Design and Analysis of a Metamaterial Absorber for Applicaion at 3.5GHz

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February 2024

DEDICATION

This thesis is a tribute to MY deserving parents and teachers.

CERTIFICATE OF APPROVAL

The Department of Electronic and Telecommunications Engineering (ETE) at International Islamic University Chittagong (IIUC) has accepted the thesis study of Sajjadul Alam Sajjad (T-191014) and Syed Mustavi Hossain (T-191007) entitled " Analysis of a S-shape metamaterial absorber operating at 3.5 GHz" as satisfactory in partial fulfillment of the requirements for the Degree of Bachelor in Electronic and Telecommunications Engineering and approved as to its style and contents for the examination held on …th February 2024.

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CANDIDATES DECLARATION

The written work that is presented in this thesis is not something that was submitted in the past for credit toward the completion of any other degrees or diplomas, nor does it contain any information that may be construed as violating any regulations that are now in effect.

Syed Mustavi Hossain

ACKNOWLEDGEMENTS

By the infinite mercy of Allah (SWT), the Most Generous. Allah (SWT) deserves all praise and gratitude for all the favors He has showered upon me and for always being there to lend love and direction. For pioneering this area of study, offering helpful counsel, and serving as an inspiration throughout our research, Md Mostafa Amir Faisal, who is supervising my thesis. His timely guidance and the first-rate facilities he has offered me are much appreciated. My parent's unconditional support and optimism have been invaluable to me. In addition, we appreciate everyone who helped in any way with developing this thesis.

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List of Symbols

GHz	**Giga Hertz**
MM	**Milimeter**
ε	**Relative Permittivity**
μ	**Relative Permeability**
dB	**Decibel**
λ	**Wavelength**
Ω	**Ohm**
Z	**Impedance**
Γ	**Reflection Coefficient**
T	**Transmission Coefficient**

List of Abbreviations

MMA	**Metamaterial Absorber**
MRI	**Magnetic Resonance Imaging**
RF	**Radio Frequency**
Hz	**Hertz**
E	**Electric fields**
H	**Magnetic fields**
VSWR	**Voltage Standing Wave Ratio**
HF	**High Frequency**
3D	**Three Dimensional**
DS	**Design studio**
MWS	**Microwave Studio**
FCC	**Federal Communications Commission**
HFSS	**High Frequency Simulation Software**
SAR	**Synthetic Aperture Radar**
VNA	**Vector Network Analyzer**
CPW	**Coplanar Waveguide**
RHCP	**Right-handed Circular Polarization**
XPD	**Cross-polarization Discrimination**
EMR	**Effective Medium Ratio**

ABSTRACT

Analysis of a metamaterial absorber with an S-shaped structure is suggested to reduce the specific absorption rate (SAR) at 3.5 GHz. This absorber exhibits single negative metamaterial characteristics and achieves an absorption rate of over 90% for all electromagnetic polarization angles. In the age of 5G, numerous applications are functioning at various frequency ranges, emitting substantial amounts of electromagnetic energy (EM) that possess an elevated SAR value. This radiation has an impact on the human body, specifically the head and hands, which are exposed to it. In Malaysia, a frequency band of 3.5 GHz has been designated for 5G communication. However, this has resulted in the emission of undesirable signals due to high Specific Absorption Rate (SAR) values. To address this issue, a proposed absorber would be implemented to reduce SAR levels.

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Chapter 1

Introduction

1.1 About metamaterials

Research on metamaterials is a fascinating and innovative field of study that falls under the umbrella of material science and engineering. These purposely created materials have garnered a lot of attention because of their exceptional properties, which are often unattainable in compounds that exist naturally. The term "metamaterial" originates from the Greek prefix "meta," which means "beyond" or "transcending." Metamaterials are materials that go beyond the typical notions of what makes a material by demonstrating special traits that push the boundaries of our knowledge and our technical ability. This is because metamaterials exhibit properties that push the frontiers of what we know and what we are capable of doing technologically [1].

The story of how metamaterial absorbers came to be is one of the more recent chapters in the long-running saga of the development of electromagnetic materials and technologies. In the 1960s, Victor Veselago laid the theoretical framework for what would later be known as metamaterial absorbers. However, it wasn't until the early 2000s that this technology was put into use. It was the pioneering work of scientists like as John Pendry, David R. Smith, and Sheldon Schultz that finally led to the first experimental demonstration of metamaterial absorbers, particularly in the microwave area. These early absorbers were meticulously built to have one-of-a-kind resonance frequencies, which enabled them to be successful in soaking up certain frequencies of electromagnetic radiation. The rapidly growing research efforts that took place in the years that followed resulted in the development of absorbers that can operate at microwave, terahertz, and optical frequencies. The application of metamaterial absorbers has been identified in a variety of diverse industries, including sensor technology, the military, stealth technologies, and telecommunications. With the introduction of tunable and multiband absorbers in the 2010s, absorbers have grown more versatile [2]. Additionally, optical and terahertz metamaterial absorbers have led the way for innovative applications in optics, imaging, and sensing. Absorbers made of metamaterials have progressed from the realm of theoretical concepts to that of actual devices, bringing with them far-reaching and possibly industry-altering repercussions for a wide variety of technologies and markets. The last several decades have seen significant developments in science and technology, and this quick transition has been mirrored in the creation of metamaterial absorbers. As the study developed, scientists discovered that electromagnetic wave absorption was only one of many possible applications. Metamaterial absorbers were an essential component in the development of stealth technology due to their capacity to efficiently consume incoming radar signals. Stealth technology has come a long way since its introduction. Absorbers with a frequency-selective bandpass filter that are designed for use in the military and other security-related applications expansion of military applications includes many different examples, one of which is connected aims. As a result of their ability to modify and exert control over light and terahertz waves, metamaterial absorbers have also contributed significantly to the advancement of the domains of optics and terahertz frequencies. As a result, new doors have been opened for exploration in the realms of imaging, sensing, and communication. They also found the value of energy harvesting devices, which collect electromagnetic energy and transform it into electricity. These systems take the energy harvested from the environment and utilize it. Studies that investigate possible applications in fields like as biological sensing, environmental monitoring, and next-generation wireless communication (5G and beyond) are helping to advance the development of metamaterial absorbers. These studies are pushing the development of metamaterial absorbers farther forward. Metamaterial absorbers have gone a long way from their theoretical origins and substantial practical application, and they have the potential to transform the future of electromagnetic wave regulation and use [3],[4].

1.2 Source of Inspiration

The concept of metamaterials may be traced back to the theoretical musings of the Soviet scientist Victor Veselago, who in 1967 published an influential article titled "The Electrodynamics of Substances with Simultaneously Negative Values of and.[5]" Veselago proposed the idea of materials that would exhibit paradoxical electromagnetic properties such as negative refraction if they had both a negative electric permittivity (ε) and a negative magnetic permeability (μ) [6]. This would result in the materials having both a negative electric permittivity (ε) and a negative magnetic permeability (μ) [7].

However, the concept of metamaterials did not begin to develop into practical use until the first decade of the twenty-first century. It is generally accepted that John Pendry, David R. Smith, and Sheldon Schultz are responsible for the experimental production of metamaterials. As a direct consequence of the work that these three individuals have done, a significant amount of research has been carried out in this field.

1.3 The Definitive Meaning of the Term "Metamaterials"

The term "metamaterial" refers to any substance that has been synthesized in a laboratory to achieve a certain purpose and end up with specific properties. In many cases, they are constructed up of subwavelength structural components, which are also referred to as "meta-atoms" or "unit cells," and which are placed in a certain fashion to obtain the features that are needed. These properties could include things like a negative refractive index, the ability to shroud, superlensing, or extraordinary optical transmission, among other things [8].

One of the most distinguishing qualities of metamaterials is their capacity to influence electromagnetic waves on length scales that are orders of magnitude smaller than the wavelengths of the radiation with which they interact. This enables metamaterials to influence electromagnetic wave behavior in innovative ways, opening the door to several potential applications in optics, electromagnetics, acoustics, and other fields [9].

1.4 The conceptual underpinnings of the argument

To have a proper understanding of metamaterials, it is necessary to investigate the theoretical foundations that underlie the design and functioning of these materials. The effective medium approximation, in which the material is thought of as a homogenized substance with averaged electromagnetic properties, is the key notion in the theory of metamaterials. Researchers can simulate and construct new kinds of materials by altering the properties of the meta-atoms that make up metamaterials.

1.4.1 A categorization for metamaterials

Several subclasses may be ascribed to metamaterials, and each of these subclasses is determined by the kind of wave that each general category of metamaterials is designed to regulate. The following items are included in the typical classifications:

- Electromagnetic metamaterials are a subcategory of metamaterials that are used to govern electromagnetic waves. These types of waves include microwaves, terahertz radiation, and visible light. They are used in a wide variety of goods, including lenses, cloaking technologies, and antennas, among others.

- Acoustic metamaterials: Made to bend or bend sound waves, acoustic metamaterials are utilized for focusing, acoustic cloaking, and noise reduction. Acoustic metamaterials are also made to bend or bend light waves.
- Thermal metamaterials are used to regulate the flow of heat, which paves the way for the creation of materials with amazing thermal properties, such as high thermal conductivity or thermal cloaking.
- Mechanical Waves and Their Modification by Mechanical Metamaterials: Mechanical waves may be modified by mechanical metamaterials, which also have the potential to be used in lightweight structural materials, vibration dampening, and shock absorption.[10].

1.4.2 Operating Frequencies

Microwave frequencies are defined as electromagnetic frequencies that range from 300 megahertz (MHz) to 300 gigahertz (GHz), and are denoted by these numerical values. These frequencies are put to use for a wide variety of applications, including telephone, radar, and the transmission of satellite communications. It is common practice to divide microwave frequencies into many bands, each corresponding to a distinct frequency range. The frequency bands listed below are those that are characteristic of microwaves:

The acronym UHF stands for ultra-high frequency. The frequency range is from 300 megahertz to three gigahertz. Amateur radio, GPS, cellular and mobile networking, and television transmission are some of the most important applications [11].

Low microwave band, often known as the L Band[12]:

- 1 to 2 gigahertz is the frequency range covered.
- The most important uses include radio navigation, communication through satellite, air and sea travel, and maritime and aerial communication.

S-Microwave Band, often known as the S-Band[13], [14]:

- Two gigahertz to four gigahertz is the frequency range.
- Communication within the military, long-range surveillance radar, and weather radar are among the most important uses.

The Companion Band, often known as the C Band[15]:

- Four gigahertz to eight gigahertz is the frequency range.

- The primary applications are in the fields of satellite communication, terrestrial microwave communication, and a few radar-related tasks.

X-Band, also known as the X-Microwave Band[16]:

- 8 GHz to 12 GHz is the frequency range covered.
- The primary uses are military radar, weather radar, terrestrial communication, and satellite communication.

(Ku-Microwave Band) Ku Band (Ku-Microwave Band)

- 12–18 Gigahertz is the frequency range covered.
- An example of a significant use is radar. Other notable applications include ground-based microwave transmission and satellite broadcasting.

K-Microwave Band, often known as the K Band[17]:

- 18–27 Gigahertz is the frequency range covered.
- Military radar, space research, and satellite communication are some of the most important uses.

The Ka-Band is also known as the Ka-Microwave Band[18].

- Frequencies ranging from 27 to 40 gigahertz
- The primary uses of satellites are for remote sensing, satellite communication, and space research.

The Very High-Frequency Band, often known as the V Band[19],

- The frequency spectrum spans from 30 GHz to 300 GHz.
- Imaging at terahertz frequencies, communication at millimeter waves, and radio astronomy are three examples of key uses.

The W Band

- The frequency range is between 75 and 110 GHz.
- The most common uses for millimeter waves are in radar, academic research, and experimental communication systems.

The D band

- It has a frequency range that spans from 110 to 170 GHz.

- Research, imaging, and remote sensing are three significant applications that make use of millimeter waves.

The G band

- It has a frequency spectrum that spans from 110 to 300 GHz.
- Applications such as terahertz imaging and spectroscopy, as well as novel high-frequency technologies, are essential [20].

1.5 Operating Field

The working field of a metamaterial absorber may be determined in part by the structure of the absorber, as well as the properties of the material, the resonance processes involved, and the tunability of the absorber. The range of frequencies that an absorber can effectively absorb is impacted by its resonance frequencies, which are defined, in turn, by the geometric arrangement of unit cells and periodicity. The dielectric constant, conductivity, and magnetic permeability of a material are the properties that define the spectrum absorption characteristics of that material. Absorption is dependent on frequency, and the working field is further determined by electric and magnetic resonance processes [21], [22]. When tuning mechanisms are provided, the frequency range may be tuned to accommodate a variety of needs. Because the working fields of absorbers may be altered to suit the requirements of a broad range of applications, they can be put to use in a wide variety of settings, ranging from stealth technology and energy harvesting to sensing and communication. This flexibility makes absorbers suitable for a wide range of applications. The operating field refers to the range of frequencies at which the absorber effectively

functions to absorb electromagnetic radiation.

1.5.1 Reflection coefficient

The reflection coefficient is a variable that is used in the study of wave transmission and reflection to define the behavior of waves at the interface between two different media or at impedance mismatches. The reflection coefficient is commonly abbreviated as " (Gamma), which stands for the Greek letter gamma [23]. When a wave encounters an interface, such as the boundary between two different materials, the amount of the wave's amplitude that is measured to be reflected is referred to as the interface reflection.

The standard definition of the reflection coefficient is as follows

$$\mathit{\Gamma} = \frac{E_{reflection}}{E_{incident}} \tag{1}$$

- Γ (Gamma) is the reflection coefficient.
- Reflection is the amplitude of the wave that is reflected.
- $E_{incident}$ is the amplitude of the incident wave.

Because it is possible to have both a magnitude (reflectance), as well as a phase (phase shift upon reflection), a complex number may be employed to express its value when it is necessary to do so. The magnitude of the reflection coefficient, which may take on values anywhere from 0 to 1, represents the percentage of the incoming wave's energy that is reflected to the observer [24].

1.5.2 Transmission Coefficient

The transmission coefficient is a measure of a material's ability to transmit electromagnetic waves. It is crucial in wave propagation studies, especially in optics and electromagnetics. The coefficient, also known as "T," is a dimensionless quantity that represents the amount of energy transmitted through a substance or structure. It is determined by comparing transmitted and incident waves' amplitudes, typically expressed as a ratio between 0 and 1.

The transmission coefficient can be determined by utilizing the formula that is as follows:

$$T = \frac{Intensity\ of\ Transmitted\ Wave}{Intesity\ of\ Incident\ Wave} \tag{2}$$

The transmission coefficient, for example, is a tool that is utilized in the field of optics to define the amount of light that passes through various optical elements. These elements include lenses, filters, and prisms. In the field of electromagnetics, having a solid understanding of how different types of matter interact with different types of electromagnetic waves is essential for working in fields such as antenna design, radar technology, and optical communication, amongst others [25], [26].

The transmission coefficient is a valuable tool in the design and study of systems that incorporate the propagation of electromagnetic waves. It is an important factor in determining how materials and structures behave and is also a vital aspect in determining how materials and structures behave.

1.5.3 Absorption

Absorption refers to a metamaterial's ability to capture and convert electromagnetic energy into heat or non-reflective energy losses. These structures, designed to reduce reflection and increase absorption, are ideal for applications like stealth technology, electromagnetic interference shielding, and solar energy collection. Metamaterials exploit resonances like surface plasmon and magnetic resonances, allowing them to produce absorption in a way not possible with naturally occurring materials [27].

1.5.4 Directivity and Gain

The directivity and gain of a device are significantly influenced by the architecture of a metamaterial absorber and its ability to control electromagnetic wave interaction. Directivity refers to the concentration and directionality of energy absorbed or scattered, while gain refers to the absorber's ability to increase the power or intensity of absorbed energy. Engineers can create absorbers that deflect and enhance radiation gain by changing the metamaterial's geometry and material properties, making them valuable in antenna design [28].

1.5.5 The ENG (epsilon negative) metamaterial

ENG metamaterials, a unique synthetic material with negative permittivity, exhibit intriguing electromagnetic behaviors like negative refraction and subwavelength imaging. Their structure allows for the inversion of electromagnetic waves, allowing for the creation of superlenses, cloaking devices, and high-performance lenses for imaging and communication systems. By ordering and sizing subwavelength unit cells, ENG metamaterials can be used in various applications.Because of this, ENG metamaterials can be utilized effectively in a wide variety of applications within the fields of optics, microwaves, and antennas[29] Lots of problem can be solved with the use of this material that effect the the growth of technological revolution for the next generation devices over time.

1.5.6 The MNG (mu-negative) metamaterial

MNG metamaterials are synthetic substances with negative magnetic permeability, exhibiting unique electromagnetic properties like negative refraction and control over magnetic fields. These properties make them useful in various applications, such as microwaves and antennas engineering. By altering the shape and size of subwavelength unit cells, MNG metamaterials can create specific magnetic responses, enabling devices like beam-steering antennas, subwavelength waveguides, and magnetic lenses to control and sculpt electromagnetic fields [30].

1.5.7 (Double-negative) Metamaterial

Double-negative (DNG) metamaterials are artificial materials with negative values of both refraction and refraction, unlike naturally occurring materials. This unique characteristic allows them to bend electromagnetic waves or light in the opposite direction, leading to groundbreaking technologies like superlenses, electromagnetic cloaking tools, and improved antenna designs. DNG metamaterials provide precise control over electromagnetic wave interactions, opening up possibilities in optics, telecommunications, and other fields [31]**.**

1.5.8 Narrow-band and Wide-band Metamaterial Absorbers

Narrow-band and wide-band metamaterial absorbers are synthetic materials used to manipulate electromagnetic wave absorption over specific frequency ranges. Narrow-band absorbers absorb radiation within a small frequency range, like a bandpass filter, while wide-band absorbers absorb waves across a larger range using resonances and impedance matching methods. They are used in filtering, sensing, stealth technology, and broadband electromagnetic interference shielding, with narrow-band used in filtering and sensing

applications and wide-band in stealth technology and shielding [32].

1.6 Applications

Metamaterials absorbers are utilized in various industries due to their unique electromagnetic properties. They enhance energy conversion efficiency in solar energy harvesting, improve antenna design, and reduce interference in radar and stealth technologies. Metamaterial absorbers have diverse applications, from stealth technology in military aircraft to solar energy harvesting and improving the sensitivity of sensors. They also enhance resolution and sensitivity in imaging and sensing, and are crucial in electromagnetic interference shielding in telecommunications. These versatile materials offer innovative solutions in medical device engineering, microwave engineering, and materials science, paving the way for significant advancements. They manipulate electromagnetic waves

1.6.1 Energy Harvesting

Metamaterial absorbers use energy harvesting to collect and convert incoming electromagnetic radiation into electrical power. They use resonant structures to maximize absorption in specific frequencies. The absorbed energy is converted into DC voltage using rectifiers and antennas. This voltage can be used in wireless sensors, remote monitoring systems, and IoT devices, providing reliable, long-lasting power without maintenance. Examples include radio waves and microwaves.

1.6.2 Radar Cross-Section Reduction

Metamaterial absorbers use energy harvesting to collect and convert incoming electromagnetic radiation into electrical power. They use resonant structures to maximize absorption in specific frequencies. The absorbed energy is converted into DC voltage using rectifiers and antennas. This voltage can be used in wireless sensors, remote monitoring systems, and IoT devices, providing reliable, long-lasting power without maintenance. Examples include radio waves and microwaves.

1.6.3 Antenna Gain & Directivity Enhancement

Metamaterial absorbers are specialized materials used in antenna design to enhance gain and directivity. They modify and control electromagnetic waves, reducing unwanted radiation while amplifying desired directions. By adjusting the metamaterial's refractive index and dispersion, engineers can achieve more gain, narrower beam widths, and improved radiation patterns. This method is beneficial in applications like satellite communications, radar systems, and wireless network infrastructure.

1.7 Manufacturing Limitation

Metamaterial absorbers offer excellent electromagnetic properties but face challenges in manufacturing. Accurate subwavelength-scale fabrication requires nanofabrication technologies, and high constraints on size, shape, and arrangement may increase production costs. There's limited material selection due to metals or dielectrics, and performance may vary due to manufacturing defects. To overcome these limitations and realize their full potential, scientists and engineers are researching advanced manufacturing processes and materials [33].

Chapter 2

Literature Review

2.1 Introduction

In[34] proposed design of a triple band ultrathin compact polarization insensitive metamaterial absorber for S, C and X-band applications. The proposed absorber consists of periodic arrangement of a modified triple circular slot ring resonator as unit cell printed on the top of a continuous metal backed FR-4 dielectric substrate. The proposed absorber is ultrathin having thickness of λ_0/135.66 at the lowest absorption center frequency. The measured wide stable absorption bands of 0.40 GHz, 0.45 GHz and 0.47 GHz with absorption peaks of 97%, 96.45% and 98.20% at absorption center frequencies of 2.90 GHz, 4.18 GHz and 9.25 GHz respectively are observed.

In[35] presented a unique metamaterial absorber for L-band, S-band and C-band applications. The unit cell of the MMA is designed by a modified square-shape closed-loop resonator printed on top of a dielectric substrate and backed by a copper layer. The absorptions occur in L, S and C bands at 1.21, 3.64 and 5.30 GHz, respectively. Moreover, the average absorption remains above 90%. The MMA structure is unique and insensitive to the angle of incidence across a wide range due to its symmetric structure. It is suitable for various applications like aircraft surveillance, satellite navigation, and non-military radiolocation radars.

In[36] presents a multi-layered structure absorber based on magnetic material with broad-band absorption in low frequency region. Artificially structured metamaterials (MMs) have attracted considerable attention because of their applications in electromagnetic absorption. Especially in S-band (2–4 GHz), the electromagnetic wave possesses the narrowest beam width, which is excellent candidate for radar detection. However, because of the long wavelength of the electromagnetic waves in the S-band, they are not easily attenuated by electromagnetic absorbers. Thus, developing high-efficiency microwave absorbers in S-band is still a big challenge.

In[37] presents a metamaterial absorber (MMA) for SAR reduction from 5G n78 mobile devices at 3.5 GHz. Specific absorption rate (SAR) by next-generation 5G mobile devices has become a burning question among engineers worldwide. 5G communication devices will be famous worldwide due to high-speed data transceiving, IoT-based mass applications, etc. Many antenna systems are being proposed for such mobile devices, but SAR is found at a higher rate that requires reduced for human health.

In[38] reported that fifth-generation wireless (5G) has already started showing its capability to achieve extremely fast data transfer, which makes itself considered to be a promising mobile technology. However, concerns have been raised on adverse health impacts that human users can experience in a 5G system by being exposed to electromagnetic fields.

In[39] a wide bandwidth angle- and polarization-insensitive symmetric metamaterial (MM) absorber for X and Ku band is proposed. A four-fold resonator was introduced in the unit cell to enhance the bandwidth. The performance of the proposed absorber is determined by both full-wave simulations and measurements. The simulated and measured absorptions are almost similar at normal incidence with 94.63%, 95.58%, 97% and 75.58% at 11.31 GHz, 14.11 GHz, 14.23 GHz, and 17.79 GHz respectively. At 45° for these frequencies, the absorptions are 95.47%, 97.2%, 97.12% and 75.29% respectively. For 90°, the absorptions are similar to those for 45° except 98.15% for 14.21 GHz. At all these angles and resonance frequencies, either permittivity or permeability was found negative, as a result, the refractive index was negative revealing metamaterial characteristics of the unit cell.

2.2 Categorization of Metamaterials

Metamaterials may be categorized into two primary groups depending on their mathematical representations. The first category consists of structures referred to as Double Negative (DNG) and Single Negative (SNG), whereas the second group comprises structures known as Photonic Band Gap (PBG) or materials that display photonic bandgaps, which may be used interchangeably. The first group is designated as "double positive" (DPS) chemicals because they have both ε and μ values that are larger than zero. The majority of goods in this category are mostly dielectrics. In the second classification, the permittivity is negative but the permeability stays positive, resulting in its categorization as an epsilon negative (ENG) material. This property is often found in a multitude of plasmas at distinct frequencies. Materials in the third category have a permittivity larger than zero and a permeability less than zero, making them mu-negative (MNG) materials. These materials are recognized for their gyrotropic magnetic characteristics. The fourth category consists of double negative (DNG) materials, which can only be produced by artificial means. This class of substance has both negative permittivity (below zero) and negative permeability (below zero). When an electromagnetic wave encounters certain materials, it experiences changes in the properties of how it moves. It is crucial to acknowledge that in the natural world, there are no substances that possess both negative permittivity and negative permeability. Based on the aforementioned list, it can be inferred that metamaterials are a specific category of materials that are intentionally designed to have negative permittivity and negative permeability. Nevertheless, as structures with distinct features and uses continue to advance, a more inclusive concept has arisen to classify metamaterials. A metamaterial is a purposely designed composite material with a regularly structured organization that is meant to interact with electromagnetic waves in a complex manner, allowing it to achieve certain performance objectives that cannot be achieved with naturally occurring materials.[40],[41].

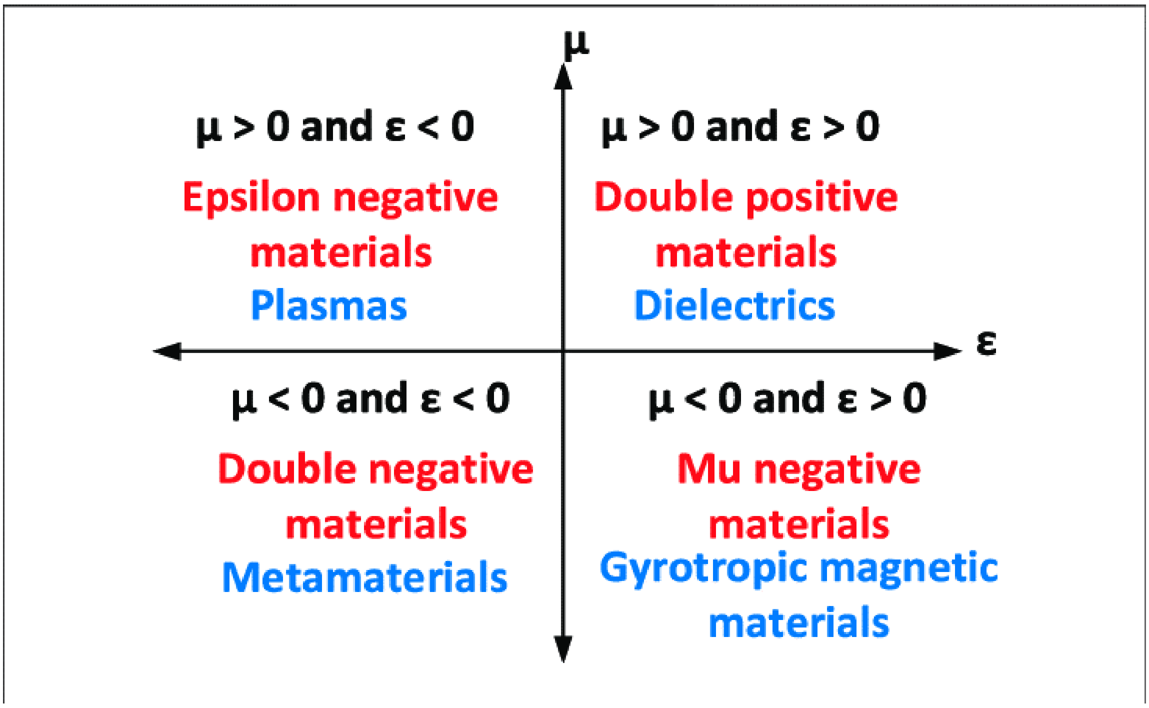


Figure 1 Classification of materials according to their permittivity and permeability properties.

2.3 Negative Epsilon Metamaterials

Epsilon-negative (ENG) metamaterials are a specific class of artificial materials designed to exhibit a negative permittivity (ε) at certain frequencies. In these materials, the electric polarizability is inverted, causing an opposite response to an applied electric field compared to natural materials. This unique property allows ENG metamaterials to interact with electromagnetic waves in unconventional ways, leading to phenomena like negative refraction [42]. The negative permittivity is typically achieved through the arrangement of subwavelength structures, creating a composite material with tailored electromagnetic properties. The apparent permittivity can be articulated as:

$$\varepsilon_p = 1-\omega^2 \mathrm{p}/\omega^2 \tag{1}$$

In the given formula, ω_p denotes the plasma frequency, and ω signifies the frequency of the propagated electromagnetic wave. As per this equation, the effective permittivity turns negative when the frequency falls below the plasma frequency. At the plasma frequency, the effective permittivity becomes zero, leading to a refractive index of zero.

Epsilon-negative (ENG) metamaterials are artificially engineered materials designed to exhibit a negative permittivity $(\varepsilon_\varepsilon)$ at specific frequencies. This unique characteristic is crucially expressed as $\varepsilon(\omega)<0\varepsilon(\omega)<0$, where ω_ω represents the frequency of electromagnetic waves. ENG metamaterials achieve this negative permittivity through the arrangement of subwavelength structures. This distinctive property allows for unconventional interactions with electromagnetic waves, leading to phenomena like negative refraction. Notably, the effective permittivity becomes negative when the frequency is lower than the plasma frequency $(\omega_p\omega_p)$. At the plasma frequency, the effective permittivity is zero, resulting in a refractive index of zero. ENG metamaterials find applications in optics and microwave engineering, enabling the development of innovative devices and functionalities.

2.4 Performance Analysis

To properly evaluate the performance of a metamaterial absorber, it is customarily necessary to take into account several significant features and characteristics. Below is a summary of some of the most important factors that should be taken into consideration in an investigation like this:

Absorption efficiency is a fundamental metric that determines what percentage of the electromagnetic energy that is introduced into the absorber it can successfully consume. Several different frequencies are often put to use while carrying out the process of performance evaluation of the absorber. The absorber's ability to properly function throughout a certain frequency range is defined by the frequency range that its bandwidth covers. Some metamaterial absorbers have broadband and can absorb across a large range of frequencies, while others have a restricted band and are designed for specific frequencies. Metamaterial absorbers can exhibit polarization sensitivity; if this is the case, the polarization of the electromagnetic waves that are coming into contact with the absorbers will affect how well the absorbers function. The absorber's sensitivity should be evaluated concerning many different polarization states as part of the performance investigation.

There is a possibility that angle affects the performance of metamaterial absorbers. It is very necessary to test the efficacy of the absorber at a variety of incidence angles, in particular for circumstances in which the angle at which the incoming wave is coming in varies. Absorbers must not be sensitive to the incidence angle to fulfill the requirements of certain applications. This property is useful in situations where electromagnetic waves could enter from diverse directions, such as stealth technologies or materials that can absorb radar. In the case of metamaterial absorbers, resonant effects are often the foundation on which they work. To fully comprehend the operation of the absorber, one must have an in-depth understanding of its particular resonance frequencies and method of operation. There is a possibility that the absorber's performance will be affected by the thickness and profile of its physical construction. Thicker designs are generally desired because they may supply better absorption but may be less effective in other instances. Low-profile designs are commonly favored because of their compactness. However, thicker designs are frequently preferred because of their potential to deliver greater absorption. Manufacturing errors can occur during the production of metamaterial absorbers, and even little alterations to the design may have an impact on how efficiently they function. It is very necessary to analyze the tolerance to manufacturing changes to achieve repeatability. The performance of metamaterial absorbers may be impacted by the choice of materials used in their construction because of losses inherent to the materials themselves. In the analysis, these losses have to be taken into consideration. The performance of certain metamaterials may change depending on the temperature, which is something to keep in mind in circumstances where there are frequent temperature shifts. For the sake of practical applications, the scalability of the absorber design and the associated manufacturing costs must be taken into consideration [43]. A comprehensive performance analysis may make use of a variety of methods, including experimental measurements, numerical simulations run on computers using specialized software such as electromagnetic simulation software, and theoretical models. If you have a better understanding of how the metamaterial absorber operates when subjected to a variety of conditions, you may aid in enhancing its design when it comes to particular applications. Evaluation of performance is essential in fields such as energy harvesting, antenna design, radar technology, and stealth application development, all of which involve the efficient management of electromagnetic energy.

2.4.1 Substrate Selection

When constructing a metamaterial absorber, the substrate selection technique involves determining which material would provide the greatest support for the needed electromagnetic properties and performance of the absorber. The technique for selecting the substrate may be summarized as follows in a few words:

- Find out the frequency range that the metamaterial absorber needs to perform properly. To accommodate a wide range of frequencies, several substrate materials are required. Substrates for microwave and terahertz absorbers might be different from one another, in contrast to optical absorbers.
- Loss tangent and dielectric constant are two essential factors that describe the substrate material. Loss tangent and dielectric constant both have a negative sign. The absorption performance of the metamaterial absorber can be increased by using a substrate that has both a high dielectric constant and a low loss.
- Mechanical Properties It is important to take into consideration the mechanical properties of the substrate, which include its thickness, strength, and flexibility since these factors have the potential to affect the way the absorber is used in practice[44].

The process of fabrication is as follows: Take into consideration how straightforward and adaptable the chosen metamaterial design is in terms of fabrication. The manufacturing processes that are utilized to build the metamaterial structure need to be compatible with the substrate for the structure to be successfully created. The choice of substrate is a key step in the construction of a metamaterial absorber because it has the potential to significantly influence the absorber's overall performance as well as its overall efficiency.

- Thermal Stability: The capability of the substrate to withstand operational temperatures without experiencing significant degradation is contingent on the application for which it is designed. Robust thermal stability is one of the most important characteristics of a good substrate.

- Environmental Factors: When evaluating the performance of a substrate, it is important to take into account any environmental factors, such as temperature, humidity, and potential exposure to chemicals, which may have an impact on the performance of the substrate.
- Consider Both the Cost and Availability of the Substrate Material One must take into consideration both the cost and availability of the substrate material. Certain components may come at a high cost or be difficult to get in large quantities.
- To acquire the requisite absorption capabilities, it is essential to verify that the substrate of choice is compatible with the design of the metamaterial. This may be done by doing the appropriate testing. This will make it possible to have the kind of interaction that is desired between the structure of the metamaterial and the substrate.
- Testing and Optimization: Once a substrate has been selected, it is essential to conduct experimental testing and optimization to determine whether or not it fulfills the absorption criteria and, if necessary, to adjust the design or the substrate.

The choice of substrate is a key step in the construction of a metamaterial absorber because it has the potential to significantly influence the absorber's overall performance as well as its overall efficiency in the process of absorbing and dispersing electromagnetic radiation at certain frequencies.While selecting the substrate for our proposed design, the first thing we considered was the availability of that particular material in the market and also the cost of it, as we have a target to fabricate the design for journal publication. Considering all of this, we want to use FR-4 as a substrate material. Because it is low in cost and easy to find, though it’s a lossy material.

2.4.2 Parameter Selection

The initial phase of developing a metamaterial absorber involves selecting and fine-tuning critical design parameters that influence its features and usefulness. These parameters include determining the specific frequency range, unit cell geometry, material properties, periodicity, thickness of metamaterial layers, angle of incidence, efficiency and bandwidth, modeling and simulation, compatibility with fabrication techniques, experimental validation, and iterative optimization. The choice of these parameters affects th absorber's ability to regulate and absorb electromagnetic waves at specific frequencies and incidence angles. Modifying the size, shape, and geometry of the unit cell can achieve the desired resonance frequency, ensuring successful absorption of electromagnetic waves. The thickness of metamaterial layers also plays a crucial role in determining both bandwidth and absorption efficiency. The design parameters are then tested in prototypes to confirm their compliance. The process of selecting the absorber's parameters is essential for achieving functionality and performance goals.

Paramete selection is a crusial task of this study, as it affects the result immensely. The stability of the ratio of inductive and capacitive elements in the absorber is affected by its width, height, and length. This ratio is what finds the resonance frequency at a certain position. Also, we have to be careful about the condition, 'subwavelength size', which we have to take care of while deciding the dimension of the absorber.

2.4.3 Paper Review

Papers selected for review are based on the impact factor of the journal where the paper was published, as well as the accomplishments of each individual paper and the advancements made by the papers from previous research.

Paper review helps to set our goals and strengthen our basic about the topic studying. To do so we reviewed lots of papers of recent time to understand the scope of working in a particular field. The first paper we reviewed was designed for a specific application field.

This research presents a suggested X and Ku band wireless use of a square enclosed split-maze-shaped (SE-SMS) metamaterial absorber. The split-maze structure was finally rendered insensitive to cross-polarization and a perfect absorber by applying a novel rotational symmetry approach and introducing two square metal enclosures around it. At frequencies of 9.33 GHz, 12.83 GHz, 13.86 GHz, and 15.61 GHz, four ideal absorption peaks were attained. For regular incidence (up to 180 degrees) and angled incidence (up to 90 degrees), the suggested metamaterial absorber (MMA) was shown to be an ideal MMA, taking incident angle insensitivity into account. Furthermore, it is unaffected by EM waves that are cross-polarized or co-polarized. Furthermore, it exhibits single negative (SNG) permittivity characteristics, resulting in a negative refractive index value, which guarantees the metamaterial features at resonance frequencies. An analogous circuit analysis was performed in order to provide an explanation for the basic electromagnetic behavior of the suggested absorber. Ultimately, the modeling findings have been verified by measuring the absorber cell unit and the array. The suggested MMA may be used with wireless devices operating in the X and Ku bands, particularly for monitoring, EM harvesting, EM-coupled reduction, and enhancing antenna gain applications.

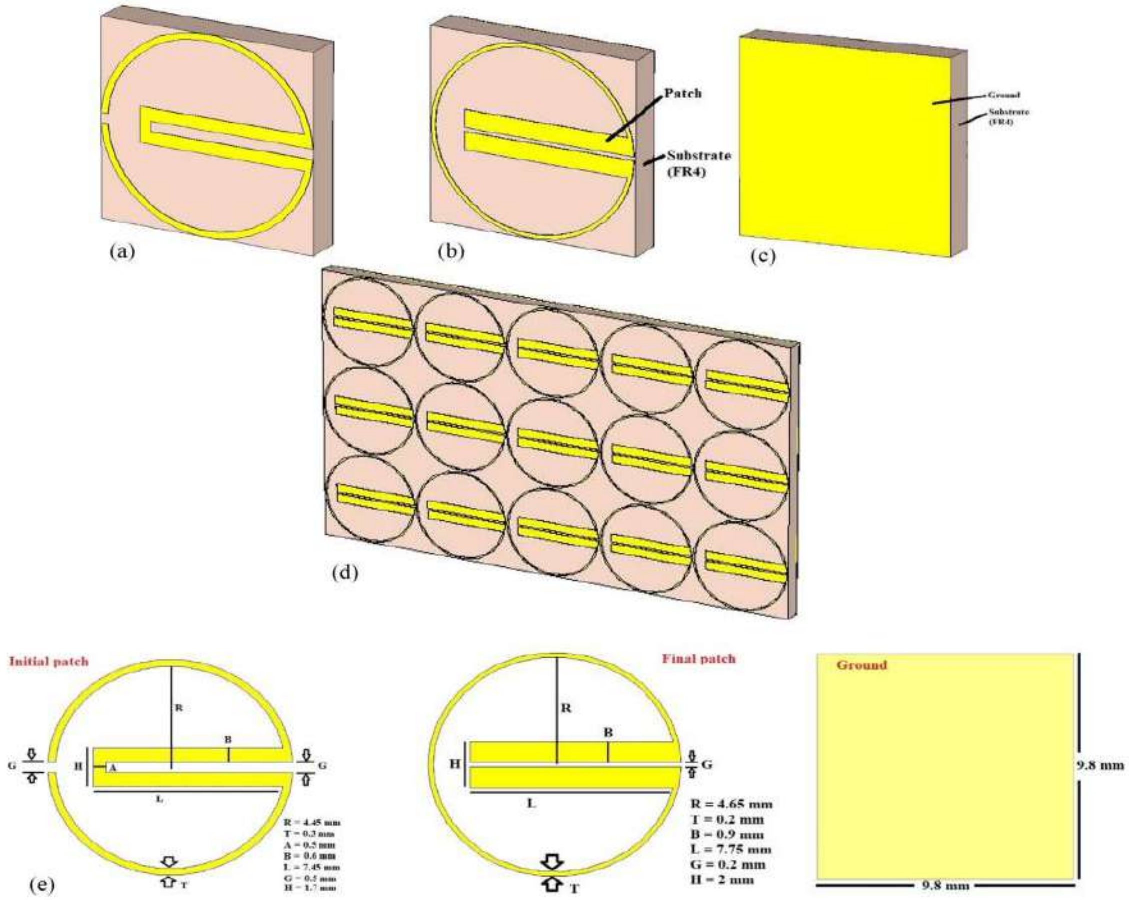
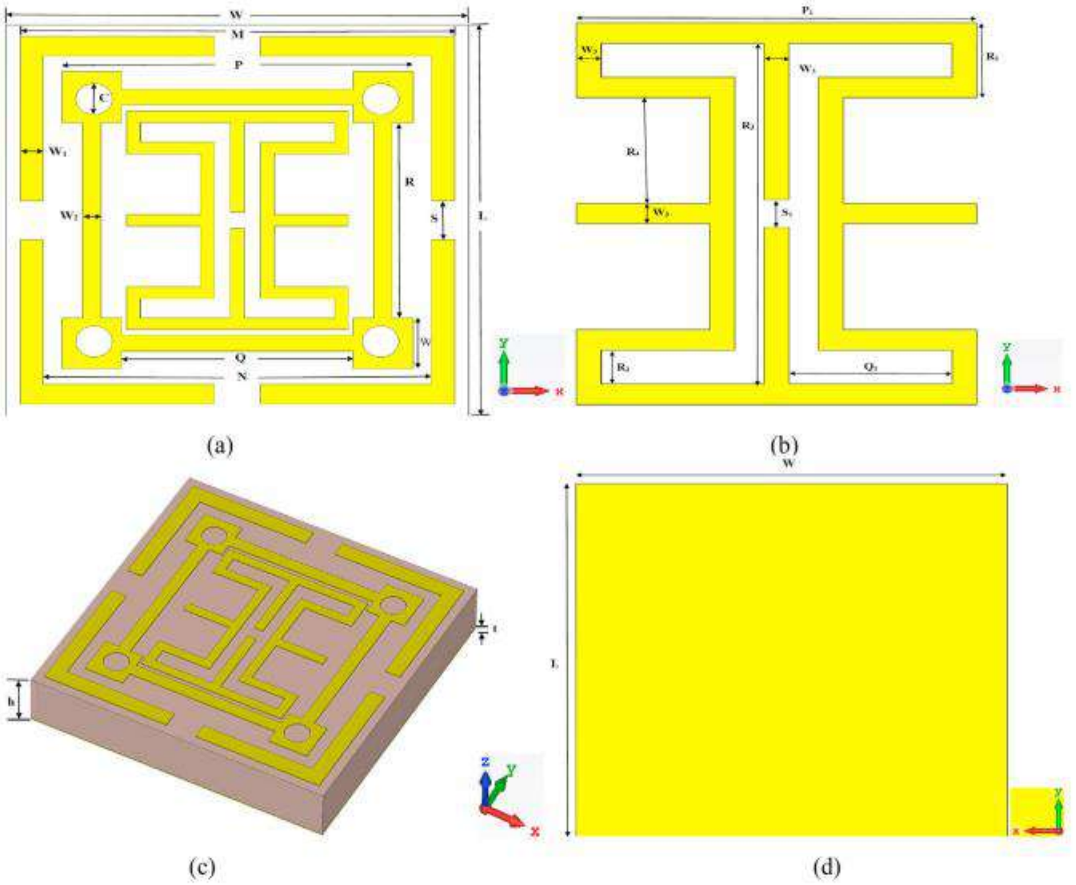


Figure 2 Absorber design

Fig 2: (a,b) Patch and substrate, (c) Ground, (d) unit cell design, (e) Initial patch.

An absorber was designed in Figure. 1, for SAR reduction of n78 electronic devices in 3.5GHz with absorption over 99% and can reduce SAR up to 33%. A co-polarization-insensitive metamaterial absorber (MMA) was used to reduce surface area radiation (SAR) from next-generation 5G n78 mobile devices. The MMA's absorptivity was tested at 3.5 GHz resonance frequency. The metamaterial's modified circular split-ring resonator allows it to absorb only the co-polarized component of the applied electromagnetic wave. Despite its effectiveness, perfect MMAs are not suitable for mobile devices due to their full signal absorption capability. Metamaterial absorbers can be designed to selectively absorb or attenuate specific frequency bands used in 5G communication. This helps in reducing interference from adjacent frequency bands, improving signal quality, and minimizing crosstalk between different communication channels. metamaterial absorbers offer versatile solutions for optimizing the performance and efficiency of 5G networks, making them an integral component in the advancement of next-generation wireless communication technologies [45].

Above 99% of the triple band frequency that Md Bellal Hossain's absorber for stealth applications and shielding against electromagnetic interference (EMI) was designed to absorb has been absorbed by the absorber. In addition to that, they use ADS circuit modeling to investigate the resonance frequency. The absorber that they constructed has a minimum resonance frequency that corresponds to a wavelength of 0.179, and as a result, the dimensions of the absorber are also 0.179λ on each side. They duplicate the absorber in both the transverse electric (TE) mode and the transverse magnetic (TM) mode when the incidence angle is greater than sixty degrees [46].



(a)

(b)

(c)

(d)

Figure 3 Absorber design

Fig 3: (a) Patch, (b) Patch, (c) Substrate (d) Ground.

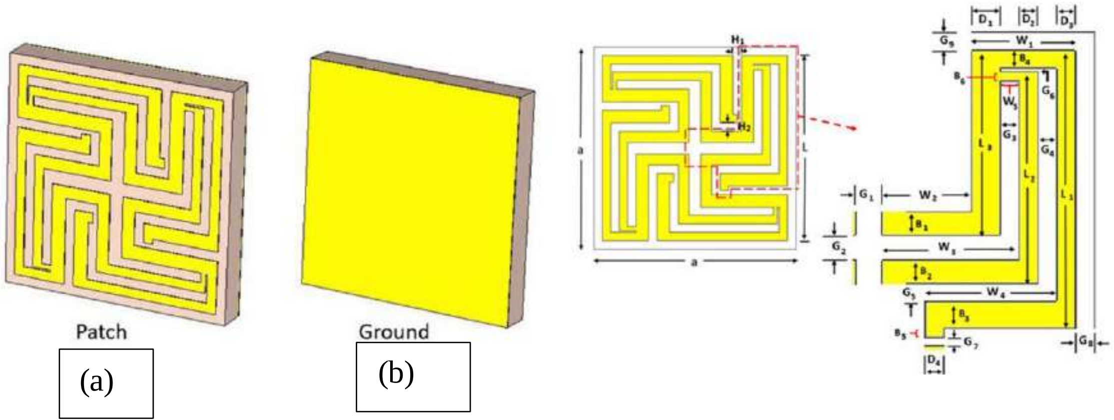
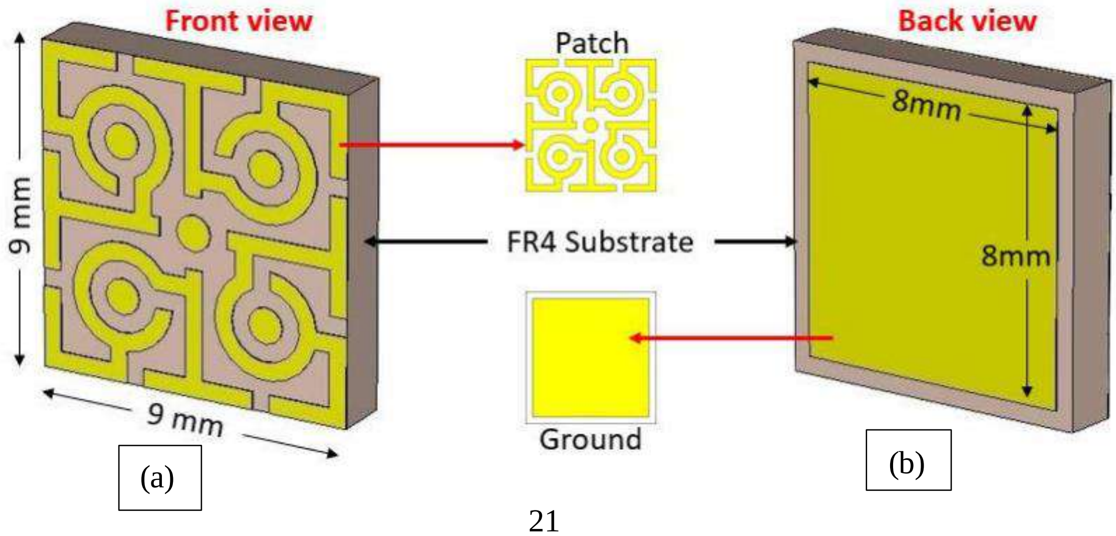
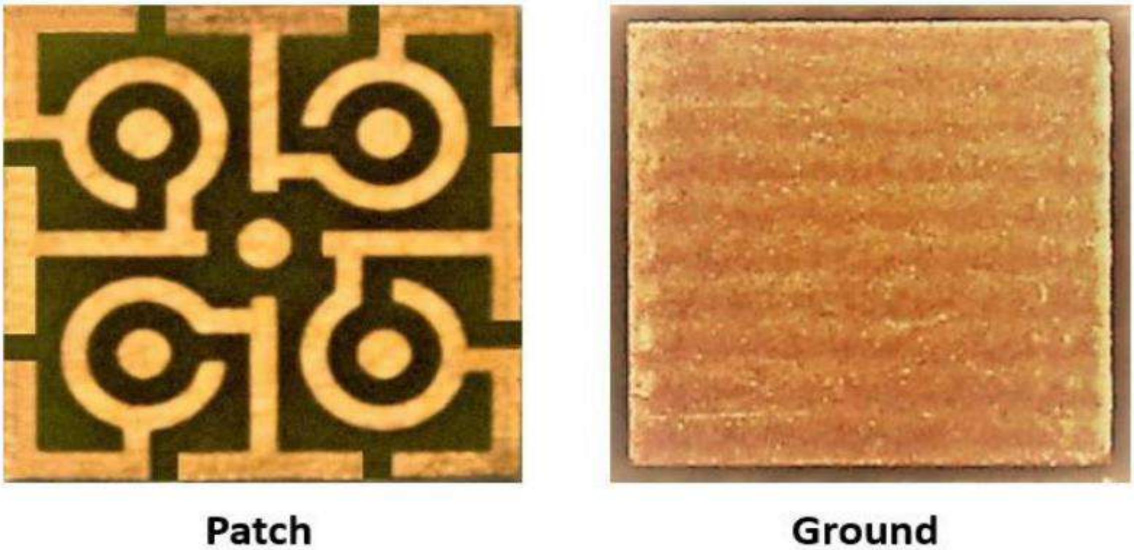


Figure 4 Absorber design

Fig 4: (a) patch, (b) ground

The metamaterial absorber is a cutting-edge invention in electromagnetic wave absorption technology. It features the characteristic plus-shaped structure of a completely linked ground plane and an enclosed copper patch, which are separated by a dielectric substrate. The fundamental objective of this metamaterial absorber is to make effective use of the properties of metamaterials to accomplish the absorption of electromagnetic radiation across a broad frequency range in an energy-efficient manner. A copper patch in the form of a plus sign (+) is the major component of the absorber. This patch is in the shape of a plus sign (+). This shape has been perfected to give superior absorption properties over a wide range of frequencies to meet the requirements of the optimization process. Because of copper's high conductivity, it has the potential to be used in applications requiring the absorption of electromagnetic radiation [47].





(c)

(d)

Figure 5 Absorber design

Fig 4: (a) Front view, (b) Back view, (c) Patch, (d) Ground.

Dr. Saif Hannan has created a metamaterial absorber with a split ring that exhibits both SNG and DNG for use in triple-band applications. Patches and grounds were made from copper, whereas the FR-4 dielectric substrate was employed. The average here is around 95%, which is quite high. A connection is created between electromagnetic waves and a split ring, leading to resonance. Applications for the absorber may be found in the X, Ku, and K bands [48].

The metamaterial absorber is just 0.118 inches on a side, yet it can withstand waves with an incidence angle of up to 90 degrees and polarizations of up to 60 degrees. The width and length are respectively 0.118 inches and 0.120 inches. The work was worthwhile since the resulting effective medium ratio of 8.47 is respectable. Because the dielectric substrate may be tailored in terms of its properties and thickness, the absorber's absorption capabilities can be tuned to suit a wide range of frequencies and applications [49].

Research paper on “Polarization-independent perfect metamaterial absorber for C, X and, Ku band applications”: For use in C, X, and Ku band antennas as well as other applications, a novel swastika-shaped sensitive chiral structure and a near-zerorefractive index-qualified, ideal metamaterial absorber have been presented in this study. Without any lumped or substrate-embedded components, the patch design was simple. 0.169λ is the unit cell size, which falls within the standards' minimum

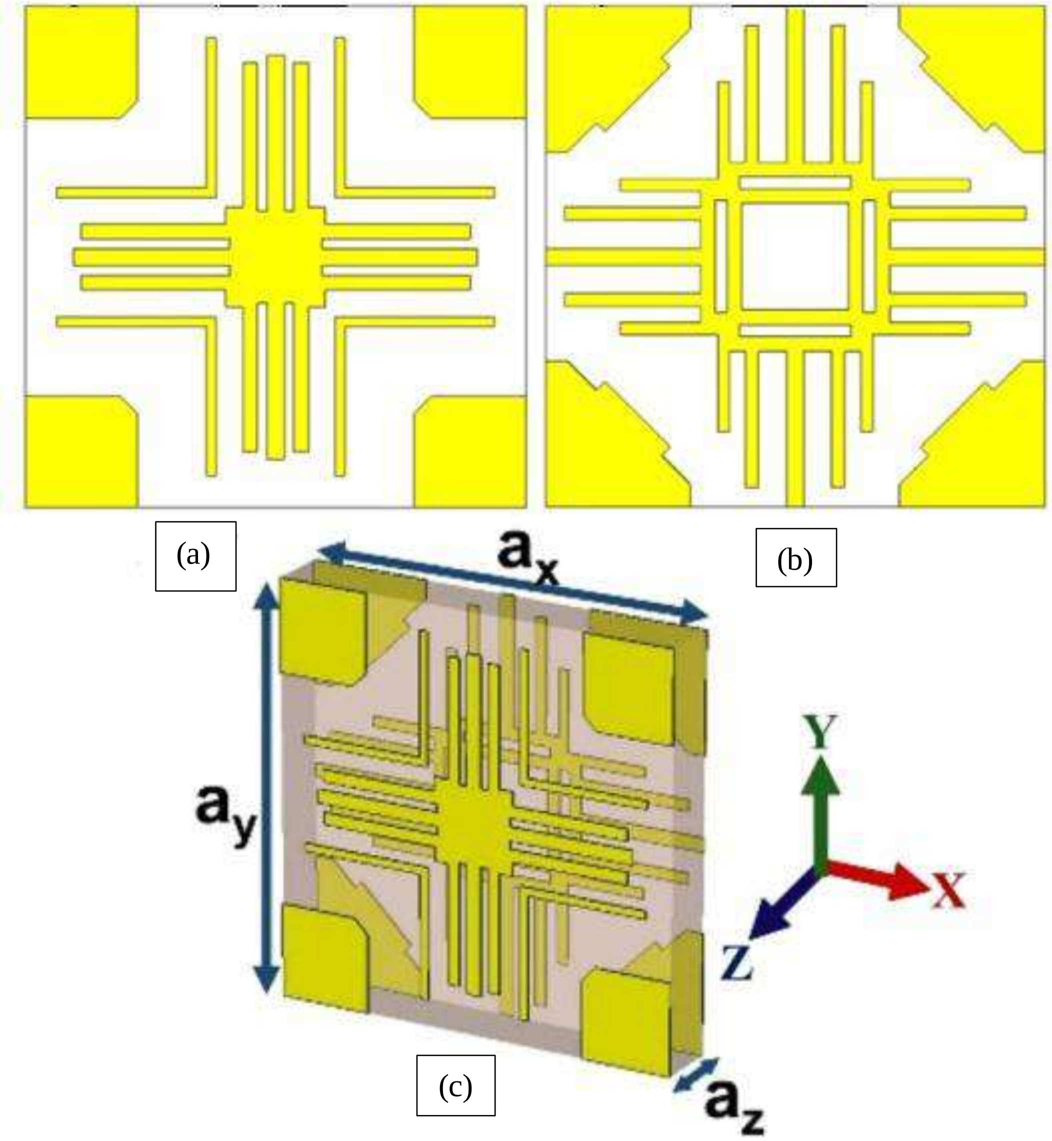


Figure 6 Absorber design

Fig 6: (a,b,c) Patch view.

dimension range. Following the calculation and testing procedure, the suggested NZIM absorber demonstrated perfect (or almost perfect) absorption rates at 4.238 GHz, 7.836 GHz, 10.482 GHz, 11.014 GHz, and 13.352 GHz. This absorber has been made ideal by the cross-polarization analysis. Furthermore, it is a perfect NZIM absorber, a feature not found in any previous related research, thanks to its near-zero refractive index characteristic at resonant frequencies and near-zero refractive index across the whole working frequency range Research paper on “Square Split Enclosed Labyrinth Maze Shaped Metamaterial Absorber for Hydrocarbon Sensing Application”: A suggested metamaterial absorber (MMA) for hydrocarbon sensing applications is presented in this study. It is shaped like a square split-enclosed labyrinth maze. Rectangular continuous and split rings serve as the resonating layer in the three-layered MMA design, which also features a laminated copper FR-4 substrate layer. Ku band and S band cooperate in this MMA. The reflection coefficient, magnetic and electric fields, surface currents, and others have all been investigated in order to better understand the absorption properties of the MMA. 99.4% and 91.65%, respectively, of the MMA's absorbance ranges are between 2.44 and 3.57 GHz. Additionally, by identifying variations in the permittivity of the test items, the suggested MMA sensor offers increased sensitivity for identifying various hydrocarbons. Moreover, 11.28 GHz was the highest reflection band for the MMA sensor configuration. The band shift between octane and hexane is the least at 0.01 GHz; the MMA's average sensitivity for several hydrocarbon materials is 1.4 GHz/ε. This MMA's high absorbance makes it appropriate for a range of 37 microwave applications, such as those involving the detection of hydrocarbons

2.5 Summary

Scientists study metamaterial absorbers to learn more about and improve their abilities to absorb and alter electromagnetic waves. The primary goal is to develop materials that can effectively absorb frequencies. To increase the functioning and efficacy of these absorbers, they examine different production processes and parameters. The end objective is to use metamaterial absorbers in a wide range of applications, including those that aim to minimize electromagnetic interference, collect energy, improve communication, increase sensitivity, or create a more covert system.The choice of material is crucial when building a metamaterial absorber, as it directly impacts its electromagnetic characteristics and effectiveness. The absorption bandwidth and effectiveness are influenced by materials with specialized electromagnetic characteristics. Materials with strong electrical conductivity, like metals, are often used for broad absorption bandwidths, while dielectric materials offer better efficiency. Materials with strong damping and low losses are preferred for efficient absorption. Mechanical strength, durability, temperature stability, and resistance to moisture, chemicals, and other environmental conditions should also be considered. Lastly, the cost and accessibility of materials should be considered.

Chapter 3

Methodology

3.1 Introduction

The absorber design process employs a methodical way to attain certain absorption results. The process commences with the delineation of absorption prerequisites and the selection of materials according to the necessary characteristics. Subsequently, the structure's configuration is fine-tuned to optimize absorption effectiveness. The design process is guided by computational simulations, and the design is brought to life using fabrication techniques. Experimental validation confirms the performance, allowing for ongoing modifications to enhance precision. A thorough analysis guarantees the durability and appropriateness of the design under various circumstances, resulting in a comprehensive report that encompasses the whole design process. This report facilitates replication and continued progress towards achieving particular absorption goals.

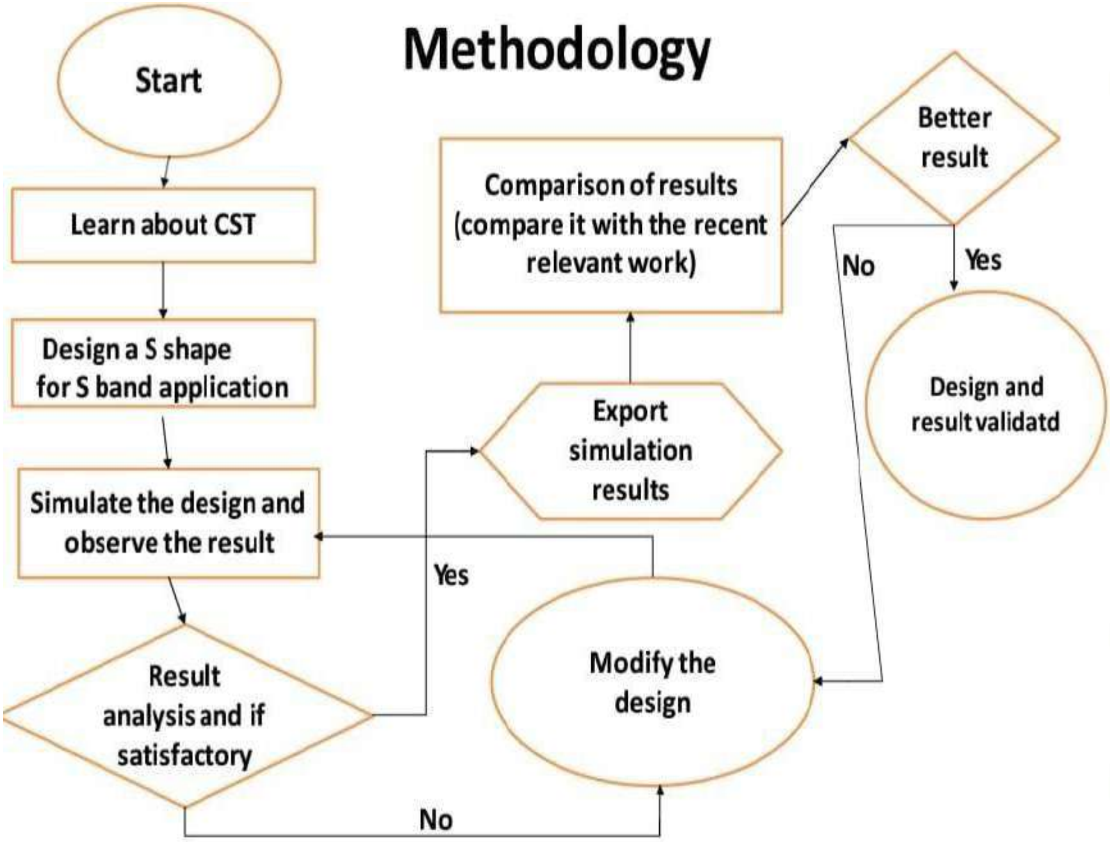


Figure 7 Methodology graph

3.2 Unit Cell Design

We utilize the CST microwave studio simulation tool's 3D coordination system to create the metamaterial. The MM absorber is composed of three layers: a ground, a dielectric substrate, and a patch. Anodized copper is frequently employed for patch and ground, while FR-4, also known as Rogers RT, is typically used as the dielectric material. FR-4 has a thickness of 1.6 43 mm, while copper has a thickness of 0.035 mm. Because of its intriguing higher-frequency behavior, FR-4 is a material that is widely used in substrate design.

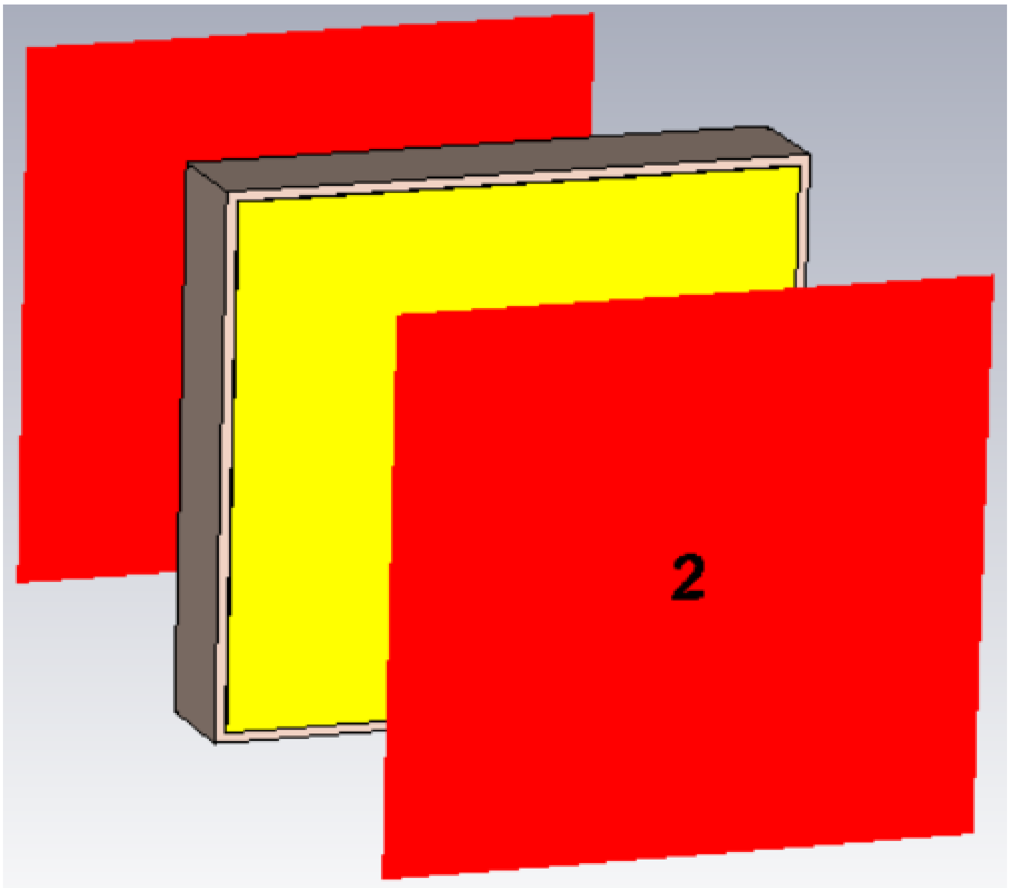


Figure 8 Metamaterial absorber design in CST Software

An absorber made of metamaterial with a 11 mm by 11 mm patch, a 11 mm by 11 mm substrate, and a 11 mm ground are the three layers that make up the design. Copper is used for the patch and the ground in this location, whereas FR-4 is used for the substrate of the dielectric layer. The buildup of this causes inductive and capacitive behavior, which traps electromagnetic waves within the absorber.

In this example, we can see that a quad repeating view with a square in the center is produced when a square is coupled with an S-shaped opening in the centre. Copper, which is a metal with a high degree of loss, was used in the construction of the absorber. When an electromagnetic wave delivers energy, that energy is absorbed at a certain frequency, which is also the frequency at which resonance reaches its greatest intensity. When the electromagnetic wave comes into contact with the patch, the square coupling works to help block it.

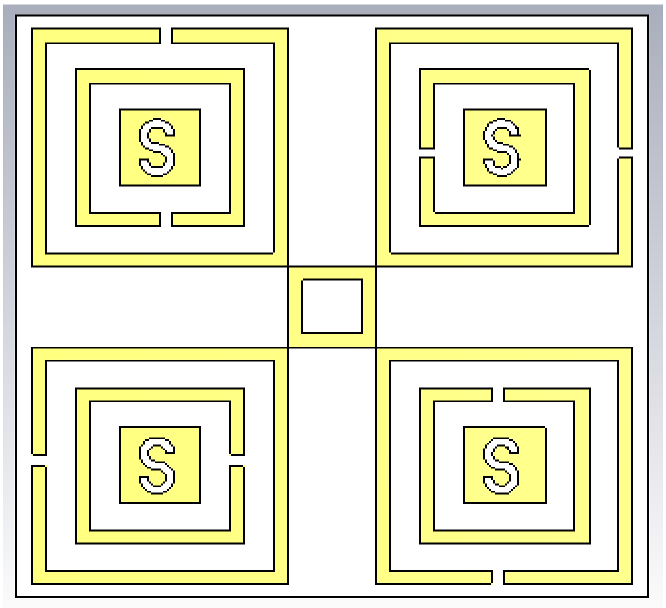


Figure 9 Unit cell front design

It is clear from this that the rear of the absorber makes use of a solid ground, which contributes to the blocking of the transmission. Because, as is well known, electromagnetic waves cannot ignore conductive metal without experiencing some kind of deflection, and this is the reason why.

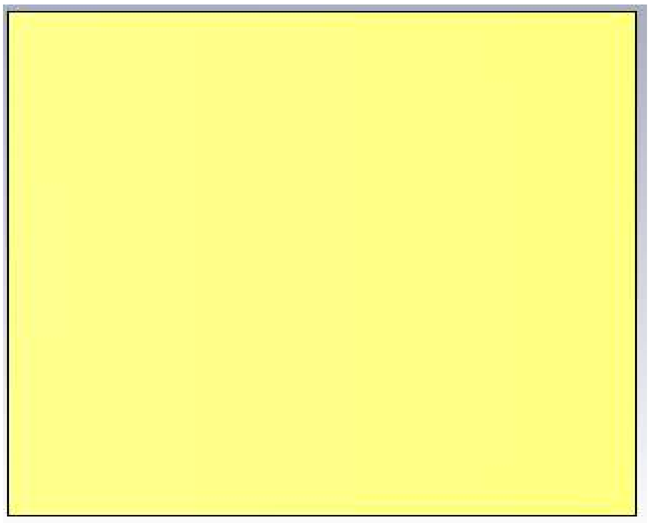


Figure 10 Unit cell ground design

3.2.1 Fundamentals of Absorption

To properly function, an absorber is required to have the capacity to take in electromagnetic radiation. To accomplish this goal, it is necessary to prevent incident waves from transmitting and reflecting as much as is humanly feasible. That being the case, absorption is dependent not only on the capability of the metamaterial absorber to prevent as much transmission and reflection as feasible but also on the capacity to store the energy inside the absorber itself. The efficacy of anything grows in direct proportion to how efficiently it is carried out. So, the absorption will be,

$$A_p = 1 - r(\omega) - T(\omega) \tag{1}$$

The symbol for reflection is denoted by the letter r(ω), where T(ω) stands for the transmission coefficient and A refers to the amount of absorption by the absorber. However, electromagnetic waves are unable to pass through a completely conductive metal, as we already know. Therefore, there will be no transmission coefficient so long as we make use of full ground. Then the equation will be,

$$A_p = 1 - r(\omega) \tag{2}$$

Both the impedance of the absorber and the impedance of the source of the transmitted power affect the reflection coefficient. In this specific section of the metamaterial absorber, there is not a power line of any kind; rather, a waveguide port is coupled with the absorber via free space. In other words, the impedance of open space measures out to be 377 ohms.

$$r(\omega) = \frac{z_a - z_0}{z_a + z_0} \tag{3}$$

By paying attention to the equation, we can deduce that there will be no reflection when the impedance of the absorber is equal to the impedance of the open space. Because load impedance and source impedance are reliant on each other for reflection impedance, matching is something that should be given a lot of attention.

$$Z_a = \sqrt{\frac{\mu_o(\omega)\mu_f(\omega)}{\varepsilon_o(\omega)\varepsilon_f(\omega)}} \tag{4}$$

The permeability of the null space and the metamaterial is denoted by the symbols μ_0 and μ_f, whereas the permittivity of the null space and the metamaterial is denoted by the symbols ε_0 and ε_f. The impedance of the absorber may be calculated using the square root ratio of the permeability and permittivity values, but the impedance of the free space can only be calculated using the ratio of the free space's permeability and permittivity value [50].

$$Z_o = \sqrt{\frac{\mu_o(\omega)}{\varepsilon_o(\omega)}} \tag{5}$$

3.2.2 Design Revolutions

Broadband metamaterial absorbers for C and X bands typically involve constructing a complex structure of metamaterial layers that can effectively absorb electromagnetic waves across these frequency bands (with frequencies roughly ranging from 3.4 GHz to 12.4 GHz for the C band and 7.0 GHz to 11.2 GHz for the X band). This is because lumped components are not used in the procedure. First, you'll need to construct a multi-layered structure, since this is the typical layout for broadband metamaterial absorbers. Each layer has to have its distinctive characteristics for total absorption over the C and X bands. Develop a fundamental construction block or unit cell, that may be applied numerous times across the full structure. The unit cell should ideally be constructed using structures or components that resonate at a wide range of frequencies within the useful frequency ranges. Select a dielectric substrate that not only offers mechanical support for the structure but also ensures that its impedance is frequency-independently matched to that of free space. Resonance behavior in the C and X bands may be achieved by constructing substructures within the unit cell. Possible substructures include but are not limited to, cross-shaped parts, SRRs, and other geometries with resonant qualities. The distance between these substructures and their arrangement within the unit cell is crucial for achieving broadband absorption. To manipulate the resonance frequencies, it is necessary to make adjustments to the relative diameters of the substructures and to relocate them to other locations. It is suggested that the substructure's characteristics and geometries be updated in stages across several levels. This smooth transition allows for the exploration of a large frequency range without the occurrence of any sudden jumps. Electromagnetic modeling tools might enhance the design. Substructures' size and features may be modified to better manage the acquisition of attributes required for broadband absorption. The C and X bands are the optimal frequency ranges for conducting simulations of the expected performance of the metamaterial construction. Proof that a material can absorb wideband frequencies may be shown by building prototypes and putting them through different tests. If the structure must be polarization- and angle-insensitive, then extra symmetry or a high number of layers will need to be included in the design. Real-world applications of the absorber need careful consideration of circumstances such as angle of incidence and proximity to other objects. Creating broadband metamaterial absorbers that don't rely on lumped parts is difficult because of the structure's complexity and the necessity for fine adjustment. It will be necessary to use optimization and simulation techniques to get the necessary performance characteristics that span both the C band and the X band. Substructure geometry and arrangement experiments are typically required to produce further improvements in the absorber's overall performance [51].

3.2.3 CST Services

For electromagnetic modeling and analysis, CST - Computer Simulation Technology has created the CST Studio Suite. It provides a comprehensive set of electromagnetic engineering services and capabilities. The most important features of CST Studio Suite are as follows:

- To model electromagnetic phenomena, such as electromagnetic fields, circuits, antennas, and microwave components, CST Studio Suite is available. It provides a reliable method for modeling and analyzing electromagnetic phenomena in complex systems.
- Microwave, radio frequency, and millimeter wave designs may all benefit from the software's ability to accurately simulate their electromagnetic fields. Antennas, filters, waveguides, and other high-frequency components may all be designed and analyzed with its help.
- Applications such as magnetic field analysis, transformer design, and power electronics may benefit from CST Studio Suite's ability to do low-frequency simulations.
- The program allows users to build intricate 3D geometries and conduct precise electromagnetic interaction analysis thanks to its 3D simulation features.
- Flexibility in Analyzing Transient and Steady-State Electromagnetic Behavior: CST Studio Suite provides time-domain and frequency-domain simulations.
- For a more all-encompassing view of device behavior, it may be utilized for multiphysics simulations, such as those including electromagnetic-thermal, electromagnetic-mechanical, and electromagnetic-circuit coupling.

- Different kinds of antennas, such as patch antennas, horn antennas, dipole antennas, and more, may be designed and analyzed by users.
- The program is useful for designing and analyzing microwave and radio frequency (RF) circuits, including filters, amplifiers, and passive components.
- Applications in particle accelerators, plasma physics, and electron beam devices may benefit from CST Studio Suite's support for charged particle dynamics simulations.
- Materials Library: This feature allows users to choose materials with the desired electromagnetic properties for simulations by providing a database of materials with these characteristics.
- The program supports optimization and design exploration, both of which may be used to hone designs and boost performance.
- Support for co-simulation with various tools and software increases interoperability and design flexibility.
- Interpreting Simulation Results and Generating Plots and Reports using Post-Processing and Visualization Tools: CST Studio Suite.
- To make the import of intricate 3D geometry easier, it interacts with common CAD programs.The aerospace, telecommunications, automotive, and electronics sectors are just a few of the many that rely on CST Studio Suite for their electromagnetic design and analysis needs. Engineers and scientists working on electromagnetic projects will benefit greatly from its full suite of services [52].

3.2.4 The requirements for CST in Minimum System

An example of an elite processing task is an EM simulation. PCs used for CST applications must meet certain specifications for RAM, CPU, and graphics in order to operate at peak efficiency. The workstation or server must, of course, have enough power and cooling. It is advised to select the required accessories and purchase the entire package from a reputable manufacturer like HP, DELL, or IBM [53].

- Processor intel: Intel Core i5, AMD Ryzen 5
- Random Access Memory (RAM): 16 Gb
- Card Graphics: 100% OpenGL compatible graphics card.
- Storage: 700GB free disk space

- System Operating: Support by 64-bit operating system. RHE Linus 8.x. and Windows 10.

3.2.5 The Solver List of CST Microwave Studio

The CST Microwave Studio is a comprehensive tool that boasts a diverse array of electromagnetic (EM) simulation solvers, each leveraging different methodologies to cater to a wide range of simulation needs. Key among these methodologies is the Finite Integration Technique (FIT), the Finite Element Method (FEM), and the Transmission Line Matrix (TLM) Method. These solvers are particularly adept at handling high-frequency simulation tasks, making them highly versatile and generally applicable for a broad spectrum of simulation assignments. To complement these solvers, CST Microwave Studio also offers additional solvers designed for high-frequency master applications. These are especially beneficial for electrically large or intricately detailed structures, expanding the scope and capability of the software. In addition to these, CST Microwave Studio is equipped with FEM solutions that are tailored for static and low-frequency applications. This includes the simulation of electromechanical components, transformers, and sensors. These frequency approaches are not limited to simple applications; they are also highly effective for charged electron molecule materials, multi-physics challenges, and complex electronic hardware. With this array of tools at their disposal, users can navigate and solve a wide variety of simulation challenges with ease and precision [54]. This versatility makes CST Microwave Studio a powerful and indispensable resource in the field of EM simulation.

3.2.6 Time Domain

This solution is highly effective for a broad range of broadband applications, demonstrating its capability to closely match the performance of the leading devices in high-repetition scenarios with just a single iteration. Its efficiency stems from the methodical tracking of field developments over time, employing a strategy that focuses on discrete spatial regions and specific time intervals. This approach allows for precise analysis and replication of complex electromagnetic behaviors, ensuring accurate and reliable performance in various applications. The technique's ability to adapt to different frequencies and rapidly changing conditions makes it particularly suitable for high-repetition tasks, where speed and accuracy are paramount. By meticulously analyzing and following the evolution of fields in these controlled segments, the solution offers a robust and versatile tool for a wide array of broadband applications, from telecommunications to advanced scientific research. This adaptability and precision position it as a competitive option in the market, capable of delivering high-quality results with minimal iterations, thereby enhancing efficiency and reducing operational costs.

3.2.7 Frequency Domain

In this approach, the finite element method (FEM) is employed to discretize Maxwell's equations within the repetition space of a tetrahedral cross-section, a key aspect of the solver's advanced capabilities. CST Studio Suite, renowned for its computational electromagnetics solutions, utilizes two distinct broadband processes to effectively address the challenges posed by repetitive space entertainment. The first process is designed to be universally beneficial, offering a broad range of applications, while the second is specifically tailored for high-Q structures that require reduced demand. This dual-process strategy enables CST to provide versatile and efficient solutions, catering to a wide array of electromagnetic problems. By balancing the needs of general applications with those of specialized high-Q structures, CST ensures that its software can handle a diverse range of scenarios, from routine simulations to complex, high-precision tasks. This adaptability is crucial in the field of computational electromagnetics, where the requirements can vary significantly depending on the specific nature of the problem being addressed. The use of FEM in discretizing Maxwell's equations within this framework further enhances the solver's

3.2.8 Eigenmode

This methodology involves detecting frequencies and mapping electromagnetic field patterns without the application of any external stimulus, a method that offers a unique viewpoint on the inherent features of the system under study. However, this approach of studying freely recurring dynamic permittivity or reluctivity offers several drawbacks. These limitations originate from the inherent problems in adequately representing the dynamic behavior of materials without external effects. To mitigate these concerns, one potential method is to leave the device linked to waveguide ports. This link allows for a more regulated environment where the electromagnetic interactions can be seen more reliably. By keeping this connection, it becomes possible to monitor the changes and responses of the system under natural conditions, providing significant insights into its underlying electromagnetic features. This method is particularly effective in applications where understanding the material's sensitivity to electromagnetic fields in its natural condition is critical. The capacity to monitor and evaluate these properties without external stimulation is a huge advantage in research and development, enabling a greater understanding of material behaviors and electromagnetic phenomena. This method is especially significant in the disciplines of material science, telecommunications, and electromagnetic compatibility, where the intrinsic properties of materials play a key role in the performance and operation of devices and systems.

3.2.9 Steady State Thermal

This approach determines the range of possible temperatures within a given framework, taking into account various sources of heat. These sources include both magnetic and electric fields, which can generate heat through electromagnetic interactions. Additionally, chemical reactions and processes contribute to the thermal profile of the system, as they often release or absorb heat. Heat fluxes, which represent the rate of heat transfer per unit area, are also crucial in understanding the temperature distribution. Well-characterized external heat sources, along with human bioheat sources – the heat produced by metabolic processes in the human body – are also considered. By analyzing these diverse heat sources and their interactions, the method provides a comprehensive understanding of the thermal behavior of the system, enabling accurate prediction and management of temperatures in various applications, from electronic devices to biological systems. This holistic approach is essential for ensuring the reliability and safety of systems where temperature plays a critical role.

3.2.10 Transient Thermal

This method is designed to determine the rate of thermal expansion in a structure, a critical aspect in understanding how materials respond to temperature changes. Various factors contribute to the generation of heat within the structure, influencing its thermal expansion. Magnetic and electric fields are significant sources, as they can induce heating through electromagnetic interactions. Chemical interactions within the material can also affect its thermal behavior, either generating or absorbing heat. Heat fluxes, which represent the flow of heat energy, play a crucial role in determining the temperature distribution across the structure. Additionally, external heat sources that have been previously identified, as well as human bio-heat – the heat produced by the human body – are considered in the analysis. These diverse sources of heat can lead to temperature variations within the structure, causing it to expand at different rates. Understanding the rate of thermal expansion is essential for ensuring the structural integrity and reliability of materials and systems, especially in applications where they are subjected to varying thermal conditions. By accurately predicting the thermal expansion, engineers and designers can make informed decisions about material selection, design modifications, and safety measures, ultimately enhancing the performance and longevity of the structure.

3.2.11 Origin Pro Services

Origin Pro is a comprehensive data analysis and graphing software package largely used by scientists and engineers for data visualization, analysis, and presentation. It's very flexible because of the many services and features it provides.

- Origin Pro's set of data analysis capabilities is extensive, including everything from basic statistics and mathematics to more advanced features like curve fitting and peak analysis. Users can preprocess data by transforming it, filtering it, or smoothing it.
- Data visualization and graphing: many different types of 2D and 3D graphs, plots, and charts may be generated using this program. Scatter plots, bar graphs, histograms, heat maps, contour plots, and more are all supported. Graphs, axes, labels, legends, and annotations may all be altered to the user's liking.
- Origin Pro makes it simple to deal with data from a variety of sources by facilitating the import and export of data in several common formats, such as Excel, CSV, text, and databases.
- Users may automate processes and do sophisticated analyses by writing scripts in Origin C, Python, or LabTalk. The software's scripting language enables for customization and expansion of its features.
- Origin Pro provides several statistical tests, including t-tests, ANOVA, regression analysis, and non-parametric tests, to evaluate hypotheses. Within the program

  Within the program itself, users may run statistical tests on their data.
- Fourier analysis, digital filtering, and convolution are only a few examples of the signal-processing operations available to users.
- Enhancing images, tracking particles, and quantifying visual content are just some of the many uses for Origin Pro's built-in image processing and analysis

features.

- The program is well suited for fitting experimental data to mathematical models since it supports several different nonlinear curve fitting models and procedures.
- Origin Pro's peak fitting features make it easy to find and fit peaks in a variety of data types, including spectra, chromatograms, and more.
- Data may be shown in three dimensions using the toolset's support for 3D surface plots and contour plots.
- Statistical Process Control (SPC) is included in Origin Pro to help customers evaluate data for process stability and quality improvement via quality control and monitoring.
- Users may create graphs, tables, and reports fit for publishing to show and discuss their results.
- Origin Pro also can connect to a wide range of laboratory devices, streamlining the process of collecting and analyzing data.
- Users may design their themes and templates to give their charts and reports a uniform appearance.
- Through the Origin Project file format, users of Origin Pro may work together and share their data, graphs, and analysis findings with their coworkers.

Data analysis, experimental data visualization, and research presentation are just some of the many scientific and technical uses for OriginPro in the classroom, lab, and office. Its broad capabilities make it a flexible tool for data analysis and presentation requirements [55].

Chapter 4

Result Analysis

4.1 Reflection Coefficient

In this particular case, for the TEM mode of operation for the absorber that has been provided, we achieve resonance at precisely 3.5 GHz, which is a singular occurrence all on its own.

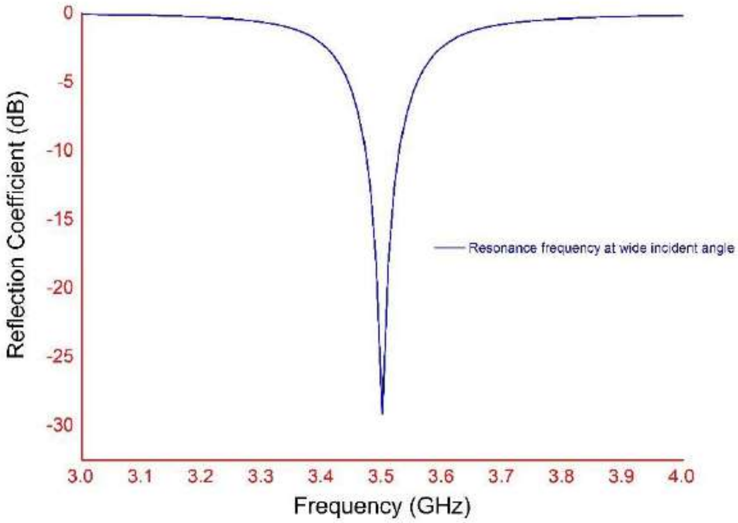


Figure 11 Reflection Coefficient for TEM mode

To measure how electromagnetic waves interact with surfaces, scientists use a complicated metric called the reflection coefficient. It offers information on the relative phase shift of the incident wave and the reflected wave, and so represents the percentage of incident wave power that is reflected from the interface. When designing devices and systems, this parameter is essential in fields like optics and microwave engineering because it enables experts in those fields to regulate the behavior of electromagnetic waves at boundaries, thereby optimizing and tailoring the waves' interactions with different materials to meet a wide range of needs. The reflection coefficient of a metamaterial absorber refers to the ratio of the reflected electromagnetic wave's intensity to the incident wave's intensity. Metamaterial absorbers are engineered structures designed to efficiently absorb electromagnetic radiation across specific frequency bands. The reflection coefficient is a crucial parameter in assessing the absorber's performance, with lower values indicating higher absorption efficiency.

Metamaterial absorbers exploit the unique properties of metamaterials, such as tailored resonances and impedance matching, to achieve desirable absorption characteristics, often surpassing conventional absorbers in efficiency and bandwidth.

4.1.1 Absorption Coefficient

When it comes to absorption, we receive an absorption of over 90% at all incidence angles, as well as in co- and cross-polarization. This is the case regardless of whether the light is being co- or cross-polarized. In this context, theta is believed to be up to 80 degrees since, in a 90-degree electromagnetic wave, it becomes parallel with the patch. Phi, on the other hand, is thought to be up to 180 degrees.

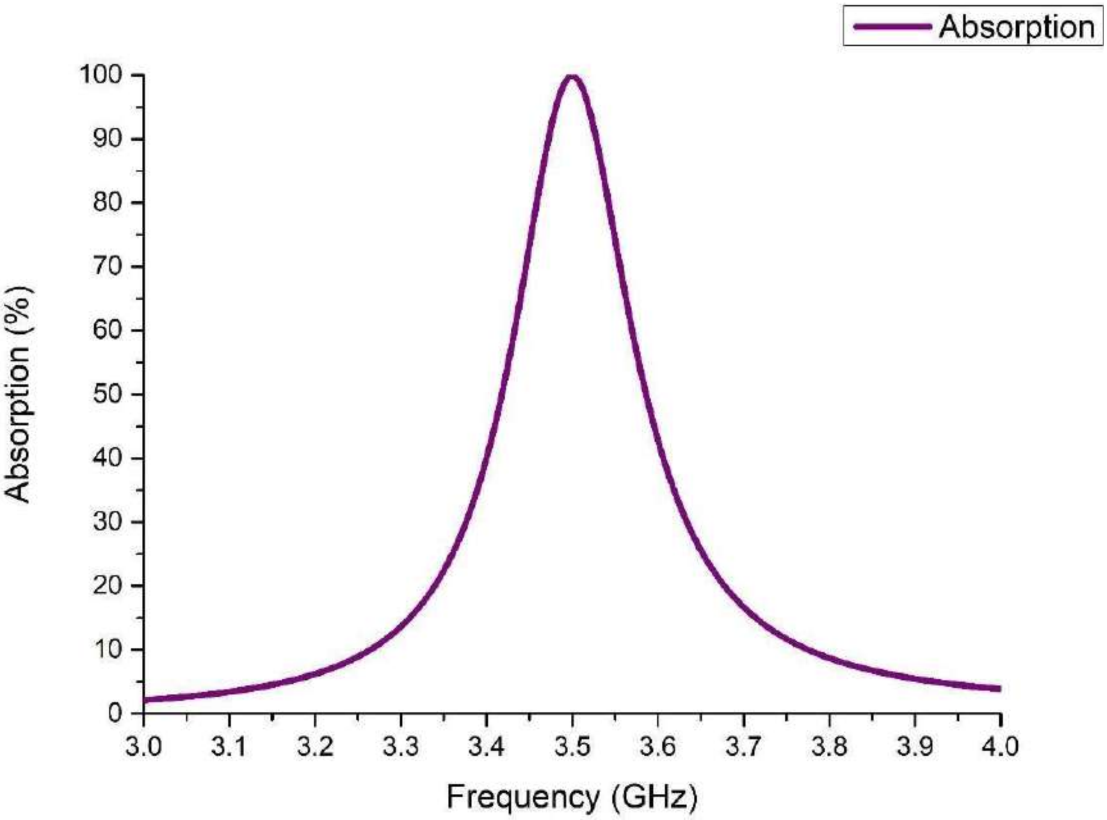


Figure 12 Absorption at resonance

The absorption coefficient of a substance is a basic attribute that measures how much energy a material can draw in from electromagnetic radiation like light. It is frequently represented by the Greek letter " (alpha). A medium's absorption or attenuation of incoming radiation is quantified using this technique. The absorption coefficient is essential in subjects like optics and materials science, where a knowledge of how light interacts with matter is essential. More incoming radiation is absorbed by a material with a higher absorption coefficient, reducing transmission, whereas a lower number suggests better transparency. To manage or reduce absorption, the absorption coefficient is utilized in the design and analysis of optical and electrical devices including solar cells, lasers, and optical filters. The absorption of metamaterials absorbers refers to their ability to capture and dissipate electromagnetic energy incident upon them. Metamaterial absorbers are engineered structures with unique electromagnetic properties, allowing them to efficiently absorb radiation within specific frequency ranges. They achieve this through mechanisms like resonant coupling, impedance matching, and lossy material components. When electromagnetic waves interact with a metamaterial absorber, they penetrate the absorber's surface and either get trapped within its structure or are converted into heat through various loss mechanisms, such as Ohmic losses or dielectric losses. This absorption process effectively reduces the intensity of the incident wave, making metamaterial absorbers valuable in applications like stealth technology, solar energy harvesting, and electromagnetic interference mitigation.

4.1.2 Permeability

For an absorber to be considered a metamaterial absorber, it must, as is common knowledge, include something that is not found in nature. When we refer to anything as "unnatural," we are referring to a value of permittivity (e) or permeability (m) that is negative or very close to zero. Within this particular patch, we measure a permeability that is greater than one that is negative. The value of an absorber is said to be double negative if it obtains an epsilon value and a mu value that are both negative. The material that results from any of them having a negative value is referred to as SNG material. The permeability of a metamaterial absorber refers to its ability to influence the propagation of magnetic fields within its structure. Metamaterials are artificial structures engineered to exhibit unique electromagnetic properties not found in naturally occurring materials. In the context of absorbers, the permeability of metamaterials can be tailored to manipulate how magnetic fields interact with the material. Metamaterial absorbers often utilize magnetic resonances to enhance absorption efficiency. By adjusting the permeability of the metamaterial,

designers can control the resonance frequency and bandwidth of the absorber. This allows for precise tuning to specific electromagnetic frequencies, enabling efficient absorption within desired frequency ranges. Furthermore, metamaterials can exhibit negative permeability, a property not found in natural materials, which can lead to unusual electromagnetic behaviors such as negative refraction and impedance matching. This capability can be harnessed in absorber designs to enhance absorption performance across a broader range of frequencies. the permeability of metamaterial absorbers plays a crucial role in shaping their electromagnetic response, allowing for tailored absorption properties and improved performance in various applications.

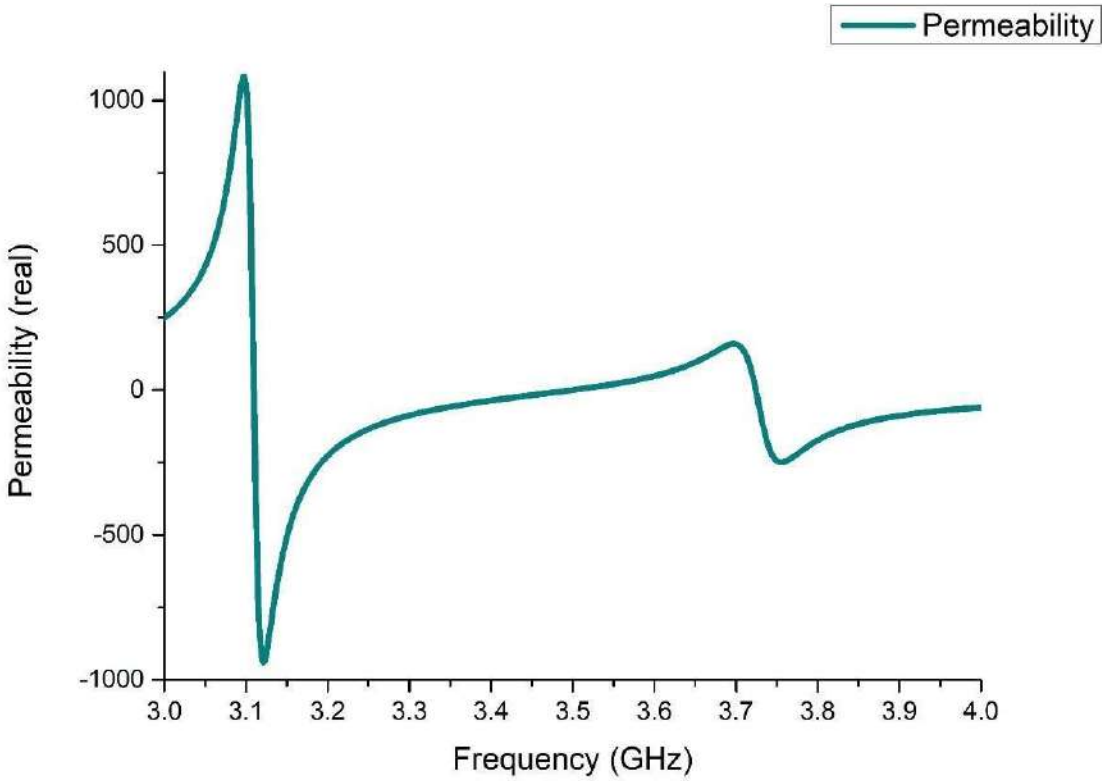


Figure 13 Mu (μ) for different incident angle

Materials can be characterized by their permeability, which is defined as the ease with which magnetic flux or magnetic field lines can move through the material. Electromagnetism relies on this fundamental parameter, which is usually represented by the symbol " (mu). Magnetic permeability and electrical permeability are two common ways of categorizing a material's permeability, which measures its capacity to conduct or support the development of a magnetic field. The ability of a material to allow for the production of a magnetic field in response to an applied magnetic force is known as its magnetic permeability, whereas the ability to allow for the formation of electric fields is known as its electrical permeability. To improve the effectiveness of magnetic circuits, high-permeability materials are employed in devices like transformers and inductors, whereas low-permeability materials can be used as a shield against magnetic interference or for tasks that require only a small amount of magnetic interaction.

4.1.3 Refractive Index

The same may be said for the value of the refractive index. At the resonance point, as was to be anticipated, we determined that the value of the refractive index was negative. The value of the metamaterial's refractive index at 3.5 GHz is -0.07392, which provides a clear indicator of the qualities of the metamaterial.

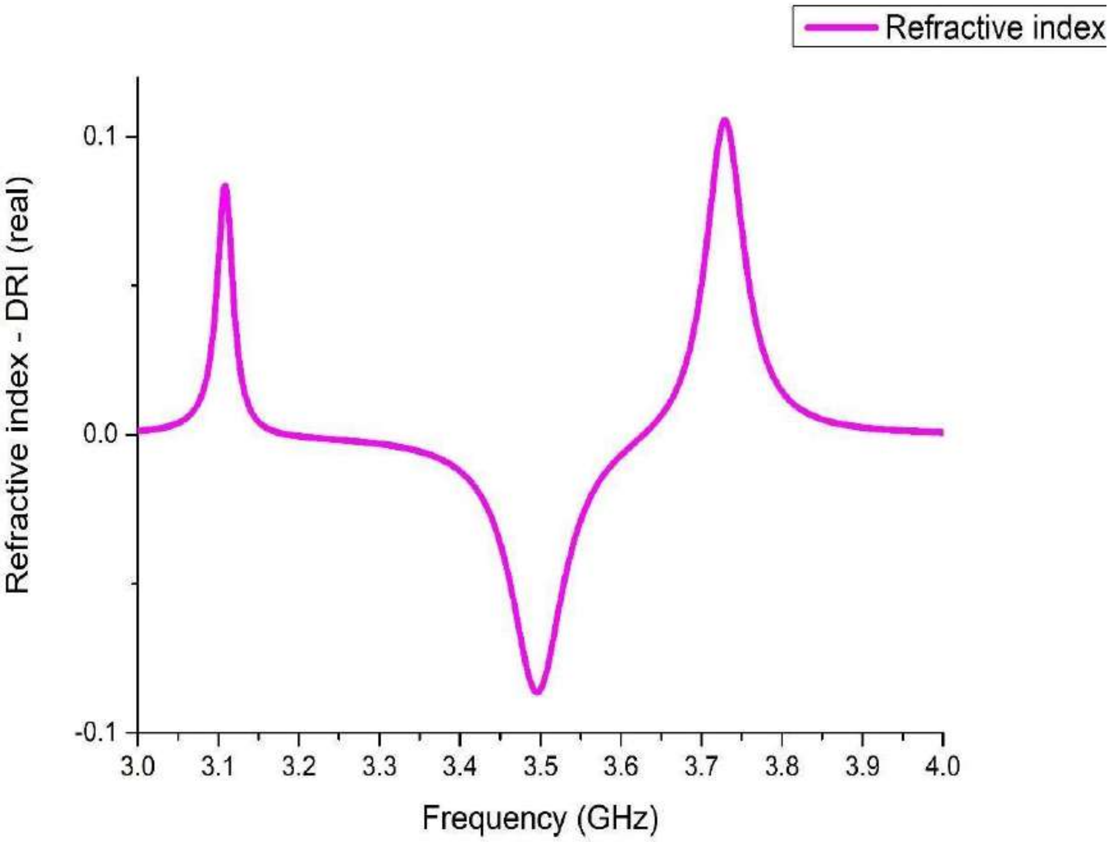


Figure 14 Refractive index

When light travels through a substance, its speed slows by a certain amount, which is measured by the refractive index (also known as the index of refraction, or simply "n"). It is a dimensionless number that expresses the comparison between the speed of light in a vacuum and the speed of light in a substance. In optics, the refractive index is a crucial characteristic that plays a significant part in regulating the amount by which light rays are bent or deviated when traveling from one medium to another, such as from air into glass or water. It controls the phenomena of refraction, wherein the light's direction changes as it enters a new medium like a lens or prism, resulting in a wide range of optical effects like lensing, dispersion, and the appearance of rainbows. The refractive index plays a crucial role in the design of optical components including lenses, prisms, and fiber optics, and in the study of the interaction between light and matter in general. The refractive index of a metamaterial absorber refers to how electromagnetic waves propagate through the material compared to their propagation in a vacuum or a reference material. Metamaterials are artificial structures engineered to exhibit unique electromagnetic properties not found in naturally occurring materials. The refractive index of a metamaterial absorber can be tailored by designing its structure and composition to manipulate the phase and velocity of electromagnetic waves. In traditional materials, the refractive index is typically a positive real number, representing the ratio of the speed of light in a vacuum to the speed of light in the material. However, metamaterials can exhibit extraordinary refractive indices, including negative values, which can lead to unconventional optical phenomena such as negative refraction and superlensing. In the context of absorbers, the refractive index of metamaterials can be manipulated to control the absorption properties of the material. By designing metamaterial absorbers with specific refractive indices, designers can tailor the absorption spectrum, resonance frequencies, and bandwidth to suit particular applications. Overall, the refractive index of metamaterial absorbers is a key parameter that influences their electromagnetic behavior and absorption performance, enabling innovative applications in areas such as stealth technology, sensing, and energy harvesting.

4.1.4 Permittivity

From fig:15 we can see the permittivity value is -0.34. For an absorber to be considered a metamaterial absorber, it must, as is common knowledge, include something that is not found in nature. When we refer to anything as "unnatural," we are referring to a value of permittivity (e) or permeability (m) that is negative or very close to zero. Within this particular patch, we measure a permeability that is greater than one that is negative. The value of an absorber is said to be double negative if it obtains an epsilon value and a mu value that are both negative. The material that results from any of them having a negative value is referred to as SNG material. The permeability of a metamaterial absorber refers to its ability to influence the propagation of magnetic fields within its structure. Metamaterials are artificial structures engineered to exhibit unique electromagnetic properties not found in naturally occurring materials. In the context of absorbers, the permeability of metamaterials can be tailored to manipulate how magnetic fields interact with the material. Metamaterial absorbers often utilize magnetic resonances to enhance absorption efficiency. By adjusting the permeability of the metamaterial, The permittivity of a metamaterial absorber refers to its ability to

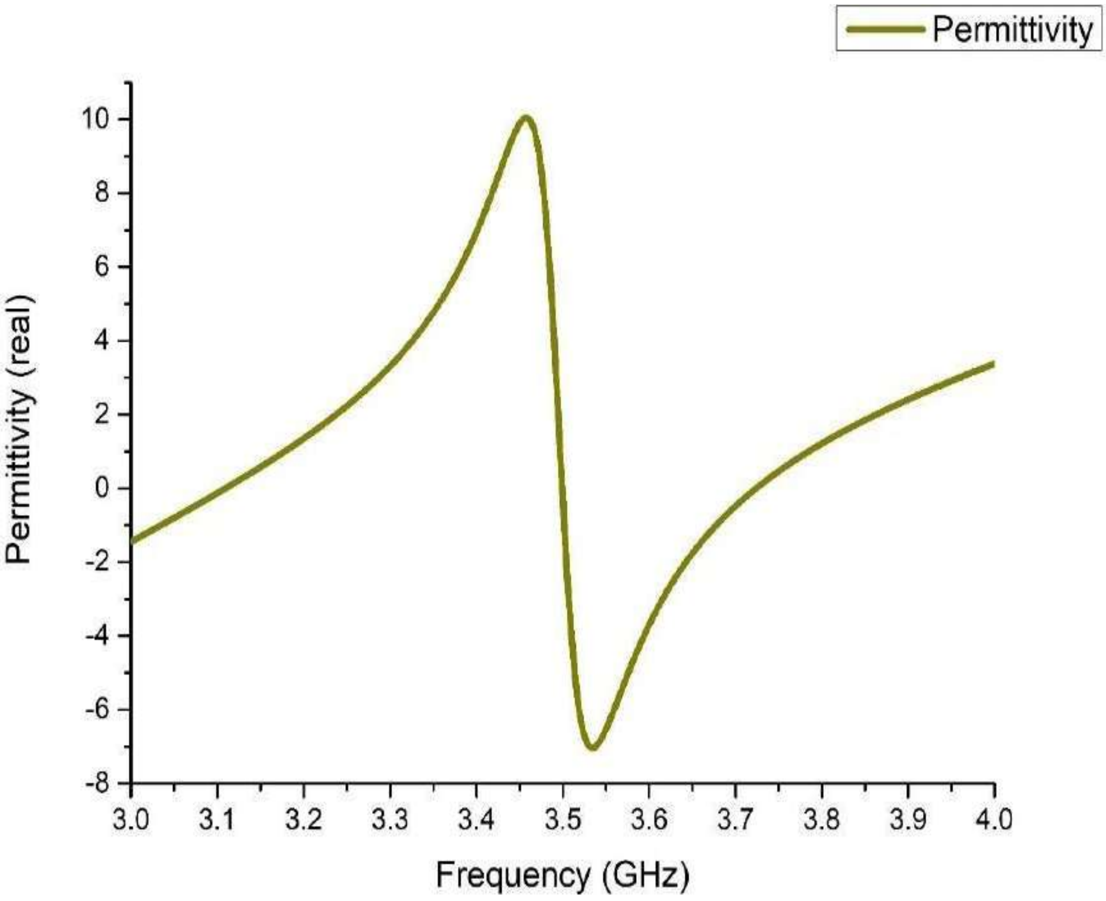


Figure 15: Permittivity

how magnetic fields interact with the material. Metamaterial absorbers often utilize magnetic resonances to enhance absorption efficiency. By adjusting the permeability of the metamaterial, The permittivity of a metamaterial absorber refers to its ability to permit the propagation of electric fields within the material. Metamaterial absorbers are designed to efficiently absorb electromagnetic radiation at specific frequencies by controlling their permittivity and permeability properties. By engineering these properties, metamaterial absorbers can achieve high absorption rates over a desired frequency range, making them useful in applications such as stealth technology, sensing, and energy harvesting. A metamaterial absorber can be realized by using various structures and shapes, such as split-ring resonators, fishnet structures, cross-shaped resonators, and patch arrays. These structures can create a negative or near-zero permittivity at certain frequencies, which can be tuned by changing the geometry and size of the structures. The permittivity of a metamaterial absorber can also be affected by the material properties, such as the dielectric constant and the conductivity, of the substrate and the metal layers.

4.1.5 Surface Current

Here is the scale we can see in the Figure. 15, represents the electric current density. The higher the conductivity, the higher the resonance and absorption. When talking about a metamaterial absorber, the term "surface current" refers to the flow of electrical currents at the interface or surface of the metamaterial structure as a result of its interaction with incident electromagnetic waves. These currents are caused by the metamaterial structure's response to the electromagnetic waves. These surface currents, which are caused by the incident radiation, are included in the behavior of a metamaterial since they are caused by the radiation. Surface currents play a crucial role in metamaterial absorbers, making it possible for these materials to absorb and disperse electromagnetic energy at the frequencies that are desired. To increase the efficiency with which the metamaterial absorbs energy, it is sometimes made to oscillate and induce resonance effects. This causes the incoming electromagnetic energy to be converted into electrical currents, which are subsequently lost as heat. To acquire optimal absorption capabilities in metamaterial absorbers, it is essential to control and regulate these surface currents. This makes metamaterial absorbers appealing for a variety of applications, including stealth technology, energy harvesting, and sensor design. The surface current of a metamaterial absorber refers to the flow of electric charge along the surface of the material when it interacts with electromagnetic waves. Metamaterials are engineered structures designed to manipulate electromagnetic waves in unconventional ways, and surface currents play a crucial role in their absorption properties. In a metamaterial absorber, incident electromagnetic waves induce surface currents due to the interaction with the material's structured surface. These surface currents are responsible for absorbing and dissipating the energy carried by the incident waves. By controlling the geometry, composition, and arrangement of the metamaterial's components, designers can tailor the surface current distribution to optimize absorption efficiency. Surface currents can be induced by various mechanisms, such as resonant coupling, impedance matching, and Ohmic losses within the material. These currents can flow along the surface of the metamaterial, effectively absorbing and dissipating electromagnetic energy across specific frequency bands. Understanding and controlling the surface current behavior is essential for designing metamaterial absorbers with desired absorption characteristics, such as broadband absorption, polarization selectivity, and tunable absorption frequencies. Overall, surface currents play a fundamental role in the functionality and performance of metamaterial absorbers in various applications, including stealth technology, sensing, and energy harvesting.

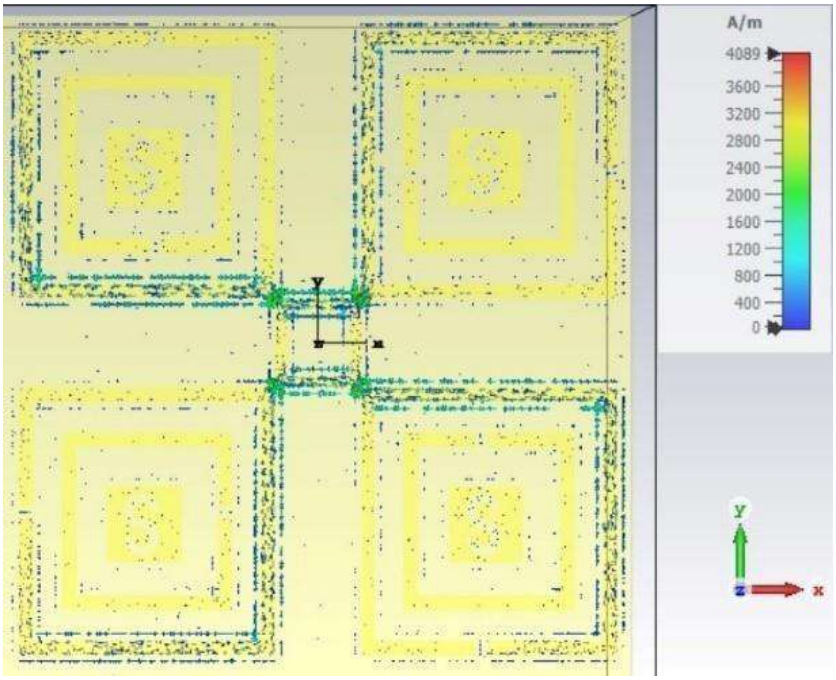


Figure 16 Surface current at 3.5GHz

The surface current of a metamaterial absorber refers to the flow of electric charge along the surface of the material when it interacts with electromagnetic waves. Metamaterials are engineered structures designed to manipulate electromagnetic waves in unconventional ways, and surface currents play a crucial role in their absorption properties. In a metamaterial absorber, incident electromagnetic waves induce surface currents due to the interaction with the material's structured surface. These surface currents are responsible for absorbing and dissipating the energy carried by the incident waves. By controlling the geometry, composition, and arrangement of the metamaterial's components, designers can tailor the surface current distribution to optimize absorption efficiency. Surface currents can be induced by various mechanisms, such as resonant coupling, impedance matching, and Ohmic losses within the material. These currents can flow along the surface of the metamaterial, effectively absorbing and dissipating electromagnetic energy across specific frequency bands. Understanding and controlling the surface current behavior is essential for designing metamaterial absorbers with desired absorption characteristics, such as broadband absorption, polarization selectivity, and tunable absorption frequencies. Overall, surface currents play a fundamental role in the functionality and performance of metamaterial absorbers in various applications, including stealth technology, sensing, and energy harvesting.

4.1.6 Comparison

The absorber is only useful at a frequency of 3.5 gigahertz, which corresponds to the frequency range that we can make use of in a particular field. The fact that this can function as a sensor is evidence of how well the design makes use of available space. The fact that this absorber has several peculiar characteristics, such as a refractive index with negative values and negative permeability values, adds validity to our arguments regarding the nature of the material since it demonstrates these characteristics. The quality of the absorber that has been recommended has been defined by earlier research, and in this article, we present a recommendation for an absorber that is based on those criteria. When we consider this information in light of Table 1, we see that there is no specific application. The authors also neglect to emphasize the SNG and DNG properties, as well as the insensitivity to incidence angle. This is something that we notice when we look at this information. However, when we applied our design to a particular application, we found that it displayed wide polarization angle neutrality in addition to incidence angle neutrality. This was a discovery that pleased us much.

Comparison with recently proposed metamaterial

TABLE:I REFERENCE TABLE

Ref	**Year**	**Substrate material**	**Resonance Frequencys(GHz)**	**Maximum Absorption peak**	**Unit cell**	**EMR**
[56]	2023	FR4	3.5 GHz	95.68%	Yes	4.28
[57]	2022	FR4	3.5 GHz	94.37%	Yes	8.7
[58]	2020	FR4	3.5 GHz	98.5%	Yes	7.1
[59]	2020	FR4	3.5 GHz	93%	Yes	6.5
[60]	2021	FR4	3.5 GHz	92%	No	2.8
Proposed Absorber	----	FR4	3.5 GHz	99.87%	Yes	7.8

Chapter 5

Conclusion

5.1 Conclusion

To summarize, the microwave metamaterial that we have built possesses the features that were desired. These characteristics include a single negative behavior (also known as SNG), negative permeability (also known as Mu negative), insensitivity to polarization, insensitivity to wide incidence angles, and a negative refractive index. These findings are consistent with the goals that we initially set out to achieve when we began this endeavor. SAR, which stands for specific absorption rate, can be decreased by using the absorber at a frequency of 3.5 GHz. SAR stands for a specific absorption rate [61]. In the fifth generation of communication, there is a general tendency toward the speedy transmission and receiving of data by using newly created technology. This can be seen as a general shift from the previous generation. Since the beginning of this current generation of communication, this pattern has been consistently seen. In this scenario, all of the antennas are now operating within the 5G spectrum, and each nation has its frequency band that it has designated for usage by the antennas that it possesses [62]. Because of the higher levels of electromagnetic (EM) energy radiation, the specific absorption rate (SAR) has experienced a significant increase in comparison to past periods. This is the direct outcome of the increased levels of EM energy radiation. As a direct result of this, it is vital to put into action policies that are centered on the reduction of SAR to safeguard the health of humans over the long term [63]. It is intended that the application of this particular metamaterial will allow for the accomplishment of the goal of reducing the specific absorption rate (SAR) of electronic devices that operate within the frequency range of 5G N78. It is anticipated that the implementation of this technology into an antenna system would result in an improvement in the quality of absorption as well as the level of directivity, while at the same time resulting in a reduction in the amount of radiation that is being unfavorably produced by the devices. They are designed to selectively absorb or manipulate specific frequencies of electromagnetic radiation, offering a range of applications across various industries. Metamaterial absorbers can be tailored to enhance the performance of antennas, mitigate interference, improve signal quality, enable miniaturization, facilitate advanced technologies like beamforming and MIMO in wireless communication systems such as 5G networks.

5.2 Accomplishments of Metamaterial Absorbers

In the realm of electromagnetic engineering, metamaterial absorbers have made significant advancements, giving innovative techniques to regulate and change electromagnetic waves over a broad range of frequency ranges. Because these absorbers enable buildings and aircraft to effectively absorb and scatter radar signals, it is now feasible to create stealth technology. Stealth technology makes it more difficult for radar systems to identify objects that are trying to hide from detection. Absorbers made of metamaterials have also been used in the construction of sensors to identify a certain frequency or substance, as well as in energy harvesting, which is the process of converting incoming electromagnetic radiation into usable energy. They were able to achieve excellent absorption efficiency at a range of frequencies, which resulted in improvements to wireless communication, antenna design, and photodetectors. In addition, metamaterial absorbers have been found to have potential applications in the realm of medical imaging. These absorbers can increase the productivity of imaging equipment such as terahertz scanners and MRI machines. Their significant accomplishments in a variety of fields shed light on the revolutionary potential of metamaterial absorbers in the capture and management of electromagnetic energy for a wide variety of applications.

5.2.1 Working Scope in the Future

Absorbers made of metamaterials have a promising future and are currently undergoing development in several significant domains, including the following:

- Advanced Stealth Technology: It is projected that metamaterial absorbers will become an increasingly vital component in military applications like stealth technology, which decreases the capacity of radar and other electromagnetic sensors to detect structures and vehicles. This sector will need consistent expansion to meet the needs of national security and defense.
- Wireless Communication and 5G: Metamaterial absorbers might play a role in the development of more advanced and efficient wireless communication systems. This would pave the way for improved signal processing, less interference, and improved signal reception in 5G and beyond.

- Energy Harvesting: It is projected that metamaterial absorbers will be used for more effective energy harvesting from ambient electromagnetic radiation, such as sunlight, radio waves, and microwave energy, as the need for renewable energy sources develops. This will allow for more efficient energy harvesting from the environment.
- Applications for metamaterial absorbers offer promise in the areas of sensing and detection, namely in the fields of security, healthcare, and environmental monitoring. It is possible to tune detectors and sensors to certain frequencies to make them very sensitive so that they can detect a wide range of substances and events.
- Imaging and Medical Diagnosis: Metamaterial absorbers may assist in enhancing healthcare diagnosis and treatment by enhancing the performance of medical imaging instruments such as magnetic resonance imaging (MRI) scanners and terahertz imaging systems.
- These absorbers have several applications, including astronomy, scientific research, surveillance, and remote sensing, and they may be included in photodetectors and imaging systems to do these tasks.
- Exploration of space and the technology behind satellites are two areas that might benefit from the usage of metamaterial absorbers. Both of these areas are looking for lightweight and efficient methods to regulate electromagnetic waves.
- A More Adaptive, Efficient, and Compact Antenna Design Metamaterial absorbers might be used to assist in the design of antennas that are more adaptive, efficient, and compact. This would result in an improvement in the operation of radars and communication systems.
- Monitoring the Environment We can solve difficulties with climate change, weather forecasting, and disaster assistance by using these absorbers for remote sensing and monitoring environmental parameters.

In the future, the working scope for metamaterial absorbers will be both expansive and dynamic. It is envisaged that further research and development would ultimately push technical and electromagnetic advancements by providing fresh applications and improved performance in several industries.

5.2.2 Achievements of this Thesis

A study investigated the reduction of SAR from 5G n78 mobile devices using a unique co-polarization-insensitive metamaterial absorber (MMA). The MMA, developed with metamaterial properties, can only absorb the co-polarized component of the applied EM wave. It showed a 33% decrease in SAR from n78 5G mobile phones while maintaining the 5G band's SAR value comparable to GSM/LTE/UMTS bands [64]. Absorbing electromagnetic waves throughout a broad range, this device requires no additional parts or directional information about the waves to function. This discovery may not only revolutionize the design of absorbers but also have far-reaching implications for industries as diverse as stealth technologies, communication systems, and energy harvesting. Our discovery represents a major advancement in the search for lightweight, high-performance absorbers. It helps further the study of metamaterials and their potential uses in the real world.

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