Metamaterial Inspired Antenna Design

Submitted in partial fulfillment of the requirements for the degree of

Bachelor of Technology

in

Electronics and Communication Engineering

by

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November, 2024

<u>DECLARATION</u>

I hereby declare that the thesis entitled “Metamaterial Inspired Antenna Design” submitted by us, for the completion of the course “BECE497J – Project 1” to the school of electronics engineering, vellore institute of technology, vellore is bonafide work carried out by me under the supervision of Dr. Kalyanbrata Ghosh.

I further declare that the work reported in this thesis has not been submitted previously to this institute or anywhere.

Place: Vellore

Date: 15/11/24

Rupam Mal.

Signature of the Candidate

CERTIFICATE

This is to certify that the thesis entitled "Metamaterial Inspired Antenna Design" submitted by Rupam Mal(21BEC2178) SENSE, Harsh Kumar(21BEC0706) SENSE, Debtonu Bose(21BEC2099) SENSE, VIT, for the completion of the course "BECE497J – Project 1", is a bonafide work carried out by him / her under my supervision during the period, 20.07.2024 to 15.11.2024, as perthe VIT code of academic and research ethics.

I further declare that the work reported in this thesis has not been submitted previously to this institute or anywhere.

15/11/24

Place : Vellore

Date : 15.11.2024

Signature of the Guide

Vivek 15/11/24

Internal Examiner

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EXECUTIVE SUMMARY

The proposed project, "Metamaterial Inspired Antenna Design," aims to innovate in the field of antenna technology by leveraging the unique electromagnetic properties of metamaterials. This antenna design focuses on applications in 4G/5G communication systems, Wi-Fi (5 GHz), and other metamaterial-based uses. By exploiting metamaterials, the project seeks to achieve enhanced adaptability, allowing the antenna to dynamically respond to varying environmental conditions and user demands.

The core objective is to develop an antenna with capabilities in frequency agility, beam steering, and polarization versatility. These features will enable the antenna to serve as a highly adaptable component in wireless communication, radar, and next-generation IoT applications, making it a critical element in the advancement of communication technology. Key performance indicators, including bandwidth, size reduction, and operational flexibility, are targeted for optimization, ensuring the antenna's compactness and efficiency.

Ultimately, this project contributes to the growing need for versatile, high-performance antennas in modern communication systems. Through careful design and implementation, the antenna aims to set new benchmarks in adaptability and efficiency, addressing the evolving requirements of wireless systems in both commercial and defense sectors.

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1. INTRODUCTION

1.1. Literature Review:

Sathishkumar and Natarajan, 2024 [1] demonstrated that zeroth-order resonance (ZOR) antennas have their ability to provide unique radiation patterns independent of physical size. Traditional ZOR antennas typically produce monopolar radiation, but this study introduces a circular microstrip patch antenna that modifies the equivalent magnetic current densities to achieve a patch-like radiation pattern. Multiband microstrip patch antenna aims to meet the increasing demand for 5G and space applications by operating at 23.9 GHz, 35.5 GHz, and 70.9 GHz. Microstrip patch antennas offer a compact design and support high-speed data transfer, making them suitable for diverse uses such as radio location, radio astronomy, and mobile communication, proposed by Punith and Praveenkumar, 2020 [2]. Miniaturized tri-wideband antenna integrates metamaterial meander lines to achieve compactness and wide bandwidth. The design offers three resonant frequency bands with a simple structure, making it suitable for WLAN, WiMAX, and other wireless applications, demonstrated by Ghasri and Nourini, 2023 [3]

A low-profile rectangular slot antenna, designed for sub-6 GHz 5G wireless applications, offering compact size and high efficiency. Chowdhury and Islam,2022 [4] proposed that It’s small form factor and superior performance make it a suitable solution for sub-6 GHz 5G networks. Vaselgo, 1968 [5] proposed the development of CRLH transmission lines, utilizing CSRRs and series gaps, has enabled the design of dual-band microwave components with improved performance. Unlike traditional transmission lines, CRLH lines provide phase shifts at arbitrary frequencies, making dual-band operation possible. This study introduces a compact, fully planar dual-band branch line coupler, marking the first use of CSRR-based dual-band impedance inverters. David Senior Elles, 2009 [6] introduced the use of CRLH transmission lines in dual-band power dividers has enabled significant size reduction, broad frequency ratios, and design simplicity compared to conventional methods. Research has demonstrated the effectiveness of Bagley Polygon power dividers for single-band applications, with advantages such as aligned output ports and flexible phase selection without the need for isolation resistors. Youzhen Wang, 2008 [7] proposed that the coupling characteristics of CRLH transmission lines have been widely studied, with recent research focusing on their integration with conventional right-handed (RH) transmission lines for improved bandwidth and coupling performance. This study proposes a simpler method to define the coupling range using average permittivity and permeability, verified through ADS simulations.

Seung-Tae Ko, 2012 [8] proposed that the hybrid zeroth-order resonance (ZOR) patch antenna has been developed to address the limitations of conventional patch antennas, particularly their narrow beamwidth. Previous approaches, such as phased arrays and multilayered structures, offered broader beamwidths but came with increased size and complexity. This study introduces a simpler design combining ZOR and conventional patch modes, achieving a 53% broader beamwidth with high efficiency and compact size. Chou and Chen, 2010 [9] demonstrated that recent advancements in left-handed metamaterials (LHM) have led to the development of devices like bandpass filters with enhanced performance. Prior work introduced CRLH transmission lines, which enable tunable gaps between left- and right-handed modes, resulting in wide rejection bands and improved out-of-band performance. This study presents an unbalanced CRLH bandpass filter with 0° feeding structure, achieving low insertion loss, wide stop-band, and additional transmission zeros for enhanced selectivity. Lee and Lee, 2007 [10] proposed that recent research on low-profile omnidirectional antennas highlights the use of zeroth-order resonator (ZOR) antennas with mushroom structures, offering compact designs and omnidirectional radiation. Unlike traditional antennas, ZOR antennas provide efficient radiation without the need for protruding structures, making them ideal for broad service areas.

Recent studies on CRLH unit cells have demonstrated their ability to support the zeroth-order mode (ZOM), enabling resonant modes independent of physical size. Zhang and gong, 2018 [11] introduces a circular microstrip patch antenna that achieves a patch-like radiation pattern without the need for complex structures. The design is validated through simulations and measurements, highlighting its efficiency in producing unique radiation patterns with simple configurations. Metamaterials, especially Composite Right/Left-Handed (CRLH) transmission lines, enable compact, high-performance antenna designs, which is proposed by Manan Gupta and Hemant Kumar, 2021 [12]. CRLH lines support both forward and backward waves, allowing antennas to resonate without specific wavelengths, thanks to Zeroth Order Resonance (ZOR). This unique resonance property enables reduced antenna size while preserving functionality. The current study uses these metamaterial principles to create a compact, broadband uniplanar quasi-Yagi microstrip antenna with end-fire radiation. This approach reduces the antenna's lateral dimensions, delivering strong directivity and a wide frequency response, making it ideal for portable wireless applications.

Shekhawat, Lodhi and Singhal,2024 [13] proposed that metamaterials, particularly those using Composite Right/Left-Handed (CRLH) transmission lines, enable advanced antenna design by exploiting left-handed material properties. These lines allow for the support of both backward and forward waves, enhancing compactness and efficiency. CRLH also enables Zeroth Order Resonance (ZOR), where antennas resonate independent of wavelength, providing miniaturization without performance loss. This study applies these concepts to develop a super wideband MIMO antenna with dual band-notching for interference rejection. By leveraging CRLH and ZOR, the antenna achieves broad bandwidth and high isolation, making it ideal for 5G/6G applications. Pranjal Borah, 2023 [14] introduced that Metamaterials, particularly using Composite Right/Left-Handed (CRLH) transmission lines, allow for innovative antenna designs that support both forward and backward wave propagation. This property enables Zeroth Order Resonance (ZOR), allowing antennas to resonate independent of wavelength, thus reducing size without sacrificing performance. This study leverages CRLH transmission lines and ZOR to develop a compact, semi-transparent, dual-band antenna ideal for vehicular applications, achieving efficient, space-saving communication capabilities. Advances in antenna design increasingly rely on unique electromagnetic structures like Composite Right/Left-Handed (CRLH) transmission lines, which enable both forward and backward wave propagation. This dual capability, proposed by Tran, Lee and Hussain [15] supports the development of compact, efficient antennas. With Zeroth Order Resonance (ZOR), these antennas achieve resonance independently of wavelength, allowing for effective miniaturization without performance loss. In this study, CRLH transmission lines and ZOR principles are utilized to create a single-layer, wideband circularly polarized patch antenna, offering enhanced bandwidth and efficiency for space-constrained wireless applications.

Zang, Jiang and Gong proposed [16] in recent years, metamaterials, including Composite Right/Left-Handed (CRLH) transmission lines, have enabled advancements in antenna design, such as zeroth-order resonance (ZOR) for size reduction and broadband capabilities. These techniques enhance phased array antennas by allowing wide-angle scanning and maintaining impedance matching, demonstrating potential for high-performance applications in radar and satellite communication. Metamaterials, particularly using Composite Right/Left-Handed (CRLH) transmission lines, enhance antenna performance through unique properties such as zeroth-order resonance (ZOR). Mookiah and Dandekar proposed [17] these features allow miniaturization and effective beam steering in antennas, improving bandwidth and channel diversity for applications in wireless networks, as demonstrated in previous studies on antenna-based device authentication. Guevara, Arteaga and Moreno proposed [18] that using Composite Right/Left-Handed (CRLH) transmission lines and zeroth-order resonance enables miniaturized, tunable antennas with enhanced performance. These structures provide compact designs with effective resonant behavior, supporting advanced communication systems and applications by achieving high efficiency without conventional size constraints. Incorporating metamaterials, particularly Composite Right/Left-Handed (CRLH) transmission lines, supports compact antenna designs by enabling zeroth-order resonance. This approach is introduced by Wang, Dong and Itoh [19] offers effective miniaturization and tuning capabilities while maintaining desired radiation characteristics, making it ideal for applications like RFID, where bandwidth and performance are critical. Composite Right/Left-Handed (CRLH) transmission lines with metamaterials, exploiting zeroth-order resonance, enable innovative antenna designs for compactness and high performance. This approach achieves efficient signal transmission and miniaturization, advancing applications like 5G, where compact, tunable, and efficient designs are crucial for seamless communication.

1.2. Research Gap:

The research gap in modern wireless communication systems lies in the need for advanced antennas that can adapt across multiple parameters, leveraging the unique properties of Composite Right/Left-Handed Transmission Line (CRLH-TL) loaded structures. Despite significant advancements in antenna technology, the following areas remain underexplored, highlighting key challenges:

- Multi-Parameter Reconfigurability: While some antenna designs achieve frequency reconfigurability, few can simultaneously adapt parameters such as polarization, beam direction, and frequency within a single radiating structure. Integrating multi-parameter reconfigurability within a compact form factor remains an area of active research.

- Environmental Adaptability: The demand for antennas that can effectively operate in varying electromagnetic environments is increasing, especially for applications in mobile and IoT devices where environmental factors like obstacles and interference can affect performance. The ability to adapt multiple antenna parameters dynamically remains a challenging task.

- CRLH-TL Application in Antennas: Although CRLH-TL structures provide unique opportunities for frequency agility and bandwidth enhancement, there are limited implementations that use these structures to achieve multi-parameter reconfigurability. The use of CRLH-TL structures for comprehensive adaptability, particularly in a single, compact antenna system, is still in the early stages of research.

- Optimizing for Size and Efficiency: Reducing the size of antennas without compromising their capabilities is a critical requirement in next-gen wireless devices. Existing designs struggle to maintain high efficiency while achieving compactness, particularly in antennas targeting 4G/5G and Wi-Fi applications.

This research addresses these gaps by designing a CRLH-TL loaded antenna that achieves multi-parameter adaptability, providing a compact, high-performance solution for evolving wireless communication needs.

1.3. Project Objective:

The primary objective of this project is to design a metamaterial-inspired antenna that addresses modern demands for adaptability, efficiency, and versatility in wireless communication systems. The project focuses on optimizing the antenna's structure to achieve enhanced performance by leveraging the unique properties of metamaterials. The objectives are outlined as follows:

- Enhanced Frequency Agility: The antenna design will enable adaptability across multiple frequencies, making it suitable for applications in 4G/5G, Wi-Fi (5 GHz), and metamaterial-based systems.

- Beam Steering Capability: The antenna will incorporate beam-steering functionality, allowing it to dynamically adjust its radiation pattern in response to changing environmental conditions, a crucial feature for applications in radar and IoT.

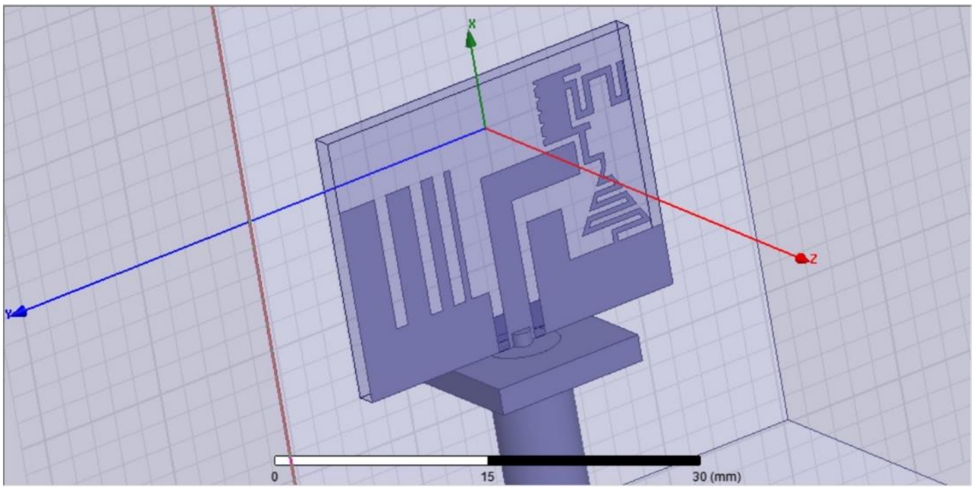
- Polarization Reconfigurability: By achieving polarization reconfigurability, the antenna will be adaptable to diverse signal conditions, increasing its operational versatility and effectiveness in various electromagnetic environments.

- Compact and Efficient Design: A key objective is to develop a compact antenna system without compromising performance, addressing size constraints typical of modern wireless devices.

- Broad Operational Flexibility: The design will prioritize an optimal balance between bandwidth and operational flexibility, making it adaptable across multiple applications, including wireless communication, radar systems, and next-gen IoT devices.

This project will ultimately contribute to creating an antenna system that meets the evolving requirements of contemporary wireless technology.

2. PROPOSED WORK



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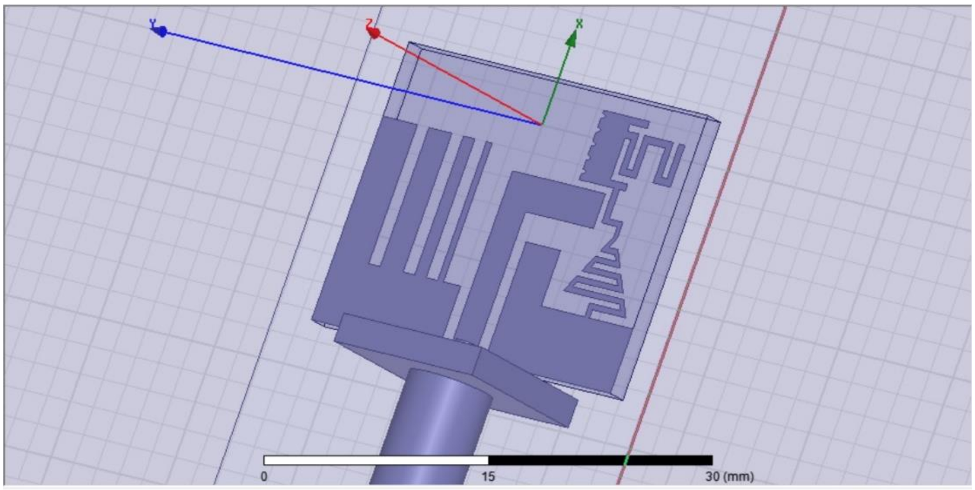

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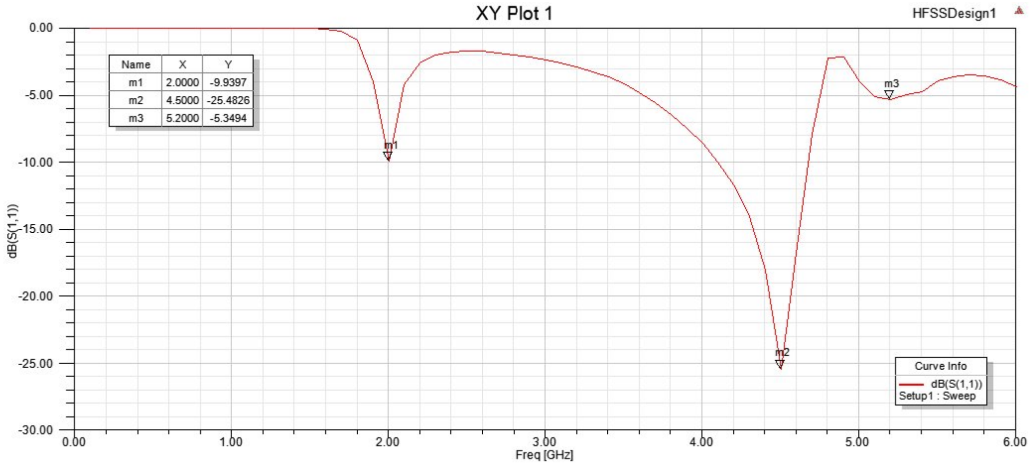

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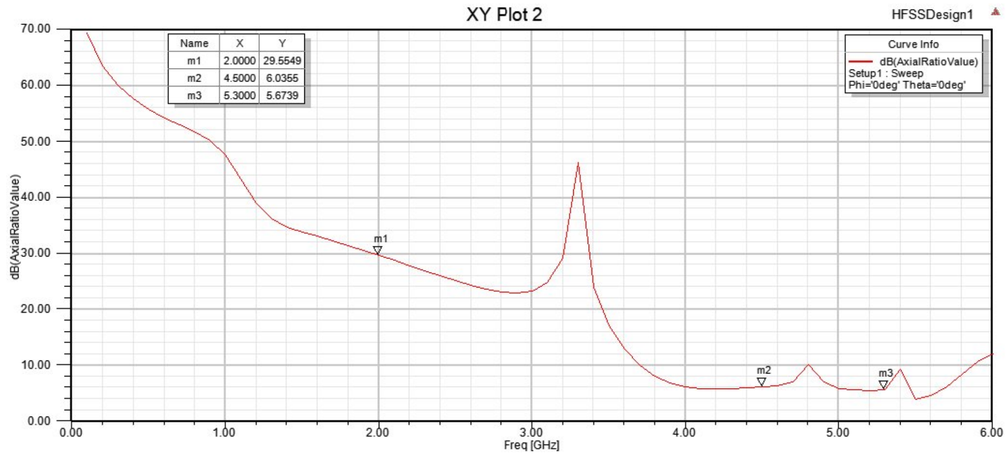

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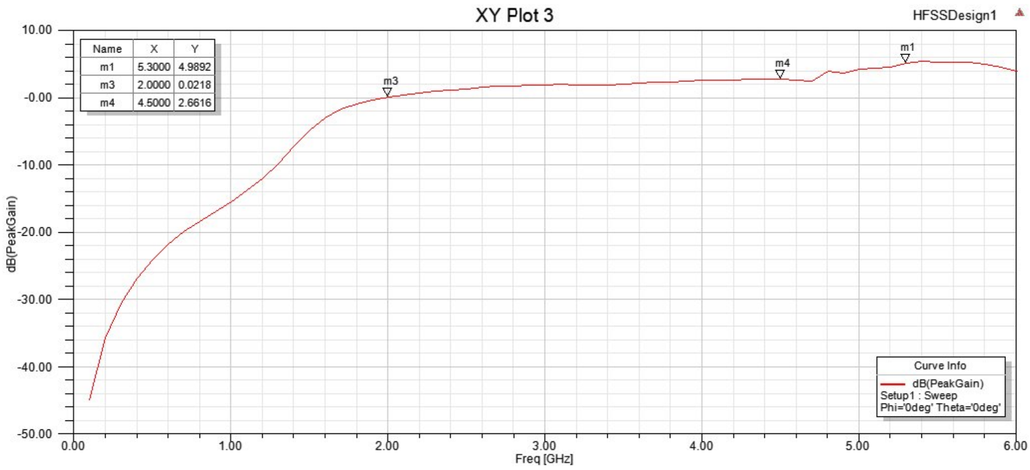

5 Gain

3. SOFTWARE TOOLS USED

Ansys HFSS 2016: Ansys HFSS 2016 is a powerful tool for simulating high-frequency electromagnetic components, specializing in antenna and RF design. It uses finite element analysis to accurately model and optimize parameters like gain, S-parameters, and radiation patterns. HFSS 2016 is essential for evaluating complex structures, enabling reliable antenna performance predictions.

Advanced Design System (ADS): Advanced Design System (ADS) by Keysight Technologies is an EDA software focused on RF, microwave, and high-speed digital designs. It provides tools for schematic capture, layout, and simulation, crucial for impedance matching and circuit analysis. ADS enables co-simulation with HFSS, ideal for detailed RF and antenna projects.

- **RESULT ANALYSIS:**

Frequency	Application
2 Ghz	• Mobile Satellite System • Military telemetry • Air traffic control (ATC) radar • GPS
4.5 Ghz	• Long-distance radio telecommunications • Nuclear Emergency Search Team (NEST) • Tethered radar balloons • Radar microwave links

4. METHODOLOGY

1. Software Tools:

-Design Simulation: Ansys HFSS (v16) is used for antenna simulations, and ADS (Advanced Design System) is applied for circuit simulations. These tools are essential for modeling, analyzing, and optimizing the electromagnetic behavior crucial for effective antenna design.

- Design Process: The project began with the design of a single-band antenna, iterating on antenna shapes and materials to enhance performance parameters such as gain, radiation efficiency, and frequency response.

2. Antenna Design Steps:

- Single-Band Antenna Design: The current focus is on developing and testing a single-band antenna with capabilities for dynamic frequency adjustment. Standard metrics like radiation efficiency and return loss are used to assess and validate performance.

- Incorporating Metamaterial Elements: Metamaterial concepts, such as Composite Right/Left-Handed (CRLH) transmission lines, are integrated to enhance the antenna's compactness and efficiency, optimizing it for 4G or 5G communication applications.

3. Testing and Simulation:

- Performance Testing: Simulations are conducted to evaluate key performance metrics, including return loss, bandwidth, and VSWR (Voltage Standing Wave Ratio). Simulated results are compared against practical measurements to validate the design.

- Design Adjustments: Ongoing refinements are being made to improve frequency agility and reconfigurability within the single-band antenna design.

4. Progress Made:

- Single-Band Antenna Design: A single-band antenna design has been successfully completed and tested using HFSS, demonstrating satisfactory performance within one targeted frequency band.

- Metamaterial Integration: Metamaterial elements have been successfully incorporated into the antenna design, showing significant improvements in signal strength and directionality.

5. WORK PLAN

6.1 Time Line:

- August – September, 2024

  We designed the antenna as a planar microstrip with some metamaterial-inspired patterns. The first dip occurs around 2 GHz, with an S11 value of around -9.94 dB The second significant dip is at 4.5 GHz, where S11 reaches -25.48 dB, indicating a strong resonance. The third minor dip at 5.2 GHz has an S11 of about -5.35 dB The S11 plot suggests this antenna operates in at least two bands, with the primary band around 4.5 GHz, which can correspond to communication standards like Wi-Fi (5 GHz) or cellular (4G/5G).

- October – November, 2024

  We started to design the antenna with the focus on reducing the antenna's physical size without sacrificing performance, using metamaterial principles to achieve compactness.

6. CONCLUSION

The objective of this project is to design a metamaterial-inspired antenna that leverages the unique electromagnetic properties of metamaterials to achieve enhanced performance in terms of frequency agility, beam steering, and polarization reconfigurability. The aim is to explore and implement a compact, efficient, and versatile antenna system that can adapt to changing environmental conditions and user requirements, suitable for applications in wireless communication, radar systems, and next-generation IoT devices. The project will focus on optimizing the antenna's design for improved bandwidth, reduced size, and increased operational flexibility

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