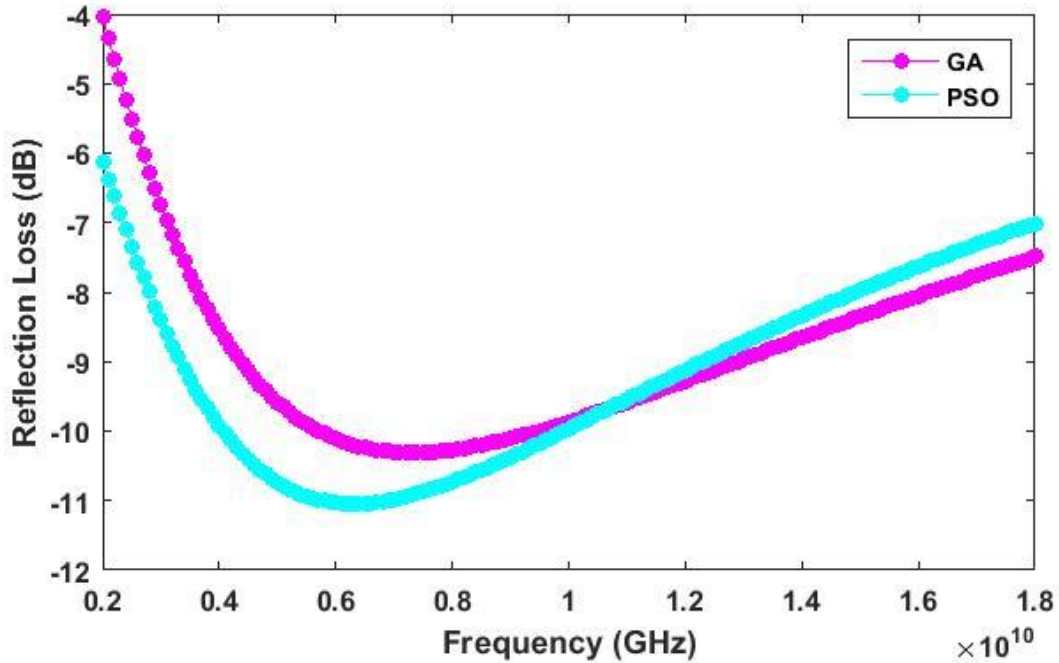


Fig. 4.8 Frequency dependant RL characteristics of 3-layered MMMS for Oblique Incidence (30°, TE mode)

Next when we consider the case of $\theta = 45^\circ$ and apply the optimisation techniques, the results obtained show that even for TE mode of polarization, PSO provides a commendable bandwidth of 15.5 GHz with a peak RL value of -20.543 dB at 11.9 GHz. The total thickness of the designed structure is 1.919 mm with materials selected to be 6, 7 and 6.

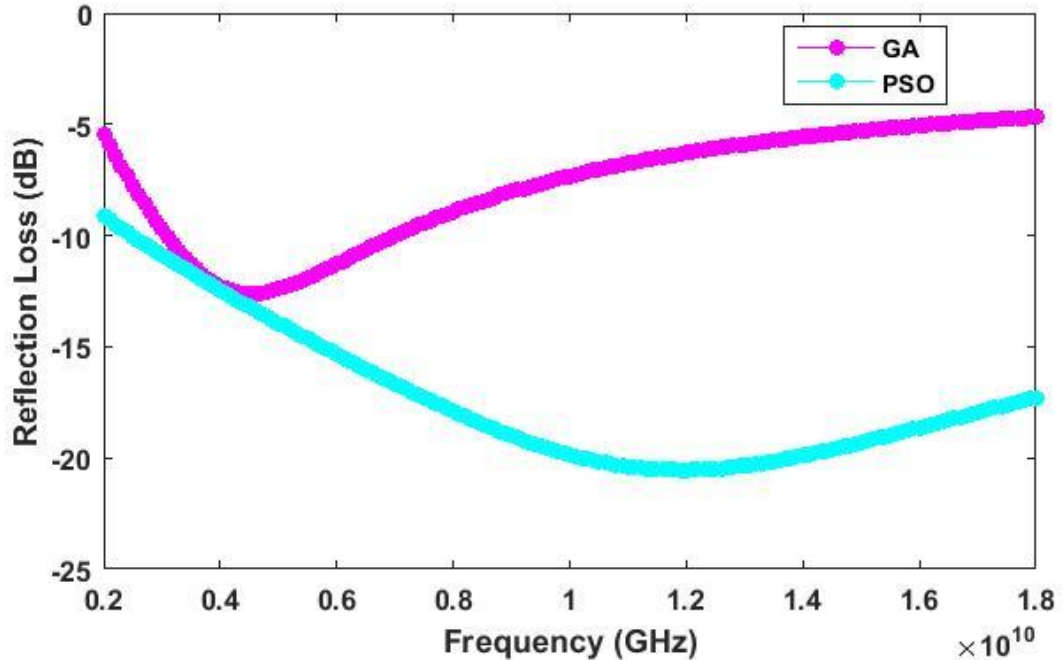
As for the performance of Genetic Algorithm, a low bandwidth of 3.9 GHz with a peak RL value of -12.607 dB is obtained. The materials selected, with the sequence are 14 (0.559 mm), 14 (0.373 mm) and material no. 2 (0.412 mm) such that the total thickness of the proposed structure comes out to be 1.344 mm.

These results have been tabulated in the following table-

Optimisation Technique	Material Sequence	Corresponding Thickness (mm)	Total thickness (mm)	Frequency of strongest RL (GHz)	Strongest RL (dB)	Bandwidth (< -10 db)
PSO	6	1	1.919	11.9	-20.543	15.5
	7	0.714				(2.5-18)
	6	0.205				
GA	14	0.559	1.344	4.5	-12.607	3.9
	14	0.373				(3.1-7)
	2	0.412				

Table 4.8 PSO and GA for 3 layered MMMS for an oblique incident wave (45° , TE)

The graphical representation showing the Reflection Loss of the MMMS as a function of frequency for the above found results is as below-

Fig. 4.9 Frequency dependant RL characteristics of 3-layered MMMS for Oblique Incidence (45° , TE mode)

CHAPTER 5

CONCLUDING REMARKS AND FUTURE SCOPE

The objective of this thesis is to explore the possibility to develop a cost effective, thin and broadband MMMS for various applications which include EMC, EM shielding which has further important implications in Stealth Technology, improving communications and reducing interferences from various obstacles.

Advanced techniques such as Multilayering are employed in order to give better performance as compared to traditional approaches such as single layered absorbent structures and embedded structures on a conductive layer. Tremendous improvement in terms of performance has been seen when multilayering is applied to the same set of databases as compared to previous approaches.

In order to implement the concept of multilayered MMMSs, the most important requirement is the optimal selection of the materials out of a database available, depending on their EM properties such as permittivity and permeability. This number of materials depends on the layering of the structure according to the specific requirement. Also other concerns are the individual thicknesses of the layers as the total absorbent structure should not be too bulky, as it would not be helpful in the practical implementation of the theoretical results. Also important is the sequence of the chosen materials as each composite material acts in a different manner with the EM wave.

So for this purpose, optimisation techniques, namely Genetic Algorithm and Particle Swarm Optimisation have been employed. Important consideration has been given to the Normal and Oblique Incidence of the EM wave.

Future Scope:

There are always possibilities and scope to extend the research further. A few major extended research areas are provided as follows:

- The commercialization of developed Multilayered Metamaterial absorbers is of great concern; therefore in future field studies can be carried out for their practical implementation.
- RCS measurements can be carried out by coating developed MMMSs on different shapes of radome structures, for development in stealth technology for the defence sector.

- Further, analysis is required to critically analyze the mechanical properties (like stress, strain and adhesion etc.) for fabricated MMMSs.
- Modifications in optimisation techniques to ensure even lesser thickness of the layers can be done, such as use of Modified PSO and Binary GA to this application can be studied on.
- Research can be done on the composition of materials for the purpose of MMMSs, such as ferrites, in order to ensure better absorption of EM wave.

REFERENCES

- [1] Wartak M., Tsakmakidis K., Hess O., "Introduction to Metamaterial Available at: <http://www.cap.ca/sites/cap.ca/files/article/1713/jan11-offprint-wartak.pdf>.
- [2] E. Michielssen, J. Sajer, S. Ranjithan, and R. Mittra, "Design of Lightweight Broad-band Microwave Absorbers using Genetic Algorithm," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-41, pp. 1024-1031, June/July 1993.
- [3] Pesque, J.J., Bouche, D.P. and Mittra, R., "Optimization of multilayer antireflection coatings using an optimal control method," *IEEE Transactions on Microwave Theory and Techniques*, 40(9), pp.1789-1796, 1992.
- [4] M. Najim, P. Smitha, V. Agarwala, and D. Singh, "Design of light weight multi-layered coating of zinc oxide-iron-graphite nano-composites for ultra-wide bandwidth microwave absorption," *J. Mater. Sci.: Mater. Electron.*, vol. 26, pp. 7367-7377, 2015.
- [5] L.C. Folgueras, M.C. Rezende, *J. Mater. Res.* 11, 245, 2008.
- [6] R. Panwar, V. Agarwala, and D. Singh, "A cost effective solution for development of broadband radar absorbing material using electronic waste," *Ceram. Int.*, vol. 41, no. 2, pp. 2924-2931, Mar. 2015.
- [7] Goudos, S. K., and Sahalos, J. N., "Microwave absorber optimal design using multi-objective particle swarm optimization," *Microw. Opt. Technol. Lett.*, vol. 48, pp. 1553-1558, 2006.
- [8] Chamaani, S., S. Mirtaheri, and M. Shooredeli, "Design of very thin wide band absorbers using modified local best particle swarm optimization," *AEU Int. J. Electron. Commun.*, vol. 62, pp. 549-556, 2008.

- [9] Liu, H., L. Zhang, Y. Gao, Y. Shen, and D. Shi, "Electromagnetic wave absorber optimal design based on improved particle swarm optimization," *EMC 2009*, pp. 797-800, IEICE, Kyoto, 2009.
- [10] Formato, R. A., "Central force optimization: A new metaheuristic with applications in applied electromagnetics," *Progress In Electromagnetics Research B*, vol. 77, pp. 425-491, 2007.
- [11] Goudos, S., "Design of microwave broadband absorbers using a self-adaptive differential evolution algorithm," *Int. J. RF and Microwave CAE*, vol. 19, pp. 364-372, May 2009.
- [12] V. V. Thakare and P. K. Singhal, "Bandwidth analysis by introducing slots in microstrip antenna design using ANN," *Progress In Electromagnetics Research M*, vol. 9, pp. 107-122, 2009
- [13] C.-C. Zhou, G.-F. Yin, and X.-B. Hu "Multi-objective optimization of material selection for sustainable products: Artificial neural networks and genetic algorithm approach," *Mater. Design*, vol. 30, pp. 1209–1215, 2009.
- [14] Balanis, Constantine A, "Advanced electromagnetic engineering," *John Wiley & Sons Comp*, 1989.
- [15] Buck, John A., W. H. Hayt, and W. Hayt., "Engineering Electromagnetics," 2004.
- [16] P.G. Lederer, "An introduction to radar absorbent materials," *Royal Signals and Radar Establishment*, no. 85016, 1986.
- [17] Dixon, P., Theory And Application Of RF / Microwave Absorbers. 2012, Emerson & Cuming Microwave Products: Randolph, 2012.
- [18] Chatterton, Paul A. and Michael A Houlden. *EMC: Electromagnetic Theory to Practical Design*. New York: John Wiley & Sons, 1992.

- [19] Vinoy, K. J.; Jha, R. M., "Radar Absorbing Materials: From theory to Design and Characterization," *Kluwer Academic Publishers*, Boston, 1996.
- [20] Kennedy, J. and R. C. Eberhart, "Particle swarm optimization," *Proc. IEEE Int. Conf. Neural Networks*, 1942–1948, Perth, Australia, 1995.
- [21] Pathak, N. N., G. K. Mahanti, S. K. Singh, J. K. Mishra, and A. Chakraborty, "Synthesis of thinned planar circular array antennas using modified particle swarm optimization," *Progress In Electromagnetics Research Letters*, Vol. 12, 87–97, 2009
- ARGUS, Coll., "H. A~ brecht et al," *Phys. Lett. B* 196, pp. 101, 1987.
- [22] ARGUS, Coll., "H. A~ brecht et al," *Phys. Lett. B* 196, pp. 101, 1987.
- [23] Livingstone, C. E., A. L. Gray, R. K. Hawkins, J. G. Halbertsma, R. A. Deane, and R. B. Olsen. "CCRS C-band airborne radar-system description and test results," In *Proceedings of the 11th Canadian Symposium on Remote Sensing*, vol. 2, pp. 503-518. 1987.
- [24] Salisbury, Edward James. "Downs & dunes," 1952.
- [25] Ruck, George T., ed. *Radar cross section handbook*. Vol. 2. Plenum Publishing Corporation, 1970.
- [26] Bornkessel, Christian, and Werner Wiesbeck, "Numerical analysis and optimization of anechoic chambers for EMC testing," *IEEE transactions on electromagnetic compatibility* 38, no. 3, pp. 499-506, 1996.
- [27] Stepanov, Dmitrii Leonidovich, F. Golshani, and Jovan Stöcklin. *Upper Permian and Permian-Triassic boundary in North Iran*. No. 12. Geological Survey of Iran, 1969.
- [28] Munk, Benedikt A, "Frequency selective surfaces: theory and design," Vol. 29. New York: John Wiley, 2000.

- [29] Knott, G., and D. Reece, "MLAB: An on-line modeling laboratory," *Beginners Guide. Div. Computer Research and Technology, Bethesda, Md*, 1979.
- [30] Lakhtakia, Akhlesh, Vasundara V. Varadan, and Vijay K. Varadan. "A parametric study of microwave reflection characteristics of a planar achiral-chiral interface." *IEEE transactions on electromagnetic compatibility* 28, no. 2, pp. 90-95, 1986.
- [31] Björkvall, J., Du Sichen, and Seshadri Seetharaman. "Thermodynamic description of Al₂O₃, CaO, MnO and Al₂O₃, FeO, MnO mets-a model approach." *Calphad* 24, pp. 353-376, 2000.
- [32] Tang, Kit-Sang, Kim-Fung Man, Sam Kwong, and Qun He. "Genetic algorithms and their applications." *IEEE signal processing magazine* 13, no. 6, pp. 22-37, 1996.
- [33] Chong, Y. D., Li Ge, Hui Cao, and A. Douglas Stone. "Coherent perfect absorbers: time-reversed lasers." *Physical review letters* 105, no. 5, pp. 053901, 2010.
- [34] Matsumoto, Morihiko, and Yoshimori Miyata, "Thin electromagnetic wave absorber for quasi-microwave band containing aligned thin magnetic metal particles," *IEEE transactions on magnetics* 33, no. 6, pp. 4459-4464, 1997.
- [35] Weile, Daniel S., Eric Michielssen, and David E. Goldberg. "Genetic algorithm design of Pareto optimal broadband microwave absorbers," *IEEE Transactions on Electromagnetic Compatibility* 38, no. 3, pp. 518-525, 1996.
- [36] Neo, C. P., and Vijay K. Varadan, "Optimization of carbon fiber composite for microwave absorber," *IEEE Transactions on Electromagnetic Compatibility* 46, no. 1, pp. 102-106, 2004.
- [37] Shin, J. Y., and J. H. Oh, "The microwave absorbing phenomena of ferrite microwave absorbers," *IEEE Transactions on Magnetism* 29, no. 6, pp. 3437-3439, 1993

- [38] Park, H-S., I-S. Choi, J-K. Bang, S-H. Suk, S-S. Lee, and H-T. Kim, "Optimized design of radar absorbing materials for complex targets," *Journal of electromagnetic waves and applications* 18, no. 8, pp. 1105-1117, 2004.

- [39] Cui, Suomin, Daniel S. Weile, and John L. Volakis, "Novel planar electromagnetic absorber designs using genetic algorithms," *IEEE transactions on antennas and propagation* 54, no. 6, pp. 1811-1817, 2006.

- [40] Parida, Ramesh C., D. Singh, and N. K. Agarwal. "Implementation of multilayer ferrite radar absorbing coating with genetic algorithm for radar cross-section reduction at X-band," 2007.

- [41] Panwar, Ravi, Vijaya Agarwala, and Dharmendra Singh, "Design and experimental verification of a thin broadband nanocomposite multilayer microwave absorber using genetic algorithm based approach," *AIP Conference Proceedings*, vol. 1620, no. 1, pp. 406-415, 2014.

- [42] N. Mohd, P. Smitha, A. Vijaya, and S. Dharmendra, "ANN-Based Two-Layer Absorber Design Using Fe–Al Hybrid Nano-Composites for Broad Bandwidth Microwave Absorption," *IEEE Trans. Magn.*, vol. 52, no. 12, Dec. 2016.

- [43] Schaubert, Daniel H., David M. Pozar, and Andrew Adrian, "Effect of microstrip antenna substrate thickness and permittivity: comparison of theories with experiment," *IEEE Transactions on Antennas and Propagation* 37, no. 6, pp. 677-682, 1989.

- [44] Shukla, Pradyumn Kumar, and Kalyanmoy Deb, "On finding multiple Pareto-optimal solutions using classical and evolutionary generating methods," *European Journal of Operational Research* 181, no. 3, pp. 1630-1652, 2007.

- [45] Truong VT, Riddell SZ, and Muscat RF., "Polypyrrole based microwave absorbers," *J. Mater. Sci.*, 33, 4971–4976, 1998.

- [46] Chew, W. C., *Waves and Fields in Inhomogeneous Media*, IEEE Press, New York, 1995.
- [47] Asi, M. J. and N. I. Dib, “Design of multilayer microwave broadband absorbers using central force optimization,” *Progress In Electromagnetics Research B*, Vol. 26, 101–113, 2010.
- [48] Dib, N., M. Asi, and A. Sabbah, “On the optimal design of multilayer microwave absorbers,” *Progress In Electromagnetics Research C*, Vol. 13, 171–185, 2010.