COMPOSITE MATERIALS AND ELECTROMAGNETIC BASED STRUCTURE FOR STEALTH APPLICATION

A DISSERTATION

Submitted in partial fulfilment of the requirement
for the award of the degree of

MASTER OF TECHNOLOGY

in

ELECTRONICS AND COMMUNICATION ENGINEERING
(With specialization in RF and Microwave Engineering)

by

VARUN PARASHAR
(17533012)

DEPTT. OF ELECTRONICS AND COMMUNICATION ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, ROORKEE
ROORKEE-247667(INDIA)
JUNE 2019

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE

CANDIDATE' S DECLARATION

I declare that the work carried out in this dissertation report titled **"COMPOSITE MATERIALS AND ELECTROMAGNETIC BASED STRUCTURE FOR STEALTH APPLICATION"** is presented on behalf of partial fulfilment for requirement of award of the degree of Master of Technology with specialization in RF and Microwave Engineering submitted to the department of **Electronics and Communication Engineering, Indian Institute of Technology Roorkee**, under the supervision and guidance of **Prof. Dharmendra Singh**, Professor, Department of Electronics and Communication Engineering, Indian Institute of Technology Roorkee.
I further certify that the matter presented in this report has not submitted for the award of any other degree or diploma.

Date: June 2019 (Varun Parashar)
Place: IIT Roorkee

CERTIFICATION

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

Date: June 2019 Professor Dharmendra Singh
Place: IIT Roorkee IIT Roorkee
UK - 247667

Contents

Chapter 5

Chapter 6

List of Figures

Abstract

Stealth technology which is also termed as low observable technology is a crucial part of military tactics and passive Electronic counter Measures. The term Stealth is not only associated with the military aircraft, but is also associated with military submarines, ships, missiles and satellites. It makes them less visible to radar, infrared, sonar and other detection methods. It corresponds to military camouflage for these parts of electromagnetic spectrum. This technology has evolved over the years as a multi-disciplinary subject and starting from 1940's various techniques have been developed in order to reduce the radar signature of the aircraft or asset of ground. Thus reduction of EM signature pivots around minimizing the radar cross-section of the target. Several techniques which are in vogue to achieve this objective, including Radar Absorbing Materials (RAM), Frequency Selective Surface (FSS) and Multilayer FSS in conjugation with RAM. This report focuses on the Electro Magnetic structure and Composite material based techniques to reduce the radar signature of the aircraft.

Acknowledgements

I would like to take this opportunity to thank all those persons, whom without their support I could not have reached at this destination.

I would like to admire and honor my supervisor 'Prof. Dharmendra Singh'. He has been always there to help me both technically and morally. I am very much thankful for his excellent guidance and inculcating research skills in me. His physical intuition and ability to resolve and simplify complex problems has always helped me excel my project. It is his zeal that I could have been able to accomplish my project work. Without his untiring efforts, stimulating discussions, and motivational examples I would not have been writing this page for completion towards my project.

I will never forget the company of my fellow students and friends. I am thankful to my present colleagues of Microwave Imaging and Space Technology Applications (MISTAL) lab Sqn Ldr D S Rawat, Amit kushwaha and Chandan kumar for the congenial cheering work environment and for the round of discussions altogether.

My special thanks go to Jaydeep Singh Baghel, Mandar Bivalkar, Rakesh Singh and Ramveer Singh for helping me out in my project work, experimental setup and patiently proofreading my dissertation thesis to help me in presenting it in a better way. I wish to convey my appreciation and my deepest prayers to all of them to achieve success and happiness in their future endeavors.

I am thankful to lab technicians Mr. Raja Ram and Mr. kamveer for helping me out in measurement and making arrangement of experiments required for the dissertation work.

List of Symbols

τ	SFCW pulse width
c	Speed of light
R	Range
Γ	Complex reflection coefficient
μ_0	Free space permeability
ε_0	Free space dielectric constant
ε_r	Relative permittivity
Z_0	Characteristic impedance
θ	Elevation angle
ϕ	Azimuth angle
λ_0	Free space wavelength
ϕ_n	Phase difference of n^{th} SFCW pulse
ΔR	Range resolution of imaging radar
ΔCR	Cross-range resolution of imaging radar
f_c	Cut-off frequency
ε'	Real part of dielectric constant
ε	Complex dielectric constant
ε''	Imaginary part of dielectric constant
Q	Quality factor
$\tan\delta$	Dielectric loss tangent
σ	Conductivity
μ	Permeability
Ω	Impedance in ohms
λ_g	Guided wavelength in the dielectric
β	Propagation constant
S_{11}	Reflection coefficient
N	Number of frequency points in SFCW radar
f_n	n^{th} discrete frequency step
Z_0	Unambiguous range of the radar
Z	Target distance from radar
Δf	Frequency step size of SFCW radar

Chapter 1

Introduction

The MISSION of Indian Air Force is “TO WIN WAR” and for any armed force its assets are the prime and the most important weapons to win war. When we look from IAF point of view Aircraft, Radar, Missiles etc are the critical assets which are to be safe guarded from enemies in the time of hostilities. Another important and prime military objectives, during hostilities, is to inflict maximum damage on strategic targets located deep inside the adversary’s territory. In the modern era of multilayered Air Defence set-up, avoiding detection by enemy radar and also safe guarding the ground assets from the enemy aircrafts is a major challenge for the offensive airborne forces. Stealth technology is the popular name for techniques for target signature reduction to reduce its observability by radars. Thus, in modern technology-driven warfare, stealth may be viewed as a mission critical system and can be the game-changer in the arena of deep- penetration, covert operations.

Electromagnetic spectrum comprising of wide frequency range, is a wide continuously expanding area of research, different parts of spectra, showing various properties, being used for various useful applications. Here a particular range of the spectra, being exploited for the purpose of detecting objects, has been studied. A wide frequency range, like ultraviolet, visible and infrared has been taken into consideration for this purpose. In the field of warfare, strength of one, always has proven to be the weakness for the counter one. Stealth is the concept of immunizing these sensitive objects from this weakness of being detected by the enemy. In literal sense, the meaning of the stealth is to move cautiously. Stealth is mostly used in case of warfare and the sense of the term takes the meaning of avoiding the detection of existing forces from the enemy. This technology gives the advantage of sudden attack, which has always proven itself to be the best tactic in any war adding to the disadvantage for the opponent. Stealth technology covers a wide range of techniques used to make aircraft, missiles, satellites, ships and submarines to be less visible/ low observable. Camouflage is the term used for employing stealth technology into effective use. Camouflage is disguising of any animal, military personal, warfare equipment by blending into surroundings, making it difficult to be identified[1].

During the initial era, the only sensor for the detection was human eye, using the visible spectrum only. That’s why the concept of camouflage was limited to concealing by blending its color with the pigment of the surroundings. With the advancement of technology, the sensors have been implemented to cover more than initially covered visible spectra. Now-a-days the frequency range being used for the detection has covered a wide band including visible, near infrared, thermal infrared and radar. Wide band of frequency has been taken into consideration for the detection of the hidden object, hence the camouflage must also be capable of covering wide band of frequency for stealth to be implemented. Detection and camouflage go hand in hand, hence the advancement in the technology of detection leads to the requirement of advancements in stealth technology, forcing researchers to develop methods of shielding targets from electromagnetic wave to make them invisible.

1.1 Motivation

The Indian Air Force is the air arm of the armed forces, it the fourth largest among all the air forces in the world. It comprises of aircrafts, state of the art weapon systems such as Radars, Missile, Weapon systems and personnel as its assets. The primary responsibility of Air Force is to safeguard Indian airspace and to conduct aerial warfare during an armed conflict to achieve its task.

The aim of the IAF is to WIN WAR and in order to achieve it becomes pertinent to protect our ground assets from enemy radar and missiles at all cost. As we all know army cannot march with empty stomach in a similar manner no war can be won without ground assets. Hence with the advancement in technology safe guarding our assets on ground over a wide band of frequency has become even more challenging.

In today's aerial warfare camouflage over wide frequency range has a very important role to play in order to protect our assets on ground form the enemy's radar. Camouflage gives us an extra edge over the enemy by making our assets invisible over wide frequency range. Thus, in a multi-dimensional warfare camouflage over wide frequency range is the need of the hour. However, there are many challenges in the development of wide band camouflage net. The property of the camouflage net should be such that it should not only absorb or reflect any type of EM radiation incident on it, but at the same time should allow friendly transmission of EM radiation in the entire wide frequency band.

1.2 Objective

Making the assets on ground stealthy for wide range of frequency without hindering their operations by using wide band camouflaging techniques. Camouflage net based on principle of scattering has been widely put into use, but camouflage net based on absorption technique is still quiet challenging.

Aforesaid techniques have been and are being applied for the coating of RAM over a substrate as a layer or paint for minimizing reflection and maximizing absorption. Minimization of coating thickness is still a huge area for research under consideration. In recent years there has been of peak interest and the research for using them as camouflage net based on absorption technique with operating frequency from 1-18GHz, for the protection of ground assets from radar detection.

The following tasks have been carried out in this dissertation thesis work: -

To develop a Wide band Camouflage net by using test fabric with experimentally known parameters as substrate and FSS for the frequency range from 1 to 18 GHz.

(i) **Task 1**: To design a symmetric FSS on HFSS with minimum less than 3dB reflection loss.

(ii) **Task 2**: To study and optimize the FSS for further reduction in reflection losses over the frequency range of 1-18 GHz.

(iii) **Task 3**: Designing of an Asymmetric FSS on HFSS with the operating frequency range of 1-18 GHz and with less than 5dB reflection losses.

(iv) **Task 4**: Fabrication of asymmetric FSS on the test fabric and verification of the result.

1.3 Reduction in detectability of the target

Reduction in detectability of the target can be achieved by using following techniques: -

- Target shaping
- Coating or painting with radar absorbing materials
- Covering the target with a material that absorbs the EM waves or scatter it in some other direction (Camouflaging)

Figure 1. F-117 and B2 Bomber [43]

1.3.1 Target Shaping

Radar cross section plays the vital role in the detection of a target by scattering the least signal back to the receiving antenna. Shaping the target is main measure to be taken into account for RCS reduction. This should be taken care of right from the beginning of the designing. For shaping of the target, first rule to be kept in mind is to avoid large flat vertical surfaces. It is also required to avoid discontinuities in the design such as abrupt change of shape and corners. Aerodynamic shape requirement for the utmost functioning is not a helping measure for radar shaping. Hence other measures must be considered for disguising the target.

1.3.2 Radar Absorbing Material (RAM) and Structures (RAS)

Radar absorbing materials (RAM) have a characteristic of acting as lossy materials for the electromagnetic wave passing through it. Having high value of imaginary permittivity (ε'') and permeability (μ''), these materials have comparatively high value of electric and magnetic loss tangent[2]. These materials absorb a part of EM waves by dissipating its energy in the form of heat with the help of various loss mechanisms. To exploit this property of RAM, material is coated over target with a certain optimized thickness so that uniform absorption can be obtained. RAM has been widely used in stealth technology, to disguise the targets to be detected by radar. Various loss mechanisms which contribute to the absorption of wave in RAM are as follows

- Resonance Loss
- Dielectric Loss
- Conductance Loss
- Magnetic Loss

1.3.3 Camouflaging

Stealth technology covers a wide range of techniques used to make aircraft, missiles, satellites, ships and submarines to be less visible/ low observable. Camouflage is the term used for employing stealth technology into effective use. Camouflage is disguising of any animal, military personal, warfare equipment by blending into surroundings, making it difficult to be identified.

Radar camouflage acts as principle component in low observable technology. It is not always practical to apply the coating of RAM over all types of targets. Hence a special type of net is now of major interest which can be used as a cover to deceive the target or army personals from being detected by the enemy radar. Textile industries have fetched enormous interest for the manufacturing of nets, providing high absorption or the random scattering of incident EM waves to deceive the prey.

Chapter 2

Techniques for Measurement and Theoretical Background

To fully understand the stealth and camouflaging technology, it would be required to have a basic understanding of the principle of radar and wave propagation inside media. Loss mechanism of the material, different types of RAM, techniques to improve material characteristics, electromagnetic and optimization techniques to improve the absorption.

2.1 Radar Range Equation and RCS

Power of EM wave is maximum near its source while it attenuates as it propagates farther from the source. This attenuation depends on the interaction of wave to the media through which it is propagating. Radar range equation relates the power transmitted by radar transmitter (P_T) to power received by radar receiver antenna (P_R) and is given by:

$$P_R = \frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 R^4} \quad (1)$$

where,
$G_{T/R}$ antenna gain of transmitting and receiving antenna, respectively:
σ - Target RCS relative to polarization and radar orientation
λ - Operating wavelength
R - Separation distance between target and radar
Radar Cross Section (RCS) is a function of electromagnetic parameters of incident and reflected wave[3]. In order to make the aircraft undetectable by different radiations, geometry shaping in which incident radiations are reflected in a different direction which must be out of range of receivers is used. This concept uses the reduced cross section of the aircraft, as shape of aircraft plays a significant role in detection [4]. RCS of a target can be defined as the ratio of spherically scattered power density to power density of incident plane wave and can be given as:

$$\sigma = \lim_{R \to \infty} \frac{4\pi R^2 \times power\ density\ in\ scattered\ field}{power\ density\ of\ incident\ plane\ wave} \quad (2)$$

One important note inferred from (2) is the dependence of radar range on the RCS of the target and is fourth root of RCS. Which means, to cut down the range of radar to its half, reduction in RCS must be 87.5% and is not very easy to obtain. Scattering is not always the solution for the stealth technology as transmitter and receiver need not to be placed at the same location hence it’s not always so obvious to decide the required scattering angle of the target. Hence the concept of radar absorbing materials has been opted for further modification.

2.2 RAM Techniques

RADAR cross-sectional (RCS) reduction is critical toward defense targets. Various measures have been attempted to devise the so-called radar absorbent materials (RAMs), which can be used on radar targets to suppress RCS levels. Depending on the RCS reduction technique used, RAM can be either a layer of coating such as paint or a tile-like structure to be applied on target surfaces. Basic RAM techniques and materials which were being used for stealth technology are as follows:

- **Impedance matching**

If Z_o is the impedance of free space and Z_M is the impedance of the target material, then the reaction co-efficient at the interface is given by following equation:

$$R = \frac{Z_M - Z_o}{Z_M + Z_o} \tag{3}$$

The impedance of the free space, called intrinsic impedance is equal to 377 ohm. If the impedance of the reacting surface is made to match with the free space impedance, there will not be any reactions.

- **Equality of medium parameters**

Second condition to reduce the reaction coefficient to zero, with incident medium as free space, is for permittivity to be equal to permeability. This implies that when the real and imaginary parts of the permittivity and permeability are equal, then the reactivity is zero.

The normalized impedance of the medium can be expressed as:

$$\frac{Z_M}{Z_O} = \sqrt{\frac{\mu_r^*}{\varepsilon_r^*}} \tag{4}$$

Since the incident waves arrive from free space, then for zero reactivity, we must have $\varepsilon' = \mu'$. In other words, if the real as well as the imaginary parts of the permittivity and permeability are equal, then the impinging waves are not reacted.

- **Attenuation**

The attenuation of the wave as it propagates through the absorbing medium may also be responsible for minimizing the reactivity. If α is the attenuation constant, the wave decays exponentially with distance x, by the factor $e^{-\alpha x}$. The attenuation constant α depends on the medium permittivity and permeability. To have larger value of α in a small thickness, we must have large values of both real and imaginary components of electrical permittivity and permeability.

2.3 Radar absorbing structures

RASs are developed with various principles based on impedance matching, wave cancellation and converting energy to heat. Based on their principle of working they can be classified under some major classes named as resonant materials and impedance matched and are described below:

➢ Resonant Materials

Resonant materials, which are alias of tuned or quarter wavelength (λ/4) absorbers, work on the principle of destructive interference of waves. The wave will undergo partial transmission and partial reflection from first and second interfaces. Reflecting wave will be at π out of phase. As the distance between two consecutive reflections from two interferences adds to a sum of λ/2, the phase difference will be amount to be π resulting in destructive interference. The destructive interference of both the reflecting wave will result in zero or minimum reflection of the wave depending on the magnitude of the reflected waves [5].

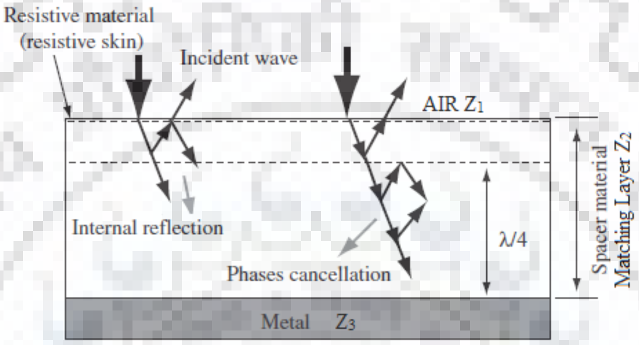


Figure 2 Mechanism of destructive interference of two reflective waves from different interfaces [5]

This mechanism is used in Salisbury Screen and Jaumann layers. The drawback of this mechanism is that it has low bandwidth, as the destructive interference directly depends on the frequency of incident wave.

➢ Salisbury Screen.

This absorber works on the principle of destructive wave interference of two reflecting waves which results in zero or minimum total reflection from the screen. As its principle is on wave interference hence this will not be depending on permittivity and permeability of the bulk layer. The setup consists of a metal plate and a resistive plate placed at a distance of odd multiple of quarter wavelength (λ/4), due to the fact that electric field intensity is maximum at this distance, usually the separating layer is filled with air, but can be filled with some other dielectric material as well[6],[7]. The impedance of the screen will be $377/\sqrt{\varepsilon_r}$ Ω per square meter and the distance of the screen should be $d = \lambda / 4\sqrt{\varepsilon_d}$, where, ε_r and ε_d are permittivity of medium and spacer respectively. The concept of impedance matching has been used to calculate the resistivity of the resistive screen.

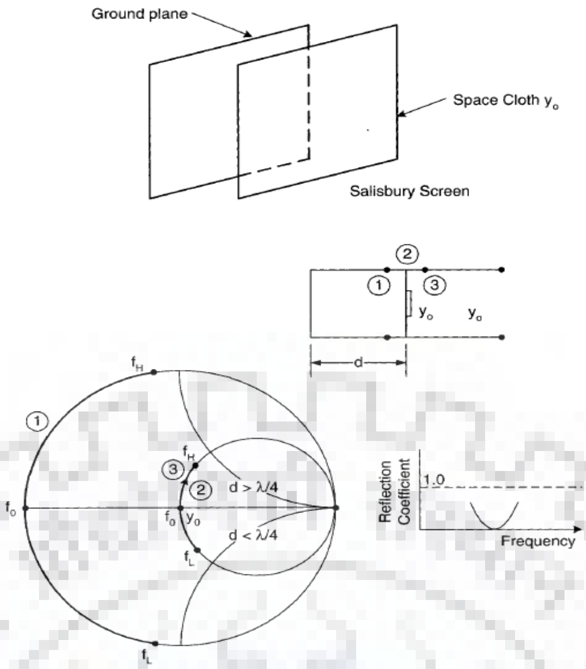


Figure 3. Salisbury Screen and smith chart representation [6]

➢ **Jaumann Layer**

Jaumann layer is a method of increasing the bandwidth of Salisbury screen. It can also be called as multilayer Salisbury Screen, as it also follows the principle of the former one. It consists of equally spaced resistive sheets in front of the conducting plane to produce minima in the reactivity, the layer are spaced at a distance of λ/4 and thus increasing the bandwidth.

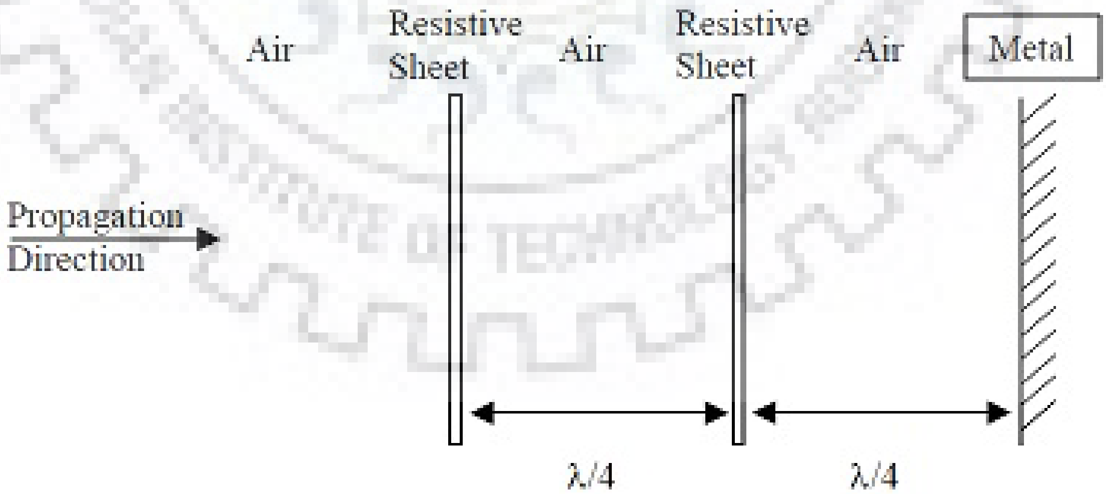


Figure 4. Jauman Layers [6][8]

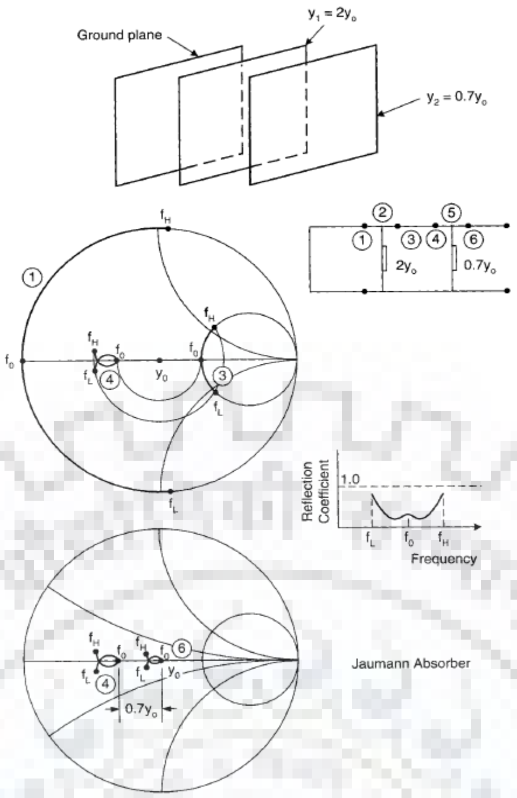


Figure 5. Jauman Layers [6][8]

- **Dallenbach Layer**

While the above two absorbers use the resonant concept for the destructive interference to minimize reflection, the next absorber uses the concept of EM wave to material interaction for the absorption of the wave while propagating through it. This structure consists of a conducting plane coated with a homogeneous layer of absorber. The thickness, permeability and permittivity of the absorber layer are adjusted as per the requirement of minimized reflection for a desired wavelength. The layer of absorber is made by filling various absorbent like, TiO_2, SiC or carbon black. This works on the principle of destructive interference of two waves, both reflecting from adjacent interfaces. The bandwidth of operation is narrow because of the single layer.

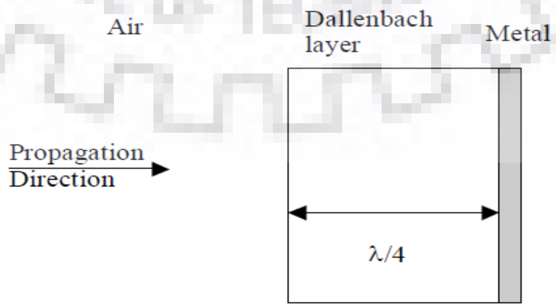


Figure 6. Dallenbach Layer[9]

The input impedance at the boundary of Dallenbach layer can be calculated with the help of [9]:

$$Z_{in}^{TE,TM} = jZ_1^{TE,TM} \tan(k_{Z_1} d_1) \tag{5}$$

where, Z_1 is intrinsic impedance of spacer and then the reflection coefficient can be calculated as [9]:

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{6}$$

2.4 Impedance Variation Method

When a wave impinges on any material it experience the phenomenon of reflection and transmission, a part of it will transmit and rest will be reflected back depending on the properties of material. To increase fraction of transmitted part and minimize the reflection, impedance matching plays a vital role. In order to achieve impedance matching following methods can be used.

➢ **Gradual Impedance using Shape**

This method uses pyramidal or conical structures of same material, to provide variable impedance with respect to distance along propagating wave. Due to this the wave observes a gradual transition of impedance while travelling from air to the observer, hence provides more impedance matching then direct change in impedance. The order of periodicity and height of the pyramids should be of unit wavelength. If the structure is shorter, the wave will meet more abrupt change in impedance. Thus pyramidal structure will have minimum operating frequency after which it will provide high attenuation. This design is widely used in anechoic chamber.

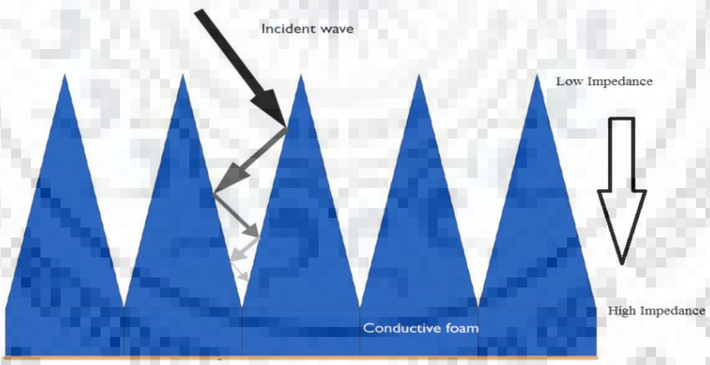


Figure 7. Pyramidal absorber with gradual impedance change depiction [11]

➢ **Diminishing Impedance by Varying Material**

In this method instead of varying shape, the material of varying property is fabricated together to provide impedance matching. Materials with decreasing characteristic impedance are fabricated in multilayered structure to provide gradual decrease impedance as going from air towards material. To obtain this diminishing impedance we can opt for layer by layer deposition of various materials with decreasing characteristic impedance or a material with the decreasing gradient of characteristic impedance perpendicular to the surface. The advantage of this method is thinner structure but lacks from pyramidal absorber due to poor performance corresponding to different wavelength.

➢ **Single Layer Absorber**

The concept of using single layer absorber is to use the spacer material between metal plate and the resistive layer, impedance of this spacer should be square root of the product of end layers impedances$(Z_1Z_2)^{1/2.}$

$$Z_S = \sqrt{(Z_1 \times Z_2)} \tag{7}$$

Single layer absorber uses the concept of impedance matching and destructive interferences of the inter-reflecting waves within the spacer material [12]. The spacer distance provokes the phase cancellation destroying the incident wave. While for the use of both the concepts the distance of the material is needed to have thickness of quarter wavelength. This will lead to the drawback of high thickness of the absorber. Dependence of thickness towards wavelength restricts the bandwidth.

2.5 Radar Absorbing Materials and Material wave interaction

Radar absorbing materials (RAM) possess different electromagnetic characteristics: high value of imaginary permittivity (ε′′) and permeability (μ′′), to absorb microwave[13]. These materials absorb a part of EM waves by dissipating its energy in the form of heat with the help of various loss mechanisms, while it passes through the material. Energy loss inside a material occurs by the damping of polarized atoms and molecules during the interaction between material and EM wave. Conductivity of the material also combines its effect on losses. The energy conservation can be used to calculate the power dissipated in the form of heat by using Poynting theorem.

$$\frac{\partial u}{\partial t} + \nabla . S = -j.E - 2\omega \operatorname{Im}(\varepsilon \left\langle |E|^2 \right\rangle + \mu \left\langle |H|^2 \right\rangle) \tag{8}$$

where,

$$u = \operatorname{Re}\left[\varepsilon_0 \frac{d(\omega\varepsilon)}{d\omega} \left\langle |E|^2 \right\rangle + \mu_0 \frac{d(\omega\mu)}{d\omega} \left\langle |H|^2 \right\rangle \right] \tag{9}$$

denotes the time average over the period of carrier frequency, and $S = E \times H$ is the Poynting vector. To exploit this property of RAM, material is coated over target with a certain optimized thickness so that uniform absorption can be obtained. RAM has been widely used in stealth technology, to disguise the targets to be detected by radar. Various loss mechanisms contributing to the absorption of wave in RAM are as follows.Dielectric Loss

In dielectric materials, an insulating materials which can be polarized on application of electric field, the positive and negative charges with distance (d) apart forms electric dipole. Initially oriented randomly, on applying electric field, dipoles align themselves in accordance with applied electric field. The movement it requires to align is dielectric dipole moment and for this movement the energy required will be a fraction of incident electromagnetic energy[14], [15]. The permittivity of a material is the ability of polarization in the presence of electric field. When current is applied, a relaxation time is observed and this is limited by higher frequencies. This opposition against applied electric field gives the concept of complex permittivity.

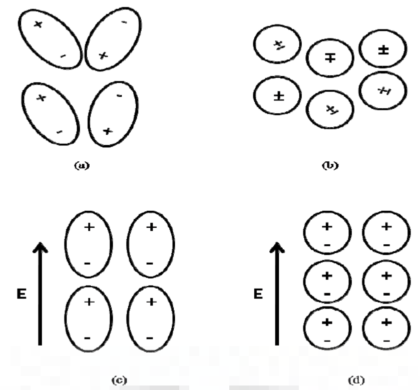


Figure 8. Alignment of dipoles in accordance with applied electric field [16]

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{10}$$

Real part of permittivity (ε') represents the energy storage, and imaginary part (ε'') represents the loss of power in Ratio of imaginary to real part of permittivity gives the loss tangent of the material, this is termed as dielectric loss tangent ($\tan \delta_\varepsilon$).

- **Conductance Loss**

Due to finite conductivity of the materials, energy of the EM wave is absorbed by the movement of electrons in the material. The energy absorbed by the free electrons is due to their movement and collision from one another, as well as with the fixed atoms of lattice and the vibration of lattice atoms around its fixed position comes under conductance loss. Total dielectric loss and conductor loss are non-separable [14][15].

$$\tan\delta = \frac{\omega\varepsilon'' + \sigma}{\omega\varepsilon'} \tag{11}$$

The power absorbed per unit volume at any instant:

$$P = \sigma|E|^2 = \omega\varepsilon_0\varepsilon' \tan\delta_\varepsilon |E|^2 \tag{12}$$

- **Magnetic Loss**

Pauli Exclusion Principle states that the attraction of unbalanced magnetic spin towards magnetic field is termed as “para-magnetism”, similar electrons in the material when interacts with the magnetic field of the EM wave, try to align with the field[14].

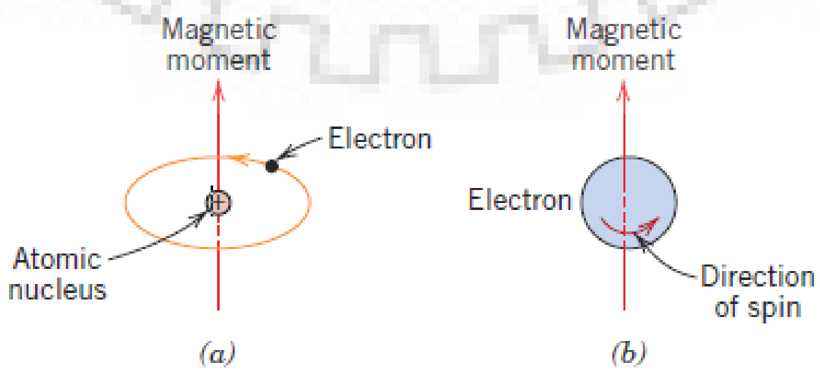


Figure 9. Moment of electron causing magnetic dipole moment [16]

This alignment of unpaired electrons with the magnetic field corresponding to EM wave will dissipate energy which is considered as magnetic loss.

$$\mu = \mu' - j\mu'' \quad (13)$$

$$\tan\delta_{\mu} = \mu''/\mu' \quad (14)$$

$$P = \omega\mu_0\mu''|H|^2 \quad (15)$$

The power absorbed can be given using [16]

$$P = \omega\mu_0\mu''|H|^2 = \omega\mu_0\mu'\tan\delta_{\mu}|H|^2 \quad (16)$$

Magnetic loss can be due to hysteresis loss (16), can be explained by B-H curve or eddy current losses, for example due to electron hopping mechanism in ferrites [17].

$$W_h = \oint BdH \quad (17)$$

$$W = \sigma\int E^2 dV \quad (18)$$

Carbonyl iron and hexa-ferrites are the bases of magnetic absorber and the range of absorbance of these materials is in the MHz and GHz. The resonant frequency of the material is related to size of the particle[9]. Ferrites having constant permittivity in a range of frequency, their microwave absorbing characteristics can be analyzed using complex permeability spectra. The study of optical properties of M-Type hexa-ferrites and measurement of absorption by the researchers has been reported. It was reported that spin resonance affects 1st matching frequency and 2nd matching frequency, due to domain wall motion, is independent

2.6 Frequency selective surfaces (FSS).

Frequency Selective Surfaces consists of periodically arranged structures of metallic patches with similar geometry, which are used as filters in microwave and optics as well. FSS based advanced EM structures comprises of metallic patches as well as their complimentary structure. FSS works on the principle of horizontal and vertical metallic strips working as inductors and capacitors depending on their orientation with respect to the polarization of incident electromagnetic wave. The perimeter of the FSS patch should be nearly equal to the wavelength of the incident wave. The period with which similar patches are being repeated should be less than the smallest wavelength [6][21].

2.6.1 Mechanism of FSS.

Interaction of incident EM wave with free electrons in the metallic patches leads to motion of electrons in the direction depending on polarization of the incident wave. This motion of free electrons makes the metallic patch to act as circuit elements and hence affects the frequency response of FSS. Figure 9 illustrates the concept of metallic stripes working as inductors and capacitors is supported by the concept of free electron oscillating due to effect of electric field associated with electromagnetic wave, which is explained below[21].

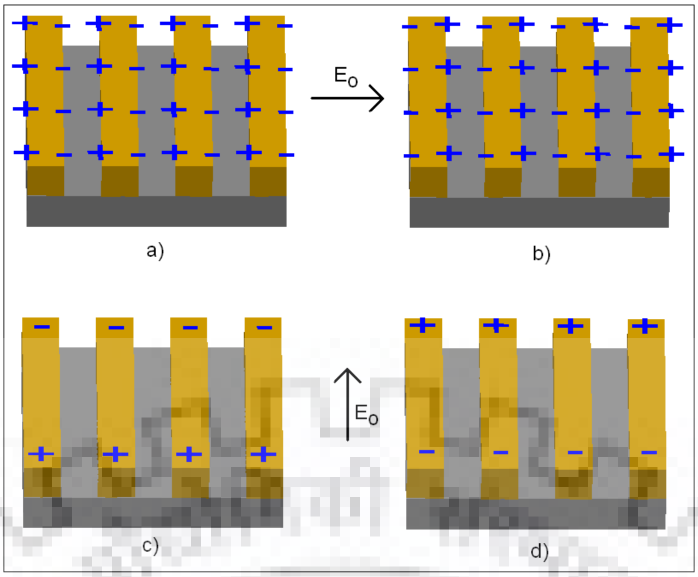


Figure 10. Effect of oscillating electrons inside metallic patch as inductor and capacitor [21]

2.6.2 FSS Equivalent Circuit Modelling.

Implementing circuitry design provides us the freedom and flexibility to design and also includes loss mechanism due to induction and capacitance. Absorption can be made sensitive to a particular frequency or can also be tuned by varying inductance and capacitance of the circuit. Research in the field of materials towards their property of absorbing microwave and dependence on their characteristics is under trial. For the appropriate calculations of the impedance due to FSS, various approximations are used. To analyze the properties of a FSS model, we create its equivalent circuit model and then compare its transmission characteristics with experimental results.

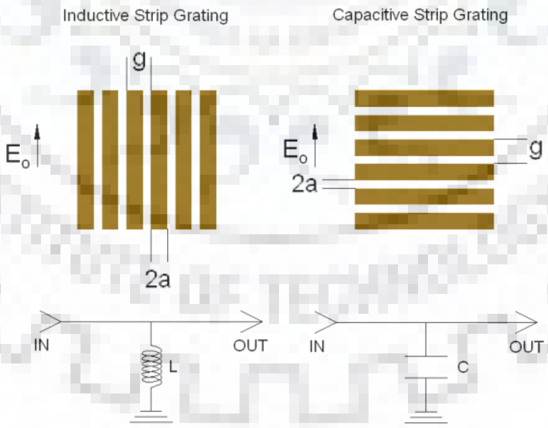


Figure 11. Equivalent circuit corresponding to parallel stripes [21]

The Figure 11 shows the working of metallic patch parallel to electric field as inductor, similarly, the patch perpendicular to electric field will work as capacitor. The equivalent circuit method includes calculation of impedance of FSS which must comprise resistive, inductive and capacitive equivalent of the structure [22].

$$Z_{FSS} = R + j\omega L + \frac{1}{j\omega C} \tag{19}$$

Total impedance of the structure will be the parallel addition of individual impedance of FSS and equivalent impedance at some distance d[22].

$$\frac{1}{Z_S} = \frac{1}{Z_d} + \frac{1}{Z_{FSS}} \tag{20}$$

This can be represented by the following figure.

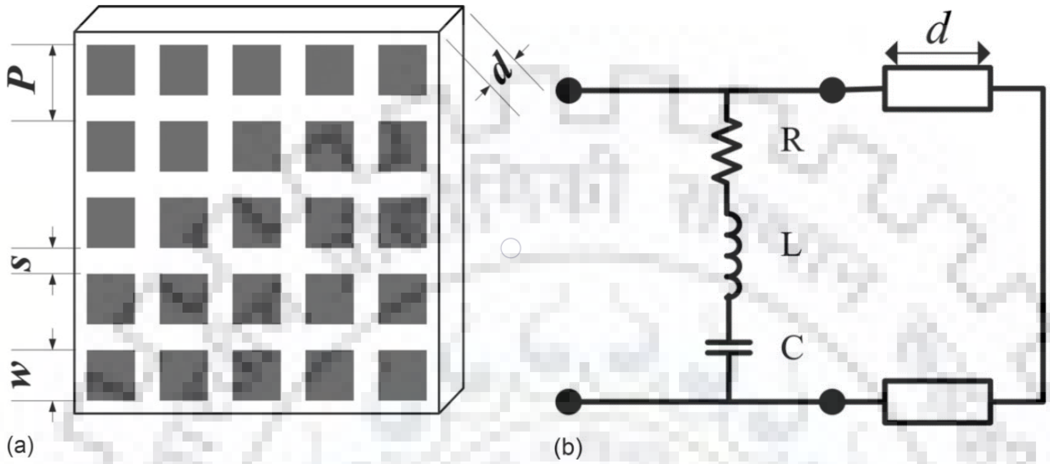


Figure 12. (a) Three dimensional structure of FSS and (b) Equivalent Circuit [22]

2.6.3 **Passive FSS.**

FSS with a predefined structure of metallic conductors cannot be modified once they are fabricated and hence leave us with no choice of variation in operating frequency or bandwidth control on real time operations as we are having fixed combination of patches. The different FSS filters are as follows:

- Band pass Filter
- Band stop Filter
- Low pass Filter
- High pass Filter

The Babinet principle is used to transform from a low-pass FSS to a high-pass FSS, from a band-stop FSS to a band-pass FSS, and vice-versa. A low-pass filter permits lower frequencies to pass through the circuitry, while the high frequencies are blocked. The high-pass FSS can be Babinet complement of the low-pass FSS as shown in Fig 12. FSS acts like a series or parallel RLC circuit based on its high pass and low pass characteristics. The Resistor and Inductor can be created by the patches of FSS, while Capacitance can be induced by the gaps between the FSS. The physical meaning of these C and L values of different FSS can be understood using simple electrostatic principles like capacitance of a parallel plate capacitor and inductance of two parallel wires. The inductive and capacitive surfaces can be combined together to produce a filter response which is desired. Any variation in the FSS dimensions leads to a corresponding change in the inductance and capacitance values [21].

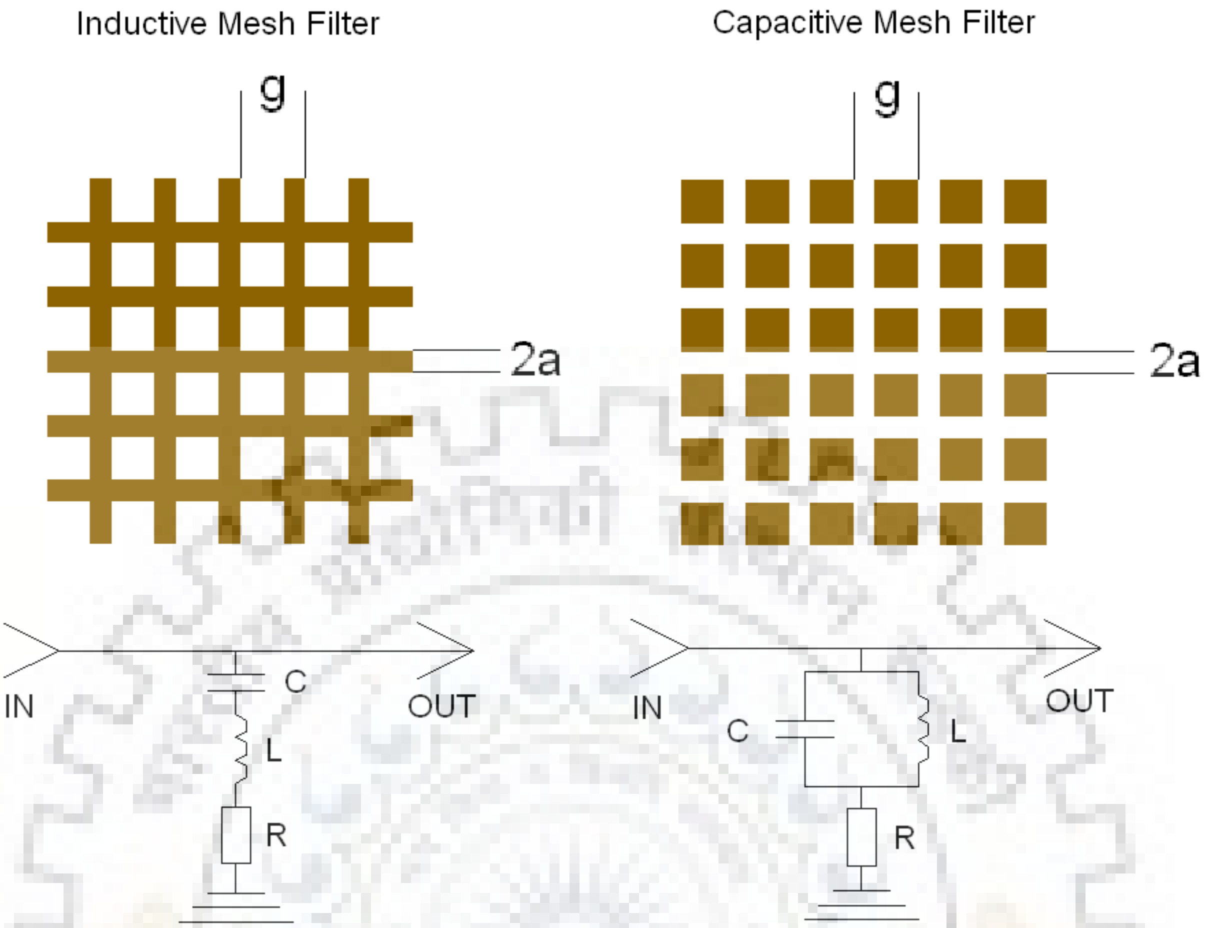


Figure 13. Equivalent circuit for FSS: Low pass filter (a and c) and Complementary FSS: High pass filter (b and d) [21]

2.7 Methodologies to improve the absorption of RAM

After thorough study of RAMs and their use in various applications, the limitation of bandwidth and rigidity in the results of fabricated products led to improvement of RAMs by various methods like multi-layering and blending the concepts of resistive screen and FSS together in circuit analog RAM.

2.7.1 Circuit Analog RAM

In circuit analog absorbers, the resistive sheets used in resonant RAMs are replaced with lossy materials deposited in geometric patterns on a thin lossless sheet. This implies that capacitance and inductance are now added to resistive sheets. The effective resistance of the RAM is determined by the thickness of the lossy material. The shape, geometry and spacing of the patterns determines the effective inductance and capacitance. These materials have improved reactivity and bandwidth performance and also have reduced thickness. Circuit analog RAMs are based on magnetic absorbers as these can be placed against the metal surface, resulting in thinner absorbers than the electrical analogs, which are spaced λ/4 wavelength from the metal surface [6].

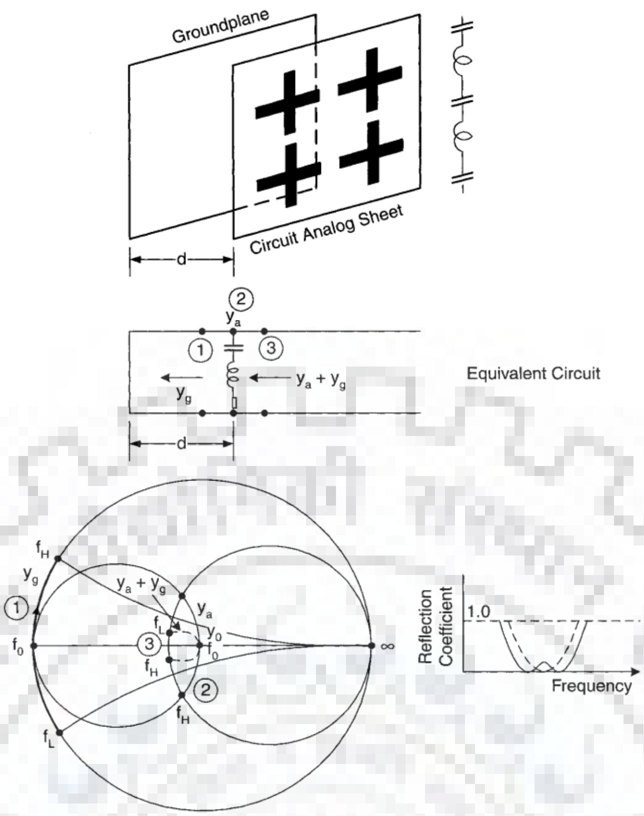


Figure 14. Circuit Analog RAM [6]

2.7.2 Multilayer RAM

Multi-layering of various RAMs with distinguishable electromagnetic properties follows the principle of impedance matching. The distinct layers with their individual thickness, permittivity and permeability give various interface which makes an incident wave to undergo various reflection and transmission. So by optimizing various parameters of the multilayer like dielectric constant, number of layers, thickness of layers, permeability etc. maximum impedance matching can be obtained by minimizing the reflection coefficient of the incident wave and hence maximum absorption is achieved.

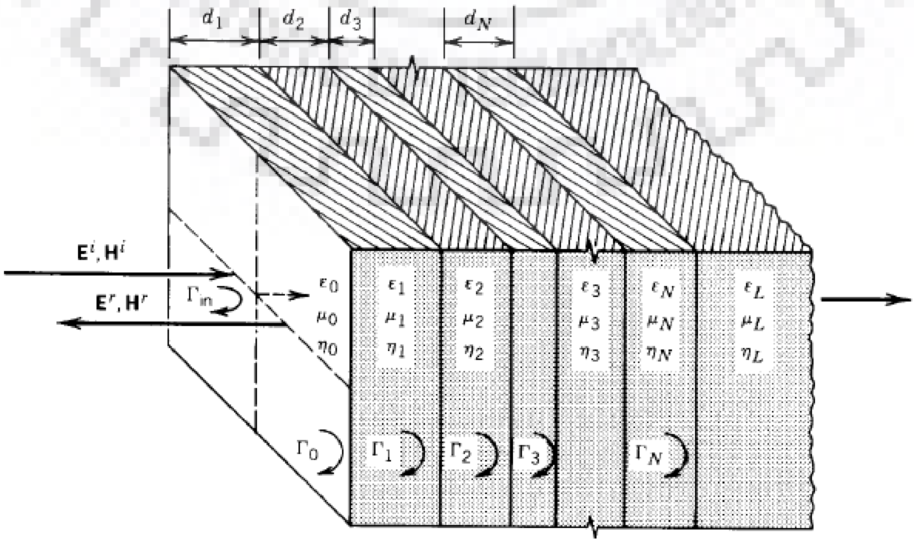


Figure 15. Schematic diagram of multilayer absorber [24]

In the Figure 15 $\varepsilon_i, \mu_i, \eta_i$ and d_i represents permittivity, permeability, intrinsic impedance and thickness of the i^{th} layer respectively.

Reflection coefficient between two consecutive layers can be calculated by the formula give as[24]:

$$R_{i,\,i+1} = \frac{R_{i,\,i+1} + R_{i+1,\,i+2}\,e^{-j2k_{i+1}d_{i+1}}}{1 + R_{i,\,i+1} + R_{i+1,\,i+2}\,e^{-j2k_{i+1}d_{i+1}}} \qquad (21)$$

Where, for TE polarization:

$$R_{i,\,i+1} = \frac{\mu_{i+1}k_i - \mu_i k_{i+1}}{\mu_{i+1}k_i + \mu_i k_{i+1}} \qquad (22)$$

and for TM polarization:

$$R_{i,\,i+1} = \frac{\varepsilon_{i+1}k_i - \varepsilon_i k_{i+1}}{\varepsilon_{i+1}k_i + \varepsilon_i k_{i+1}} \qquad . \qquad (23)$$

$k_i = \omega\sqrt{\varepsilon_i \mu_i}$ and R represents recursive calculation of total reflection coefficient of multilayer. The multilayer absorber is plagued with the absorption for all band of frequency, which limits its efficiency towards absorption. To overcome this a concept of Frequency Selective Surface as introduced [24] [25].

Chapter 3

Literature Review

3.1 Radar absorbing material

3.1.1 Polymer composite filled with carbon particles

Control over bonding between carbon and other particles by varying chemical reaction and atmospheric conditions, provides tremendous application of C. Tailored down carbon with the help of nanotechnology, making it in the form of carbon nanotubes opened a whole new capability of carbon as the filler in polymer matrix. C based materials filled inside polymer matrix. C based materials filled inside polymers show extensive strength and durability providing mechanical advancements and the electrical conductivity of the fillers come out to be helping for microwave absorption mechanisms.

V.B. Berger analyzed and reported advantages of ferromagnetic nanoparticle composite compared to bulk properties of the same, examines the properties of nanocomposite and contribution to microwave absorption. Use of metallic nanoparticles as inclusion has been compared to that as inclusions has been compare to that of common dielectric and ferromagnetic absorbers and significantly better characteristics has been reported [29]

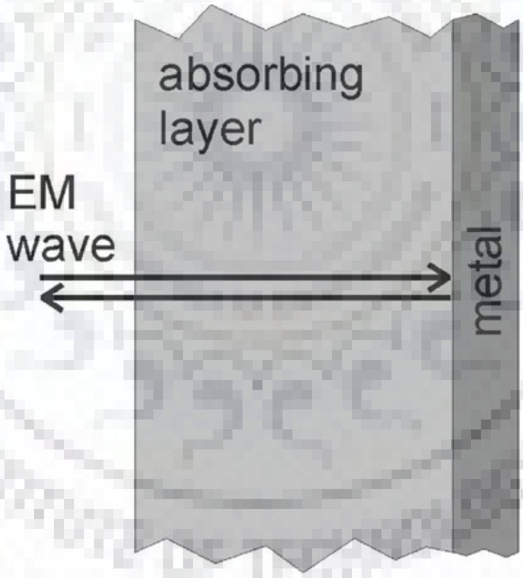


Figure 16. Radar absorbing material of ferromagnetic nanoparticle composite.

3.1.2 Composites reinforced with metal particles

Hai Yan Chen et. al., in year 2010 designed an ultra-thin radar absorber with thickness of 2 mm and then enhances its bandwidth by using FSS. Authors used concept of minimum thickness of absorber discussed by Rozanov in year 2000. Authors found an increase of 1 GHz in bandwidth by using single layer FSS and of 1.22 GHz by using double layer FSS. Effects of polarization and angle of incidence have been studied and find that operating frequency for TM is decreasing whereas for TE increasing [33].

Liangkui Sun et al., in 2012, designed a magnetic radar absorber equipped with resistive FSS working in the frequency range of 1-18GHz. The absorber layer with thickness of 5 mm and density of 0.62 g/cm3 over which embedded with resistive FSS reported an enhancement in microwave absorbing capability. The square patch FSS has been made the unit cell which exhibits absorption of -10 dB, the value obtained from Genetic algorithm- the optimization tool. The operating bandwidths of 4.07–18 and 3.19–18 GHz of the single-layer and double-layer FSS-embedded RAs has been reported by the author [31].

A. terber et. al., in 2016, in their paper presented a coating of highly conductive , magnetic materials nickel and Cobalt over polymer polyacrylonitrile (PAN), to obtain high electric and magnetic tangent losses resulting for a wideband absorption for 14GHz to 18GHz, 10dB RLBW and approximate 2GHz BW corresponding to 20 dB RL [34].

3.2 Concept of camouflage

3.2.1 Knitted camouflage material

E.W Wallin, in Dec 1977 claimed an invention of a base fiber for a radar defeating camouflage. The invention comprised of knitted fiber with a plurality of holes in it making it stretchable. The strands used to fabricate constitutes of spun mixed of non–continuous electrical conducting material blend with polymeric fiber like nylon or polyester. Conducting material with a total weight percentage of 2-10%. Average diameter of electrical conducting fiber kept to be about 0.008 to 0.02 mm and average length was kept about 70 mm, varied as per the requirement of frequency response. The yarn knitted has been given a diamond shape structure to make it stretchable. The aim kept in mind was to make it reflect about 40% of what a metal plate with equal area would reflect, so as to make it blend with the surroundings. Cross and co-polarization detection has been taken care by not arranging the metal fibers in a particular orientation [ ].

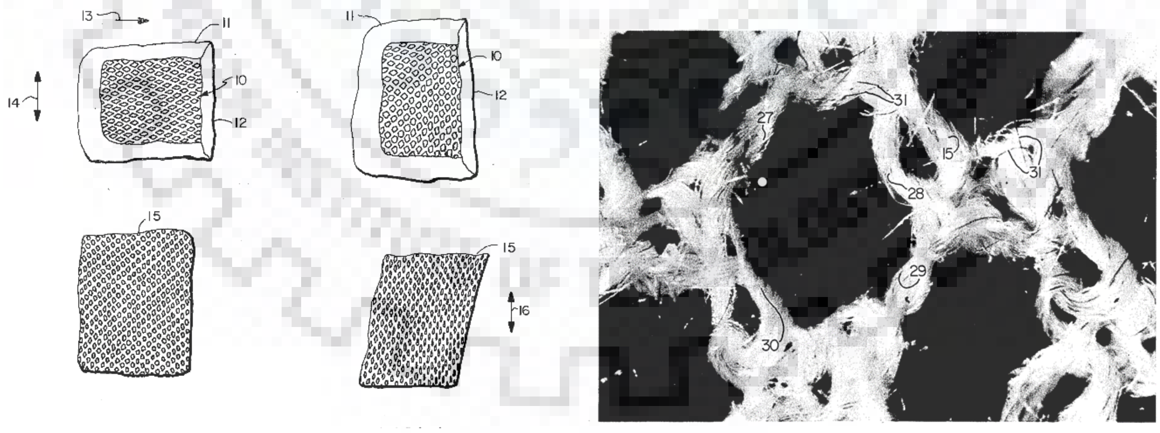


Figure 17. Hexagonally knitted camouflage material

For the calculation of power to be absorbed or scattered by the conducting elements present in the invention, which are acting as array of dipole antennas, the reference cam be taken from the following governing equations for scattered and absorbed power in receiving antenna [35]:

$$\{[Z]+[Z_L]\}[I]=[V] \quad (24)$$

$$V_i=\int F_i(x)E_x dx \quad (25)$$

$$P_L = [I]^t[Z_L][I]^* \quad (26)$$

$$P_s = [I]^t[Z][I]^* \quad (27)$$

Where, $F_i(x)$ is the piecewise sinusoidal expansion mode function, P_L being the power absorbed by dipole array, P_s being power scattered and $[Z_L]$ being the diagonal matrix of load impedance.

G. Redlich wt. al. in 2014 presented newly designed knitted and woven textile for camouflage radar, they emphasized on distribution of electrically conducting yarns over the entire arrangement. Polyester has been taken as sample for the observation of radar camouflage. Various arrangements of knitted fiber has been combined to form the two dimensionally oriented material. Time domain method has been taken for analyzing in the free space measurement. The fabricated material has been analyzed for vertical as well as horizontal polarization [36].

3.2.2 Multilayered camouflaging

P.M. Francis et. Al., in May, 1994 claimed invention of a camouflage blanket with non-flammable carbonaceous material providing wide heat and radar signature reduction. They claimed to have used the flexible non-conducting layer of carbonaceous fiber and second flexible layer of electrically conducting fibers for absorption of EM waves. Through the use of different layers, they made it possible for the structure to absorb radar waves over required band of frequency by using multilayer concept. Authors used the inclusion of randomly oriented dipole material having a semi-conductive property of half wavelength dimensions [27].

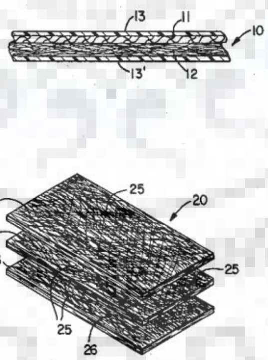


Figure 18. Multi-layered camouflage blanket [27]

A.D. Child, in Sep, 2011, claimed a radar camouflage fabric with average transmission of 50% in the bandwidth 6 to 8 GHz. The camouflage claimed here is comprising of two layers, top layer being the electrically conductive garnish with a plurality of holes to provide partial transmission of EM waves, while base layer is having a resistive value of about 10000Ω per square acting as EM wave transparent layer. Standard deviation (deviation described in MIUL-PRF-53134) has been taken as a measure of ability to camouflage the material. Conductive polymer has been considered to be more effective than the carbon based coating as it does not result into thick coating as in case of carbon based coating [37].

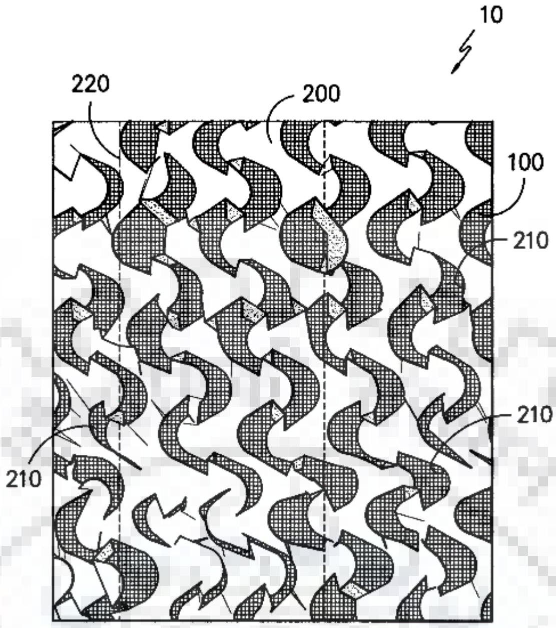


Figure 19. Double layer camouflage fabric with conductive garnish and resistive base layer [37]

3.2.3 **FSS Embroidery**

M.S. Hesarian et. al. presented a paper on the use of conductive fiber for knitting of FSS on the clothing to obtain the frequency selective property on the woven cloth. He has used this mechanism for EM shielding of GSM 1800 frequency band. The same model can be used for using frequency selectivity in the camouflaging net [38].

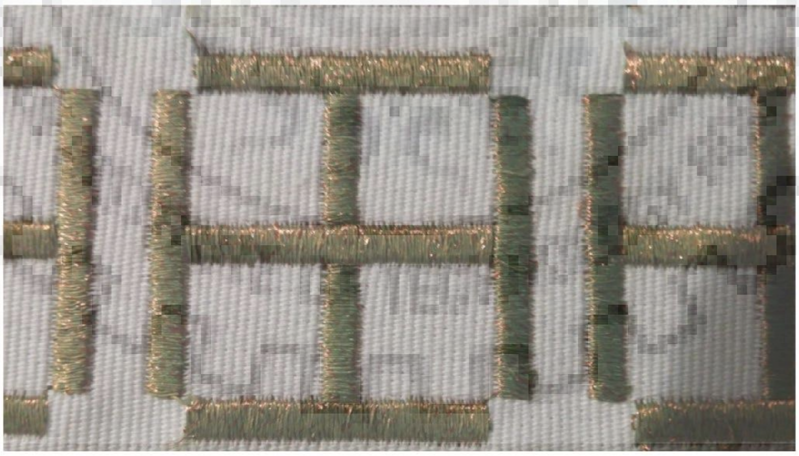
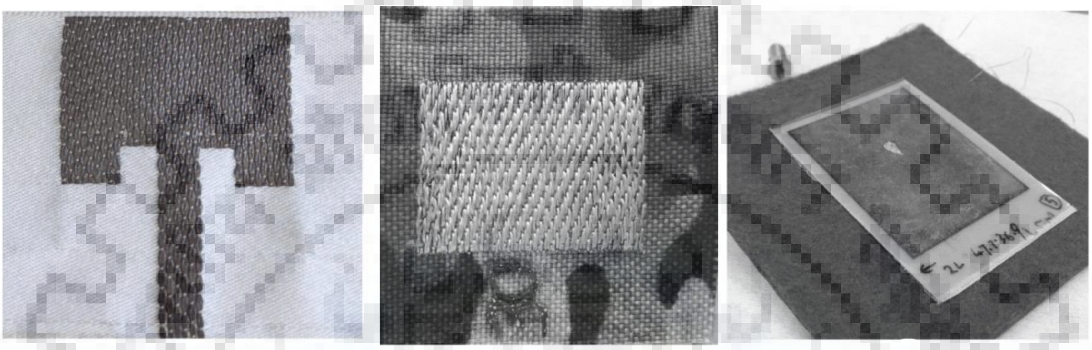


Figure 20. FSS embroidery on plane cloth [39]

A. Chauraya et.al., demonstrated the possibility of highly flexible FSS design of FSS on textile using embroidery. They have simulated and measured the wearable design of knitted structure for the shielding at 2 GHz frequency for wearable filters [40].

S. Zhang et. al., reported wearable material with antenna and FSS on them. They have compared the embroidery, weaving and inkjet printing of conductive ink over the wearable.

Antenna and FSS structure have been fabricated onto textiles with the help of all three above mentioned methods and it was found that embroidery is easy and can be created over any textile even afterwards but adds thickness to existing textile material, weaving the textile with the conducting yarn with previously selected patterns would be better for unadded thickness hence wearable comfort, while both weaving and embroidery can be used only for larger structure which means covering lower frequency only, but in the case of higher frequency, as the antenna and FSS sizes will start decreasing and hence will not be practically possible to implement above techniques hence will have to shift towards ink jet printing even being costlier [41].



(a) (b) (c)

Figure 21. Textile manufacturing techniques (a) weaving (b) embroidery and (c) ink jet printing [41]

Chapter 4

Development of Camouflage net for frequency range from 1-18 GHz

Camouflage acts as principle component in low observable technology. It is not always practical to apply the coating of RAM over all types of targets. Hence a special type of net is now of major interest which can be used as a cover to deceive the target or army personals from being detected by the enemy radar for a wide band of frequency. Textile industries have fetched enormous interest for the manufacturing of nets, providing high absorption or the random scattering of incident EM waves to deceive the prey. Various techniques being used for camouflaging net are: -

(i) Yarns made of electrically conductive fiber and polymeric fabric coated with RAM. [36]

(ii) Knitting of FSS using conductive fiber on clothing. [38]

(iii) Weaving, Embroidery and inkjet printing of conductive paint on cloth to achieve FSS properties [41].

4.1 Theoretical Background of the concept for absorption in Camouflage

Frequency Selective Surfaces consists of periodically arranged structures of metallic patches with similar geometry, which are used as filters in microwave and optics as well. FSS based advanced EM structures comprises of metallic patches as well as their complimentary structure. FSS works on the principle of horizontal and vertical metallic strips working as inductors and capacitors depending on their orientation with respect to the polarization of incident electromagnetic wave. The perimeter of the FSS patch should be nearly equal to the wavelength of the incident wave. The period with which similar patches are being repeated should be less than the smallest wavelength [6][21]. Based on the structure of FSS which is desired for camouflaging can be broadly classified as:-

- Symmetric FSS
- Asymmetric FSS

4.1 Symmetric FSS

In order to attain desired wide band absorption symmetric FSS are widely designed. Symmetric FSS exhibit wide band absorption based on the scattering or the reflection techniques. In scattering based technique the only parameter which needs to be optimized is the reflection coefficient i.e S_{11}. Scattering based camouflage net as seen from various above-mentioned papers can only provide low observability for a very narrow band of frequency or for a particular frequency which is the resonating frequency for the designed FSS. Symmetric FSS based on the arrangement of elements can be classified into four groups []:-

- Group 1: The center connected or N–pole such as the Jerusalem cross, square spiral.
- Group 2: The loop type structures such as the square, hexagonal loops.
- Group 3: Solid interior of plate types of various shapes.
- Group 4: Combination of any two of above mentioned group.

In order to understand it better few designed symmetric FSS are shown below.

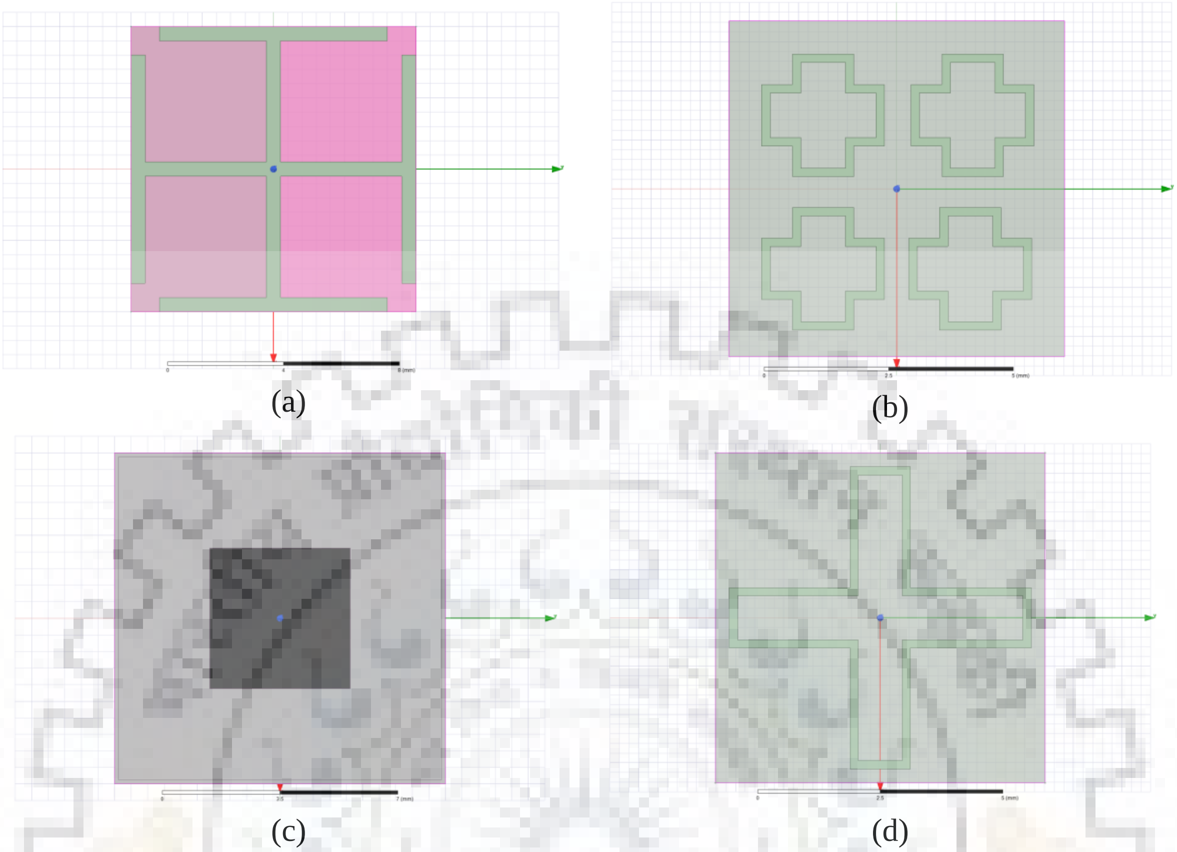


Figure 22. Symmetric FSS (a) Jerusalem Cross (b) Multi cross FSS (c) Square patch FSS (d) Cross FSS

4.2 Asymmetric FSS

An asymmetric FSS is a multi- layered structure which has different design or arrangement of patches on its either side. Such FSS are designed when it is desired that both the transmission and the reflection co-efficient need not be conjugate of each other at resonating frequency of that particular structure. One the other hand camouflage net based on absorption techniques provides low observability for a very large band of frequency, in our case from 1-18 GHz. Both the reflection and transmission co-efficient i.e S_{11} and S_{21} should be below -5dB in order to get desired absorption. Wide band absorption-based camouflage can be achieved by using a asymmetric FSS design by providing special emphasis to the dimension and the thickness of the substrate. Absorption of EM waves for any material is governed by[]:-

$$|A| = 1 - |S_{11}|^2 - |S_{21}|^2 \tag{28}$$

Therefore to design a wide band camouflage net based on the absorption principle, design of asymmetric FSS becomes a very important factor. The designed asymmetric FSS for camouflage net is shown in the Figure 23.

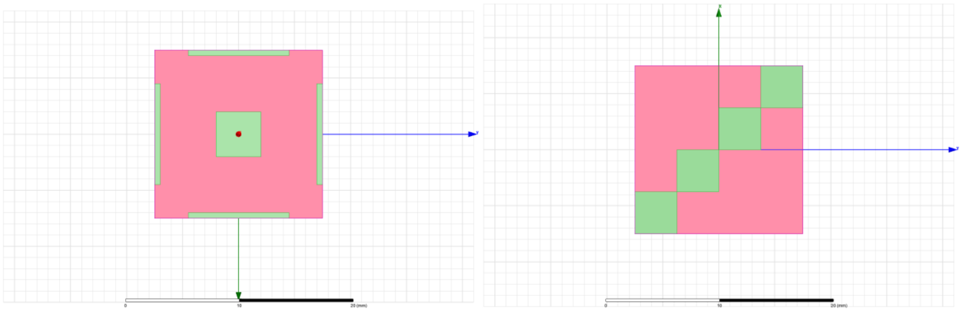


Figure 23. Top and Bottom view of an Asymmetric FSS

4.2.1 Design Parameters for Asymmetric FSS

The operation mechanism of FSS is based on the resonant elements. The idea is that a plane-wave illuminates an array of metallic elements, thus exciting electric current on the elements. The amplitude of the current generated depends on the strength of the coupling of energy between the wave and the elements. The coupling reaches its highest level at the fundamental frequency where the length of elements. As a result, the elements are shaped so that they are resonant near the frequency of operation. Various design parameters which determine the resonating frequency for FSS are: -

- Length
  Increasing the length of the patch reduces the resonant frequency.
- Width
  Increasing the width of the patches increases the bandwidth and increases the resonant frequency slightly.
- Thickness
  Increasing the substrate thickness decreases the resonant frequency.
- Corners
  Rounding the corners of the crosses increases the resonant frequency.
- Center-to center Spacing
  Increasing the center-to-center spacing of the crosses decreases the bandwidth.

4.2.2 Fabrication of Asymmetric FSS

The desired asymmetric FSS was printed on the test cloth with known permittivity and permeability of ε =1.5 and μ=1.05 using a copper conductive paint. An array of unit cell was printed on the cloth with dimensions of 1feet × 1feet using frame printing techniques. The top and bottom array of unit cell is as shown.

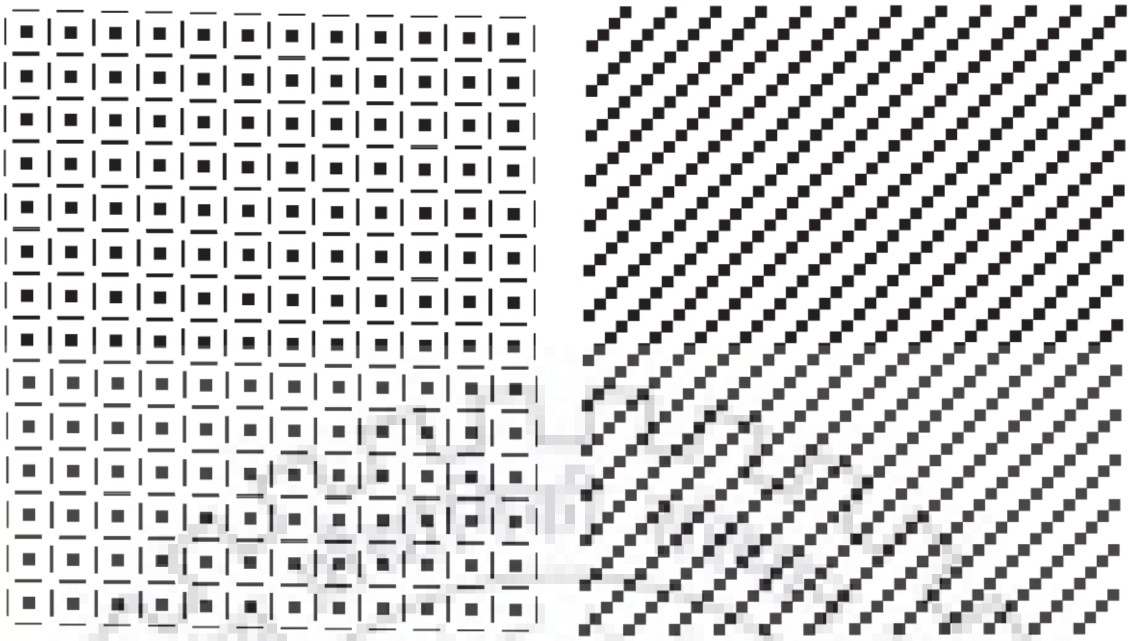


Figure 24. Top and Bottom view of asymmetric FSS to be fabricated

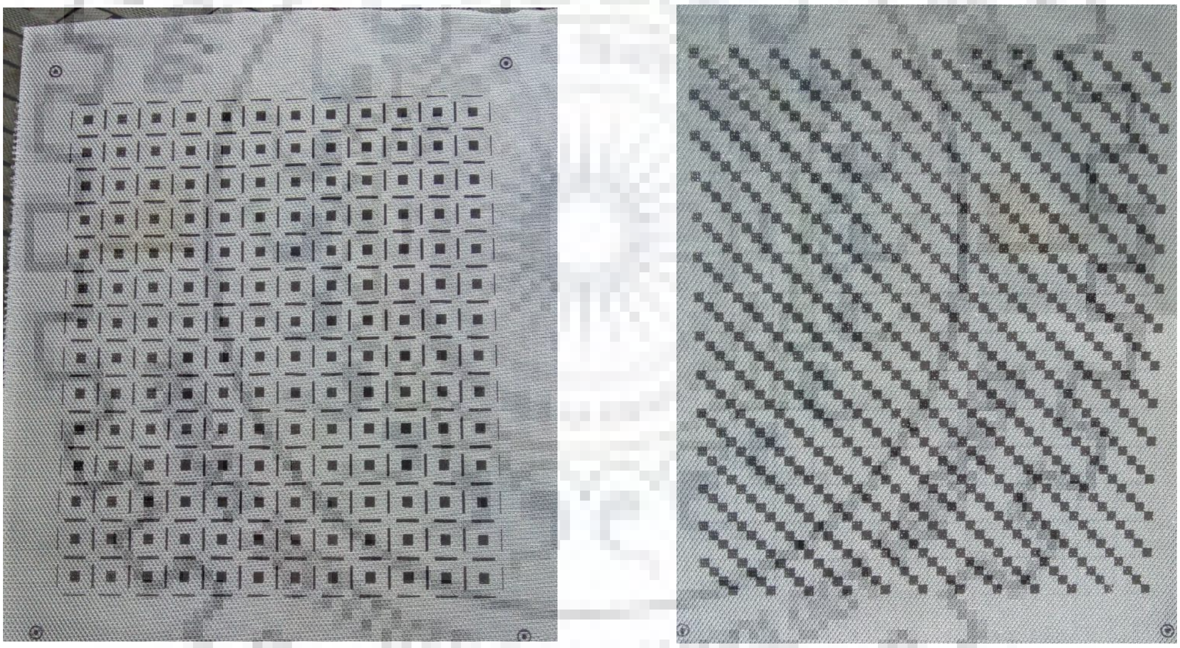


Figure 25. Top and Bottom view of fabricated Asymmetric FSS

Chapter 5

Result and Discussion

In order to design and fabricate a wide band camouflage net with a frequency range of 1-18 GHz, we have started our work by first designing FSS on FR4 as substrate and further designing of an asymmetric FSS with the test cloth as substrate for camouflage net based on principle of absorption.

5.1 Symmetric Square Patch FSS

We have started with symmetric FSS which was designed and simulated on HFSS software (a square loop with a patch at the center) over Fr4 substrate with permittivity 4.4. FSS is a combination of an inductor and a capacitor which acts as a band pass filter for the desired wavelength. The dimensions of the patch were optimized in order to get resonating frequency at 9 GHz for a wide band absorption in the frequency range of 1-18 GHz.

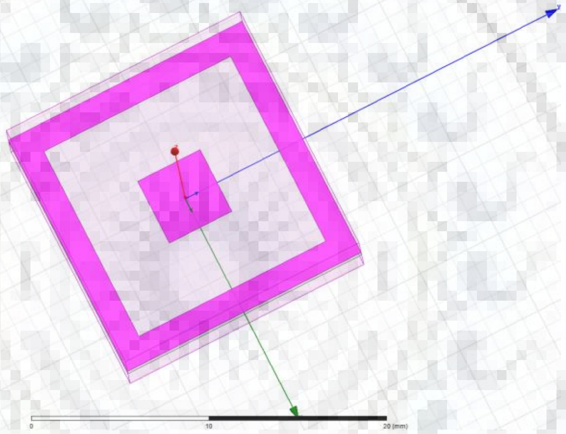


Figure 26. Square patch structure for simulation in HFSS.

Further the simulation was carried out and it was observed that only the reflection loss was below -10dB is obtained for a frequency range of 9 to 11.5 GHz whereas the transmission loss was above -2.5 dB for the same frequency range, which was undesired.

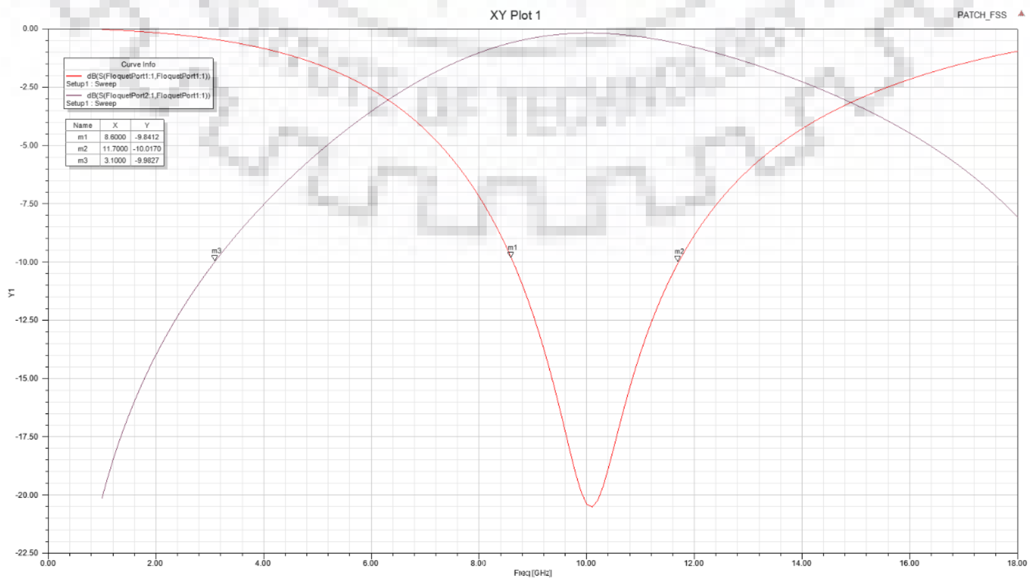


Figure 27. Transmission and Reflection Coefficient (S_{11} and S_{21}) for Square patch

Further to get the desired result the length of the outer patch was increased as the resonant wavelength is directly proportional to the length of the FSS. To shift the resonant frequency to a lower band. The size of the center patch was further increased to increase the Bandwidth.

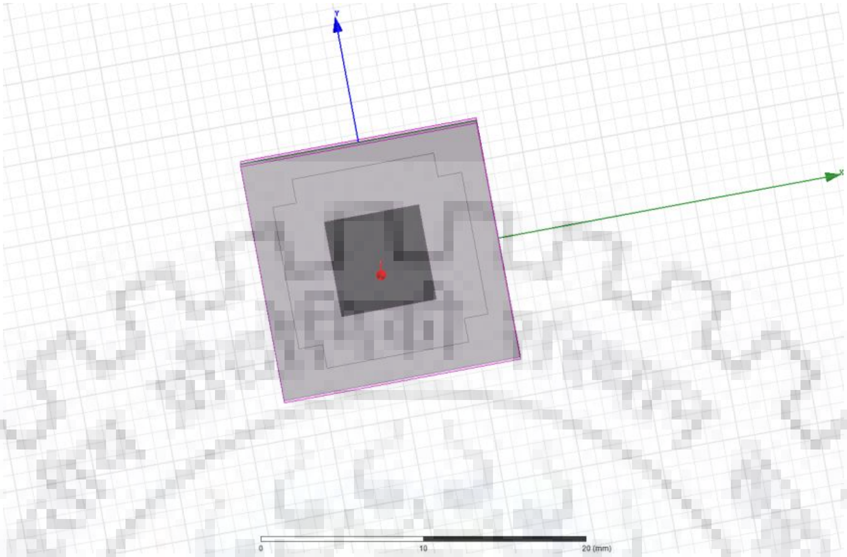


Figure 28. Square patch structure with extended corners for simulation in HFSS

The simulation results of Reflection and transmission loss S_{11} and S_{21} with FR4 substrate show that the reflection loss below -10dB was obtained for a lower frequency range of 7 to 8.5 GHz. Further with the variation in center patch size the BW and the frequency band also varied.

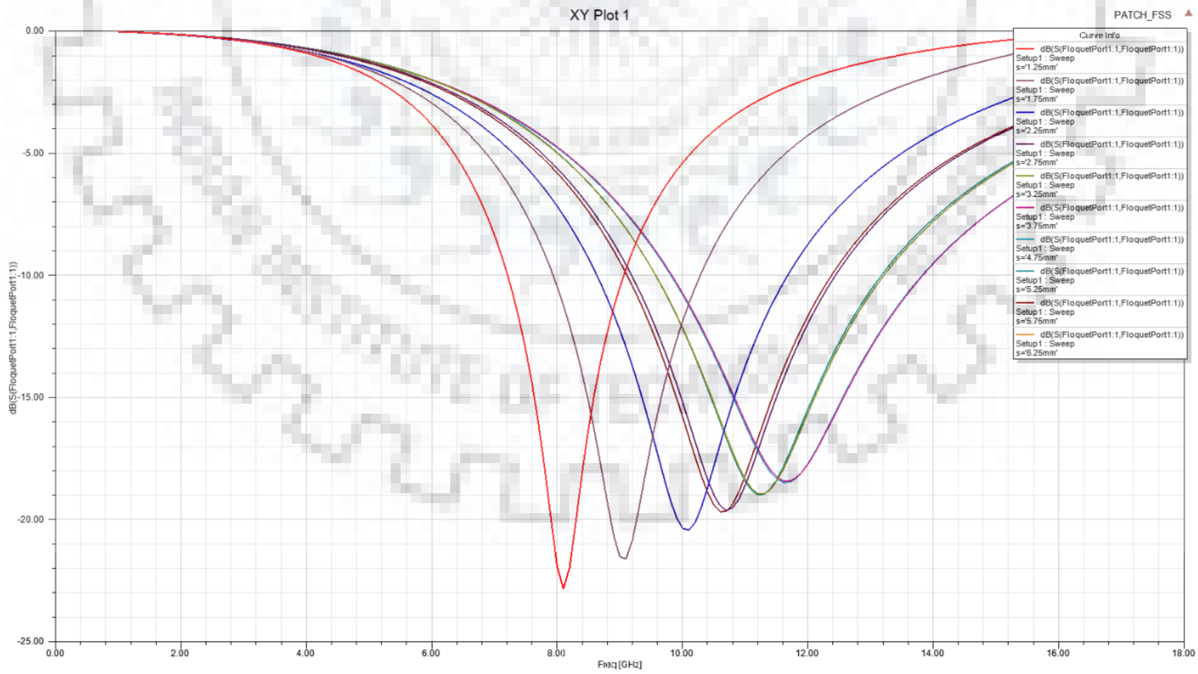


Figure 29. Reflection Coefficient (S_{11})

In both the above mention cases desired result of S_{11} and S_{21} below -5dB was not achieved therefore to take the study further a combination FSS was designed.

5.2 Symmetric Cross Loop and Patch FSS

A symmetric combination FSS was further designing and simulated on HFSS, where the dimension of the FSS were equal to the wavelength of the center frequency which is 9 GHz for the frequency range from 1 to 18 GHz.

Figure 30. FSS for frequency range 2-18 GHz

The simulation of Electric Field interaction shows that it is more with the electrons on the left and right sides of the loop, which implies more absorption taking place from these two sides as compared to the other sides of the loop, due to which FSS has Reflection Loss less than -5dB. Electric field distribution over the entire FSS is as shown.

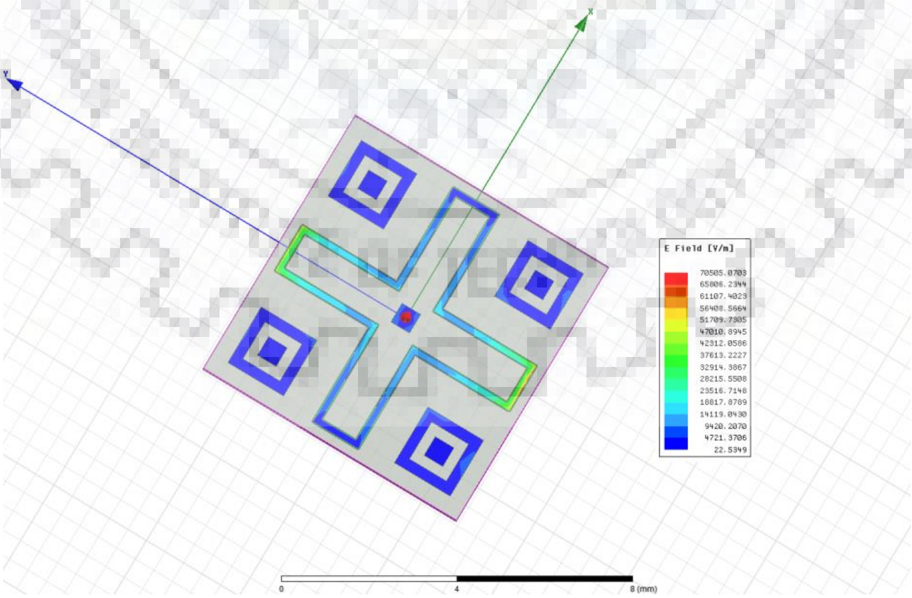


Figure 31. Electric field distribution on FSS structure

After the simulation on Fr4 substrate the design simulation was carried out on test fabric (cloth) as substrate who's permittivity and permeability were experimentally obtained and were used.

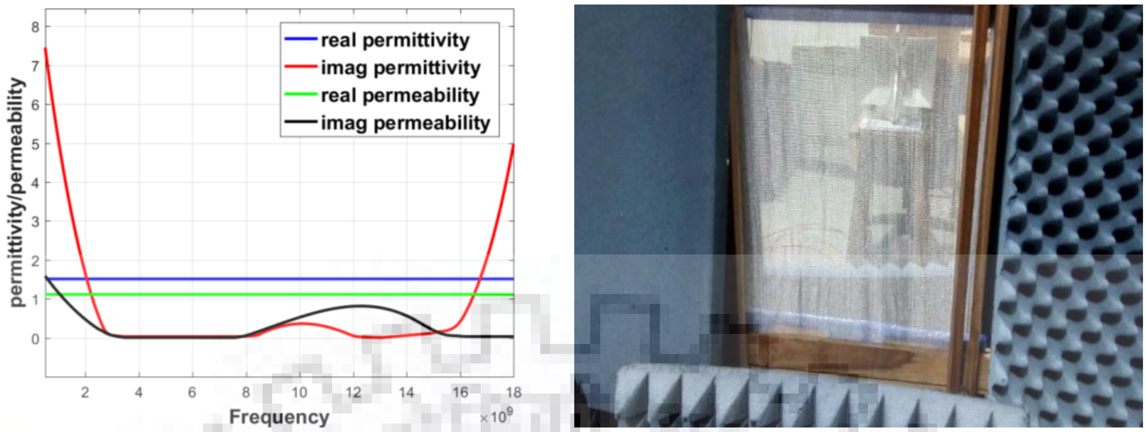


Figure 32. (a)Permittivity/Permeability Vs Frequency for cloth (b) Prototype Cloth

Simulation results of Reflection and transmission loss with test fiber as substrate shows that the reflection loss below -5dB is obtained through out the frequency range of 1 to 18 GHz and further the transmission loss of below -5dB from 9.4 to 14 GHz and 15.5 to 18 GHz is obtained.

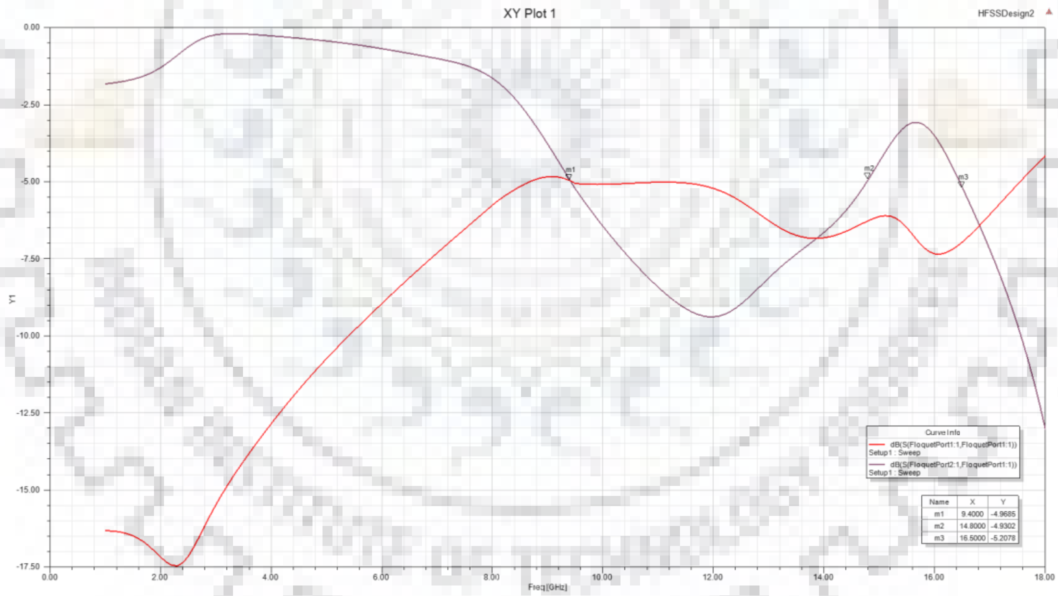


Figure 33. Transmission and Reflection Coefficient (S_{11} and S_{21}) of the designed FSS

As it is observed from the above result that both S_{11} and S_{21} are below -5dB which is very much desired, but with a fixed frequency band. Thus, in order to obtain the desired result over the wide frequency range i.e from 1-18 GHz an asymmetric FSS was design, optimized and finally fabricated.

5.3 Fabricated Asymmetric FSS for camouflage net

To design a wide band camouflage net with operating frequency of 1-18 GHz based on absorption principle, it is desired to have both S_{11} and S_{21} less than -5dB which was achieved by designing an asymmetric FSS with test cloth as the substrate with $\mathscr{E}$ of 1.3 and μ of 1. The designing of the FSS was carried out on HFSS software and simulation were carried out to obtain the desired results.

5.3.1 Design of Asymmetric FSS

The asymmetric FSS is a type of combination FSS on both the sides of the substrate. In our case it is a combination of square patch and square loop on the front face, a combination of square patch on bottom face. The above said FSS acts as a multi band pass filter with two resonating frequencies i.e 8.4 GHz and 15.8 GHz. The structure of the FSS is as shown:-

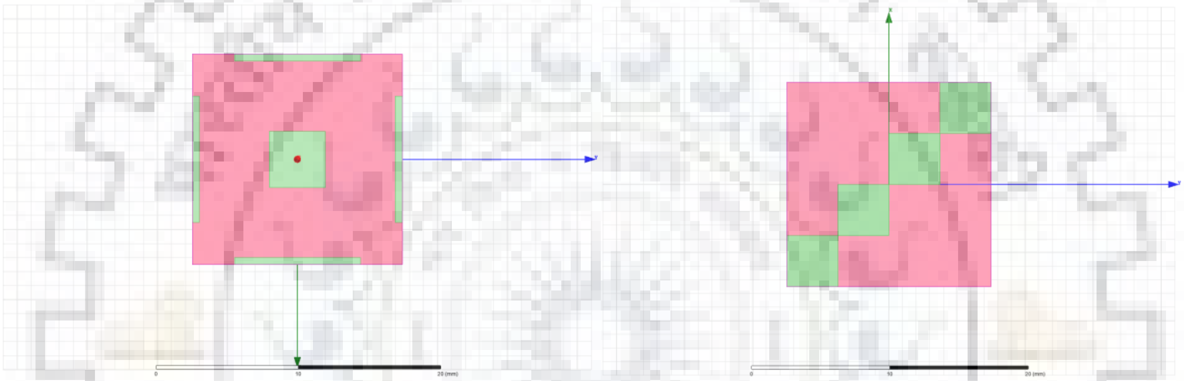


Figure 34. Top and Bottom view of an Asymmetric FSS

Further the dimensions of the square patch and the square loop were optimized by using parametric method in order to get the precise result. Various simulations were carried out by varying one parameter at time, whereas keeping the other parameters constant.

- **Optimization of outer square patch with dimension 'c'**

Table 1. Variation of S11 and S21 with dimension 'c'

Dimension 'C' (mm)	F1= 8.4 GHz	F2=15.8 GHz
0.5	S11= -9.38dB S21= -4.23dB	S11= -12.4dB S21= -2.45dB
0.55	S11=-9.95dB S21=-4.23dB	S11=-10.45dB S21= -7.51dB
0.6	S11= -2.23dB S21=-13.36dB	S11=-12.83dB S21=-5.42dB
0.65	S11= -9.88dB S21= -4.28dB	S11= -9.38dB S21=-7.80dB
0.7	S11= -1.20dB S21=-13.77dB	S11=-11.68dB S21= -2.62dB

➢ Simulation result for optimization of outer square patch

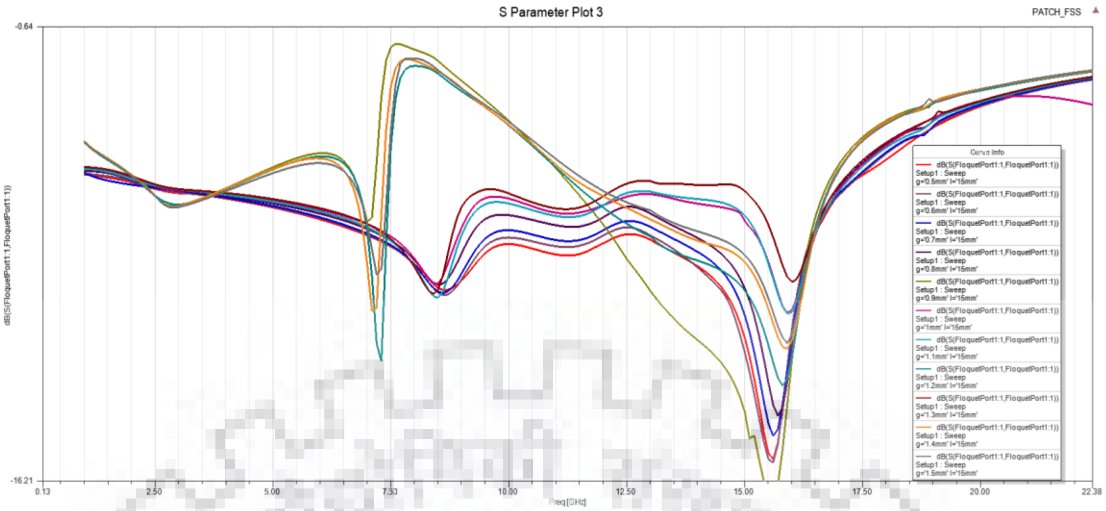


Figure 35. Variation in S_{11} with changes in the thickness of outer most patch

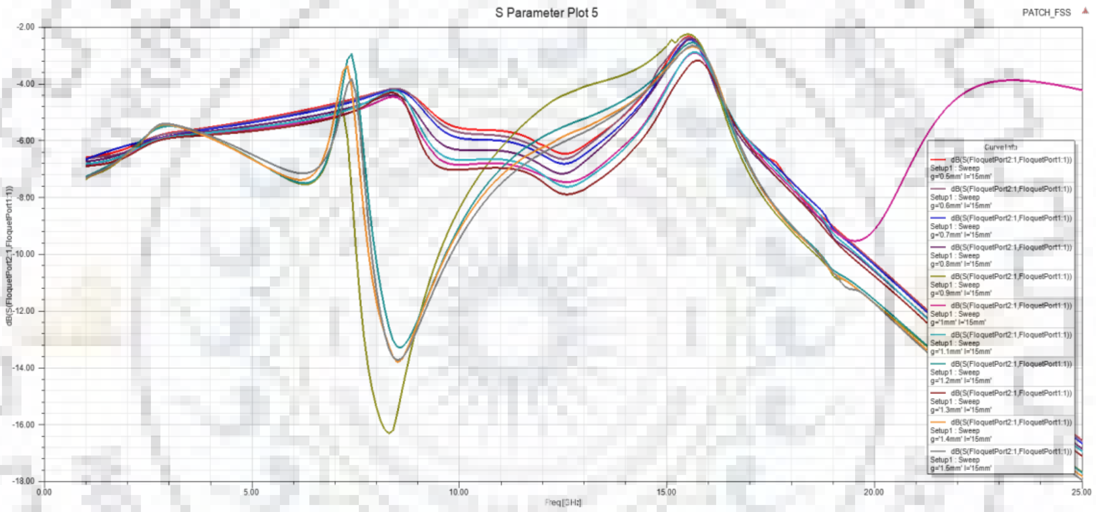


Figure 36. Variation in S_{21} with changes in the thickness of outer most patch

➢ Optimization of the Inner Patch with dimension 'a'

Table 2. Variation of S11 and S21with dimension 'a'

Dimension 'a' (mm)	F1= 8.4 GHz	F2=15.8 GHz
4.4	S11= -1.79dB S21= -14.73dB	S11= -17.77dB S21= -2.41dB
4.2	S11=-9.59dB S21=-4.38dB	S11=-13.24dB S21= -2.58dB
4.0	S11= -9.92dB S21= -4.22dB	S11=-12.40dB S21= -2.64dB
3.8	S11= -9.58dB S21= -4.38dB	S11=-10.42dB S21=-2.90dB
3.6	S11= -9.92dB S21=-14.07dB	S11=-9.10dB S21= -2.61dB

➢ Simulation result for optimization of inner square patch

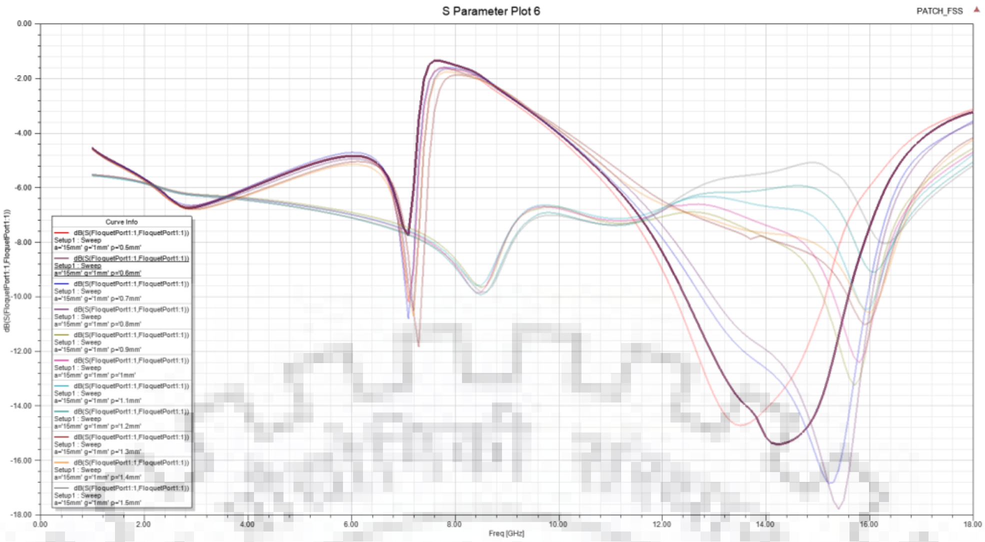


Figure 37. Variation in S_{11} with changes in the thickness of inner most patch

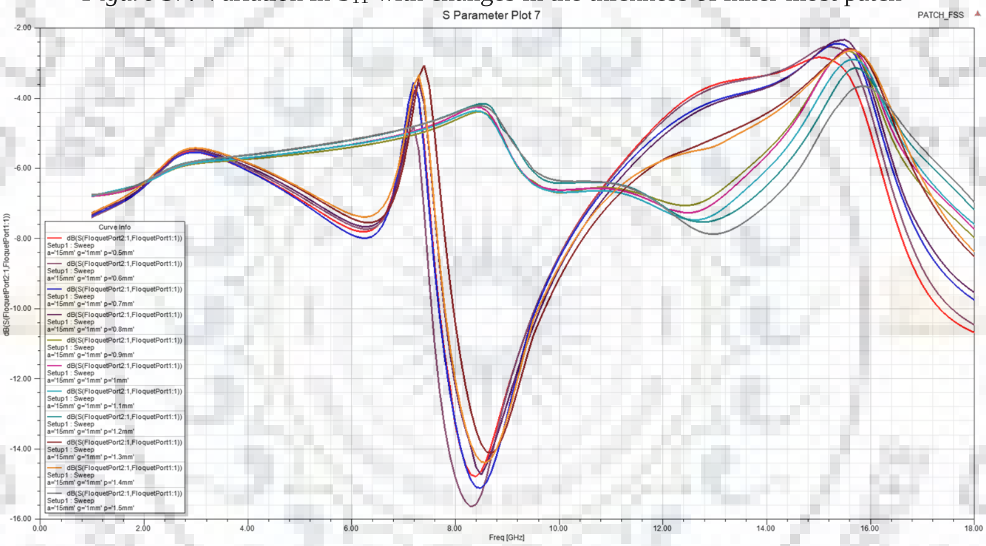


Figure 38. Variation in S_{21} with changes in the thickness of inner most patch

➢ Optimization of the Lower Patch with dimension 'x'

Table 3. Variation of S11 and S21 with dimension 'x'

Dimension 'x' (mm)	F1= 8.4 GHz	F2=15.8 GHz
2.5	S11= -7.85dB S21= -2.61dB	S11= -5.82dB S21= -5.54dB
2.75	S11=-6.52dB S21=-2.48dB	S11=-6.11dB S21=-5.28dB
3.0	S11= -5.86dB S21= -4.22dB	S11=-4.511dB S21= -6.57dB
3.25	S11= -6.28dB S21= -5.77dB	S11=-5.29dB S21=-5.17dB
3.5	S11= -7.20dB S21=-5.87dB	S11=-6.08dB S21= -4.34dB
3.75	S11= -9.82dB S21=-4.27dB	S11=-12.40dB S21= -2.61dB

- **Simulation result for optimization of lower square patch**

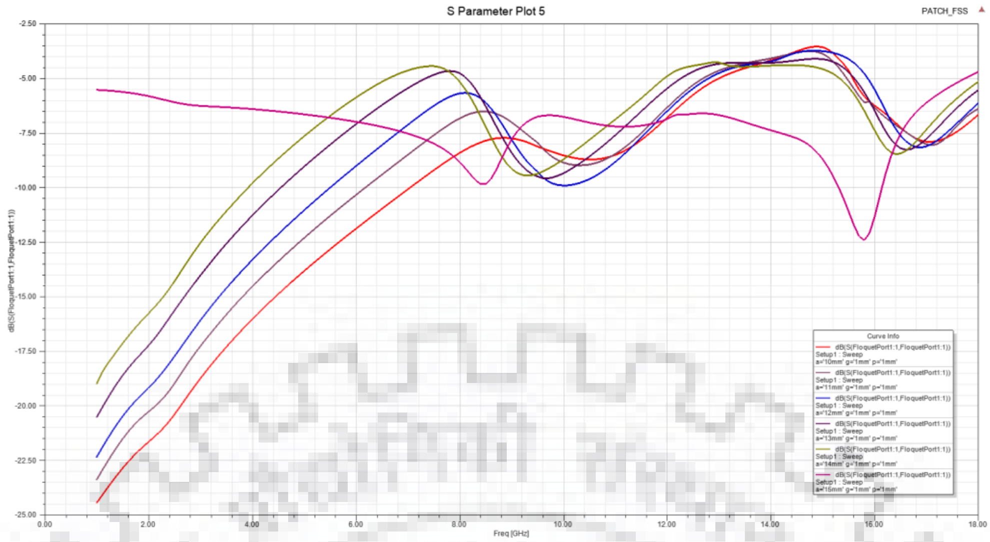


Figure 39. *Variation in S_{11} with changes in the thickness of lower patch*

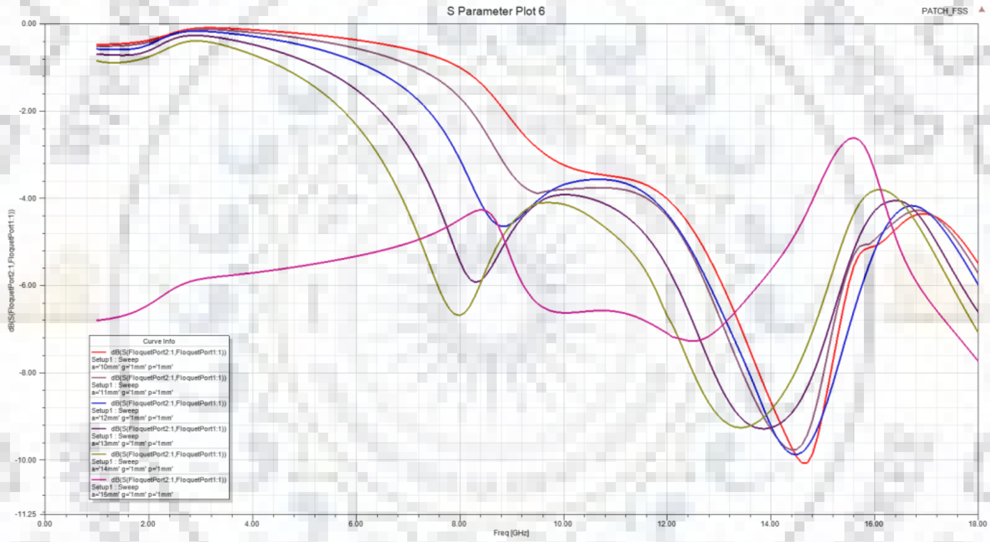


Figure 40. Variation in S_{11} with changes in the thickness of lower patch

5.3.2 Optimized dimension of Asymmetric FSS post parametric analysis

An asymmetric FSS was designed of HFSS software for the camouflage net with an operating frequency from 1-18 GHz is shown below:-

Table 4. Dimensions of asymmetric FSS post parametric analysis

Sides	Size (mm)
L	15
a	4
b	9
c	0.5
x	3.75
y	3.75

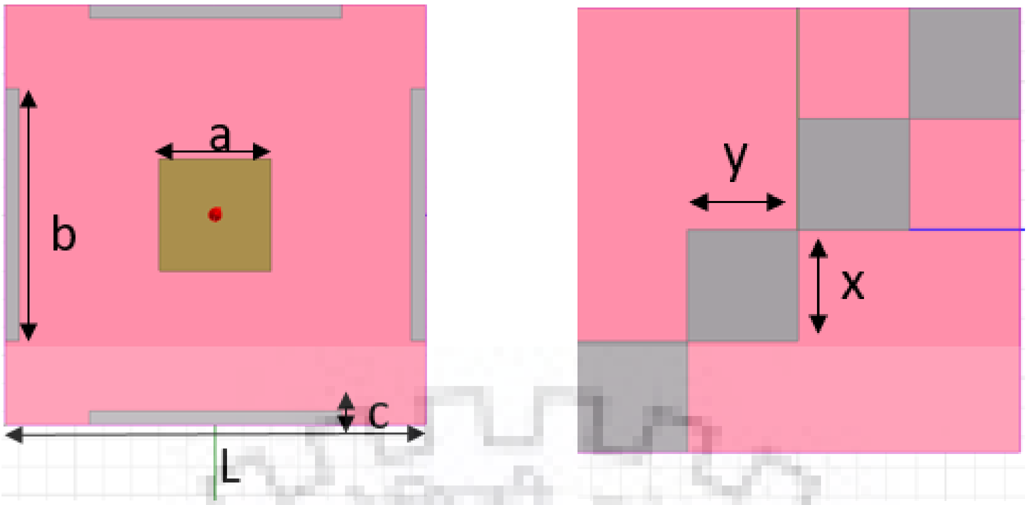


Figure 41. Dimensions of Top and Bottom view of an Asymmetric FSS

5.3.2 Simulated result post parametric analysis

Simulation of the asymmetric FSS is carried out on ANSYS software and it was observed that the reflection coefficient is less than -5dB throughout the frequency range of 1 to 18 GHz. whereas the transmission coefficient was less than -5dB except in the frequency range from 7.2 to 8.9 GHz and 14.4 to 16.4 GHz.

- **Simulate result is as shown below**

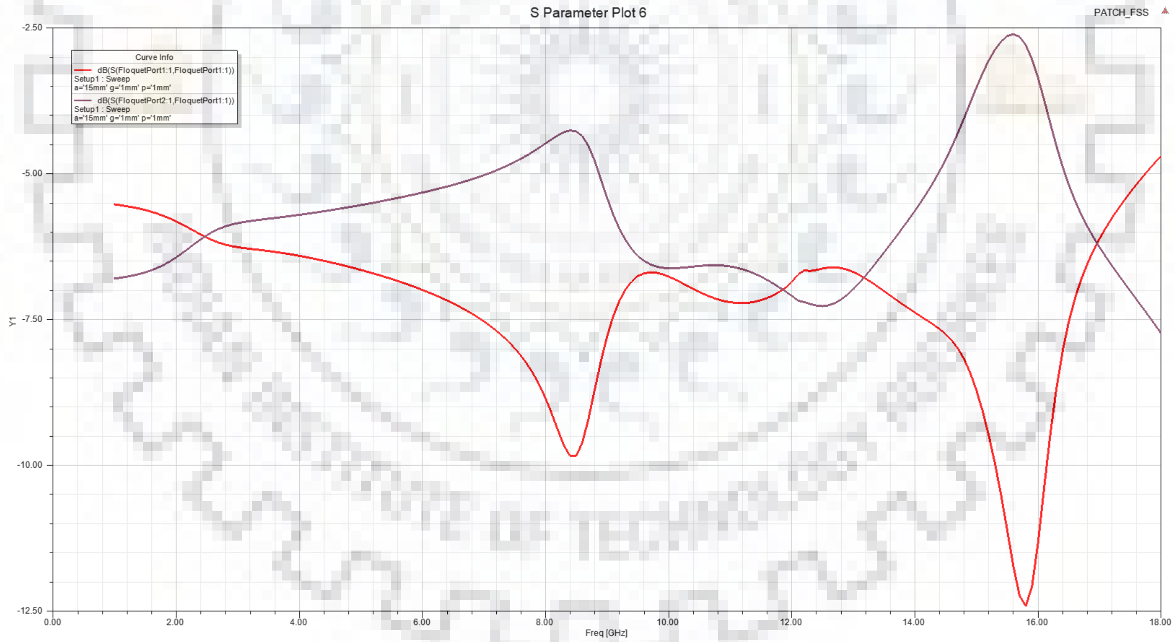


Figure 42. Variation of transmission and reflection coefficient with frequency

Table 5. Frequency Vs S11and S21

Frequency (GHz)	S_{11} (dB)	S_{21} (dB)
8.4	-9.83	-4.26
15.8	-12.40	-2.61

➢ **Abroption result post calculation**

Post simulation absorption calculation was carried out for the designed asymmetric FSS by using matlab. It was observed that the absorption is above -3dB for the the frequency range of 1 to 14.8 GHz. It is having its peak value of -2.2dB at 12.4 GHz.

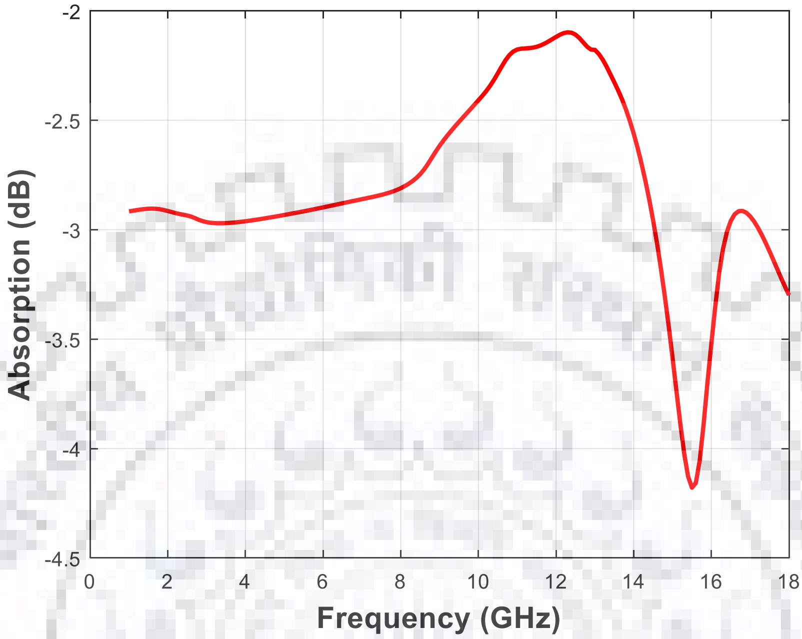


Figure 43. Absorption Vs frequency graph for Asymmetric FSS in dB

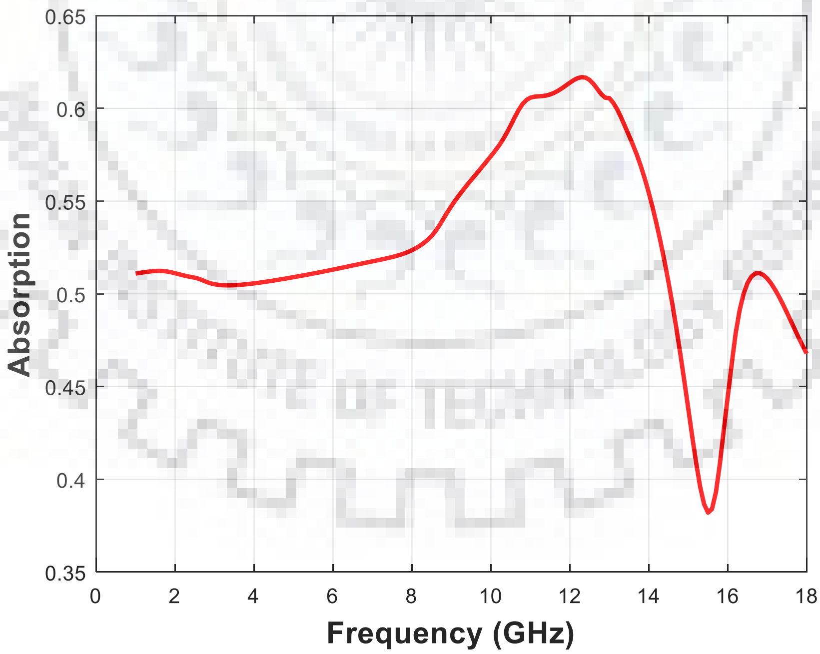


Figure 44. Absorption Vs frequency graph for Asymmetric FSS in percentage

- **Experimental Setup post Fabrication of cloth**

Post fabrication of the FSS practical values of Reflection and Transmission loss was ascertained with the help of experimental set up.

Figure 45. Images of experimental setup for absorption calculation

- **Experimentally calculated value of Absorption for fabricated cloth**

It is observed that the absorption by the fabricated Asymmetric FSS on the test cloth is maximum i.e less than -3dB for a frequency around 13 GHz. Absorption is less than -5dB for maximum number of frequencies in the wide band range from 1 to 18 GHz.

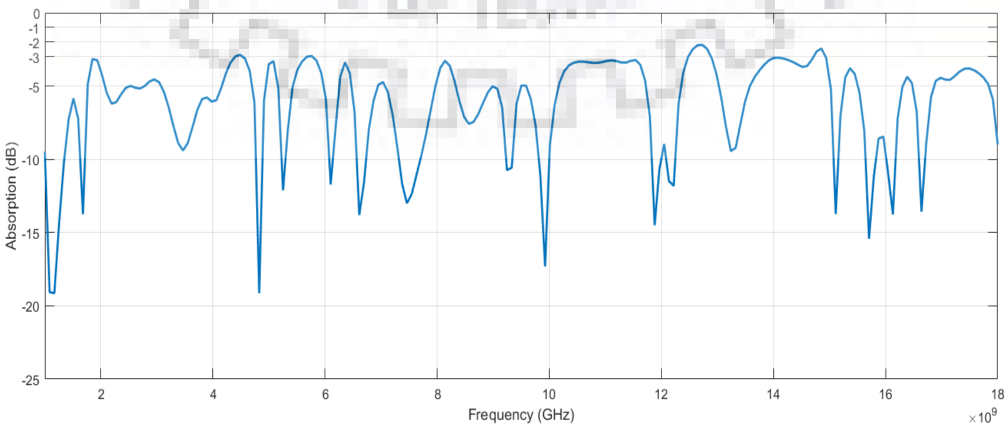


Figure 46. Absorption Vs Frequency

The result shown in figure 46 is representing the continuous absorption throughout the frequency band. Maximum absorption we are getting at the frequency of 12.5 GHz, which is in following the trend of simulated result. Absorption in entire frequency range is about 3 to 5 dB, which a quite acceptable in range as considering the thickness of the cloth. Though a perfect overlap with the simulated results could not be obtained due to fabrication error, equipment limitation as well as the requirement of the high conductivity of the metal paint, which is limited due to thickness of copper paint that has been used for the fabrication purpose.

Chapter 6

Conclusion and Future scope

- Maximum Absorption achieved is about 61% at the frequency 13 GHz.
- Absorption is observed to be less than -5 dB through-out the frequency range from 1-18 GHz but within small pockets of frequency bands.
- Difference in the simulated and experimental value of absorption can be further minimized by adopting advance printing techniques and improved experimental setup.
- A multilayered FSS can be further implemented to obtain wideband absorption pattern for desired frequency range.
- Cost effective RAM may be further used over fabric for enhancing its absorption.
- Enhanced experimental setup to determine the parameters of the test fabric to be used as substrate such as permittivity and permeability.
- Finally to design a cost effective combination of FSS and the substrate, which can be easily fabricate.

References

[1] J. V. R. Rao, *Introduction to Camouflage and Deception*. New Delhi: Defence Research & Development Organisation, 1999.

[2] A. Kumar, V. Agarwala, and D. Singh, "Microwave absorbing behavior of metal dispersed TiO2 nanocomposites," *Adv. Powder Technol.*, vol. 25, no. 2, pp. 483–489, 2014.

[3] R. B. Dybdal, "Radar cross section measurements," *Proc. IEEE*, vol. 75, no. 4, pp. 498–516, 1987.

[4] S. Cadirci, "RF stealth (or low observable) and counter-RF stealth technologies: implications of counter-RF stealth solutions for Turkish air force," NAVAL POSTGRADUATE SCHOOL MONTEREY CA DEPT OF INFORMATION SCIENCES, 2009.

[5] L. de C. Folgueras and M. C. Rezende, "Multilayer radar absorbing material processing by using polymeric nonwoven and conducting polymer," *Mater. Res.*, vol. 11, no. 3, pp. 245–249, Sep. 2008.

[6] B. A. Munk, Frequency selective surfaces: theory and design. John Wiley & Sons, 2005.

[7] R. L. Fante and M. T. Mccormack, "Reflection properties of the Salisbury screen," *IEEE Trans. Antennas Propag.*, vol. 36, no. 10, pp. 1443–1454, 1988.

[8] L. J. Du Toit, "Analysis and synthesis algorithms for the electric screen Jauman electromagnetic wave absorber," PhD Thesis, Stellenbosch: Stellenbosch University, 1993.

[9] P. Saville, "Review of radar absorbing materials," Defence Research and Development Atlantic Dartmouth (CANADA), 2005.

[10] S. Kent and I. Catalkaya, "Optimized geometry pyramidal absorber for normal incidence case," in *Recent Advances in Space Technologies (RAST), 2013 6th International Conference on*, 2013, pp. 177–179.

[11] S. Kent and I. Catalkaya, "Optimized geometry pyramidal absorber for normal incidence case," in *2013 6th International Conference on Recent Advances in Space Technologies (RAST)*, 2013, pp. 177–179.

[12] H. Mosallaei and K. Sarabandi, "A one-layer ultra-thin meta-surface absorber," in *Antennas and Propagation Society International Symposium, 2005 IEEE*, 2005, vol. 1, pp. 615–618.

[13] D. Richardson, Stealth Warplanes. Deception, Evasion and Concealment. Osceola, 2001.

[14] D. M. Pozar, *Microwave engineering*. John Wiley & Sons, 2009.

[15] S. Das, A. Bansal, and A. K. Sharma, Theory of Welding of Metallic Parts in Microwave Cavity Applicator. 2012.

[16] C. W. D Jr, Materials science and engineering: an introduction. 2007.

[17] A. J. Moulson, *Electroceramics: Materials, Properties, Applications*. Routledge, Chapman & Hall, Incorporated, 1992.

[18] J. Y. Shin and J. H. Oh, "The microwave absorbing phenomena of ferrite microwave absorbers," *IEEE Trans. Magn.*, vol. 29, no. 6, pp. 3437–3439, Nov. 1993.

[19] P. D. Mangalgiri, “Composite materials for aerospace applications,” *Bull. Mater. Sci.*, vol. 22, no. 3, pp. 657–664, May 1999.

[20] F. Qin and C. Brosseau, “A review and analysis of microwave absorption in polymer composites filled with carbonaceous particles,” *J. Appl. Phys.*, vol. 111, no. 6, p. 4, 2012.

[21] B. Hooberman, “Everything you ever wanted to know about frequency-selective surface filters but were afraid to ask,” *N. Y. NY Tech. Rep. Dep. Phys. Columbia Univ.*, 2005.

[22] Y. Pang, Y. Zhou, and J. Wang, “Equivalent circuit method analysis of the influence of frequency selective surface resistance on the frequency response of metamaterial absorbers,” *J. Appl. Phys.*, vol. 110, no. 2, p. 023704, Jul. 2011.

[23] X. Wu *et al.*, “Active microwave absorber with the dual-ability of dividable modulation in absorbing intensity and frequency,” *AIP Adv.*, vol. 3, no. 2, p. 022114, Feb. 2013.

[24] M. Asi and N. I. Dib, “Design of multilayer microwave broadband absorbers using central force optimization,” *Prog. Electromagn. Res.*, vol. 26, pp. 101–113, 2010.

[25] W. C. Chew, Waves and fields in inhomogeneous media. IEEE press, 1995.

[26] E. W. Wallin, “Knitted camouflage material,” US4064305A, 20-Dec-1977.

[27] F. P. M. Jr, L. R. Novak, and D. M. Hall, “Camouflage material,” US5312678A, 17-May-1994.

[28] J. L. Wallace, “Broadband magnetic microwave absorbers: fundamental limitations,” *IEEE Trans. Magn.*, vol. 29, no. 6, pp. 4209–4214, Nov. 1993.

[29] V. B. Bregar, “Advantages of ferromagnetic nanoparticle composites in microwave absorbers,” *IEEE Trans. Magn.*, vol. 40, no. 3, pp. 1679–1684, May 2004.

[30] M. Murugan and V. K. Kokate, “Microwave absorbing polymer composites,” in *2009 International Conference on Emerging Trends in Electronic and Photonic Devices Systems*, 2009, pp. 336–339.

[31] L. Sun, H. Cheng, Y. Zhou, and J. Wang, “Design of a Lightweight Magnetic Radar Absorber Embedded with Resistive FSS,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 11, pp. 675–677, 2012.

[32] Y. Yang, M. C. Gupta, K. L. Dudley, and R. W. Lawrence, “Novel Carbon Nanotube−Polystyrene Foam Composites for Electromagnetic Interference Shielding,” *Nano Lett.*, vol. 5, no. 11, pp. 2131–2134, Nov. 2005.

[33] H. Y. Chen, H. B. Zhang, and L. J. Deng, “Design of an Ultra-Thin Magnetic-Type Radar Absorber Embedded with FSS,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 9, pp. 899–901, 2010.

[34] A. Teber, I. Unver, H. Kavas, B. Aktas, and R. Bansal, “Knitted radar absorbing materials (RAM) based on nickel–cobalt magnetic materials,” *J. Magn. Magn. Mater.*, vol. 406, pp. 228–232, May 2016.

[35] D. Pozar, “Scattered and absorbed powers in receiving antennas,” *IEEE Antennas Propag. Mag.*, vol. 46, no. 1, pp. 144–145, Feb. 2004.

[36] G. Redlich *et al.*, “New textiles designed for anti-radar camouflage,” *Fibres Text. East. Eur.*, 2014.

[37] A. D. Child, “Radar camouflage fabric,” US8013776B2, 06-Sep-2011.

[38] M. S. Hesarian, S. Shaikhzadeh Najar, and R. Sarraf Shirazi, “Design and fabrication of a fabric for electromagnetic filtering application (experimental and modeling analysis),” *J. Text. Inst.*, vol. 109, no. 6, pp. 775–784, 2018.

[39] M. S. Hesarian, S. Shaikhzadeh Najar, and R. Sarraf Shirazi, “Design and fabrication of a fabric for electromagnetic filtering application (experimental and modeling analysis),” *J. Text. Inst.*, vol. 109, no. 6, pp. 775–784, Jun. 2018.

[40] A. Chauraya, R. Seager, W. Whittow, S. Zhang, and Y. Vardaxoglou, “Embroidered frequency selective surfaces on textiles for wearable applications,” in *Antennas and Propagation Conference (LAPC), 2013 Loughborough*, 2013, pp. 388–391.

[41] S. Zhang, R. Seager, A. Chauraya, W. Whittow, and Y. Vardaxoglou, “Textile manufacturing techniques in RF devices,” in *Antennas and Propagation Conference (LAPC), 2014 Loughborough*, 2014, pp. 182–186.

[42] A. L. Eldredge, “Object camouflage method and apparatus,” US3127608A, 31-Mar-1964.

[43] https://en.wikipedia.org/wiki/Stealth_%28film%29