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BACHELOR OF SCIENCE IN ELECTRONIC AND TELECOMMUNICATION ENGINEERING (ETE)

Incident Angle Insensitive Eye Shaped Metamaterial Absorber For Multiband Applications

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DEDICATION

This thesis is dedicated to my respected educators and dear parents, acknowledging their prayers and encouragement in helping me reach my objectives.

CERTIFICATE OF APPROVAL

The thesis entitled as "Eye Shaped Labyrinth Metamaterial Absorber For C, X, Ku & K Band Applications." Submitted by **Omar Faruk** ID No. **T193004** to the Department of Electronic and Telecommunication Engineering (ETE) of International Islamic University Chittagong (IIUC) has been accepted as satisfactory to fulfill the bachelor's degree criteria in Electronic and Telecommunication Engineering and approved as to its style and contents for the examination held on 24^{th} February 2024.

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I affirm that all the content in this thesis is of my own creation, excluding duly recognized selections and prospectus.

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ABSTRACT

In the microwave frequency domain, I introduce a simple design aimed at designing a multi-band polarization-insensitive MA. Polarization-insensitive MA are currently highly appealing owing to their distinctive absorption characteristics across various polarization angles. This design involves imprinting a specific structure onto a metal-backed dielectric substrate Fr-4, which comprises an eye-shaped labyrinth structure. Upon conducting a series of diverse analyses at an angle of incidence perpendicular to the surface, it has been determined that the proposed arrangement exhibits significant levels of absorption, reaching 94.93% at frequencies of 5.76 GHz, 97.73% at frequencies of 7.432 GHz, 95.89% at frequencies of 10.644 GHz, 98.28% at frequencies of 13.813 GHz, 93.18% at frequencies of 19.048 GHz, 98.72% at frequencies of 21.006 GHz, 99.9% at frequencies of 22.856 GHz, 91.85% at frequencies of 23.756 GHz, and 99.15% at frequencies of 24.746 GHz. To gain deeper insights into the absorption mechanism intrinsic to this design, provide visualizations of surface current distributions.

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LIST OF ABBREVIATIONS

MM	Metamaterial
MMA	Metamaterial Absorber
PMA	Perfect Metamaterial Absorber
WLAN	Wireless Local Area Network
LAN	Local Area Network
BSM	Blind Spot Monitoring
SAR	Specific Absorption Rate
RF	Radio Frequency
MIMO	Multiple Input Multiple Output
IoT	Internet of Things
mm	Millimeter
Gbps	Gigabits per second
ENG	Epsilon Negative
SNG	Single Negative
DNG	Double Negative
DPS	Double Positive
MNG	Mu-negative
PBG	Photonic Bandgap
SRR	Split-ring resonator
ZIM	Zero Index Metamaterial
CRECGR	Couple ring enclosed circular geometric resonator
TE	Transverse Electric

TM	Transverse Magnetic
RCS	Radar Cross-Section
IEEE	Institute of Electrical and Electronics Engineers
Wi-Fi	Wireless fidelity
ITO-FET	Indium Tin Oxide-Polyethylene Terephthalate
LC	Inductance-Capacitance
LCR	Inductance-Capacitance-Resistance
LTE	Long Term Evolution
S-parameter	Scattering Parameter
ADS	Advanced Design System
CSRR	Concentric Split-Ring Resonator
CST	Computer Simulation Technology
dB	decibel
DB-WS	Dual Band Wi-Fi Signal
DB-WSA	Dual Band Wi-Fi Signal Absorber
DRI	Direct Refractive Index
E-field	Electric Field
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMR	Effective Medium Ratio
FFS-CSRA	Four-Fold Symmetric-Circular Split-Ring Absorber
FF	Filling Factor
FR4	Flame Retardant 4

Chapter 1

Introduction

1.1 Background

Metamaterial absorbers are advanced engineered materials designed to effectively capture and imbibe electromagnetic emission, typically within distinct frequency ranges. They are created by arranging subwavelength structures in a precise manner to achieve impedance matching with incident waves, thereby minimizing reflection and maximizing absorption.

The development of metamaterial absorbers has been driven by the need for materials that can efficiently absorb electromagnetic waves across a wide spectrum, from microwaves to terahertz and beyond. Traditional materials often struggle to achieve high absorption rates within specific frequency bands, making metamaterial absorbers a valuable innovation.

Designing metamaterial absorbers with the desired absorption characteristics is a complex task that often involves advanced fabrication techniques. Researchers continue to explore new materials and designs to optimize performance and expand the range of potential applications.

In summary, metamaterial absorbers represent a significant advancement in materials science and electromagnetic engineering. They offer precise control over electromagnetic absorption, making them valuable in a wide range of applications that require efficient absorption within specific frequency bands.

1.2 Metamaterials

Metamaterials are synthetic materials engineered to have properties not typically found in nature. These materials are designed at the micro or nanoscale to exhibit specific electromagnetic characteristics, allowing them to control and manipulate waves such as light and sound in unconventional ways. One key feature of metamaterials is the ability to possess a negative refractive index, enabling the bending of light in ways not achievable with natural materials. These materials are structured at the microscopic or nanoscopic level to manipulate electromagnetic waves in innovative ways [1].

Metamaterials find applications across various fields, including optics, telecommunications, and acoustics. Metamaterial absorbers find applications in various fields, including communication devices, sensors, and imaging technologies. They have the potential to create innovative devices such as super lenses, cloaking devices, and highly efficient antennas. The design of metamaterials involves intricate structures and patterns, often smaller than the wavelength of the waves they interact with. Research in metamaterials is ongoing, exploring ways to expand their capabilities, improve efficiency, and develop practical applications. Challenges include scaling up production, addressing limitations in certain frequency ranges, and optimizing performance for diverse real-world scenarios. Despite these challenges, metamaterials hold promise for revolutionizing numerous technological advancements in the future.

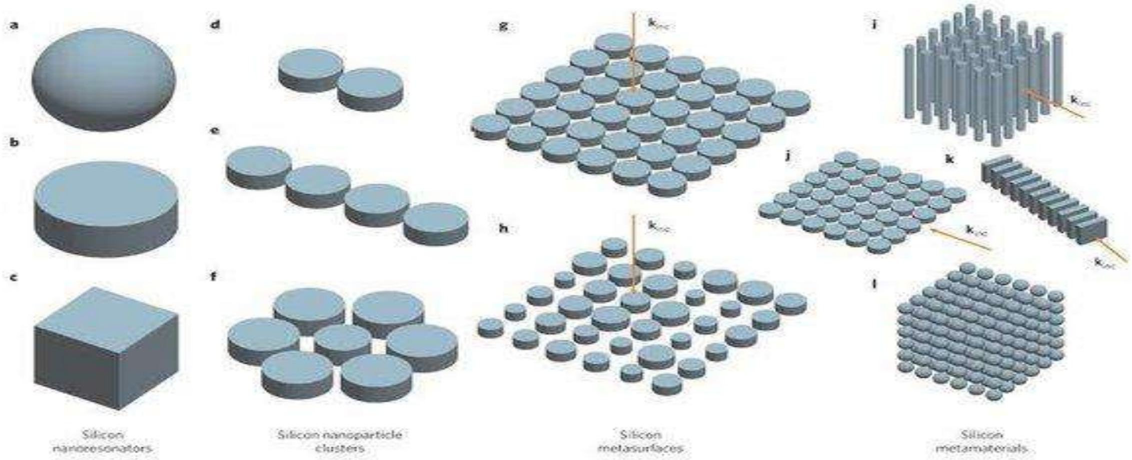


Figure 1.1: Metamaterials [2]

1.3 Metamaterial Absorber (MMA)

Metamaterial absorbers are specialized structures engineered to efficiently absorb electromagnetic waves, typically in specific frequency ranges. These absorbers are designed with micro or nanostructures that interact with incident waves, converting their energy into heat. One key advantage is their ability to achieve near-perfect absorption in the targeted frequency band

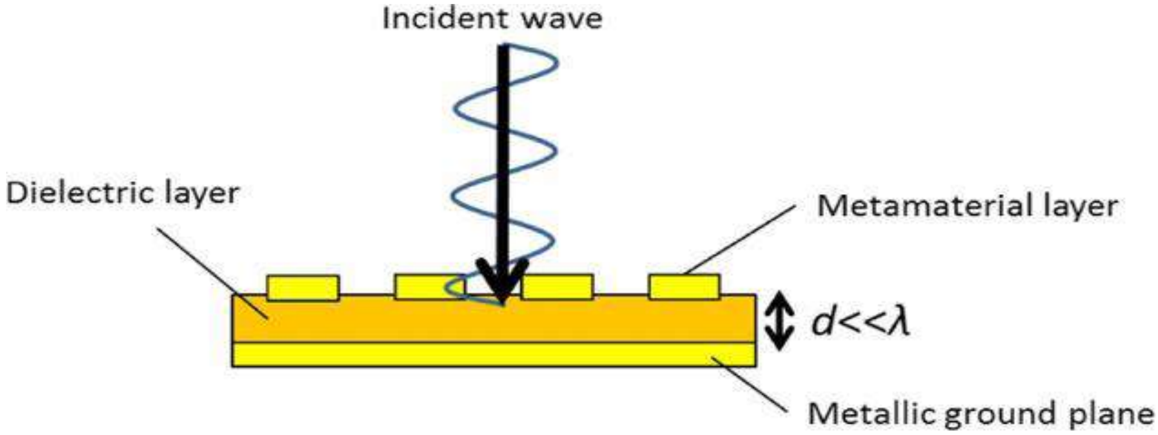


Fig 1.2: Metamaterial Absorber (MMA)[3]

Metamaterial absorbers find applications in various fields, including communication devices, sensors, and imaging technologies. The design of these absorbers involves carefully tailoring the geometry and composition of the metamaterial to achieve desired absorption characteristics. They offer advantages over traditional absorbers by providing enhanced performance and flexibility in

controlling absorption properties. Metamaterial absorbers are crucial in creating efficient energy-harvesting devices and improving the sensitivity of sensors.

Researchers continue to explore novel designs and materials to optimize metamaterial absorbers for specific applications. Challenges include scalability and practical implementation, but ongoing advancements hold the potential for significant breakthroughs in energy harvesting, communication, and sensing technologies.

1.4 Perfect Metamaterial Absorber (PMA)

A perfect metamaterial absorber is an advanced structure engineered to achieve near-complete absorption of electromagnetic waves in specific frequency bands. This absorber is designed with precise micro or nanostructures that efficiently capture and convert incident waves into heat. Its unique properties allow for superior absorption performance, making it highly desirable for applications such as energy harvesting, sensing, and stealth technology. The design of a perfect metamaterial absorber involves optimizing the composition and geometry of the material to attain exceptional absorption characteristics. Unlike traditional absorbers, perfect metamaterial absorbers can achieve absorption rates close to 100% in targeted frequency ranges. This capability is harnessed in various technological applications, from enhancing the efficiency of solar cells to improving the sensitivity of sensors.

Researchers continually explore innovative designs and materials to enhance the performance and versatility of perfect metamaterial absorbers. Overcoming challenges in scalability and practical implementation remains a focus for ongoing advancements in this cutting-edge field, promising significant contributions to diverse technological domains [4].

1.5 Characteristics of Metamaterial Absorber

Metamaterials can be defined by diverse factors that delineate their electromagnetic characteristics. Key factors encompassing these properties consist of:

1.5.1 Electrostatic Field (E-field)

In the domain of metamaterials, the electric field assumes a pivotal role in influencing their electromagnetic attributes. The interplay between the electric field and the subwavelength structures or components within the metamaterial gives rise to distinctive and precisely customized electromagnetic features.

The concept of the electric field is rooted in the influence exerted by nearby electric charges and is a fundamental principle in electromagnetism. Denoted as 'E,' the electric field is a vector field characterized by both its magnitude and direction. It emerges as a consequence of the presence of electric charges, with positive charges emitting outward-reaching electric fields, and negative charges projecting fields that converge inward. The strength and polarity of nearby charges directly affect the intensity of the electric field at a specific point in space. The electric field serves as a cornerstone in the study of electricity and magnetism, providing insights into how electric charges interact and behave in diverse scenarios. Its significance is evident in numerous real-world applications, including the establishment of electrical grids, the operation of computer equipment, and the generation and transmission of electricity [5].

In the context of metamaterials, electric fields profoundly influence their electromagnetic characteristics. This influence allows for the intentional manipulation of the material's response to electric fields at different frequencies, enabling the achievement of desired properties like a negative refractive index, enhanced absorption, or the fine-tuning of resonant behavior.

1.5.2 Magnetic Field (M field)

In the context of metamaterials, the term "magnetic field" refers to the region or space surrounding the metamaterial where magnetic influences and interactions occur. In metamaterials, engineers manipulate the arrangement of subwavelength structures to control and enhance the magnetic properties, allowing for unique and tailored responses to magnetic fields.

A magnetic field, a fundamental principle within electromagnetism, pertains to the impact exerted on a magnetic charge or a mobile electric charge by adjacent magnetic or electric fields. Denoted as 'B,' this notion is expressed as a vector field, possessing both magnitude and direction. Magnetic fields originate from either magnetic charges, also termed poles, or the movement of electric charges. In the absence of magnetic charges, magnetic fields arise from the motion of electric charges, such as electrons traversing a conductor. The orientation of the magnetic field at a specific spatial point is dictated by the current flow or the arrangement of magnetic poles [6].

1.5.3 Surface Current

Surface current refers to the flow of electric charge on the surface of a conductor or material. It occurs when electric charges, typically electrons, move along the surface of a material, such as a metal or a dielectric, rather than flowing through the material's bulk. Surface currents can result from various factors, including electromagnetic radiation, induced currents, or intentional design in applications like antennas and microwave devices. Surface currents play a crucial role in the interaction of electromagnetic waves with materials, affecting properties like reflection, absorption, and scattering. Understanding and controlling surface currents are essential in various fields, including electromagnetics, electronics, and telecommunications.

1.5.4 Transmission

Metamaterial absorbers are capable of efficiently soaking up specific frequencies or bands of electromagnetic energy. Consequently, it is expected that at the absorption frequency or within the absorption spectrum, the metamaterial absorber will exhibit minimal transmission. In other words, The anticipation is that the metamaterial absorber will significantly decrease or completely block incoming electromagnetic radiation within the designated absorption frequency or bandwidth.

Nevertheless, contingent upon the absorber's configuration, the metamaterial absorber might still convey incoming radiation to a certain degree at frequencies outside the absorption spectrum. This signifies that the transmission of the metamaterial absorber is not completely nonexistent but can be regulated by modifying the structural parameters of the absorber [7].

1.5.5 Reflectance

Metamaterial absorbers are engineered to enhance absorption by reducing the reflection of electromagnetic energy within a particular frequency spectrum. The absorption efficiency of a metamaterial absorber is impacted by diverse design elements, encompassing substrate characteristics, absorber width, and the dimensions and composition of individual unit cells.

In theory, it is possible to amplify the absorption capabilities of a metamaterial absorber by diminishing its reflectivity. This entails crafting a metamaterial absorber with a heightened absorption efficiency within the specified frequency range. Strategic placement of the absorber is critical to avert undesired reflections or scattering of incoming radiation, which could detrimentally affect the system's functionality. The assessment of a metamaterial absorber's performance through simulations and empirical observations across various frequencies and incident angles is imperative to formulate an absorber with minimal reflectivity. Through the adjustment of design parameterssuch as unit cell size and composition, absorber thickness, and substrate properties, it becomes feasible to curtail reflectivity while upholding a heightened level of absorption efficacy [8].

1.5.6 Absorption

The term "metamaterial absorber absorption" pertains to the capacity of a metamaterial structure to effectively capture electromagnetic radiation within a specified frequency band. Metamaterial absorbers are crafted using synthetic materials with electromagnetic properties not inherent in traditional materials. Their objective is to achieve heightened absorption efficiency within a restricted frequency range. Various design elements, including unit cell size and composition, absorber width, and substrate characteristics, determine how efficiently a metamaterial absorber can absorb electromagnetic emission. Modifying these elements enables the development of selective metamaterial absorbers, targeting specific frequencies, or absorbers with elevated absorption efficacy across a broad spectrum of frequencies.

Experimental assessment of the absorption efficiency of a metamaterial absorber can be carried out through techniques such as assessing reflectance and transmittance, offering insights into the absorber's absorption performance. The absorption coefficient, usually represented numerically, gauges the fraction of incoming electromagnetic radiation captured by the absorber. Metamaterial absorbers play a role in various fields like sensing, imaging, and energy harvesting, where effective absorption of electromagnetic radiation within a defined frequency spectrum is paramount [9].

1.5.7 Relative Permittivity (ε_r)

Permittivity is a property inherent to materials that quantifies their resistance to the establishment of an electric field. Symbolized by the Greek letter ϵ, it denotes the quantity of charges required to generate one unit of electric flux within a specific medium. This property is crucial in understanding and characterizing the interaction of materials with electric fields.

The minimum attainable permittivity is observed in a vacuum, commonly known as the Permittivity of Free Space or the electric constant, denoted as ε_0, with a value of 8.85 x 10^-12 Farad/meter. Even in dielectric materials, the resistance to the establishment of electric field lines is evident. Conversely, relative permittivity signifies the proportion of a dielectric's absolute permittivity to the electric constant, reflecting its permittivity relative to that of a vacuum [10].

It is a unitless measure and is expressed as:

$$\text{Permittivity} = \frac{Displacement\ of\ Electric}{Intensity\ of\ Electric\ field} \text{------------------------------}(1.1)$$

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o} \text{ --(1.2)}$$

where

ϵ_0 is the permittivity of free space.

ϵ_r represents the dielectric constant.

Ɛ denotes the intrinsic permittivity of that substance.

1.5.8 Permeability (µ)

Permeability is the quality of a substance that allows the formation of magnetic lines of force or a magnetic field. It defines the material's capacity to be magnetized in response to an external magnetic field. Put more plainly, magnetic permeability can be described as "how much a substance allows magnetic field lines to penetrate" or "a material's capacity to guide magnetic field lines." It is typically represented by the Greek symbol µ.

$$\text{Permeability} = \frac{\mathit{Magnetic\ induction\ of\ Magnituide}\ (B)}{\text{Strength of the magnetic field}(H)} \text{ ----------------------------(1.3)}$$

$$\mu = \frac{B}{H} \text{ ---(1.4)}$$

To categorize its magnetization characteristics, a material is classified based on its magnetic permeability. When the material's magnetic permeability is lower than µ0, it is categorized as diamagnetic. Conversely, if the material's magnetic permeability surpasses µ0, it is classified as paramagnetic [10].

1.5.9 Refractive Index

The refractive index, also known as the refraction index or index of refraction, is the ratio between the speed of light in a vacuum and the speed of light in a specific medium. The characteristics of a medium dictate the velocity of light within it. The velocity of electromagnetic waves depends on the optical density of the medium, which indicates the propensity of its components to release absorbed electromagnetic energy. A substance with higher optical density will cause light to travel more slowly. The refractive index serves as an indicator of a medium's optical density.The refractive index is a dimensionless quantity, representing how much slower light travels in the medium compared to a vacuum [11]. Represented as 'n,' it signifies the ratio of the speed of lightin a vacuum to the speed of light in the specific intermediate.

The equation for the refractive index is as follows:

$$n = \frac{c}{v} \quad \text{---(1.5.)}$$

Here,

'n' represents the refractive index.

'c' denotes the speed of light in a vacuum (3 × 10^8 m/s),

'v' stands for the speed of light in a material.

1.6 Satellite communication

Satellite communication refers to the transmission of information, data, or signals between two or more locations via communication satellites in Earth's orbit. This technology allows for long-distance communication and is commonly used for various purposes, including television broadcasting, internet connectivity, telephone calls, and data transfer.

Satellite communication systems typically involve ground stations, uplink facilities, satellites in space, and downlink stations. Ground stations transmit data to satellites, which then relay the information to another location on Earth or other satellites for further distribution. This technology is particularly useful for connecting remote or geographically isolated areas and is widely used in global telecommunications, broadcasting, military and defense applications, navigation systems, and more.

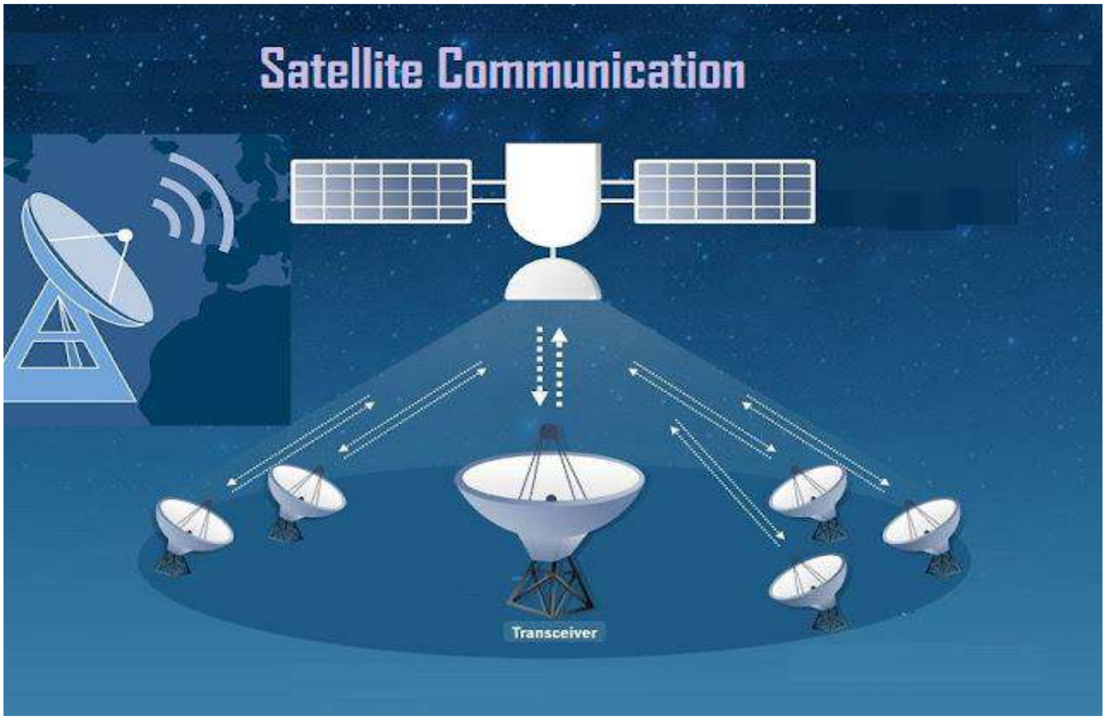


Figure1.3: Satellite communication [12]

1.7 Satellite Frequency Range

The application of satellite technology is continually expanding, driven by swift progress in the field. Satellites perform diverse functions beyond radio communications, spanning applications in astronomy, weather forecasting, broadcasting, cartography, and numerous other domains.

1.7.1 L-band range (1–2 GHz):

L-band refers to the frequency range between 1 and 2 gigahertz (GHz). This spectrum is commonly utilized in satellite communication, mobile networks, and various wireless applications. Its characteristics make it suitable for balancing a trade-off between signal propagation and data transmission.

1.7.2 S-band range (2–4 GHz):

The S-band encompasses frequencies between 2 and 4 gigahertz (GHz). This frequency range is widely employed in radar systems, weather monitoring, and satellite communication. S-band signals offer advantages in terms of atmospheric absorption and penetration, making it suitable for long-range radar applications. Additionally, it finds use in mobile communication and aviation systems. The allocation of S-band frequencies is regulated by international telecommunications organizations.

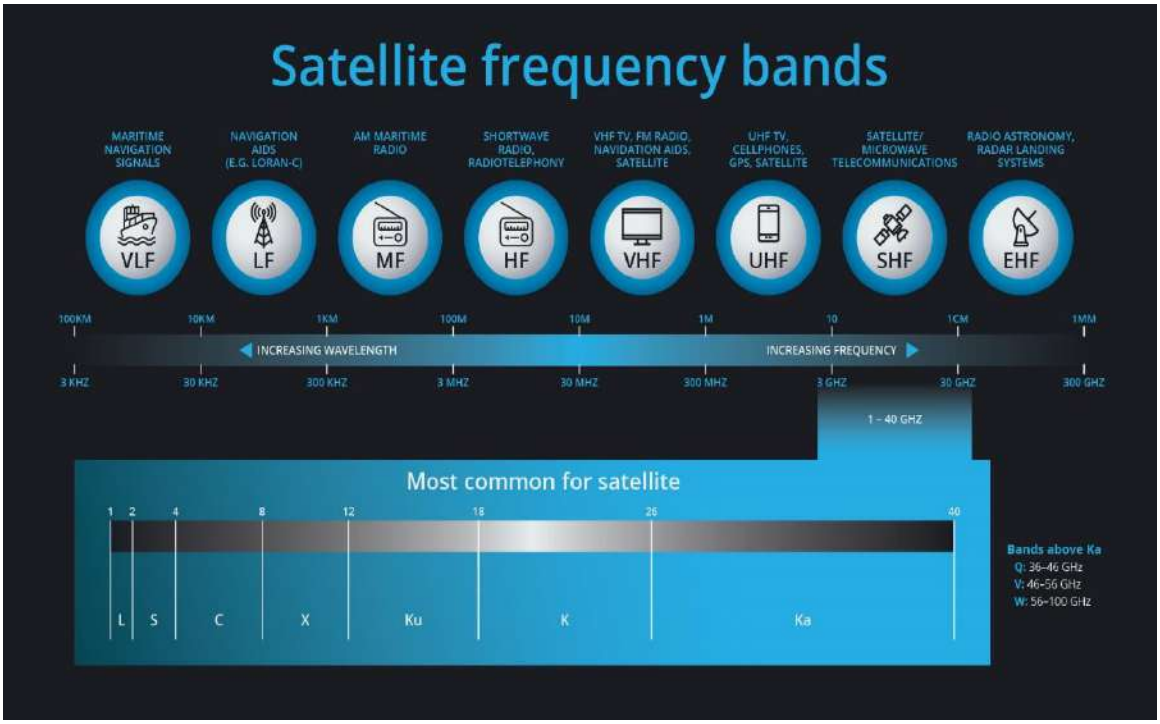


Figure 1.4: Satellite Frequency Bands [13]

1.7.3 C-band range (4–8 GHz):

C-band ranges from 4 to 8 gigahertz (GHz) and is commonly utilized for satellite communication, broadcasting, and radar systems. Its frequencies offer a balanced compromise between atmospheric absorption and data transmission efficiency. C-band is known for its resilience to rain fade, making it suitable for reliable communication in adverse weather conditions. This spectrum is regulated by international telecommunications agreements, and its widespread use contributes to global connectivity through satellite links. The C-band is vital for various applications, including television broadcasting, telecommunication networks, and weather monitoring.

1.7.4 X-band range (8–12 GHz):

X-band spans from 8 to 12 gigahertz (GHz) and is widely employed in radar systems, satellite communication, and military applications. The higher frequencies in the X-band offer advantages such as finer resolution in radar imaging and reduced atmospheric interference. Its use in defense applications includes communication, surveillance, and missile guidance.

1.7.5 Ku-band range (12–18 GHz):

The Ku-band ranges from 12 to 18 gigahertz (GHz) and is extensively used in satellite communication, broadcasting, and broadband services. Its higher frequencies allow for greater data transmission rates, making it suitable for high-speed internet via satellite. Ku-band is favored for its ability to support smaller antennas, enhancing its applicability in consumer satellite services. It is susceptible to rain fade, but technological advancements mitigate these challenges. The Ku-band is regulated internationally to ensure efficient and equitable use across various communication services, including television broadcasting and broadband internet [14].

1.8 Wireless Local Area Network (WLAN)

A Wireless Local Area Network (WLAN) is a technology that allows devices to connect to a local area network (LAN) without the need for physical wired connections. WLANs use wireless communication protocols, such as Wi-Fi, to establish connections between devices, such as computers, smartphones, tablets, and other wireless-enabled devices, within a limited geographic area, typically within a home, office, or public space. WLANs typically cover a limited geographic area, often within a single building or a specific area. They are designed for local use and are not meant to provide wide-area coverage. Wi-Fi, short for Wireless Fidelity, is the most common technology used for WLANs. It operates on various frequency bands, such as 2.4 GHz and 5 GHz, and allows devices to connect to the network via access points or routers.WLANs offer ease of use and mobility, allowing users to move around within the network's coverage area without losing their connection. WLANs include security features, such as encryption and authentication protocols, to protect data transmission from unauthorized access. WLANs are commonly used for internet access, file sharing, and network connectivity within homes, offices, airports, cafes, and other public places. High-performing network access, security, and resiliency for the campus and branch across WLAN, LAN, and SD-WAN.Use BLE-enabled Aruba Tags with our enterprise wireless LAN to enhance mobile engagement through media-rich apps, indoor wayfinding, asset tracking, as well as granular analytics.

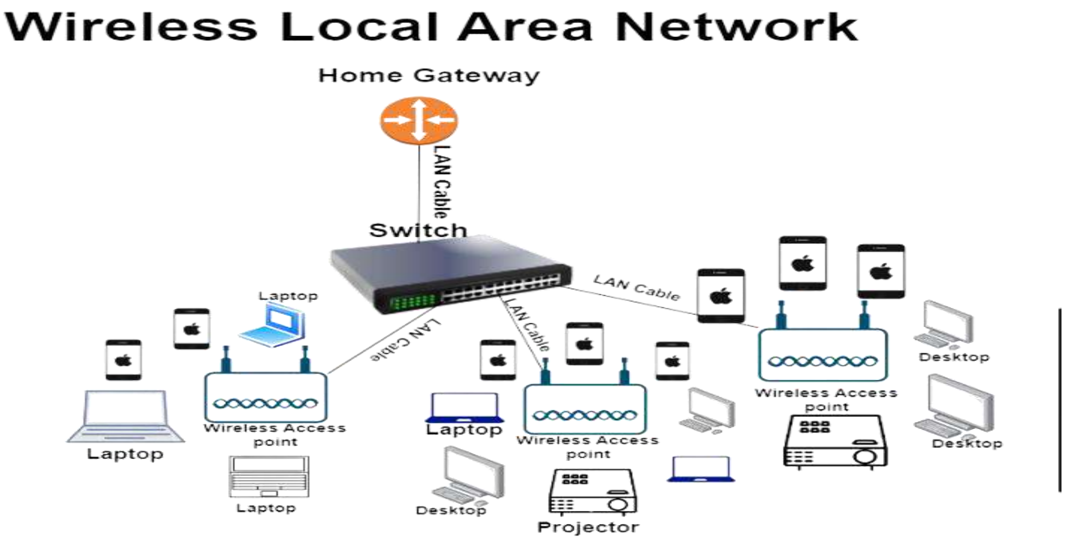


Figure 1.5: Wireless Local Area Network [15]

1.9 Weather Radar Systems

Weather radar systems are sophisticated instruments designed to detect, monitor, and analyze weather conditions, particularly the presence and movement of precipitation. These systems play a

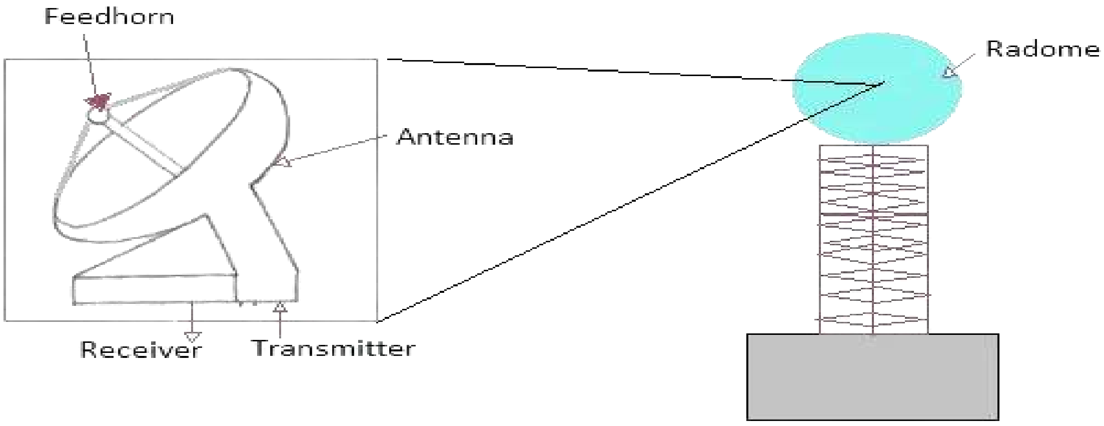


Figure 1.6: Weather Radar Systems [16]

pivotal role in meteorology and provide critical data for weather forecasting, early warning systems, and research.Weather radar systems are a fundamental component of modern meteorology, enabling meteorologists to monitor and forecast weather conditions, issue warnings, and research to better understand the Earth's atmosphere. These systems are vital for public safety and disaster management.

1.10 Radio Astronomy

"Radio Astronomy" by John D. Kraus, originally published in 1966 and last updated in 1986, remains highly relevant today. While some terminology has evolved since its publication, the book provides fundamental physics and electromagnetics concepts that have not changed. The book covers a wide range of topics in radio astronomy, including solar system radio sources, celestial radio sources, radio wave polarization, wave propagation, radio-telescope antennas, and receivers. It also discusses spectra, the Milky Way galaxy, pulsars, extragalactic radio astronomy, radio surveys, and the search for extraterrestrial intelligence (SETI). The book is praised for its practicality, with a focus on real-world applications and practical examples. It contains numerous illustrations, equations, and problems, making it a valuable resource for both amateur and professional radio astronomers. Kraus's accessible writing style and detailed coverage of various aspects of radio astronomy make this book a classic in the field, deserving of the titles "classic text" and "bible of radio astronomy." While some of the technology and surveys mentioned have evolved, the foundational knowledge they provide is still invaluable. The book's extensive content is well-organized and contains 12 chapters and seven appendices, making it a comprehensive resource for anyone interested in radio astronomy. The Cygnus-Quasar edition of the book provides additional utility with its spiral binding and inclusion of a solutions manual. Despite being over 30 years old, "Radio Astronomy" continues to be a valuable reference for those with a basic understanding of integral calculus [17].

1.11 Automotive Radar Systems

Future challenges for automotive radars are driven by two significant trends. The first trend involves the integration of complex safety functions into small, high-volume car platforms. This has been demonstrated with the introduction of radar-based systems like Collision Prevention Assist® in the new Mercedes Benz B-Class, marking the first successful series implementation. The second trend is the application of driver assistance and active safety systems in diverse environments, including rural and urban inner-city scenarios. Radar technology is the preferred choice for these systems across various automotive brands, primarily due to its ability to perceive objects beyond human vision. Radars operate effectively during day and night, in various weather conditions, and dynamic situations. However, these evolving market trends present four key development challenges for future radar developers. First, ensuring worldwide interoperability is crucial. Second, addressing worldwide frequency regulation is necessary to guarantee high availability. Additionally, a "world sensor" approach allows leveraging economies of scale to reduce costs. The third challenge is enabling radar systems with imaging capabilities to handle urban scenarios and complex system responses. Achieving this involves providing imaging features to radars and employing new signal processing techniques, particularly in the context of 360° multi-radar setups within a single vehicle.

Finally, for smaller car platforms, there's a need for radar sensors with improved standalone performance to maintain cost-effectiveness while meeting safety requirements. Consequently, the design and functionality of these sensors must surpass those of current Adaptive Cruise Control (ACC) or Blind Spot Monitoring (BSM) radar systems.

In summary, this article highlights the primary challenges facing future automotive radar technology and offers potential solutions and strategies to address these challenges [18].

Chapter 2

Literature Review

2.1 Introduction

Metamaterials, artificial structures with unique electromagnetic properties, have garnered substantial interest in recent literature. This review explores their applications in various fields, including optics, telecommunications, and sensing. Investigations delve into the design, fabrication, and performance optimization of metamaterials for tailored electromagnetic responses. The evolving research landscape continues to unveil innovative uses and advancements in this fascinating field.

In this section, an examination is conducted on the development of metamaterials (MM) and metamaterial-based devices (MMA), encompassing core aspects such as definition, criteria, merits, and usage. The crucial elements in the design of metamaterial-based devices, including the reciprocal values of unit cell periodicity, refractive index, permeability or permittivity, transmission and reflection coefficients, as well as absorption capabilities, are extensively addressed in this section.

2.2 Categorization of Metamaterials

Metamaterials can be classified into two principal clusters based on their mathematical representations. The initial group includes structures identified as Double Negative (DNG) and Single Negative (SNG), while the second group encompasses structures known as Photonic Band Gap (PBG) or materials exhibiting photonic bandgaps, interchangeably.

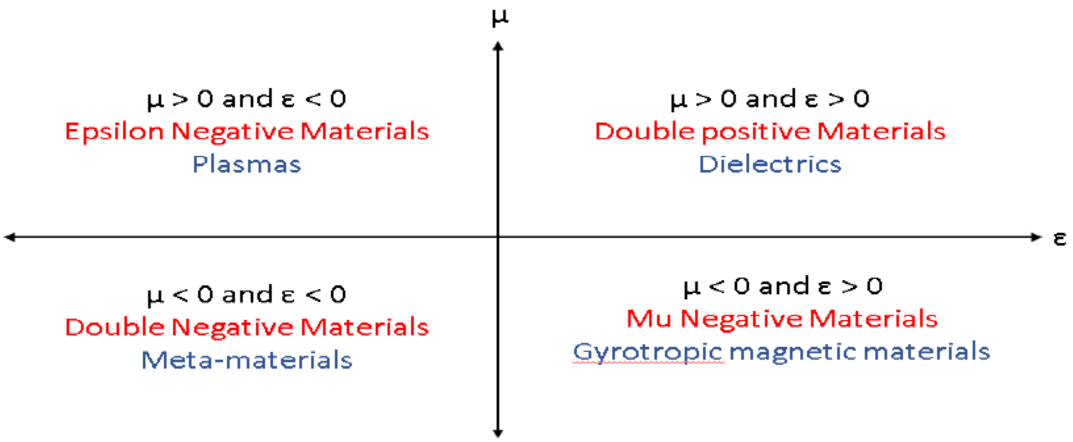


Figure 2.1: Categorization of materials based on their permittivity and permeability characteristics. [19]

The initial category is labeled as "double positive" (DPS) substances due to their possession of both ε and μ values greater than zero. Most items within this category are predominantly dielectrics. In the second classification, the permittivity is below zero while the permeability remains above zero, leading to its designation as an epsilon negative (ENG) material. This characteristic is often observed in numerous plasmas at specific frequencies. Materials falling into the third group exhibit a permittivity greater than zero but a permeability less than zero, defining them as mu-negative (MNG) materials, known for their gyro-tropic magnetic properties. The fourth group comprises double negative (DNG) materials, which can only be artificially created.This category of material exhibits both negative (below zero) permittivity and negative (below zero) permeability. When an electromagnetic wave enters such materials, it undergoes alterations in its propagation characteristics. It's important to note that in nature, there are no materials with both negative permittivity and negative permeability. From the previously mentioned list, we can deduce that metamaterials represent a distinct class of materials deliberately engineered to possess negative permittivity and negative permeability [20]-[24]. However, with the ongoing development of structures with unique properties and applications, a more comprehensive definition has emerged for categorizing characterize as metamaterials. A metamaterial is a deliberately engineered, macroscopic composite featuring a periodic cellular arrangement intended to intricately interact with electromagnetic waves, thereby accomplishing distinct performance goals unattainable with naturally existing materials [25,26].

2.3 Microwave Metamaterial Configuration

A Microwave Metamaterial Configuration refers to an artificially engineered structure designed at the microscopic level to manipulate and control electromagnetic waves at microwave frequencies. This specialized configuration typically exhibits unique electromagnetic properties not found in naturally occurring materials. The metamaterial's composition and arrangement enable it to interact with microwaves in unconventional ways, leading to applications in areas such as communication, imaging, and sensing.

By exploiting the precise design of its constituent elements, the configuration achieves tailored responses, including negative refraction and effective permeability. These properties contribute to enhancing the performance of microwave devices and systems. The development of Microwave Metamaterial Configurations represents a significant advancement in materials science, offering opportunities for creating innovative technologies with improved capabilities in the microwave frequency range. Researchers continue to explore and refine these configurations for various practical applications in the field of electromagnetic engineering.

2.3.1 Categorization System

Metamaterials can be divided into two principal categories based on their mathematical representation. The initial category consists of structures characterized as Double Negative (DNG) and Single Negative (SNG), while the second category encompasses structures known as Photonic Band Gap (PBG) or materials recognized as photonic crystals. As previously stated, the internal inclusions within Double Negative (DNG) and Single Negative (SNG) materials are notably smaller than the operational wavelength, resulting in their overall uniformity and characterization using the notion of an effective medium. In contrast, the elements composing Photonic Band Gap (PBG) structures are positioned at around half the wavelength or beyond. Therefore, materials known as photonic crystals should not be considered uniform mediums. They are commonly identified by Bragg reflection, a phenomenon that has a limited impact on Double Negative (DNG) and Single Negative (SNG) structures, requiring the application of distinct methodologies for periodic media.

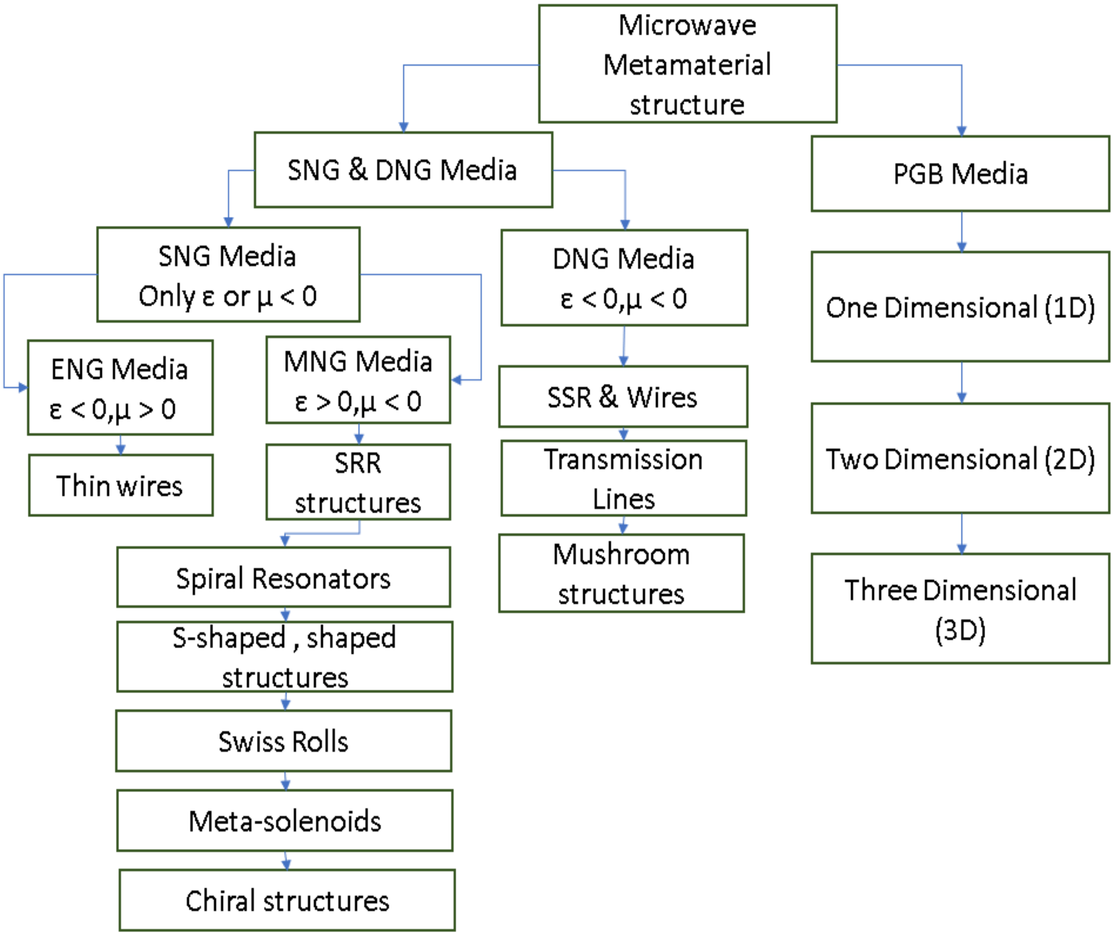


Figure 2.2: Categorization of Microwave Metamaterial Structures [27]

After a comprehensive review of scholarly articles and specialized literature highlighting essential metamaterial strategies for microwave applications, a classification framework depicted in this Figure has been formulated [27].

2.4 Negative Epsilon Metamaterials

Epsilon-negative (ENG) metamaterials are a specific class of artificial materials designed to exhibit a negative permittivity (ε) at certain frequencies. In these materials, the electric polarizability is inverted, causing an opposite response to an applied electric field compared to natural materials. This unique property allows ENG metamaterials to interact with electromagnetic waves in unconventional ways, leading to phenomena like negative refraction [28]. The negative permittivity is typically achieved through the arrangement of subwavelength structures, creating a composite material with tailored electromagnetic properties. The apparent permittivity can be articulated as:

$$\mathcal{E}_p = 1 - \omega^2\text{p}/\omega^2 \text{ ---(2.1)}$$

In the given formula, ωp denotes the plasma frequency, and ω signifies the frequency of the propagated electromagnetic wave. As per this equation, the effective permittivity turns negative when the frequency falls below the plasma frequency. At the plasma frequency, the effective permittivity becomes zero, leading to a refractive index of zero [29].

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

2.5 Negative Mu Metamaterials

Mu-negative (MNG) metamaterials are artificially created materials designed to exhibit a negative permeability (μμ) at specific frequencies. In these materials, the magnetic response is inverted, leading to unique interactions with electromagnetic waves. This characteristic is expressed as μ(ω)<0μ(ω)<0, where ωω is the frequency of the electromagnetic wave.

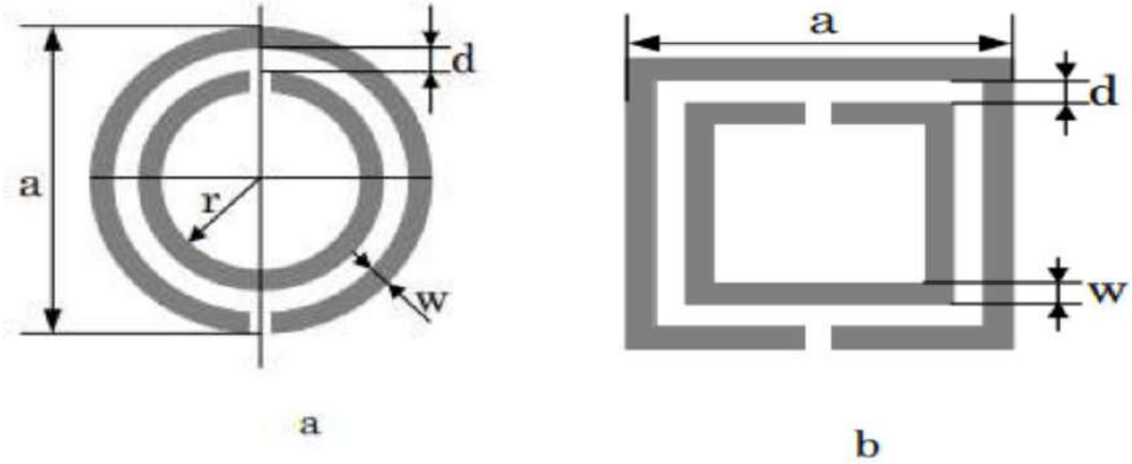


Figure 2.3: The initial unit cells of the mu-negative (MNG) material: a) circular, b) square

MNG metamaterials achieve this negative permeability through the arrangement of subwavelength structures. This property allows for unconventional electromagnetic behavior, such as negative refraction and backward-wave propagation. MNG metamaterials are often used in combination with epsilon-negative (ENG) materials to create double-negative (DNG) metamaterials, enabling even more sophisticated control over electromagnetic waves. Applications include antennas, imaging devices, and other microwave engineering technologies [27].

2.6 Metamaterial Absorbers

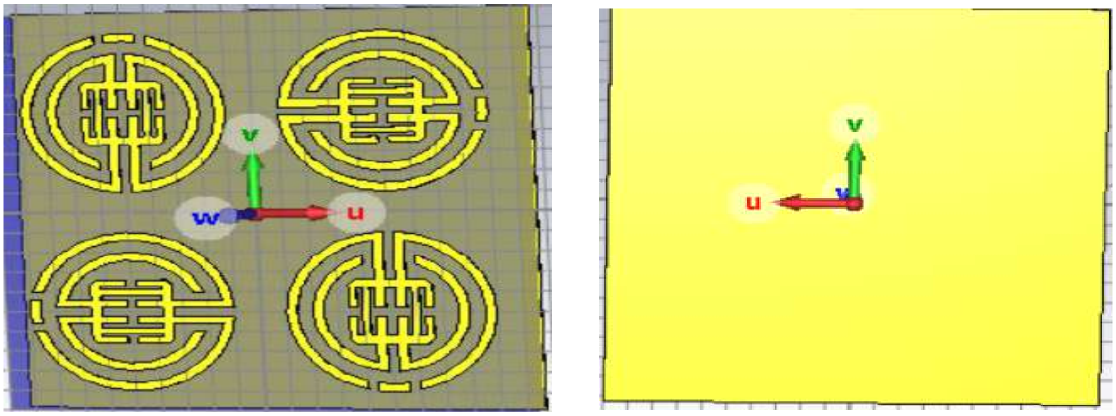
Metamaterials are intentionally crafted structures with properties not naturally occurring, allowing them to manipulate electromagnetic (EM) waves [30]. Typically, these materials consist of a dielectric substrate with metallic layers on one or both sides, featuring diverse patterns involving strips and capacitive gaps. Metamaterials can manifest negative values for permittivity, permeability, and refractive index, impacting the EM wave propagation within the dielectric medium of devices like antennas, radar systems, or microwave sensors. The designed metallic layers on the dielectric substrate profoundly influence the overall permittivity and permeability, resulting in these synthetic metamaterial characteristics. Depending on whether they demonstrate a single negative (SNG) or double negative (DNG) value for permittivity and permeability in the dielectric substrate under EM wave influence, metamaterials are categorized as such [31].

Typically composed of thin layers of conductive and dielectric materials, it exploits resonance effects to capture and convert incident radiation into heat. This selective absorption makes it valuable in applications such as stealth technology, energy harvesting, and sensor devices. Metamaterial absorbers are customizable to target desired frequency bands, offering versatility in electromagnetic wave absorption. Their design enables them to achieve superior absorption performance compared to conventional absorbers, contributing to advancements in various technological fields.

2.6.1 Configuration of Metamaterial Absorber

A metamaterial absorber is a type of material designed to absorb electromagnetic waves at specific frequencies. It is composed of artificial structures, often engineered at the nanoscale, to achieve unique electromagnetic properties. The configuration of a metamaterial absorber depends on the desired absorption characteristics, including the frequency range, bandwidth, and efficiency. A schematic representation of an MMA is depicted in Figure 2.4.

MMA is designed to allow electromagnetic (EM) waves to pass through it from any direction, with the intent of effectively absorbing these EM waves at its specific resonance frequencies. Its structure incorporates unit cells tailored to resonate at the target frequency, optimizing absorption efficiency.



Patch View

Ground View

Figure 2.4: Visual Representation of Metamaterial Absorber Structure

2.6.2 Characteristics of Metamaterial Absorber

The overarching formula assesses metamaterial absorbers concerning electromagnetic wave absorption.

$$A = 1 -|s11^2| -|s21^2| \quad \text{---}(2.3)$$

The reflection coefficient represents the proportion of the incident wave that gets reflected, while the transmission coefficient signifies the fraction of the incident wave that is transmitted. We use $|s11|^2$ to indicate the reflection coefficient and $|s21|^2$ to represent the transmission coefficient. The concept of metamaterial absorbers can be comprehended by observing the illustration.

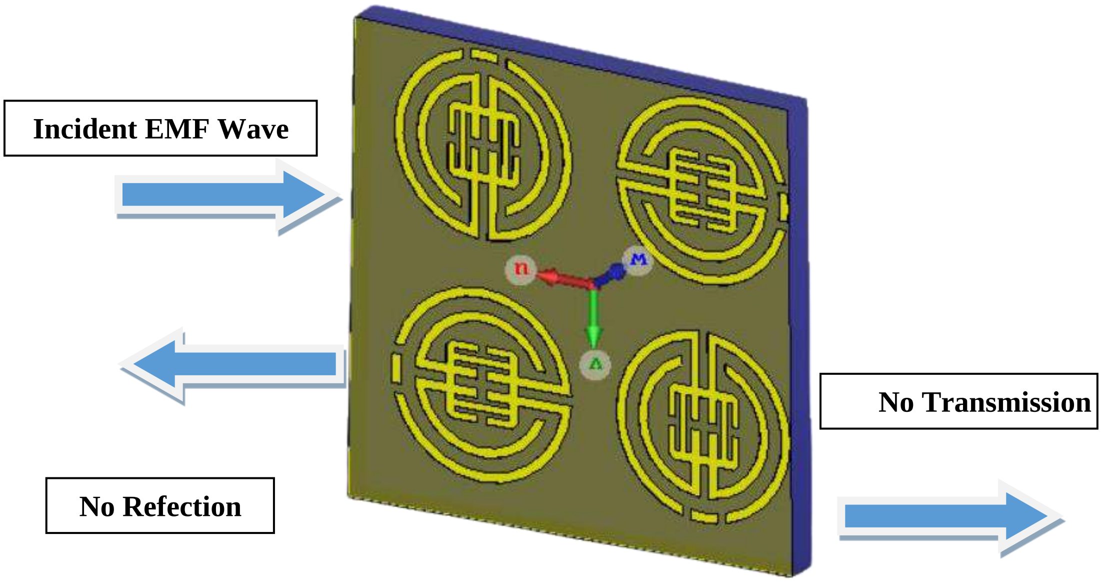


Figure 2.5: Absorption through a Metamaterial Absorber

Usually, a set of waveguide ports is utilized on both ends of the Microwave Measurement Device (MMA) to analyze its S parameters. The evaluation of the scattering (S) parameters (s21 and S11) can be explained in the following manner:

$$S_{11} = \frac{Reflected\ power\ wave\ at\ port\ 1}{Incident\ power\ wave\ at\ port\ 1} \qquad \text{---(2.4)}$$

$$S_{21} = \frac{Transmitted\ power\ wave\ at\ port\ 2}{Incident\ power\ wave\ at\ port\ 1} \qquad \text{---------------------------------------(2.5)}$$

The S parameters can be expressed concerning the electric field, as described by Liu et al. in 2012. The electric field computed at the port is a combination of the excitation and the reflected field.

Metamaterial absorbers exhibit specialized structures known as unit cells. These unit cells are designed to resonate at specific frequencies. The arrangement and dimensions of unit cells determine absorption characteristics. Metamaterial absorbers can be configured for various applications and frequency ranges. Precision fabrication techniques, such as lithography, areemployed to create nanostructures for optimal performance [32].

2.6.3 Single Negative Metamaterial Absorbers

A Single Negative (SNG) Metamaterial Absorber is a specialized type of metamaterial with distinct electromagnetic characteristics. It belongs to the category of metamaterials characterized by negative permittivity and negative permeability, exhibiting unique responses to incident electromagnetic waves. The negative values of both properties allow for simultaneous negative refraction, making SNG metamaterials valuable in applications like lensing and cloaking devices. The design of SNG metamaterial absorbers typically involves periodic unit cells that exploit resonant interactions to absorb specific frequencies effectively. This resonant behavior arises from the combination of electric and magnetic resonances within the unit cells. SNG metamaterial absorbers can be engineered to operate in specific frequency bands, providing a level of tunability and customization. Applications of SNG metamaterial absorbers span various fields, including telecommunications, medical imaging, and radar technology. The unique properties of SNG metamaterials contribute to advancements in electromagnetic wave manipulation and hold promise for future innovations in communication and sensing technologies.

2.6.4 Metamaterial Absorber with Near Zero Index

Metamaterials exhibiting either zero permittivity, zero permeability, or both at a specific frequency are denoted as zero-index metamaterials (ZIM). In such materials, electromagnetic waves demonstrate quasi-infinite phase velocity and infinite wavelength, resulting in an almost negligible refractive index. This distinctive attribute causes nearly uniform phase distribution as the dipoles within these metamaterials oscillate perfectly in sync. Consequently, zero-index media facilitate the propagation of highly directional waves with minimal phase shifts [33]. Zero-index metamaterials possess the potential to reduce the width of far-field antenna patterns, yielding a radiation field characterized by consistent phase, leading to an exceptionally focused and tightly collimated outgoing beam over an extended planar surface, as referenced in [34]. Additionally, ZIM can augment the directivity of microstrip patch antennas by effectively managing the emission direction, as detailed in [35]. The zero-index metamaterial category encompasses epsilon near zero (ENZ) and Mu near-zero (MNZ) metamaterials, where metamaterials with nearly zero real permittivity are termed epsilon-near-zero (ENZ) metamaterials.

Likewise, metamaterials featuring a real permeability value that approaches zero are identified as Mu near-zero (MNZ) metamaterials. These materials have potential uses in spatial filtering [36], enhancing radiation directivity [37], and enabling the efficient coupling and concentration of electromagnetic energy [38]. Leveraging their rapid wave propagation traits and intrinsic negative polarizability, ENZ metamaterials can be applied in transparency and cloaking applications [39].

2.7 Metamaterial Absorber with Frequency-Specific Targeting

A Frequency Targeted Metamaterial Absorber is a specialized absorber designed to selectively absorb electromagnetic waves at specific frequencies. Its structure incorporates unit cells tailored to resonate at the target frequency, optimizing absorption efficiency. By manipulating these factors, the absorber can be engineered to respond to a narrow or broad range of frequencies based on application requirements. This type of metamaterial is crucial in applications where precise control over electromagnetic interference or energy absorption is essential, such as in communication devices, sensors, and stealth technology. The Frequency Targeted Metamaterial Absorber plays a significant role in tailoring the absorption characteristics to match specific frequencies, providing a versatile solution for various technological applications. Researchers continually explore novel designs and fabrication techniques to enhance the performance and versatility of these absorbers for practical use in different frequency-dependent scenarios. This technology plays a crucial role in advancing the efficiency and functionality of devices that rely on controlled absorption or manipulation of electromagnetic waves in targeted frequency bands.

TABLE I. OVERVIEW OF DISCOVERIES IN EXISTING FREQUENCY TARGETED ABSORBERS

Ref.	**Design of unit cell (mm)**	**Resonant Frequencies (GHz)**	**Thickness and Substrate (mm)**	**Polarization Insensitivity**	**Applications**	**Observations**
[40]	34	2.4 5	FR4 (3.2)	Not mentioned	Wi-fi absorption	Relatively extensive size, a substrate with multiple layers lacking metamaterial characteristics.
[41]	40 (0.29 λ)	2.2-5.85	ITO-PET (11 mm)	90°	Wi-fi absorption	Multi-layered transparent substrate for wide absorption and no MM properties
[42]	18 (0.14 λ)	2.4 & 5.1	Rogers RO 3003 (1.75 mm)	90°	Crowd estimation in Wi-Fi area	Multi-layered substrate and lumped element in patch for RF energy harvesting, no MM properties
[43]	14	1.246, 3.794& 4.858	FR4 (1.6 mm)	45°	SAR reduction	Not perfect absorption and MM properties

						at undefined 5G frequencies
[44]	24	3.65, 7 & 11.07	FR4 (6.8 mm)	45°	RCS reduction	Multiple frequencies-targeted MMA with the lumped element in the patch and thick substrate.
[45]	9	7,16 & 22	F4B (3 mm)	75°	RCS reduction	Multiple frequency targeted absorbers with no specific practical applications

2.8 Assessment of the Effectiveness of Metamaterial Absorber

Evaluating the performance of metamaterial absorbers involves assessing key factors such as absorption efficiency, frequency response, bandwidth, polarization sensitivity, and angle of incidence. The absorber's ability to dissipate electromagnetic waves efficiently and its response to various frequencies and polarizations are crucial metrics. Additionally, evaluating bandwidth helps determine the absorber's versatility across different frequency ranges. Examining its stability, tunability, and fabrication consistency are equally important, ensuring structural integrity over time, adaptability for specific applications, and reliable mass production. Thickness optimization is a consideration, striking a balance between absorption efficiency and practicality. A thorough performance evaluation provides insights into the absorber's effectiveness under real-world conditions and guides further refinement in design and implementation for specific applications.

2.9 Metamaterial Design Challenges and Prospects for Future Advancements

The previous sections have shown that while it's relatively straightforward to design metamaterial absorbers (MMA) for arbitrary resonance frequencies, it's rare to find MMAs tailored for specific practical applications based on frequency requirements. The era of designing MMAs arbitrarily is giving way to a more practical approach, where MMAs need to be developed for specific applications and target frequencies.Recent literature lacks examples of MMAs designed for actual applications or specifically for frequencies designated by organizations like IEEE. Furthermore, the number of frequency-selective perfect MMAs is also limited, and there is no established technique or formula available for designing MMAs tailored to particular frequencies or applications.MM properties have been serendipitously discovered in many proposed absorbers, making it challenging to tailor these properties to desired resonance frequencies. Because commercially accessible substrate materials are the main preference for designing metamaterial absorbers (MMAs), there is a requirement for an engineering approach or equation to craft MMAs with specific frequency objectives using these substrates accurately. Metamaterials, including MMAs, have emerged as promising technologies to enhance communication system performance. Therefore, engineering these metamaterials has become a timely requirement for this decade.

The challenge in metamaterial design lies in creating structures with tailored electromagnetic properties, often requiring intricate and precise engineering at the nanoscale. Achieving desired functionalities, such as negative refraction or absorption at specific frequencies, demands careful manipulation of material parameters and unit cell geometry. Future developments hinge on overcoming challenges related to fabrication techniques, scalability, and material constraints. Innovations in fabrication methods, like 3D printing or advanced lithography, are crucial for producing intricate metamaterial structures efficiently. Additionally, exploring new materials with unique electromagnetic properties is a key avenue for advancement. Addressing these challenges will open doors to a wide range of applications, including improved communication technologies, advanced imaging systems, and enhanced energy harvesting devices, driving the evolution of metamaterials in various fields. The evolution of metamaterial absorber (MMA) design could result in absorbers with a single layer, devoid of lumped elements, customized for practical applications or specific frequencies. Crafting these absorbers requires an engineering method or formula that enables the manipulation of metamaterial properties at desired levels, similar to the design process for frequency-targeted antennas with specific values and properties to align with our needs and objectives. Researchers continually explore novel designs and fabrication techniques to enhance the performance and versatility of these absorbers for practical use in different frequency-dependent scenarios.

2.10 Review of Earlier Studies

This portion will assess the pertinent research efforts by other scholars concerning the Eye-Shaped Labyrinth Metamaterial Absorber in the context of applications such as wireless local area networks (WLAN), satellite communications, radio astronomy, weather radar, aerospace and radar systems, and automotive radar systems.

1. Triple band frequency tunable polarization-insensitive metamaterial absorber for WLAN and 5G applications.

This paper presents a triple-band metamaterial absorber (MMA) designed on an FR4 substrate to target WLAN and 5G frequencies. The resonating patch comprises three modified concentric copper rings with an overall unit cell size of 0.16λ0 × 0.16λ0 × 0.0128λ0, where λ0 represents wavelength at 2.4 GHz. The MMA demonstrates exceptional peak absorption at 2.4 GHz (99.3%), 3.5 GHz (95.68%), and 5.85 GHz (99.5%). The inclusion of adjustable metallic stubs on the innermost ring allows for tuning the peak absorption frequency within the range of 5.67 GHz to 5.98 GHz.An analysis of the MMA's absorption process is conducted by examining the distribution of surface current. The MMA exhibits insensitivity to incident angle and polarization over a wide range (up to 60°) for both TE and TM modes, with almost no polarization conversion. The resonance characteristics are validated through equivalent circuit modeling, using Advanced Design software (ADS), and the measured absorption closely matches the simulation results. Furthermore, the compact MMA design, along with its high effective medium ratio of 6.25, underscores its suitability for WLAN and 5G applications, particularly in microwave shielding and sensing, owing to its compact structure, insensitivity to incident and polarization angles, and nearly complete absorption at application-specific frequencies [46].

2. A wide-angle polarization-insensitive multi-band metamaterial absorber for L, C, S, and X band applications.

The MA design consists of two main components: an outer structure composed of a split circular ring and an inner structure resembling four fan blades. These metallic resonating components are situated on a dielectric substrate (FR-4) and are shielded by a complete ground plane. The structure exhibits an impressive total of thirteen distinct absorption peaks, each exceeding 80% absorption efficiency, within the desired frequency range. These peaks occur at frequencies of 1.50, 2.92, 3.88, 4.84, 5.50, 7.09, 7.65, 8.54, 8.81, 9.26, 9.90, 11.69, and 12.02 GHz, with corresponding absorption rates of 88.58%, 98.27%, 80.62%, 88.76%, 91.32%, 81.74%, 81.21%, 88.47%, 81.95%, 96.16%, 98.67%, 98.58%, and 96.26%, respectively. The metamaterial characteristics of the structure are confirmed by visualizing the real and imaginary parts of permittivity (ε), permeability (μ), and normalized impedance (Z). To provide insights into the absorption mechanism, current distribution patterns are depicted on both the front and back sides of the structure at independent frequencies within the L, C, S, and X band spectrums. The research also investigates the structure's polarization insensitivity under different angles of incidence, whether normal or oblique.

In a comparative analysis with previously documented multi-band absorbers, the proposed design stands out for its superior performance, offering a higher number of absorption peaks and encompassing a broader frequency range, including the L, C, S, and X bands simultaneously. This multi-band absorber holds significant potential for practical applications in various fields, such as the Internet of Things (IoT), biomedical sensing, energy harvesting, radar cross-section reduction, military applications, back lobe reduction for antennas, satellite communications, Wi-Fi devices, and more [47].

3. A compact wideband metamaterial absorber for Ku band applications.

This paper introduces a compact wideband metamaterial absorber (MA) designed for applications in the Ku band, which falls within the microwave frequency range of 12 to 18 GHz. The proposed MA is engineered to effectively absorb incident waves spanning from 11.39 to 20.15 GHz, providing a substantial bandwidth of 8.76 GHz that entirely encompasses the Ku band. This compact structure measures just 10 mm by 10 mm and is fabricated on an FR4 substrate. The simulation results were obtained using ANSYS HFSS 19.1. The absorption mechanism is elucidated through the calculation of effective electromagnetic (EM) parameters, and the current distribution is visualized to support the understanding of the absorption process. The structure's performance is also evaluated under various angles (ranging from 0 to 90 degrees) for both oblique and normal incident waves. To validate the effectiveness of the proposed MA, experiments were conducted within an Anechoic Chamber, and the results closely aligned with the simulated data, falling within acceptable tolerance limits. Finally, a comparative analysis is performed, contrasting the proposed MA with previously reported absorbers. The MA introduced in this paper holds potential for applications in satellite communication, radar surveillance, and other defense-related uses [48].

4. A Multiple-Bands Metamaterial Absorber Based on X, Ku, and K-Band.

Creating an efficient, multi-band metamaterial absorber is a current research priority. This paper introduces a multi-band metamaterial absorber designed to operate in the X, Ku, and K-bands. Initially, we designed two basic unit cells, one in the X-shape and the other in the cross-shape. These cells were then arranged in a multi-layer structure to achieve wideband absorption and multiple absorption bands. The proposed absorber functions effectively across multiple bands, featuring six peaks within the 8–24 GHz frequency range, all exhibiting near-perfect absorption. Notably, the sixth peak offers wideband absorption at 2.93 GHz. Furthermore, the absorber was tested for polarization insensitivity and oblique incidence, demonstrating polarization insensitivity with nearly perfect absorption [49].

5. Parallel LC-shaped metamaterial resonator for C and X band satellite applications with wider bandwidth.

The electromagnetic characteristics of dielectric materials combined with metal have opened up new possibilities for innovation in millimeter and sub-millimetre technology. In this research, we've introduced a metamaterial resonator shaped like a parallel LC circuit with a significantly broader bandwidth. We've achieved a negative refractive index for two distinct resonant frequencies, ranging from 5.1 to 6.3 GHz and 10.4 to 12.9 GHz, where the negative refractive index spans from 5.4 to 6.3 GHz and 10.5 to 13.5 GHz. When electromagnetic waves interact with the proposed structure, featuring a parallel LC-shaped metallic configuration, it exhibits an intriguing response with a wider bandwidth to external electric and magnetic fields. This paper primarily addresses the design of the conductive layer for the suggested configuration, which includes parallel metallic arms, aiming to analyze the mutual coupling effects in scattering responses. Notably, the sub-branch in the metallic design yields more resonant frequencies while maintaining a compact structure. The proposed structure is subjected to analysis involving various metallic arrangements and array structures under different boundary conditions [50].

6. Depiction and analysis of a modified theta-shaped double negative metamaterial for satellite application.

This paper primarily addresses the design of the conductive layer for the suggested configuration, which includes parallel metallic arms, aiming to analyze the mutual coupling effects in scattering responses.we have introduced a modified metamaterial structure with a compact, double-negative design in the shape of Theta, tailored for satellite communication applications. This structure combines two E-shaped resonators facing in opposite directions, connected by a significant Theta element to create a cohesive unit. We have used a low-profile dielectric substrate, specifically FR-4, to fashion the unit cell, which measures 9 × 9 mm². This unit cell exhibits a concise structure, and its resonator behavior is explored through both simulation and experimentation. The proposed metamaterial showcases a transmission coefficient at 13 GHz, offering a bandwidth of 500 MHz in the middle. We've also examined the correlation between the fundamental unit cell and array configurations, providing a comparison among 1 × 2, 2 × 2, and 4 × 4 array structures using 1 × 2, 2 × 2, and 4 × 4 unit-cell arrangements to validate the performance of the metamaterial. Resonating frequencies were analyzed using the Nicolson–Ross–Weir approach. The effective electromagnetic parameters derived from S-parameter simulations reveal that this metamaterial structure exhibits negative refraction bands. It displays negative permittivity within the frequency ranges of 2.60 to 5.16 GHz, 6.63 to 9.31 GHz, and 13.03 to 16.18 GHz, as well as negative permeability at 7.74 to 13.07 GHz and 13.88 to 16.55 GHz, respectively. Notably, it demonstrates double-negative characteristics in the X and Ku bands, spanning approximately 1.17 GHz (8.14 – 9.31 GHz) and

1.42 GHz (13.80 – 15.22 GHz), respectively. With its promising design and extensive double-negative attributes, this structure holds potential applications in satellite communication systems [51].

7. Dual stop band frequency selective surface for C and WLAN band applications.

This paper introduces a miniaturized unit cell design for a Frequency Selective Surface (FSS) aimed at creating stop band characteristics for two distinct frequency bands. The unit cell structure presented in this study demonstrates effective band filtering features tailored for two specific frequency bands: the C-band, commonly used in satellite communication, and the Wireless Local Area Network (WLAN) band. The FSS structure is composed of metallic strips shaped as "I" and "modified I." Each of these individual unit cells is scrutinized for its band filtering capabilities, and eventually, they are combined into a single unit cell to enable dual-band filtering functionality. The "I" shaped unit cell exhibits band filtering properties centered around 4 GHz, while the "modified I" shaped unit cell operates at a center frequency of 5.5 GHz. The designed FSS is modeled on an FR-4 substrate with a dielectric constant of 4.4, and the unit cell's dimensions are $10 \times 10 \times 1.6\ mm^3$. The fabricated FSS structure is subjected to simulation and measurement to verify its characteristics, including S11 and S21. The results show a satisfactory agreement between the simulated and measured data [52].

8. Broadband Wide angle Polarization insensitive Metamaterial Absorber for K band application.

This paper is centered on the creation and examination of a broadband metamaterial absorber optimized for the K band, offering strict polarization insensitivity and wide angular stability. The unit cell of this metamaterial absorber comprises a copper ladder-shaped structure symmetrically positioned on a metal-backed FR-4 substrate. Under normal incidence, the absorber showcases a notable absorption bandwidth of 7 GHz, spanning from 21.20 GHz to 28.20 GHz, which effectively covers the K band. The proposed structure exhibits an absorption capacity exceeding 91% for both TE and TM polarized waves. To comprehend the absorption mechanism of this design, electromagnetic field, and surface current distributions are visualized from both the top and bottom perspectives. The proposed structure is characterized by a four-fold symmetry and demonstrates polarization insensitivity across a range of angles (Φ) from 0° to 90° for TE and TM polarized waves. Additionally, the structure exhibits over 60% absorption when subjected to oblique incidence angles (θ) ranging from 0° to 90° for both TE and TM polarized waves. Notably, the absorber's thickness is $\lambda 0/8$, corresponding to the center frequency, making it compact and well suited for commercial applications such as radar cross-section reduction and energy harvesting within the K band [53].

9. S-shaped Metamaterial Absorber for K-band Applications.

This study entails the development of an S-shaped metamaterial absorber intended for applications in the K-band. The designed metamaterial is proficient at absorbing incident waves within the frequency ranges of 20.99 - 21.51 GHz and 24.2 - 25.02 GHz, achieving an absorption rate exceeding 86%. The proposed structure is compact, occupying a total area of 7 x 7 mm^2, and is constructed on an FR4 substrate. The design, simulation, and optimization processes are conducted using CST Microwave Studio software. The metamaterial boasts unique attributes, including its compact design, sub-wavelength characteristics, and super-resolution capabilities not typically found in conventional materials. These qualities position it as a promising candidate for K-band applications, particularly in the domains of satellite and radar communication systems [54].

10. Bandwidth Enhanced Nearly Perfect Metamaterial Absorber for K-Band Applications.

This paper introduces a highly efficient metamaterial absorber with enhanced bandwidth and polarization insensitivity. The fundamental unit cell of this design comprises outer split rings and inner asterisk-shaped resonators, which are printed on an FR4 dielectric substrate. The resulting metamaterial absorber exhibits a wide bandwidth of 2.01 GHz and exceptional absorptive capabilities, with peak absorption rates reaching 99.98% and 99.94% at 19.4 and 19.8 GHz, respectively. Simulation results confirm the absorber's polarization insensitivity, both for waves incident at oblique angles (25°) and normal angles (85°). Additionally, effective parameters are extracted, and the field distributions are thoroughly examined. This metamaterial absorber is especially well-suited for applications in the K-band, including radar and satellite communications, with potential applications in weather radar, imaging radar, and air traffic control systems [55].

11. Polarization Insensitive Symmetric Single-layer Metamaterial Absorber Using Lumped Resistors for Ku-band Applications.

This paper introduces a novel metamaterial absorber design tailored for Ku-band applications. The absorber comprises a 2.4 mm (0.117 λ) thick dielectric layer placed on a metal support, featuring copper microstructures with four resistors on its upper surface. A parametric study was conducted to optimize its performance for broadband operation under normal incidence. The findings reveal that this proposed structure achieves broadband absorption exceeding 80% in the Ku band, and it exhibits polarization insensitivity for both TE and TM polarizations. To comprehend the role of the resistors in the optimized design, the paper investigates the absorption characteristics with and without the lumped resistors. Moreover, the study delves into the electrical, magnetic field, and surface current distributions on the upper and lower sides of the absorber, shedding light on the various mechanisms behind its absorption capabilities. The research also examines how the structure achieves a near-ideal impedance match, aligning its input impedance with that of air, which contributes to broadband absorption. In a comparative analysis with other existing broadband absorbers in the literature, it is demonstrated that certain trade-offs must be considered in optimizing a metamaterial structure. Parameters influencing the optimization include losses due to resistors, the dielectric substrate (FR4), and the simplicity of manufacturing the proposed structure. This metamaterial absorber is well-suited for applications in radar and satellite communications, particularly in contexts such as weather radar, imaging radar, and air traffic control systems [56].

12. Left-handed compact multi-band circular metamaterial for S-, C- and Ku-band applications.

This study aims to introduce a multi-band circular metamaterial structure designed for use in S, C, and Ku-band applications. This research was motivated by the exploration of unique characteristics that metamaterials can offer. The proposed circular metamaterial was numerically simulated using the widely available Computer Simulation Technology (CST) software. The metamaterial design consists of four distinct circular rings placed on an FR-4 substrate measuring 8 × 8 mm^2 and 1.6 mm in thickness.

The simulation covers a frequency range from 2 to 18 GHz. The designed unit cell metamaterial exhibits resonance frequencies in multiple bands, specifically at 3.38 GHz (S-band), 6.28 GHz (C-band), and 12.76 and 16.92 GHz (Ku-band). The corresponding resonance frequencies demonstrate acceptable magnitude values, measuring at approximately -19.53 dB, -22.56 dB, -22.32 dB, and -19.79 dB, respectively. Furthermore, this circular metamaterial displays left-handed characteristics at all four resonance frequencies. In specific frequency ranges such as 3.42 to 3.80 GHz (S-band), 6.43 to 7.27 GHz (C-band), and 13.28 to 13.69 GHz (Ku-band), the metamaterial exhibits unique properties. As a result, this circular metamaterial, with its distinct attributes, has the potential for diverse applications in fields such as wireless headphones, wireless computer networks, satellite communications, and weather monitoring, among others [57].

13. Multiband polarization-insensitive cartwheel metamaterial absorber.

Metamaterials are custom-engineered materials designed to exhibit electromagnetic properties that are not naturally found in conventional materials. Multi-band metamaterial (MM) absorbers have gained significant attention in research due to their utility in applications like sensing, filtering, and stealth technology. These absorbers typically feature complex, multi-layered geometrical structures.

In this study, a single-layered cartwheel-shaped (CWS) metamaterial absorber, which is insensitive to polarization and operates in the microwave band, is introduced. The absorber exhibits four primary resonance peaks at frequencies of 13.64, 17.15, 18.4, and 19.23 GHz, all with absorptivity exceeding 0.9. It demonstrates robust angular stability, achieving multiple absorption peaks through various electric and magnetic resonances. Notably, its characteristics remain consistent under different polarization angles of incident waves, ranging from 0° to 75°.When examined under oblique incidence of both TE and TM modes, the absorber maintains absorption peaks with performance levels exceeding 80%. Furthermore, the absorption properties can be adjusted by altering the substrate thickness. Comparing the simulated results with the measured results reveals a strong agreement between the two. This absorber holds promise for applications in microwave devices, particularly in the realms of sensing and filtering [58].

14. Cross-coupled interlinked split ring resonator-based epsilon negative metamaterial with high effective medium ratio for multiband satellite and radar communications.

This paper introduces a metamaterial based on cross-coupled interlinked split ring resonators (CCI-SRRs). The metamaterial achieves an epsilon-negative (ENG) response with a highly effective medium ratio (EMR). The unit cell of this metamaterial comprises a square-shaped split ring resonator and two rectangular rings, with the rectangular rings situated inside the outer square split ring. Internal rings are interconnected using a cross-shaped metal segment, and these inner rings are further linked to the outer ring using metal strips. This interconnection increases the electrical length and modifies the inductance of the unit cell, resulting in multiple resonances that cover the C, X, and Ku bands. The CCI-SRR unit cell's symmetric nature is advantageous in minimizing noise and harmonics. It is designed on an FR4 substrate with a thickness of 1.6 mm. The overall dimensions of the unit cell are $0.124\lambda \times 0.124\lambda$, with λ being the wavelength calculated at the lower resonance frequency of 4.15 GHz. Three resonances are observed in $|S21|$ at frequencies of 4.15 GHz, 10.38 GHz, and 14.93 GHz through numerical simulations in CST Microwave Studio.

The paper explores the permittivity, permeability, refractive index, and impedance using the Newton-Ross-Weir (NRW) method. ENG behavior is observed within frequency ranges from 3.95 to 5.65 GHz, 9.57 to 11.46 GHz, and 13.68 to 16 GHz. Near-zero refractive index is achieved within frequency ranges of 4.16 to 5.75 GHz, 10.16 to 11.58 GHz, and 14.46 to 16 GHz. An LC equivalent circuit is designed, and component values are determined using Advanced Design

Software (ADS), confirming |S21| results obtained from CST. The study of the interaction between electromagnetic waves and the unit cell within a double-positive medium reveals the unit cell's evanescent wave properties. The unit cell's compact nature is verified by calculating an EMR value of 8.03. Electromagnetic coupling effects are examined for 2 × 2 arrays in various orientations. The |S21| performance of 2 × 2, 4 × 4, and 8 × 8 arrays aligns with the unit cell's behavior. Given its symmetric patterns, near-zero refractive index, negative permittivity, and high EMR, the proposed unit cell has the potential to enhance the performance of microwave devices designed for C, X, and Ku-bands, particularly in the context of satellite and radar communications [59].

15. An Optically Transparent Broadband Metamaterial Absorber for C-, X- and Ku- Bands.

In this study, an optically transparent broadband microwave absorber is developed using an indium-tin-oxide film and a polymethyl methacrylate (PMMA) substrate. The absorber demonstrates the ability to provide -10dB attenuation within the frequency range of 6.85-17.7 GHz and exhibits a wide-angle absorption characteristic for obliquely incident electromagnetic waves, regardless of whether they are polarized as transverse electric (TE) or transverse magnetic (TM).Importantly, this absorber is independent of polarization and achieves an absorptivity exceeding 90% for a portion of the C-band and the entire X- and Ku-bands, with a relative bandwidth of 88.4% [60].

16. Novel Metamaterial-Element-Based FSS for Airborne Radome Applications.

This paper introduces a novel metamaterial (MTM) element designed for radome applications, demonstrating negative permittivity and permeability characteristics at specific frequency ranges. The MTM element consists of Swastika-shaped conductors tightly printed on both sides of a dielectric substrate. The electromagnetic (EM) analysis of this structure is conducted using full-wave simulation software, and the results are validated through experiments.Furthermore, the MTM structure is enhanced by introducing shorting strips at its edges to improve its bandpass frequency selective surface (FSS) response, achieving flat-top and sharp roll-off characteristics in both microwave and millimeter-wave frequency ranges. To demonstrate its suitability for airborne radome applications, a multi-layered hemispherical radome is designed by embedding this structure in the mid-plane of the radome wall. The EM performance of the antenna-radome system is analyzed using a 3-D ray tracing geometrical optics approach, along with the aperture integration method, considering the transmission characteristics of the MTM-FSS-based radome wall using CST Microwave Studio. The MTM-FSS-based radome exhibits superior EM performance characteristics compared to a conventional optimized monolithic radome across the frequency range of 8.5-10.3 GHz. It achieves high transmission efficiency (~0.30) and minimal boresight error (~4 mrad) over the entire beam steering range [61].

17. Compact and Polarization Insensitive Satellite Band Perfect Metamaterial Absorber for Effective Electromagnetic Communication System.

This paper introduces a commercially viable triple-band metamaterial absorber configured with a metal-dielectric-metal structure. The absorber is composed of four compact symmetric circles with a swastika-shaped metal structure, connected by two split-ring resonators (SRRs). Copper with an electrical conductivity of 5.8 × 10^7 Sm^{-1} is used for the ground plate and the resonator portion of the top layer, while an FR-4 dielectric with a permittivity of 4.3 serves as the substrate. The structural parameters of the unit cell were determined through a trial and error method.

The proposed perfect metamaterial absorber (PMA) was characterized using FIT-based 3D simulation software, specifically CST Microwave Studio version 2019. The simulation revealed three resonance peaks at frequencies of 3.03, 5.83, and 7.23 GHz, each with high absorbance values of 99.84%, 99.03%, and 98.26%, respectively. The numerical results were validated using authentic verification methods. Subsequently, experimental measurements were performed using a microwave network analyzer (PNA) from Agilent N5227, which featured waveguide ports. The simulation and experimental results exhibited strong agreement.

The proposed PMA distinguishes itself with a unique design, compact dimensions, and superior absorption performance compared to other contemporary studies. This particular type of polarization-insensitive S- and C-band PMA is designed for telecommunications systems, including satellite communication and radar feeds [62].

18. Broadband and Wide-angle Microwave Metamaterial Absorber with Effective EM Wave Absorption in the S-, C-, X- and Ku-band.

This paper introduces a broadband microwave metamaterial absorber with wide-angle characteristics. The absorber offers effective absorption with over 90% absorptivity across a broad frequency range from 2.2 GHz to 18.4 GHz. This wide bandwidth spans nearly the entire spectrum of S-, C-, X-, and Ku-bands, resulting in a relative absorption bandwidth of 157%. The absorber's total thickness is 15 mm, equivalent to 0.11λ at the lowest operating frequency.To achieve effective wide-angle and broadband frequency matching, the unit cell design incorporates a wide-angle impedance matching layer. The proposed absorber maintains more than 80% absorptivity for TE polarization and over 90% absorptivity for TM polarization across the S-band to Ku-band, as long as the incident angle is less than 50°. The equivalent circuit method is employed to analyze the proposed absorber, and the circuit model analysis results exhibit strong agreement with numerical full-wave simulations [63].

19. Wideband metamaterial absorber for Ku and K band applications.

This paper introduces a highly compact and straightforward double square-shaped Meta-material Absorber (MA) design. Each square has dimensions of 1.41×1.41 mm², and the overall unit cell structure measures 5×5 mm². The absorber achieves a wideband of absorption spanning from 14.44 GHz to 27.87 GHz, encompassing a bandwidth of 13.43 GHz at -10 dB, which effectively covers the Ku (12 GHz–18 GHz) and K (18 GHz–27 GHz) bands. This design has practical applications in radar and satellite communications. The full-width half-maximum bandwidth achieved is 16.39 GHz, ranging from 13.61 GHz to 30.00 GHz. Three distinct absorption peaks are observed at 16.54, 20.54, and 25.81 GHz, with absorptivities of 99.89%, 99.95%, and 99.96%, respectively. The proposed MA is simulated using ANSYS HFSSv19.1 and fabricated on an FR4 (Flame Retardant) substrate using a printed circuit board. The analysis covers both normal and oblique incident angles, and the measured results closely align with the simulated results, with minor variations attributed to fabrication tolerances [64].

20. Polarization-Insensitive Ultra-wideband Metamaterial Absorber for C-, X- and Ku-bands.

This paper discusses the design and analysis of a metasurface-based wideband microwave absorber that incorporates lumped resistors. This absorber operates in the C-, X-, and Ku-bands and has a thickness on the order of 0.05λ mm. The structure is micro-machined onto an FR-4 sheet, arranged in a periodic array of 15x15 unit cells, with each unit cell measuring 12x12 mm.

The proposed absorber design exhibits excellent broadband absorption characteristics, offering a relative bandwidth (RBW) of 93.3%. It covers a bandwidth of 8.02 GHz, ranging from 5.42 GHz to 13.44 GHz. The absorption mechanism is elucidated using characteristic impedance and surface current densities within the operational range.

Importantly, the designed absorber is polarization-angle independent and demonstrates wide incidence angle stability for incident microwaves. When comparing the results from the physical prototype to the simulated results, there is a strong alignment with the simulation outcomes. This absorber structure holds potential for use in camouflage applications during times of warfare [65].

2.11 Brief Overview

In this chapter, a comprehensive and current overview of microwave metamaterial absorbers (MMAs) and their design methodologies is presented, drawing from a review of existing literature. The fundamental parameters governing the properties of metamaterials (MM) were examined, encompassing various types of MM properties, and the limitations of current MMAs were addressed. Their unique properties allow for the customization of absorption characteristics, making them valuable in frequency-selective devices. Advances in fabrication techniques, along with ongoing research, aim to optimize MMAs for improved performance and versatility. The future of MMA design may involve single-layered absorbers tailored for specific applications, utilizing engineering methods for precise control over metamaterial properties.

Chapter 3

Approach and Design Methodology

3.1 Introduction

The methodology and design process are critical aspects of any research endeavor, providing a structured framework for investigation. This section outlines the systematic approach employed to address research questions and objectives. It encompasses the selection of research methods, data collection techniques, and analytical tools to ensure rigor and reliability. The methodology serves as a roadmap, guiding researchers through the logical sequence of steps required for a comprehensive study.

The design process involves the conceptualization and planning of experiments or data collection strategies, emphasizing clarity and coherence. Balancing the research design with the chosen methodology ensures the successful execution of the study, fostering a systematic and organized research approach. Ultimately, a well-defined methodology and design process contribute to the validity and credibility of the research findings.

3.2 Design of the Study

The all-encompassing strategy formulated to tackle the research inquiries is referred to as the research design. This entails delineating the research subject, detailing both independent and dependent variables, sketching out the experimental structure, and, if applicable, elucidating methodologies for data investigation as well as a statistical analysis blueprint.

The approach employed in this study centers on:

1. Investigating Metamaterial Absorbers.
2. Analyzing the properties of Metamaterial Absorbers.
3. Examining the procedures for designing Metamaterial Absorbers and utilizing CST software tools for this purpose.
4. Calculating the essential parameters for creating a metamaterial absorber.
5. Exploring potential applications of this research.

3.3 Method of Analysis

The research commences by briefly addressing the design methodology for optimal Metamaterial Microwave Absorbers (MMA) and deliberating on their design criteria. The development of a unit cell to attain polarization angle insensitivity is subsequently examined through three distinct configurations.Following that, methodologies for creating metamaterial absorbers (MMAs) that target specific frequencies and remain insensitive to co-polarization are examined. Each methodology entails three distinct structures customized for diverse applications. The simulation of these absorbers utilized CST Microwave Studio, a finite difference time domain-based tool. Lastly, the research investigates the equivalent circuit design approach for these absorbers, elucidating the essential equations.

3.3.1 Design of the Research Methodology

Step 1: First, Develop a Metamaterial Absorber.

Step 2: Create the configuration for the Metamaterial Absorber utilizing an FR-4 substrate, with the metamaterial dimensions set at 20*20mm².

Step 3: Modeling the configuration.

Step 4: Analyze outcomes, such as surface current, permeability, permittivity, and absorption, to attain a metamaterial absorber design with dual-negative (DNG) or single-negative (SNG) properties for nearly flawless absorption.

Step 5: Choosing the suitable applications.
Step 6: Summary and suggestions for action.

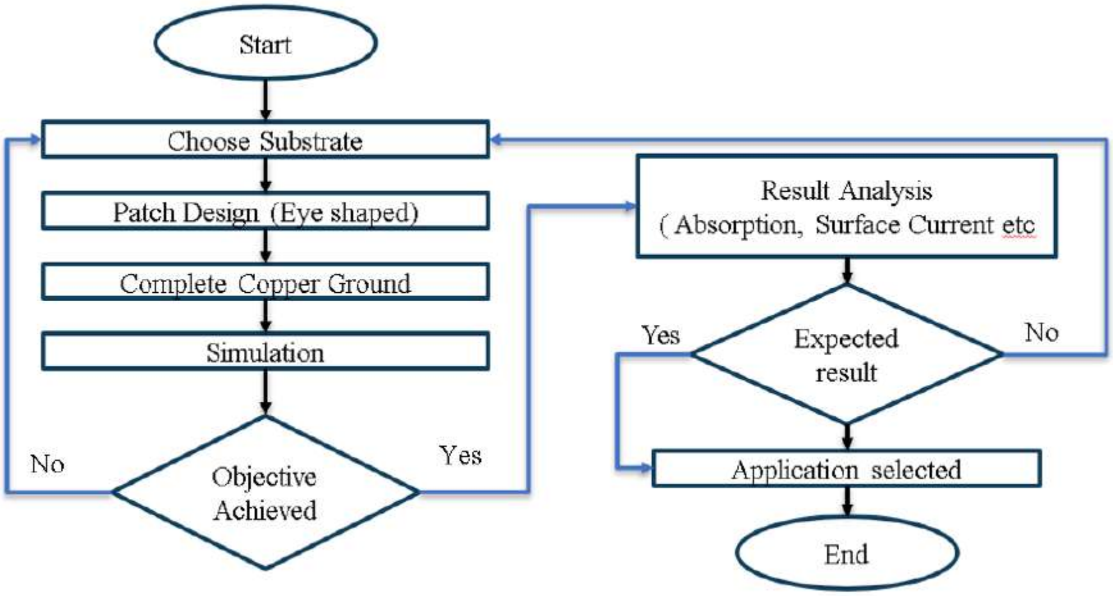


Figure 3.1: Flowchart for metamaterial absorber develop

3.4 Design of Metamaterial Absorbers

The proposed metamaterial absorber's design is illustrated in Figure 1. This metamaterial absorber consists of three layers. This individual unit cell consists of a dielectric material in the middle, separating the upper metal patch from the lower metal plane. which uses a 1.6mm thick FR-4 material with a relative permittivity (εr) of 4.3 for this. The substrate layer measures 20mm x 20mm. The inner and outer surfaces are made of copper, with a conductivity (σ) of 5.8 x 10^7/m and a thickness of 0.035mm.During the metamaterial creation, we employed a three-dimensional coordinate system within the (CST Microwave Studio) orientation software.

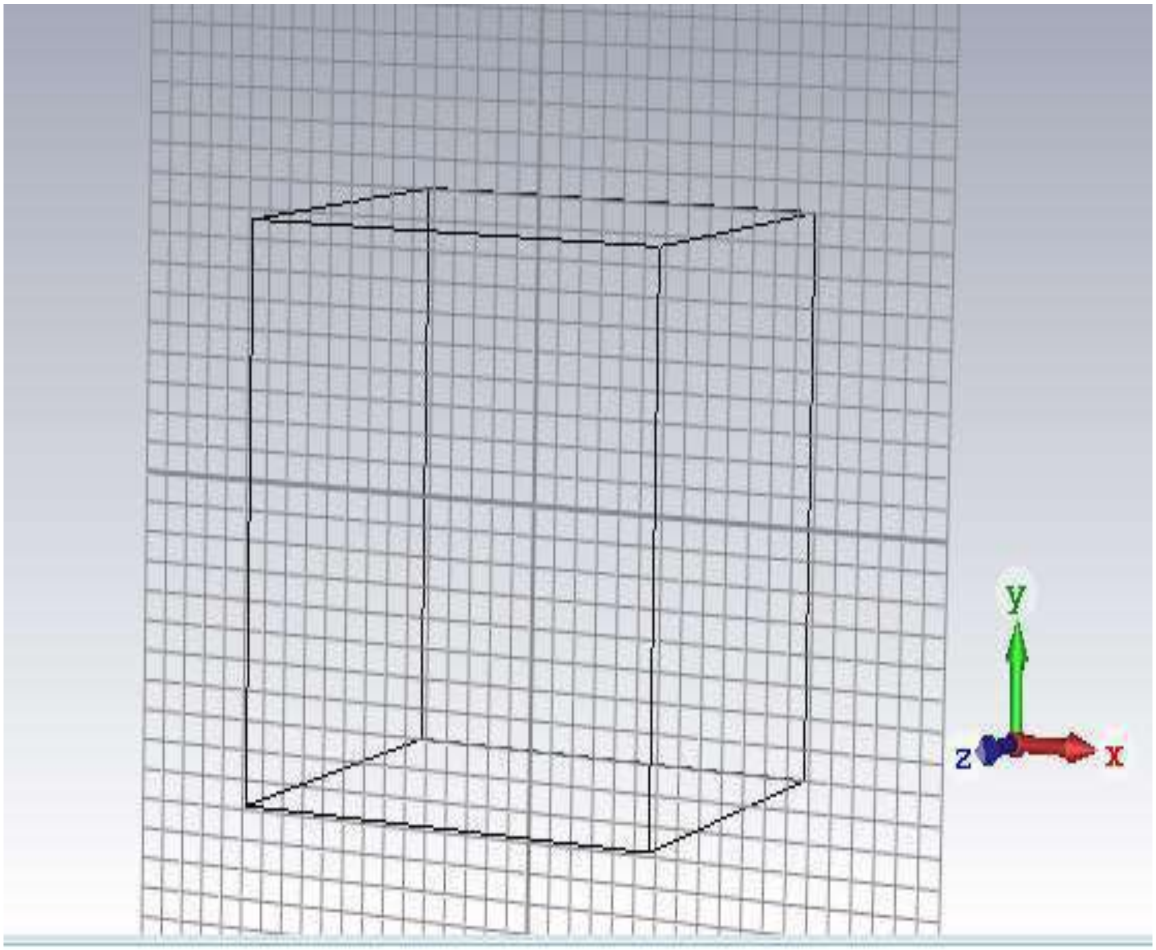
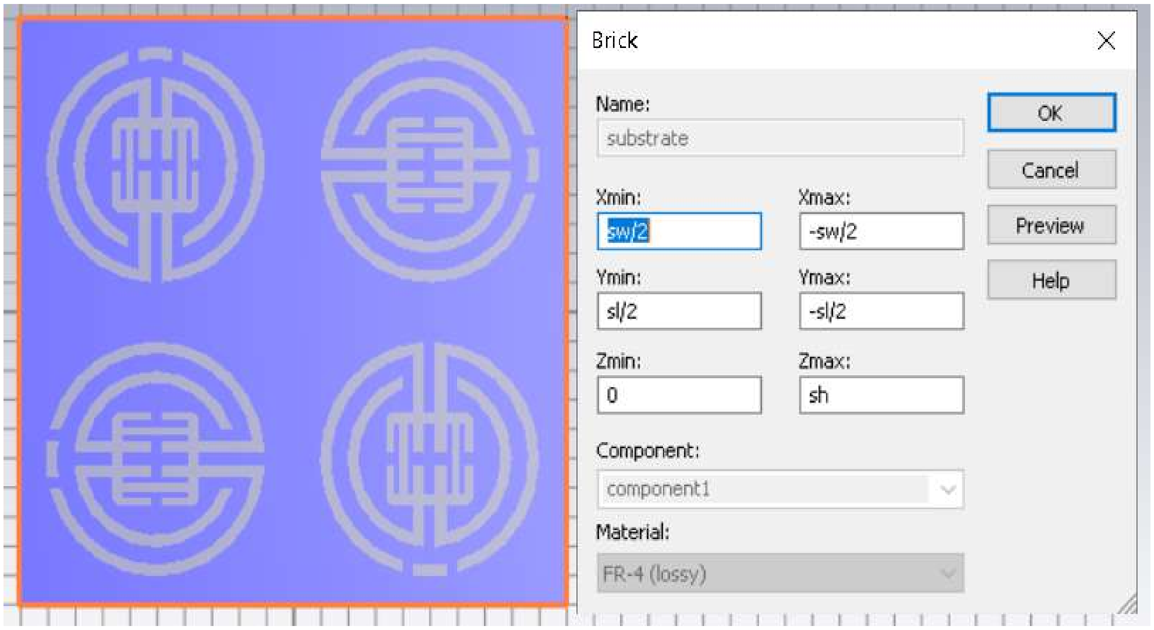


Figure 3.2: 3D co-ordination view in CST software

Copper is also utilized in the patch, with the FR-4 having a thickness of 1.6mm, and the copper layer measuring 0.035mm in thickness. Specific geometric parameters are outlined in the table. The unit cell of the metamaterial absorber is generated and assessed using the CST STUDIO SUITE, a commercial full-wave simulation software.

3.4.1 Substrate-layer

The substrate has a width and length both measuring 20 mm, with a thickness of 1.6mm. In this configuration, a substrate material of FR-4 (without losses) has been employed.



Brick

Name: substrate

Xmin: sw/2
Xmax: -sw/2
Ymin: sl/2
Ymax: -sl/2
Zmin: 0
Zmax: sh

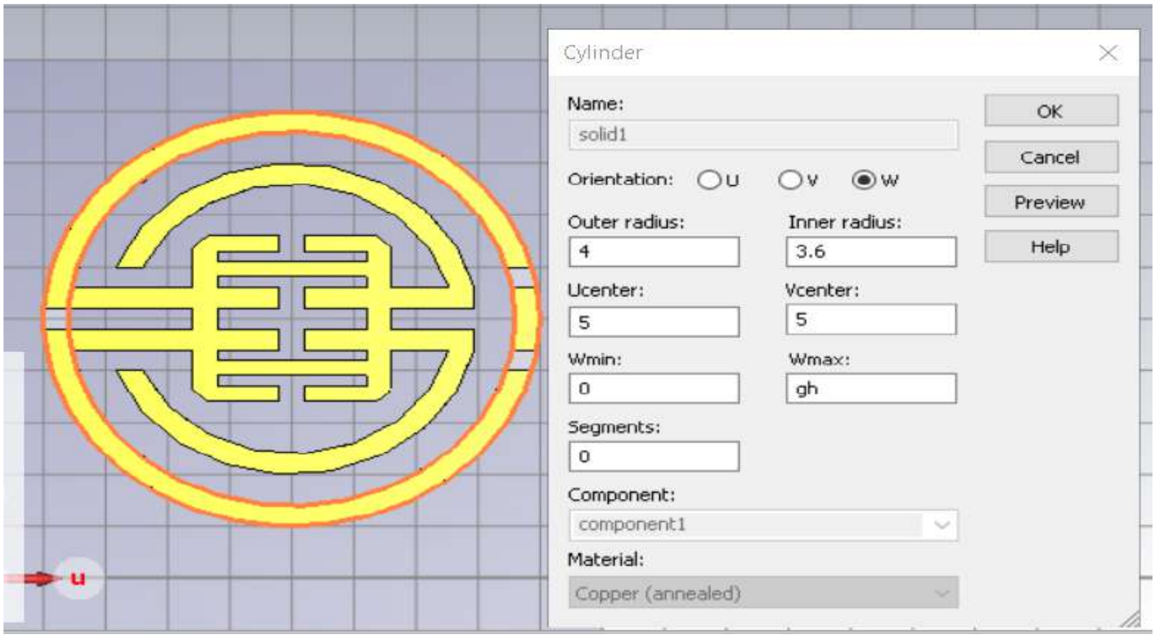
Component: component1

Material: FR-4 (lossy)

Figure 3.3: Substrate-layer

3.4.2 Patch Design (Step 1)

First, design a large circle for Eye-Shaped. Here we show the specifications by those figures.



Cylinder

Name: solid1

Orientation: ○ U ○ V ● W

Outer radius: 4
Inner radius: 3.6
Ucenter: 5
Vcenter: 5
Wmin: 0
Wmax: gh
Segments: 0

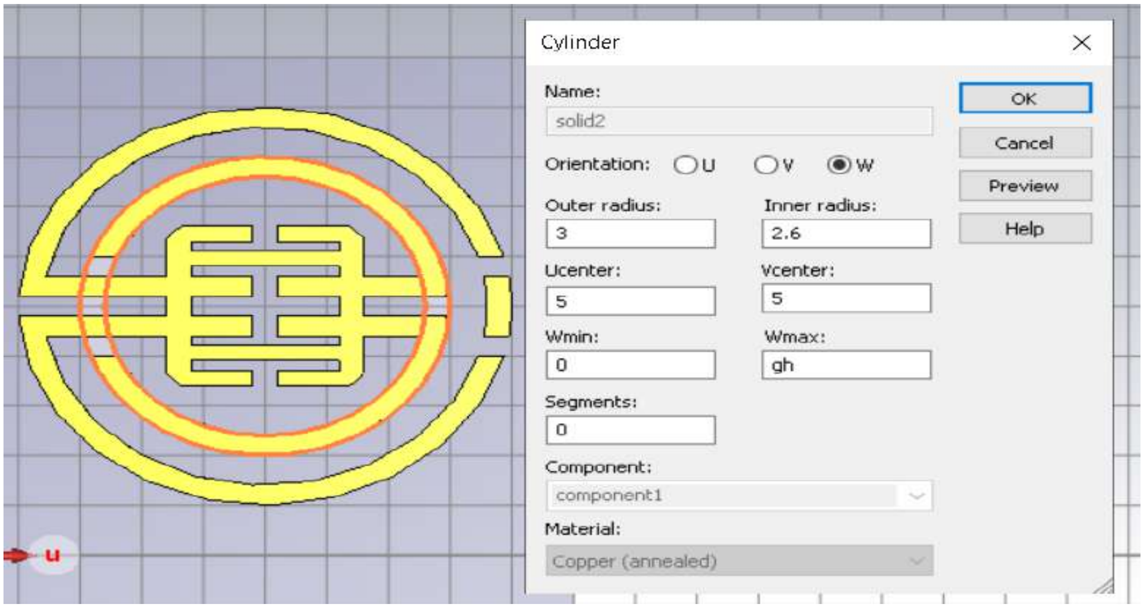
Component: component1

Material: Copper (annealed)

Figure 3.4: Large circle design of Eye-Shaped

3.4.3 Patch Design (Step 2)

Design another small circle for Eye-shaped. In this instance, we illustrate the design procedure through these visual representations.



Cylinder

Name: solid2

Orientation: ○ U ○ V ● W

Outer radius: 3

Inner radius: 2.6

Ucenter: 5

Vcenter: 5

Wmin: 0

Wmax: gh

Segments: 0

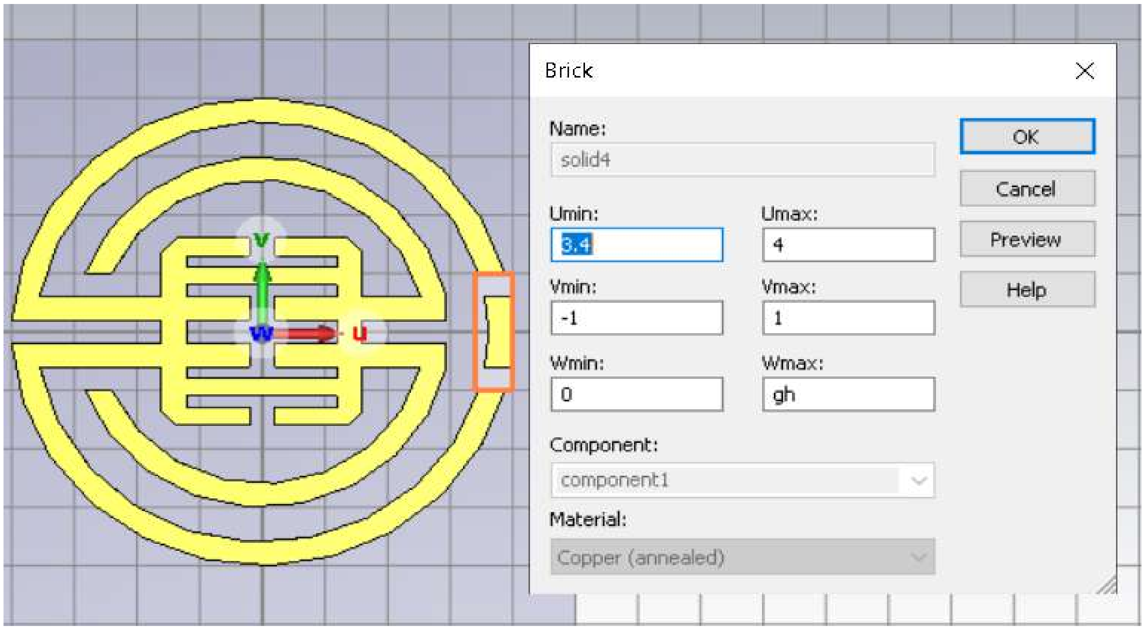
Component: component1

Material: Copper (annealed)

Figure 3.5: Small circle design of Eye-Shaped

3.4.4 Patch Design (Step 3)

Design outer subtract for Eye-shaped. In this instance, we illustrate the design procedure through these visual representations.



Brick

Name: solid4

Umin: 3.4

Umax: 4

Vmin: -1

Vmax: 1

Wmin: 0

Wmax: gh

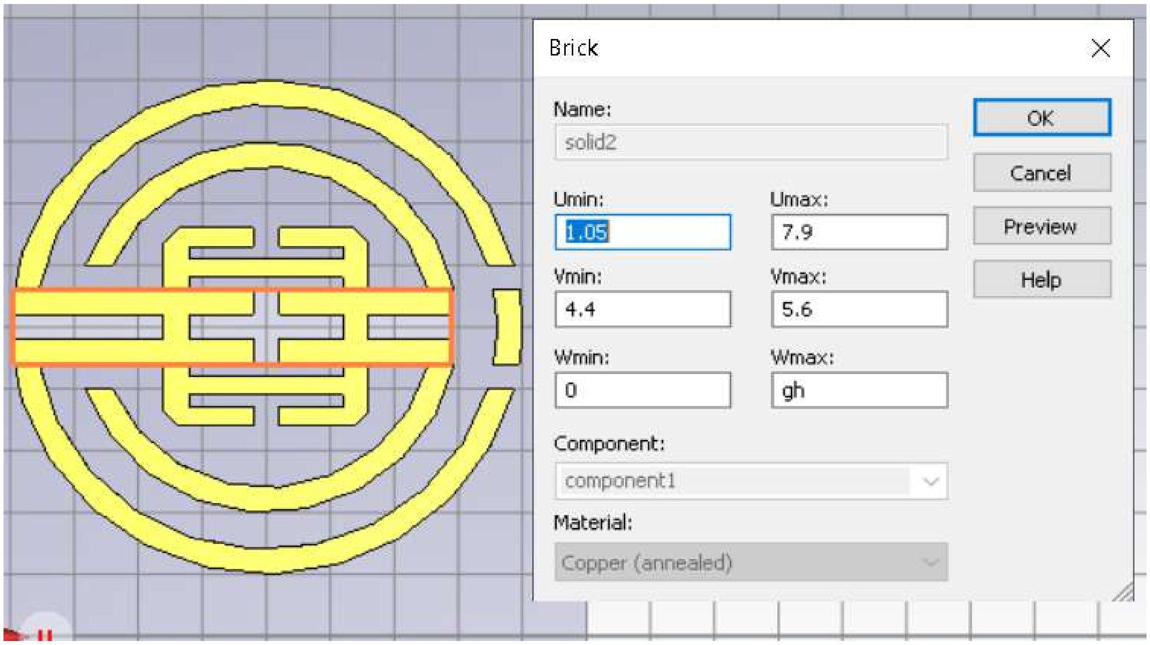
Component: component1

Material: Copper (annealed)

Figure 3.6: Outer Subtract of the eye-shape

3.4.5 Patch Design (Step-4)

Create a rectangular segment with an eye-shaped configuration. In this instance, we depict the design procedure through these visual representations.

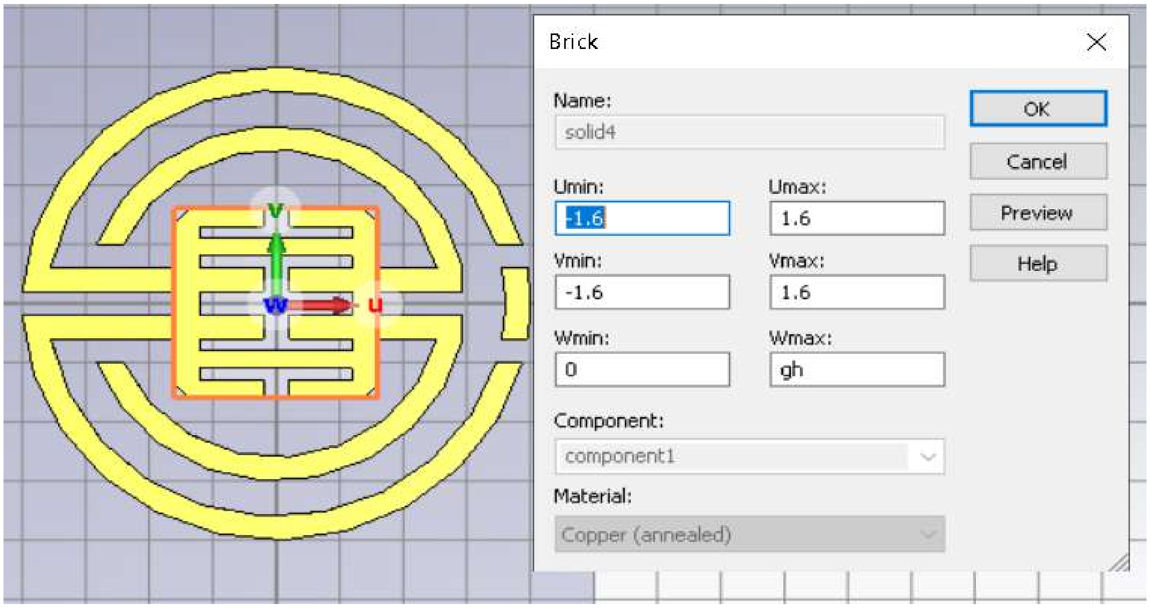


Name: solid2
Umin: 1.05
Umax: 7.9
Vmin: 4.4
Vmax: 5.6
Wmin: 0
Wmax: gh
Component: component1
Material: Copper (annealed)

Figure 3.7: Rectangular part of eye-shape

3.4.6 Patch Design (Step 5)

Design the inner square part of the Eye-shaped. In this instance, we depict the design procedure through these visual representations.



Name: solid4
Umin: -1.6
Umax: 1.6
Vmin: -1.6
Vmax: 1.6
Wmin: 0
Wmax: gh
Component: component1
Material: Copper (annealed)

Figure 3.8 Inner square part of eye-shape

3.4.7 Final Patch View

In Figure 3.8, we present the ultimate outlook of the MMA, and we additionally incorporate it in one line.

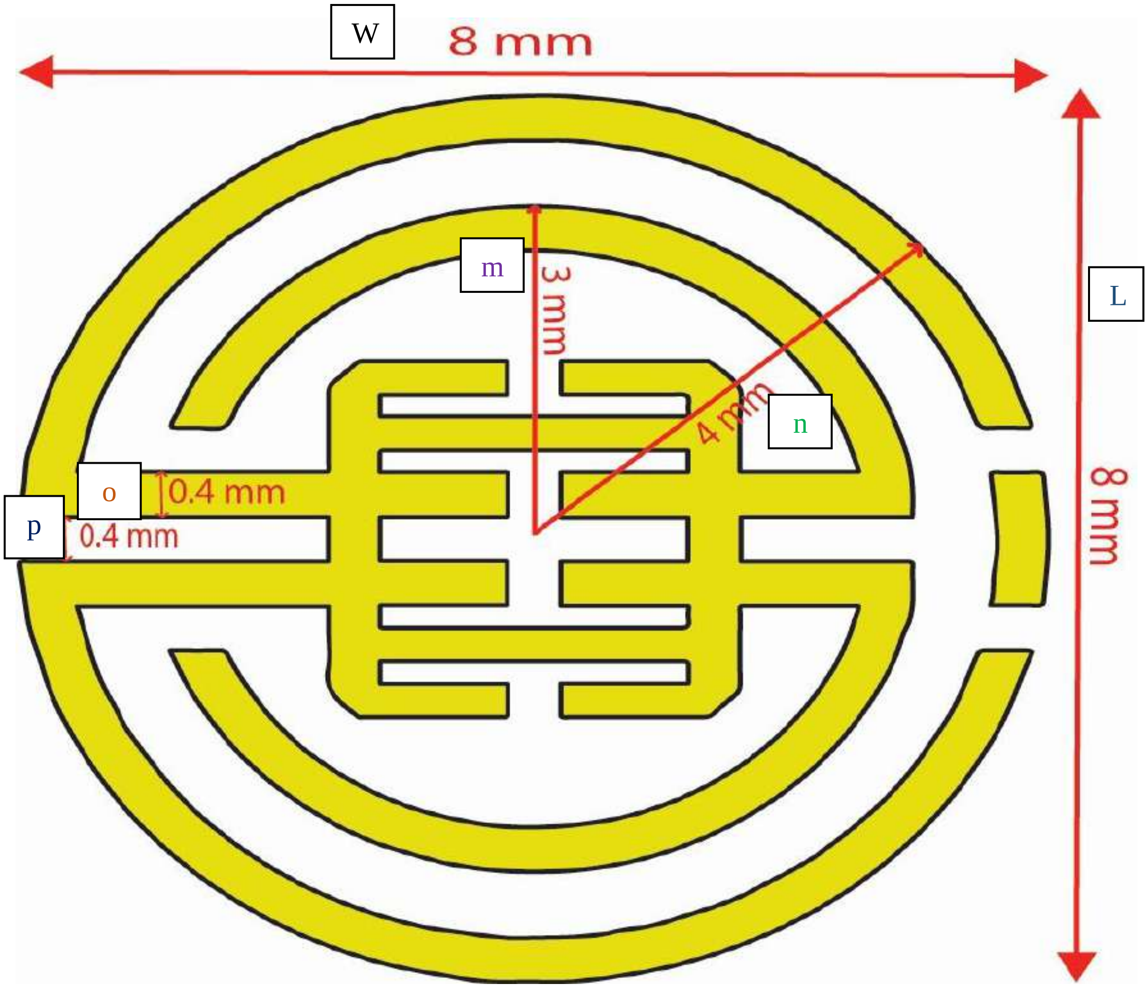


Figure 3.9: Final Design

TABLE II. FRAMEWORK OF THE MMA STRUCTURE

Parameters	Size(mm)	Parameters	Size(mm)
L	8	o	0.4
W	8	p	0.4
m	3	-	-
n	4	-	-

3.4.8 Incorporate a waveguide port.

Choosing the waveguide port is crucial for the simulation. In this instance, we employ two waveguide ports, with one designated as negative and the other as positive. The flow is directed from one side of the metamaterial to the opposite side.

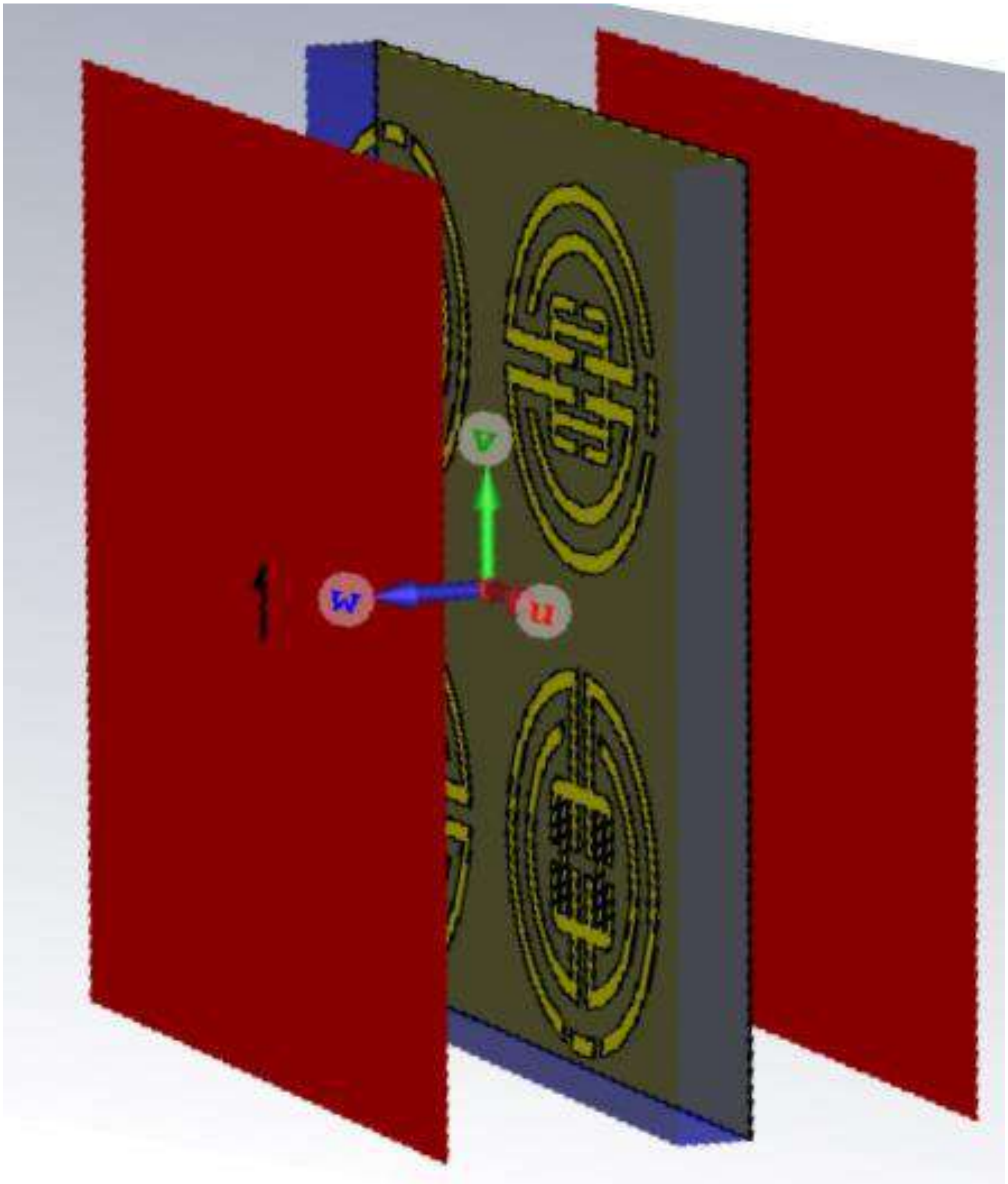


Figure 3.10: After applying the waveguide port

3.4.9 Design of the Unit Cell

Crafting a metamaterial absorber involves tailoring the configuration, material composition, and arrangement of unit cells to achieve targeted absorption characteristics in a defined frequency spectrum. These absorbers are intentionally engineered structures capable of selectively absorbing electromagnetic waves, typically within the terahertz, microwave, or optical frequency spectrums.

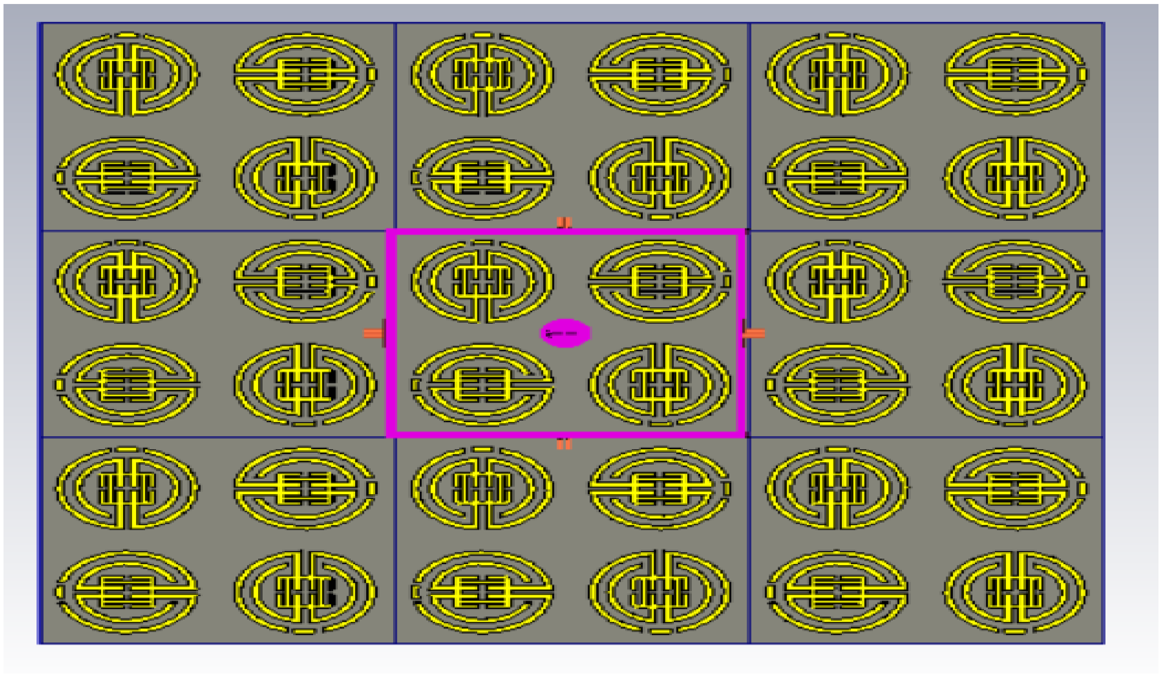


Fig 3.11: Design of the Unit cell

Chapter 4

SIMULATION AND RESULT ANALYSIS

4.1 Introduction

Electromagnetic metamaterials are specially engineered composites that gain unique properties from their basic unit [66]. They're created by dispersing substances in a way that allows for extraordinary electromagnetic characteristics, often not found in nature due to their extremely small size compared to incoming radiation wavelengths [67]. These materials, known for features like negative refractive index, are now being tested in applications like cloaking [68], perfect lenses [69], and antennas [70]. They offer potential advantages over traditional absorbers due to their straightforward production processes Metamaterial absorbers usually have a middle layer of insulating material sandwiched between two layers of metal. By manipulating electromagnetic fields [71], these structures can have matching permittivity and permeability at specific frequencies. While single-layer absorbers offer increased bandwidth, multi-resonant structures can be more challenging to control due to their intricate patterns [72]. Broadband absorption can be achieved by combining different resonant structures, although some designs may have limitations, like large unit cell dimensions [73]. Additionally, thickness can be a drawback in absorber design, particularly when multiple metallic layers are involved [74].

As a general practice, designing millimeter-wave (MM) absorbers commonly entails the utilization of meticulously crafted precision patches or patch arrays on a single face of a dielectric substrate, while a ground plane of the same material is positioned on the opposite side of the substrate [75]. While annealed copper is frequently employed for both the patches and the ground in most absorbers, the choice of substrate material is a critical aspect of achieving optimal MM absorber performance. Researchers are actively working on developing various substrate materials to create perfect MM absorbers. However, these newly developed substrates, while unique, often pose challenges in terms of commercial fabrication and practical installation in electromagnetic wave devices. As a result, commercially available substrates like FR4, Rogers RT, or RO are increasingly used due to their widespread applicability and ready availability in recent times [76]-[78].

This paper introduces a metamaterial absorber with a single-layered substrate featuring a unique rotational and eye-shaped labyrinth structure. The absorber employs a standard 1.6 mm thick FR-4 substrate with a dielectric constant of 4.3. Additionally, it utilizes copper as a dielectric with a metal thickness of 0.035. This custom design exhibits nine resonance frequencies, achieving an impressive absorption rate. Also, the absorber remains unaffected by electromagnetic waves, whether they hit at a normal or oblique angle.

4.2 Analysis of Metamaterial Absorber Results

The absorber created exhibits metamaterial absorber characteristics across different resonant frequencies (5.782 GHz, 7.432 GHz, 10.644 GHz, 13.813 GHz, 19.048 GHz, 21.006 GHz, 22.856 GHz, 23.756 GHz, and 24.746 GHz), as illustrated in Figure 1. The attainment of necessary inductance, resistance, and capacitance for these resonance frequencies was achieved by incorporating central parallel strips, emphasizing their crucial role in the design.

4.2.1 Reflection Co-efficient (Γ)

The developed absorber effectively demonstrates the essential metamaterial characteristics across various resonance frequencies, specifically at 5.782 GHz, 7.432 GHz, 10.644 GHz, 13.813 GHz, 19.048 GHz, 21.006 GHz, 22.856 GHz, 23.756 GHz, and 24.746 GHz. Precise adjustments to the central parallel strips played a critical role in finely adjusting the resonance frequencies within the S-band and KU band spectrums. This meticulous tuning process ensured that the patch possessed the necessary inductance, resistance, and capacitance to resonate at the designated frequencies.

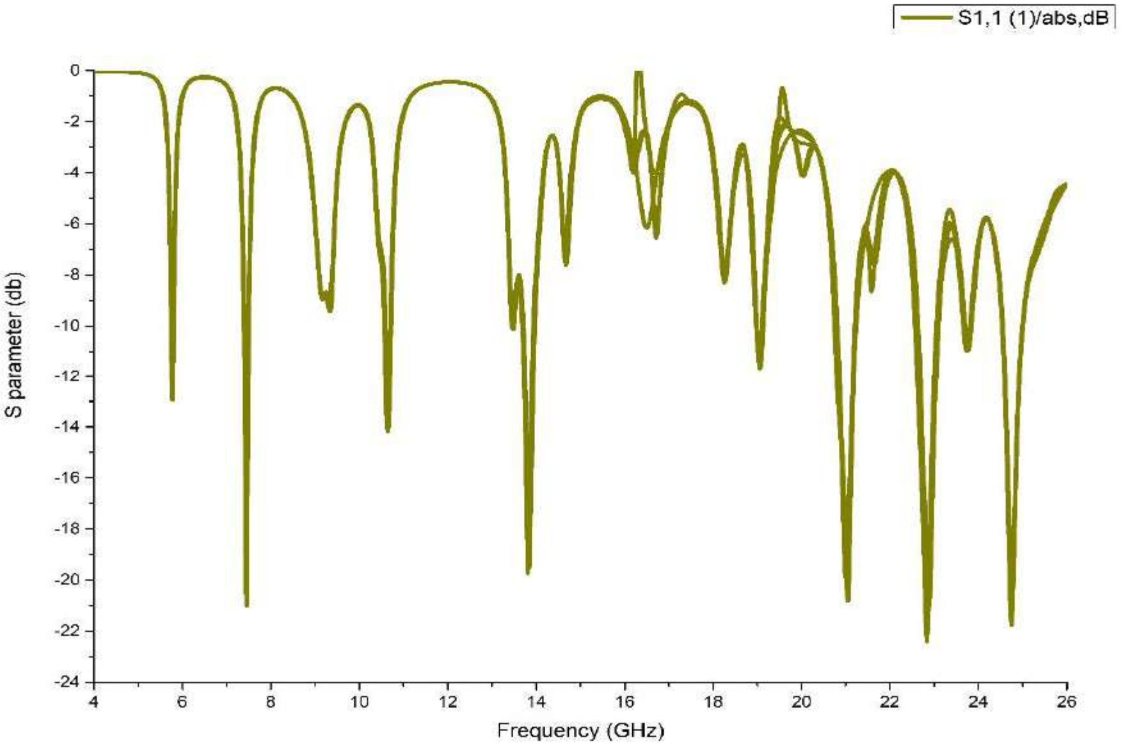


Figure 4.1: Simulation Graph of Reflection Co-efficient

4.2.2 Reflectance

In Figure 4.2, it is evident that there is zero reflectance at the specified resonant frequencies.

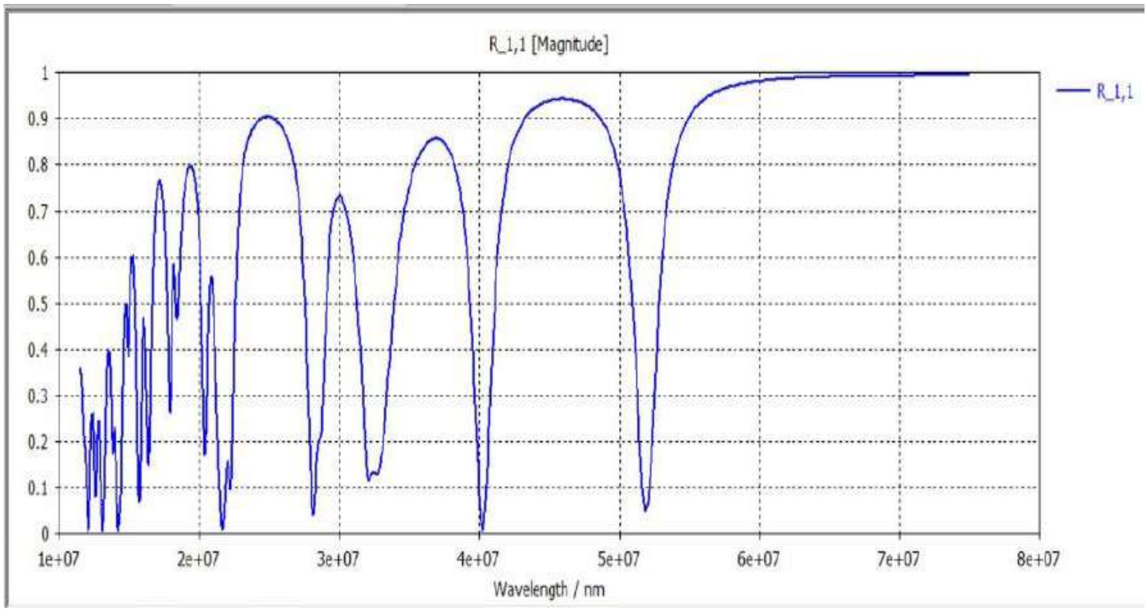


Figure 4.2: Simulation Graph of Reflectance

4.2.3 Transmission

In Figure 4.3, the depicted outcome is the transmission result. It is observable that there is no transmission at the designated resonant frequencies.

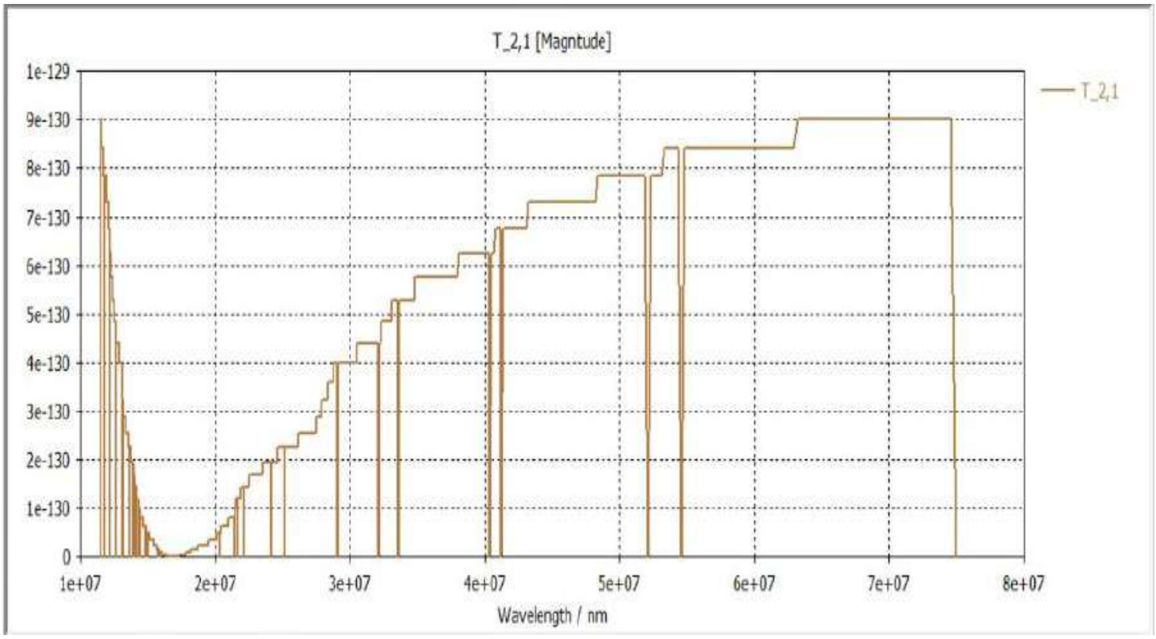


Figure 4.3: Simulation Graph of Transmission

4.2.4 Absorption

The resonance frequencies span a spectrum of bands, comprising the C, X, Ku, and K bands, with specific values at 5.782 GHz, 7.432 GHz, 10.644 GHz, 13.813 GHz, 19.048 GHz, 21.006 GHz, 22.856 GHz, 23.756 GHz, and 24.746 GHz. Furthermore, our proposed Metamaterial Absorber (MMA) demonstrated exceptional performance, achieving absorption percentages ranging from 94.93%, 97.73%, 95.89%, 98.28%, 93.18%, 98.72%, 99.9%, 91.85%, and 99.15% at the specified resonance frequencies.

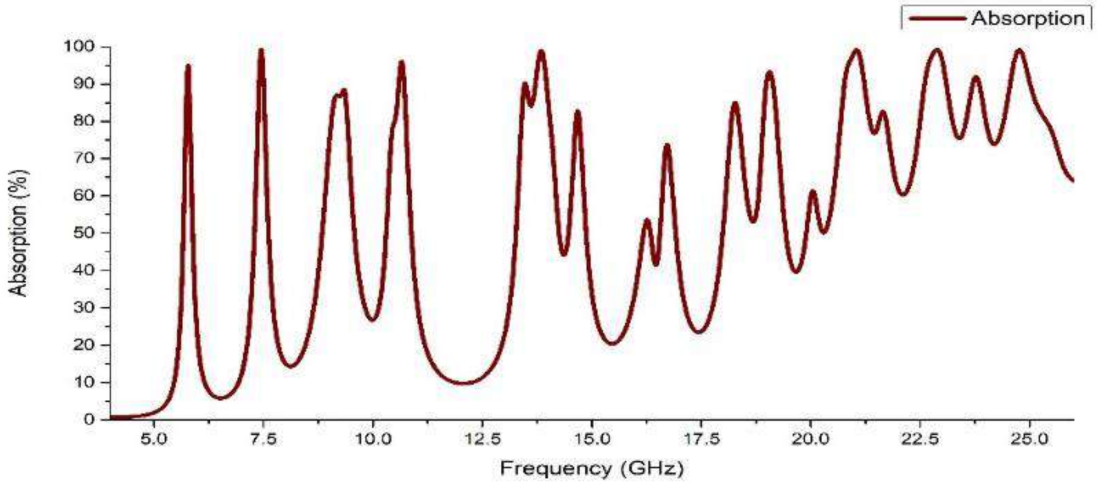


Figure 4.4: Absorption in various Frequencies

4.2.5 Polarization Insensitivity

In fig-4.5, these simulations conducted at various incident angles (phi and theta), consistently yielded identical results. This underscores the polarization insensitivity of the structure. Which indicates its efficient performance regardless of the angle of the incident waves.

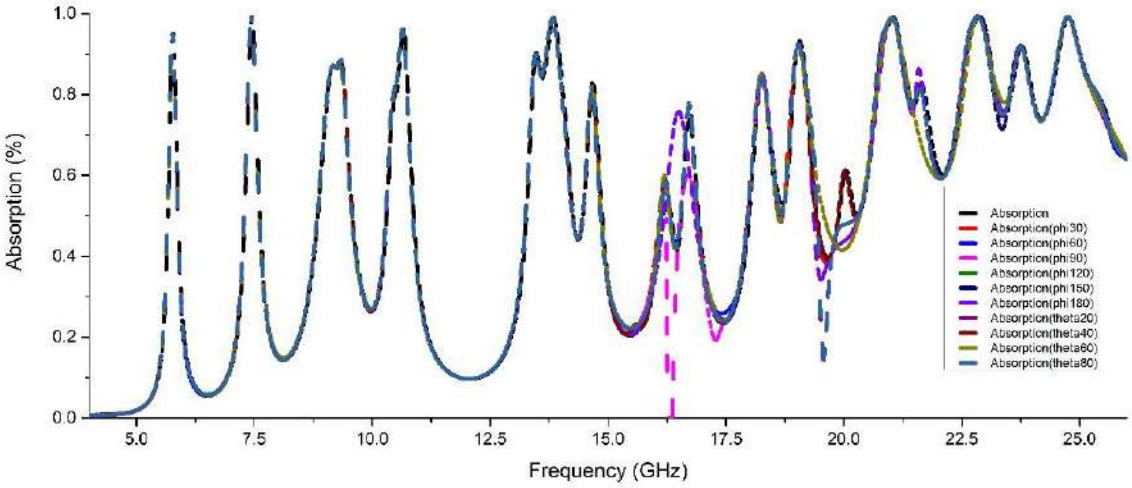


Figure 4.5: Polarization Insensitivity

4.2.6 Permittivity (ε)

Figure 4.6 illustrates the permittivity across various resonance frequencies (5.782 GHz, 7.432 GHz, 10.644 GHz, 13.813 GHz, 19.048 GHz, 21.006 GHz, 22.856 GHz, 23.756 GHz, and 24.746 GHz). It is evident that a majority of the permittivity values are negative.

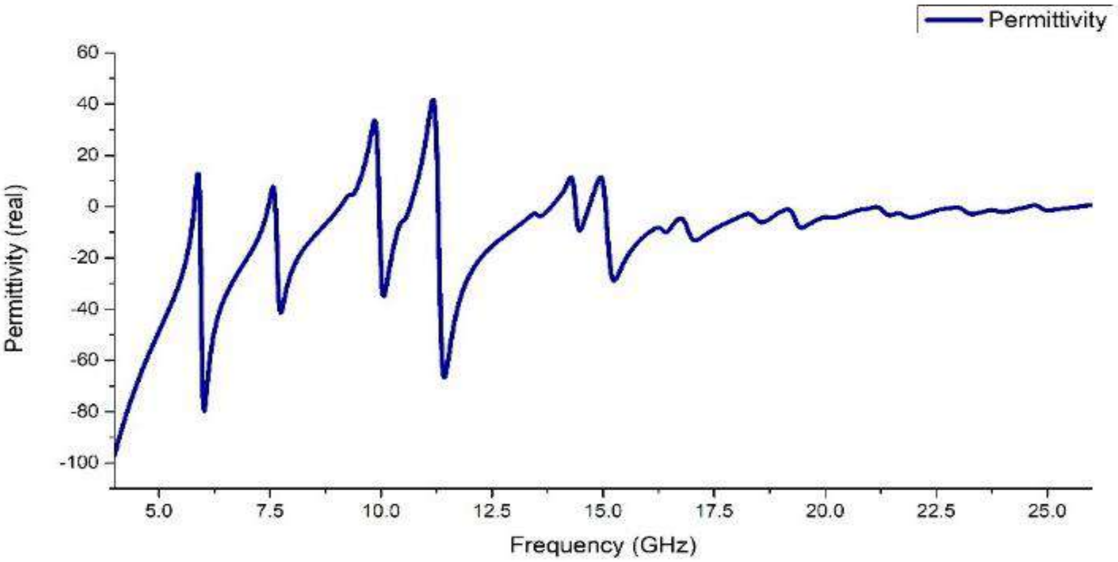


Fig 4.6: Permittivity(real)

4.2.7 Permeability (μ)

In Figure 4.7, the depicted information reveals the permeability across various resonance frequencies (5.782 GHz, 7.432 GHz, 10.644 GHz, 13.813 GHz, 19.048 GHz, 21.006 GHz, 22.856 GHz, 23.756 GHz, and 24.746 GHz). It is observable that a majority of the permeability values are positive.

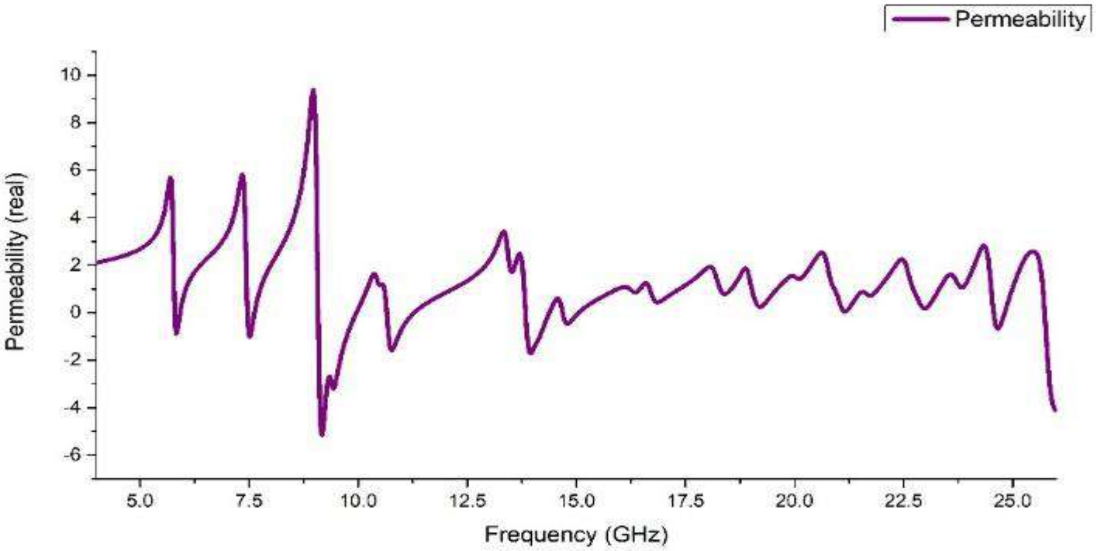


Figure 4.7: Permeability(real)

4.2.8 Refractive Index

In Figure 4.8, the presented data represents the result of the refractive index. In this case, the refractive index value is zero.

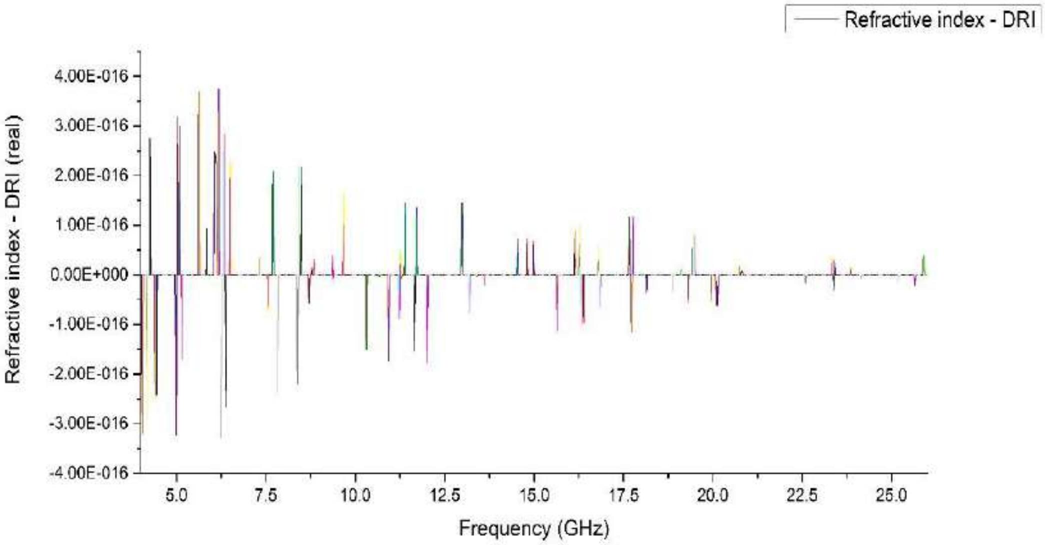


Figure 4.8: Refractive Index

In Figures 4.6, 4.7, and 4.8, the diagrams depict the plots for refractive index, permeability, permittivity, and across various resonance frequencies (5.782 GHz, 7.432 GHz, 10.644 GHz, 13.813 GHz, 19.048 GHz, 21.006 GHz, 22.856 GHz, 23.756 GHz, and 24.746 GHz).

Observing that the permittivity is negative and the permeability is positive, we categorize this absorber as an (SNG). Additionally, it's noteworthy that the refractive index attains a value of zero at the designated resonant frequency.

TABLE III. PROPERTIES OF THE PROPOSED METAMATERIAL ABSORBER

Band	**Resonant Frequency**	**Relative permittivity(ε)**	**Relative permeability(μ)**	**Absorption (%)**	**Applications**
C	5.782GHz	-2.17	0.91	94.93%	Wireless Local Area Networks (WLAN)
	7.432GHZ	-2.33	2.15	97.73%	Satellite Communication
X	10.644GHZ	-0.54	0.24	95.89%	Weather Radar
Ku	13.813GHZ	0.440	0.69	98.28%	Radio Astronomy

K	19.048GHz	-1.60	0.792	93.18%	Satellite Communication
	21.006GHz	-0.622	0.560	98.72%	Satellite Communication
	22.856GHz	-0.479	0.443	99.9%	Aerospace and Radar Systems
	23.756GHz	-1.36	1.162	91.85%	Automotive Radar Systems
	24.746	0.4275	-0.389	99.15%	Automotive Radar Systems

4.2.9 Result of S11 for the unit cell

The configuration of the unit cell plays a pivotal role in metamaterial absorbers, encompassing choices related to materials, geometry, and the resonance features of the repetitive design within the absorbers. The emphasis of this design is on enhancing absorption efficiency. Crafting a metamaterial absorber involves tailoring the configuration, material composition, and arrangement of unit cells to achieve targeted absorption characteristics in a defined frequency spectrum. Figure 4.9 portrays the S11 outcomes corresponding to the intended resonance frequency linked to the unit cell design.

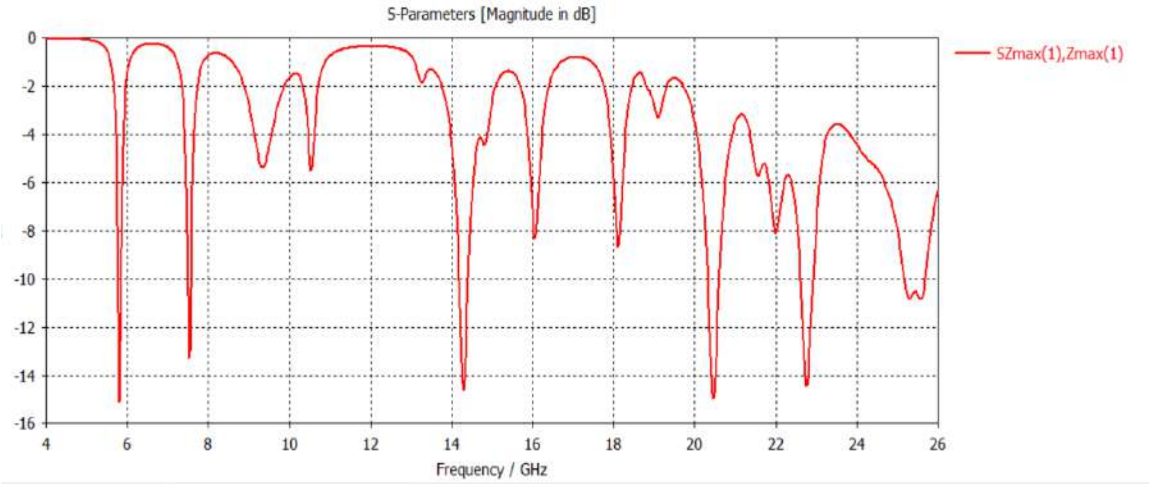
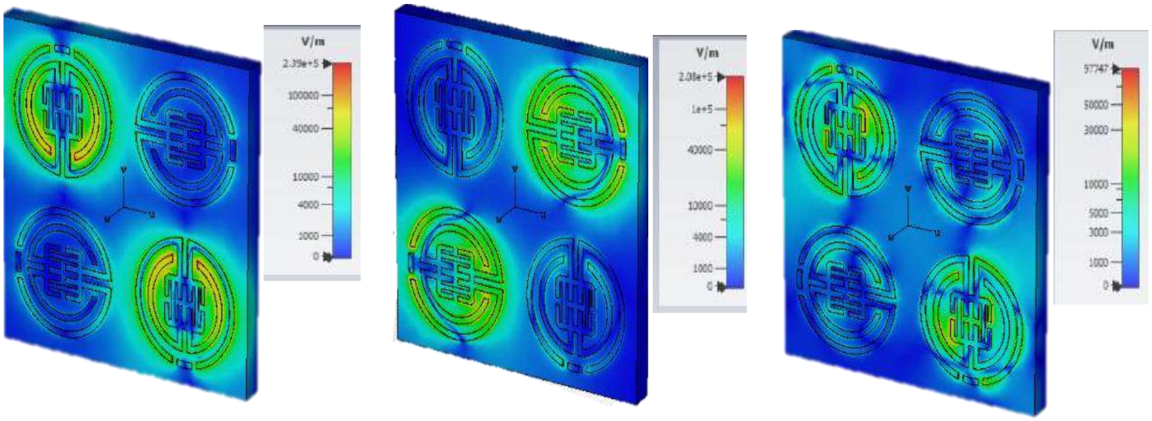


Figure 4.9 S11 Result of Unit Cell

4.2.10 Metamaterial Absorber (E-field)

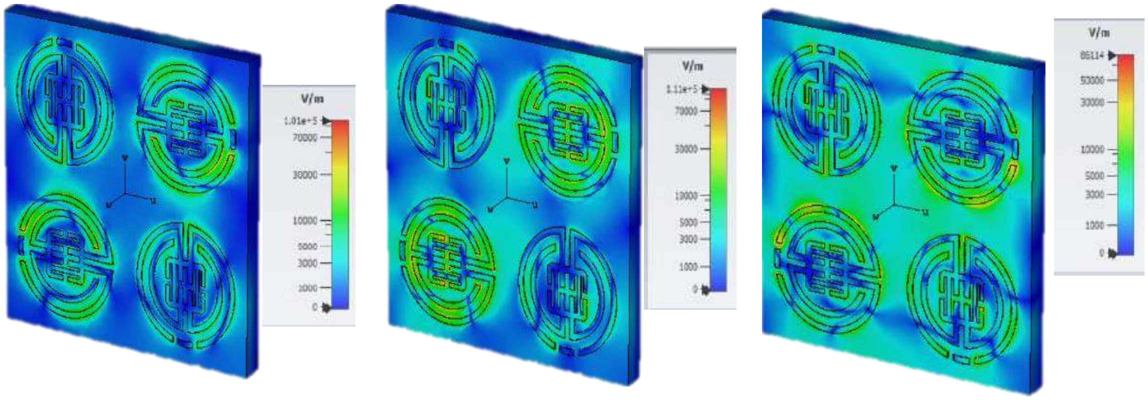
Metamaterial Absorbers (MMA) are engineered structures designed to interact with the electric field (E-field) of electromagnetic waves. The unique arrangement of metamaterial unit cells in MMAs allows for efficient absorption of electromagnetic energy. The E-field interacts with these structured materials, leading to resonance and absorption within specific frequency ranges. The tailored design of MMAs optimizes their performance in selectively absorbing and attenuating electromagnetic radiation.



At 5.782GHz

At 7.432GHz

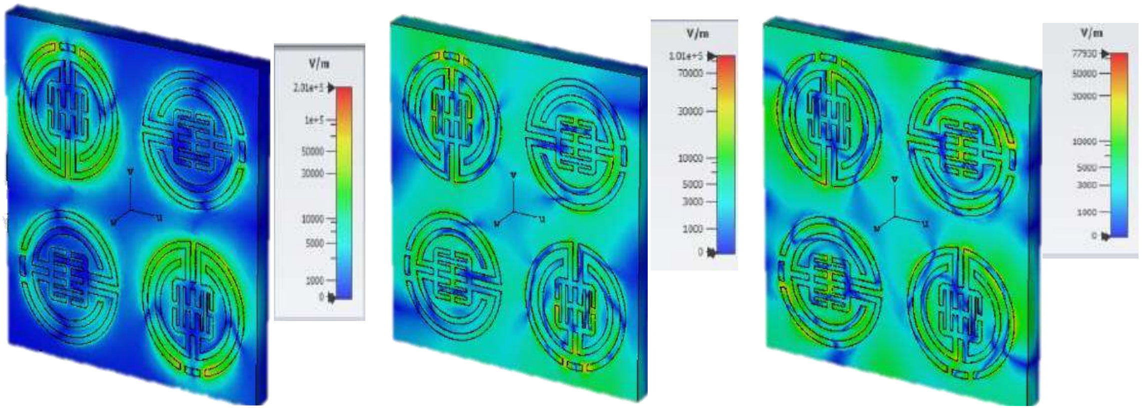
At 10.644GHz



At 13.813GHz

At 19.048GHz

At 21.006GHz



At 22.855GHz

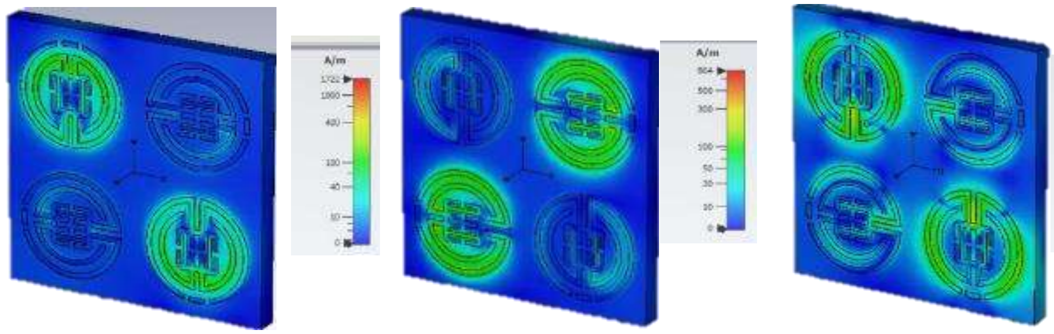
At 23.756GHz

At 24.747GHz

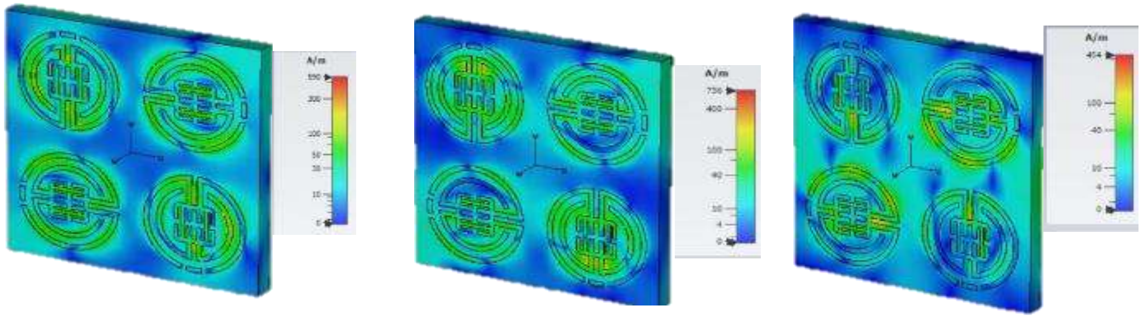
Figure 4.10: E-field for respectively 5.782 GHz, 7.432 GHz, 10.644 GHz, 13.813 GHz, 19.048 GHz, 21.006 GHz, 22.856 GHz, 23.756 GHz, and 24.746 GHz.

4.2.11 Metamaterial Absorber (H-field)

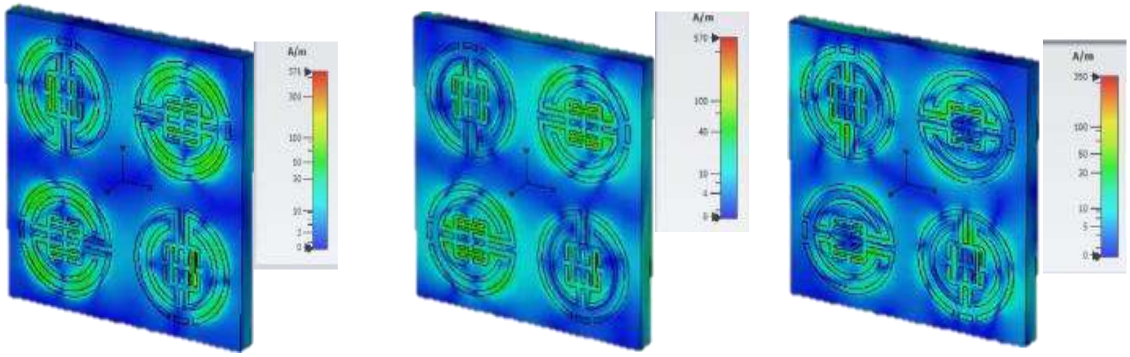
Metamaterial Absorbers (MMAs) are engineered structures designed to interact with the magnetic field (H-field) of electromagnetic waves. The specialized unit cells within MMAs are strategically arranged to efficiently absorb and attenuate the magnetic components of incoming electromagnetic radiation. The interaction with the H-field leads to resonance within specific frequency bands, enabling effective absorption. The tailored design of MMAs allows for customization, making them valuable in scenarios where selective absorption of magnetic components is required.



At 5.782GHz At 7.432GHz At 10.644GHz



At 13.813GHz At 19.048GHz At 21.006GHz

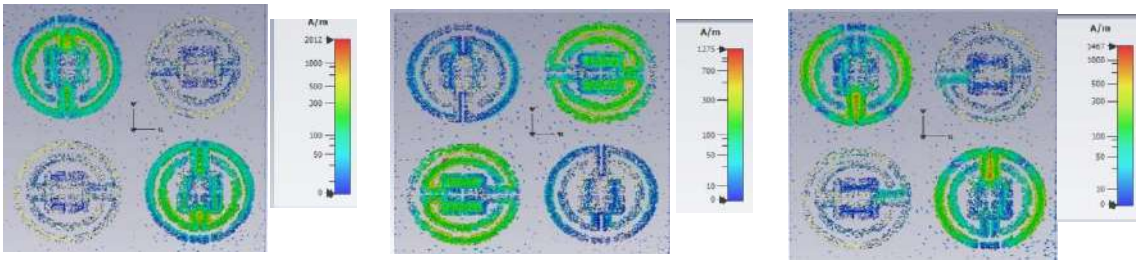


At 22.855GHz At 23.756GHz At 24.747GHz

Figure 4.11 H-field for respectively 5.782 GHz, 7.432 GHz, 10.644 GHz, 13.813 GHz, 19.048 GHz, 21.006 GHz, 22.856 GHz, 23.756 GHz, and 24.746 GHz.

4.2.12 Surface Current

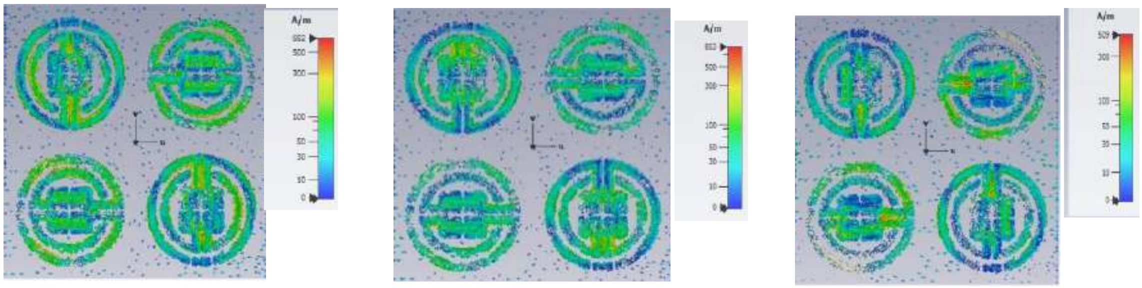
In this Figure, The lower surface current distribution on the metal surface flows in the opposite direction to that of the top surface of the unit cell. This contrast in the current direction results in substantial absorption at the resonant frequencies, brought about by magnetic resonance occurring in both the top and bottom surfaces, both of which are experiencing surface currents.



At 5.782GHz

At 7.432GHz

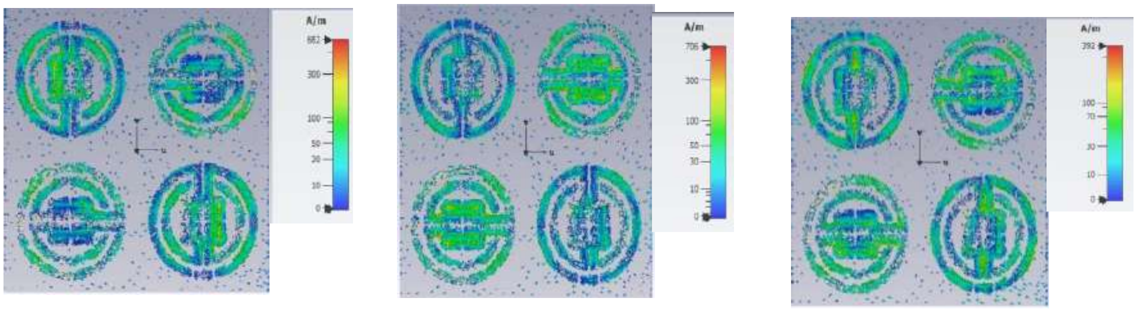
At 10.644GHz



At 13.813GHz

At 19.048GHz

At 21.006GHz



At 22.856GHz

At 23.756GHz

At 24.747GHz

Figure 4.12: surface-current for respectively 5.782 GHz, 7.432 GHz, 10.644 GHz, 13.813 GHz, 19.048 GHz, 21.006 GHz, 22.856 GHz, 23.756 GHz, and 24.746 GHz.

Figures 4.10, 4.11, and 4.12 display the anticipated distributions of the MMA's electric field, magnetic field, and surface current. These distributions can be understood through analysis. Notably, the magnetic field (h-field) exhibits a significantly more agitated behavior compared to the electric field (e-field). Regions with a red hue signify higher surface current density as well as higher electric and magnetic field intensity.

TABLE IV. COMPARISON TABLE

Ref.	**Operating Frequency (GHz)**	**Substrate material and Dimension**	**SNG or DNG properties**	**Absorption**	**Maximum Polarization Angle Insensitivity**
[80]	2.4 5	FR-4 (1.6mm) and 10×10 mm^2	SNG	91.9 % 97.35 %	180^0
[81]	4.192 5.24 8.632 9.264 10.152	FR-4 (1.6mm) and 16× 16 mm^2	Not Mentioned	Average 99.5 %	80^0(theta) 180^0(Phi)
[82]	6 8 15.3	FR-4 (1.6mm) and 10× 10 mm^2	SNG	97%, 93% 83%	Not Mentioned
[83]	2.44 3.5 12.039 15.516 16.713	FR4 (1.6 mm) and 20× 20 mm^2	SNG	99.4%, 91.65% 98.75% 95.37% 95.77%	Not Mentioned
this design	5.782 7.432 10.644 13.813 19.048 21.006 22.856 23.756 24.746	FR4 (1.6 mm) and 20 × 20 mm2	SNG	94.93% 97.73% 95.89% 98.28% 93.18% 98.72% 99.9% 91.85% 99.15%	80^0(theta) 180^0(Phi)

In this comparison, qualitative measures were utilized among several contemporary research works to demonstrate enhancements, such as improved absorption without polarization sensitivity and enhanced metamaterial properties. These comparisons serve as evidence, highlighting the originality and uniqueness of this paper.

Chapter 5

Conclusion

5.1 Summary

A new microwave-frequency metamaterial absorber (MMA) is designed as an eye-shaped labyrinth structure. This innovative configuration maximizes absorbance, with adjusted parameters for optimal signal absorption at various frequencies. The MMA achieves high absorptivity, exhibiting absorbance values of 94.93%, 97.73%, 95.89%, 98.28%, 93.18%, 98.72%, 99.9%, 91.85%, and 99.15% across nine frequencies at 5.782 GHz, 7.432 GHz, 10.644 GHz, 13.813 GHz, 19.048 GHz, 21.006 GHz, 22.856 GHz, 23.756 GHz, and 24.746 GHz.

The performance of the Metamaterial Absorber (MMA) is further clarified through an examination of surface current distributions, as well as the patterns of magnetic and electric fields. This reveals the resonant behavior of the MMA at various frequencies. This versatile design finds applications in C, X, Ku, and K band absorption.

5.2 Conclusion

A novel Eye-shaped labyrinth metamaterial absorber has been developed, featuring ultra-wideband and ultrathin properties across various frequency bands (C, X, Ku, and K). Remarkably, our research reveals absorption rates exceeding 91.5% for the frequencies of 5.782 GHz, 7.432 GHz, 10.644 GHz, 13.813 GHz, 19.048 GHz, 21.006 GHz, 22.856 GHz, 23.756 GHz, and 24.746 GHz. To illustrate the absorption process, we employed surface current plots and electromagnetic field distribution analyses, offering valuable insight.

Furthermore, our absorber exhibits consistent absorption characteristics at different polarization angles. Polarization-insensitive metamaterial absorbers (MAs) are vital due to their ability to absorb electromagnetic waves regardless of polarization. Their importance lies in versatile applications, practicality in diverse wave conditions, simplified designs without polarization-specific components, robust performance across angles, and broad usability in communication, radar, and imaging technologies. They ensure consistent and efficient functionality across varying polarization conditions, simplifying design and advancing technological domains.[84]

In comparison to previously introduced absorbers, our design significantly expands the bandwidth. This innovative absorber presents an effective alternative to existing broadband absorbers and holds vast potential across diverse applications, including wireless local area networks (WLAN), satellite communications, radio astronomy, weather radar, aerospace and radar systems, and automotive radar systems.

5.3 Achievements

The Metamaterial Absorber (MMA) has achieved remarkable success in resonating at diverse frequencies, including 5.782 GHz, 7.432 GHz, 10.644 GHz, 13.813 GHz, 19.048 GHz, 21.006 GHz, 22.856 GHz, 23.756 GHz, and 24.746 GHz. Notably, its absorption rates at these frequencies surpass an impressive threshold of 91.5%. This groundbreaking accomplishment underscores the MMA's unparalleled efficiency in absorbing electromagnetic waves across a broad spectrum. The precise tuning of the absorber has resulted in exceptional performance, positioning it as a pivotal advancement in metamaterial technology. This achievement holds great promise for applications requiring selective and highly efficient absorption within various frequency bands.

5.4 Limitation

<u>Temperature Sensitivity</u>: Some metamaterial absorbers may exhibit temperature-dependent performance. Temperature changes can affect the materials' properties and, in turn, the absorption characteristics.

<u>Limited for Non-Planar Surfaces</u>: Metamaterial absorbers are typically designed for planar surfaces. They may not be suitable for curved or irregularly shaped surfaces, limiting their applicability.

<u>Complex Design and Fabrication</u>: Creating metamaterial absorbers with precise structures and properties can be challenging and costly. The fabrication process often involves complex lithography techniques, making it impractical for some applications.

<u>Material Losses</u>: Metamaterials are often associated with intrinsic material losses, which can reduce their overall efficiency.

5.5 Future Work

- Enhancing Integration with Other Technologies: Foster the synergy between absorbers and complementary devices, such as antennas and sensors, to enable multifunctional applications.

- Exploring Nano-Scale Applications: Delve into the realm of minuscule absorbers tailored for nanoelectronics and cutting-edge technologies.

- Adaptive Environmental Response: Develop absorbers capable of adjusting to dynamic changes in environmental factors, including humidity and temperature.

- Advancing Nonlinear and Active Absorbers: Enable absorbers to perform functions like signal modulation and frequency conversion, expanding their utility.
- Exploring Bio-Medical Applications: Investigate the potential of absorbers in the realm of medical imaging, sensing, and therapeutic applications.
- Optimizing for Space and Aerospace: Fine-tune absorbers to excel in the demanding conditions of space, including vacuum and extreme temperature variations.
- Streamlining Manufacturing Efficiency: Enhance fabrication processes to achieve cost-effective and scalable production of absorbers.
- Conducting Real-World Testing: Validate the performance of absorbers in practical environments to ensure their effectiveness and reliability.

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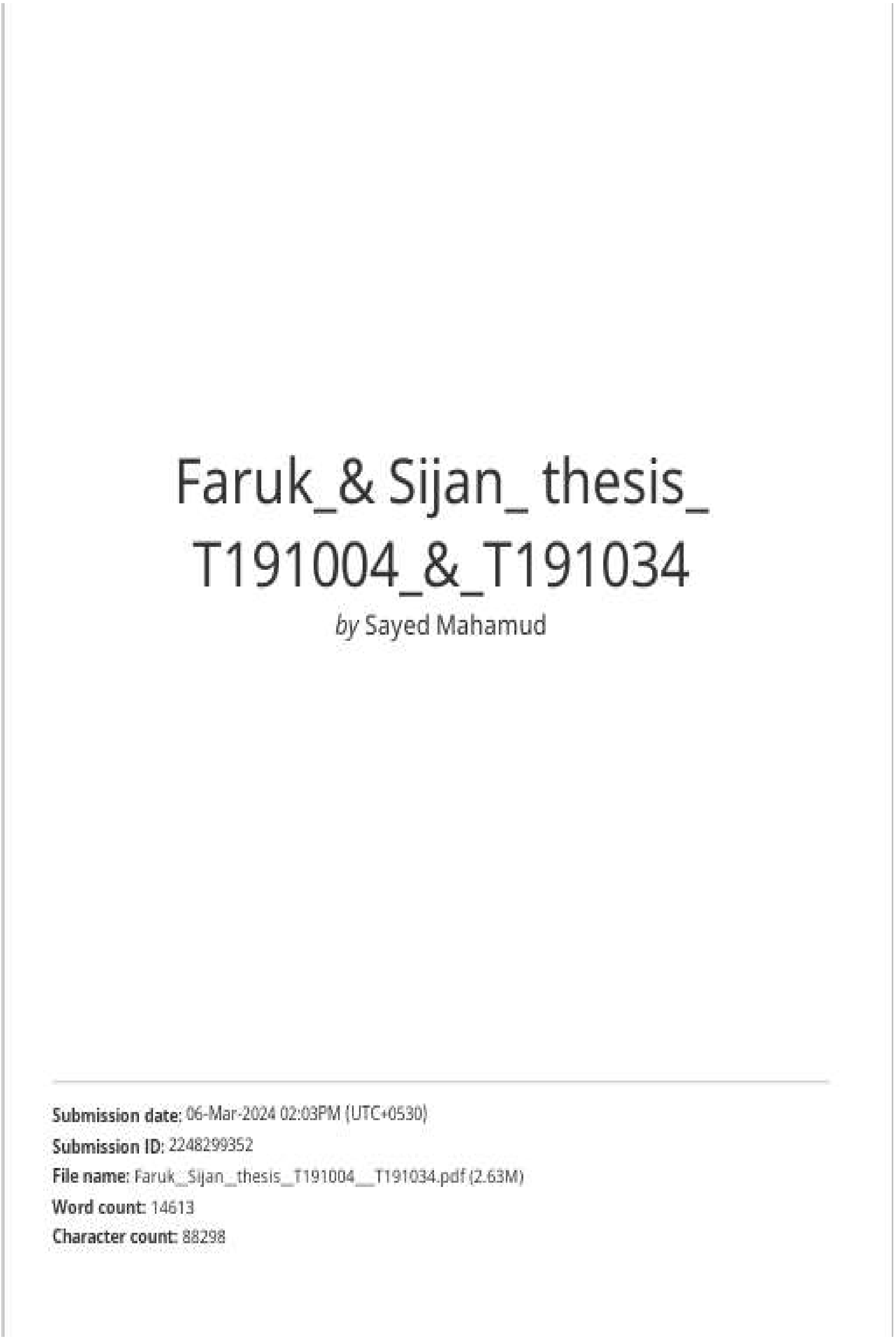

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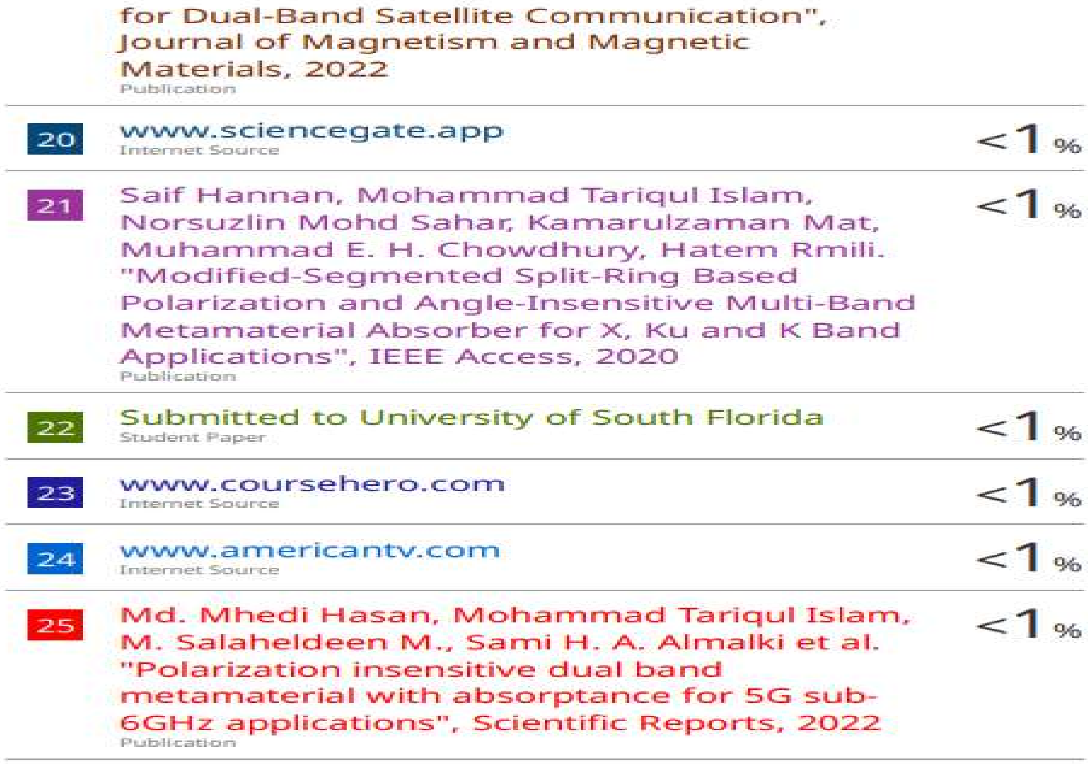

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