BACHELOR OF SCIENCE IN ELECTRONIC AND TELECOMMUNICATION ENGINEERING

Design and Analysis Co Polarization Insensitive Metamaterial Absorber for C, X and Ku Band Applications

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Certification of Approval

The Caption of this Project is "Design and Analysis Polarization Insensitive Metamaterial Absorber for C, X and Ku Band Applications." This Project is submitted by Nahidul Islam (T183023) and Mohammed Faysal (T191009) to the department of Electronic and Telecommunication Engineering (ETE) of International Islamic University Chittagong (IIUC). It has been satisfactory for the partial fulfillment of the requirements for the Bachelor degree of Science in Electronic and Telecommunication Engineering (ETE). It was approved by my supervisor for the examination.

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Declaration

It hereby states that we have completed this work and that no portion of the work found in this thesis has been submitted elsewhere for this thesis has not been before submitted for any degree.

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Abstract

This study proposes a metamaterial absorber (MMA) based on rotational symmetry to design a wide-angle, polarization-insensitive wireless system for S, C, X, and Ku bands. The MMA comprises electric ring resonators (ERR) arranged in a single layer with four-fold interconnected rotational symmetry, fabricated using FR-4 substrate. In the frequency range of 4 to 18 GHz, the MMA shows five distinct absorption peaks. Notably, absorption levels at 4.882 GHz, 6.464 GHz, 7.882 GHz, 11.3 GHz, and 17.216 GHz reach 99.3%, 94.9%, 94.5%, 98.7%, and 92.5%, respectively. The compact unit cell, with dimensions of $0.162\lambda \times 0.162\lambda \times 0.026\lambda$ at 4.882 GHz, achieves 99% mean absorptivity. Furthermore, the MMA exhibits stable absorption characteristics across azimuth and elevation angles (phi= 0 to 90 degrees, Theta = 0 to 60 degrees). Resonances demonstrate near-zero or negative refractive index traits, offering tunable multifunctionality. The MMA's compactness, high effective medium ratio (EMR), negative permittivity, permeability, and near-zero refractive index make it suitable for various wireless applications, enhancing gain and antenna directivity in fixed-mobile and multiband scenarios.

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List of Symbols

O	Gain
B	Bandwidth
ε	Permittivity
σ	Conductivity
μ	Permeability
η	Wave impedance
S_{11}	Return loss (Reflection coefficient in dB)
Γ	Reflection coefficient
Er	Constant of the substrate
Hs	Height of the substrate
W	Width of the patch
L	Length of the Patch
h	Thickness
c	Speed of light
F	Frequency
ΔL	Length extension
f_0	Resonance Frequency
ε_{eff}	Effective Dielectric Constant
L_{eff}	Effective length
R	Radius
Hz	Hertz
Mb	Megabit
Gb	Gigabit
Nm	Nano-meter

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
EM	Electromagnetic
MWS	Microwave Studio
DS	Design studio
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
FCC	Federal Communications Commission
SES	Single European Sky
MCPTT	Mission-critical push-to-talk
LAA	License Assisted Access

Chapter 1
Introduction

1.1 Background

The telecommunications landscape is rapidly evolving, with a burgeoning demand for miniaturization and multifunctionality in devices like smartphones, tablets, GPS units, and secure wireless gadgets [1]. To meet these demands, the components within these devices must be not just compact, but also versatile, capable of performing across various frequency bands. Central to this challenge is the humble antenna, now tasked with conforming to sleek device designs, shrinking in size, yet robustly supporting multiple frequencies of our ever-smarter gadgets. In the quest to meet these stringent requirements, antenna design has undergone a renaissance [2].

Various innovative techniques have been employed. Consider microstrip antenna technologies: they harness high-permittivity dielectric substrates, employ shorting walls and pins, and even dabble in the complex world of fractal geometry to shrink their footprint. However, each of these methods comes with its own set of drawbacks, be it limited bandwidth or reduced gain.

Enter the game-changing use of electromagnetic metamaterials in antenna design. This novel approach isn't just about reducing size; it's a paradigm shift. Metamaterials enhance key antenna characteristics, expanding bandwidth, boosting gain, and enabling the creation of multiband frequencies. This breakthrough allows for the operation of multiple antennas within the confined space of modern telecommunication devices. The metamaterial revolution in antenna design is more than a mere technical advancement; it's a crucial step toward keeping our devices sleek yet powerful, ensuring they not only fit in our pockets but also keep pace with the rapid strides of communication technology [3].

1.2 Brain Tumor

Metamaterials, or MMs, a blend of 'meta' and 'material', stand apart in the material world, as highlighted by Walser. Their essence, they are macroscopic composites, two- or three-dimensional, boasting properties at microwave and optical frequencies that traditional materials can't fathom. Imagine materials exhibiting the reverse Doppler effect, possessing negative refractive indices, capable of full lensing, demonstrating left-handed behavior, cloaking electromagnetic waves, and achieving perfect absorption – feats unheard of in conventional materials [4].

The realm of Metamaterial-based absorbers (MMAs) is particularly enthralling. They epitomize perfect absorption, catapulting them to the forefront for applications in solar energy, sensor technology, bolometers, wireless power transfer, and as impeccable light absorbers. Landy et al [5-6]. Were the first to describe these MMAs, which were notably thinner and smaller than their conventional counterparts. Since then, the evolution of MMAs has been relentless. Tailored for use in solar cells, sensors, and thermal imaging, these absorbers have been designed with multiband, broad-band, and polarization properties in mind. A plethora of MMAs has been constructed across microwave and optical frequencies, each with its unique applications thoroughly discussed in various studies [7-8]. However, marrying high efficiency with multiband functionality in MMAs remains a formidable challenge. The conditions for perfect absorption are delicate, easily disturbed.

A comprehensive review of the literature suggests a systematic approach is necessary to craft the ideal metamaterial-based absorber. This design process considers numerous factors: maximizing absorption bands, enhancing operational conditions, developing polarization-controllable absorbers, and judicious material selection. In recent years, the ability of metamaterials to control absorbance has piqued scientific curiosity. Within the MM structure, absorption becomes a controllable, tunable event, triggered by altering the electromagnetic wave resonance frequency between patches.

This paper reviews several studies on metamaterial absorbers, exploring the nuances of frequency-selectable absorption through manipulation of the MMA's polarization properties. Multiband absorption is attainable too, by adjusting the distance or spacing between coupling elements. Furthermore, the diversity in patch shapes plays a crucial role in achieving near-perfect absorption [9]. Additionally, fine-tuning MMA parameters such as dielectric thickness, unit cell period, and material choice can lead to near-unity absorption. Each section of this article offers a glimpse into metamaterial absorbers operating within specific frequency ranges.

The use of metamaterials and electromagnetic band gap (EBG) structures to enhance antenna performance has become a standard practice in the field [10], underscoring the transformative potential of these advanced materials.

1.3 Statistics

The thesis pivots around several core ideas, each a cornerstone in the intricate world of Metamaterial Absorbers (MMAs) and their application in satellite technology. Firstly, it delves into the crux of MMA technology, tailored specifically for satellite applications. This isn't just a surface-level exploration; it's a deep dive into how MMAs can revolutionize satellite functionality. The next focal point is a challenging yet fascinating endeavor: to envelop the satellite uplink frequencies within the Ka-band spectrum using MMA technology. This task isn't trivial; it's about precision, pushing the boundaries of what's possible in satellite [11-13].

communication. Lastly, the thesis doesn't just aim to design a metamaterial absorber; it sets the ambitious goal of achieving over 75% absorption. This target is more than a number; it's about efficiency, effectiveness, and pushing the limits of metamaterial technology to new heights [14]. In summary, the thesis stitches together these pivotal themes, weaving a narrative that's not just about understanding MMAs but also about applying them innovatively in the realm of satellite technology.

1.3.1 Fundamental ideas of Metamaterial

In the dynamic world of absorber technology, a material block known as an absorber plays a pivotal role. It captures kinetic energy from particles, transforming it into heat. This area of research, burgeoning with possibilities, finds relevance in high-efficiency solar cells, sensors, and stealth technologies. Particularly notable are its military and stealth applications, where radar-absorbing materials in covert tech render aircraft nearly invisible to ground-based radar [15].

These absorbers, like those pioneered by Dallenbach, Salisbury, and Jaumann, mitigate or nullify the radar signals reflected from an aircraft's surface. Yet, conventional absorbers often fall short in practical scenarios due to their bulk and complexity. The focus has thus shifted to metamaterial absorbers (MMAs), seeking a blend of compact design and simplicity.

Recent years have seen a surge in interest in MMAs, attributed to their high absorption efficiency, low density, and thin layers. Strategically placed, MMAs can convert electromagnetic radiation into thermal energy. Metamaterials (MMs), as defined by Walser [16-17], are substances with superior qualities compared to standard materials.

These MMs are composites, either two- or three-dimensional, exhibiting extraordinary properties at microwave and optical frequencies. Traits like negative refractive index, perfect lensing, left-handed behavior, electromagnetic wave cloaking, and complete absorption are rarities in traditional materials.

MMAs, known for their flawless absorption, are ideal for applications ranging from solar energy collection to sensors and wireless power transfer. Landy et al. marked a breakthrough with the first thin and compact metamaterial absorber. Since then, numerous improvements have been proposed, with MMAs being designed for multiband, broadband, polarization, and tunability to cater to diverse applications [18-19].

A decade has passed since the introduction of MMAs for microwave and optical frequencies [22], with numerous novel applications emerging. Yet, creating a high-efficiency multiband MMA remains a challenge, with delicate absorption conditions often compromised. The field indicates that overcoming these obstacles requires a systematic approach. Designers of MMAs face challenges in maximizing absorption bands, improving operational conditions, developing polarization-adjustable absorbers, and material selection. The phenomenon of absorption through metamaterials has increasingly captivated scientists. This absorption results from the resonant interaction between electromagnetic waves and the alternating coupling between patches in the MM structure [20].

The study reviews articles on metamaterial absorbers (MMAs) and absorption techniques, emphasizing achieving frequency-selective absorption through polarization property alterations. Modifying the separation between coupling elements enables multiband absorption, while diverse patch shapes contribute to near-perfect absorption. The article suggests that adjusting MMA parameters, dielectric thickness, unit cell period, and material choice can lead to near-unity absorption, highlighting the versatility of metamaterials in tailoring absorption properties for various applications.

This study is structured to provide a comprehensive overview of metamaterial absorbers across a broad spectrum of frequency ranges [21]. Fundamental to the concept of metamaterial absorbers are their low-profile, lightweight, and adjustable absorption capacities. These man-made surfaces, composed of periodic unit cells, have been a research hotspot for decades. The operating principal hinges on the impedance match between the metamaterial absorbers and open space. Key electromagnetic properties of these absorbers are their effective permeability and permittivity [22-23]. To ensure compatibility with free space, the impedance of the metamaterial absorber, calculated as $Z = \sqrt{(\varepsilon 0\varepsilon eff/\mu 0\mu eff)}$, should match that of free space, $Z0 = \sqrt{(\varepsilon 0/\mu 0)}$, resulting in $\varepsilon eff = \mu eff$ for the absorbers. Typically, these absorbers' permeability and effective permittivity are determined using their S-parameters. However, since MMAs are often one-port devices, the input impedances can be compared directly to the impedance of empty space (120π), bypassing the need to compute the effective permittivity and permeability [24].

1.3.2 Reflection co-efficient

The importance of the reflection coefficient in measuring the amount of electromagnetic wave reflected due to impedance changes in a transmission medium. This parameter holds significance in calculating Voltage Standing Wave Ratio and assessing compatibility between components such as feeders and loads. The article hints at the versatility of determining the reflection coefficient, suggesting various methods for obtaining this crucial parameter in the analysis of electromagnetic wave behavior in transmission systems. It may be determined using the fundamental definition of the reflection coefficient and data on the incident and reflected voltages. To ensure compatibility with free space, the impedance of the metamaterial absorber, calculated as $Z = \sqrt{(\varepsilon 0\varepsilon eff/\mu 0\mu eff)}$, should match that of free space, $Z0 = \sqrt{(\varepsilon 0/\mu 0)}$, resulting in $\varepsilon eff = \mu eff$ for the absorbers [25]. Typically, these absorbers' permeability and effective permittivity are determined using their S-parameters.

This absorption results from the resonant interaction between electromagnetic waves and the alternating coupling between patches in the MM structure.

$$\Gamma = \frac{Vref}{Vfwd} \quad \text{...(1)}$$

Where:

Γ = Reflection coefficient

V_{ref} = Reflected voltage

V_{fwd} = Forward voltage

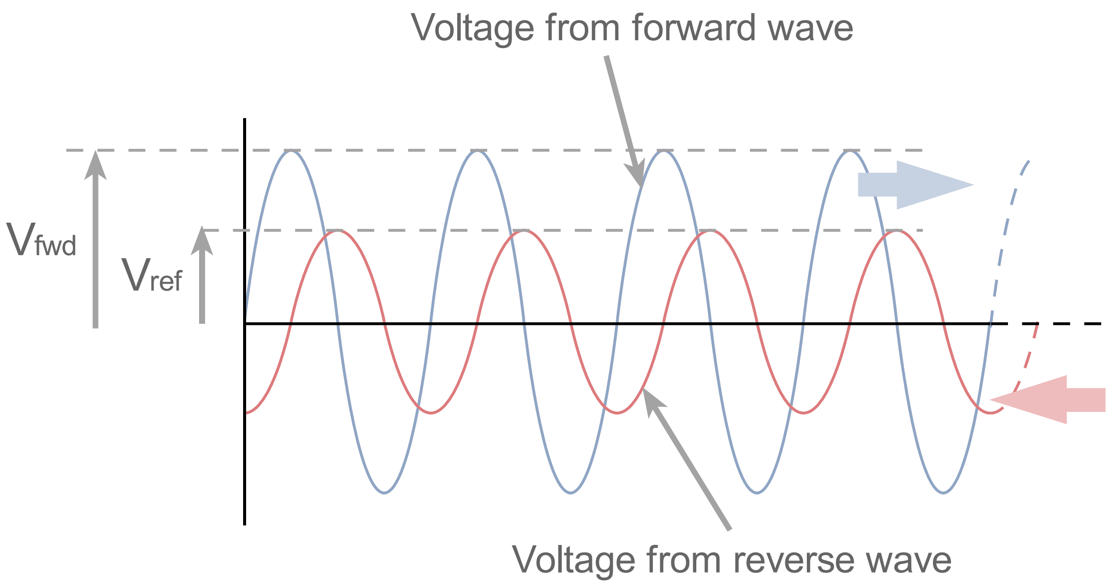


Figure 1 The voltages employed in the reflection coefficient calculation [26]

1.3.3 Absorption

When light travels through a semiconductor, its intensity is greatly diminished. In other words, the photon flux drops as light travels through the material because some photons are absorbed [27]. This relationship holds true for all wavelengths of light. Therefore, both the wavelength of the incident light and the distance from the surface of the semiconductor influence the total number of photons that reach a certain location. Monochromatic (nearly single-wavelength) light's exponential decline as it passes through a semiconductor is modelled by the following equation [28]:

$$F(x) = F(x_0)\ e\text{-}\ \alpha\ (x\text{-}\ x_0) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where:

F(x) = The strength at depth x below a semiconductor's surface

$F(x_0)$ = At a surface location x_0, the intensity is given by α = absorption coefficient

The absorption coefficient varies from one substance to another. Materials with a high absorption coefficient take in light at a faster rate, allowing more electrons to reach the conduction band [29]

1.3.4 Field Regions

When a high-frequency current courses through a radio antenna, it engenders an electromagnetic field that permeates the surrounding space, frequency by frequency.

This process, intricate in its execution, relies heavily on the specific characteristics of the antenna [30].

Close to the antenna, the scenario is somewhat more graspable. Under certain fundamental academic conditions, it's possible to deduce the electric and magnetic fields without delving into complex numerical calculations [31]

Yet, as one moves farther from the antenna, the field begins to resemble a spherical wave more distinctly. The transformation of the field with distance is fascinating: the farther the void, the more pronounced the spherical wave's representation becomes. This area near the antenna is methodically divided into three distinct zones based on established guidelines. Each zone represents a different aspect of the field's interaction with its environment, illustrating how the field evolves from being tightly bound to the antenna to becoming a more expansive and spherical entity [32] This gradation of the field's characteristics provides a nuanced understanding of how electromagnetic waves propagate in space, especially in the context of radio antennas.

- Radiating Near Field or Fresnel Region.
- Reactive Near Field.
- Far Field or Fraunhofer Region.

This option's far field area stands out due to its resemblance to the radiation pattern emitted by the receiving appliance [33].

1.3.5 Far-Field Region

In the complex world of radio telecommunications, the concept of the far-field is defined as the regions beyond the immediate vicinity of the radio antenna. This domain is characterized by a radiation pattern that typically lacks distinctive features. Moreover, the far-field is governed by the transmitted field approach, wherein the electric (E) fields and magnetic (H) fields are orthogonal to each other, giving rise to the formation of planar waves. The transformation of the field with distance is fascinating: the farther the void, the more pronounced the spherical wave's representation becomes. In certain instances, dealing with these vast or 'limitless' cables that transmit radio waves becomes a challenge [34]. Specifically, when considering a standard Far-field, it might be impractical or even impossible to isolate the emitting far field or to relocate the antenna due to its excessive length or other logistical constraints. Consequently, the task of determining antenna far-field patterns often requires reliance on measurements taken from the near-field zone. This approach is not just convenient; in many cases, it's a necessity. Three primary methods have proven effective in achieving this translation from near-field to far-field data. The first technique involves a filtering field probe that meticulously examines the initial phase and intensity distributions. Following this analysis, the near-field data undergoes a transformation process, effectively translating it into far-field information [35-36]. This approach underscores the intricate relationship between the near and far fields of an antenna, highlighting the complexities and ingenious methodologies employed in modern radio antenna design.

1.3.6 Near-Field Reactive Region:

Since the E and H fields are separated by 90 degrees, it follows that the fields are symmetrical when it comes to creating or transmitting fields, like being stationary yet moving through time, since the maximum responsiveness occurs at this point [37].

It possesses radiation components in addition to its inductive action, hence it is sometimes called an inductive field [38].

1.3.7 Near Field Radiating Region:

There is a shift away from reactive fields and towards transmitting fields in this area. In any case, unlike in Far Sector, isolation might drastically alter the results of the radiation test.

1.3.8 Directivity and Gain

The antenna's ability to focus its signal in a certain direction is crucial. Directivity is the capacity to point in a certain direction. In the far reaches of an antenna, the guideline is the product of the maximum power density and its value. This is a quantitative measurement of an antenna's ability to direct its radiated power in a particular direction across a certain solid angle. When an antenna emits or receives electromagnetic radiation in a predetermined direction, guiding is achieved. It's possible to represent the instruction in database [39]. Better navigation is possible thanks to a three-dimensional antenna layout. This domain is characterized by a radiation pattern that typically lacks distinctive features. Moreover, the far-field is governed by the transmitted field approach, wherein the electric (E) fields.

1.3.9 Impedance

Impedance, in the realm of antenna technology, is a critical concept that encapsulates the relationship between current and voltage at the juncture of the antenna's functionality. This notion of impedance is not merely theoretical; it reflects the actual behavior of an antenna, indicating whether power is radiating from or being absorbed by it [40-41]. This tangible aspect of impedance is closely linked to the energy in the vicinity of the antenna, representing power that, intriguingly, is not transmitted but rather remains localized. In the intricate dance of antenna operations, it's posited that an ideal antenna, with precisely tuned input impedance, exists. The fascinating part here is that the antenna's impedance is not static; it shifts with changes in frequency. This dynamism places the radio antenna in a unique position, functioning akin to various types of RF loads or signal sources [42]. It assumes the role of either a generator or a load, depending on the context. Achieving optimal performance from an antenna system involves a delicate balance. An antenna feeder plays a crucial role in this process, ensuring synchronization with the antenna. This harmony is pivotal for the efficient transfer of electricity. Similarly, to enhance performance further, it's imperative to understand the feed impedance of the antenna—a target impedance that needs to be accurately acquired.

The concept of feed impedance, often simply referred to as 'the impedance' of the antenna, is a complex one. It comprises three fundamental components: resistance, capacitance, and inductance. Each of these elements contributes to the overall impedance, shaping how the antenna interacts with the electrical currents and voltages at play [43-44]. Understanding and optimizing these interrelated factors is essential for the effective design and operation of radio antennas.

1.3.10 Frequency:

Frequency, a concept central to physics and chemistry, particularly resonates in the world of waves – spanning radio, light, and sound. Essentially, it denotes the regularity of occurrence within a unit of time, a phenomenon known as frequency activity. The term 'frequency' encapsulates the interval required for a wave to complete its journey from one point to another, a reference point being the table through which it traverses.

Each wave cycle's frequency is intrinsically tied to its length or duration. The standard measurement unit for frequency is the hertz (Hz), a contemporary equivalent to the older unit of cycles per second (CPS). This measurement captures the essence of a wave's repetitive nature, whether it be considered in secular terms or on a per-moment basis. Diving deeper, the concept of frequency is exemplified when considering unfinished cycles [45].

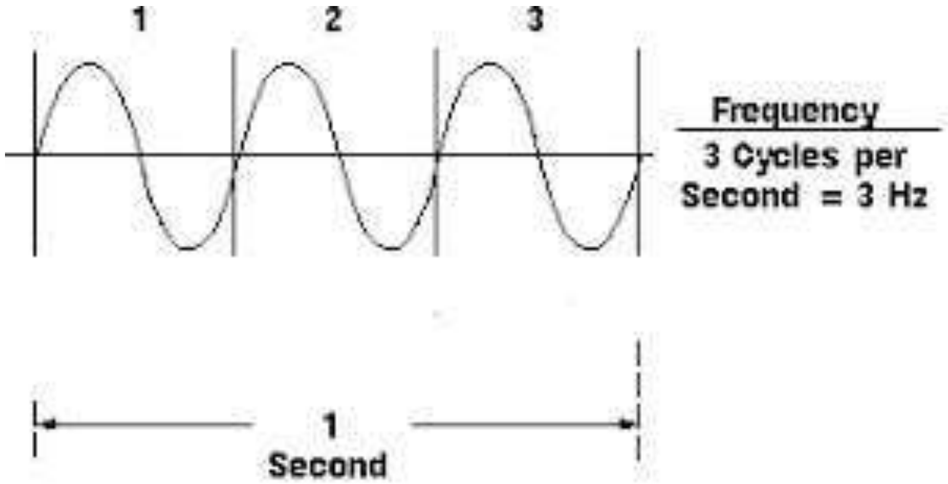


Figure 2 Frequency [9]

For instance, a frequency initially set to 200 Hz signifies those 200 incomplete cycles of a wave are completed each second [46-47]. This quantification of frequency, whether in hertz or the equivalent older unit of cycles per second, provides a crucial metric for understanding the temporal characteristics of various waveforms. By measuring how many cycles a wave completes in a given time frame, we gain insights into its speed, duration, and overall behavior in different mediums and contexts.

1.4 Metamaterial-classification based on their properties

Veselago scientists first suggested that the metamaterial categorization by taking into account the "permittivity and permeability of a homogeneous substance. Because of this, strange scientific phenomena including the inversion of the Snell Law, the Cerenkov Effect, and the Doppler Shift occur when and are both negative. This specific point is critical: all electromagnetic waves are reflected if their frequency is lower than the array's cutoff frequency. This reflection phenomenon bears similarities to the transmission of electromagnetic waves through a plasma [48-49]. The parameters defining the plasma frequency in this setup are the lattice constant, 'p', and the radii of the individual wires in the array. optimizing the dual components of the dielectric layers (illustrated in Figure 3c).

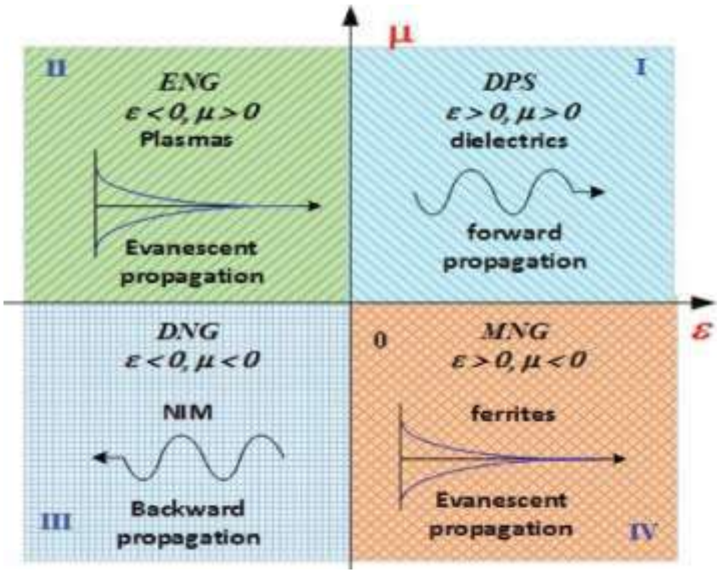


Figure 3 Classifications - on signs of the ε and μ electromagnetic MTMs based [50]

DNG metamaterials, composed of thin wire intermediates and SRRs media, display a pronounced frequency dependence. This is largely due to their strong resonance behavior, which can be modeled using Drude-Lorentz models. The resultant DNG metamaterials thus exhibit a unique frequency-dependent behavior, underlining the intricate interplay of structure and function in the realm of advanced metamaterial design [51].

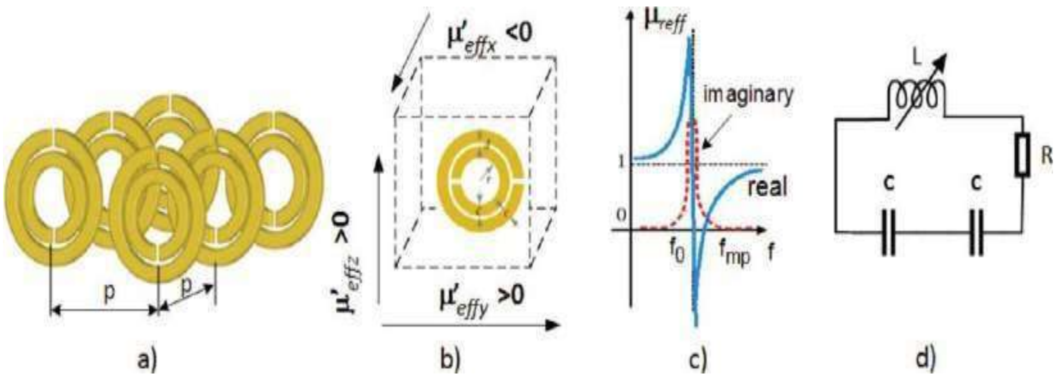


Figure 4 SRR array (a), single cell of an SRR (b), SRR array efficient permeability (c), analogous circuit (d) [52]

For the construction of DNG (double negative) metamaterials, a crucial prerequisite is the coplanarity of the negative aspects of both ENG (electric negative) and MNG (magnetic negative) structures [53].

In this intricate alignment, the ENG domain is characterized by a permittivity ep equal to the permittivity of free space e0, while in the MNG domain, the permeability m0 equals the permeability mp. It’s important to note that in the case of electrically continuous wires, the resonance frequency is essentially zero (e0 = 0).

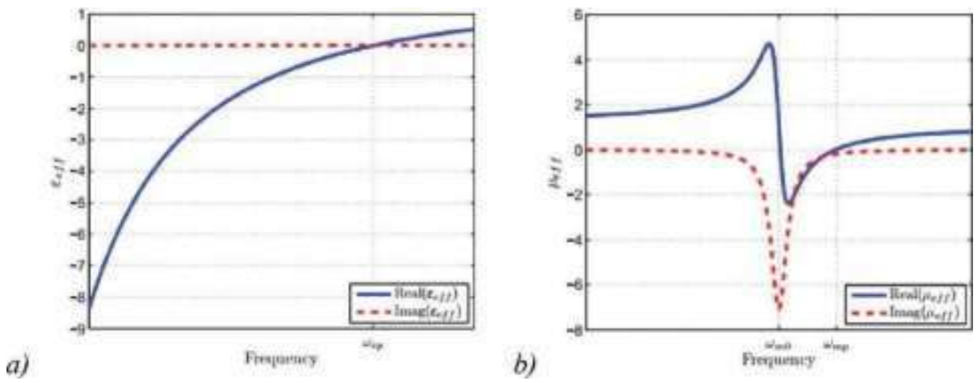


Figure 5 (a) effective permittivity, (b) permeability of DNG metamaterial [54]

When delving into the realm of electric resonator metamaterials, the DNG efficiency is observed to diminish. This decrease is attributed to the ENG zone being more extensive than the MNG region. Conversely, in magnetic resonator metamaterials, where the focus is on magnetic properties, the MNG efficiency remains relatively stable, unaffected by this disparity [55].

The dynamics within DNG metamaterials are further defined by several key parameters: the collision frequency (denoted by yc), the amplitude ratio (F), and the damping factor (γ). These elements play pivotal roles in the overall behavior of the DNG structure.

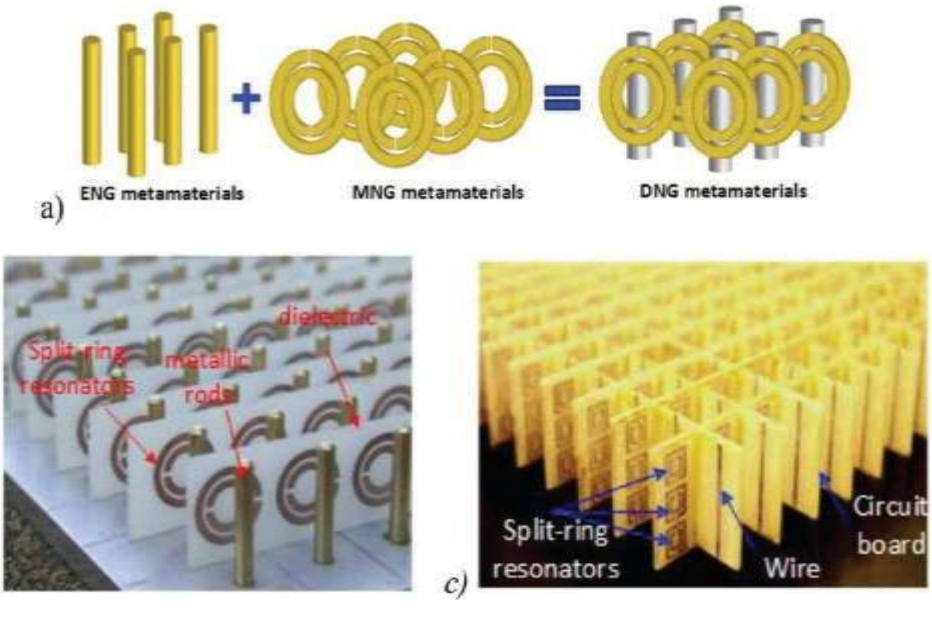


Figure 6 DNG metamaterials (a) combination of thin SRR wires, DNG realizations instances [56]

Chapter 02
Literature Review

2.1 Overview

In this section, we will go over some of the prior works that are linked to our thesis, **"Design and Analysis of Co Polarization Insensitive Metamaterial Absorber for C, X and Ku Band Applications".** It is required for successful research and the achievement of superior results.

2.1.1 Introduction

Metamaterial absorbers represent a cutting-edge area in materials science, where research methodologies are both diverse and complex, encompassing theoretical modeling and experimental validation. The primary goal in this field is to predict and analyze the electromagnetic behavior of metamaterial structures, for which computational simulations play a crucial role. Two common simulation techniques are the Finite Element Method (FEM) and the Finite-Difference Time-Domain (FDTD) approach. These methods are indispensable for understanding how electromagnetic waves interact with metamaterials and for optimizing designs before physical fabrication. FEM is particularly useful for dealing with complex geometries and material properties, allowing researchers to model the detailed behavior of metamaterials under various conditions [57]. FDTD, on the other hand, is renowned for its ability to model time-dependent phenomena, making it ideal for studying the dynamic response of metamaterials to electromagnetic waves. Beyond computational methods, experimental techniques are equally important in metamaterial research. Advanced nanofabrication techniques, such as electron beam lithography and photolithography, are commonly employed to create precise metamaterial structures. These techniques enable the fabrication of metamaterials with intricate patterns that are often required for achieving desired electromagnetic properties [58]. Once fabricated, metamaterials undergo rigorous testing to characterize their absorptive properties. Techniques like terahertz time-domain spectroscopy and microwave anechoic chamber testing are employed to measure the metamaterials' response to electromagnetic waves. These measurements are critical for validating the theoretical models and for understanding the real-world performance of the metamaterials. The choice of research methodology in metamaterial absorber studies is influenced by several factors, including the frequency range of interest, the desired material properties, and the specific application. Researchers must carefully consider these factors to select the most appropriate methods [59]. Balancing the precision and accuracy of these methods with practical considerations such as cost and fabrication complexity is a key challenge in this field. This balance is essential for advancing the development of metamaterial absorbers and for realizing their potential in various applications [60].

2.1.2 Paper selection

Selecting papers for a research project, particularly one as specialized as "Design of a Dual Band Metamaterial Absorber for Satellite Communication," is a nuanced and critical process. It involves not just reading a vast array of research papers but also discerning which of these papers will most effectively contribute to the development of a robust and insightful thesis. The ability to craft a compelling research proposal is a significant skill, requiring the topic to be sufficiently narrow to maintain focus, yet broad enough to encompass a wide range of relevant data and perspectives [61].

The chosen thesis topic aims to establish fundamental principles or scientific hypotheses in the realm of dual-band metamaterial absorbers, particularly for satellite communication applications. This topic was selected with several key considerations in mind. Firstly, it aligns closely with the ultimate goal of advancing knowledge in the field of metamaterials and their applications in communication technology. The topic's relevance to current technological needs and future advancements in satellite communication makes it both timely and significant [62]. A brainstorming session can be an invaluable step in this process, providing an opportunity to explore various facets of the topic, identify gaps in current research, and refine the research focus. Such sessions can foster creative thinking and lead to the development of innovative approaches to the research problem. Understanding the existing literature is crucial for any research project [63].

The chosen topic should enable a deep dive into the relevant studies, theories, and findings in the field of metamaterial absorbers [64]. This understanding forms the foundation upon which new research is built, ensuring that the project contributes meaningfully to the body of knowledge. Flexibility in research is also important. The ability to adapt to new findings, alternate perspectives, and evolving technologies is essential for keeping the research relevant and forward-thinking. The chosen topic should allow for such adaptability, accommodating shifts in focus or methodology as required. Finally, a clear research statement is key. It succinctly defines the purpose, scope, and objectives of the research. A well-crafted research statement guides the entire project, ensuring that every aspect of the research is aligned with the overarching goals [65]. It serves as a roadmap, directing the research process and helping to maintain focus on the central questions and hypotheses. In summary, the selection of papers and the formulation of a research topic are critical steps that lay the groundwork for a successful and impactful research project in the field of metamaterial absorbers. Choosing this topic previously, our key attention points are-

- Selecting a topic that resembles my ultimate goal; Is a brainstorming session necessary?
- Will this topic help you understand the literature?
- Is the work flexible?

2.1.3 Subtract Selection

In our research, we meticulously analyzed a range of scholarly papers to gain a deeper understanding of the design principles for optimal shapes in Metamaterial Absorbers (MMAs) [66]. This analysis was instrumental in identifying the most effective geometrical configurations for MMAs, tailored to enhance their absorptive capabilities. Drawing from this rich pool of information, we proceeded to design our own metamaterial absorbers, incorporating the most promising shapes and structures identified in our review. Subsequently, we conducted a comparative analysis of these designs, focusing on various settings and parameters. This comparative approach allowed us to evaluate the effectiveness of different designs and to understand the impact of specific geometrical features on the performance of MMAs. Through this process, we aimed to establish a set of optimized design guidelines for metamaterial absorbers, contributing to advancements in this field [67].

2.1.4 Parameter Selection

In our study, we meticulously measured a set of key parameters to comprehensively assess the performance of Metamaterial Absorbers (MMAs). These parameters include

MMA absorption, field region, directivity, gain, impedance, and efficiency. Each of these plays a pivotal role in determining the overall effectiveness and applicability of MMAs. MMA absorption is a critical measure of how efficiently the metamaterial can absorb electromagnetic waves, which is fundamental to its functionality. The field region parameter helps in understanding the spatial distribution and intensity of the electromagnetic field around the absorber, providing insights into the interaction between the metamaterial and incident waves [68]. Directivity and gain are essential for evaluating how the MMA directs and amplifies electromagnetic energy, which is crucial in applications like antenna design and electromagnetic shielding. Impedance matching is vital for ensuring minimal reflection and maximal absorption at the MMA's surface. Lastly, efficiency encapsulates the overall performance, taking into account various losses and practical limitations. By analyzing these parameters, we can thoroughly evaluate the performance of MMAs, understanding their strengths and limitations in various applications. This comprehensive approach allows us to optimize the design and functionality of MMAs, ensuring they meet the specific requirements of their intended applications [69].

2.1.5 The Method of Performance Analysis

The selection of Metamaterial Absorbers (MMAs) as the focus of our research is primarily driven by their critical role in modern wireless communication networks. MMAs have emerged as a key component in enhancing signal quality and reducing interference, making them indispensable in the rapidly evolving landscape of wireless technology. In our study, we explored the design and performance of MMAs using various substrates, each tailored to operate effectively at different frequencies. This diversity in substrates and frequencies allowed us to investigate the versatility and adaptability of MMAs in a range of communication scenarios. For the design process, we utilized the MMA CST Studio Suite 2020, a sophisticated simulation tool that enabled us to model and analyze the electromagnetic behavior of each MMA design accurately. This software was instrumental in allowing us to fine-tune various parameters of the MMAs, such as gain, directivity, radiation pattern, S11 parameter (or return loss), and physical size. Each MMA was designed on a distinct substrate, with careful consideration given to its operational frequency and the specific requirements of its intended application. Our methodology included the calculation of key performance metrics for each MMA, such as gain, directivity, and loss. We compiled these data into a comprehensive list, which served as the basis for our comparative analysis. This analysis aimed to identify which MMA components were most efficient under different conditions, such as changes in height and frequency. By examining how these variables influenced the performance of MMAs, we gained valuable insights into the design principles that govern their effectiveness. Through this systematic approach, we sought to uncover the underlying factors that contribute to the optimal performance of MMAs. Our findings are expected to provide a deeper understanding of how MMAs can be tailored to meet the specific demands of various wireless communication applications, ultimately contributing to the advancement of this crucial technology.

2.1.3 Paper Review

This section delves into the critical aspect of designing Metamaterial Absorbers (MMAs) for various substrates at different frequencies, a key element in advancing satellite communication technologies. The ability to tailor MMAs for specific substrates and frequency ranges is fundamental to optimizing their performance in satellite communication systems. This involves a detailed exploration of how different materials and frequency responses impact the efficacy of MMAs. Through comprehensive simulation and design processes, we aim to develop MMAs that exhibit superior performance characteristics such as enhanced absorption, improved bandwidth, and better impedance matching [70]. This research is pivotal in creating MMAs that can effectively meet the demanding requirements of modern satellite communication networks, thereby contributing significantly to the field of wireless communication and electromagnetic wave manipulation. The insights gained from this study are expected to pave the way for more efficient and versatile satellite communication solutions, leveraging the unique properties of metamaterials to overcome existing challenges in this domain.

[1] Research paper on "Dual-band Metamaterial Absorber for Ka-Band Satellite Application" [43]

We present a microwave-optimized Metamaterial Absorber (MMA) in this comprehensive study, demonstrating exceptional absorption efficiency. The unusual design of this metamaterial allows 99.99% absorption at 27.5 GHz and 31 GHz resonance frequencies. The absorptive features of this MMA are determined by two different frequency bands. The first band encompasses a range of 0.38 GHz, covering frequencies from 27.325 GHz to 27.705 GHz, whereas the second band is larger, spanning across 1.76 GHz and containing frequencies from 29.505 GHz to 31.264 GHz. The paper dives deep into the physics underlying this dual-band absorption phenomena, giving a complete examination of the interplay between different essential elements. These include the electric field distribution, the unique mechanism of absorption, the distribution of surface current, and the behavior of the magnetic field. This exploration is crucial in deciphering the fundamental principles that underlie the dual-band absorption characteristic displayed by the MMA. Furthering the analysis, the research explores how the MMA performs under varied polarization angles, a critical factor in understanding its versatility and adaptability in different application settings. Additionally, the study scrutinizes the impact of the physical size of the MMA on its absorptive capabilities, an important element in practical implementations. This extensive analysis not only reveals the metamaterial's outstanding absorption rates at specific frequencies but also greatly contributes to the broader understanding of metamaterial capabilities and applications in microwave technology. The insights gained from this work are invaluable, offering new avenues for the creation and application of metamaterials in different domains, including satellite communications, radar technology, and electromagnetic wave manipulation. The discoveries of this research have the potential to transform the design and functionality of devices in the microwave frequency range, using the unique features of metamaterials to attain unprecedented levels of performance and efficiency [71].

[2] Research paper on "A dual-band metamaterial microwave absorber"

This study proposes the construction of an X-band metamaterial microwave absorber, uniquely designed to encompass a secondary, lower frequency band within the 8-12 GHz range. Central to the absorber's design is a unit cell featuring an electric LC (ELC) resonator, complemented by a supporting ground plate and a slender FR4-epoxy substrate, measuring merely 0.8 mm in

thickness. To efficiently utilize the available space and achieve dual resonance, the design employs an ELC resonator composed of asymmetric triangular split-ring resonators. A pivotal aspect of this study involves elucidating the operational mechanism of the absorber. This is achieved by analyzing effective medium parameters, which are derived from S-parameters, thereby providing valuable insights into the electromagnetic (EM) behavior of the unit cell. The dimensions of this unit cell are specifically set at 8 mm x 8 mm x 0.8 mm. Empirical observations at frequencies of 8.2 GHz and 12 GHz indicate two significant absorption peaks, each exceeding 98.5% efficiency. These peaks are characterized by full width at half maximum (FWHM) values of 8.4% and 7.25%, respectively. Additionally, the absorber demonstrates robust absorptivity performance for EM waves at incidence angles ranging from 0 to 60 degrees, showcasing its effectiveness over a wide angular spectrum. This design not only highlights the absorber's high efficiency at specific frequencies but also underscores its capacity to maintain strong absorptive qualities across a range of incidence angles [72].

[3] Research paper on "A metamaterial absorber for the terahertz regime: design, fabrication and characterization"

This study employs the Finite Integration Technique (FIT)-based modeling to conduct an in-depth analysis of a metamaterial absorber featuring multi-layer resonance structures. The research meticulously explores how the metamaterial's layered configuration influences its absorption capabilities. The findings, validated through experimental methods, demonstrate a significant relationship between the number of layers in the metamaterial and its ability to absorb electromagnetic energy. As the number of layers increases, the metamaterial exhibits enhanced absorption, resulting in the formation of up to nine distinct absorption peaks.

This multi-peak characteristic enables the metamaterial to cover a broad and multiband frequency range, effectively extending from 5 to 8.9 GHz. The study further investigates the tunability of structural parameters in a four-layer configuration of the metamaterial. This aspect of the research focuses on adjusting the physical dimensions and material properties of each layer to optimize the absorption peaks. The ability to fine-tune these parameters allows for the achievement of absorption intensities exceeding 90 percent, a remarkable feat in metamaterial design. The optimized absorption peaks closely match the results obtained from experimental trials, underscoring the accuracy and reliability of the FIT-based modeling approach. The implications of these findings are far-reaching, particularly in the fields of radar shielding and military weaponry design. The study's insights into the design and optimization of metamaterials with high absorption rates across multiple frequencies pave the way for the development of advanced defensive and strategic technologies. Such metamaterials can be tailored to specific frequency ranges, making them highly effective for applications in stealth technology, where reducing the radar signature of military assets is crucial. Moreover, the ability to create metamaterials with precise absorption characteristics opens new possibilities in electromagnetic wave manipulation. This can lead to innovations in communication systems, sensor technology, and energy harvesting. The study's contributions to the understanding of multi-layer metamaterials not only enhance the current state of metamaterial research but also provide a foundation for future advancements in various technological domains. The potential to transform the landscape of military applications and beyond with these metamaterials highlights the significance of this research in the broader context of material science and electromagnetic engineering [73].

[4] Research paper on "A metamaterial absorber for the terahertz regime: design, fabrication and characterization"

This study centers on the development of an innovative metamaterial, specifically engineered to function as a highly efficient absorber at terahertz (THz) frequencies. The design features a bilayer unit cell, meticulously crafted to enable independent modulation of both electrical permittivity and magnetic permeability.

This unique capability for modulation is crucial in fine-tuning the absorber's performance, allowing for optimal efficiency in THz frequency absorption. The experimental results of this study are particularly noteworthy. The metamaterial demonstrates an impressive absorptivity of 70% at a frequency of 1.3 terahertz. This high level of absorption is a significant achievement in the field of metamaterial research, particularly at such challenging THz frequencies. One of the key aspects of this design is its structural efficiency. Remarkably, the high absorption is achieved using just a single unit cell in the propagation direction.

This efficient configuration leads to a substantial absorption coefficient of 2000 cm^-1, a testament to the effectiveness of the design. The metamaterial's small volume and low density, coupled with its narrow band response, make it exceptionally well-suited for thermally based THz imaging applications. These properties address some of the specific challenges encountered in THz imaging, such as the need for compact and efficient absorbers that can selectively target specific THz frequencies. The ability of these metamaterials to capture THz frequencies with high efficiency opens up new possibilities in thermal imaging, potentially enhancing image resolution and clarity. This advancement in metamaterial technology represents a significant step forward in THz imaging. The design and properties of these metamaterials provide a solution that is not only highly efficient but also compact and targeted. This makes them ideal for a range of applications, including security screening, biomedical imaging, and non-destructive testing, where the unique properties of THz radiation can be leveraged for improved imaging capabilities. The potential of these metamaterials to enhance THz imaging technologies is substantial, offering new opportunities for advancements in various fields that rely on high-resolution thermal imaging [74].

[5] Research paper on "Design, fabrication, and characterization of a flexible dual-band metamaterial absorber."

This article delves into the intricacies of designing, modeling, fabricating, and evaluating a microwave resonant flexible dual-band Metamaterial (MM) absorber. The structure of this MM absorber is akin to a sandwich, comprising a periodic arrangement of T-shaped metallic patches atop a continuous metallic plane, with a flexible dielectric layer nestled in between. A series of simulations utilizing CST 2015's full wave finite integration method were conducted to pinpoint the optimal geometric parameters. Computational electromagnetics wave propagation simulations reveal that this MM absorber exhibits two distinct absorption peaks at frequencies of 16.77 GHz and 30.92 GHz. The absorption ratios at these frequencies are impressively high, standing at 98.7 and 99.3, respectively. Notably, the absorber's thickness is remarkably thin, measuring only 0.2403 mm. This dimension is a mere fraction of the wavelengths at the resonance frequencies – approximately 1/74 at 16.77 GHz and 1/40 at 30.92 GHz. The study also encompassed a plethora of simulations to scrutinize the impact of material properties and structural curvature on absorbency. This MM absorber demonstrates excellent absorption capabilities across a broad spectrum of incidence angles and shows a high sensitivity to the polarization of incoming electromagnetic waves. Insights into the absorption mechanism are gleaned by analyzing the electric field and surface current distributions at the two resonance frequencies. The modeling studies suggest that the integration of two unique resonance modes within a single patterned metallic resonance structure is pivotal for achieving dual-band functionality. The sample of the proposed absorber was fabricated using laser ablation, with electromagnetic wave arrival times in both measured and simulated scenarios aligning closely. The mechanical flexibility of the constructed MM absorber is a notable feature, allowing it to be seamlessly contoured into unconventional shapes like cylinders, pyramids, and spheres.

This adaptability opens up possibilities for expanding its use in diverse applications such as antennas, sensing, thermal imaging, and detection, especially when this design approach is applied to different absorber architectures and frequency ranges. One particularly promising application is in the development of projectile-borne conformal antenna arrays. Here, an ultra-thin, flexible MM absorber could be strategically placed between the antenna and the projectile body, significantly reducing radiation interference, coupling loss, and Radar Cross Section (RCS). This absorption performance was meticulously evaluated through numerous simulations, investigating the influence of material parameters and structural curvature on the absorber's effectiveness [75].

[6] Research paper on "Maximum Power Design and Simulation for a Low Return Loss Wearable Microstrip Patch Antenna."

In their book, the authors present an innovative design for a single-band rectangular microstrip patch antenna, specifically engineered for wearable technology applications. This antenna design is distinguished by its unique structure, featuring a ground plane on one side of the substrate and a radiating patch on the opposite side. The dimensions of the antenna are approximately 39 x 47 mm^2, making it exceptionally compact relative to the wavelength at its operating frequency. This compactness is a crucial factor in its suitability for wearable applications, where size and form factor are of paramount importance. A standout feature of this antenna design is its remarkably low return loss, which represents a significant advancement in the field of antenna engineering [76].

This low return loss translates to improved efficiency and reduced signal reflection, enhancing the overall performance of the antenna. Additionally, the antenna is characterized by a low Specific Absorption Rate (SAR) value, an important safety consideration for wearable devices. This low SAR value ensures that the antenna is safe for use in close proximity to the human body, minimizing any potential health risks associated with electromagnetic radiation. The antenna also exhibits impressive performance metrics, including a high gain of 58.84 dB, a bandwidth of 95 MHz, and an antenna gain of 2.85 dB. These characteristics contribute to the antenna's effectiveness in wearable applications, offering a balance of efficiency, safety, and compactness. The combination of these features makes the antenna an ideal choice for integration into wearable technology, where it can provide reliable and high-quality wireless communication while maintaining user comfort and safety. The design and performance of this microstrip patch antenna demonstrate the potential for innovative antenna solutions in the rapidly growing field of wearable electronics, addressing the unique challenges and requirements of these applications.

[7] Research paper on "Highly efficient microstrip patch antenna for wireless gigabit alliance applications."

In this work, the authors delve into the capabilities of the wireless gigabit alliance (WiGig), renowned for its expansive bandwidth and utilization of the unlicensed 60 GHz spectrum. This spectrum is particularly advantageous for millimeter-wave band applications that demand exceptionally high data speeds over short ranges. The research introduces an efficient, compact microstrip patch antenna specifically designed for WI Gig, boasting an impressively low return loss of 50.45 dB at 60 GHz. The antenna proposed in this study stands out with its considerable gain and directivity, measured at 13.01 dB and 13.42 dBi, respectively. It demonstrates an exceptional efficiency of around 91%, significantly enhancing its operational effectiveness. Furthermore, the antenna extends its capabilities to cover the 95 GHz millimeter-wave frequency, broadening its applicability in the realm of high-speed wireless communication. This combination of high gain, directivity, and efficiency, along with its expanded frequency range, makes the proposed antenna a valuable component in the advancement of WI Gig technology, particularly in applications where rapid data transmission over limited distances is crucial.

[8] Research paper on "Design and Analysis of Multiband Microstrip Patch Antenna Array for 5G Communications." [77]

The Multiband Microstrip Patch Antenna (MMPA) stands out as a pivotal element in modern wireless communication technology, renowned for its numerous benefits. Among its key attributes are cost-effectiveness, a low-profile design, lightweight construction, ease of manufacturing, and the versatility to adapt to various shapes. These features make the MMPA a highly sought-after component in the dynamic world of wireless communications, where adaptability and efficiency are paramount. Despite its array of advantages, the MMPA is not without limitations. One of the primary challenges it faces is a relatively narrow bandwidth, which can restrict its utility in applications requiring broader frequency coverage. Additionally, MMPAs often exhibit lower gain compared to other antenna types, which can impact signal strength and quality. Another concern is their limited capacity, particularly in handling high-power applications or in environments with dense signal traffic. These drawbacks necessitate a careful balance between leveraging the MMPA's strengths and addressing its performance limitations.

This balance is crucial for the continued evolution and application of MMPA technology in the field of wireless communications. Engineers and designers are continually exploring ways to enhance the MMPA's performance, such as employing advanced materials, innovative design techniques, and integrating it with other technologies. By addressing these challenges, the MMPA can continue to play a significant role in meeting the diverse and growing demands of wireless communication systems, contributing to the development of more efficient, reliable, and versatile communication solutions.

[9] Research paper on "Return loss and gain improvement for 5g wireless communication based on single band microstrip square patch antenna." [78]

This study proposes a single-band micro-strip square patch antenna, specifically designed to operate at 28GHz. Patch antennas, characterized by their low manufacturing costs, lightweight design, and compatibility with microwave frequencies, are highly effective and widely employed in wireless communication systems. However, these antennas are not without limitations, as they often suffer from low efficiency and gain. In the context of future 5G wireless communication, which prominently features millimeter-wavelength antennas, the requirements become more stringent. High gain and robust protection against path loss become critical factors for ensuring efficient and reliable communication.

This necessity arises from the fundamental characteristics of 5G technology, which aims to provide faster data speeds and more reliable network connections. The proposed antenna in this study is designed with these requirements in mind, aiming to address the traditional shortcomings of patch antennas while meeting the demanding needs of upcoming 5G wireless communication systems.

[8] Research paper on "TeraHertz Antenna for Biomedical Application." [79]

This paper focuses on the intricate design process of a terahertz antenna, specifically tailored for the detection of riboflavin. The design and simulation of this proposed antenna are meticulously carried out using CST Studio Suite 2020. The construction of the microstrip antenna incorporates a three-layered approach. At the forefront of the design, the top layer features a rectangular patch, meticulously modeled to meet the specific requirements of terahertz frequency operation and riboflavin detection. The middle layer is dedicated to the substrate, a crucial component that supports the patch and plays a significant role in the antenna's overall performance. Finally, the bottom layer of the design houses the ground plane, an essential element for the proper functioning of the microstrip antenna.

This layered architecture not only ensures the antenna's functionality at terahertz frequencies but also optimizes its sensitivity and accuracy for detecting riboflavin, showcasing the careful consideration of both structural and functional aspects in the antenna's design process. The chosen topic should enable a deep dive into the relevant studies, theories, and findings in the field of metamaterial absorbers.

This understanding forms the foundation upon which new research is built, ensuring that the project contributes meaningfully to the body of knowledge. Flexibility in research is also important. The ability to adapt to new findings, alternate perspectives, and evolving technologies is essential for keeping the research relevant and forward-thinking. The chosen topic should allow for such adaptability, accommodating shifts in focus or methodology as required.

Finally, a clear research statement is key. It succinctly defines the purpose, scope, and objectives of the research. A well-crafted research statement guides the entire project, ensuring that every aspect of the research is aligned with the overarching goals. It serves as a roadmap, directing the research process and helping to maintain focus on the central questions and hypotheses. In summary, the selection of papers and the formulation of a research topic are critical steps that lay the groundwork for a successful and impactful research project in the field of metamaterial absorbers. It can also be integrated into numerous industry-standard workflows through the CST STUDIO SUITE interface.

As a result, CST MICROWAVE STUDIO is increasingly becoming a standard tool for designers in various ventures. This feature enables users to search for the optimal design to meet specific requirements or achieve certain objectives. They can also modify material properties to align with particular data. While local optimizers ensure rapid convergence, they risk converging to a local minimum rather than the best overall solution. Conversely, global optimizers require exploring the entire problem space thoroughly. Enhancing its versatility, CST MWS can import specific CAD files and extract SPICE parameters, broadening the scope for design and simulation. This feature enables users to search for the optimal design to meet specific requirements or achieve certain objectives. They can also modify material properties to align [80].

2.2 Multiple Bands Metamaterial Absorbers

Wideband metamaterials, renowned for absorbing electromagnetic waves across a broad frequency spectrum, are highly valued in applications that demand such wideband capabilities. However, in certain scenarios, metamaterial absorbers are favored for their unique ability to selectively absorb electromagnetic radiation at specific frequencies. To create a multiband metamaterial absorber effectively, the most efficient approach involved utilizing multiple resonators, with each resonator tailored to a distinct absorption band [81]. The resonator size can be varied to adjust the operating bands, though the bandwidths of these metamaterial absorbers are typically constrained by the resonators' resonance features. Generally, multiband metamaterial absorbers exhibit bandwidths narrower than 1.0%, as outlined in studies. Addressing this limitation, the authors in proposed a technique for constructing a multiband absorber with considerably wider absorption bandwidths, leveraging the principles of impedance matching theory. Their strategy entailed the integration of multilayer and multiple square-ring structures to form a triple-band frequency selective surface (FSS). By tweaking the dimensions of the various square rings, the bandwidth of each passband could be precisely controlled. Implementing a matched load to one of the FSS's ports effectively kept the reflection coefficient constant, thus simplifying the two-port FSS into a single-port absorber. The wideband absorber mentioned earlier can be employed to attain the matching load required to neutralize the FSS. This novel triple-band absorber, as expounded in, achieved fractional bandwidths exceeding 5.0%. These bandwidths were significantly broader than those reported in earlier studies [82], marking a notable advancement in the field of metamaterial absorber design. This development highlights the evolving nature of metamaterial technology, continually pushing the boundaries of what's achievable in terms of selective frequency absorption and bandwidth enhancement

2.3 Polarization Insensitive Wide-Angle Metamaterial Absorber

Polarization-insensitive metamaterial absorbers offer a more cost-effective solution compared to single-polarization absorbers, especially considering the often-unpredictable polarization of incoming electromagnetic waves. The key to achieving polarization insensitivity lies in the design of the unit cell layouts of these metamaterial absorbers. As detailed in studies, these absorbers are comprised of unit cells with high symmetry. This exceptional symmetry allows the unit cells to respond similarly to both x- and y-polarized waves at normal incidence.

Essentially, they have the capability to decompose any incoming electromagnetic wave's polarization into its x- and y-polarized components. For a metamaterial absorber to be truly polarization-insensitive, it must effectively handle dual polarization. This means that its frequency responses for both orthogonal polarizations should be identical. Such absorbers, when constructed with wide-angle metamaterials, are capable of capturing electromagnetic waves from an extensive range of directions. This attribute makes polarization-insensitive metamaterial absorbers particularly valuable in applications where the direction and polarization of incoming waves are variable and unpredictable [83].

2.4 Applications of Metamaterial Absorber on Antennas

This study focuses on using metamaterial absorbers to antennas. The most apparent use for metamaterial absorbers is as a covering to lower the scattering performance of a metal object, because these materials can absorb incoming electromagnetic waves. Figure 8 depicts a loading resistor-activated metal plate with single-polarized wideband metamaterial absorbers. In the intricate domain of antenna design, comparing theoretical predictions with actual performance is crucial. Figure 12a in the cited study showcases the realized gains of a proposed design at various frequencies, juxtaposing calculated outcomes with measured results. Figure 12b delves deeper, analyzing the measured monostatic scattering characteristics of the proposed design against a reference antenna. This reference is a metal-grounded dipole antenna, identical in size to the ideal design. While the dipole antenna exhibits satisfactory radiation performance within the notch band, its scattering performance outside this band is significantly inferior compared to the reference antenna. The unit cell of a reflect array antenna must provide phase alterations to counteract phase shifts resulting from varying propagation paths between the feed source and the unit cells. To achieve a low-scattering reflect array, each cell must be capable of both phase-shifting and absorbing electromagnetic waves. In [83], the authors describe using band-notched absorbers for full reflectance and electromagnetic wave absorption, while a dielectric lens facilitates the necessary phase shift. By adjusting the height of the dielectric lens, the reflection phase coverage can span a complete 360 degrees.

Chapter 3
Methodology

3.1 Software

CST MICROWAVE STUDIO stands out as a prominent tool, widely recognized for its utilization of 3D electromagnetic (EM) simulation in the frequency domain [46]. CST MWS is renowned for providing accurate and swift simulation of high-frequency (HF) components, including antennas, couplers, filters, multi-layer and planar technologies, as well as EMC analysis and SI effects [84].

Its ease of use and detailed insights into the EM behavior of high-frequency designs make it particularly valuable for users. CST prides itself on pioneering advanced technology for 3D EM simulation. Users of this software benefit from considerable flexibility in handling a vast array of applications through various open solver methodologies. CST MWS is particularly adept at using its leading module, often the Frequency Domain solver and the open Time Domain solver, along with other solver modules for specific applications.

Enhancing its versatility, CST MWS can import specific CAD files and extract SPICE parameters, broadening the scope for design and simulation. It can also be integrated into numerous industry-standard workflows through the CST STUDIO SUITE interface. As a result, CST MICROWAVE STUDIO is increasingly becoming a standard tool for designers in various ventures. The CST Studio Suite is adept at automating development schedules for electromagnetic systems and devices. Models in the CST Studio Suite can be categorized based on numerical values or material properties, allowing users to assess how device behavior changes with varying properties.

This feature enables users to search for the optimal design to meet specific requirements or achieve certain objectives. They can also modify material properties to align with particular data. The Suite offers a range of optimization algorithms, both local and global [85]. While local optimizers ensure rapid convergence, they risk converging to a local minimum rather than the best overall solution. Conversely, global optimizers require exploring the entire problem space thoroughly. High-performance computing cycles can accelerate propagation and optimization in complex scenarios or problems involving large distributed computing techniques datasets. The effectiveness of global optimizers can be significantly enhanced by employing.

3.1.1 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 [86].

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. (31)

- 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.

3.1.2 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 [87]. This versatility makes CST Microwave Studio a powerful and indispensable resource in the field of EM simulation. 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.

3.1.3 Higher Frequency Solver

Higher Frequency Solvers are made up of the Seven Sub-Solvers.

3.1.4 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.

3.1.5 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 accuracy and reliability, making it a powerful tool for engineers and researchers working in various domains of electromagnetic analysis. Challenges posed by electrically large models, enabling more efficient and effective solutions in the field of computational electromagnetics. These frequency approaches are not limited to simple applications; they are also highly effective for charged electron molecule [88].

3.1.6 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.

3.1.7 Integral Equation

The utilization of the Multilevel Fast Multipole Method (MLFMM) significantly enhances the efficiency of solving for electrically large models. This advanced technique leverages the inherent properties of such models, allowing for the effective discretization of the fundamental condition solver. MLFMM is particularly adept at handling the complexities associated with large-scale electromagnetic problems, streamlining the computational process and reducing the time required for simulations. In the context of asymptotic methods, the repetition region is analyzed using a beam-following approach. This technique is instrumental in examining scenarios that involve antenna and scattering phenomena across electrically large areas. Asymptotic figures are employed to model and understand the behavior of electromagnetic waves as they interact with large structures [89]. This approach is particularly useful for simulating real-world conditions where the size of the objects significantly influences the propagation and scattering of electromagnetic waves. By applying these methods, researchers and engineers can gain a more accurate understanding of how electromagnetic fields behave in complex environments, leading to more precise and reliable designs in applications such as radar systems, wireless communications, and electromagnetic compatibility studies. The combination of MLFMM and asymptotic methods provides a powerful toolkit for tackling the challenges posed by electrically large models, enabling more efficient and effective solutions in the field of computational electromagnetics.

3.1.8 Lower Frequency Solvers

By dividing the computational process into two Sub-Solvers, we can create a dedicated Lower Frequency Solver. This approach allows for the automatic selection of the most suitable method for solving equations, based on the total number of equations involved. This tailored approach enhances efficiency and accuracy in solving lower frequency problems [90].

3.1.9 Static Solvers

The effectiveness of Static Solvers, emphasizing their tripartite structure consisting of three Sub-Solvers tailored for specific aspects of static electromagnetic problems. This structured approach enhances the precision and efficiency of solving static electromagnetic fields. By addressing distinct elements of static analysis, these Sub-Solvers contribute to a more comprehensive understanding and resolution of a broad spectrum of static electromagnetic scenarios.

The article underscores the significance of this tripartite structure in optimizing the handling of static electromagnetic problems, showcasing its potential to offer nuanced solutions and improve overall accuracy in static analysis.

3.1.10 Electrostatic

The significance of employing a 3D solver in simulations of static electric fields, emphasizing its role in delivering detailed and precise analyses. The specialized nature of this solver caters to the complexities inherent in three-dimensional static electric fields. By doing so, it becomes a powerful tool for comprehensively understanding and predicting the behavior of these fields across diverse environments and application [91].

The use of a 3D solver suggests a commitment to capturing the intricacies of real-world scenarios where static electric fields operate. Its application ensures that simulations can account for spatial variations and interactions, providing a more accurate representation of the actual behavior of static electric fields. This article underscores the importance of leveraging advanced tools, such as 3D solvers, in enhancing the quality and reliability of simulations related to static electric fields, ultimately contributing to a deeper understanding of their dynamics and applications.

3.1.11 Magneto static

The crucial role of a specialized 3D solver in simulating static magnetic fields, emphasizing its capacity to provide detailed insights into the behavior of these fields. By leveraging its three-dimensional capabilities, the solver enables precise modeling and analysis of magnetic field interactions and distributions. This specificity positions the 3D solver as an indispensable tool for comprehending the intricacies and intricacies of systems that involve static magnetic fields across diverse applications.

The use of the 3D solver implies a commitment to accuracy and depth in understanding magnetic field dynamics. Its application facilitates a nuanced examination of how magnetic fields behave in three-dimensional space, allowing for a more comprehensive and realistic representation in simulations. This not only aids in understanding existing systems but also proves valuable in the design phase of new systems involving static magnetic fields. In summary, the article highlights the significance of the 3D solver as a versatile and essential instrument in the realm of static magnetic field simulations, offering detailed insights crucial for both understanding and designing systems in various applications [92].

3.1.12 Stationary Current

The effectiveness of the 3D solver in simulating DC current flow within systems, particularly when incorporating lossy components. This specialized solver proves invaluable by accurately modeling current distribution and assessing the impact of resistive elements. Its advanced capabilities offer crucial insights into the performance and efficiency of electrical systems operating under direct current conditions. By focusing on DC currents and lossy components, the 3D solver provides a detailed understanding of how resistive elements influence current flow, enhancing the accuracy of simulations. This emphasis on accurate modeling positions the 3D solver as a vital tool for engineers and researchers seeking precise insights into the behavior of electrical systems, especially those dealing with DC currents and components that contribute to losses in the system.

3.1.13 Multiphysics Solvers

The effectiveness of Multiphysics Solvers, comprising four Sub-Solvers designed to tackle distinct aspects of complex physical phenomena. This integrated approach facilitates a comprehensive analysis spanning multiple physical domains, including electromagnetic, thermal, and structural interactions. The versatility of this suite makes it a powerful tool for solving intricate Multiphysics problems in diverse engineering and scientific applications. By addressing the interplay of different physical phenomena, the Multiphysics Solvers enable a more holistic understanding of complex systems, enhancing the accuracy and efficiency of simulations. This emphasis on integration across various domains underscores the suite's applicability in scenarios where multiple physical factors influence the overall behavior of a system.

The article positions Multiphysics Solvers as a valuable asset for researchers and engineers seeking a unified and versatile solution to address the challenges posed by complex, multifaceted physical interactions in their respective fields.

3.1.14 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 [93].

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.

3.1.15 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.

3.1.16 Conjugate Heat Transfer

This method effectively measures device heating by integrating techniques that replicate the heating of solid and liquid components. It incorporates fan cooling and convection mechanisms, providing a comprehensive approach to understanding and managing the thermal behavior of devices. This holistic strategy is crucial for ensuring optimal performance and longevity in various applications.

3.1.17 Mechanical

This methodology offers both linear and non-linear approaches for accurately estimating structural deformation and displacement. These techniques cater to a range of scenarios, from simple linear behavior to complex non-linear responses under various loads and conditions, providing essential tools for analyzing and predicting the structural integrity and behavior of different materials and designs [94].

3.1.18 Particle Dynamics Solvers

Particle Dynamics Solvers, emphasizing their three-tiered structure tailored to address specific facets of particle behavior and interactions. This tripartite arrangement allows for a comprehensive analysis of particle dynamics, encompassing crucial aspects such as motion, collisions, and the impact of external forces.

This design positions Particle Dynamics Solvers as a robust framework for studying and simulating complex particle-based systems in diverse scientific and engineering applications. The tripartite structure suggests a well-defined approach to understanding particle dynamics, ensuring a nuanced examination of the various forces and factors influencing particle behavior. By delving into motion, collisions, and external forces, these solvers offer a versatile toolset for researchers and engineers working on particle-centric systems. Overall, the article underscores the significance of Particle Dynamics Solvers in providing a structured and comprehensive solution for the analysis and simulation of particle behavior. The suite's applicability across scientific and engineering domains reflects its potential as a valuable resource for those seeking to gain insights into complex particle dynamics in diverse contexts.

3.1.19 PCB Solvers

PCB Solvers are characterized by a single Sub-Solver, which is specifically designed to handle the complexities of Printed Circuit Board (PCB) design and analysis.

3.1.20 Packages & PCBs

A specialized tool designed for evaluating Printed Circuit Board (PCB) performance, with a primary focus on three pivotal aspects: Power Integrity (PI), Electromagnetic Compatibility (EMC), and Signal Integrity (SI).

This tool serves as a comprehensive solution, offering robust analysis capabilities to ensure that PCBs adhere to essential standards in power distribution, electromagnetic interference, and signal transmission quality. The tool's overarching objective is to optimize the functionality and reliability of PCBs by addressing critical performance parameters [95].

The emphasis on Power Integrity underscores the tool's ability to evaluate and maintain stable power distribution within the PCB, vital for preventing voltage fluctuations and ensuring consistent power delivery to components. Electromagnetic Compatibility assessment signifies the tool's role in mitigating potential electromagnetic interference, safeguarding against disruptions that could compromise the functionality of nearby electronic devices. Lastly, the focus on Signal Integrity highlights the tool's capability to analyze and enhance the quality of signal transmission, crucial for maintaining data integrity across the PCB.

In conclusion, this specialized tool emerges as an indispensable asset for engineers and designers, offering a holistic approach to evaluating and optimizing the performance of PCBs across critical domains such as Power Integrity, Electromagnetic Compatibility, and Signal Integrity.

3.1.21 Cable Solvers

Cable Solvers are unified into a single Sub-Solver, a specialized tool designed to analyze and simulate the behavior of cables in various environments. This integration allows for efficient examination of cable performance, including signal transmission, electromagnetic interference, and thermal effects, providing essential insights for the design and optimization of cable systems.

3.1.22 Cable Suite

It is devoted to the 3D study of radiated emission (RE), signal integrity (SI), electromagnetic susceptibility (EMS), and conducted emission (CE) in electrically large systems including intricate cable architectures.

3.1.23 Systems and Circuits

The problem at hand offers two distinct solutions: "circuits" and "systems." To address this, the CST Microwave Studio is employed, specifically for measuring electromagnetic fields in cable scenarios. This tool provides precise analysis of electromagnetic interactions in cables, crucial for understanding and optimizing circuit and system performance in various applications [96].

3.1.24 Schematic

This tool offers a user-friendly and efficient approach to system and circuit schematic design. It simplifies the design process, enabling users to quickly create and modify schematics with ease. Its effectiveness lies in its intuitive interface and powerful features, making it an ideal solution for both novice and experienced designers.

3.1.25 Assembly

An approach in engineering and design that revolves around crafting structures specifically to enable the integration of advanced synthesis and optimization techniques. This strategic emphasis on integration aims to enhance the efficiency and effectiveness of the design process, ultimately enabling the creation of sophisticated and innovative solutions. The key strength of this approach lies in its deliberate focus on amalgamating cutting-edge synthesis and optimization methods. By doing so, it acknowledges the symbiotic relationship between these two processes, emphasizing their interplay in achieving superior design outcomes. This integration not only streamlines the design workflow but also ensures that the chosen structures are finely tuned to harness the full potential of the most advanced techniques available. In essence, the article advocates for a design philosophy that recognizes the synergy between synthesis and optimization, positioning the integration of these processes as a cornerstone for achieving efficient, effective, and advanced solutions. This approach aligns with the evolving landscape of engineering, where the collaboration of diverse methodologies is increasingly vital for pushing the boundaries of innovation.

3.1.26 Addons and Enhancements

A systematic categorization of three sub-solvers into two distinct groups: enhancements and additions. This classification strategy serves to delineate the objectives and functions of each sub-solver, providing a structured approach to their development and refinement. Within the framework, enhancements are directed at improving existing capabilities and performance. This signifies a commitment to refining and optimizing the functionalities of the sub-solvers that are already in place. The focus on improvements indicates a recognition of the need for continuous enhancement to keep up with evolving requirements and advancements in technology. On the other hand, additions introduce new functionalities and features. This reflects an adaptive approach, acknowledging the necessity of incorporating novel elements to address emerging demands and applications. The emphasis on additions highlights a commitment to innovation, ensuring that the sub-solvers remain versatile and aligned with the evolving landscape of their respective fields. The categorized approach, distinguishing between enhancements and additions, contributes to a more transparent and goal-oriented development process. It not only facilitates a targeted improvement of existing capabilities but also ensures that the introduction of new functionalities is strategic and aligned with the evolving needs of diverse requirements and applications.

3.1.27 Optimization & Design Study

The versatility and efficacy of integrating parametric analysis and optimization tools across various stages of the design process. This flexibility is portrayed as a key advantage, providing designers the freedom to seamlessly incorporate these tools at any point in the development cycle. This adaptability enhances the overall efficiency and effectiveness of the design process.

The incorporation of parametric analysis and optimization tools offers designers a systematic approach to exploring diverse design variations. This systematic exploration is highlighted as a means to refine and optimize performance parameters, leading to the development of more sophisticated and effective solutions. The emphasis on optimization aligns with the contemporary trend in design where achieving optimal outcomes is paramount.

The article implicitly acknowledges the dynamic nature of the design process, suggesting that the integration of parametric analysis and optimization tools caters to the evolving needs and complexities encountered during development. This adaptability enables designers to fine-tune their solutions iteratively, ensuring that the final result aligns closely with the desired performance metrics. Overall, the article advocates for a fluid integration of these tools throughout the design cycle as a means to enhance the exploration, refinement, and optimization of design variations [71].

3.1.28 Hardware Acceleration

The one- or two-attachment workstation, a cornerstone of this system, significantly impacts abroad spectrum of facilities. Its key value lies in its adaptability and performance, catering to

various computational needs. To further enhance system efficiency, additional tokens can be purchased. These tokens unlock the potential for accelerated processing, particularly when used in conjunction with advanced hardware such as graphics processing units (GPUs). They also enable the integration with quad attachment systems, offering even greater computational power.

Moreover, the system supports distributed computing, allowing for workload sharing across multiple machines. This scalability and flexibility make it an ideal solution for handling complex, resource-intensive tasks, ensuring optimal performance and efficiency in diverse computing environments. The ability to customize the system with these tokens provides users with the flexibility to tailor the workstation's capabilities to their specific requirements, ensuring that they can effectively manage and process large volumes of data with ease.

3.2 Procedure of Design

Initially, a condition-based Metamaterial Absorber (MMA) is meticulously designed to operate effectively within the C, X, and Ku frequency bands. This design process is tailored to meet specific MMA planning requirements, ensuring that the absorber is optimized for its intended application. The design takes into account the unique electromagnetic properties of these bands, aiming to maximize absorption efficiency and bandwidth.

In the second step, the MMA's parameters and substrate are carefully sized. This involves selecting appropriate materials and dimensions to achieve the desired electromagnetic characteristics. The substrate plays a crucial role in determining the overall performance of the MMA, influencing factors such as resonance frequency, bandwidth, and absorption efficiency [91].

The third step involves selecting the optimal substrate material, substrate height, feeding method, and metamaterial for MMA designs at 4.882 GHz, 6.464 GHz, 7.882 GHz, and 11.3 GHz. This selection process is critical for ensuring that the MMA performs effectively at these specific frequencies. Each design decision is made based on a thorough analysis of how different materials and configurations affect the MMA's performance. In the fourth step, the simulation results are saved, and the antenna is constructed based on these findings. This step marks the transition from theoretical design to practical implementation, allowing for the physical realization of the MMA.

The fifth step involves saving the result if the MMA-defined criteria are met. This step ensures that the final design adheres to the predefined specifications and performance targets. It is a crucial checkpoint in the design process, confirming that the MMA meets the necessary standards. In the sixth step, the optimized MMA is now performing better than before.

This improvement is a testament to the effectiveness of the design and optimization process. The optimized MMA exhibits enhanced performance characteristics, such as higher absorption efficiency, broader bandwidth, and better impedance matching.

Finally, in the seventh step, the results are evaluated against the current MMA. This comparative analysis provides valuable insights into the improvements achieved through the optimization process. It allows for a detailed assessment of how the new design outperforms the existing MMA, highlighting the advancements made in metamaterial absorber technology. This evaluation is essential for validating the design choices and for demonstrating the efficacy of the newly developed MMA.

3.3 Design of Proposed MMA

Optimizing impedance is a critical aspect in the development of a metamaterial absorber, as it significantly enhances the absorber's effectiveness. Achieving an impedance match with the air's intrinsic impedance minimizes reflections, a key factor in maximizing absorption. The metamaterial's absorption ratio is determined by its reflection and transmission coefficients. In an ideal scenario, a perfectly matched absorber would have a ground-reflected wave amplitude close to zero. To further improve performance, applying a metal coating to the base of the structure can effectively achieve zero wave transmission, ensuring that no waves pass through the absorber. This approach is essential for creating highly efficient metamaterial absorbers, as it has gone to optimizes the interaction between the metamaterial and electromagnetic waves, leading to superior absorption capabilities. By carefully designing the metamaterial's structure and materials, it is possible to fine-tune its electromagnetic properties, achieving the desired balance between reflection, transmission, and absorption. This optimization process is crucial for developing metamaterial absorbers that can be effectively used in a wide range of applications, from electromagnetic (EM) shielding to enhancing the performance of antennas and sensors [61].

The table presents the parameters of the proposed metamaterial absorber, detailing its structural dimensions. 'H' and 'W' represent the length and width of the dielectric metamaterial platform, respectively. These dimensions are crucial in defining the overall size and shape of the absorber. The top copper plate, a key component in the absorber's design, has its width and length denoted by 'h' and 'w'. Additionally, 'D' specifies the thickness of the substrate, an important factor influencing the absorber's electromagnetic properties. On the back of the substrate, a copper strip is placed, mirroring the substrate in both width and length. This symmetrical design ensures consistent electromagnetic behavior across the absorber.

The fifth step involves saving the result if the MMA-defined criteria are met. This step ensures that the final design adheres to the predefined specifications and performance targets. It is a crucial checkpoint in the design process, confirming that the MMA meets the necessary standards. In the sixth step, the optimized MMA is now performing better than before [29].

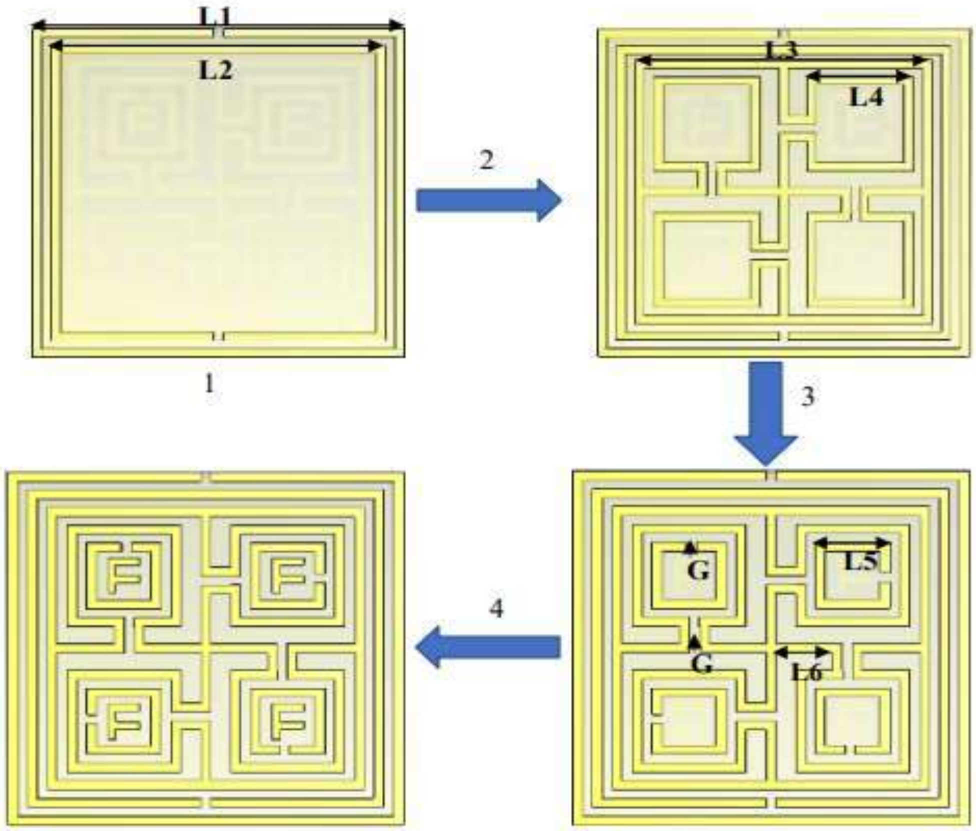


Figure 7 Front, Right, And Back of Proposed MMA Unit Cell

A table of the parameter of the Metamaterial design is given below to get the better understanding of the design structure:

TABLE I PROPOSED MMA DESIGN PARAMETER.

Parameters	**Dimension (mm)**
L1	10
L2	9
L3	8
L4	2.88
L5	1.88
L6	1.4
G	0.25
Substrate thickness	1.6
Ground / Patch Thickness	0.035

Chapter 04

Result Analysis

4.1 Simulation result of the Metamaterial Absorber

The S-Parameters template provided by the CST post-processing module was used to extract material properties [9]. This approach provides the values for the permittivity, permeability, and index of refraction of the specified unit cell. In the context of CST, a reliable retrieval technique is used to extract the pertinent parameters. Furthermore, the values of relative permittivity (ε_r) and relative permeability (μ_r) may be determined and represented using equations (1) and (2).

$$\varepsilon_r = \frac{c}{j\pi f d} \times \frac{(1 - V_1)}{(1 + V_1)} \qquad (3)$$

$$\mu_r = \frac{c}{j\pi f d} \times \frac{(1 - V_2)}{(1 + V_2)} \qquad (4)$$

Here d is the substrate's depth, and c is the speed of light.

A higher frequency region's synthetic magnetism property with negative permittivity provides the refractive index, which describes how an electromagnetic wave is propagated through a material.

$$\text{Refractive index: } \eta = \frac{1}{kd}\{[[e^{inkd})]'' + 2m\pi] - i[\ln(e^{inkd})]' \qquad (5)$$

In the conducted CST numerical simulation, the outputs of permittivity (ε), permeability (μ), and refractive index (η) were pivotal in analyzing the transmission characteristics. Figures 23 and 24 visually depict the results, highlighting resonating frequencies where the transmission coefficient exhibited a remarkable attenuation, dropping below -10 dB. Notably, these frequencies were identified as 4.882 GHz, 6.464 GHz, 7.882 GHz, 11.3 GHz, and 17.216 GHz, encompassing the S, C, X, and Ku bands within the electromagnetic spectrum.

The robust retrieval technique implemented in CST, coupled with the NRW methodology in MATLAB, played a crucial role in extracting and analyzing the pertinent data. This comprehensive approach ensures the accuracy and reliability of the retrieved information, contributing to a thorough understanding of the electromagnetic behavior under consideration.

4.2 Permittivity and Permeability

Utilizing a finite integration technique (FIT) based 3D electromagnetic computer simulation technology (CST) microwave studio simulator, the effective parameters of the proposed SSRR unit cell structure are located between two waveguide ports of positive Z axis and negative Z- axis that are energized by the electromagnetic wave towards Z-axis, have been assessed shown in figure 23. The ideal electric and magnetic field may be achieved by establishing boundary.

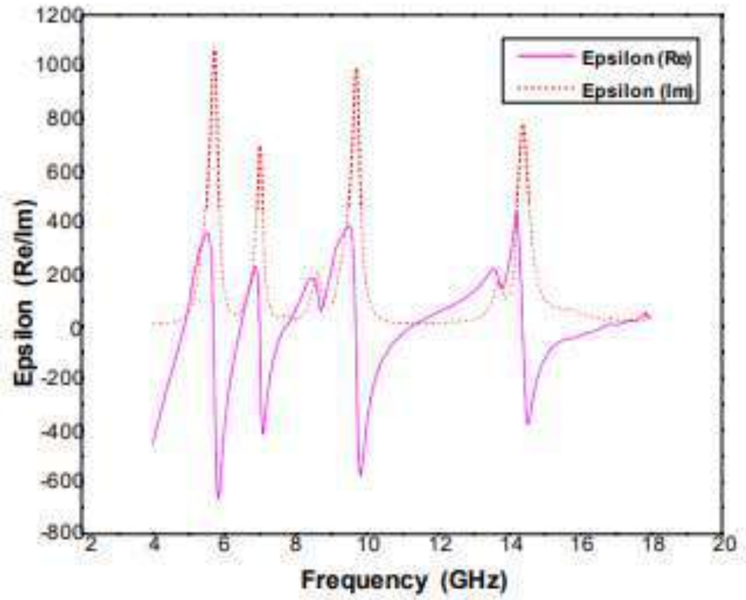


Figure 8 Permittivity (Re/Im)

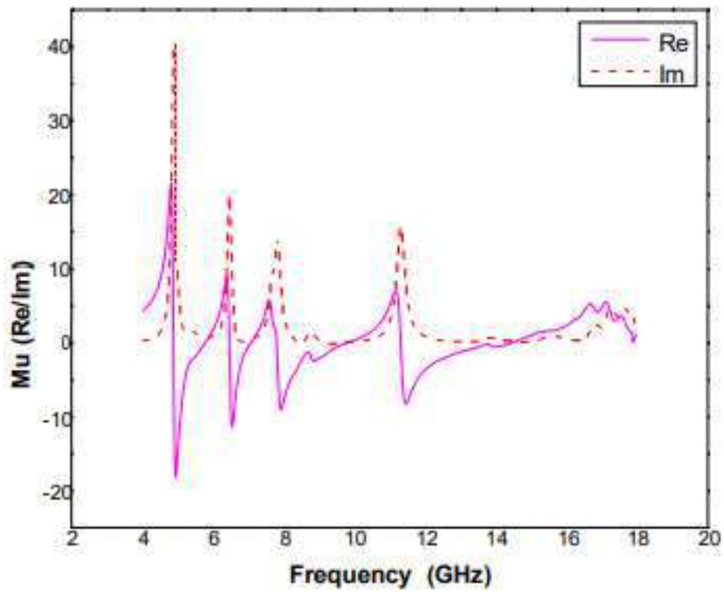


Figure 9 Permeability (Re/Im)

At a lower resonance frequency (4.882 GHz), the values of permeability are positive, and permittivity are negative. This results in ENG Negative (ENG) metamaterial behavior in the lower frequency range. But at 6.464 GHz, the material shows negative permeability and permittivity. Hence, we can refer to this as Double Negative (DNG) behavior. Besides, at 7.882 GHz, it shows Mu Negative (MNG) behavior. However, at 11.3 GHz, it shows DNG Characteristic the Drude function may also be used as an explanation for the negative permittivity:

$$(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega+i\Gamma)} \text{.......................................(6)}$$

4.3 Refractive Index

The |S11| minima and each of the resonances have this pattern. Regarding the resonance frequencies, the refractive index graph in Figure 24 shows an almost zero value. Bandwidth may be increased using the ENG property, While the near-zero refractive index property can be used to improve the gain and directivity of an antenna [92].

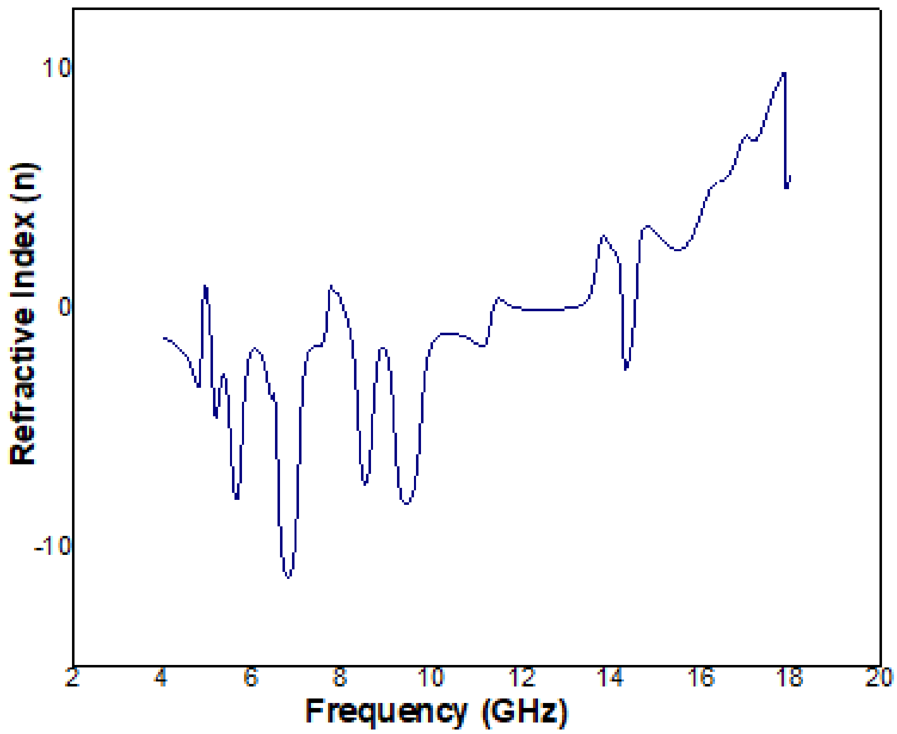


Figure 10 Refractive Index

This absorber has achieved 99.3%, 94.9%,92%, 94.5%,98.7% and 92.5% at 4.882, 6.464, 7.882, 11.3, and 17.216 GHz, respectively, as shown in Figure 25. Beside absorbance for different azimuth angle have been tested to check the insensitiveness.

It is found that the absorbance is remain unchanged for phi =900 and Theta =600 shown in figure.

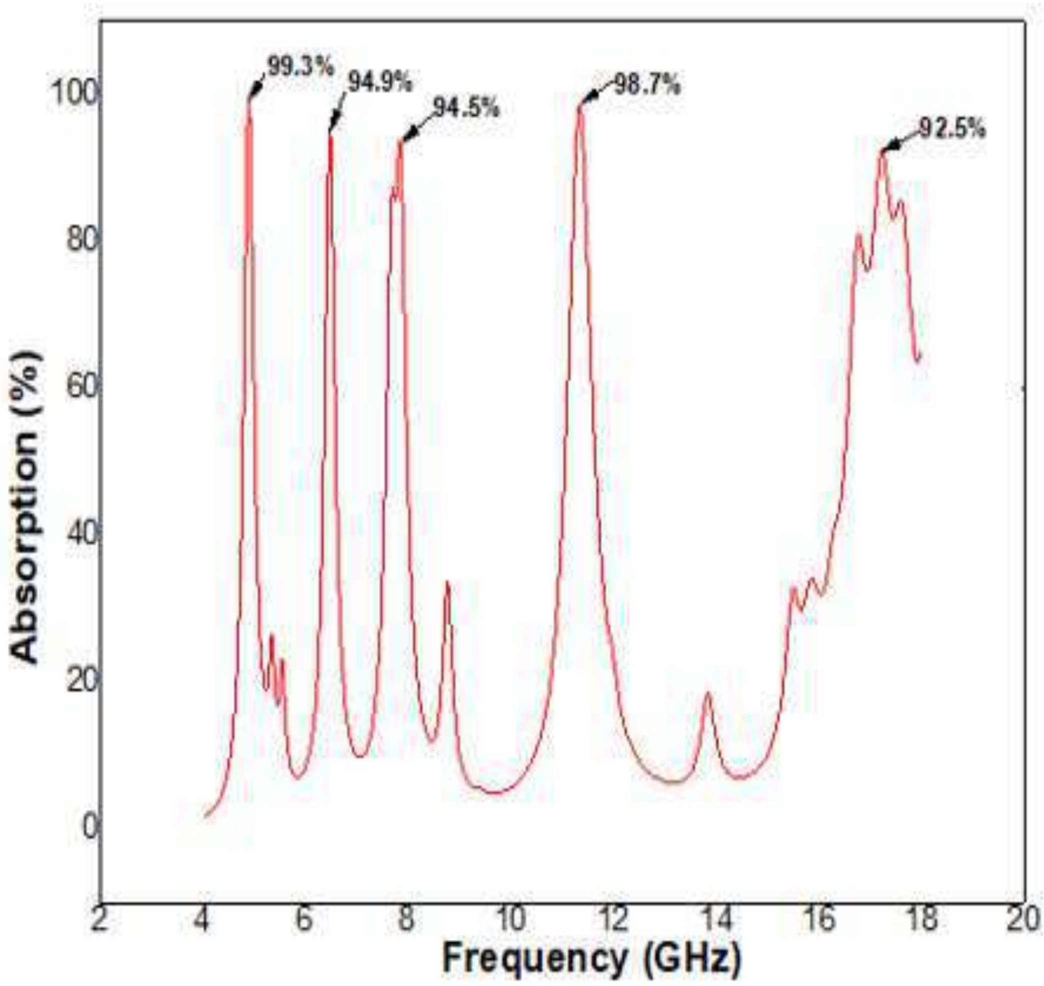


Figure 11 Absorbance of the proposed design

4.4 Absorption of the Proposed Design

Figure 12 shows the SSRR's surface current distribution at 6 GHz, 8 GHz, and 15.36 GHz. The nature of the forces and fields emitted by a metamaterial is determined by its internal charge. Surface current in metamaterials has a close relationship to the underlying magnetic and electric fields. Curl equation [94] of Maxwell describes the development of an electric and magnetic field.

$$\nabla \times H = J + \frac{\partial D}{\partial t} \quad \text{.......................................(7)}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad where, \nabla = \left[\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right] \quad \text{........................(8)}$$

However, the equations do not represent the interplay between material, electric, and magnetic fields.

$$D(t) = \varepsilon(t) * E(t) \ldots\ldots(9)$$

$$B(t) = \mu(t) * H(t) \ldots\ldots(10)$$

The equations in (8) provide a helpful framework for modeling this association.

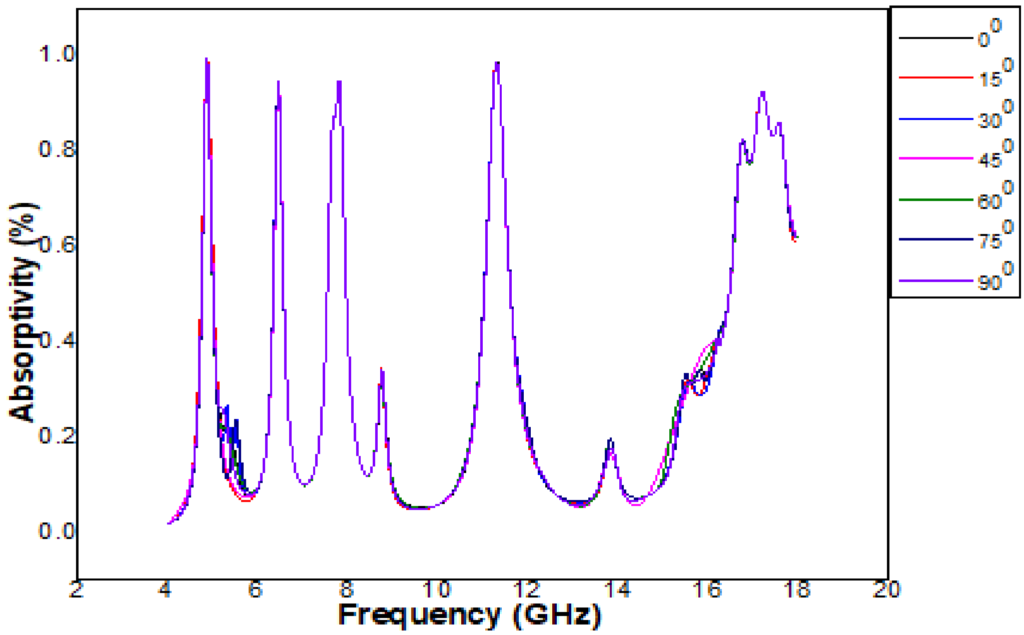


Figure 12 Absorbance of the proposed design (For phi=90)

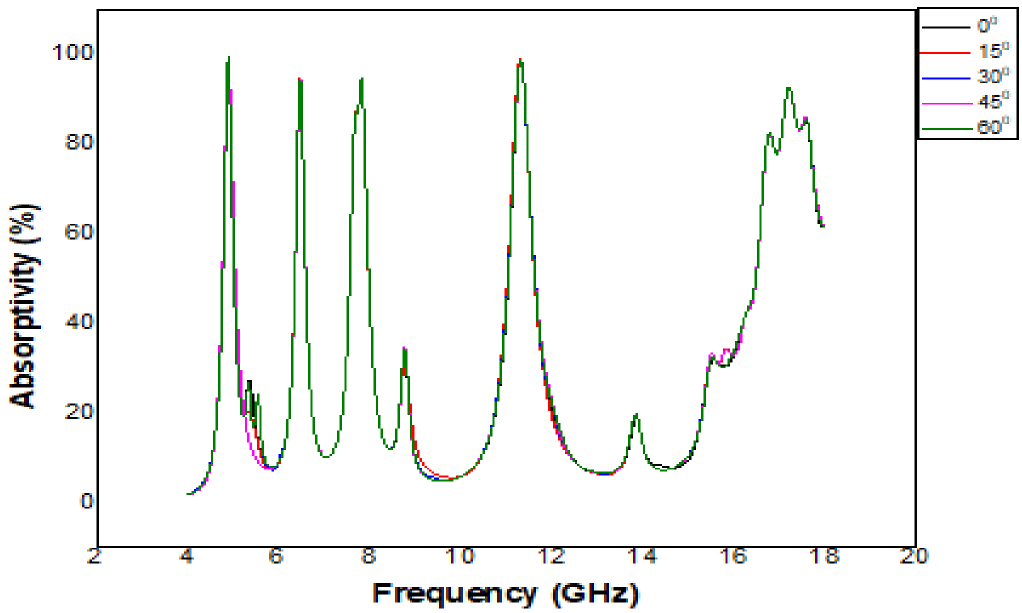


Figure 13 Absorbance of the proposed design (For phi=90)

4.5 Surface Current

Here the surface current flow has been given below, so that we can understand the current flow in the split cut options. Both electric field and magnetic field has been given below:

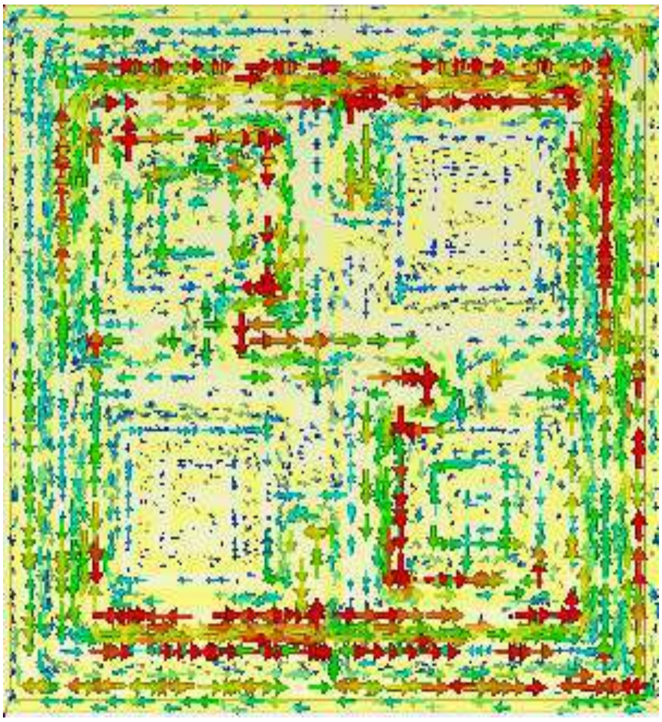


Figure 14 Surface current of 4.88GHz

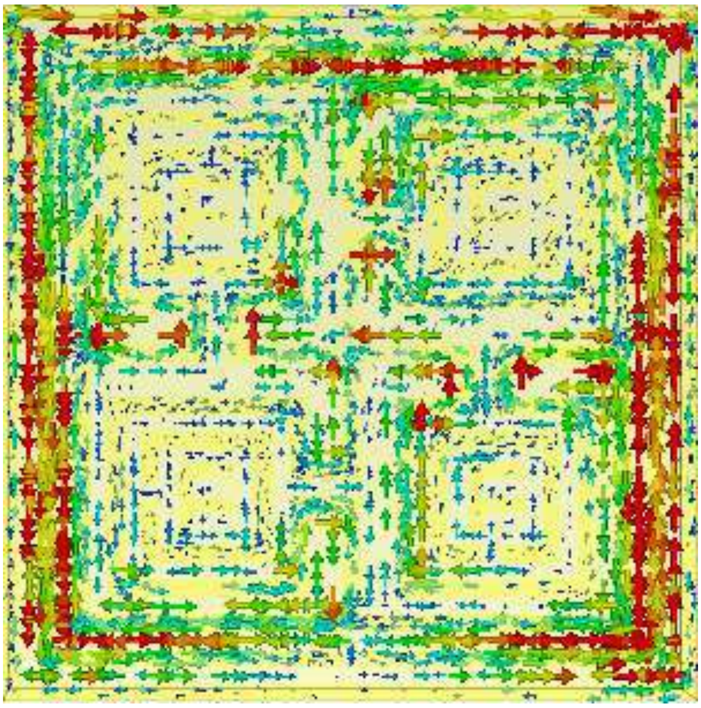


Figure 15 Surface current of 6.464GHz

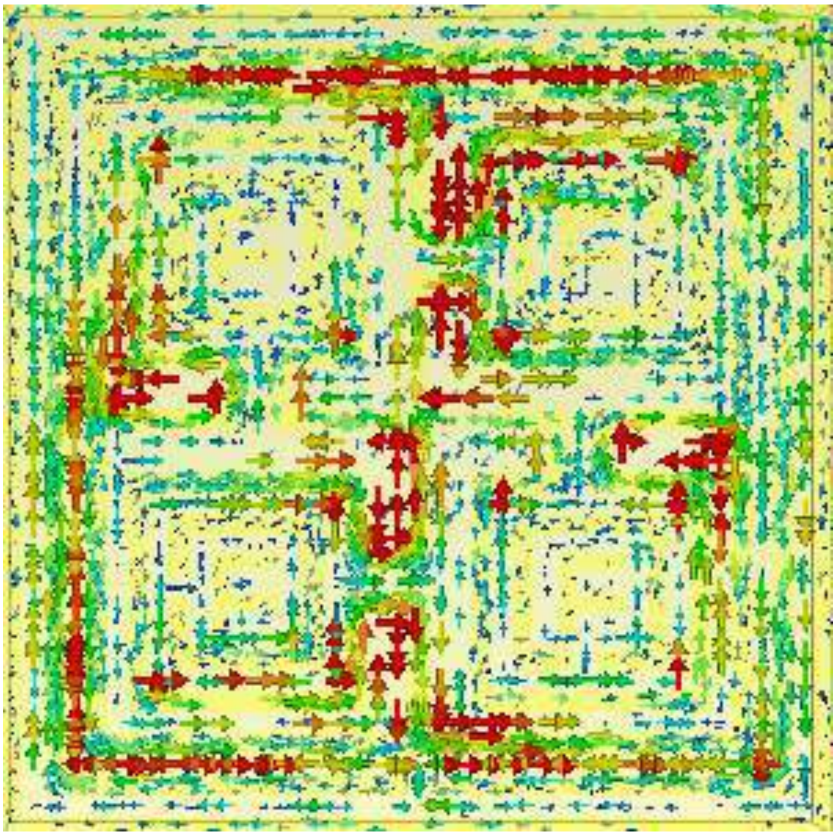


Figure 16 Surface current of 11.3GHz

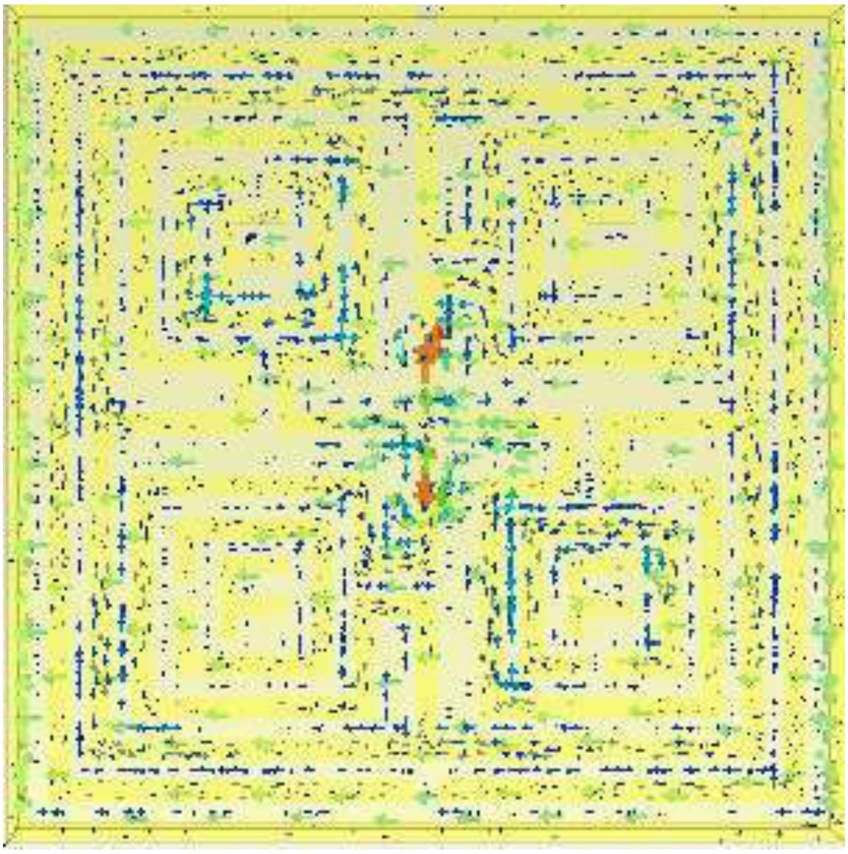


Figure 17 Surface current of 17.216GHz

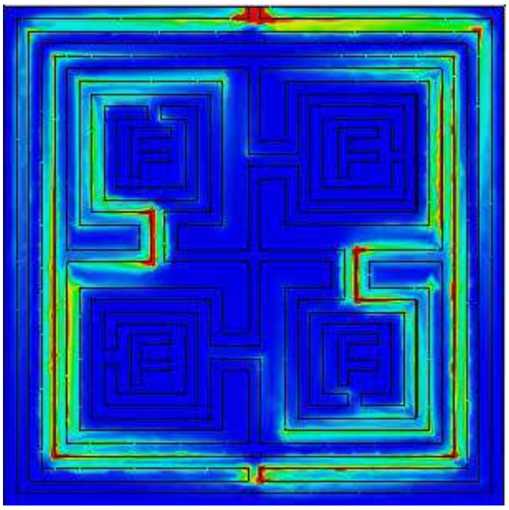
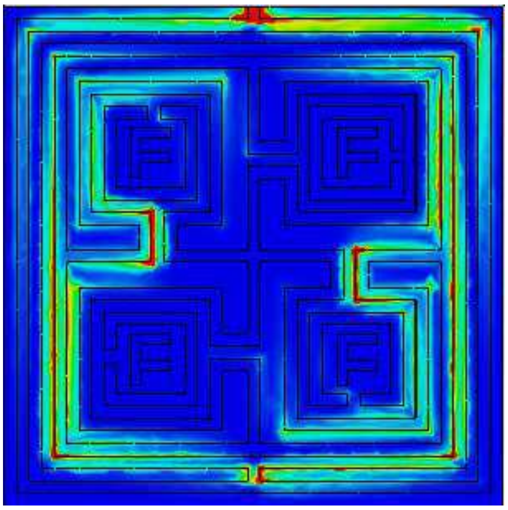
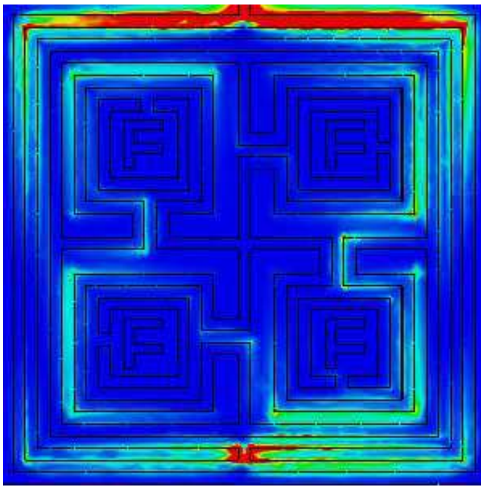
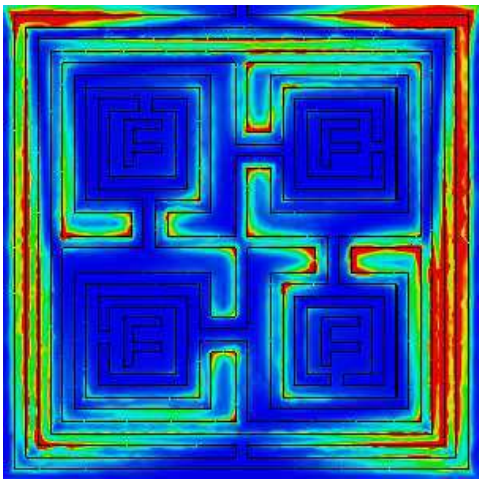
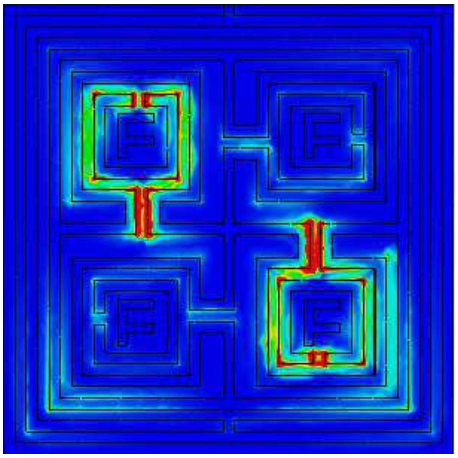
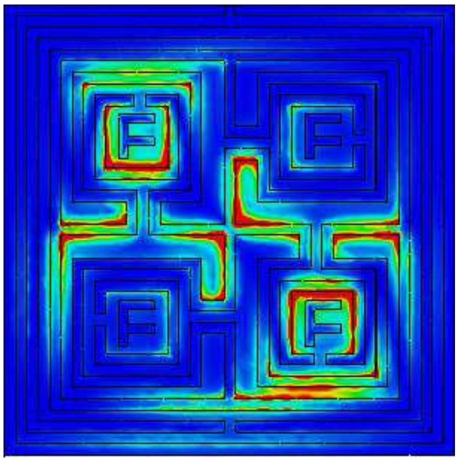
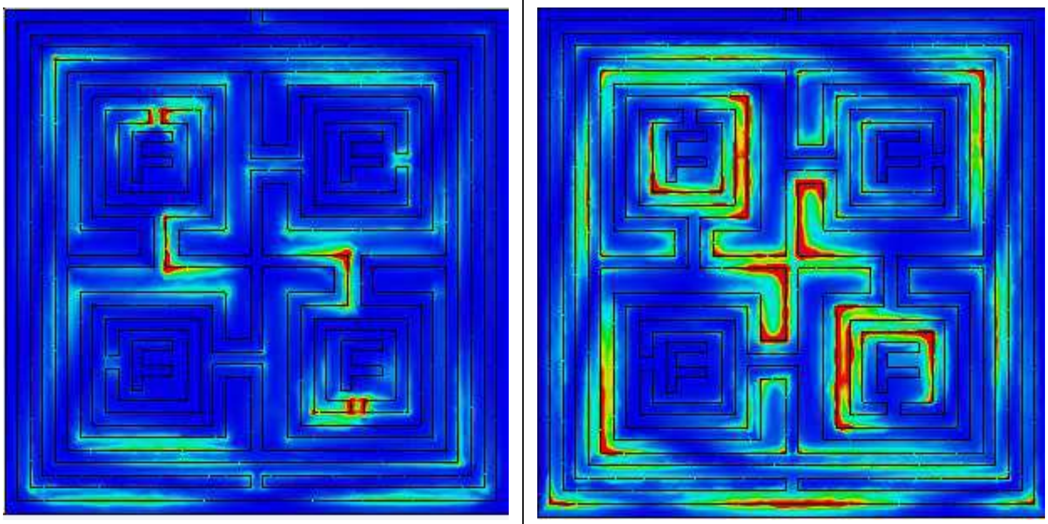
E-Field	H-Field
 (a)	 (b)
 (c)	 (d)
 (e)	 (f)

Figure 18 E-Field and H-Field of the designed absorber(a), (b), (c), (d), (e), (f)



(g) (h)

Figure 19 E-Field and H-Field of the designed absorber (g), (h)

4.7 Comparison Table

The study conducted by the authors presents a multiband absorber based on SNG (subwavelength nanostructures) that has a peak electromagnetic radiation (EMR) value of 8.57. Hence, the research study by reference proposes the use of a metamaterial absorber that exhibits a remarkable absorption efficiency of 98.5%. Furthermore, the research article referenced as presents a metamaterial absorber that exhibits an absorptivity of 99%. However, it should be noted that the dimensions of this absorber are not compact. The study presents a microwave absorber that exhibits a high absorption rate of 80% and has a considerable size.

The investigation conducted by the authors in reference showcases a multiband absorber leveraging subwavelength nanostructures (SNG). This absorber demonstrates a notable peak electromagnetic radiation (EMR) value, reaching an impressive 8.57. Moving forward, the research discussed in reference introduces a metamaterial absorber with a remarkable absorption efficiency of 98.5%, highlighting its potential for effective electromagnetic wave absorption.

Building on this, reference contributes to the field with a metamaterial absorber boasting an absorptivity of 99%, although it is important to note that the dimensions of this absorber are comparatively larger.

TABLE II COMPARISON BETWEEN OTHER WORKS

Ref	Number of Absorption peak	Absorption (%)	Dimension (mm^3)	Maximum angle of absorption (degree)	Co & cross polar absorption	Effective medium ratio (EMR)
[58]	3	Not mentioned	11×11×1.6	Not mentioned	No	7.8, & 2.63
[59]	1	98.5	10×10×1.6	up to 60	No	Not mentioned
[60]	2	99.25, 99.4	17×17×1.6	Not mentioned	No	Not mentioned
[61]	2	98,95	40 × 40 × 11	Not mentioned	No	3.40
[62]	2	<97	18×18×1.75	Upto 80	No	6.94
[63]	2	<80	Not mentioned	<30 upto 45	NO	2.34
[64]	1	98.7	Not mentioned	Not mentioned	No	6.05
[65]	3	94	33.5×33.5×1.6	Upto 60	Yes	5.11
Proposed	5	99.3, 94.9, 94.5, 98.7, 92.5	10×10×1.6	Phi =90 Theta =60	Yes	6.143

In a related study, a microwave absorber is presented, featuring a high absorption rate of 80%. However, it is worth noting that this absorber exhibits a considerable size. Meanwhile, the authors of reference have developed a polarization-insensitive metamaterial (MTM) absorber with a unique application - estimating crowd sizes through the measurement of electromagnetic radiation. This innovative approach adds a practical dimension to the utility of metamaterial absorbers.

The exploration of novel materials for electromagnetic absorption extends to transparent and flexible solutions, as demonstrated in reference [81]. The presented absorbent material effectively covers the entire Wi-Fi waveband, showcasing its potential for transparent and flexible applications in communication systems. Furthermore, reference introduces a creatively designed metamaterial absorber in the shape of a flower, operating specifically at a frequency of 5.5 GHz, adding an aesthetic and functional dimension to absorber design.

In the context of RF energy harvesting, reference [65] discusses the application of a thin, adjustable, dual-layer metamaterial absorber with a triple band. This absorber not only facilitates effective absorption but also holds promise for harvesting radiofrequency energy.

These diverse studies collectively contribute to the evolving landscape of metamaterial absorbers, demonstrating their potential across various frequencies, absorption efficiencies, and practical applications. The continuous exploration of new designs, materials, and functionalities in absorber technology underscores its significance in contemporary research and technological advancements. To further improve performance, applying a metal coating to the base of the structure can effectively achieve zero wave transmission, ensuring that no waves pass through the absorber. This approach is essential for creating highly efficient metamaterial absorbers, as it optimizes the interaction between the metamaterial and electromagnetic waves, leading to superior absorption capabilities. By carefully designing the metamaterial's structure and materials, it is possible to fine-tune its electromagnetic properties, achieving the desired balance between reflection, transmission, and absorption. This optimization process is crucial for developing metamaterial absorbers that can be effectively used in a wide range of applications, from electromagnetic shielding to enhancing the performance of antennas and sensors. Move into forward, the research discussed in reference introduces a metamaterial absorber with a remarkable absorption efficiency of 98%, highlighting its potential for effective electromagnetic wave absorption. Building on this, reference [82] contributes to the field with a metamaterial absorber boasting an absorptivity of 99%, although it is important to note that the dimensions.

Chapter 5
Conclusion

5.1 Overview

This article delves into an in-depth exploration of a novel metamaterial absorber (MMA), distinguished by its intricate F-shaped structure constructed with a rotationally symmetric Square Split Ring Resonator (SSRR) as its fundamental building block. The significance of this technology lies in its exceptional potential for seamless integration into conventional wireless environments, offering robust performance amidst polarization fluctuations and maintaining consistent effectiveness when subjected to electromagnetic waves at non-perpendicular angles.

The proposed metamaterial absorber (MMA) showcases a remarkable insensitivity to incidence angles, exhibiting resilience under both normal (up to 80°) and oblique (up to 90°) conditions. Moreover, the resonances demonstrated by this MMA display intriguing characteristics associated with near-zero or negative refractive indices, embracing Single Negative (SNG), Epsilon Negative (ENG), Mu Negative (MNG), and Double Negative (DNG) properties, showcasing its adjustable multifunctional capabilities.

It's essential to note that the field of metamaterials is dynamic, and new developments may have occurred since my last update. Researchers and engineers are likely to explore these and other directions to further enhance the capabilities and applications of metamaterial absorbers in the future [83].

The compactness of the metamaterial array (MMA) is effectively highlighted through the enhanced Effective Medium Ratio (EMR) of the suggested unit cell. The compact dimensions, coupled with the inverse permittivity, permeability, and near-zero refractive index attributes, position this metamaterial (MTM) absorber as highly versatile for a spectrum of wireless applications across S, C, X, and Ku bands. This inclusivity extends to fixed mobile and multiband systems, where the absorber's exceptional gain and enhanced antenna directivity make it particularly noteworthy.

In conclusion, the described metamaterial absorber emerges as a promising and versatile technology with potential applications spanning various wireless contexts. Its unique design, coupled with resilient performance characteristics, positions it as a valuable asset in the ever-evolving landscape of wireless communication systems, offering improved functionality and adaptability across diverse frequency bands and operational scenarios. Creating absorbers with tunable properties could be a significant area of future research. Tunability would allow the adjustment of absorption characteristics in real-time enable.

5.2 Future Work

Currently, the design of this MMA absorber is underway for various wireless applications. Subsequent endeavors will focus on the implementation of such technology in antenna or wireless systems. The efficacy of the MMA has not been evaluated in either simulated or real-life scenarios. In order to assess the true performance of the designed and simulated MMA, it is essential to produce it and observe its behavior inside the designated environment. This will enable a comparative analysis of the simulation's projected affects with the real outcomes. As of my last knowledge update in January 2022, [94] metamaterial absorbers have been a subject of extensive research and development with various applications in areas such as telecommunications, imaging, and energy harvesting. The future work of metamaterial absorbers may involve several directions and advancements, some of which could include:

5.2.1 Multiband and Wideband Absorption

Researchers may focus on developing metamaterial absorbers that can operate across multiple frequency bands or have wideband absorption capabilities. This could be crucial for applications such as communication systems and sensing technologies.

5.2.2 Tunable Metamaterial Absorbers

Creating absorbers with tunable properties could be a significant area of future research. Tunability would allow the adjustment of absorption characteristics in real-time, enabling adaptability to changing environmental conditions or specific requirements.

5.2.3 Nonlinear Metamaterial Absorbers

Investigating the nonlinear behavior of metamaterial absorbers could open up new possibilities for applications in signal processing, frequency mixing, [95] and even in developing nonlinear optical devices.

5.2.4 Integration with Other Technologies

Researchers might explore the integration of metamaterial absorbers with other technologies, such as micro-electromechanical systems (MEMS) or nano-opto mechanics, to enhance performance or enable novel functionalities [96].

5.2.5 Enhanced Efficiency and Durability

Improving the efficiency and durability of metamaterial absorbers is an ongoing goal. This may involve finding new materials, optimizing fabrication processes, or exploring innovative design approaches to enhance performance under various conditions.

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