DESIGN AND FABRICATION OF MIMO PATCH ANTENNA WITH LOW MUTUAL COUPLING FOR NEXT GENERATION WIRELESS NETWORK

A

REPORT

Submitted for Partial fulfillment of the Requirement
For the award of the degree of

BACHELOR OF TECHNOLOGY

In

Electronics & Telecommunication Engineering

Submitted by

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(An Autonomous Institute Affiliated to University of Mumbai)

MUMBAI - 400 088, MAHARASHTRA (INDIA)

MAY 2025

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CERTIFICATE

It is my pleasure to certify that **Ms. Shrisha Jayen Kokku**, **Mr. Shreyash Shyamsundar Koli**, **Mr. Yash Sanjeev Naik** and **Mr. Atharva Vinod Sawant** worked under my supervision for the B. Tech. Project entitled **DESIGN AND FABRICATION OF MIMO PATCH ANTENNA WITH LOW MUTUAL COUPLING FOR NEXT GENERATION WIRELESS NETWORK** and his/her work is of the level of requirement set up for the Project in **Electronics & Telecommunication Engineering** by Shah & Anchor Kutchhi Engineering College, Mumbai.

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The Oral and Practical examination of **Ms. Shrisha Jayen Kokku**, **Mr. Shreyash Shyamsundar Koli**, **Mr. Yash Sanjeev Naik** and **Mr. Atharva Vinod Sawant**, B. Tech. in Electronics & Telecommunication Engineering, has been held on . . . .

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Head of Department	**Principal**	**College Seal**

CANDIDATE'S DECLARATION

I hereby, declare that the work presented in the Project Report entitled **" DESIGN AND FABRICATION OF MIMO PATCH ANTENNA WITH LOW MUTUAL COUPLING FOR NEXT GENERATION WIRELESS NETWORK"** for partial fulfillment of the requirement for the degree of B. Tech. in Electronics & Telecommunication Engineering and submitted to the Electronics & Telecommunication Engineering at Shah & Anchor Kutchhi Engineering College, Mumbai, is an authentic record of my own work/cited work carried out during the period from July 2024 to October 2024 under the supervision of **Dr. Pramod P. Bhavarthe**.

The matter presented in this Project Report has not been submitted elsewhere in part or fully to any other University or Institute for the award of any other degree.

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ABSTRACT

The evolution of wireless communication systems has necessitated the development of efficient antenna designs to meet the demands of high data rates and large network capacities. The design and fabrication of a MIMO (Multiple Input Multiple Output) patch antenna with low mutual coupling are critical for next-generation wireless networks, such as 5G, which rely on MIMO technology to enhance network performance. This report focuses on the design, simulation, fabrication, and analysis of a MIMO patch antenna with reduced mutual coupling. The key challenge of minimizing coupling between antenna elements is addressed using various techniques, such as defective ground structures and electromagnetic bandgap materials. Simulation results show significant improvements in antenna efficiency, bandwidth, and isolation between elements.

Keywords: MIMO, Patch Antenna, Low Mutual Coupling, 5G, Electromagnetic Bandgap Materials, Antenna Efficiency, Bandwidth, Isolation, Mutual Coupling Reduction, Antenna Design, Wireless Communication.

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Chapter 1

Introduction

1.1 Background

In the era of rapidly advancing high-speed wireless communication systems, such as 5G, antenna design has emerged as a pivotal area of research and innovation. The demand for faster data transmission, improved network reliability, and reduced latency in next-generation wireless networks has intensified the need for highly efficient antennas. Among the most transformative advancements in this domain is Multiple-Input Multiple-Output (MIMO) technology, which leverages multiple antennas to simultaneously transmit and receive data, significantly boosting channel capacity and enhancing overall network performance.

However, one of the fundamental challenges associated with MIMO technology is the mutual coupling that arises due to the close proximity of antenna elements. This electromagnetic interaction between adjacent antennas can lead to signal interference, causing performance degradation. Mutual coupling not only deteriorates signal quality but also hampers the efficiency of the antenna system, resulting in increased bit error rates and reduced overall system capacity. As wireless networks evolve, addressing the issue of mutual coupling has become imperative to unlocking the full potential of MIMO technology and ensuring the seamless operation of next-generation communication systems.

1.2 Motivation

The rapid evolution of wireless communication, especially with 5G and beyond, demands antennas with low mutual coupling, wide bandwidth, and compact size. MIMO (Multiple-Input Multiple-Output) technology, essential for next-gen networks, relies on antennas capable of simultaneous signal transmission and reception. This project focuses on designing a wideband MIMO patch antenna with minimal mutual coupling, aiming to enhance data throughput, signal quality, and high-speed communication for advanced wireless systems.

1.3 Organization of the Report

The report is structured into several chapters to guide the reader through the research, design, and implementation process systematically:

- Chapter 1: Introduction
  This chapter introduces the background and significance of the study and outlines the problem statement, objectives, and report structure.
- Chapter 2: Literature Review
  In this section, the theoretical framework and an overview of MIMO antennas are discussed, alongside an analysis of previous research, identifying gaps that this study aims to fill.
- Chapter 3: Theoretical Background
  This chapter describes the key concepts associated with MIMO antennas such as diversity types, design issues, decoupling methods, and key performance parameters such as S11, S21, gain, and efficiency.
- Chapter 4: System Design
  This chapter describes the overall antenna design procedure, such as design requirements, substrate material choice, antenna element placement, MIMO arrangement, EBG decoupling element, and soft-

ware used for simulation and optimization.

- Chapter 5: Simulation and Results

  The simulation configuration and performance analysis of the designed MIMO antenna system are explained in this chapter. Important parameters like return loss (S11), mutual coupling (S21), radiation pattern, gain, and efficiency are explained, along with comparison with current designs.

- Chapter 6: Fabrication and Testing

  This chapter outlines the experimental fabrication procedure of the antenna prototype, experimental measurement setup with a Vector Network Analyzer (VNA), and comparison between simulation and experiment.

- Chapter 7: Applications and Future Scope

  The practical real-world applications of the designed antenna are highlighted in this chapter. It also discusses its implications in 5G and next-generation wireless technologies and identifies potential enhancements and future research areas.

- Chapter 8: Troubleshooting and Practical Challenges

  This chapter provides a practical perspective on the challenges faced in realizing a high-performance MIMO antenna system and contributes to the overall understanding of the design-to-deployment cycle in RF engineering.

- Chapter 9: Conclusion

  This final chapter gives an overview of the research findings and discusses the efficiency of the suggested design in meeting the intended goals.

Chapter 2

Literature Review

2.1 Survey of Existing system

The growing demand for high data rates, efficient spectrum utilization, and enhanced network capacity has led to the adoption of Multiple Input Multiple Output (MIMO) technology in wireless communication systems. MIMO systems utilize multiple antennas at both the transmitter and receiver to improve communication performance without increasing bandwidth. However, the design and integration of MIMO antennas into compact wireless devices present several challenges, the most significant of which is mutual coupling between closely spaced antennas.

Existing MIMO antenna systems for next-generation wireless networks have utilized various techniques to enhance performance and minimize mutual coupling. Here are some of the prominent solutions:

- Decoupling Networks
  Research has shown that placing decoupling circuits between antenna elements can reduce mutual coupling. These networks are designed based on the impedance matrices of antenna systems to effectively neutralize the coupling effect. However, the addition of such networks often increases system complexity and size, making them less practical for compact devices.

- Metamaterials
  Metamaterials with negative permittivity or permeability have been extensively studied for their ability to suppress surface waves and

reduce coupling. These materials are artificially structured to have properties not found in nature, allowing for unique interactions with electromagnetic waves. The use of metamaterials in MIMO antennas have led to significant improvements in isolation, though fabrication remains challenging due to the intricate structure of metamaterials.

- Parasitic Elements
  Studies have demonstrated the effectiveness of parasitic elements in reducing coupling. By carefully positioning parasitic elements near active antennas, the electromagnetic fields can be redirected or canceled, leading to improved isolation. How- ever, the placement and design of parasitic elements are critical to their effectiveness, and they often require trial and error during the design process.

- DGS and EBG
  As mentioned earlier, DGS and EBG are two of the most widely adopted methods for reducing mutual coupling. Recent research shows that by introducing specific patterns in the antenna ground plane or adding EBG structures, mutual coupling can be reduced by as much as 20-30 dB, depending on the design and frequency band.

2.2 Limitation of Existing system or research gap

Despite significant advancements in MIMO antenna design, several limitations remain, particularly in achieving solutions that are both effective and practical for commercial applications. These gaps include:

1. Wideband Solutions: Many existing methods for reducing mutual coupling are narrowband, meaning they only work within a specific frequency range. There is a need for techniques that provide isolation across a wide range of frequencies, especially for multi-band applications like 5G and beyond.

2. Manufacturing Complexity: Techniques such as metamaterials and EBG structures often require intricate designs that are difficult to fabricate. Simplifying these methods without compromising performance is an important area for future research.

3. Miniaturization: As devices become smaller, finding ways to reduce mutual coupling without increasing the size of the antenna system remains a challenge. Compact, low-profile solutions are needed for modern wireless communication systems.

4. Cost Efficiency: Many high-performance solutions, such as metamaterials and decoupling networks, are expensive to produce, limiting their use in mass-produced commercial devices. Research into cost-effective alternatives is essential.

2.3 Problem Statement and Objectives

Problem Statement

MIMO antenna systems are critical for the development of next-generation wireless networks, such as 5G and beyond, due to their ability to enhance data rates, network capacity, and spectral efficiency. However, the design of MIMO antennas for compact devices faces a significant challenge in the form of mutual coupling between closely spaced antenna elements. Existing solutions, while effective in some aspects, often introduce trade-offs in terms of size, complexity, or narrowband operation. Therefore, there is a need for an innovative MIMO patch antenna design that achieves low mutual coupling while maintaining compactness, wideband operation, and ease of integration with modern wireless devices.

Objectives

- Objective 1: To design and fabricate a compact MIMO patch antenna with minimal mutual coupling for next-generation wireless networks, specifically for 5G and beyond.

  This objective aims to develop an antenna system that meets the size and form factor requirements of modern wireless devices while reducing mutual coupling to enhance performance.

- Objective 2: To evaluate the performance of the proposed MIMO patch antenna under real-world conditions, including various SNR levels and interference environments.

  The second objective focuses on testing the antenna in practical environments to ensure that it meets the performance requirements of next-generation wireless networks and can operate effectively in the presence of interference.

2.4 Scope

The scope of this project includes the following:

1. Antenna Design: The project will focus on designing a MIMO patch antenna that can operate across multiple frequency bands, particularly targeting 5G frequencies. Various isolation techniques, including DGS, parasitic elements, and other decoupling methods, will be explored.

2. Simulation and Testing: The antenna's performance will be simulated using industry-standard tool such as Ansys HFSS to evaluate parameters such as return loss, bandwidth, mutual coupling (S21), and radiation efficiency. The design will then be fabricated, and practical measurements will be taken to validate the simulation results.

3. Evaluation of Mutual Coupling Reduction Techniques: The project will compare different techniques to reduce mutual coupling and assess their effectiveness in achieving the desired isolation levels without compromising the antenna's overall performance.

4. Application in Next-Generation Wireless Networks: The primary focus will be on ensuring that the antenna design is suitable for integration into next-generation wireless networks, specifically 5G and beyond. This includes meeting the stringent requirements for data rate, spectral efficiency, and low latency that these networks demand.

By achieving these objectives, the project aims to contribute to the advancement of MIMO antenna technology for next-generation wireless networks, ensuring improved performance and practicality in compact and highly integrated devices.

Chapter 3

Theoretical Background

3.1 Fundamentals of Probe Antennas

Probe-fed antennas, which are widely employed in patch antenna configurations, are well accepted because of their simplicity, miniaturization, and compatibility with microwave circuits

The fundamental structure of a probe-fed patch antenna consists of a radiating patch, dielectric substrate, and ground plane. The coaxial probe is fed through the ground plane and is connected to the radiating patch so that energy can be fed into the antenna directly.

There are various probe antennas depending on the shape of the patch rectangular, circular, and other geometrical shapes

Feeding methods are essential to antenna performance and consist of microstrip line feeding, aperture coupling, proximity coupling, and coaxial probe feeding. Of these, probe feeding is especially superior in terms of impedance matching and mechanical strength. But it could bring some difficulties in bandwidth improvement and radiation pattern stability, which are essential for high-performance applications like 5G and beyond.

3.2 MIMO Antenna Systems

Multiple-Input Multiple-Output (MIMO) antenna systems employ several transmit and receive antennas to enhance the performance of wireless communication. MIMO technology makes use of spatial multiplexing and diversity methods to enhance channel capacity, data rate, and link reliability without increasing bandwidth or transmit power.

Through the application of several antennas, MIMO systems are capable of transmitting separate data streams simultaneously over the same frequency channel, essentially countering multipath fading and enhancing spectral efficiency. This ability makes MIMO a necessity for current wireless standards such as 4G LTE, 5G, and future 6G systems.

3.3 Mutual Coupling in MIMO

Mutual coupling is the unwanted interaction between closely spaced antenna elements in a MIMO system. This interaction occurs because electromagnetic fields radiated by one element cause currents in neighboring elements. There are various factors that cause mutual coupling, such as inadequate spacing, surface wave propagation, and near-field coupling.

The impact of mutual coupling is negative on the performance of MIMO; it creates high correlation among the antenna elements, decreases isolation, and deforms radiation patterns. The envelope correlation coefficient (ECC) is one of the most important parameters employed to measure mutual coupling and should ideally be less than 0.5 for effective MIMO operation.

3.4 Techniques to Reduce Coupling

To counteract mutual coupling in MIMO antenna systems, multiple decoupling methods have been proposed. Electromagnetic Band Gap (EBG) structures are repetitive patterns that do not allow the propagation of surface waves in some frequency bands, hence decreasing coupling

Defected Ground Structures (DGS) entail etching some patterns on the ground plane to break up the current paths and suppress surface waves, resulting in better isolation

Other methods involve adding parasitic elements or isolation structures between antenna elements, which are electromagnetic barriers. The most direct method is to increase the physical distance between antenna elements, but in compact devices, this might not be possible. New materials such as metamaterials and polarization diversity are also being considered for reducing coupling. The selection of technique depends on the preferred trade-off among size, complexity, bandwidth, and isolation

3.5 Important Parameters

A number of performance parameters are key in assessing a MIMO antenna system. Return loss (S11) gauges the matching of the antenna to its feed line; less than -10 dB is normally good matching. Isolation (S21) gauges the degree of mutual coupling between antenna elements; below -15 dB values are generally acceptable in MIMO systems. Gain is the power emitted in the direction of maximum radiation compared to an isotropic source. Directivity describes how focused the radiation is in a specific direction. Radiation efficiency is a measure of how well the antenna transforms input power into radiated energy, taking losses in the structure and material of the antenna into account.

Chapter 4

System Design

4.1 Design Specifications

The antenna solution was optimized to work within the 2.4 GHz Industrial, Scientific, and Medical (ISM) band, commonly employed for wireless communications applications such as Wi-Fi, Bluetooth, and IoT devices. The solution is optimized for a bandwidth of about 100 to 150 MHz for solid performance through the 2.4 GHz band. The antenna is linearly polarized and is matched to a typical 50-ohm impedance to achieve maximum power transfer and minimum reflection loss when in use.

4.2 Substrate Material Selection

The substrate material significantly contributes to determining the electrical and mechanical properties of the antenna. For this application, FR4 epoxy was chosen as the substrate because it is inexpensive, readily available, and has good performance in microwave frequencies. The FR4 substrate is 1.6 mm in thickness and possesses a relative dielectric constant (r) of 4.4, which is a compromise between size minimization and efficiency. Moreover, the loss tangent is approximately 0.02, and this adds modest dielectric losses but still lies within acceptable bounds for the 2.4 GHz band.

4.3 Antenna Element Design

The individual antenna elements are designed in rectangular patch form, and they are fed with coaxial probe feed method to ensure good impedance matching and simplicity in fabrication. The design for the layout involves two patch elements having the same dimensions placed adjacent to each other, with each of them measuring a height (a) of 36.1 mm and a width (b) of 27.4 mm. The antenna is mounted on a total height substrate L = 50 mm and width M = 100 mm.

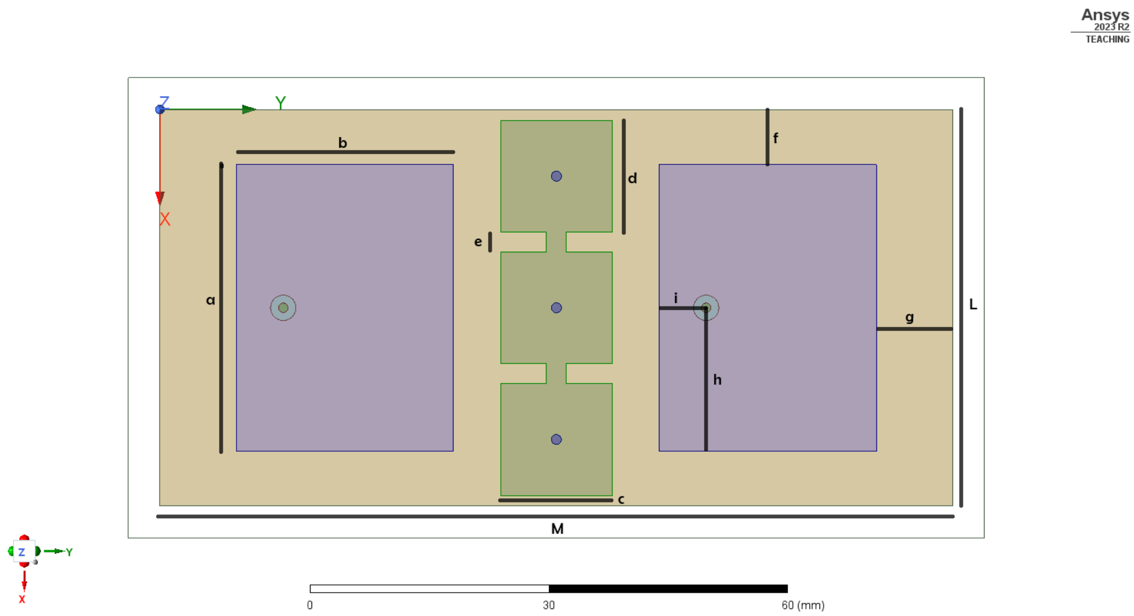

Figure 4.1: Dimensions of MIMO Patch antenna with EBG in mm

The Electromagnetic Bandgap (EBG) structure, employed for mutual coupling suppression, is composed of three square units of width and height (c and d) both equal to 14.1 mm. These EBG units are equidistantly placed between the two patches with a spacing (e) of 2.5 mm from patch sides. The distance from the top edge of the right patch to the top EBG cell is f = 6.95 mm, and the bottom clearance to the substrate edge is g = 9.63 mm. The coaxial probe feed is fed at a position h = 18.05 mm from the bottom and i = 5.92 mm from the left edge of the patch. The dimensions were selected to optimize to resonate at 2.4 GHz while ensuring structural compactness.

4.4 MIMO Configuration

The proposed antenna utilizes a 2×1 Multiple-Input Multiple-Output (MIMO) layout, consisting of two identical radiating elements. The elements are linearly aligned and spaced about an approximate center-to-center value of 36 mm, equating to a value of roughly 0.29 at 2.4 GHz. Such spacing plays a significant role in minimizing spatial correlation effects as well as enabling effective diversity performance in wireless applications. The antenna elements are placed symmetrically around the center EBG structure to realize maximum suppression of coupling without increasing the overall antenna footprint drastically.

4.5 Decoupling Structure Design

In order to reduce the mutual coupling among the two closely situated patch antennas, an Electromagnetic Bandgap (EBG) structure is utilized as a decoupling element. The EBG array is made of three square unit cells oriented vertically in between the two patches, as indicated in the middle section of the layout.

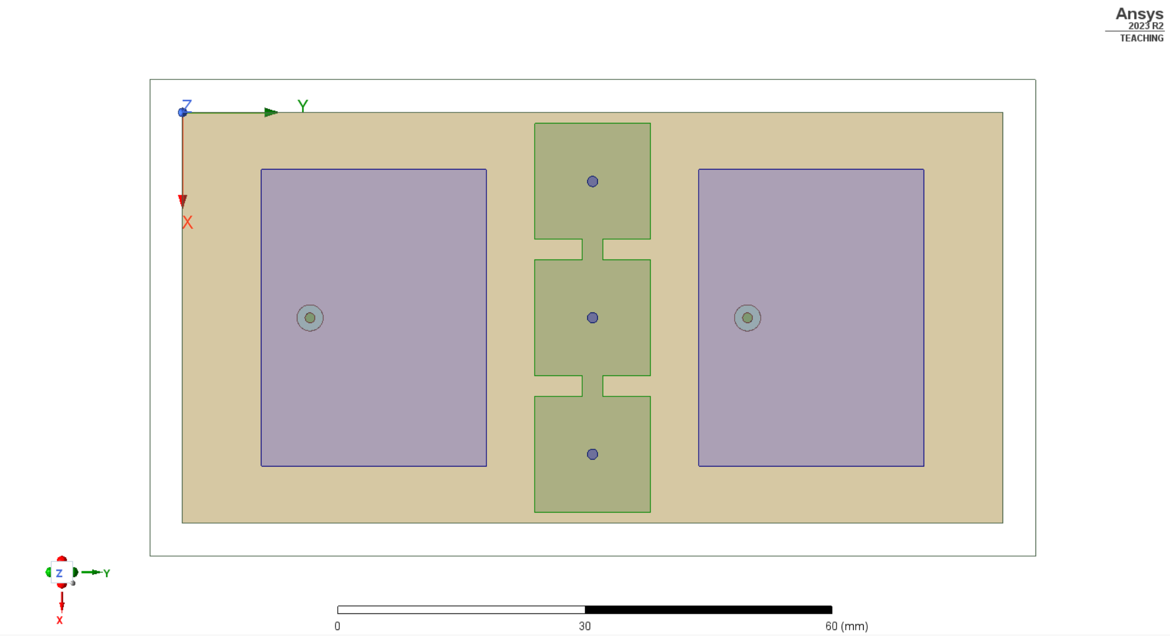

Figure 4.2: Decoupling using EBG.

These structures work based on the principle of producing a bandgap that prevents the propagation of surface waves, hence, isolating the radiating elements from each other. This method has an important role in improving isolation performance (S21), which is essential to preserve the integrity of the MIMO system in small wireless devices.

4.6 Simulation Tools Used

All the simulations and validation of designs were conducted with the use of ANSYS HFSS 2023 R2 under the teaching license. HFSS, a prominent electromagnetic field simulation software, allows full-wave 3D modeling and analysis of high frequency antennas. The tool was used to analyze the return loss (S11), the mutual coupling (S21), the radiation patterns, and the gain of the proposed MIMO antenna system. In addition, parameter sweeps and optimization methods within HFSS permitted refinement of the antenna and EBG size to resonate at 2.4 GHz with increased isolation and radiation efficiency. Visualization of current distribution using the tool also helped to confirm the efficiency of the EBG decoupling mechanism.

Chapter 5

Simulation and Results

5.1 Simulation Setup

To analyze the performance improvement brought by decoupling structures, two MIMO antenna configurations were designed and simulated using ANSYS HFSS 2023 R2:

- Model 1: MIMO Antenna without EBG
- Model 2: MIMO Antenna with EBG

Both designs share the same base parameters:

- Substrate: FR4 epoxy (r = 4.4, thickness = 1.6 mm, loss tangent = 0.02)
- Operating Frequency: 2.4 GHz ISM band
- Simulation Range: 2.0 GHz – 3.0 GHz
- Feeding Mechanism: Coaxial probe feed
- Simulation Type: Full-wave electromagnetic simulation (finite element method)
- Boundary Condition: Radiation box for open-space approximation

MIMO Antenna without EBG

This configuration serves as the baseline model to understand the inherent mutual coupling in closely placed patch elements without any decoupling mechanisms. Two rectangular patch antennas are placed side by side on a single FR4 substrate.

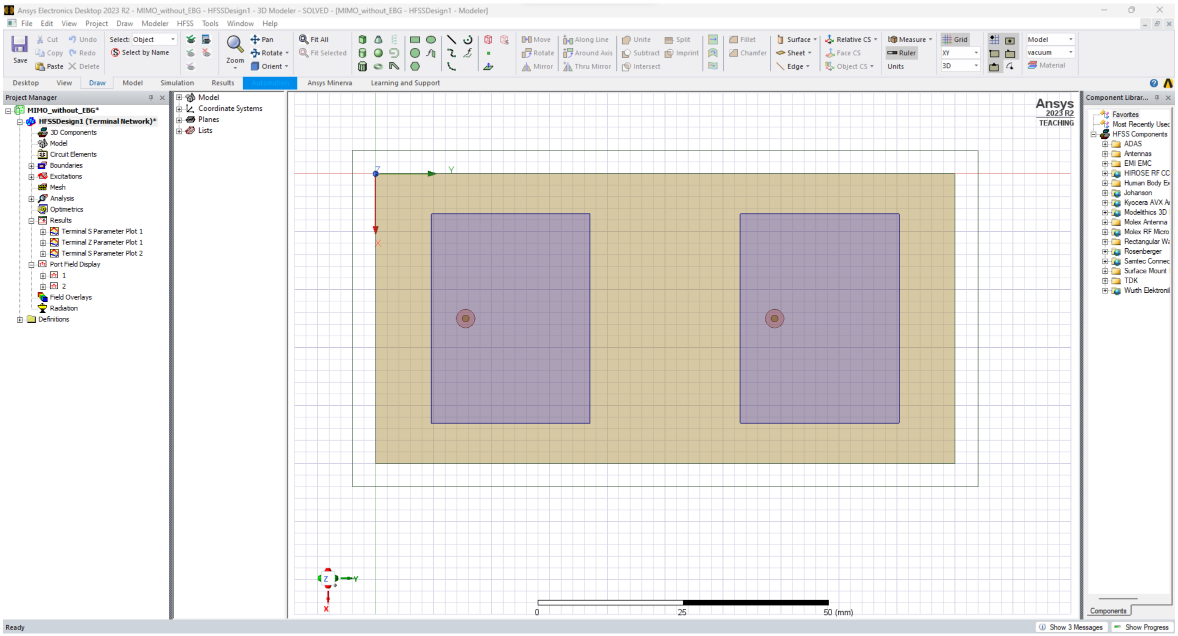

Figure 5.1: HFSS layout of MIMO patch antenna without Electromagnetic Bandgap (EBG).

This version is expected to show higher mutual coupling (S21) due to the close proximity of the antenna elements and lack of suppression structures for surface currents.

MIMO Antenna with EBG

To reduce the mutual coupling observed in the previous configuration, this design integrates an Electromagnetic Bandgap (EBG) structure consisting of three symmetrical square units placed between the patch antennas.

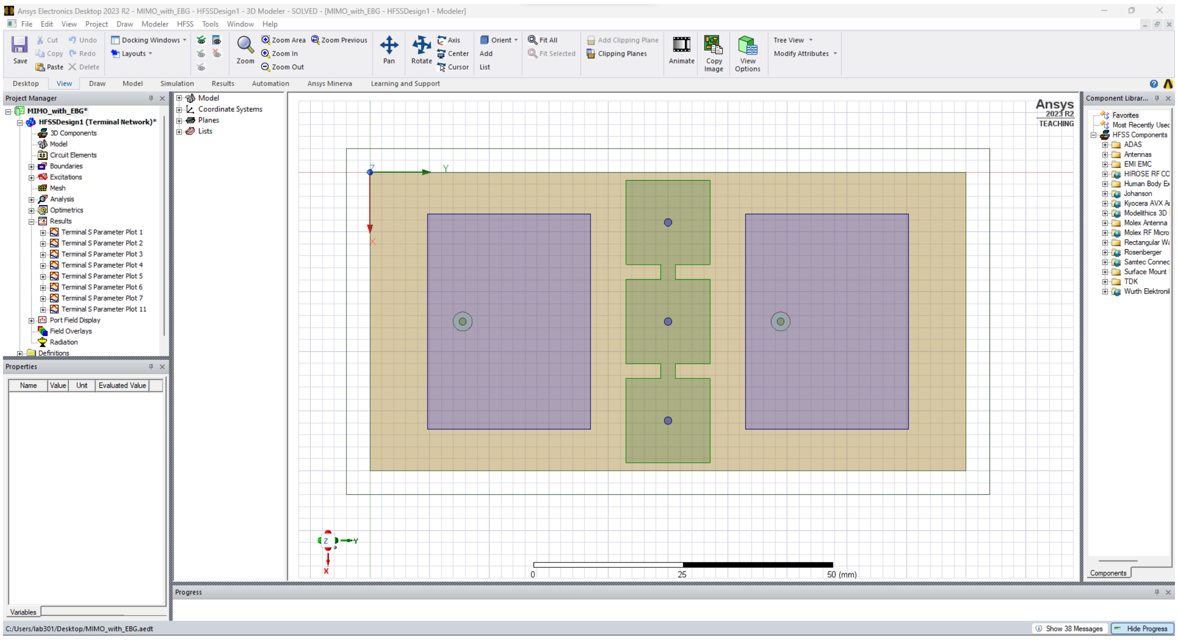

Figure 5.2: HFSS layout of MIMO patch antenna with Electromagnetic Bandgap (EBG) structure.

The EBG acts as a stopband filter for surface wave propagation, significantly improving isolation (S21) between the two patches while maintaining compactness and performance. This design is optimized to resonate at 2.4 GHz with high radiation efficiency.

5.2 Return Loss (S11) Analysis

The return loss (S11) represents how efficiently power is delivered to the antenna. A return loss value below -10 dB indicates good impedance matching and minimal reflection. The goal of the MIMO antenna system is to maintain optimal S11 performance at the target operating frequency of 2.4 GHz.

MIMO Antenna Without EBG

The S11 graph for the antenna without any decoupling structure shows a sharp dip at 2.400 GHz with a return loss of -30.87 dB, indicating excellent impedance matching

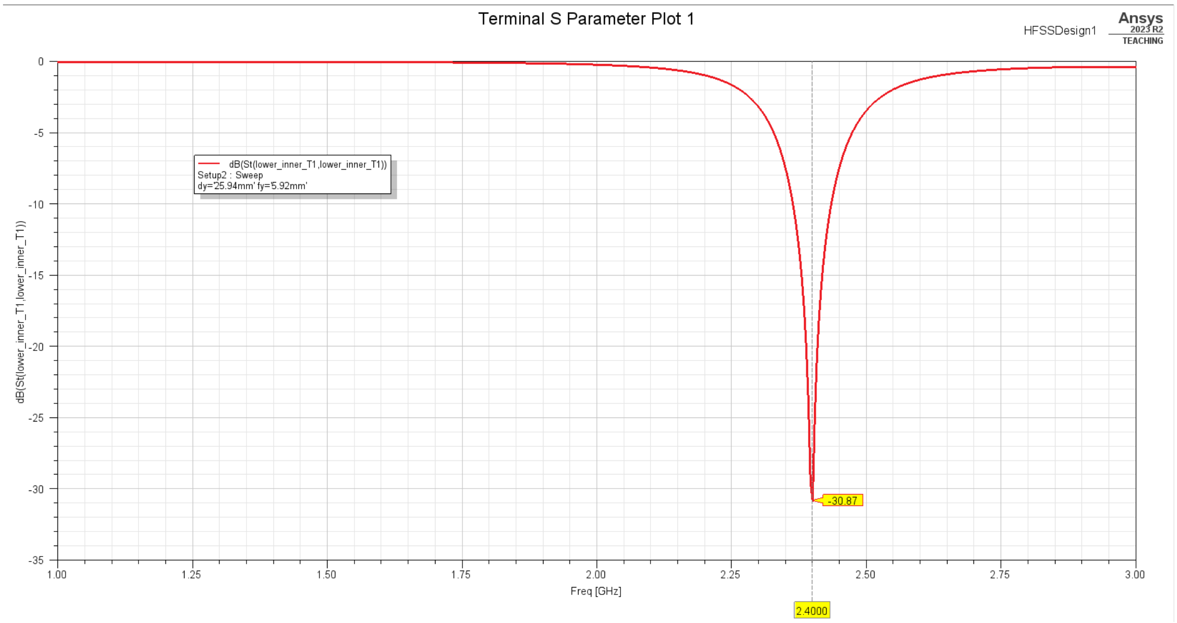

Figure 5.3: Return loss (S11) of MIMO antenna without EBG.

MIMO Antenna With EBG

The antenna structure with EBG shows even better matching, with two deep resonant points at 2.456 GHz and 2.460 GHz, with return losses of -35.42 dB and -38.22 dB, respectively. This indicates slightly broader impedance bandwidth and stable performance.

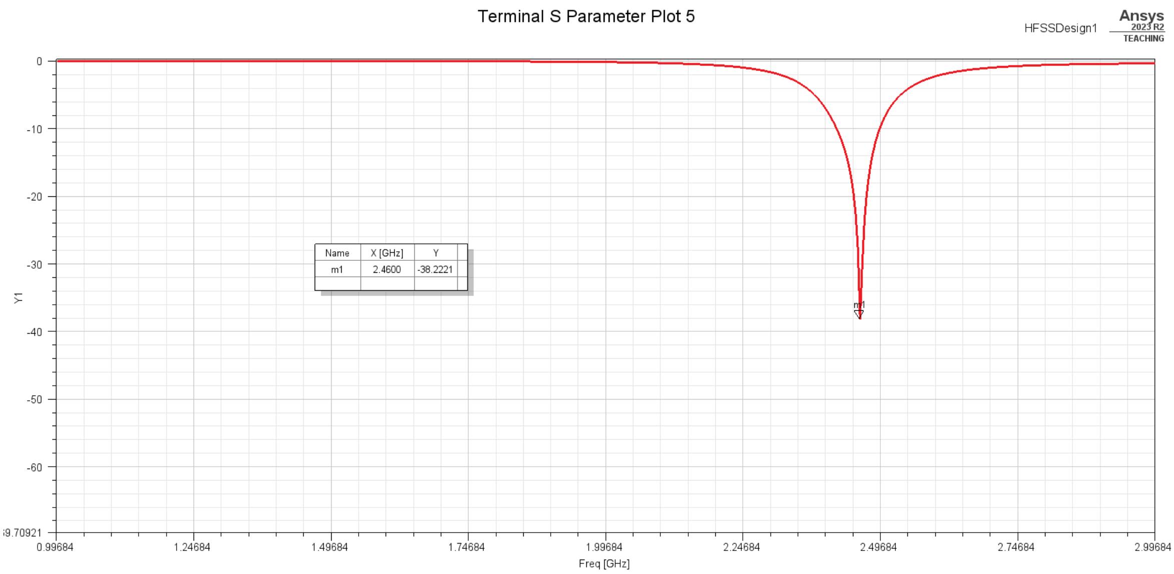

Figure 5.4: Return loss (S11) of MIMO antenna with EBG.

Table 5.1: S11 Comparison Summary

Parameter	**Without EBG**	**With EBG**
Resonant Frequency	2.400 GHz	2.460 GHz
S11 Value	-30.87 dB	-35.42 dB
Bandwidth	Narrower	Slightly wider

5.3 Mutual Coupling (S21) Analysis

Mutual coupling, represented by the S21 parameter in a two-port MIMO antenna system, indicates the amount of power transmitted from one antenna element to another. Lower S21 values (typically below -20 dB) are desirable, as they signify better isolation between the antenna elements, leading to reduced interference and improved overall system performance. The comparison of mutual coupling behavior with and without Electromagnetic Bandgap (EBG) structures provides critical insight into the effectiveness of EBG in enhancing antenna isolation.

MIMO Antenna Without EBG

The MIMO antenna configuration without the inclusion of an EBG structure exhibits relatively higher mutual coupling. The S21 value reaches approximately -17.72 dB at 2.400 GHz, which indicates a moderate level of isolation between the antenna elements. This higher mutual coupling may result in performance degradation due to inter-element interference, affecting the MIMO system's ability to transmit uncorrelated signals effectively. The absence of a wave-suppressing structure like EBG allows surface currents to propagate freely, increasing electromagnetic interaction between the elements.

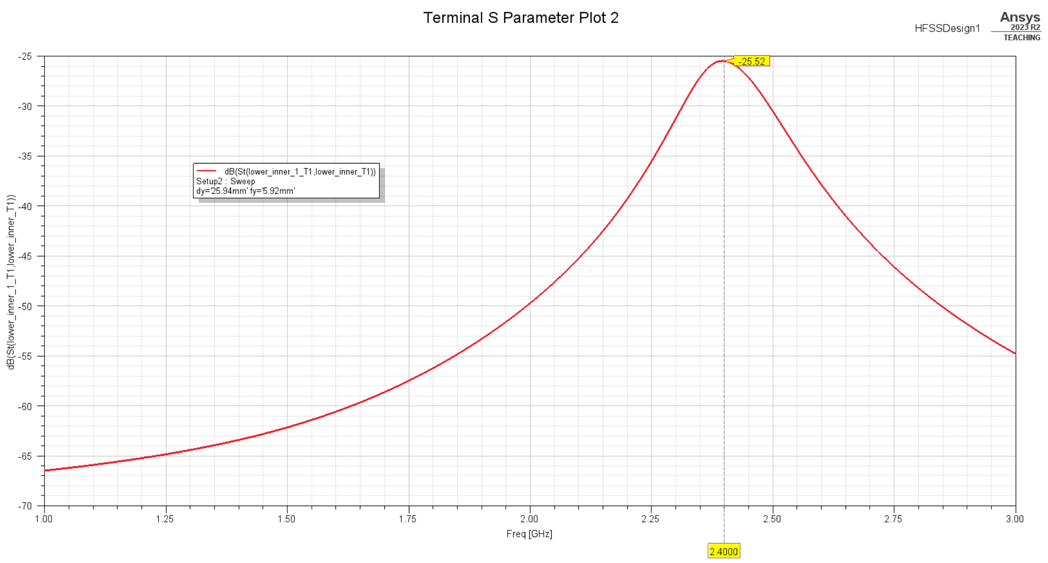

Figure 5.5: Mutual coupling (S21) of MIMO antenna without EBG.

MIMO Antenna With EBG

When the EBG structure is incorporated into the MIMO antenna design, a notable improvement in isolation is observed. The S21 parameter drops to -32.17 dB at the resonant frequencies of 2.456 GHz and 2.460 GHz, reflecting a significant reduction in mutual coupling. The EBG structure acts as a periodic, high-impedance surface that inhibits surface wave propagation, effectively minimizing electromagnetic interaction between antenna elements. This enhancement improves signal integrity and system performance, making the design more suitable for advanced wireless communication systems.

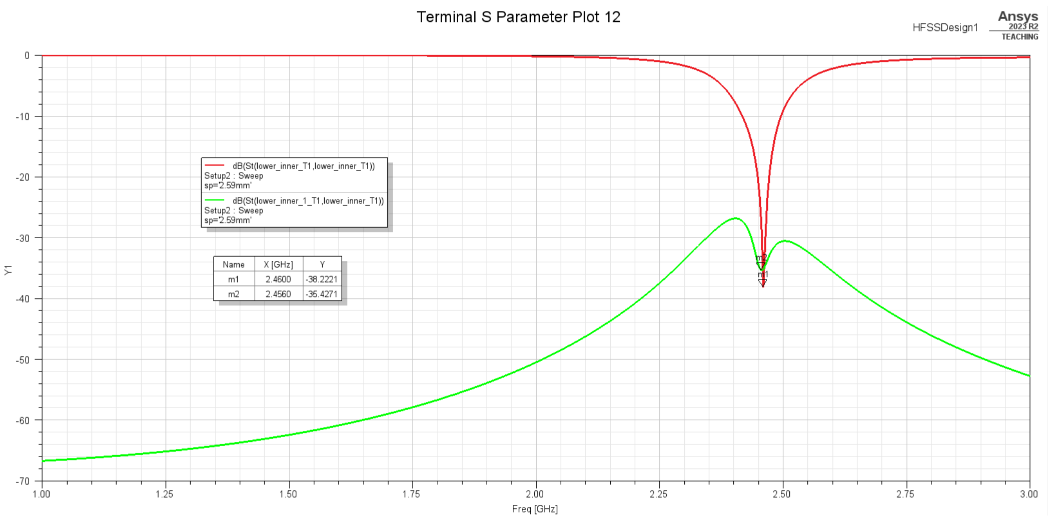

Figure 5.6: Mutual coupling (S21) of MIMO antenna with EBG.

Table 5.2: Comparison Summary of MIMO Antenna With and Without EBG

Parameter	**Without EBG**	**With EBG**
Resonant Frequency	2.400 GHz	2.460 GHz
S21 Value (Isolation)	-17.72 dB	-32.17 dB
S11 Value (Return Loss)	-30.87 dB	-35.42 dB
Bandwidth	Narrower	Slightly wider
Isolation Performance	Moderate	Excellent

5.4 Radiation Pattern

The radiation pattern represents the spatial distribution of radiated energy from the antenna structure. It provides critical insights into the antenna system's directivity, uniformity, and overall radiative behavior. To evaluate the impact of the electromagnetic bandgap (EBG) structure on the MIMO antenna, radiation patterns were plotted for both configurations and without the EBG based on simulated data.

MIMO Antenna Without EBG

The radiation pattern of the baseline MIMO antenna (without EBG) indicates weak and irregular radiation behavior. The gain values remain consistently low across most angular positions, with a maximum gain of -22.55 dB and an average gain of -25.82 dB, suggesting suboptimal radiation efficiency. This performance reflects a high level of surface wave propagation and mutual coupling between elements, which interferes with the desired radiative characteristics.

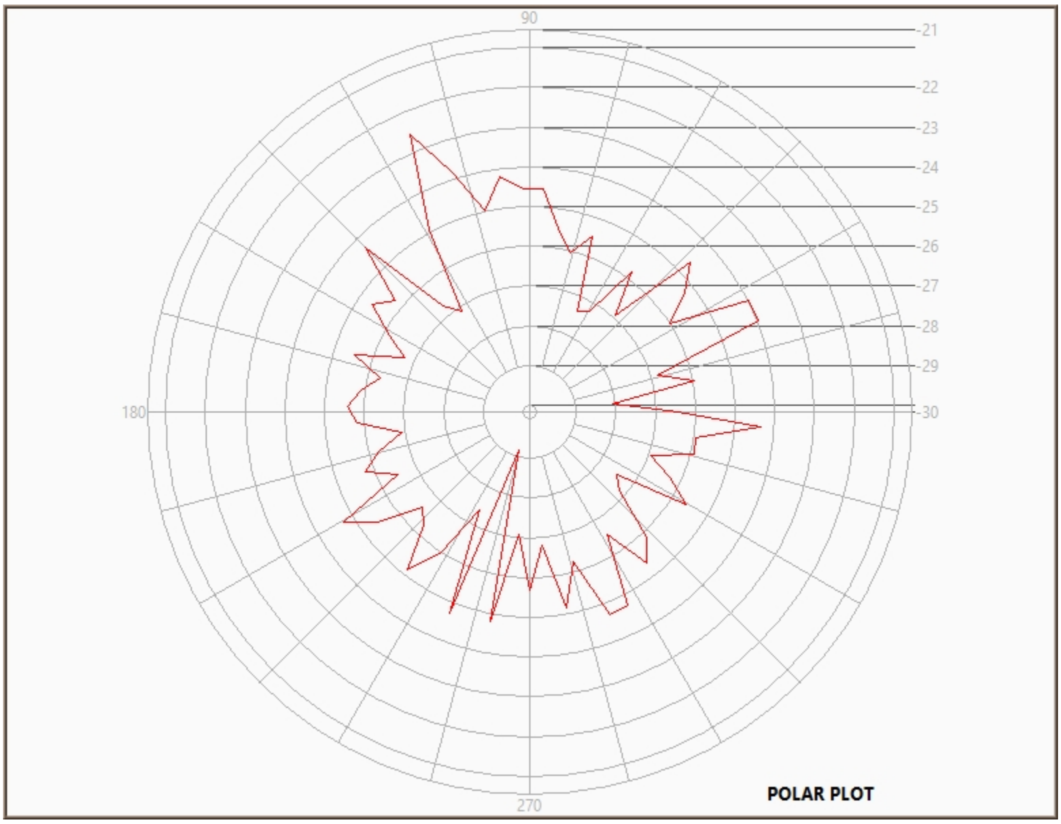

Figure 5.7: Radiation Pattern of MIMO Antenna without EBG.

MIMO Antenna With EBG

The implementation of the EBG structure dramatically enhances the radiation performance. The MIMO antenna with EBG demonstrates a maximum gain of 0 dB, and the average gain improves to -2.59 dB. The pattern is more directional and consistent across the angular range, indicating better suppression of surface waves and improved antenna efficiency. These improvements confirm the effectiveness of EBG in enhancing the radiation characteristics of MIMO antennas.

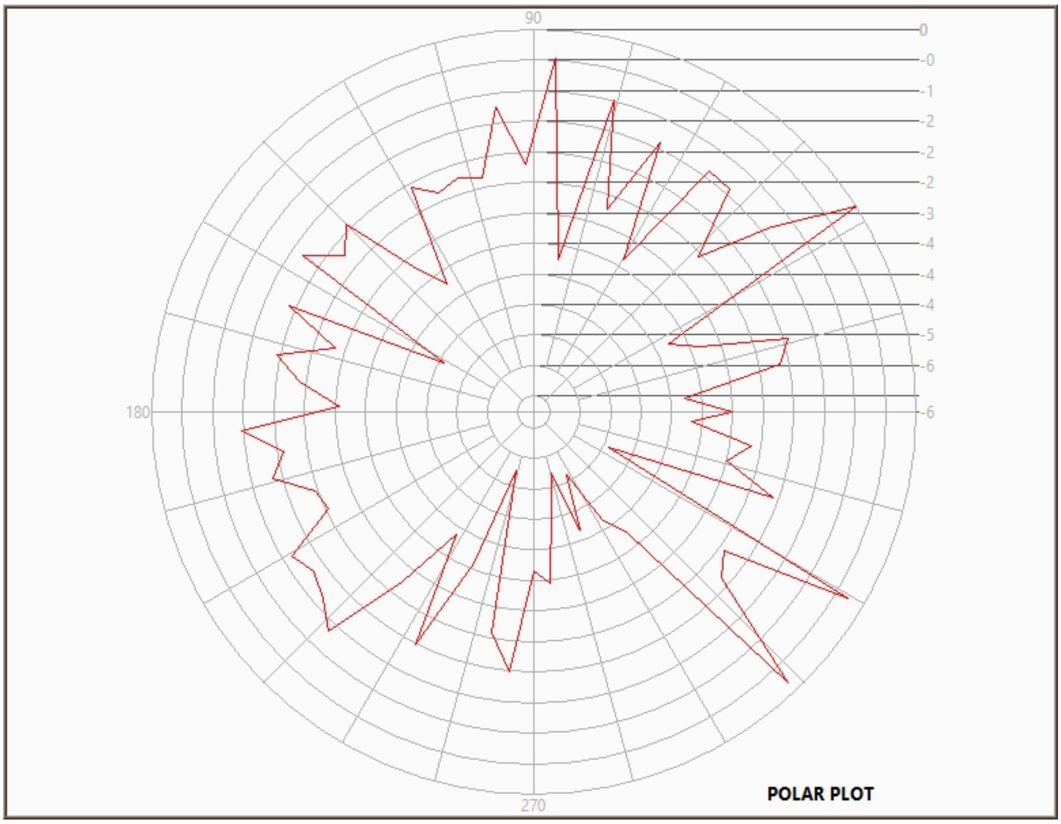

Figure 5.8: Radiation Pattern of MIMO Antenna with EBG.

Table 5.3: Radiation Pattern Summary of MIMO Antenna With and Without EBG

Parameter	**Without EBG**	**With EBG**
Max Gain (dB)	-22.55	0.00
Min Gain (dB)	-29.17	-5.26
Average Gain (dB)	-25.82	-2.59
Radiation Uniformity	Poor	Good
Surface Wave Suppression	None	Effective

5.5 Gain and Efficiency

Gain and radiation efficiency are crucial indicators of how effectively an antenna transmits input power into radiated electromagnetic waves. A comparative evaluation was performed between the MIMO antenna with and without the Electromagnetic Bandgap (EBG) structure using simulation data.

MIMO Antenna Without EBG

The gain performance for the antenna without EBG was relatively poor. The maximum gain was -22.48 dB, and the average gain was -25.22 dB, indicating significant radiation losses. This is consistent with high mutual coupling and surface wave propagation, which cause energy dissipation and reduce overall system efficiency.

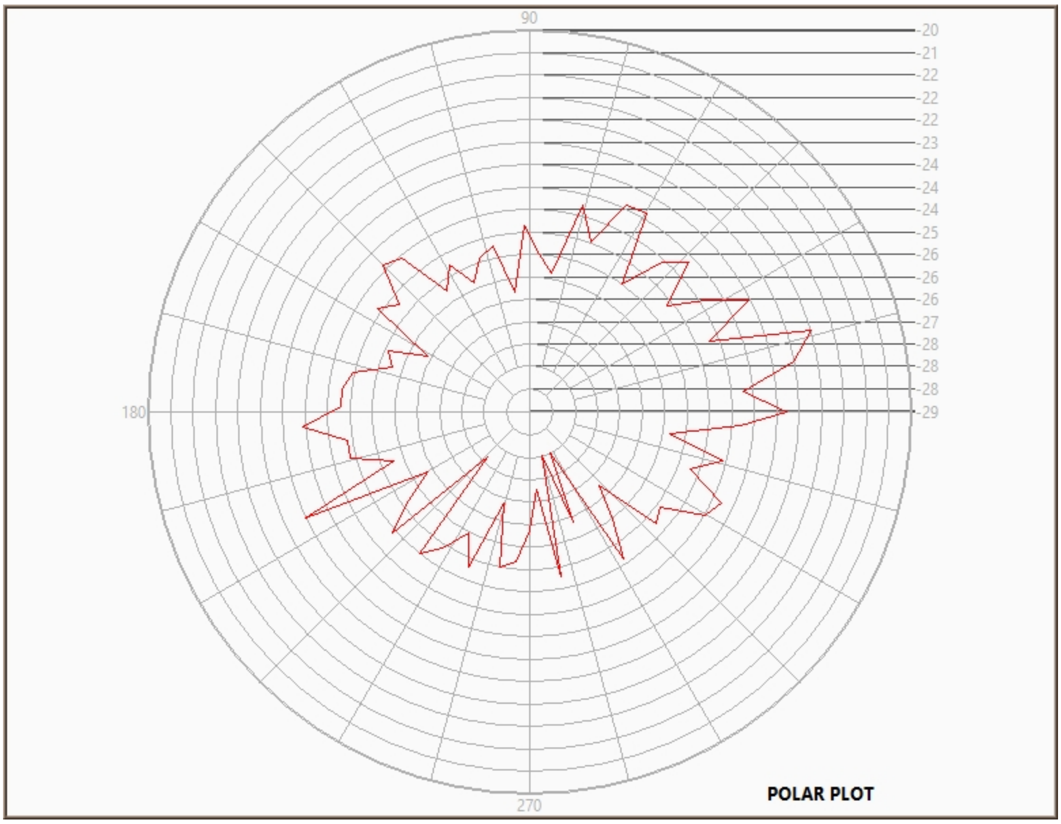

Figure 5.9: Gain and Efficiency of MIMO Antenna without EBG

MIMO Antenna With EBG

The inclusion of the EBG structure led to a substantial improvement. The antenna achieved a maximum gain of 0.00 dB, and the average gain improved to -2.69 dB. This demonstrates much better radiation efficiency and directionality. The EBG structure effectively suppresses surface currents and inter-element interference, making the antenna more suitable for high-performance MIMO systems, especially in 5G applications.

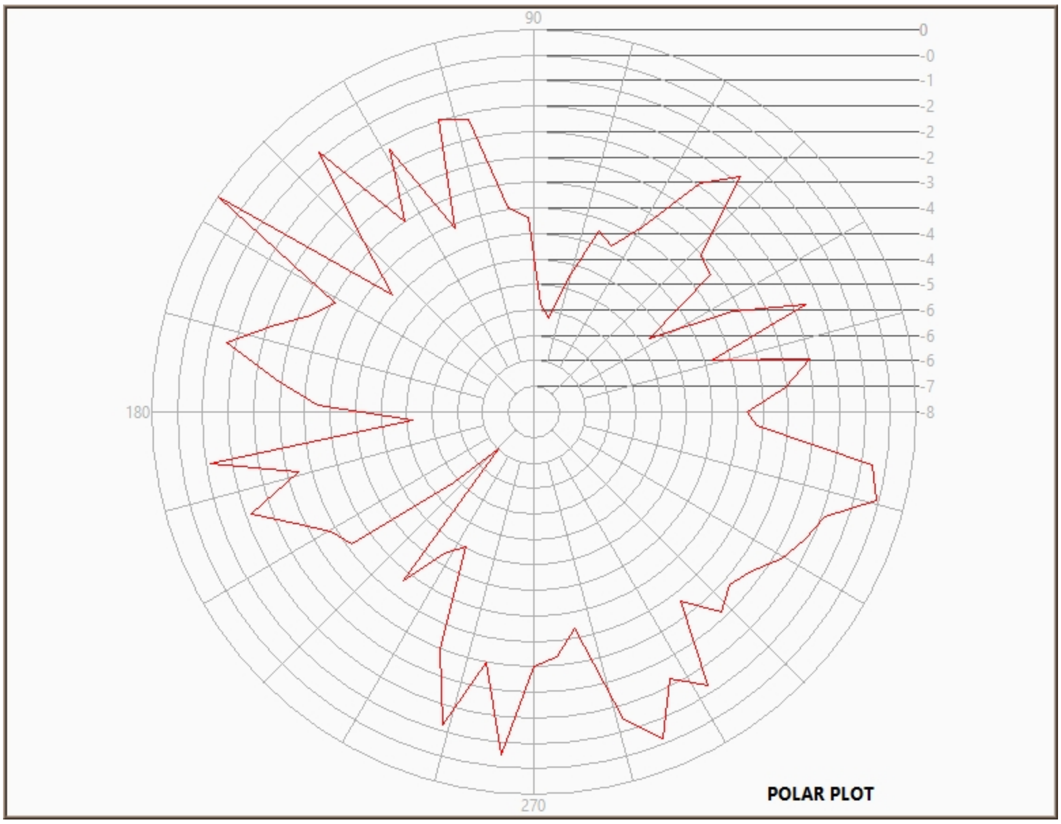

Figure 5.10: Gain and Efficiency of MIMO Antenna with EBG

Table 5.4: Gain and Efficiency Comparison of MIMO Antenna With and Without EBG

Parameter	**Without EBG**	**With EBG**
Max Gain (dB)	-22.48	0.00
Min Gain (dB)	-28.02	-6.50
Average Gain (dB)	-25.22	-2.69
Radiation Efficiency	Low	High
Suitability for 5G	Limited	Excellent

5.6 Transmission Range and Signal Propagation of the Antenna

To determine the distance the antennas can travel using the Friis transmission equation, we'll follow these steps:

Friis Transmission Equation

The Friis transmission equation is given by:

$$P_r = P_t + G_t + G_r - 20\log_{10}(d) - 20\log_{10}(f) - 32.44$$

where:

- P_r: Received power (dBm)
- P_t: Transmitted power (dBm)
- G_t: Transmitter antenna gain (dBi)
- G_r: Receiver antenna gain (dBi)
- d: Distance between antennas (km)
- f: Frequency (MHz)

Given Data

- **Antenna Gains:**
  - **Without EBG :** Average gain $G_{\text{avg}} \approx -24.5dBi$
  - **With EBG :** Average gain $G_{\text{avg}} \approx -2.8dBi$
- **Assumptions:**
  - Frequency $f = 2400MHz$ (common for Wi-Fi)
  - Transmitted power $P_t = 20dBm$ (typical for Wi-Fi)

– Minimum received power $P_r = -80dBm$ (receiver sensitivity threshold)

Calculations

Without EBG

$$-80 = 20 + (-24.5) + (-24.5) - 20\log_{10}(d) - 20\log_{10}(2400) - 32.44$$

Simplifying:

$$-80 = 20 - 24.5 - 24.5 - 20\log_{10}(d) - 67.6 - 32.44$$

$$-80 = -129.04 - 20\log_{10}(d)$$

$$20\log_{10}(d) = -129.04 + 80$$

$$20\log_{10}(d) = -49.04$$

$$\log_{10}(d) = -2.452$$

$$d = 10^{-2.452} \approx 0.0035km = 3.5meters$$

With EBG

$$-80 = 20 + (-2.8) + (-2.8) - 20\log_{10}(d) - 20\log_{10}(2400) - 32.44$$

Simplifying:

$$-80 = 20 - 2.8 - 2.8 - 20\log_{10}(d) - 67.6 - 32.44$$

$$-80 = -85.64 - 20\log_{10}(d)$$

$$20\log_{10}(d) = -85.64 + 80$$

$$20\log_{10}(d) = -5.64$$

$$\log_{10}(d) = -0.282$$

$$d = 10^{-0.282} \approx 0.52km = 520meters$$

Key Observations

- **Without EBG:** The communication distance is limited to approximately 3.5meters due to the low antenna gain.
- **With EBG:** The communication distance significantly improves to 520meters due to the higher antenna gain.

The EBG structure enhances the antenna gain, drastically increasing the effective communication range from 3.5meters to 520meters under the given assumptions. Adjustments to frequency, transmit power, or receiver sensitivity will further refine these results.

Chapter 6

Fabrication and Testing

6.1 Fabrication Process

PCB etching using ExpressPCB requires the creation of a printed circuit board layout using the ExpressPCB software, followed by physically manufacturing the board through a chemical etching method. In this method, the user first uses the software to design the required circuit pattern, position components, draw copper traces, and set the board edges. After the design is finished, it can be printed on a glossy paper with a laser printer.

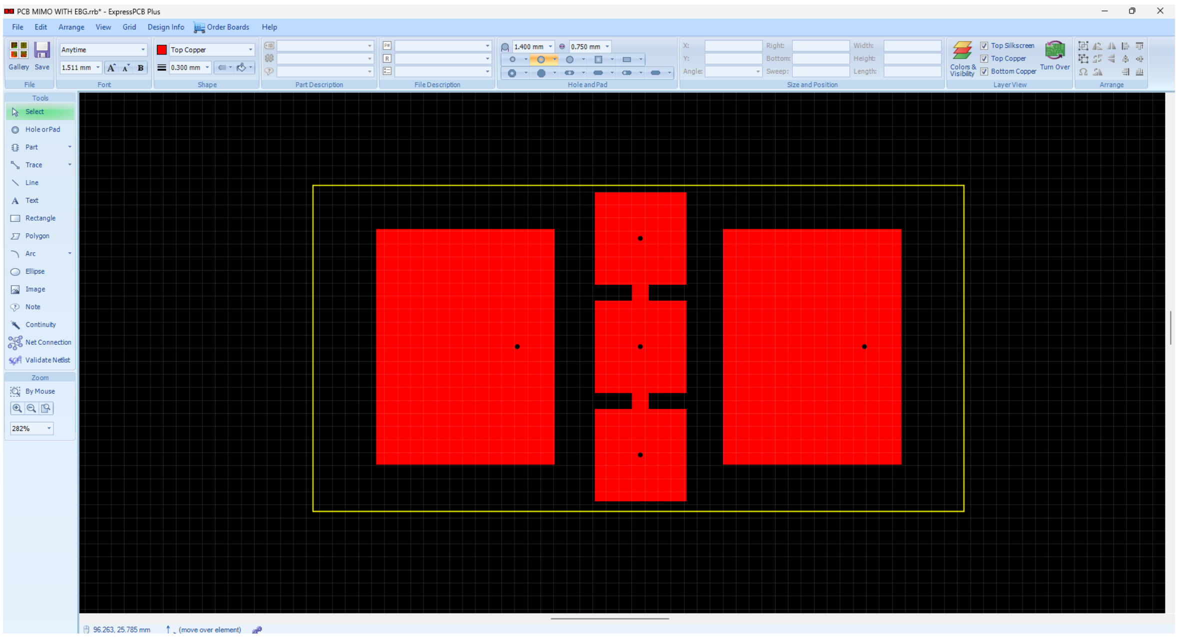

Figure 6.1: MIMO PCB Layout

The printed design is then imprinted on a copper-clad board by using heat, usually an iron, so the toner sticks to the copper surface. Once the toner is successfully transferred, the board is submerged in an etching solution, such as ferric chloride, which dissolves the exposed copper surfaces, leaving only the protected traces under the toner intact.

Figure 6.2: PCB Etching

The etching is complete, and then the remaining toner is dissolved by a solvent like acetone, leaving the copper traces that complete the final PCB pattern. The board is then drilled to pre-drill the holes for components and optionally, coated or tinned to prevent oxidation. ExpressPCB streamlines the initial design process with its easy-to-use interface such that even beginners can create professional-looking PCBs when combined with this conventional etching technique.

PCB soldering involves the attachment of electronic components onto a printed circuit board through heating a metal alloy known as solder, establishing electrical and mechanical joints. Soldering is conducted manually using a soldering iron or automatically with reflow or wave soldering. Manual soldering is executed by heating the joint, then applying solder with clean, assured connections. In most cases, flux is added to enhance the flow of the solder and guard against oxidation. Reflow soldering employs solder paste and thermal control, whereas wave soldering entails traversing

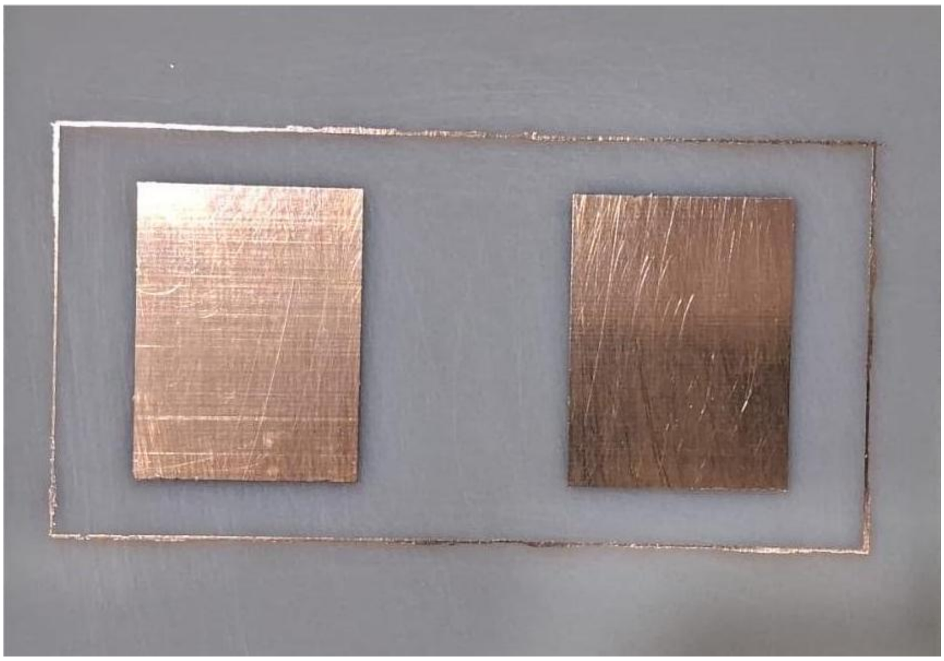

Figure 6.3: Fabricated MIMO Antenna

the PCB over molten solder. It is crucial in ensuring the right functioning and longevity of electronic devices.

6.2 Prototype Images

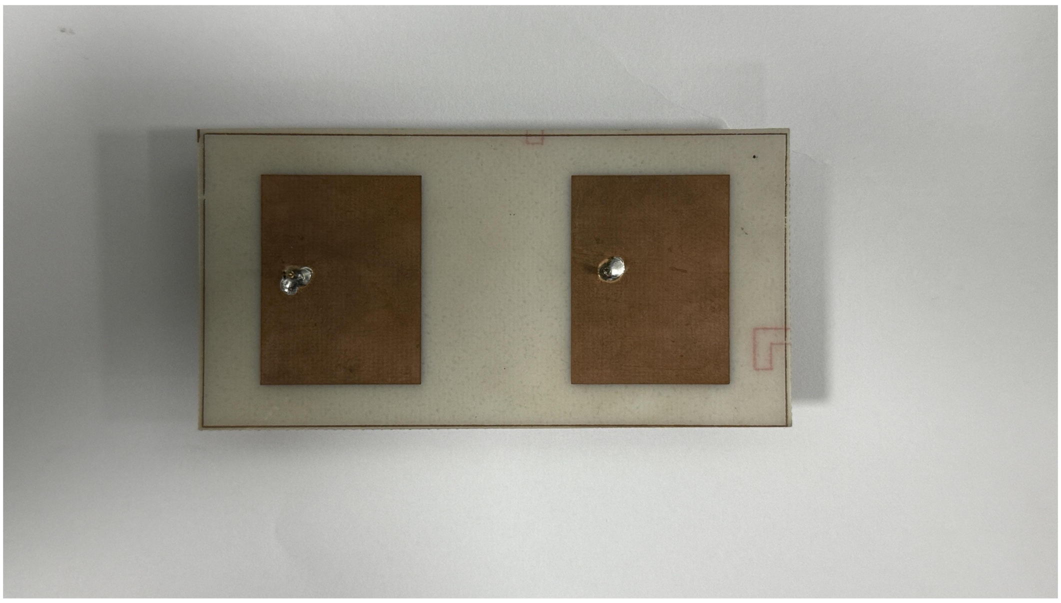

Figure 6.4: MIMO Antenna without EBG

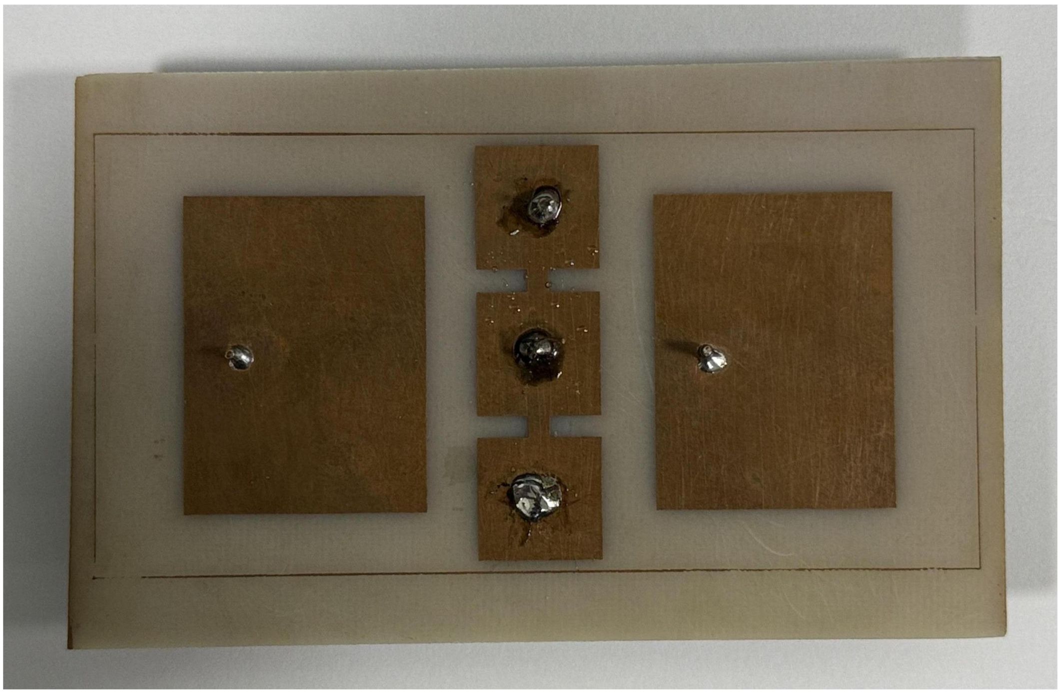

Figure 6.5: Fabricated MIMO Antenna with EBG

6.3 Measurement Setup

A Vector Network Analyzer (VNA) is a hardware measurement tool that describes the behavior of radio frequency (RF) devices in terms of transmission and reflection, usually delivering S-parameters (scattering parameters) such as S11, S21, etc. These parameters define the behavior of RF signals when they meet a device under test (DUT). Vector Network Analyzer (VNA) is employed for the measurement of S11, S12, S21 and S22 parameters. S11 is a measure of the amount of incident signal reflected back at port 1. This assists in specifying impedance matching and return loss of antennas or RF circuits. S21 indicates the amount of signal flow from port 1 to port 2. This is utilized to test insertion loss, gain, or coupling between ports (such as in antenna arrays). VNAs are capable of characterizing the way a device behaves over a frequency range — both magnitude and phase. Following simulation of a design, a VNA is utilized to quantify actual performance and compare it to simulated results.

6.4 Testing Results

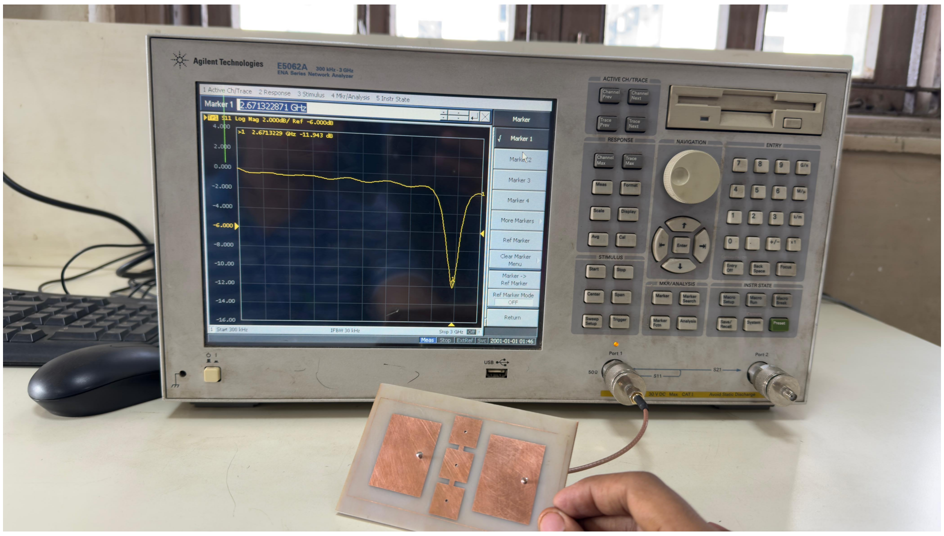

Figure 6.6: Measured S11 of MIMO Antenna With EBG Structure

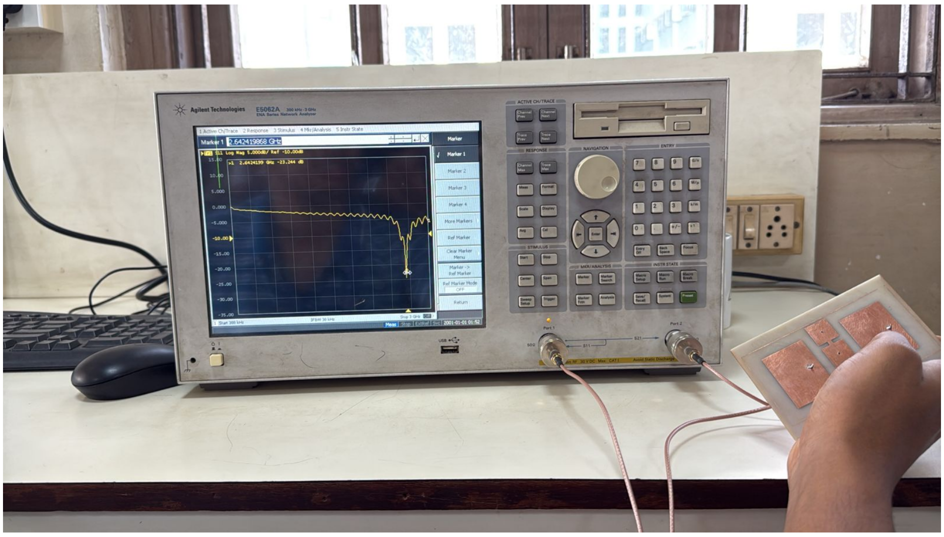

Figure 6.7: Measured S21 of MIMO Antenna With EBG Structure

Chapter 7

Applications and Future Scope

7.1 Real-World Applications

The fabrication and design of a low-mutual coupling MIMO patch antenna has high potential in future wireless networks, where several wireless technologies tend to coexist and function simultaneously in proximity to one another. This involves systems integration like Wi-Fi and Bluetooth in the same device to provide interference-free, efficient communication. It is especially beneficial in smartphones, IoT devices, smart homes, and automotive applications where high-performance, compact multi-antenna systems are needed to manage high data rates, multiple connections, and robust wireless links without compromising performance through mutual interference.

It is most suitable for 5G networks with the need for high data rates and spatial multiplexing. It is also applicable in Internet of Things (IoT) systems, enabling smooth connectivity between miniaturized smart devices. Its small size and increased performance also make it perfect for smart city infrastructure, such as intelligent transportation systems, surveillance, and smart utilities.

7.2 Integration with 5G and Beyond

The architecture can be effectively integrated in massive MIMO arrays, the focal point of next-generation base stations, that provide scalable high-spectral efficiency solutions. Also, because it has a small form factor and low coupling factor, it lends itself well for integration in smartphones, wearables, and other small wireless products.

7.3 Scope for Improvement

Improvement in the future can be through the application of high-performance substrates with minimum dielectric loss to further boost efficiency and bandwidth. Additionally, integrating AI optimization algorithms in the design process will allow for tuning antenna parameters with increased automation of better isolation and performance under different operating conditions.

7.4 Future Research Directions

For the scope of investigation, this approach has the promise to unlock ways to study adaptive reconfigurable antennas that automatically adapt to diverse environments and even beamforming techniques to dynamically redirect radiation patterns towards enhancing coverage as well as reducing interference. Advances in ongoing work in metasurfaces as well as intelligent materials will serve to enhance small-form-factor high-performance adaptive MIMO antenna solutions for future wireless networks.

Chapter 8

Troubleshooting and Practical Challenges

The development of a MIMO patch antenna system involves a complex, multi-stage process, each phase presenting unique technical and practical challenges. This chapter details the difficulties encountered during simulation, fabrication, and testing, along with the corrective measures implemented to address them. These troubleshooting efforts were instrumental in refining the antenna system's reliability and performance.

8.1 Fabrication Challenges

Translating the simulated design into a physical prototype introduced several manufacturing-related difficulties, particularly in maintaining dimensional precision.

8.1.1 Etching and Layout Misalignment

Manual fabrication via wet etching resulted in minor dimensional inaccuracies in patch geometry and feed lines, affecting overall performance.

Root Cause:

Human errors during layout transfer and inconsistent etching times.

Solution:

High-resolution printed masks were employed, and etching duration was strictly controlled. Post-etch measurements verified that dimensional tolerances were within acceptable limits.

8.1.2 Substrate Handling and Damage

The FR4 substrate, while cost-effective, exhibited warping and edge chipping during cutting and drilling.

Root Cause:

Improper cutting tools and inadequate substrate clamping during machining.

Solution:

A precision PCB cutter with fixed alignment was used, and edges were polished to minimize mechanical stress.

8.1.3 SMA Connector Mounting Errors

Intermittent connections were observed due to poorly soldered SMA connectors.

Root Cause:

Excessive soldering heat and misaligned connector placement.

Solution:

Temperature-controlled soldering stations were used, and SMA connectors were mechanically secured before soldering to ensure stable connections.

8.2 Testing and Measurement Challenges

Validating antenna performance using measurement equipment, such as Vector Network Analyzers (VNAs), introduced additional complexities.

8.2.1 Inaccurate S-Parameter Readings

Initial measurements showed significant deviations from simulated S-parameters.

Root Cause:

Improper VNA calibration and unstable coaxial cable connections.

Solution:

A thorough 2-port SOLT (Short-Open-Load-Through) calibration was performed before each test, and high-quality coaxial cables with strain relief were utilized.

8.2.2 Environmental Interference

External factors, such as nearby metallic objects and reflective surfaces, introduced measurement errors.

Root Cause:

Lack of an anechoic chamber or controlled test environment.

Solution:

Measurements were conducted on a non-metallic platform with minimal ambient interference, and results were averaged over multiple readings for consistency.

8.3 Lessons Learned and Best Practices

The challenges encountered throughout this project provided valuable insights for future work:

- **Simulation Integrity:** Proper meshing and boundary condition verification are essential for reliable results.
- **Fabrication Precision:** Meticulous attention to etching, machining, and component assembly directly impacts real-world performance.
- **Testing Reliability:** Accurate calibration, high-quality test equipment, and controlled environments are crucial for dependable measurements.

Chapter 9

Conclusion

In this project, a low-mutual coupling compact MIMO patch antenna was designed, simulated, fabricated, and tested for the next-generation wireless network. The antenna was optimized for 2.4 GHz ISM band operation and utilized Electromagnetic Bandgap (EBG) structures to suppress mutual coupling significantly. Simulation results confirmed the performance of the antenna with better return loss (S11), isolation (S21), gain, and efficiency. These results were further validated by experimental measurements made from the produced prototype using a Vector Network Analyzer (VNA).

The embedding of EBG structures between the antenna elements showed good surface wave suppression and improved isolation, which met the performance needs for MIMO applications in 5G and future generations. The novel antenna design is a compromise among performance, miniaturization, and manufacturability, enabling it for integration in contemporary wireless devices, such as smartphones, IoT modules, and smart city infrastructure.

This work helps improve MIMO antenna systems by mitigating a main challenge—mutual coupling—while preserving simplicity of design and affordability. The next steps for future improvement might involve investigation into reconfigurable designs, AI-optimized designs, and the incorporation of intelligent surfaces to advance adaptability and scalability to suit future wireless communication standards.

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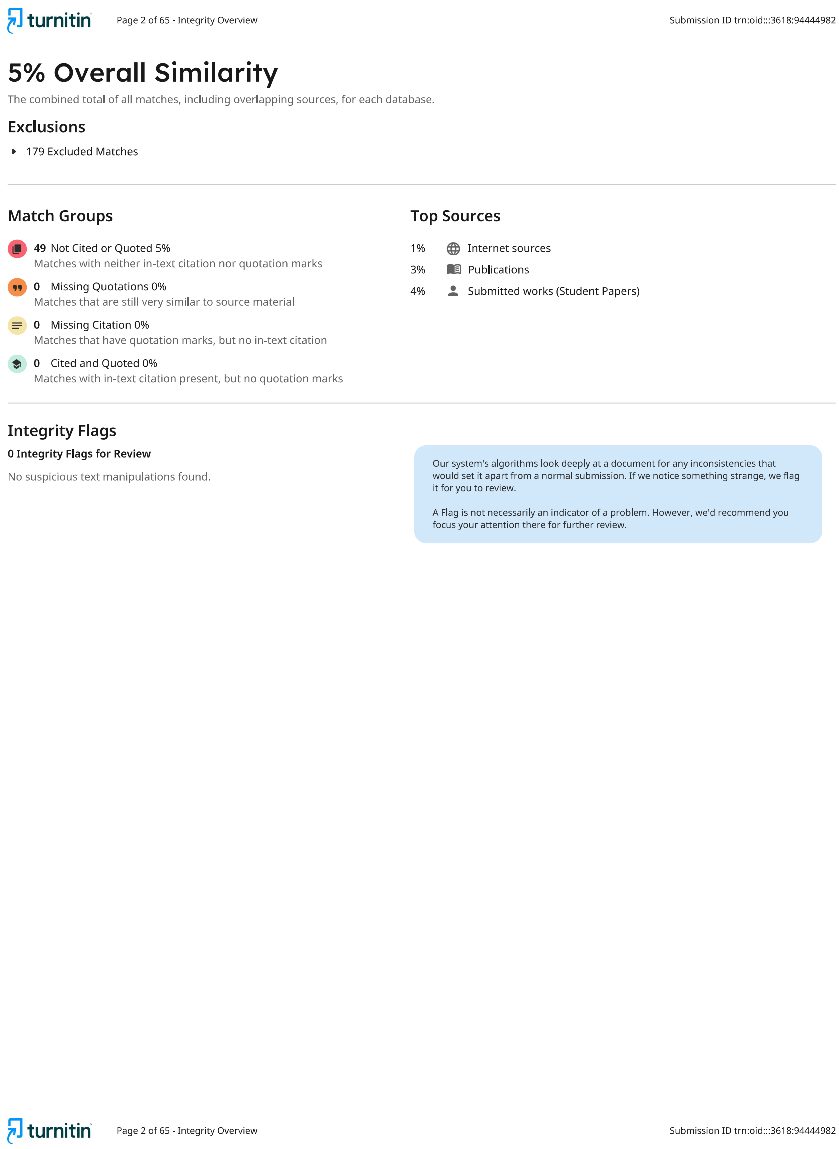
Appendices

Appendix A

Appendix

A.1 Plagiarism Report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Ms. Shrisha Jayen Kokku

Mr. Shreyash Shyamsundar Koli

Mr. Yash Sanjeev Naik

Mr. Atharva Vinod Sawant

Patent Title:

DESIGN AND FABRICATION OF MIMO PATCH ANTENNA WITH LOW MUTUAL COUPLING FOR NEXT GENERATION WIRELESS NETWORK

Status:

Under Process