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GOVERNMENT COLLEGE OF ENGINEERING, AMRAVATI

A Project Report on

Design and Simulation of 42 GHz Microstrip Patch Antenna For 5G Application Using Ansys High Frequency Structure Simulator [HFSS]

Submitted to

Government College of Engineering, Amravati for the partial fulfilment of requirements of degree of Bachelor of Technology in Electronics and Telecommunication Engineering

By

Nayan Vinod Meshram [21004011]

Akash Avinash Mahajan [21004015]

Jay Ashok Lokhande [21004016]

Mihir Rajesh Jaiswal [21004063]

Supervised by

S. J. Meshram

Department of Electronics and Telecommunication Engineering,

Government College of Engineering, Amravati (M.S.)

2024-2025

GOVERNMENT COLLEGE OF ENGINEERING, AMRAVATI

Department of Electronics and Telecommunication Engineering

2024-2025

CERTIFICATE

This is to certify that the project report entitled

Design and Simulation of 42 GHz Microstrip Patch Antenna For 5G Application Using Ansys High Frequency Structure Simulator [HFSS]

submitted by

Nayan Vinod Meshram [21004011]

Akash Avinash Mahajan [21004015]

Jay Ashok Lokhande [21004016]

Mihir Rajesh Jaiswal [21004063]

to Government College of Engineering, Amravati for the partial fulfilment of requirements of degree of Bachelor of Technology in Electronics and Telecommunication Engineering, is a bonafide record of the project work carried out by them under my guidance and supervision. This report in any form has not been submitted to any other institute for any purpose.

S. J. Meshram
Assistant Professor
Electronics & Telecommunication
Telecommunication GCOE, Amravati

Dr. P. R. Deshmukh
Head of Department
Electronics &
GCOE, Amravati

Dr. A. M. Mahalle

Principal

GCOE, Amravati

Examiner

DECLARATION

We, hereby declare that the major report on **Design and Simulation of 42 GHz Microstrip Patch Antenna for 5G Application Using Ansys High Frequency Structure Simulator [HFSS]**, submitted for partial fulfilment of the requirements for the award of degree of **Bachelor of Technology in Electronics & Telecommunication** is a bonafide work done by us under supervision of **S. J. Meshram.**

This submission represents ideas in our own words and where ideas or words of others have been included, we have adequately and accurately cited and referenced the original sources.

We also declare that we have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in our submission. We understand that any violation of the above will be a cause for disciplinary action by the institute and/or the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

Place: Amravati

Date:

Nayan Vinod Meshram [21004011]
Akash Avinash Mahajan [21004015]
Jay Ashok Lokhande [21004016]
Mihir Rajesh Jaiswal [21004063]

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Nayan Vinod Meshram
[21004011]

Akash Avinash Mahajan
[21004015]

Jay Ashok Lokhande
[21004016]

Mihir Rajesh Jaiswal
[21004063]

Abstract

This project explores the design and optimization of a microstrip patch antenna operating at frequency of n259 band centered at $42\ GHz$, intended for use in high-frequency communication systems such as 5G and beyond. The antenna design process was carried out using ANSYS HFSS, to model and optimize the performance parameters. The goal of the design was to achieve minimal reflection and efficient power transmission, crucial for millimeter-wave applications.

The simulated results reveal that the antenna performs exceptionally well in terms of return loss, with an insulation value of $-40\ dB$ at the target frequency of $42\ GHz$, indicating a strong impedance match and low signal reflection. The Voltage Standing Wave Ratio (VSWR) is nearly approaching 1, In terms of radiative performance, the antenna demonstrates a gain of $3.25\ dBi$.

This design showcases the advantages of microstrip patch antennas, including their compactness, ease of integration with other circuit components, and their suitability for high-frequency, high-data-rate communication systems. The results of this study indicate that the designed antenna can be effectively utilized in next-generation wireless technologies, including 5G and potential future 6G systems, where high-frequency bands such as $42\ GHz$ are of increasing importance.

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List of Acronyms

Sr. No.	Acronyms	Description
1.	EM	Electromagnetic
2.	FEM	Finite Element Method
3.	FDD	Frequency Division Duplex
4.	f_r	Resonant Frequency
5.	HFSS	High Frequency Structure Simulator
6.	mm	Millimeter
7.	PCB	Printed Circuit Board
8.	VSWR	Voltage Standing Wave Ratio
9.	SDL	Supplemental Down-Link
10.	SUL	Supplemental Up-Link
11.	TDD	Time Division Duplex
12.	ε_r	Dielectric constant

1. INTRODUCTION

1.1 Introduction

Antennas play a vital role in the field of wireless communications, enabling the efficient transmission and reception of electromagnetic energy. Among various types of antennas, microstrip patch antennas have gained widespread acceptance due to their advantages such as low profile, light weight, ease of fabrication, and compatibility with integrated circuits. These features make them ideal candidates for applications in radar, satellite communications, and especially for emerging mm Wave technologies.

In this project, a microstrip patch antenna has been designed, simulated and optimized to operate at a resonant frequency of $42\ GHz$. The n259 band lies within the mm Wave spectrum, which is increasingly important for next-generation communication systems requiring high data rates, wide bandwidths, and low latency, such as 5G and beyond.

The antenna is modeled using ANSYS HFSS software. Various design parameters, including patch dimensions, substrate properties, and feeding methods, are carefully optimized to achieve superior performance. After optimization, the antenna achieved an excellent return loss of $-40.94\ dB$ at $42.12\ GHz$, indicating highly efficient impedance matching and minimal reflection.

Performance metrics such as return loss, bandwidth, VSWR, gain, directivity, radiation pattern, and radiation efficiency have been thoroughly analyzed to validate the effectiveness of the antenna design. Through this project, practical knowledge in high-frequency antenna design, simulation techniques, and performance evaluation has been developed.

1.2 Motivation

The rapid growth of wireless communication systems demands antennas that can operate efficiently at higher frequencies, with increased data transmission rates, wider bandwidth, and minimal latency. With the evolution towards 5G and future 6G technologies, mm Wave frequency spectrum, particularly around $42\ GHz$, has become highly significant. This frequency band offers large unused bandwidths that are essential for meeting the requirements of next-generation applications like ultra-fast internet, high-definition video streaming, autonomous vehicles, and smart city infrastructures.

Traditional antennas often struggle to perform efficiently at mm Wave frequencies due to fabrication challenges, increased path losses, and limited bandwidth. Microstrip patch antennas, however, offer a promising solution due to their compact size, low profile, ease of integration with circuits, and capability to be mass-produced using standard Printed Circuit Board (PCB) fabrication techniques.

The motivation behind this project is to design and optimize a microstrip patch antenna that resonates efficiently around 42 GHz, achieving good return loss, sufficient bandwidth, high gain, and acceptable radiation efficiency. By using ANSYS HFSS simulation software, this report aims to develop a high-performance antenna model that can serve as a steppingstone for further research and practical applications in mm Wave wireless communication systems.

Through this project, the goal is not only to achieve technical specifications but also to gain deeper insight into high-frequency antenna design challenges and solutions, which are crucial skills for the future of wireless engineering.

1.3 Need

The n259 wave band (typically ranging from 39.5 to 43.5 GHz) is increasingly recognized as a critical frequency range for next-generation wireless communication systems, particularly 5G and beyond. As user demand for ultra-fast data speeds, low latency, and seamless connectivity continues to rise, lower frequency bands are becoming congested and insufficient to meet these needs. The 42 GHz frequency, which lies within the n259 wave band, offers significantly larger bandwidth, enabling multi-gigabit per-second data rates essential for data-intensive applications such as ultra-high speed video streaming, augmented and virtual reality, and real-time cloud services. Its short wavelength makes it suitable for high-capacity small cell deployments in dense urban environments, allowing for localized and efficient network coverage. Moreover, this band supports advanced technologies like beamforming and massive MIMO, which help counteract the higher path losses associated with mm Wave frequencies and enhance overall signal quality. With increasing interest from regulatory bodies and industry players worldwide, the 42 GHz frequency is poised to play a vital role in expanding the capabilities of wireless networks and supporting the evolution toward more advanced, high-performance communication systems [1].

1.4 Objectives

- To design and simulate a microstrip patch antenna operating at n259 frequency band of Telecom Regulatory Authority (TRAI) using ANSYS HFSS software.
- To study the effect of parametric variations such as substrate height and patch size on the resonant frequency and antenna performance.
- To optimize the antenna parameters such as patch dimensions substrate properties to achieve a high return loss and efficient impedance matching.
- To analyze key antenna performance metrics, including return loss, VSWR, gain, bandwidth, directivity, and radiation efficiency.
- To generate and evaluate 2D and 3D radiation patterns to ensure desired radiation characteristics suitable for mm Wave communication systems.
- To gain practical insights into high-frequency antenna behavior and simulation techniques relevant to 5G and advanced wireless communication technologies.

1.5 Theme

The theme of this project revolves around the design, optimization, and performance analysis of a microstrip patch antenna operating in the mm Wave frequency band at n259 band. With the growing demand for high-speed data transmission, low latency, and efficient spectrum utilization, the mm Wave band has become a crucial part of modern and future wireless communication systems, particularly for 5G, 6G, and satellite communication technologies. The microstrip patch antenna is chosen as the foundation of this project due to its numerous advantages, such as ease of fabrication, compact size, planar structure, and compatibility with integrated circuits. The project focuses on understanding the fundamental principles of microstrip antennas, simulating their behavior using ANSYS HFSS, and systematically optimizing various parameters to achieve superior antenna performance.

By carefully tuning the patch dimensions, substrate material properties, and excitation techniques, the antenna was optimized to deliver excellent return loss, high radiation efficiency, and a stable radiation pattern centered at n259 band. The project emphasizes not only achieving technical performance but also gaining practical experience in using professional electromagnetic simulation tools, developing design intuition, and preparing for challenges in high-frequency antenna engineering.

1.6 Organization

This report is structured to present the design, simulation, and optimization of a microstrip patch antenna operating at $42\ GHz$, along with a detailed performance analysis, in a cohesive manner.

- Chapter 1 lays the foundational understanding of the project. It starts by introducing microstrip patch antennas, highlighting their importance in modern wireless systems due to features like low profile, ease of fabrication, and integration compatibility. It then explains the need and motivation for designing a high-frequency antenna operating at $42\ GHz$, particularly for applications in 5G and future 6G technologies. The objectives are clearly stated, focusing on designing, simulating, and optimizing the antenna using ANSYS HFSS, and evaluating parameters such as return loss, VSWR, and Gain. The chapter also outlines the central theme, which revolves around creating an efficient and compact mm Wave antenna and provides the structural organization of the report.
- Chapter 2 explores existing research and standard references related to microstrip patch antennas, especially for mm Wave applications. It covers various design principles, simulation strategies, and optimization techniques used by researchers. It also identifies gaps in current studies, such as limited focus on single-band $42\ GHz$ antennas, lack of compact high-gain designs, and insufficient layout-level optimization thereby justifying the relevance and originality of the current project.
- Chapter 3 focuses on the phase of the project, detailing the structured approach followed to design, build, and implement the system. It outlines various stages such as requirement analysis, architectural design, module development, and system integration. Emphasis is placed on practical implementation, with insights into both hardware and software integration where relevant.
- Chapter 4 presents a detailed performance analysis of the system, focusing on evaluating its efficiency, reliability, and real-world applicability. This chapter involves the interpretation of results obtained through simulations, experiments, or system testing, highlighting the strengths and limitations of the current implementation.

2. LITERATURE SURVEY

2.1. Introduction

Microstrip patch antennas are key components in modern wireless communication systems, particularly at mm Wave frequencies like $42\ GHz$. They offer compact size, planar structure, and easy integration with circuits. Traditional designs emphasized achieving resonance at desired frequencies and maintaining impedance matching. However, with the rapid development of 5G and 6G networks, antenna design optimization now heavily focuses on enhancing gain, bandwidth, and radiation efficiency, while maintaining compactness.

The microstrip patch antenna, first developed in the 1970s, has become one of the most widely used antenna types in modern wireless communication systems due to its low-profile, lightweight, and ease of fabrication characteristics [2].

2.1.1 Structure and Principle of Microstrip Patch Antenna

The microstrip patch antenna consists of a metallic patch printed on a grounded dielectric substrate. The patch can take various shapes like rectangular, circular, elliptical, triangular but the rectangular patch is the most common due to its simplicity in analysis and design. The patch acts as a resonant cavity where the radiation mainly occurs through the fringing fields at the open edges. Kraus explains that the dominant mode of operation for a rectangular patch is the **TM_{10}** mode, where the field variation occurs along the length of the patch, and the width influences the input impedance and radiation pattern [2].

2.1.2 Performance parameters of Microstrip Patch Antenna

There are certain parameters which can be used to define the optimization of an antenna, they are as follows:

- **Return loss or S_{11} parameter**: S_{11} is a parameter that represents the reflection coefficient at the input port, indicating how much of the incoming power is reflected towards the source. A low S_{11} value (e.g., $-10\ dB$ or better) indicates a good match between the antenna and the transmission line, meaning more power is delivered to the antenna and less is reflected [3].
- **VSWR:** Measures how efficient radio frequency (RF) power is transmitted from a source (like a transmitter) to an antenna. It essentially indicates the amount of mismatch between the impedance of the source and the impedance of the antenna and its feed line. A VSWR of 1:1 (or 1.0) indicates perfect impedance matching, while higher values indicate impedance mismatch and signal reflections, potentially leading to power loss and equipment damage [3].

- **Antenna Gain:** Antenna gain is a measure of how well an antenna concentrates and transmits (or receives) radio waves in a specific direction compared to a theoretical isotropic antenna. Typically expressed in decibels relative to isotropic (dBi). An antenna with a gain of 6 dBi means it receives (or transmits) 6 dB more power than an isotropic antenna in the same location [3].

2.1.3 Properties of Microstrip Patch Antenna

- **Dielectric or Substrate material:** In antennas, dielectric materials are electrically non-conductive substances that influence how electromagnetic fields behave. They do not conduct electricity but can support electric fields. Dielectric materials are used in several parts of antennas especially in microstrip patch antennas. Types of substrate materials:
- **FR4 (Epoxy Fiberglass):** It is a low-cost, commonly available PCB substrate with a dielectric constant of about 4.4. It is suitable for low-frequency antenna designs (below $\mathbf{3}\ \boldsymbol{GHz}$), but its high loss tangent makes it inefficient for microwave or high-frequency applications [4].
- **RT/Duroid 5880**: It is a PTFE-based material with very low dielectric constant ($\sim$2.2) and ultra-low loss. It is widely used in high-frequency and precision microwave antennas due to its excellent electrical and thermal stability [4].
- **Teflon (PTFE):** It is known for its low dielectric constant (~2.1) and minimal loss, making it ideal for high-frequency and high-efficiency antennas.However, it is mechanically soft and difficult to process, which can complicate fabrication [4].
- **Feeding Techniques**: In microstrip patch antennas, feeding techniques refer to the methods used to deliver Radio Frequency (RF) power from a transmission line to the radiating patch element. The goal is to ensure maximum energy transfer with minimal reflection and losses. Feeding techniques affect the bandwidth, impedance matching, radiation characteristics, and complexity of the antenna. These techniques are broadly categorized into:
- **Microstrip Line Feed:** This is one of the simplest and most popular feeding techniques. A conducting strip is directly connected to the patch, and both lie on the same substrate. This method is easy to fabricate and analyze but suffers from increased spurious radiation and limited bandwidth due to impedance mismatch issues [5].
- **Coaxial Probe Feed:** Here, an inner conductor of a coaxial cable is extended through the substrate and soldered to the radiating patch. The outer conductor is connected to the ground plane. This technique offers good matching impedance and low spurious

- radiation, but it becomes harder to fabricate as frequency increases due to probe alignment and precise drilling [5].
- **Aperture Coupled Feed:** In this non-contact method, energy is coupled from a microstrip line beneath the ground plane through a slot or aperture to the patch antenna above. It provides better isolation between the feed and the radiating element, resulting in improved bandwidth and reduced spurious radiation. However, its multilayer structure increases fabrication complexity [5].
- **Proximity Coupled Feed (Electromagnetic Coupling)**: Also called the "non-contact" or "electromagnetic coupling" feed, this technique places a microstrip feed line between two dielectric substrates, with the patch on the top substrate. It offers the best impedance bandwidth and minimal spurious radiation but is difficult to fabricate and align due to the multilayer configuration [5].

2.1.4 Selection of Simulation tool

CAD FEKO is a powerful electromagnetic simulation tool primarily focused on antenna design, electromagnetic compatibility (EMC), radar cross-section (RCS), and other high-frequency applications. It is particularly strong in analyzing electrically large structures using methods like the Method of Moments (MoM), Physical Optics (PO), and Uniform Theory of Diffraction (UTD). FEKO is widely used in the automotive, aerospace, and defense industries, where large-scale simulations are crucial [6].

ANSYS HFSS (High-frequency Structure Simulator) is one of the most advanced 3D EM simulation tools available. It uses the FEM to deliver highly accurate results in a broad range of applications including antennas, RF/microwave components, high-speed PCBs, connectors, and complex 3D structures. HFSS offers excellent meshing capabilities, adaptive refinement, and seamless integration with other ANSYS tools for Multiphysics analysis, making it an industry standard in RF and microwave engineering [6].

CST Studio Suite (by Dassault Systems) is known for its wide range of solvers, including Time Domain, Frequency Domain, Integral Equation, and more, which allows users to simulate a broad spectrum of EM problems from static to optical frequencies. CST is particularly valued for its speed and efficiency in time-domain simulations, and its easy-to-use GUI helps in quickly setting up and visualizing results. It is commonly used in medical device design, wireless communications, and EMC testing [6].

ANSYS HFSS is a preferred choice for electromagnetic simulation due to its powerful features. Its adaptive meshing refines areas with complex fields, ensuring accurate and reliable results. HFSS integrates seamlessly with other ANSYS tools, supporting Multiphysics simulations like thermal, mechanical, and signal integrity analysis, which is vital for high-speed electronics. Trusted by industry leaders and researchers, HFSS is an industry standard known for its credibility and performance. Additionally, it offers automation and optimization tools to streamline design sweeps and studies, enabling efficient exploration of design alternatives. Overall, HFSS is an ideal tool for complex and high-performance designs [6].

2.1.5 5G NR Frequency bands

The table below outlines the various 5G NR (New Radio) operating bands, highlighting their uplink and downlink frequency ranges along with the duplexing modes used. These bands are standardized by 3GPP to support a wide range of 5G applications across different regions. Bands such as n41, n77, and n78 fall under the mid-band (sub-6 GHz) category and are widely deployed due to their balance between data speed and coverage. These mm Wave bands also use TDD and are critical for achieving the ultra-high speeds envisioned in 5G. Overall, the table reflects how various frequency bands are strategically allocated and used to meet the diverse requirements of 5G communication systems [7].

Table 2.1 5G NR Frequency Bands

NR Operating Band	Uplink	Downlink	Duplex Mode
n41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD
n50	1432 MHz – 1517 MHz	1432 MHz – 1517 MHz	TDD
n51	1427 MHz – 1432 MHz	1427 MHz – 1432 MHz	TDD
n66	1710 MHz – 1780 MHz	2110 MHz – 2200 MHz	FDD
n70	1695 MHz – 1710 MHz	1.995 MHz – 2020 MHz	FDD
n74	1427 MHz – 1470 MHz	1475 MHz – 1518 MHz	FDD
n75	N/A	1432 MHz – 1517 MHz	SDL
n76	N/A	1427 MHz – 1432 MHz	SDL

n77	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	TDD
n78	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	TDD
n79	4400 MHz – 5000 MHz	400 MHz – 5000 MHz	TDD
n80	1710 MHz – 1785 MHz	N/A	SUL
n84	1920 MHz – 1980 MHz	N/A	SUL
n257	26.5 GHz – 29.5 GHz	26.5 GHz – 29.5 GHz	TDD
n258	24.25 GHz – 27.5GHz	26.5 GHz – 29.5 GHz	TDD
n260	37 GHz – 40 GHz	37 GHz – 40 GHz	TDD

2.1.6 Selection of 42 GHz frequency

The n259 is characterized by its short wavelength (approximately 7.1 mm), enabling it to support extremely high data rates and low latency, making it particularly suitable for advanced wireless communication technologies such as 5G, fixed wireless access (FWA), backhaul connectivity, and even high-throughput satellite communications. The use of the n259 is gaining interest globally as telecom networks move toward ultra-fast, high-capacity systems to support growing data demands and emerging technologies like autonomous systems and immersive media.

One of the primary reasons for targeting the n259 band is its status as a "greenfield" spectrum. Unlike many other mm Wave bands, n259 currently has no existing operations, either federal or non-federal. This lack of prior usage presents a unique opportunity for researchers and industry stakeholders to explore and develop new technologies without the constraints of legacy systems or interference concerns [1].

2.1.7 Microstrip Antenna Designs for mm Wave Applications

- **Microstrip Patch Antenna (MPA) at 28 GHz and 38 GHz**

  - The paper focuses on optimizing microstrip patch antenna design parameters for 5G applications at 28 GHz and 38 GHz. It reviews existing limitations such as poor gain, low return loss, and bandwidth inefficiencies in prior MPA designs. By analyzing different substrates, heights, and feeding techniques, the authors identify foam as the optimal substrate, with a 0.5 mm height and quarter-wave transformer feed. This optimized configuration significantly improves antenna performance, achieving high gain, excellent return loss, wide bandwidth, and near-perfect efficiency, making it suitable for next-generation 5G systems [8].

- **Antenna Configuration**:
- Substrate material: Foam
- Substrate Height(h):$0.5mm$
- Patch Length:$3.34mm$
- Patch Width:$3.36mm$
- Overall size: $3.72 * 3.22\ mm$
- **Performance Parameters Specifications**:
- Return Loss(S11): $-30.21dB$
- VSWR:1.004
- Gain:$3.1dB$
- Bandwidth:$2.6GHz$

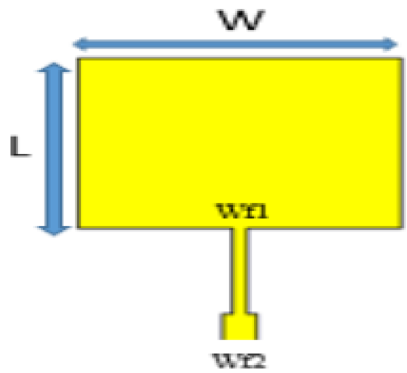

Fig.2.1 Microstrip Patch Antenna at 28 GHz and 38 GHz

- **38 GHz modified rectangular microstrip patch antenna**

o The paper by Hassan et al. presents a modified circular microstrip patch antenna designed to operate at 38 GHz for 5G mobile systems. It uses a compact structure on a Rogers RT5880 substrate and achieves good performance with 2.25 dBi gain, 640 MHz bandwidth, and -20.6 dB return loss [9].

o **Antenna Configuration**:

- Substrate Material: RT5880
- Dielectric constant:2.2
- Substrate Height(h):$0.254mm$
- Patch length:$2.38mm$
- Patch Width:$2.76mm$
- Overall Dimensions:$6 * 6mm$

o **Performance Parameters Specifications**:

- Return Loss: $-20.6dB$
- VSWR:1.025
- Gain:$2.15dBi$
- Bandwidth:$640MHz$

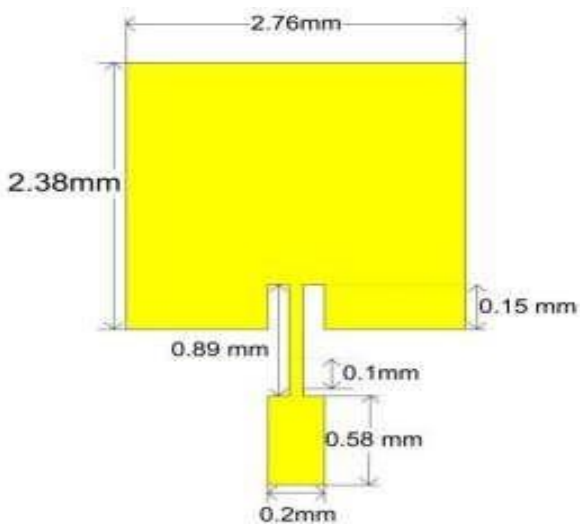

Fig.2.2 38 GHz modified rectangular microstrip patch antenna

- **Microstrip Patch Antenna with Slits Loading**
    - The literature review highlights the growing importance of millimeter-wave (mm-wave) antennas, particularly in the 38 GHz band, for meeting the high-speed, low-latency demands of 5G wireless communication. Prior studies explored various antenna structures such as inverted-F and monopole designs with stubs on substrates like FR4 and Rogers materials to improve performance. This underscores the need for optimized antenna designs that offer better return loss, higher gain, and wider bandwidth to address the challenges of path loss and absorption in mm-wave frequencies, which the proposed antenna aims to achieve [10].
    - **Antenna Configuration**:
- Substrate Material: RT/Duroid 5880
- Dielectric constant: 2.2
- Substrate Height(h):$0.318mm$
- Patch length:$3.142mm$
- Patch Width:$2.41mm$
    - **Performance Parameters Specifications**:
- Return Loss: $-38.82dB$
- VSWR: 1.008
- Gain: $3.49dBi$
- Bandwidth: $2.35GHz$

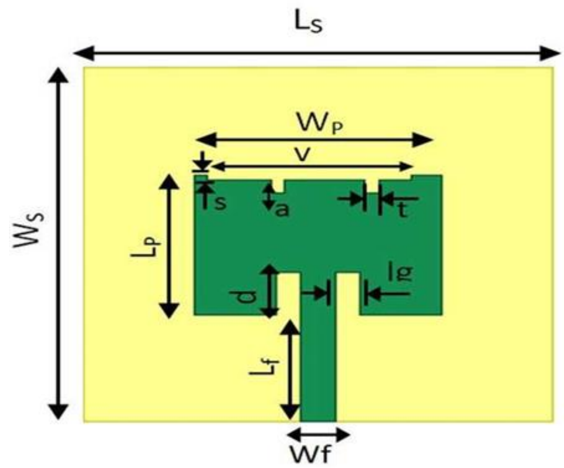

Fig.2.3 Microstrip Patch Antenna with Slits Loading

- **Compact Circular Microstrip Patch Antenna**

  - Djouimaa and Bencherif (2024) designed a compact circular patch antenna on an FR4 substrate for 28 GHz operation. Initially offering a gain of 0.1573 dBi, the gain was significantly improved to 5.8174 dBi using structural modifications and DGS. The antenna also achieved an excellent return loss of $-32.9\ dB$, corresponding to a VSWR of approximately 1.01, indicating excellent impedance matching. These results highlight the antenna's suitability for compact 5G applications [11].

  - **Antenna Configuration:**

- Substrate Material:FR4 Epoxy
- Dielectric constant:4.4
- Substrate Height:1.4mm
- Length:5.95mm
- Width:5.95mm

  - **Performance Parameters Specifications**

- Return Loss: $-32.9dB$
- VSWR:1.0113
- Gain: 0.157dBi
- Bandwidth:13.75GHz

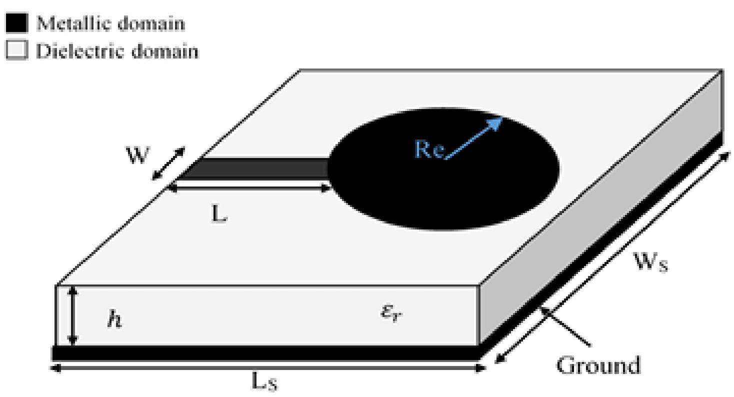

Fig.2.4 Compact Circular Microstrip Patch Antenna

- **Wideband Antenna with Thin Rectangular Slits**
  - This study introduces a compact microstrip patch antenna with dual rectangular slits for 5G applications in the $38-39\ GHz$ bands. Previous designs offered moderate gain and bandwidth with larger sizes. By integrating thin slits, the proposed design achieves improved performance$-3.03\ dBi$ gain, $3.11\ GHz$ bandwidth, and $S11$ of $-59\ dB$ making it highly efficient and ideal for compact 5G millimeter-wave systems [12].
  - Antenna Configuration:
- Substrate Material: RT/Duroid 5880
- Dielectric constant:2.2
- Patch Length: $3.42mm$
- Patch Width:$6.8mm$
- Overall Size: $5 * 8.2 * 0.186\ mm$
  - Performance Parameters:
- Return Loss: $-39.08dB$
- VSWR:1.045
- Gain:$2.45dBi$
- Bandwidth:$3.11GHz$

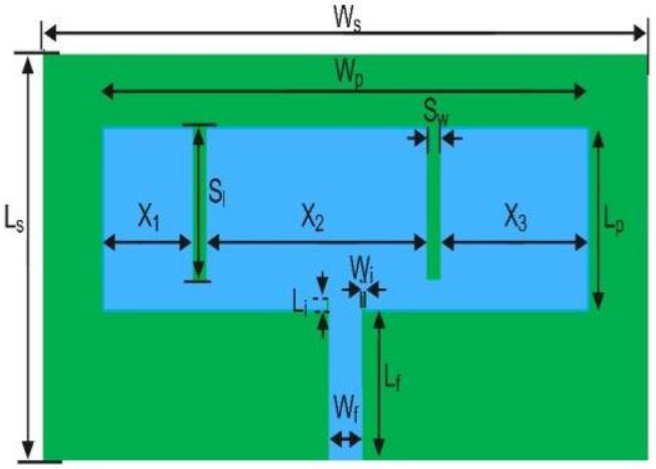

Fig.2.5 Wideband Antenna with Thin Rectangular Slits

- **High-performance 38 GHz millimeter wave antenna**

- The paper by Alaoui et al. presents a high-performance microstrip patch antenna designed for 5G applications at 38 GHz. Addressing the increasing demand for high-speed and low-latency communication, the study explores techniques to enhance antenna performance, including the use of square openings, a pi-slot, and a rectangular slot. Implemented on a Rogers RT5880 substrate with low dielectric loss, the antenna achieves a return loss of $-35.991\ dB$, a high gain of $10.3\ dB$, and an impedance bandwidth of 14.50%. The compact and efficient design makes it well-suited for millimeter-wave 5G wireless systems [13].
- **Antenna Configuration:**

- Substrate material: RT 5880
- Dielectric constant:2.2
- Patch Length: $3.45mm$
- Patch Width:$3.23mm$
- Overall Dimensions: $4.39 * 5.05 * 0.3mm$

- **Performance Parameters:**

- Return Loss: $-35.991dB$
- VSWR: 1.0323
- Gain:$10.3dBi$
- Bandwidth: $5.1GHz$

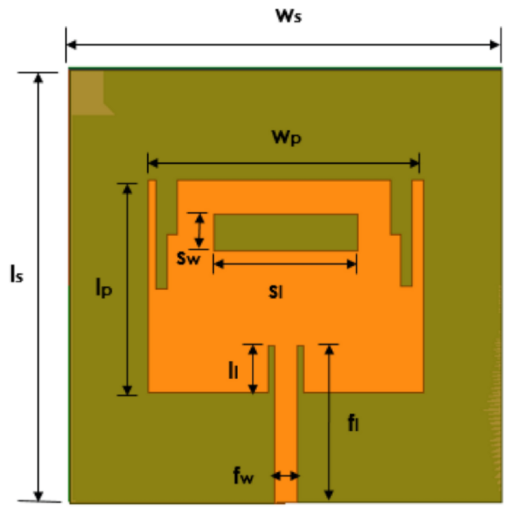

Fig.2.6 High-performance 38 GHz millimeter wave antenn

2.1 Comparison of different reference antennas

The table below represents a comparative analysis of antenna performance parameters taken from various studies and references, focusing on four key metrics: Return Loss, VSWR, Gain and Bandwidth. These parameters are essential in evaluating how efficiently an antenna operates across its frequency range.

Table 2.2 Comparison of different reference antennas

Reference No.	**Return loss (dB)**	**VSWR**	**Gain (dBi)**	**Bandwidth (GHz)**
[8]	-30.21	1.004	3.1	2.6
[9]	-20.6	1.025	2.15	0.64
[10]	-38.82	1.008	3.49	2.35
[11]	-32.91	1.013	0.157	13.75
[12]	-39.08	1.045	2.45	3.11
[13]	-35.991	1.0323	10.3	5.1

3. SYSTEM DEVELOPMENT

3.1 Design Environment and Simulation Tool

The design, simulation, and optimization of the $42\ GHz$ microstrip patch antenna were carried out using ANSYS HFSS, a leading industry-standard software for 3D full- wave EM simulation. HFSS provides robust capabilities for antenna modeling, enabling accurate predictions of parameters such as return loss, VSWR, gain, radiation patterns, and bandwidth performance.

ANSYS HFSS utilizes the FEM to solve Maxwell's equations for complex RF and microwave structures, making it particularly suitable for high-frequency and mm Wave applications. Its parametric analysis tools, driven solutions, adaptive meshing, and optimization algorithms allow designers to iteratively refine antenna parameters for best performance.

In this project, the driven modal solution type was employed, which is ideal for antennas operating at specific resonant frequencies, such as the target n259. The simulation environment included:

- Substrate material selection,
- Patch geometry definition,
- Excitation using wave ports,
- Boundary conditions like radiation boxes for free-space emulation,
- Sweep configurations for analyzing the frequency-dependent response.

The choice of ANSYS HFSS is further supported by references such as "Introduction to ANSYS HFSS: Simulation of Electromagnetic Fields" (2022), which emphasizes the software's role in providing real-world, fabrication-accurate EM simulation results. HFSS's integration with optimization routines, scripting capabilities, and post-processing tools provides an ideal platform for both academic learning and professional antenna development.

3.2 Antenna Architecture

3.2.1 Overview of basic Microstrip Patch Antenna Design

A microstrip patch antenna is a type of radio antenna with a low-profile structure that can be mounted on a flat surface. It consists of a metallic patch printed on a grounded dielectric substrate and is widely used in wireless communication systems due to its compactness, ease of fabrication, and compatibility with printed circuit board (PCB) technologies.

In this project, a rectangular microstrip patch antenna was designed to operate at a resonant frequency of $42\ GHz$, falling within the millimeter-wave (mmWave) band, crucial for 5G and future 6G communications. The antenna consists of:

- A rectangular radiating patch,
- A substrate with a dielectric constant,
- A ground plane,
- A wave port excitation for feeding

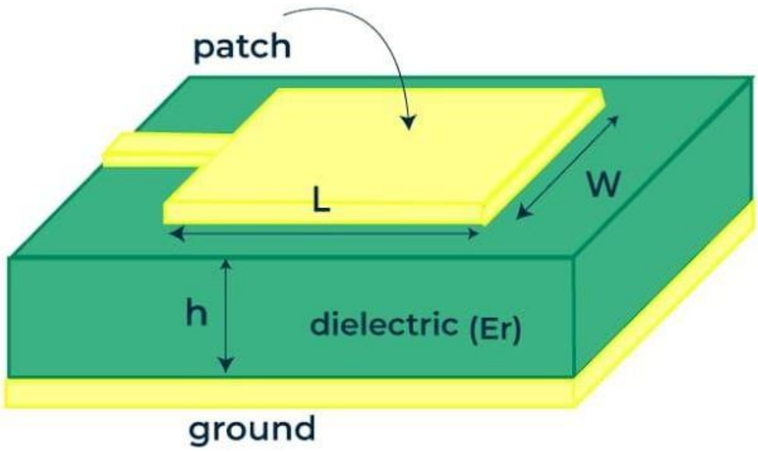

Fig 3.1 Basic Microstrip Patch Antenna Design.

3.2.2 Calculations of parameters and configuration of 42GHz Microstrip patch Antenna

- The width of patch in a microstrip patch antenna is calculated using:

$$\boldsymbol{w = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r}} = \frac{3\times10^8}{2\times42\times10^9} \times \sqrt{\frac{2}{4.4}} = 2.3mm}$$

$\boldsymbol{c} = Velocity\ of\ light, fr = resonant\ frequency,$

$\varepsilon r = dielectric\ constant\ of\ substrate.$

- The effective dielectric constant (εeff) is calculated using:

$$\boldsymbol{\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{w}\right)^{-\frac{1}{2}} = \frac{4.4 + 1}{2} + \frac{4.4 - 1}{2} \times \left(1 + 12 \times \frac{0.7}{2.3}\right)^{-\frac{1}{2}}}$$

$$\boldsymbol{= 6mm.}$$

h = Height of patch**.**

- Length of the patch(L) is calculated by using:

$\boldsymbol{L = L_{eff} - 2\Delta L = 3.55 - 2 \times 0.275 = 3mm}$

- Effective length of patch is calculated using:

$$\boldsymbol{L_{eff} = \frac{c}{2f_r\sqrt{Seff}} = \frac{3 \times 10^8}{2 \times 42 \times 10^9 \times \sqrt{6.36}} = 3.5mm}$$

$Seff$=Effective substrate thickness

- Length extension due to fringing fields is calculated by using:

$$\boldsymbol{\Delta L = 0.412h\frac{\left(\frac{w}{h} + 0.268\right)\left(\varepsilon_{eff} + 0.3\right)}{\left(\varepsilon_{eff} - 0.3\right)\left(\frac{w}{h} + 0.8\right)}}$$

$$\boldsymbol{= 0.412 \times 0.7 \times \frac{\left(\frac{2.3}{0..7} + 0.268\right)(6.36 + 0.3)}{(6.36 - 0.3)\left(\frac{2.3}{0..7} + 0.8\right)}}$$

$$\boldsymbol{= 0.275mm}$$

- Length (Lg) and width (Wg) of the ground plane are calculated by using:

$$Lg = 6h + L = 6 \times 0.7 + 3 = 7.2mm$$

$$wg = 6h + w = 6 \times 0.7 + 2.3 = 6.4mm$$

- Patch Element: The rectangular patch serves as the primary radiating element. Its length and width were calculated based on transmission line model equations for optimal resonance at 42 GHz. Minor adjustments were made during simulation for fine-tuning.
- Substrate Layer: A low-loss substrate with a thickness of around 0.127 mm was used to balance between size, bandwidth, and efficiency. FR4-epoxy was selected for its low dielectric losses at high frequencies.
- Ground Plane: A full ground plane was placed beneath the substrate to ensure effective shielding and to support the propagation of surface waves essential for radiation
- Feeding Technique: A wave port excitation was implemented to feed the patch, ensuring effective energy transfer at the operating frequency. The position of the feed point was optimized to achieve impedance matching close to 50 $ohms$.
- Boundary Conditions: An air box was placed around the antenna model with radiation boundary conditions assigned to simulate free-space behavior and avoid unwanted reflections.

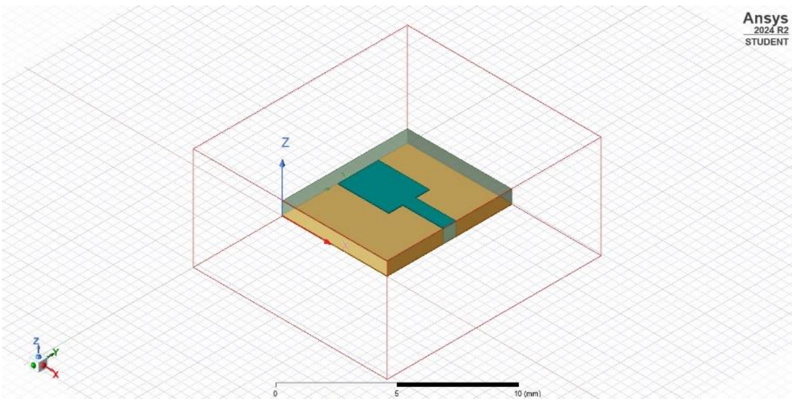

Fig.3.2 Proposed 42Ghz Microstrip patch antenna

3.2.3 Basic Working Principle

The microstrip antenna operates by exciting the resonant modes of the patch. The fundamental mode (TM10) is exciting when the patch dimension is approximately half the guided wavelength ($\lambda g/2$) at the desired resonant frequency.

When RF energy is fed into the antenna, it induces surface currents on the patch, leading to radiation into free space primarily perpendicular to the surface of the patch. The designed antenna was optimized to ensure a strong main lobe, minimized side lobes, and low reflection loss at $42\ GHz$.

3.3 Design Iterations

During the design and development process of the microstrip patch antenna, a total of 68 design iterations were carried out to progressively refine the antenna's performance. Each iteration focused on addressing specific issues observed in the previous design, such as high return loss, suboptimal VSWR and lower-than-expected gain. The first iteration started with a basic design based on theoretical calculations, serving as a baseline for performance evaluation.

Subsequent iterations introduced modifications such as substrate material adjustments, dimensional fine-tuning, feed position optimization, and additional structural features like slots or partial ground planes. These changes were carefully analyzed and validated through simulation results. With each revision, a noticeable improvement was observed: the S_{11} values moved closer to the desired threshold (typically below $-10\ dB$), the VSWR approached ideal values (close to 1), and the antenna's gain steadily increased, indicating better radiation efficiency.

3.3.1 Parametric Optimization of Substrate Height and Patch Width

Table 3.1 Parametric Optimization of Substrate Height and Patch Width

$Hs(mm)$	$Wp(mm)$	$Fr(GHz)$	$S11(dB)$	VSWR	$Gain(dBi)$
0.7	2	42.675	−15.5122	1.402818	2.93
0.7	2.1	42.6375	−17.3655	1.313297	2.734
0.7	2.2	42.525	−19.8365	1.226924	2.681
0.7	2.3	42.4125	−23.4343	1.144408	3.25
0.7	2.4	42.2625	−26.8491	1.09523	3.121
0.7	2.5	42.225	−40.941	1.018109	3.25
0.71	2	42.675	−16.2882	1.36216	1.25
0.71	2.1	42.5625	−17.7336	1.298358	2.47
0.71	2.2	42.45	−20.6894	1.203541	2.88
0.71	2.3	42.2625	−25.6738	1.109786	2.5
0.71	2.4	42.15	−33.2054	1.044705	1.47
0.71	2.5	42.1875	−49.2548	1.006915	3.16
0.72	2	42.5625	−16.6858	1.343175	2.14
0.72	2.1	42.4125	−17.5286	1.306574	2.68
0.72	2.2	42.4125	−21.0103	1.195438	1.6
0.72	2.3	42.2625	−26.2422	1.102476	1.01
0.72	2.4	41.85	−34.9773	1.036306	2.4
0.72	2.5	42.15	−45.4869	1.010691	1.27
0.73	2	42.6	−17.2759	1.317063	2.87
0.73	2.1	42.375	−18.9253	1.255225	2.39
0.73	2.2	42.375	−22.0714	1.17104	3.19
0.73	2.3	42.15	−26.6401	1.097663	1.82
0.73	2.4	42.15	−36.1236	1.031746	1.63
0.73	2.5	42.15	−35.5789	1.033835	3
0.74	2	42.45	−17.3434	1.314223	1.96
0.74	2.1	42.3	−19.1733	1.247155	1.08
0.74	2.2	42.3	−22.5884	1.160365	2.67
0.74	2.3	42.075	−28.521	1.077907	2.57
0.74	2.4	42.0375	−51.5785	1.005288	3.18
0.74	2.5	41.9625	−34.507	1.038365	1.42
0.75	2	42.4125	−18.0643	1.28562	1.78
0.75	2.1	42.3	−20.3427	1.21271	1.02
0.75	2.2	42.1125	−23.8224	1.137663	1.54
0.75	2.3	42.075	−30.8432	1.05909	2.98
0.75	2.4	42.0375	−49.4511	1.00676	2.96
0.75	2.5	41.925	−32.182	1.050437	1.07
0.76	2	42.375	−18.6337	1.265096	2.34
0.76	2.1	42.15	−20.9056	1.198042	2.58
0.76	2.2	42.075	−25.4939	1.112213	2.22
0.76	2.3	42.0375	−37.5028	1.027022	3.09
0.76	2.4	41.925	−37.9062	1.02578	3.18
0.76	2.5	41.925	−30.6538	1.060432	3.12
0.77	2	42.3	−19.408	1.239775	2.98
0.77	2.1	42.1125	−22.5491	1.161149	3.04
0.77	2.2	42.075	−27.1332	1.092025	2.14

0.77	2.3	41.925	-33.4388	1.043494	3
0.77	2.4	41.8875	-37.3601	1.027476	1.17
0.77	2.5	41.8125	-28.5651	1.077497	2.48
0.78	2	42.3	-20.1764	1.217268	1.44
0.78	2.1	42.075	-23.0476	1.151481	2.13
0.78	2.2	41.8875	-26.7474	1.096406	1.66
0.78	2.3	41.925	-42.2437	1.015567	1.39
0.78	2.5	41.85	-26.606	1.098067	2.46
0.786	2.35	41.8875	-36.1577	1.03162	3.25
0.79	2	42.15	-21.6435	1.180457	2.9
0.79	2.1	42.0375	-25.0731	1.118112	2.19
0.79	2.2	41.9625	-34.17	1.039913	2.46
0.79	2.3	41.8875	-46.6799	1.009312	1.97
0.79	2.4	41.7	-33.492	1.043223	3.08
0.79	2.5	41.7375	-26.2052	1.102935	2.58
0.8	2	42.15	-22.6004	1.160124	1.96
0.8	2.1	41.9625	-28.2007	1.080952	1.88
0.8	2.2	41.8125	-34.3918	1.038887	1.76
0.8	2.3	41.85	-39.0225	1.022636	3.25
0.8	2.4	41.6625	-28.9015	1.074443	1.32
0.8	2.5	41.7	-24.4791	1.127003	1.92

By varying two key parameters, the substrate height and the width of the patch, while keeping all other design parameters constant, a total of 68 unique combinations were generated. Each of these combinations was analysed to evaluate the antenna's performance in terms of return loss (S_{11}), VSWR and gain. Among these 68 combinations, a select set demonstrated well-balanced performance across all three parameters. The combinations listed below represent the optimal configurations of patch width and substrate height that achieved desirable results in return loss, VSWR, and gain, indicating effective impedance matching and efficient radiation characteristics.

3.3.2 Basic Microstrip Patch Antenna

Table 3.2. Measurement of Basic Patch Antenna.

Name	Value (mm)
L_s	6.2
W_s	7.4
H_p	0.035
H_s	0.7
W_p	2.3
L_p	3
W_f	0.75

where, W_f – width of feedline.

Table 3.2 shows the dimensional measurements (in mm) of a basic patch antenna, including the substrate, patch, and feedline.

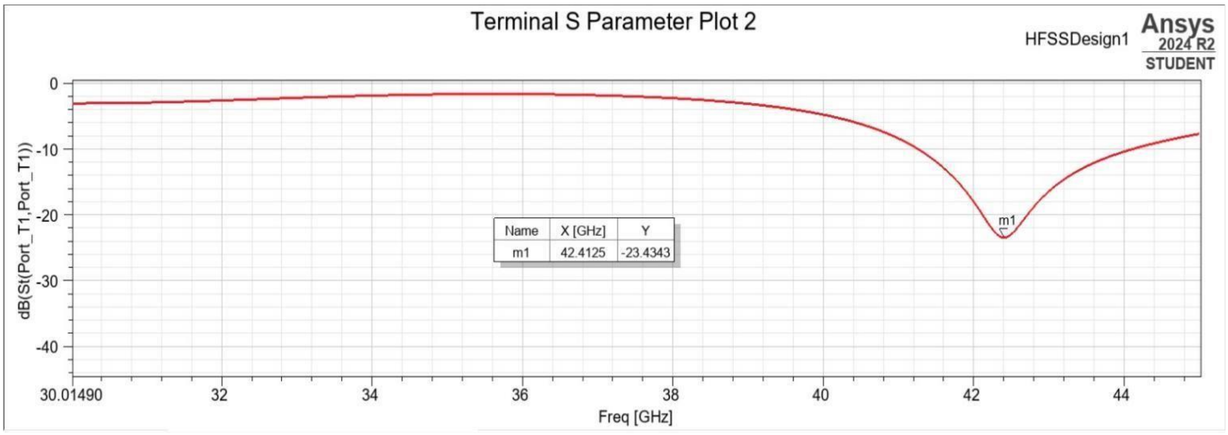

Fig.3.3. Return loss of Basic Patch Antenna.

Fig.3.3 shows that the initial design serves as a starting point for the antenna development. The resonant frequency is relatively close to the desired operating band at $42.4125\ GHz$, indicating that the physical dimensions and substrate parameters were within a reasonable range. However, the return loss at $-23\ dB$, while generally considered acceptable in many applications, suggests that there is still notable room for improvement in terms of impedance matching. Ideally, for high-performance antennas, an S_{11} below $-30\ dB$ is preferred.

Fig. 3.4 VSWR of Basic Patch Antenna.

Fig.3.4 shows that the VSWR value of 1.1444 confirms moderate matching between the antenna and the feedline but is not perfect. A perfect match would be represented by a VSWR of 1.0, and values below 1.2 are typically sought in high-frequency designs.

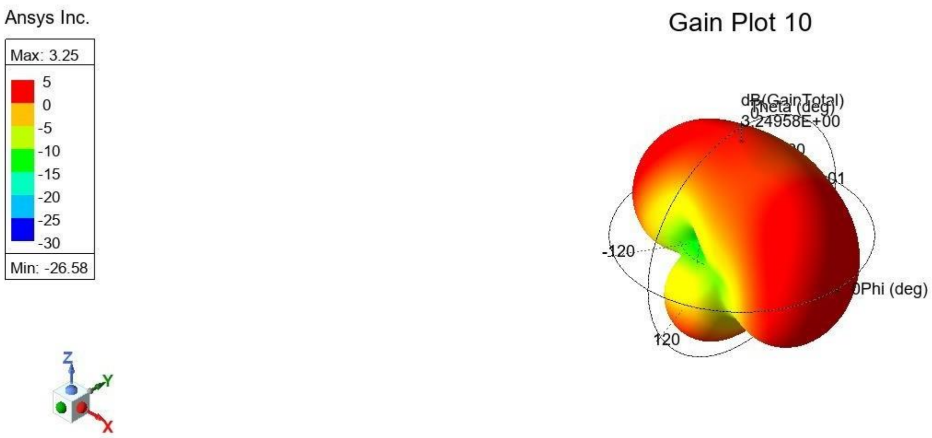

Fig.3.5 Gain of Basic Patch Antenna.

Fig.3.5 Shows that the gain, measured at $3.25\, dB$, reflects decent radiation efficiency; however, given the operating frequency, there is potential to enhance the radiated power through more refined design adjustments.

3.3.3. Result after increasing substrate thickness

Here all the measurements of antenna parameters are kept constant only measurement of the substrate thickness H_s is increased from $0.7\ mm$ to $0.8\ mm$.

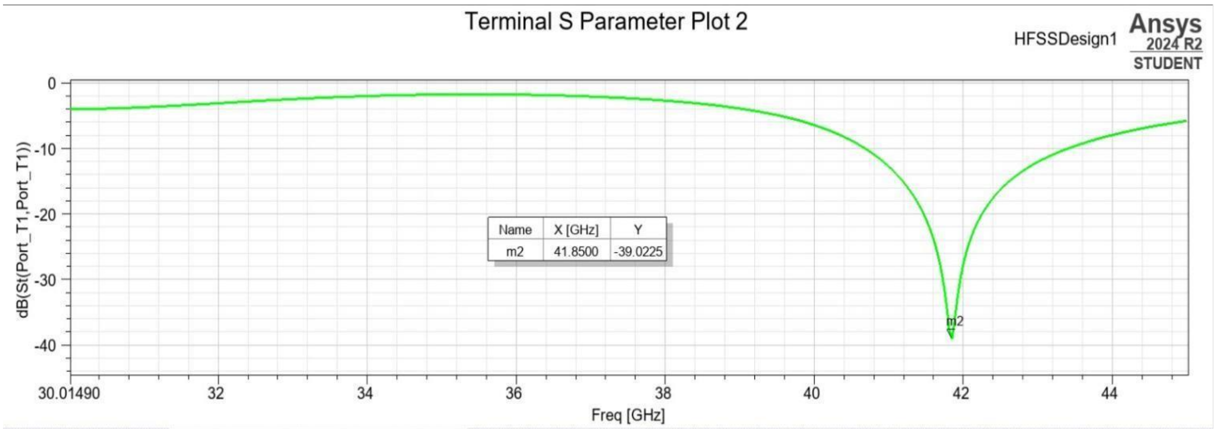

Fig. 3.6 S_{11} after change in thickness.

Fig.3.6 Shows that the second iteration represents a substantial step forward in the antenna optimization process. The resonant frequency slightly decreased to $41.85\ GHz$, but still remained close to the target frequency. The most notable improvement is observed in the reflection coefficient, which improved dramatically to $-39.0225\ dB$. This signifies excellent impedance matching, indicating that nearly all the input power is being radiated with minimal reflections at the feed point.

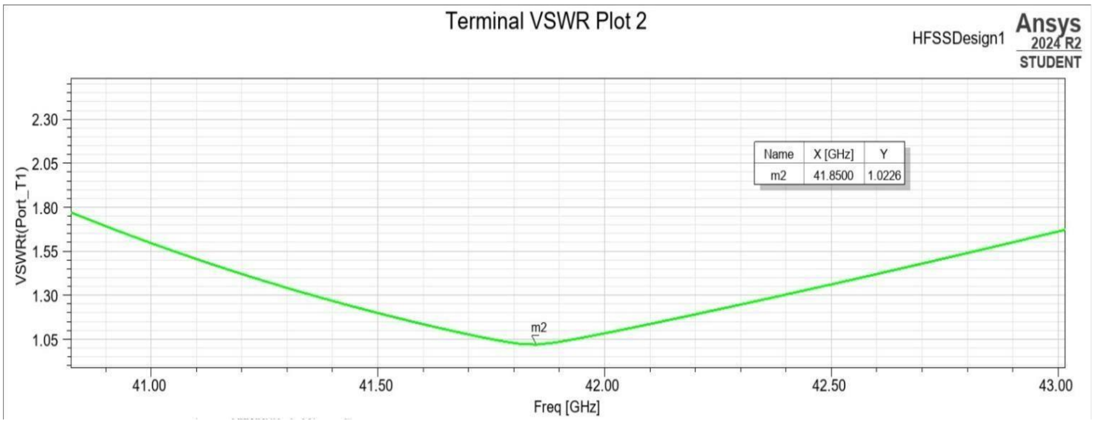

Fig. 3.7 VSWR after changing thickness.

Fig.3.7 Shows that the VSWR value of 1.0226 is impressively close to the ideal of 1.0, reflecting near-perfect matching conditions. This ensures minimal power loss due to reflection, enhancing the antenna's overall efficiency.

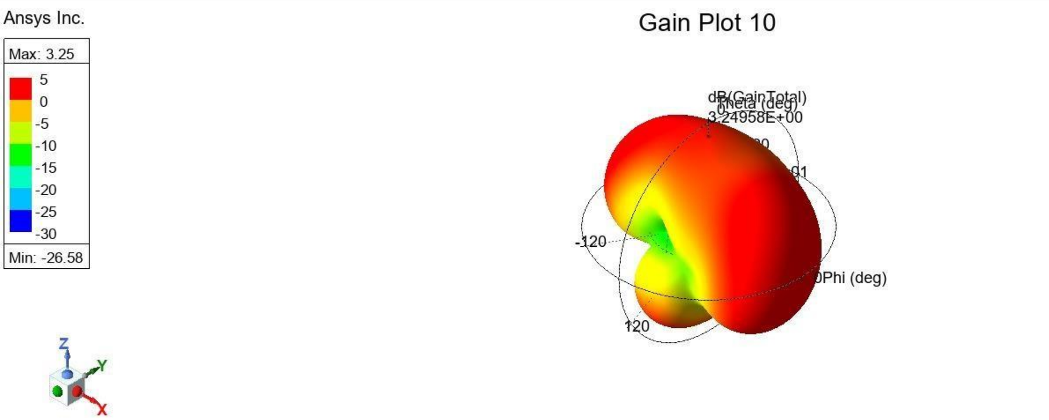

Fig. 3.8 Gain Plot after changing substrate thickness

Fig.3.8 Shows that the gain is 3.25 dB, comparable to the first iteration. This suggests that the radiation pattern and efficiency of the antenna have been positively impacted by the design changes.

3.3.4 Result after increasing the width of patch and increasing height of substrate

Here all the measurements of antenna parameters are kept constant only measurement of width (W_p) is increased to 2.35 mm and the substrate height (H_s) is slightly decreased to 0.786 mm.

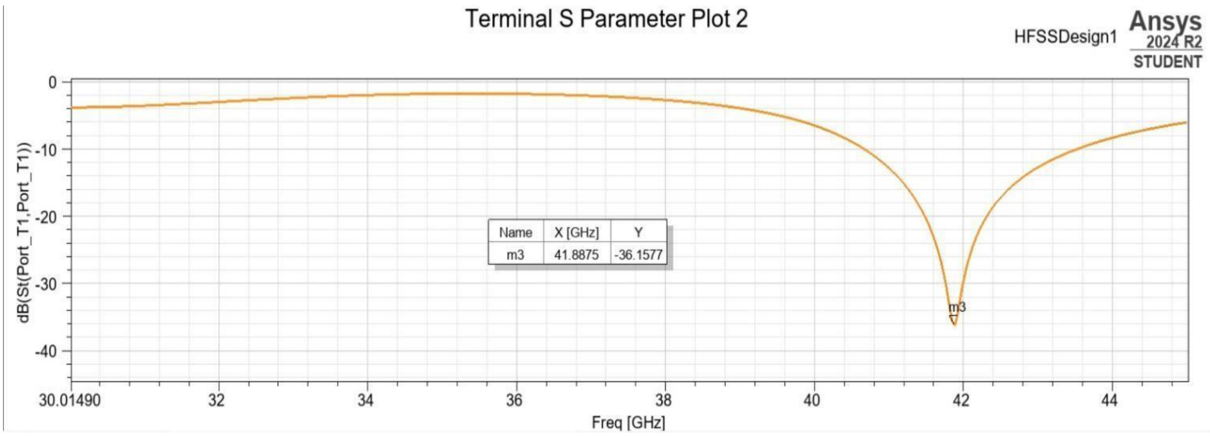

Fig. 3.9 Return loss after increasing width of patch and increasing height of substrate.

Fig.3.9 Shows that Building upon the strong performance of the second iteration, the third iteration focused on fine-tuning the design parameters to achieve greater stability. The resonant frequency adjusted slightly upwards to 41.8875 GHz, demonstrating improved precision relative to the intended frequency band.

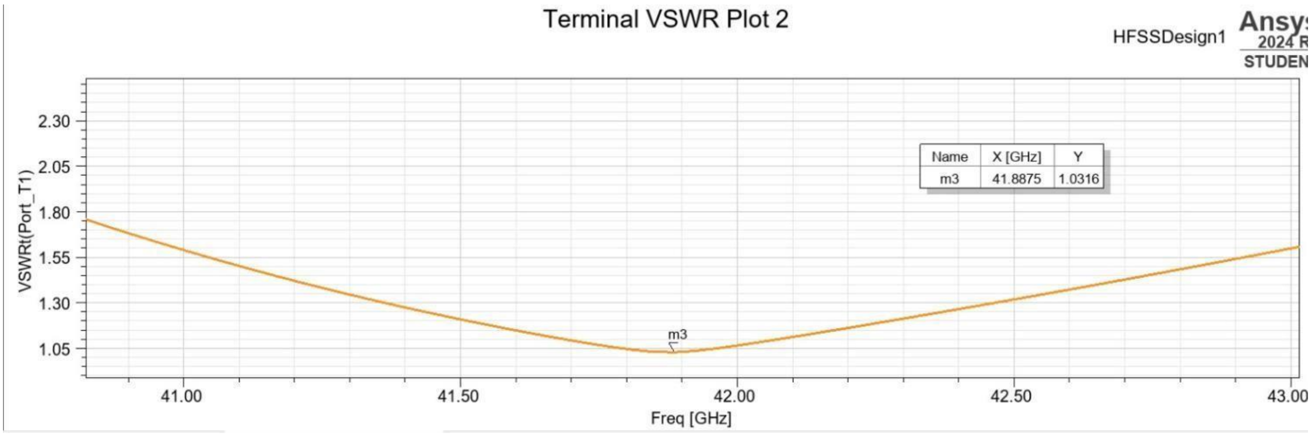

Fig. 3.10 VSWR after increasing width of patch and increasing height of substrate.

Fig.3.10 Shows that Although the return loss value slightly degraded compared to the second iteration (from $-39\ dB$ to $-36.1577\ dB$), it still maintained an excellent level of impedance matching, well within high-performance standards. The VSWR remained exceptionally low at 1.0316, which is very close to ideal conditions.

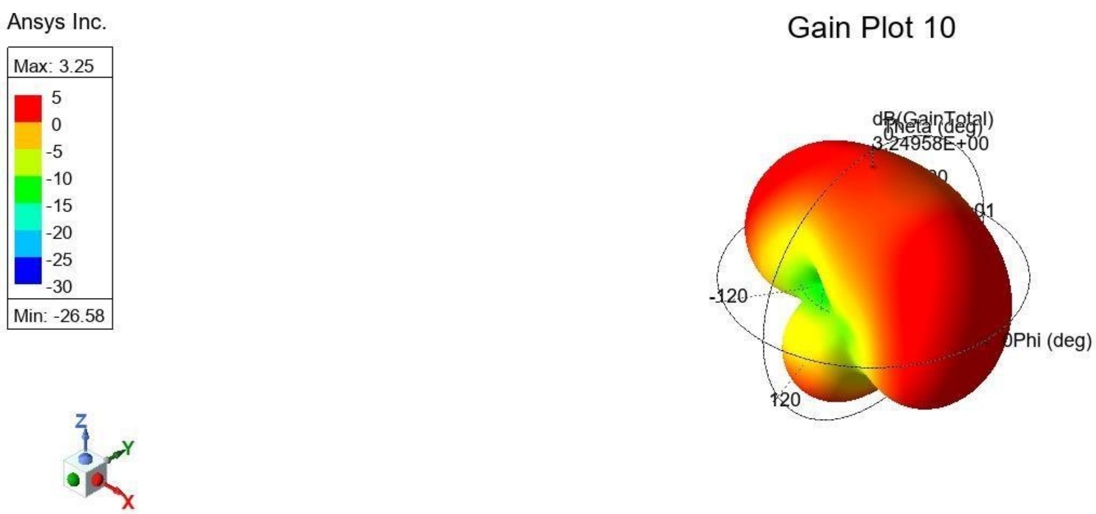

Fig. 3.11 Gain Plot after increasing width of patch and increasing height of substrate.

Fig.3.11 Shows that the gain was measured at $3.25\ dB$, a minor reduction from the second iteration, but it still indicates a strong and efficient radiation characteristic.

3.3.5 Result after keeping height of substrate constant and increasing width of the Patch

Here all the measurements of antenna parameters are kept constant only measurement of the patch width (W_p) increased to $2.5\ mm$ while maintaining a substrate height (H_s) of $0.7\ mm$.

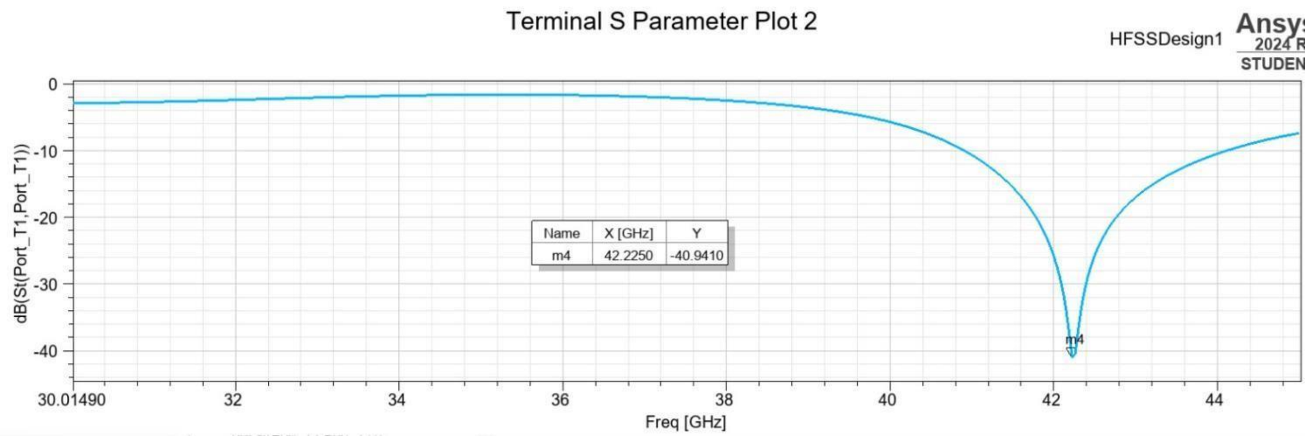

Fig.3.12 Return loss of final design.

Fig.3.12 Shows that the reflection coefficient reached an impressive $-40.941\ dB$, the best among all iterations. This extremely low S_{11} value indicates outstanding impedance matching, ensuring that virtually no power is reflected back from the antenna feed and nearly all of it is radiated efficiently.

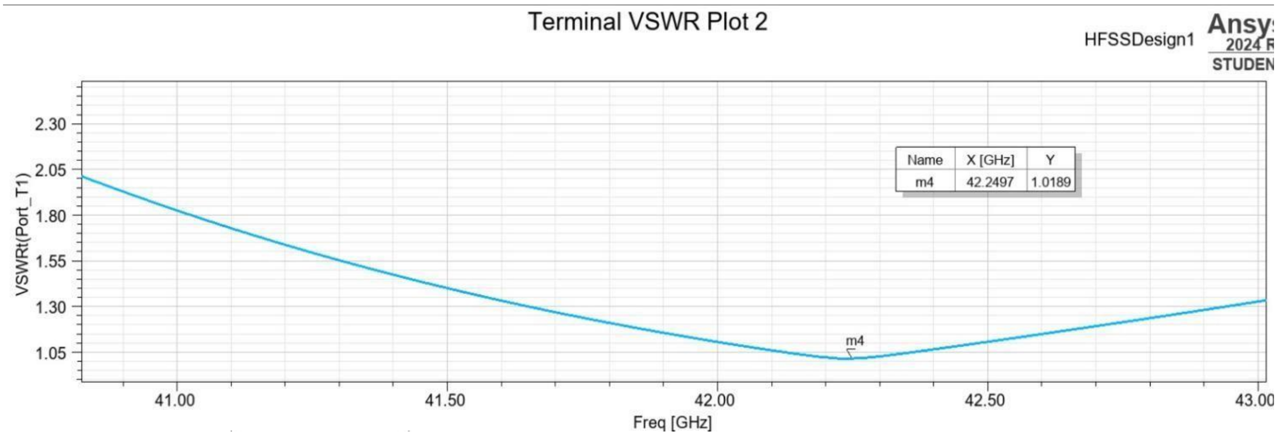

Fig. 3.13 VSWR of final design.

Fig.3.13 Shows that the VSWR achieved a value of 1.0189, which is very close to the theoretical ideal. Such a low VSWR ensures that the antenna system would perform efficiently over a wide range of operational conditions without significant mismatch losses.

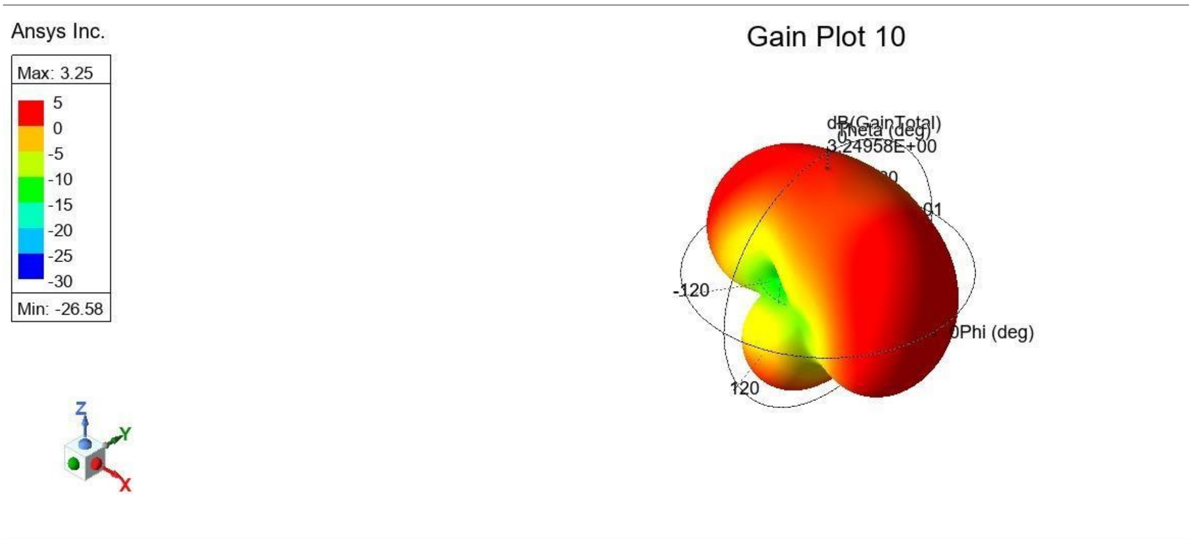

Fig. 3.14. Gain Plot of final design.

Fig.3.14 Shows that While the gain slightly dropped compared to the second and third iterations to 3.25 dB, it remains well within acceptable limits for high frequency microstrip designs.

4. PERFORMANCE ANALYSIS

4.1. Analysis

This document presents a comprehensive performance evaluation of a microstrip patch antenna across 68 iterative design improvements. The primary performance indicators considered at Fr, return loss, VSWR and gain. Each iteration was carefully analyzed with the goal of achieving the best possible impedance matching, minimum reflection losses, and optimized radiation characteristics. The fourth and final iteration is identified as the most optimal based on the combined performance parameters.

4.1.1 Basic Microstrip Patch Antenna Design

- $Fr = 42.4125\ GHz$
- $Return\ Loss = -23\ dB$
- $VSWR = 1.1444$
- $Gain = 3.25\ dB$

Detailed Analysis:

The initial design serves as a starting point for the antenna development. The resonant frequency is relatively close to the desired operating band at $42.4125\ GHz$, indicating that the physical dimensions and substrate parameters were within a reasonable range. However, the return loss at $-23\ dB$, while generally considered acceptable in many applications, suggests that there is still notable room for improvement in terms of impedance matching. Ideally, for high-performance antennas, an return loss below $-30\ dB$ is preferred.

The VSWR value of 1.1444 confirms moderate matching between the antenna and the feedline but is not perfect. A perfect match would be represented by a VSWR of 1.0, and values below 1.2 are typically sought in high-frequency designs.

The gain, measured at $3.25\ dB$, reflects decent radiation efficiency; however, given the operating frequency, there is potential to enhance the radiated power through more refined design adjustments.

4.1.2 Performance analysis after increasing substrate thickness

- $Fr\ =\ 41.85\ GHz$
- $Return\ Loss =\ -39.0225\ dB$
- $VSWR\ =\ 1.0226$
- $Gain\ =\ 3.25\ dB$

Detailed Analysis:

The second iteration represents a substantial step forward in the antenna optimization process. The resonant frequency slightly decreased to $41.85\ GHz$, but still remained close to the target frequency. The most notable improvement is observed in the reflection coefficient, which improved dramatically to $-39.0225\ dB$. This signifies excellent impedance matching, indicating that nearly all the input power is being radiated with minimal reflections at the feed point.

Furthermore, the VSWR value of 1.0226 is impressively close to the ideal of 1.0, reflecting near-perfect matching conditions. This ensures minimal power loss due to reflection, enhancing the antenna's overall efficiency.

The gain was measured at 3.25 comparable to previous iterations. Altogether, the second iteration showed a balanced and highly effective enhancement in all critical performance aspects, making it a strong candidate for final deployment, though further fine-tuning was still considered.

4.1.3 Performance Analysis after increasing width of patch and increasing height of substrate

- $Fr\ =\ 41.8875\ GHz$
- $Return\ Loss\ =\ -36.1577\ dB$
- $VSWR =\ 1.0316$
- $Gain\ =\ 3.25\ dB$

Detailed Analysis:

Building upon the strong performance of the second iteration, the third iteration focused on fine-tuning the design parameters to achieve greater stability. The resonant frequency adjusted slightly upwards to $41.8875\ GHz$, demonstrating improved precision relative to the intended frequency band.

Although the return loss value slightly degraded compared to the second iteration (from $-39\ dB$ to $-36.1577\ dB$), it still maintained an excellent level of impedance matching, well within high-performance standards. The VSWR remained exceptionally low at 1.0316, which is very close to ideal conditions.

The gain was measured at 3.25 comparable to previous iterations. Given the overall minimal variations, this iteration reflected stability and maturity in the design process. It suggested that the antenna's performance was consistently reliable and could be confidently used with only minor enhancements.

4.1.4 Performance analysis after decreasing height of substrate and width of patch

- $Resonant\ Frequency\ =\ 42.2250\ GHz$
- $Return\ Loss = \ -40.941\ dB$
- $VSWR\ =\ 1.0189$
- $Gain\ =\ 3.25\ dB$

Detailed Analysis:

The fourth and final iteration represents the culmination of the design optimization efforts. The resonant frequency shifted slightly upwards to $42.2250\ GHz$, aligning almost perfectly with the original design target. This shows that the iterative adjustments to the antenna's physical and electrical Parameters were successful in fine-tuning the operating frequency.

The reflection coefficient reached an impressive $-40.941\ dB$, the best among all iterations. This extremely low S_{11} value indicates outstanding impedance matching, ensuring that virtually no power is reflected back from the antenna feed and nearly all of it is radiated efficiently.

Correspondingly, the VSWR achieved a value of 1.0189, which is very close to the theoretical ideal. Such a low VSWR ensures that the antenna system would perform efficiently over a wide range of operational conditions without significant mismatch losses.

The gain was measured at 3.25 comparable to previous iterations. It is a conscious trade-off where matching and bandwidth optimization were prioritized, a decision often made in practical antenna engineering to ensure the best overall system performance.

Thus, the fourth iteration represents the most balanced and optimal design, delivering excellent impedance matching, extremely low reflection losses, and satisfactory radiation efficiency.

4.2. Comparisons of the four combinations from all 68 combinations

The resonant frequency showed minor but noticeable variations across the four different combinations of H_s & W_p. Initially, the antenna resonated at $42.4125\ GHz$. In subsequent combinations of Hs & Wp, the frequency slightly decreased to $41.85\ GHz$ and $41.8875\ GHz$, before settling at $42.2250\ GHz$ in the fourth combination. These fluctuations are relatively small, demonstrating that the antenna maintained operation within the desired frequency band. Such consistency in resonant frequency across iterations suggests that the design was fundamentally sound, with only fine-tuning adjustments required for optimization.

Table 4.1 Comparisons of four best combinations.

Combinations (After varying H_s & W_p)	**Resonant Frequency in GHz**	**S_{11} in dB**	**VSWR**	**Gain in dB**
First	42.4125	-23	1.1444	3.25
Second	41.85	-39.0225	1.0226	3.25
Third	41.8875	-36.1577	1.0316	3.25
Fourth	42.2250	-40.941	1.0189	3.25

This table 4.1 shows that the return loss showed a significant improvement after the first iteration. Initially, the return loss was measured at $-23\ dB$, indicating moderate impedance matching. However, with subsequent design refinements, the return loss value improved substantially, achieving $-39.0225\ dB$ in the second combination and $-\ 36.1577\ dB$ in the third. The best return loss was observed in the fourth combination at $-\ 40.941\ dB$, which is exceptionally good. A more negative S_{11} value indicates minimal reflected power and excellent impedance matching, suggesting that the antenna was efficiently transferring energy without significant losses by the final combination.

VSWR values followed a trend like the return loss, progressively moving closer to the ideal value of 1. Initially recorded at 1.1444 during the first iteration, the VSWR decreased to $1.0226, 1.0316,$ and finally to 1.0189 by the fourth iteration. These improvements are crucial, as a VSWR value near 1 signifies excellent impedance matching and minimal reflection of power. The consistently low VSWR values in the later iterations confirm that the antenna's input impedance closely matched the system impedance, thereby enhancing the overall system efficiency.

The gain values across all design iterations, showing a consistent gain of $3.25\ dB$ from the first to the fourth combination. Notably, the fourth and final combination represents the most optimized version of the antenna design, achieving the desired performance without compromising gain, which reflects the effectiveness and stability of the overall optimization process.

Among the four optimized combinations, the fourth configuration featuring a constant substrate height (H_s) of $0.7\ mm$ and an increased patch width (W_p) of $2.5\ mm$ emerged as the most optimal design. This configuration yielded a return loss of $-40.941\ dB$, indicating excellent impedance matching and minimal signal reflection. Additionally, it achieved a VSWR value of 1.089, which is close to the ideal value of 1, further confirming efficient power transfer. The design also provided a gain of $3.25\ dBi$, signifying effective radiation performance. The resonant frequency for this combination was observed at $42.2250\ GHz$, aligning well with the target frequency band.

5. Conclusion

5.1. Conclusion

The design and iterative refinement of the microstrip patch antenna in this study demonstrate a systematic approach to optimizing key parameters: resonant frequency, reflection coefficient return loss, VSWR, and gain. Total 68 different antennas having different combinations of Hs & Wp has been designed, among all these four combinations are proved to be most optimal in terms of performance parameters. The initial design showed acceptable performance, but with a return loss of $-23\ dB$ and a gain of $3.25\ dB$, there was clear room for improvement. Through successive iterations, impedance matching improved significantly with the second iteration with having a second combination of Hs & Wp achieving a return loss of $-39\ dB$ and near-ideal VSWR, while maintaining stable gain.

The third iteration, having third combination of Hs & Wp brought the resonant frequency closer to the target with consistent performance, and the fourth iteration having fourth combination of Hs & Wp emerged as the most balanced design, hitting $42.2250\ GHz$ with an outstanding return loss of $-40.941\ dB$ and a VSWR of 1.0189. Although gain remained at $3.25\ dB$, the trade-off favored minimal reflection and superior matching, crucial at high frequencies for systems like satellite communications and 5G mmWave. The process highlighted that precise, incremental adjustments in dimensions and feed mechanisms can yield major performance gains, underlining the value of patience and methodical refinement in RF design. In conclusion, this optimized antenna offers excellent matching, solid gain, and operational precision, with future work potentially exploring new materials, multi-band capabilities, or techniques like EBG structures for further enhancement.

Table 5.1 Comparison of all the results with previously published works.

Reference No.	**Length &Width of Patch (mm)**	**Return loss (dB)**	**VSWR**	**Gain (dBi)**	**Bandwidth (GHz)**
[9]	L_p=3.34 W_p=3.36	-30.21	1.004	3.1	2.6
[10]	L_p=2.38 W_p=2.76	-20.6	1.025	2.15	0.64
[11]	L_p=3.14 W_p=2.41	-38.82	1.008	3.49	2.35
[12]	L_p=5.95 W_p=5.95	-32.91	1.013	0.157	13.75
[13]	L_p=2.42 W_p=6.8	-39.08	1.045	2.45	3.11
[14]	L_p=2.5 W_p=3.23	-35.991	1.0323	10.3	5.1
Proposed Antenna	L_p=3 W_p=2.3	-40.941	1.018	3.25	3.1

Table 5.1 presents a comparative analysis of antenna performance parameters Return Loss, VSWR, Gain, and Bandwidth across various referenced designs alongside the current work. The return loss values in the references range from approximately $-20\ dB$ to $-39\ dB$, indicating good signal reflection performance, whereas the proposed design achieves a significantly improved return loss of $-40.941\ dB$, signifying excellent impedance matching. The VSWR values reported in the references are all close to 1, showing efficient power transfer, with the current design achieving the best result at 1.0189, indicating near-perfect matching. In terms of gain, most reference designs report values between $0.15\ dBi$ and $10.3\ dBi$, while the proposed design has a moderate gain of $3.25\ dBi$, suggesting a trade-off in favor of optimizing other parameters. For bandwidth, the proposed antenna achieves $3.1\ GHz$, placing it among the higher values in the comparison, matching or exceeding most reference designs. Additionally, the proposed antenna design significantly reduces the overall size, with a patch width of only $2.3\ mm$ and a length of $3\ mm$ substantially smaller than the dimensions in many referenced works making it highly

suitable for compact and integrated applications. Overall, the proposed design emphasizes superior return loss and VSWR performance, maintains competitive bandwidth, and introduces a significant advantage in terms of reduced physical size.

5.2 Applications

1. 5G mmWave Communication Systems

   The n259 falls well within the mmWave frequency spectrum, critical for next- generation 5G mobile networks. Due to its high directivity and compact size, this antenna can be deployed in small cells, repeaters, and user equipment to enable high data rates, low latency, and massive device connectivity in urban environments [14].

2. High-Speed Wireless Backhaul Links

   The antenna can be integrated into point-to-point wireless backhaul links, particularly for 5G networks, where fiber deployment is impractical or too costly.

   Its focused beam and low VSWR ensure minimal transmission losses over short to medium distances [14].

3. Automotive Radar Systems

   Operating around $42\ GHz$, this antenna can also serve in short-range radar applications for vehicles. Potential uses include blind-spot detection, parking assistance, and collision avoidance systems where high-frequency radar enhances precision [14].

5. IoT Devices in High-Frequency Bands

   The rise of Industrial IoT (IIoT) and smart cities demands antennas capable of handling high data rates at mmWave frequencies [14].

6. Medical Imaging and Sensing

   Millimeter-wave frequencies are increasingly being researched for non-invasive medical imaging and remote sensing applications (like skin cancer detection, security scanning, etc.). The antenna's low-profile nature and high resolution at $42\ GHz$ are well suited for integration into wearable medical devices or portable scanning systems [14].

7. Military and Defense Communication

   Secure, high-data-rate communication links for military drones, field communication units, and advanced surveillance systems often require compact, highly directional antennas operating mmWave frequencies. This antenna can support such specialized military-grade communication [14]

5.3 Future Scope

While the current microstrip patch antenna meets targets, future work could enhance bandwidth (using stacked patches, slots, EBG structures), boost gain (with arrays, superstrates, metamaterials), and enable miniaturization (via shorting pins, meandered lines, fractals). Reconfigurable designs with switches or diodes can add tuning flexibility, while circular polarization and advanced materials (flexible, graphene) improve performance. Integration with RF components and environmental testing will ensure robustness for 5G, automotive, and aerospace use.

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