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Ambient RF Energy Harvesting

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PROJECT REPORT

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DEDICATION

This project is devoted to Allah Almighty, as His guidance has been crucial for its realization. It is also dedicated to our cherished parents, who have consistently inspired and supported us in every aspect of life, including morally, spiritually, emotionally, and financially. Lastly, this endeavor would not have been possible without our enthusiasm, diligent efforts, intellectual abilities, unwavering commitment, and the good health that Allah has blessed us with.

CERTIFICATE OF APPROVAL

It is to certify that the project "**Ambient RF Ebergy Harvesting**" was done by **NC Muhammad Farhan Abdullah Shah, NC Muhammad Asif Sattar, PC Malik Hammad Hussain,** under the supervision of **Dr. Zubair Ahmed** and the co-supervision of **Ma'am Sobia Hayee.**

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DECLARATION

We hereby declare that no portion of the work referred to in this Project Thesis has been submitted to support an application for another degree or qualification of this or any other university or institute of learning. If any plagiarism is found, we are fully responsible for every disciplinary action taken against us, depending upon the seriousness of the proven offense, even the cancellation of our degree.

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ABSTRACT

Ambient RF (Radio Frequency) energy harvesting is a promising technology that aims to harness and utilize the ubiquitous electromagnetic radiation present in our environment. This form of energy harvesting offers a novel approach to power low-power electronic devices, opening up new possibilities for sustainable and autonomous applications.

The concept behind ambient RF energy harvesting is to leverage the abundance of radio waves that are constantly present in our surroundings. These radio waves originate from various sources such as television and radio broadcasts, Wi-Fi networks, cellular signals, and other wireless communication systems. Instead of letting this energy go to waste, RF energy harvesting technology enables the capture and conversion of these radio waves into usable electrical energy.

The project comprised two main components: an antenna and a rectifier. For the antenna, we designed a wideband omni-directional antenna capable of covering the WiFi bands at 2.4 GHz and 5.8 GHz. To ensure efficient power transfer, we developed a multiband impedance matching network, incorporating a multi-section transformer. Our project aimed to harness ambient RF energy as a sustainable power source, utilizing innovative antenna design and impedance matching techniques.

SUSTAINABLE DEVELOPMENT GOALS

The project of Ambient RF Energy Harvesting directly contributes to SDG 7 by providing affordable and clean energy solutions, and to SDG 9 by promoting industry, innovation, and infrastructure. Through its potential to enable renewable energy generation and enhance the efficiency of various sectors, this project plays a vital role in advancing sustainable development and addressing global challenges.

SDG 7: Affordable and Clean Energy

Our project on Ambient RF Energy Harvesting contributes to SDG 7 by providing an affordable and clean energy solution. By harnessing ambient radio waves, we offer a renewable power source for low-power devices, reducing reliance on traditional batteries and fossil fuels. This technology promotes access to sustainable energy and helps address energy poverty.

SDG 9: Industry, Innovation, and Infrastructure

Our project aligns with SDG 9 by promoting innovation and fostering resilient infrastructure. Ambient RF Energy Harvesting introduces a novel approach to powering devices, driving advancements in energy harvesting and sustainable industrialization. By integrating this technology, we optimize energy usage, enhance efficiency, and contribute to economic growth.

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Chapter 1 : INTRODUCTION

1.1 Introduction to RF energy Harvesting:

What is RF energy harvesting and what applications are there for RF Energy Harvesting, information about this all is in the following below.

1.1.1 Overview of Ambient RF Energy Harvesting

The literature on ambient RF energy harvesting provides an overview of the principles, techniques, and applications associated with this emerging field. Researchers have investigated various methods to harness and convert RF energy, ranging from rectenna-based approaches to utilizing ambient signals from Wi-Fi networks and cellular networks.

1.1.1.1 What is a rectenna?

One of the key components in ambient RF energy harvesting systems is the rectenna, a device that combines a rectifier and an antenna. The term "rectenna" is a portmanteau of "rectifier" and "antenna." The rectenna's primary function is to capture RF energy from the environment and efficiently convert it into direct current (DC) electricity.

The rectifier within the rectenna is responsible for converting the alternating current (AC) signal of the captured RF energy into a DC signal. This conversion is achieved through the use of diodes, which allow the current to flow in only one direction. The antenna, on the other hand, is responsible for capturing the RF energy from the surrounding environment and delivering it to the rectifier for conversion.

The design and optimization of rectennas are critical to ensure high energy conversion efficiency. Factors such as the operating frequency, antenna size and shape, rectifier circuitry, and matching network all play a role in determining the overall performance of the rectenna system.

Rectennas can be designed to operate at specific frequencies or to capture a broad spectrum of RF energy. The choice of operating frequency depends on the intended application and the availability of RF sources in the environment. Additionally, rectenna systems can be designed for different power levels, ranging from microwatts to several watts, depending on the power requirements of the target devices.

In recent years, advancements in rectenna design and optimization techniques have led to significant improvements in energy conversion efficiency, making ambient RF energy harvesting a viable and attractive option for powering low-power electronic devices and wireless sensor networks.

1.1.2 RF Energy Harvesting Techniques

Rectenna-based energy harvesting is a widely studied technique that involves the use of rectifying antennas (rectennas) to capture and rectify RF energy for subsequent power conversion. These rectennas typically consist of an antenna element for RF signal capture and a rectifier circuit for energy conversion.

In addition to rectenna-based techniques, researchers have explored other RF energy harvesting approaches. For example, harvesting energy from Wi-Fi signals has gained attention due to the prevalence of Wi-Fi networks in both residential and commercial settings. Similarly, energy harvesting from cellular networks, leveraging the ubiquitous nature of mobile communications, has shown promise as a viable power source.

1.1.3 Applications of Ambient RF Energy Harvesting

Ambient RF energy harvesting has significant potential for various applications, including wireless sensor networks, IoT devices, and wearable electronics. Wireless sensor networks, consisting of numerous interconnected sensors, can benefit from ambient RF energy harvesting as a means to extend the operational lifespan of these devices and reduce the need for frequent battery replacements.

The IoT ecosystem, with its ever-growing number of connected devices, can greatly benefit from RF energy harvesting, enabling self-sustaining IoT deployments. Furthermore, wearable electronics, such as smartwatches and health monitoring devices, can leverage ambient RF energy to enhance user convenience and eliminate the need for frequent charging.

1.2 Motivation

In recent years, the demand for wireless electronic devices has experienced exponential growth. These devices, ranging from smartphones and wearable gadgets to sensors and Internet of Things (IoT) devices, have become an integral part of our daily lives. However, their reliance on traditional battery power poses significant challenges, including limited battery life, frequent replacements, and environmental implications due to the disposal of used batteries. As a result, there is a growing need for alternative and sustainable energy sources to power these devices.

Ambient radio frequency (RF) energy harvesting has emerged as a promising solution to address the power limitations of wireless devices. RF energy harvesting involves the extraction and conversion of electromagnetic energy present in the surrounding environment into usable electrical power. The ubiquity of RF signals, which include broadcast signals, Wi-Fi networks, and cellular communications, offers a vast potential for capturing and utilizing this ambient energy.

1.3 Research Problem

The successful implementation of RF energy harvesting requires overcoming several challenges and addressing key research questions. Firstly, the low power density of ambient RF signals necessitates the development of highly efficient energy capture and conversion mechanisms. Additionally, the design and optimization of antennas for RF energy harvesting, considering factors such as frequency range, size, and radiation efficiency, play a crucial role in maximizing energy harvesting performance. Furthermore, the efficient storage and management of harvested energy, along with effective power delivery and voltage regulation, are critical aspects that need to be addressed for practical applications.

1.4 Objectives

The primary objective of this research is to explore and advance the field of ambient RF energy harvesting. This study aims to design, develop, and evaluate an efficient RF energy harvesting system that can provide a sustainable power source for low-power electronic devices. The specific objectives of this research include:

- Investigating the fundamental principles of RF energy harvesting and understanding the various mechanisms involved in capturing and converting ambient RF energy.
- Designing and optimizing antennas for RF energy harvesting, considering factors such as frequency range, antenna gain and radiation pattern.
- Developing efficient energy conversion circuits and power management systems, such as impedance matching networks, Multi-Section Transformers and T

Junctions, to maximize the conversion efficiency and regulate the harvested energy.

- Conducting extensive experimental analysis and performance evaluation to validate the effectiveness of the proposed RF energy harvesting system.
- Exploring real-world applications and deployment scenarios for ambient RF energy harvesting, including wireless sensor networks, IoT devices, and wearable electronics.

1.5 Scope and Limitations

This research focuses on the exploration and development of ambient RF energy harvesting techniques for low-power electronic devices. The study encompasses the design and optimization of antennas, energy conversion circuitry, and power management systems. Experimental analysis and performance evaluation will be conducted to assess the efficiency and viability of the proposed system. However, it is important to acknowledge that this research may have certain limitations, such as the specific frequency ranges and power levels considered, as well as the environmental factors that may affect energy harvesting performance. [1]

Chapter 2 : LITERATURE REVIEW

2.1 Background

The increasing proliferation of wireless electronic devices, such as smartphones, IoT devices, and wearable technologies, has led to a growing demand for sustainable and efficient power sources. Traditional battery-powered systems face challenges related to limited battery life, frequent replacements, and environmental concerns associated with battery disposal. To address these issues, researchers have turned their attention to ambient RF energy harvesting as a viable solution.

Ambient RF energy harvesting involves capturing and converting the electromagnetic energy present in the surrounding environment, particularly in the form of RF signals, into usable electrical power. The ubiquity of RF signals, which include broadcast signals, Wi-Fi networks, and cellular communications, offers an abundant and untapped source of energy that can potentially power low-power electronic devices.

2.2 Challenges and Limitations in RF Energy Harvesting

Despite the potential benefits, several challenges and limitations need to be addressed for effective RF energy harvesting. One significant challenge is the low power density of ambient RF signals, which necessitates the development of highly efficient energy capture and conversion mechanisms. Efficient antenna design and optimization, taking into account factors such as frequency range, size, and radiation efficiency, are crucial for maximizing energy harvesting performance.

Moreover, the efficient storage and management of harvested energy, as well as power delivery and voltage regulation, pose additional challenges. Developing energy conversion circuits and power management systems that can maximize conversion efficiency and regulate the harvested energy is essential for practical applications.

2.3 Related Works and Research Gaps

The existing body of literature on ambient RF energy harvesting includes a range of research studies and implementations. These works contribute to the understanding of RF energy harvesting principles, design considerations, and system performance evaluation. However, there are still research gaps that need to be addressed. For instance, there is a need for further investigations into antenna design techniques, energy conversion circuitry, and system integration approaches to improve the overall efficiency and practicality of RF energy harvesting systems.

In summary, the background and literature review of ambient RF energy harvesting have provided an overview of the principles, techniques, applications, challenges, and research gaps in this field. The review highlights the potential of ambient RF energy harvesting as a sustainable power source for wireless electronic devices, while acknowledging the need for further research and development to address the existing limitations and enhance system performance. [1]

2.4 What is a Rectifier?

A rectifier is an electronic device that converts alternating current (AC) to direct current (DC). It is used to convert the sinusoidal AC voltage or current into a unidirectional flow of current, allowing the current to flow only in one direction.

The most common type of rectifier is a diode rectifier, which utilizes one or more diodes. A diode is a two-terminal electronic component that allows current to flow in one direction while blocking it in the opposite direction. In a rectifier circuit, diodes are arranged in such a way that they only conduct during the positive half cycles of the AC input, effectively removing the negative half cycles.

2.5 Purpose of diode in RF Energy Harvesting:

The purpose of a diode in RF energy harvesting is to rectify the alternating current (AC) signal received from the RF source into a direct current (DC) signal that can be used to power electronic devices or stored in a battery or capacitor. The diode acts as a one-way valve for the electrical current, allowing it to flow in only one direction while blocking the reverse current.

In RF energy harvesting, the diode is typically connected in a rectifier circuit, which consists of one or more diodes and other components such as capacitors and inductors. The diode rectifies the AC voltage induced by the RF signals, converting it into a pulsating DC voltage waveform. The rectifier circuit filters and smooths the pulsating DC signal, resulting in a relatively stable DC output.

The key purposes of the diode in RF energy harvesting are:

2.5.1 Rectification:

The diode acts as a rectifier, allowing the current to flow in only one direction. It ensures that the positive half-cycles of the RF signal are conducted while blocking the negative half-cycles. This rectification process converts the AC signal into a unidirectional DC signal that can be used to power electronic devices or stored for later use.

2.5.2 Energy Conversion:

By rectifying the RF signal, the diode enables the conversion of RF energy into electrical energy. This electrical energy can be utilized to power low-power devices or charge energy storage components such as batteries or capacitors. The diode's rectification function plays a crucial role in extracting usable power from the RF signals.

2.5.3 Voltage Regulation:

The diode also provides voltage regulation in the RF energy harvesting circuit. It prevents the reverse flow of current, maintaining a relatively stable DC output voltage. This helps to ensure that the harvested energy is efficiently utilized or stored without loss or damage to the energy harvesting system.

2.5.4 Efficiency Improvement:

The diode contributes to improving the overall efficiency of the RF energy harvesting system. By rectifying the RF signals, it minimizes power loss during the conversion process. Diodes with low forward voltage drop (VF) characteristics are preferred as they result in lower power losses and higher conversion efficiency.

It's important to note that the specific diode type, such as Schottky diodes, tunnel diodes, or PN junction diodes, may be chosen based on the frequency range, power levels, and other requirements of the RF energy harvesting system. The diode, along with other components in the rectifier circuit, ensures that the captured RF energy is efficiently converted into a usable form of electrical energy for powering wireless devices or storing it for future use. [1]

2.6 Preferred diodes for RF Energy Harvesting:

When it comes to diodes for RF energy harvesting, several types are commonly used due to their specific characteristics and performance in RF energy conversion. Here are some preferred diode options for RF energy harvesting applications:

2.6.1 Schottky Diodes:

Schottky diodes are widely used in RF energy harvesting due to their low forward voltage drop (VF) and fast switching characteristics. These diodes have a low barrier potential, allowing for efficient rectification of RF signals even at low power levels. Schottky diodes offer high conversion efficiency and are suitable for moderate to high-frequency RF energy harvesting applications.

2.6.2 Tunnel Diodes:

Tunnel diodes are known for their extremely fast switching speed and high-frequency operation. They exhibit negative resistance characteristics, making them useful for harvesting RF energy in microwave and millimeter-wave frequency ranges. Tunnel diodes can offer high conversion efficiency, especially in applications where the frequency of the RF signals is in the gigahertz range.

2.6.3 Varactor Diodes:

Varactor diodes, also known as voltage variable capacitors, are commonly used in RF energy harvesting systems for tuning and impedance matching purposes. They can be employed to optimize the energy harvesting circuit's resonance frequency and maximize power transfer. Varactor diodes exhibit a voltage-dependent capacitance, allowing for dynamic tuning of the circuit based on the received RF signals.

2.6.4 PN Junction Diodes:

PN junction diodes, such as standard silicon diodes, can also be used for RF energy harvesting applications, especially at lower frequencies. While they may have slightly higher forward voltage drops compared to Schottky diodes, PN junction diodes offer good rectification efficiency and are readily available at a lower cost.

2.6.5 RF-Switching Diodes:

RF-switching diodes, also known as PIN diodes, are commonly used in RF circuits for their fast-switching speed and low capacitance. They can be utilized in RF energy harvesting systems to provide switching capabilities for impedance matching, signal routing, or power regulation. RF-switching diodes offer good linearity and high breakdown voltage, making them suitable for higher power RF energy harvesting applications.

When selecting diodes for RF energy harvesting, it is important to consider the specific requirements of your application, including frequency range, power levels, conversion efficiency, and cost constraints. Additionally, consulting with diode manufacturers, reviewing datasheets, and considering application notes can provide valuable insights into the performance characteristics and suitability of diodes for RF energy harvesting. [1]

2.7 Selection criteria of diodes:

When selecting diodes for RF energy harvesting applications, several factors need to be considered to ensure optimal performance and efficiency. Here are some key considerations for diode selection in RF energy harvesting: [1]

2.7.1 Frequency Range:

Diodes used in RF energy harvesting should be capable of operating within the desired frequency range of the RF signals to be harvested. Different diode technologies have different frequency limitations, so it is important to select diodes that are suitable for the specific application frequency range.

2.7.2 Power Handling Capability:

Diodes should have sufficient power handling capability to handle the expected power levels of the RF signals. This is particularly important in applications where the RF signals can have higher power levels, such as in close proximity to the RF source or in strong signal environments.

2.7.3 Reverse Voltage and Current Ratings:

Ensure that the selected diodes have appropriate reverse voltage and current ratings to handle the potential reverse voltage and current induced during the energy harvesting process. Exceeding these ratings can lead to diode breakdown or damage.

2.7.4 Low Forward Voltage Drop:

Look for diodes with low forward voltage drop (VF) characteristics. Low VF minimizes the power loss across the diode, allowing for more efficient energy conversion from RF signals to electrical energy.

2.7.5 Fast Recovery Time:

Diodes with fast recovery times are preferred for RF energy harvesting applications. Fast recovery diodes minimize the reverse recovery time, reducing power loss and improving the overall efficiency of the energy harvesting system.

2.7.6 High Conversion Efficiency:

Select diodes with high conversion efficiency to maximize the power conversion from RF signals to usable electrical energy. Diodes with high efficiency will help to maximize the overall energy harvesting system performance.

2.7.7 Temperature Range:

Consider the operating temperature range of the RF energy harvesting system and choose diodes that can withstand the temperature extremes without significant performance degradation.

2.7.8 Package and Mounting:

Consider the diode package and mounting options that are suitable for the specific application requirements. This may include surface-mount (SMD) diodes or through-hole packages, depending on the design and assembly considerations.

2.7.9 Cost:

Evaluate the cost of the diodes and consider the budgetary constraints of the project. Balancing the performance requirements with the cost is crucial in selecting the most suitable diodes for the RF energy harvesting system.

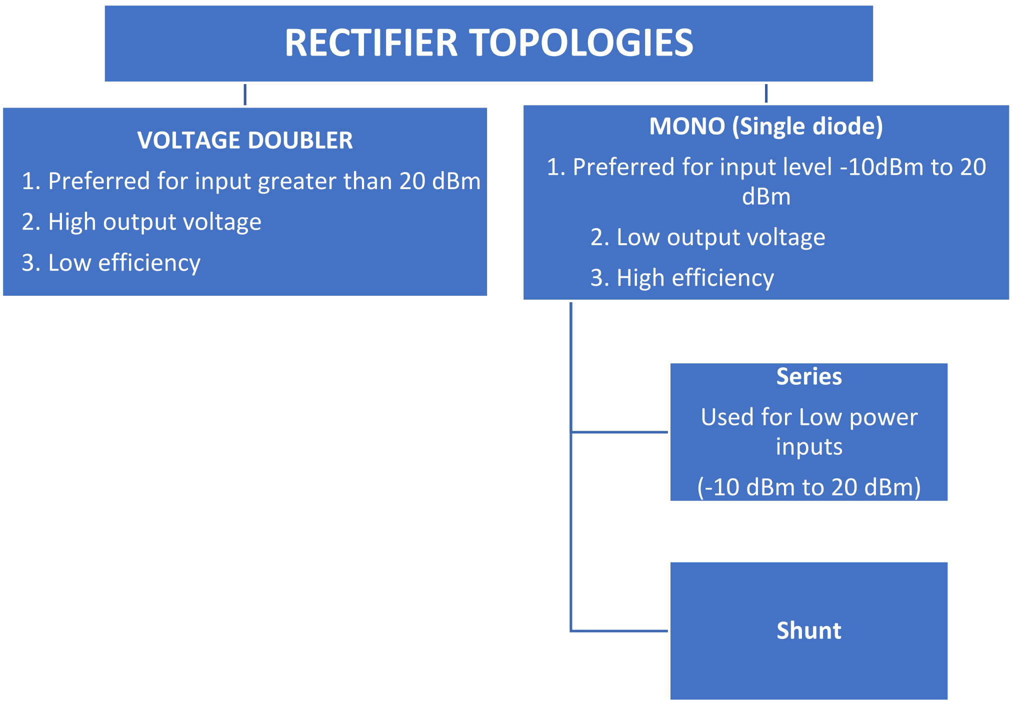
2.7.10 Manufacturer and Availability:

Choose diodes from reputable manufacturers to ensure quality and reliability. Additionally, check the availability of the selected diodes in the market to ensure a consistent supply for production and future maintenance.

It is important to note that the selection of diodes may also depend on the specific topology and configuration of the RF energy harvesting system, such as rectifier type (e.g., half-wave, full-wave, active rectifiers), impedance matching requirements, and desired output voltage or current levels. Therefore, it is recommended to consult datasheets, application notes, and technical resources provided by diode manufacturers to determine the most suitable diodes for a particular RF energy harvesting application.

2.8 Rectifier topologies:

In the field of RF energy harvesting, two commonly used rectifier topologies are the voltage doubler and the mono rectifier. The mono rectifier further consists of two types: series and shunt rectifiers. The voltage doubler topology employs a cascade of diodes and capacitors to double the input voltage. On the other hand, the mono rectifier types, series and shunt, are designed to rectify the RF signal in a single direction, with the series configuration offering higher output voltage and the shunt configuration providing improved efficiency.



2.8.1 Voltage doubler:

The voltage doubler is a rectifier topology that is commonly used in various electronic applications, including energy harvesting, where a higher DC voltage is required. It employs a combination of diodes and capacitors to effectively double the input voltage. [2] Figure 2.1 shows the structure of voltage doubler topology.

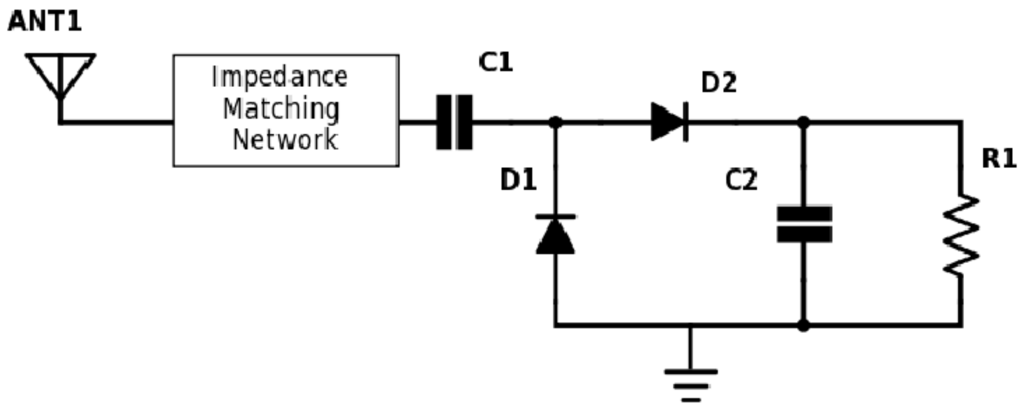


Figure 2-1: Voltage Doubler Topology

Here's a detailed explanation of the voltage doubler rectifier topology:

2.8.1.1 Components:

Typically, Schottky diodes are used in voltage doubler circuits due to their low forward voltage drop and fast switching characteristics. These diodes allow the current to flow in one direction while blocking it in the reverse direction.

Capacitors are used to store and transfer electrical charge. They play a crucial role in the voltage doubling process by storing energy during specific phases of the input signal.

The load resistor is connected to the output of the voltage doubler circuit, providing a load for the rectified voltage.

2.8.1.2 Operation:

The voltage doubler rectifier topology operates as follows:

- During the positive half-cycle of the input AC signal, the upper diode conducts and charges the first capacitor to the peak value of the input voltage.

- During the negative half-cycle, the upper diode blocks the current flow, while the lower diode conducts. This allows the second capacitor to be charged in series with the first capacitor, effectively doubling the voltage across the load resistor.
- The charging and discharging of the capacitors continue in subsequent cycles, resulting in a doubled voltage at the output of the voltage doubler circuit.

2.8.1.3 Benefits and Considerations:

The voltage doubler rectifier topology offers several benefits and considerations:

- Voltage Boost: The primary advantage of the voltage doubler topology is its ability to double the input voltage. This is beneficial in situations where a higher DC voltage is required, such as in energy harvesting applications that need to meet specific voltage thresholds for powering electronic devices.
- Simplicity: The voltage doubler topology is relatively simple, requiring only a few components, which can make it cost-effective and easy to implement.
- Output Ripple: The voltage doubler circuit may exhibit higher output ripple compared to other rectifier topologies due to the charging and discharging of the capacitors. Additional filtering may be necessary to reduce the ripple and achieve a smoother DC output voltage.
- Power Losses: The voltage doubler topology may experience higher power losses compared to other rectifier topologies, which can affect the overall efficiency of the energy harvesting system.

2.8.1.4 Component Selection:

Proper selection of diodes and capacitors is essential to ensure their voltage and current ratings meet the requirements of the application and to achieve optimal performance.

The voltage doubler rectifier topology provides a simple and effective way to double the input voltage in energy harvesting and other applications. However, it is important to carefully consider the output ripple, power losses, and component selection to ensure the desired performance and efficiency of the energy harvesting system.

2.8.2 Mono diodes:

In RF energy harvesting systems, diodes can be connected in series or parallel configurations to achieve specific objectives based on the desired performance, voltage requirements, and power handling capabilities. Let's explore the characteristics and applications of series and parallel diode connections: [2]

2.8.2.1 Series Diode Connection:

i. When diodes are connected in series, the total voltage across the diode combination is divided among the individual diodes.
ii. The forward voltage drops (VF) of each diode adds up in a series connection, resulting in a higher overall forward voltage drop.
iii. Series diode connections are commonly used when a higher voltage drop is required or when specific voltage thresholds need to be met.
iv. Series diode connections can also be employed for voltage sharing and voltage balancing in certain applications. [2] Figure 2.2 shows the circuit of Series Topology.

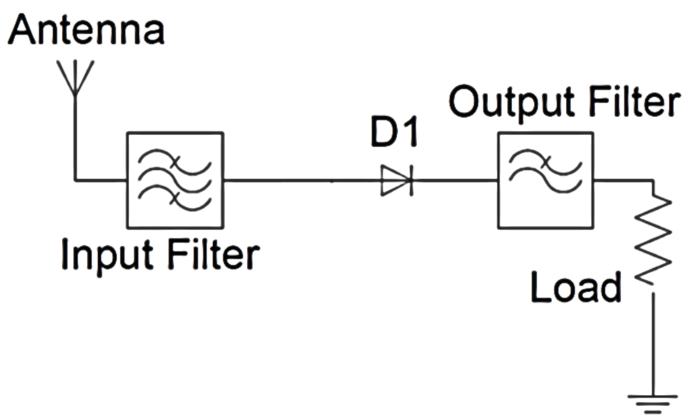


Figure 2-2: Series Diode Topology

2.8.2.2 Parallel Diode Connection:

i. When diodes are connected in parallel, each diode shares the current based on its individual forward voltage drop (VF) and impedance characteristics.
ii. Parallel diode connections allow for increased current handling capacity as the load current is distributed among multiple diodes.
iii. The overall forward voltage drop of the parallel diodes is equal to the forward voltage drop of the diode with the lowest VF.

iv. Parallel diode connections are commonly used when higher current capacity is required or when redundancy and reliability are essential.

v. Parallel diode connections can also be used for improved power handling and heat dissipation. [2] Figure 2.3 shows the circuit of Shunt Topology.

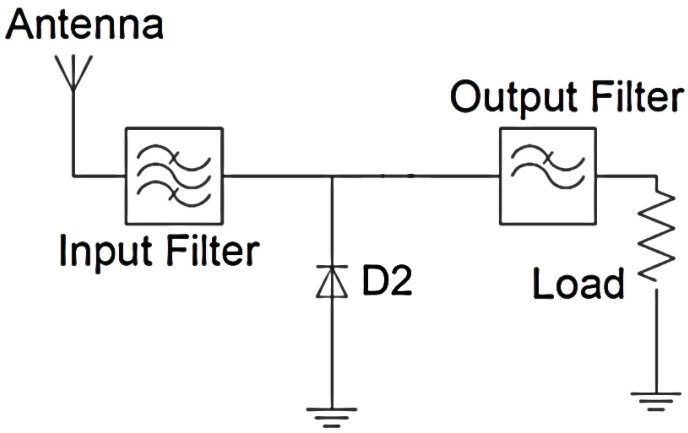


Figure 2-3: Shunt Diode Topology

2.8.2.3 Factors when connecting diodes in series or parallel:

It's important to consider the following factors when connecting diodes in series or parallel:

i. Forward Voltage Drop (VF): Series diode connections result in an increased overall forward voltage drop, which should be within the acceptable range for the energy harvesting system.

ii. Current Sharing: Parallel diode connections ensure that the load current is shared among the diodes, preventing one diode from bearing the entire current. It's important to ensure that each diode is capable of handling its portion of the current.

iii. Reverse Leakage Current: When diodes are connected in parallel, it's important to consider the leakage current characteristics of each diode, as excessive leakage currents can affect the overall performance and efficiency of the system.

The choice between series and parallel diode connections depends on the specific requirements of the RF energy harvesting system, including voltage levels, current capacity, efficiency considerations, and system constraints. Careful analysis and consideration of these factors will help determine the most suitable diode connection configuration for a given application. The focus is to select diodes with low threshold voltage, high breakdown voltage, low series resistance and low junction capacitance. After watching all the availabilities and criteria of selection we are using HSMS 2850 diode with series topology. The table below shows the diodes under consideration.

Diode	Vth	Vbr	Power handling capacity	Junction capacitance	Series resistance
HSMS 2850	150mV	3.8V	Low	0.18 pF	25 Ohm
HSMS 2860	350mV	7V	High	0.30 pF	6 Ohm
HSMS 2820/ HSMS 2822	340mV	15V	High	1 pF	6 Ohm
HSMS 8101	280mV	7V	High	0.26 pF	6 Ohm
SMS 7630 071	180mV	2V	Low	0.14 pF	20 Ohm
SMS 7621 079F	260mV	3V	Low	0.1 pF	12 Ohm
SMS 7630 079LF	240mV	2V	Low	0.14 pF	20 Ohm

Table 1: Diode Selection Criteria

2.9 Softwares:

Softwares used for our final year project are following:

- ADS
- HFSS

2.9.1 ADS (Advance Design System)

ADS (Advanced Design System) is a comprehensive electronic design automation software developed by Keysight Technologies. It is widely used in RF, microwave, and high-speed digital circuit design. ADS offers a user-friendly interface and various simulation techniques to design and analyze circuits accurately. It provides predefined RF components, custom modeling capabilities, and electromagnetic simulation tools for circuit and EM-level analysis. ADS also includes optimization algorithms and post-processing features to fine-tune designs and visualize simulation results. Leveraging ADS in our FYP project enhances our ability to design and optimize RF circuits and systems for improved performance and functionality. [3]

2.9.2 HFSS (High Frequency Structural Simulator)

HFSS (High-Frequency Structural Simulator) is a powerful electromagnetic simulation software developed by Ansys. It is extensively utilized in RF and microwave engineering for designing, analyzing, and optimizing high-frequency electronic components and systems. HFSS employs a Finite Element Method (FEM) approach to accurately model and simulate complex electromagnetic phenomena. It offers a user-friendly interface, advanced solver capabilities, and post-processing tools for visualizing and analyzing simulation results. By leveraging HFSS in our FYP project, we aim to design and optimize RF components and systems, ensuring improved performance and efficiency. [4]

Chapter 3 : ANTENNA DESIGN

3.1 Introduction:

Antennas are critical components in the transmission and reception of electromagnetic waves in the area of telecommunications. They are critical components of wireless communication systems such as radio, television, mobile phones, satellite communication, and radar. An antenna serves as a link between electrical currents running through conductors and electromagnetic waves travelling across space.

3.1.1 Types of Antenna:

There are several types of antenna available.

3.1.1.1 Dipole Antenna:

A dipole antenna is the most basic and extensively used form of antenna. It is made up of two conductive parts that are symmetrically positioned and coupled to a transmission line, usually in the form of wires or rods. The dipole antenna is mostly used for transmitting or receiving radio waves with a frequency range defined by its physical dimensions. It emits energy in all directions perpendicular to its axis and has an omnidirectional radiation pattern.

3.1.1.2 Yagi-Uda Antenna:

The Yagi-Uda antenna, often known as a Yagi antenna, is a highly directed, high-gain antenna. A driving element (dipole), one or more parasitic elements (director and reflector), and a support structure comprise it. To accomplish beam focusing, the parasitic components are placed at particular lengths and distances from the driving element. Long-distance communication with Yagi-Uda antennas is used in television reception, point-to-point communication, and amateur radio.

3.1.1.3 Patch Antenna:

A patch antenna, also known as a micro strip antenna, is a low-profile, small antenna design that is widely used in wireless communication systems, notably in mobile phones, Wi-Fi routers, and satellite communications. A metallic patch is printed on a dielectric substrate, with a ground plane on the other side. Typically, the patch is square, rectangular, or circular in form. Patch antennas are well-known for their inexpensive cost, simplicity of construction, and directed emission patterns. They are frequently constructed for specific frequency bands and can be optimized for a variety of applications, including GPS, Bluetooth, and wireless local area networks (WLANs).

3.1.1.4 Parabolic Reflector Antenna:

The parabolic reflector antenna focuses incoming or outgoing electromagnetic waves using a curved reflector surface. It is made up of a parabolic-shaped metal dish and a feed element, such as a dipole or a horn antenna, situated at the focal point. The reflector catches and redirects waves into the feed element, resulting in a high gain and highly focused beam. Satellite communication, radar systems, and microwave communications all use parabolic reflector antennas.

3.1.1.5 Loop Antenna:

A loop antenna is a small antenna design that makes use of a closed-loop loop of wire or conductor. It might be as basic as a loop or as complicated as a structure with several turns. Loop antennas can be electrically tiny or big, depending on their physical size in relation to the operating frequency's wavelength. They are commonly found in mobile devices, RFID systems, and magnetic field sensing applications.

3.1.1.6 Monopole Antennas:

Monopole antennas are basic, vertically orientated antennas that are extensively employed due to their adaptability and wide frequency range. It is made up of a single conducting element, which is usually a metal rod or wire with one end linked to the ground plane or a ground reference. The other end serves as a radiating element. Monopole antennas are noted for their large bandwidth, which allows them to function efficiently across a wide variety of frequencies. They are widely employed in radio and television broadcasting, wireless communication systems, and RFID (Radio Frequency Identification) systems.

Antennas are essential components of contemporary communication systems because they allow for the effective transmission and reception of electromagnetic waves. With its broad frequency range, the monopole wideband antenna provides a flexible solution that is appropriate for a variety of applications. The patch antenna, on the other hand, has a small and low-profile form that makes it excellent for devices with limited space. In today's linked world, understanding the many types of antennas and their features is critical for building and implementing successful wireless communication systems.

3.2 Target Parameters for Antenna Design:

- Frequency Range
- Antenna gain
- Radiation Pattern

3.2.1 Frequency Range:

The number of cycles or oscillations of an electromagnetic wave that occur every second in an antenna is referred to as its frequency. It determines how fast the antenna emits or receives signals. Antennas are tuned to certain frequencies, such as FM radio, Wi-Fi, or cellular bands. The frequency is measured in Hertz (Hz) and influences the antenna's performance, range, and capacity to properly transmit or receive signals. The required frequency values for the antenna to be designed is 2.4GHz and 5.8GHz. Main objective is to design such an antenna which should cover the band of 2GHz to 6GHz and resonate at the required frequencies. For this purpose, either two different antennas are used or single wide band antenna is used to acquire the required frequency range. [5]

3.2.2 Antenna gain:

The second target is to check the Gain of an antenna. Antenna gain is a measurement of an antenna's ability to focus or concentrate its radiated energy in a certain direction. The intensity of radiation in the desired direction is compared to that of an ideal isotropic radiator. The amplification or concentration of energy in a certain direction is represented by antenna gain, which is denoted in decibels (dB). A greater gain implies improved directivity and signal intensity in the intended direction, which improves the antenna's reception or transmission capabilities. So, the main target is also on the gain so that antenna should receive more and more radiations which would be helpful to generate more power at the output side. [5]

3.2.3 Radiation Pattern:

A radiation pattern is a graphical depiction of an antenna's radiation's directional qualities. It demonstrates how the antenna emits or receives electromagnetic radiation in three dimensions. The radiation pattern depicts the relative intensity and dispersion of transmitted or received signals at different angles around the antenna. It aids in the visualization of the antenna's directivity, gain, and beam width, allowing engineers to better understand and optimize the antenna's performance for specific purposes such as directing radiation in a certain direction or giving a wide coverage area. [5]

3.3 Substrate material

The substrate used in the Antenna design is RO4003C with a thickness of 60 mil (1.524 mm). The datasheet provides important numerical values for this substrate, including the dielectric constant (εr) of approximately 3.55, a loss tangent (tan δ) of around 0.0027, and a conductivity of 5.5 x 10^7 (S/m). These values play a crucial role in determining the electrical and mechanical properties of the substrate, enabling efficient energy conversion and overall performance of the rectenna system. [9]

3.4 Approach to design Antenna

There are two approaches to design an antenna.

i. To design two separate patch antennas which should be properly resonate at 2.4 GHz and at 5.8GHz separately.
ii. To design a single wide band antenna which will cover the both frequency ranges.

3.4.1 First Approach – Multi-Band Antenna

3.4.1.1 Patch Calculation 2.4GHz

The first approach for the design is the 2.4GHz patch antenna and the dimensions' values for the antenna are given below. Determine all the important dimensions of the patch antenna by using the book named "Antenna Theory Analysis and Design By Constantine

A Balanis " then cross check for the values is done by using online software emtalk.com. The design that antenna on High Frequency Structure Simulator (HFSS) based on the values which we have manually calculated. Then, find the length and width of the patch antenna and the point of Impedance matching. The impedance matching point is that point where the impedance of the coaxial cable (50 ohms) is matched with impedance of the patch (204.75 ohms). [6]

Given:

- Di-electric of Substrate (RO4003C) = $\varepsilon_r = 3.55$
- Resonant Frequency = $f_r = 2.4GHz$
- Height = h = 60 mil = 1.524 mm
- Width = ? , Length = ? , Impedance Matching = ?

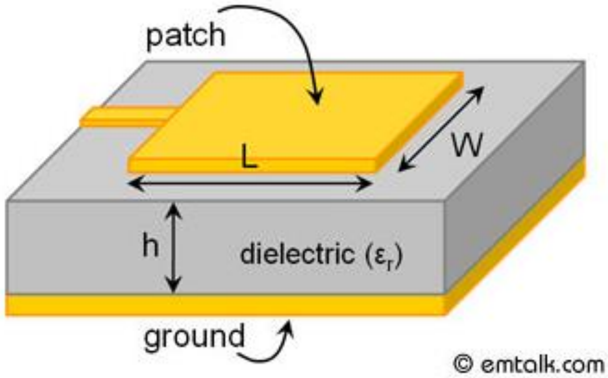


Figure 3-1: Micro-Strip Patch Antenna (emtalk.com)

<u>Width:</u>

Formula:

$$W = \frac{1}{2 * f_r * \sqrt{\mu_0 \varepsilon_0}} * \sqrt{\frac{2}{\varepsilon_r + 1}}$$

$$W = \frac{c}{2 * f_r} * \sqrt{\frac{2}{\varepsilon_r + 1}}$$

$$W = \frac{3 * 10^8}{2 * 2.4 * 10^9} * \sqrt{\frac{2}{3.55 + 1}}$$

$$W = 41.44mm$$

Length:

Formula:

$$L = \frac{1}{2 * f_r * \sqrt{\varepsilon_{r-eff}}\sqrt{\mu_0 \varepsilon_0}} - 2\Delta L - - - (i)$$

So, we find ε_{r-eff}:

$$\varepsilon_{r-eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}(1 + 12\frac{h}{W})^{-\frac{1}{2}}$$

Plug-in the values:

$$\varepsilon_{r-eff} = \frac{3.55 + 1}{2} + \frac{3.55 - 1}{2}(1 + 12\frac{1.524}{41.44})^{-\frac{1}{2}}$$

$$\varepsilon_{r-eff} = 3.34$$

Now find ΔL:

$$\frac{\Delta L}{h} = 0.412 * \frac{(\varepsilon_{r-eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{r-eff} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

$$\Delta L = h * 0.412 * \frac{(\varepsilon_{r-eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{r-eff} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

$$\Delta L = 1.524mm * 0.412 * \frac{(3.34 + 0.3)\left(\frac{41.44}{1.524} + 0.264\right)}{(3.34 - 0.258)\left(\frac{41.44}{1.524} + 0.8\right)}$$

$$\Delta L = 1.524mm * 0.412 * 1.58$$

$$\Delta L = 0.73mm$$

$refer\ to\ equation\ (i)$

$$L = \frac{1}{2 * f_r * \sqrt{\varepsilon_{r-eff}}\sqrt{\mu_0 \varepsilon_0}} - 2\Delta L$$

$$L = \frac{c}{2 * f_r * \sqrt{\varepsilon_{r-eff}}} - 2\Delta L$$

Plug-in the values:

$$L = \frac{3 * 10^8}{2 * 2.4 * 10^9 * \sqrt{3.34}} - (2 * 0.73mm)$$

$$L = 32.74mm$$

3.4.1.1.1 For Impedance Matching:

The impedance of coaxial cable is 50 ohms and the input impedance of the patch is mention in the Fig-A1

$$R_{in}(y = y_o) = Impedance\ of\ coaxial\ cable$$

$$R_{in}(y = 0) = Input\ impedance\ of\ patch$$

$$R_{in}(y = y_o) = R_{in}(y = 0)\cos^2(\frac{\pi * y_o}{L})$$

$$50 = 204.75\cos^2(\frac{\pi * y_o}{L})$$

$$0.244 = \cos^2(\frac{\pi * y_o}{L})$$

Taking Square-root:

$$0.494 = \cos(\frac{\pi * y_o}{L})$$

$$\cos^{-1}(0.494) = \frac{\pi * y_o}{L}$$

$$\therefore L = 32.74\ mm$$

$$y_o = \frac{1.05 * 32.74mm}{\pi}$$

$$y_o = 10.9\ mm$$

Now, cross check the values of the Patch using online simulator whether our values are correct or not.

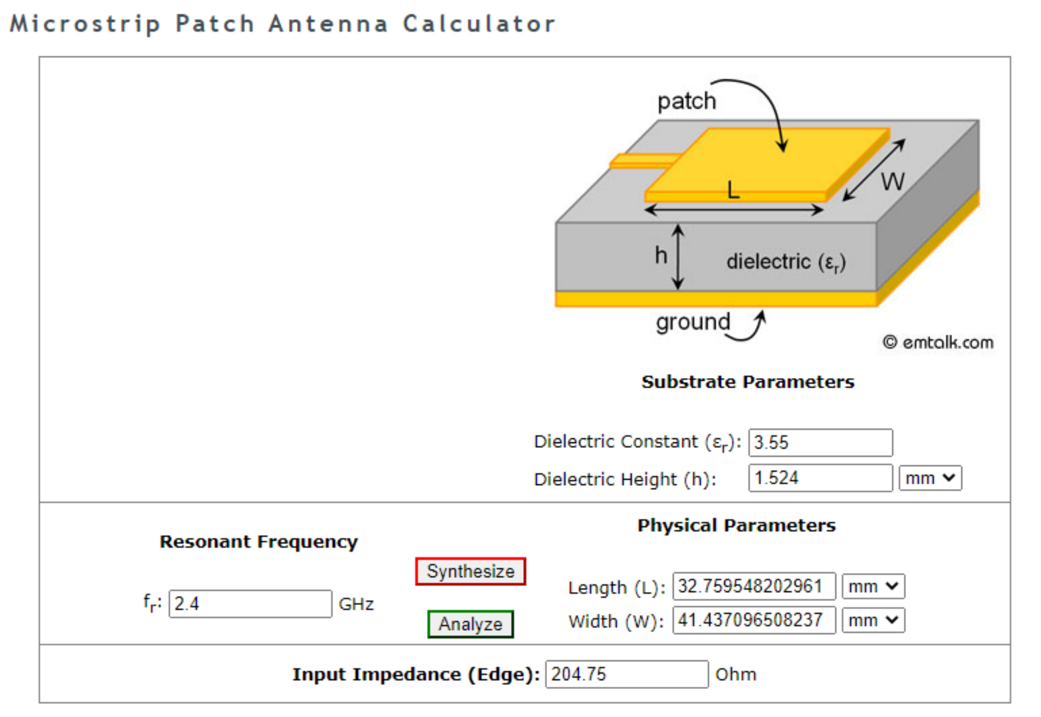


Figure 3-2: Micro-Strip Patch Antenna Calculations for 2.4 GHz Frequency (emtalk.com)

From the calculations and the results, it demonstrates clearly that the dimensions calculated before, matches with the values in Figure 3.2.

3.4.1.2 Patch Calculation 5.8GHz

Use the book's equations and design procedures to compute the length and breadth of the patch antenna for the 5.8GHz frequency. To validate the design, cross-check these measurements using internet tools such as emtalk.com. Once the dimensions are validated, use the High-Frequency Structure Simulator (HFSS) to model the antenna's performance. In HFSS, import the antenna geometry with the validated dimensions and analyze its behavior. [6]

Given:

- Di-electric of Substrate (RO4003C) = $\varepsilon_r = 3.55$
- Resonant Frequency $= f_r = 5.8GHz$
- Height = h = 60 mil = 1.524 mm
- Width = ? , Length = ? , Impedance Matching = ?

<u>To Find:</u>

Find Width and Length=?

Impedance Matching = ?

<u>Width:</u>

Formula,

$$W = \frac{1}{2 * f_r * \sqrt{\mu_0 \varepsilon_0}} * \sqrt{\frac{2}{\varepsilon_r + 1}}$$

$$W = \frac{c}{2 * f_r} * \sqrt{\frac{2}{\varepsilon_r + 1}}$$

$$W = \frac{3 * 10^8}{2 * 5.8 * 10^9} * \sqrt{\frac{2}{3.55 + 1}}$$

$$W = 0.01714$$

$$W = 17.14\, m$$

<u>Length:</u>

Formula:

$$L = \frac{1}{2 * f_r * \sqrt{\varepsilon_{r-eff}} \sqrt{\mu_0 \varepsilon_0}} - 2\Delta L - -(ii)$$

So, we find ε_{r-eff}:

$$\varepsilon_{r-eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}(1 + 12\frac{h}{W})^{-\frac{1}{2}}$$

Plug-in the values:

$$\varepsilon_{r-eff} = \frac{3.55 + 1}{2} + \frac{3.55 - 1}{2}(1 + 12\frac{1.524}{17.14})^{-\frac{1}{2}}$$

$$\varepsilon_{r-eff} = 3.16$$

Now find ΔL:

$$\frac{\Delta L}{h} = 0.412 * \frac{(\varepsilon_{r-eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{r-eff} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

$$\Delta L = h * 0.412 * \frac{(\varepsilon_{r-eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{r-eff} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

$$\Delta L = 1.524mm * 0.412 * \frac{(3.16 + 0.3)\left(\frac{17.14}{1.524} + 0.264\right)}{(3.16 - 0.258)\left(\frac{17.14}{1.524} + 0.8\right)}$$

$$\Delta L = 0.72mm$$

Refer to equation (ii)

$$L = \frac{1}{2 * f_r * \sqrt{\varepsilon_{r-eff}}\sqrt{\mu_0 \varepsilon_0}} - 2\Delta L$$

$$L = \frac{c}{2 * f_r * \sqrt{\varepsilon_{r-eff}}} - 2\Delta L$$

Plug-in the values:

$$L = \frac{3 * 10^8}{2 * 5.8 * 10^9 * \sqrt{3.16}} - (2 * 0.72mm)$$

$$L = 13.11mm$$

3.4.1.2.1 For Impedance Matching:

The impedance of coaxial cable is 50 ohms and the input impedance of the patch is mention in the Fig-A2

$$R_{in}(y = y_o) = Impedance\ of\ coaxial\ cable$$

$$R_{in}(y = 0) = Input\ impedance\ of\ patch$$

$$R_{in}(y = y_o) = R_{in}(y = 0)\cos^2(\frac{\pi * y_o}{L})$$

$$50 = 204.75\cos^2(\frac{\pi * y_o}{L})$$

$$0.244 = \cos^2(\frac{\pi * y_o}{L})$$

Taking Square-root:

$$0.494 = \cos(\frac{\pi * y_o}{L})$$

$$\cos^{-1}(0.494) = \frac{\pi * y_o}{L}$$

$$\therefore L = 13.11\ mm$$

$$y_o = \frac{1.05 * 13.11mm}{\pi}$$

$$y_o = 4.38\ mm$$

Based on the calculations and results in Figure 3.3, It's is evident that manually calculated values have the exact match with the values calculated in Figure 3.3.

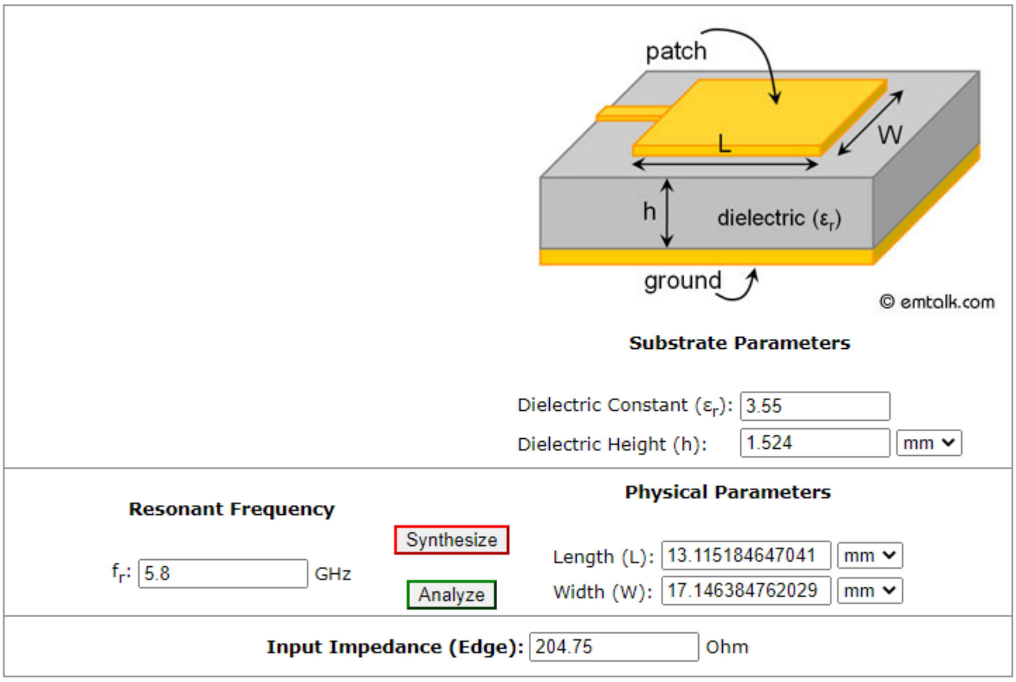


Figure 3-3: Micro-Strip Patch Antenna Calculations for 5.8 GHz Frequency (emtalk.com)

3.4.2 HFSS Simulations' Results for Patch Antennas

The Results obtained after implementing the final parametric values of each antenna in HFSS are given below.

3.4.2.1 Simulations of Patch Antenna 2.4GHz

Now, it's time to simulate the design which have been made using software High Frequency Structure Simulator (HFSS). The all-important dimensions of patch have been found. The dimension of substrate taken as L/4 and dimension of radiation box is taken as L/2. By plugging in the rest of parameters, a final diagram of structure is shown in Figure 3.4.

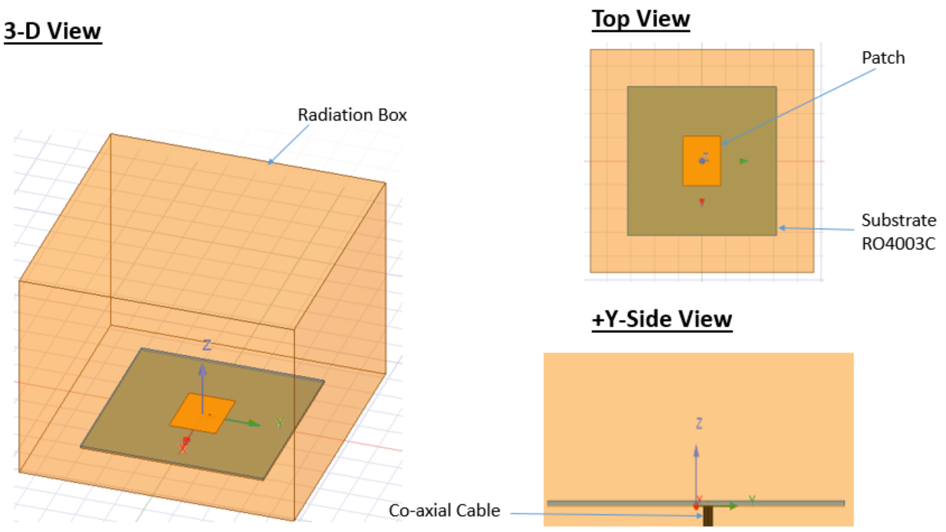


Figure 3-4: Patch Antenna for 2.4 GHz 3-D View

3.4.2.1.1 S-Parameters of 2.4GHz

Initially, the antenna was not resonating at desired frequency. Then the length of the patches was changed by 1mm. After so many simulations, the antenna is finally resonating at desired frequency which is 2.4GHz and easily can be seen in the Figure 3.5. As one can easily see that, at -10dB the impedance bandwidth is very low. This low bandwidth is unable to receive more signals from the environment.

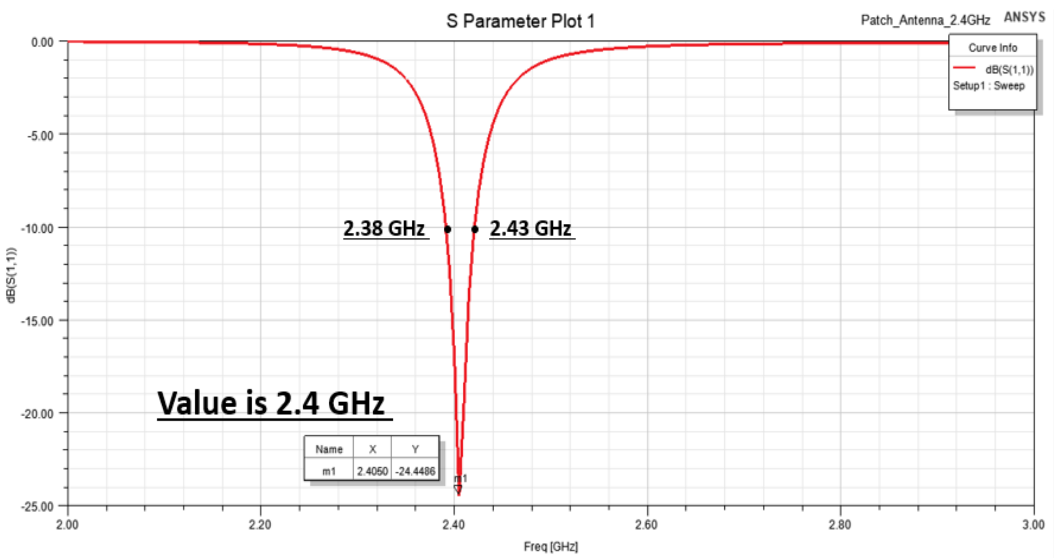


Figure 3-5: S-parameters of 2.4 GHz patch Antenna

3.4.2.1.2 Radiation Pattern

A patch antenna's radiation pattern is controlled by its shape, size, substrate material, and feeding method. Patch antennas often have a directed emission pattern that consists of a main lobe and multiple secondary lobes or nulls. The principal direction in which the antenna transmits the majority of its energy is represented by the main lobe, while the minor lobes indicate alternate emission directions. Nulls, on the other hand, are areas where the radiated power is greatly reduced. The radiation pattern is most in the positive z-direction. Radiation Pattern shown in Figure 3.6.

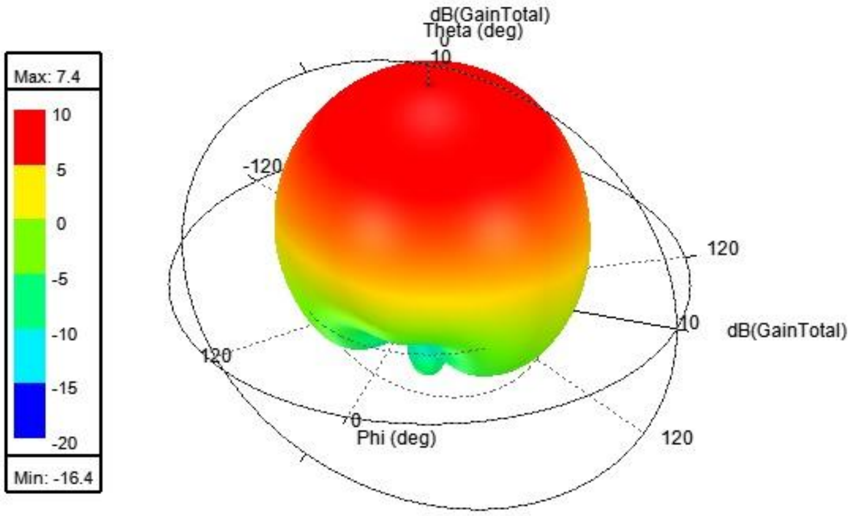


Figure 3-6: Radiation pattern of 2.4GHz Patch Antenna

3.4.2.2 Simulations of Patch Antenna 5.8GHz

Again, using all the dimensions which already calculated, there’s a HFSS design model in the Figure 3.7.

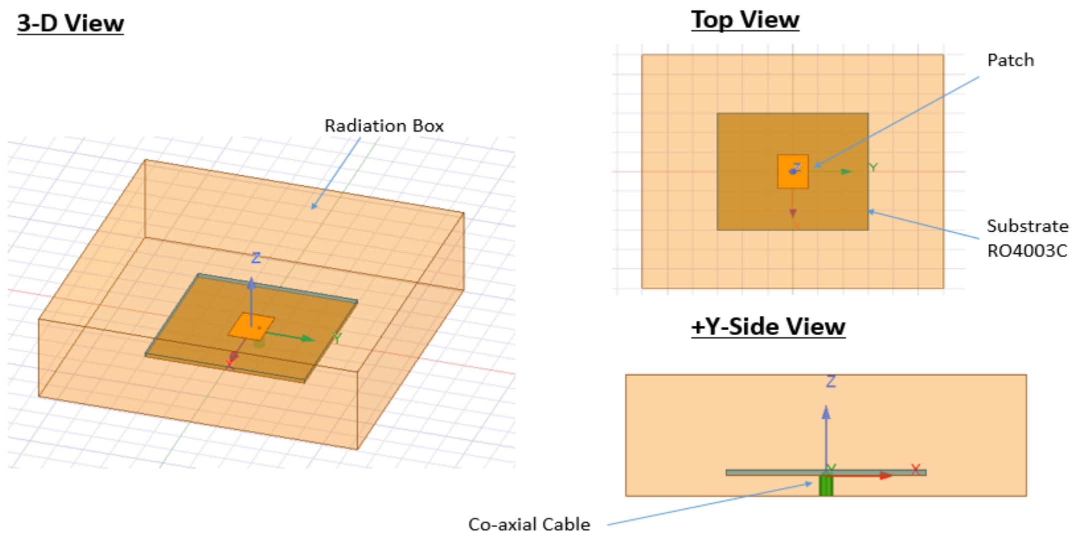


Figure 3-7: 5.8GHz Patch Antenna 3-D View

3.4.2.2.1 S-Parameter at 5.8 GHz

It can easily be seen in the Figure 3.8, there's a much better bandwidth of this antenna rather than the previous antenna. While keeping in the bandwidth and the cost factor, wide band antenna is much better than designing the two different patch antenna having moderate bandwidth.

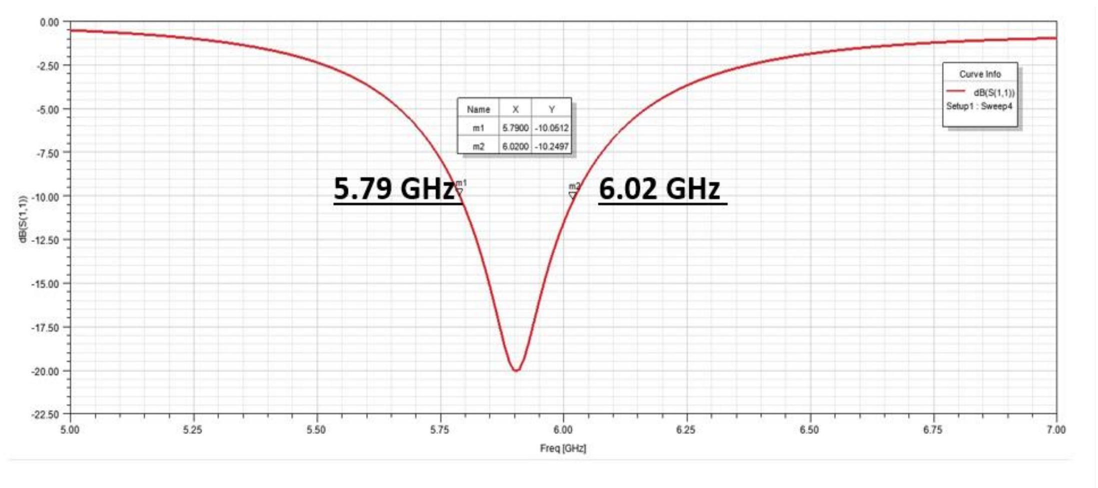


Figure 3-8: S-parameters for 5.8 GHz Patch Antenna

3.4.2.2.2 Radiation Pattern

As, the main lobe represents the primary direction in which the antenna transmits the majority of its energy, while the minor lobes show other emission directions. Nulls, on the other hand, are places with much less radiated power. The radiation pattern is primarily positive in z-direction in Figure 3.9.

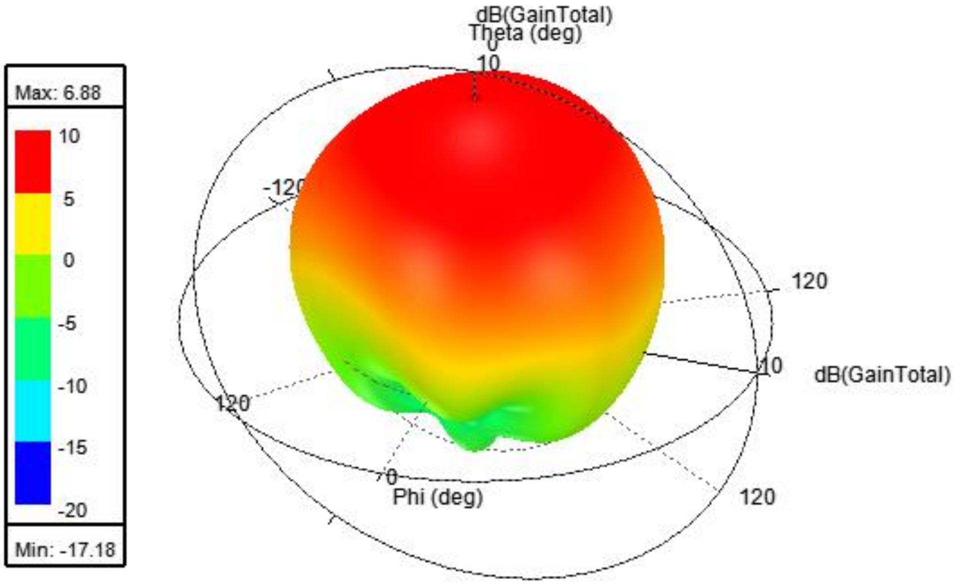


Figure 3-9: Radiation Pattern for 5.8Ghz Patch Antenna

3.4.3 Second Approach – Wide Band Antenna

A wideband antenna is intended to function over a large frequency range, generally over numerous frequency bands. It has the advantage of being versatile, allowing for smooth communication across a wide range of wireless systems and applications. Wideband antennas can broadcast and receive electromagnetic waves across a broad range, making them compatible with various frequency allocations and wireless protocols. To attain the needed broad performance, these antennas are frequently constructed with specific features such as numerous radiating components or advanced impedance matching methods. As studied, a single monopole wide band antenna can be used for any frequency range. The desired frequency range is about 2.3GHZ – 6.1GHz. To design a wide band antenna, the article named "*Efficiency Enhanced Seven-Band Omnidirectional Rectenna for RF Energy Harvesting*" is referred. [7] The reason for using wide band antenna is that:

- Versatility: Wideband antennas may function across a wide frequency range; they are suited for a variety of wireless communication systems. They may support numerous frequency bands, enabling seamless communication across networks and devices.

- Economical: Using a wideband antenna reduces the requirement for several narrowband antennas devoted to different frequency bands. As fewer antennas are required to cover a wide variety of frequencies, the overall cost of antenna placement is reduced.
- Simplified Installation: Using a wideband antenna reduces installation time by eliminating the need to position and install several antennas for different frequency bands. This saves time, effort, and resources when it comes to setting up wireless communication networks. [7]

3.4.3.1 Wide Band Antenna parametric calculations

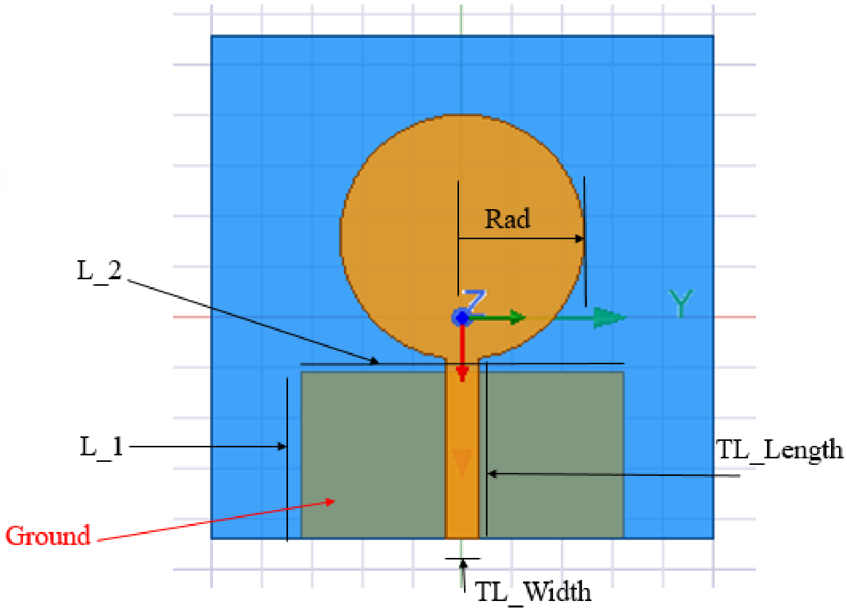


Figure 3-10: Wideband (Omni-Directional) Antenna Labelling

Initial values are taken from that article which are as follow:

$$\lambda = \frac{c}{f} = \frac{3*10^8}{4.1*10^9} = 73.17mm \because f = (2.4GHz+5.8GHz)/2$$

$$Radius\ of\ the\ circle = \frac{\lambda}{4} = 18.30mm$$

$$L\_1\ of\ the\ Ground = \frac{\lambda}{4} = 18.30mm$$

$$L\_2\ of the\ Ground = \frac{\lambda}{2} = 36.58mm$$

$$Length\ of\ TL\_Length = \frac{\lambda}{8} = 9.15mm$$

3.4.3.2 HFSS Simulations of Wide Band Antenna

3.4.3.2.1 Initial Values Results

Refer to the section 3.4.3.1, there are some initial parameters given. That values are applied on the substrate that used in this project gives the following design in the Figure 3.11. One can easily see that the circle of the antenna is too big and the effect of it on antenna can be seen in s-parameter section. [7]

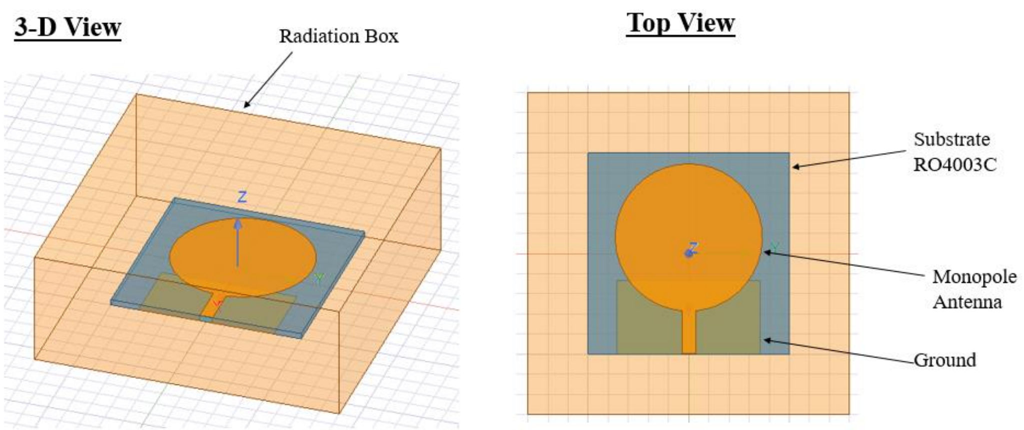


Figure 3-11: Wideband Antenna 3-D View at Initial Values

3.4.3.2.2 S-Parameters

The s-parameters results in Figure 3.12 doesn't match with the results according to the desire. At -10dB the bandwidth of the wide band antenna isn't favorable. So, there are following methods to set the bandwidth at -10dB

- Change the radius of the circle and check out the results again and again.
- Change the dimensions of the ground and check the results after every change.

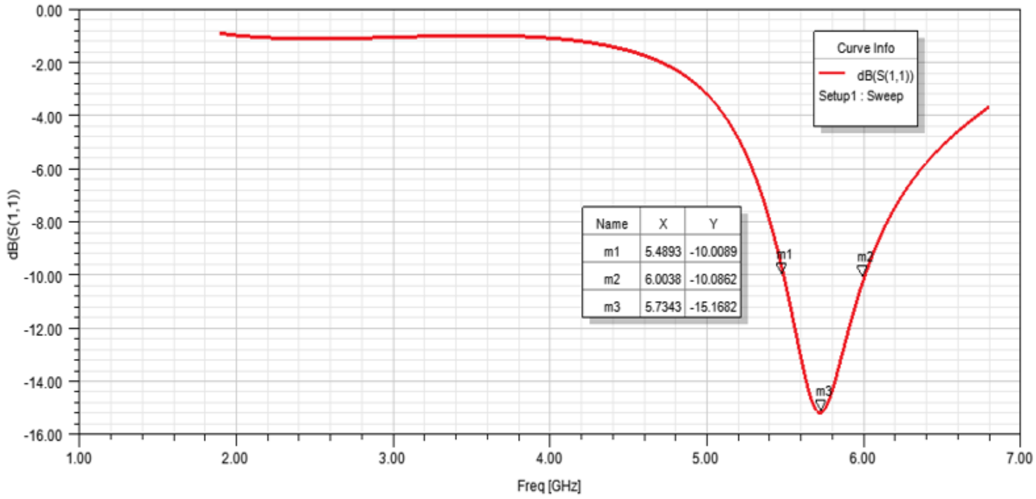


Figure 3-12: S-parameter of Wideband Antenna on Initial Values

3.4.3.2.3 S-Parameter by changing radius

Multiple simulations are done in which the radius is kept changed, here is a clear view Figure 16 that after many simulations the radius of the circle gives wide range. After the careful change in the radius following results are observed Figure 3.13. After the deep analysis the radius value of 12.15mm is to be selected. [7]

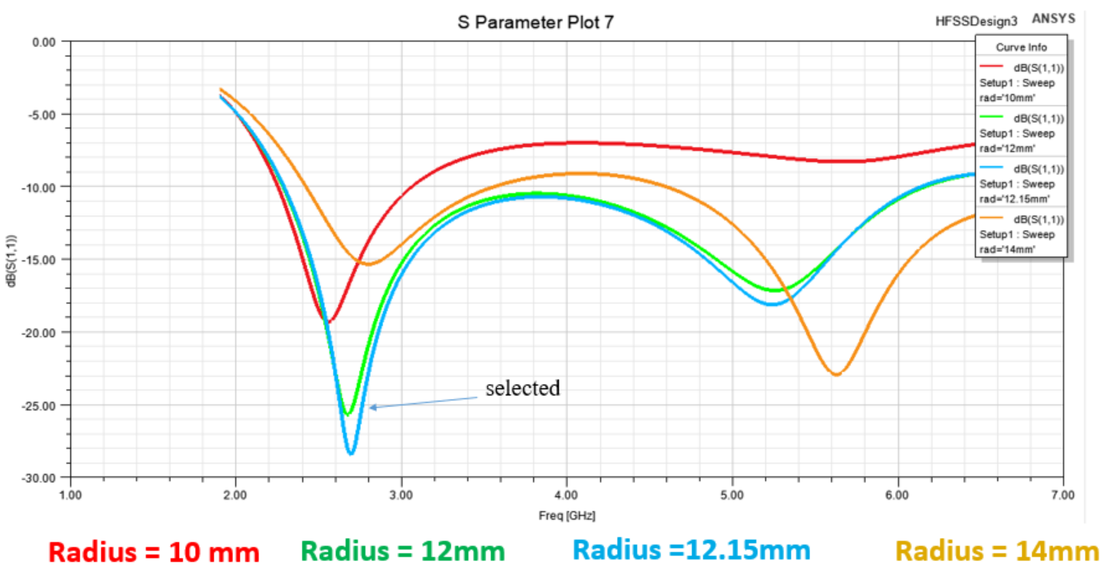


Figure 3-13: Change in S-parameter of Wideband Antenna by changing Radius

3.4.3.2.4 S-Parameter by changing L_1 and L_2:

Similarly changing the lengths of the ground also impact the range of the antenna. Different combinations of lengths have been made and after numerous simulation the

L1=16.6mm and L2=32mm is selected. The reason the selection is that the frequency range is fall between what we desired. In Figure 3.14 and Figure 3.15 shows clearly the different dimensions of the L_1 and L_2 and their results.

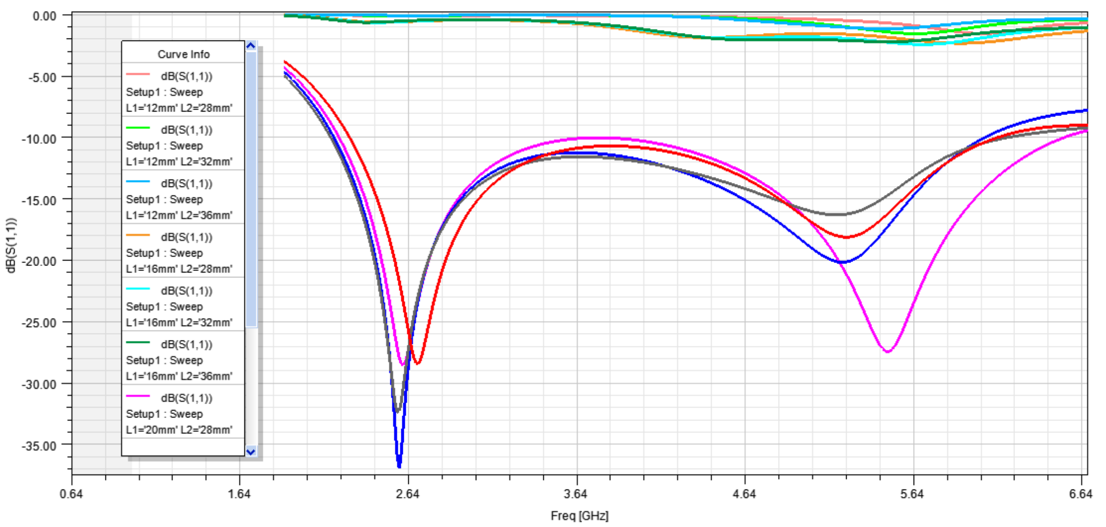


Figure 3-14: Change in S-parameter of Wideband Antenna by changing Ground Plane Lengths

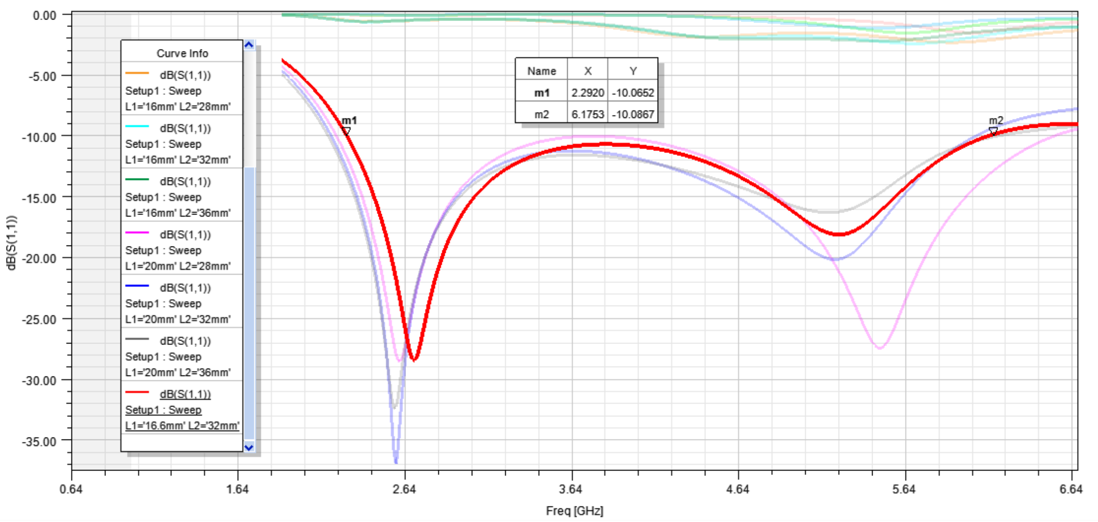


Figure 3-15: Change in S-parameter of Wideband Antenna by changing Ground Plane Lengths

3.4.3.2.5 Finalized Values

So, after multiple simulations our final values are as following:

Radius	TL_Length	TL_Width	L_1	L_2
12.15 mm	21.9 mm	3.39 mm	16.6 mm	32 mm

Table 2: Wideband Antenna Finalized Dimensions

Here's a s-parameter file of the final results in Figure 3.16 which we deducted after large number of simulations.

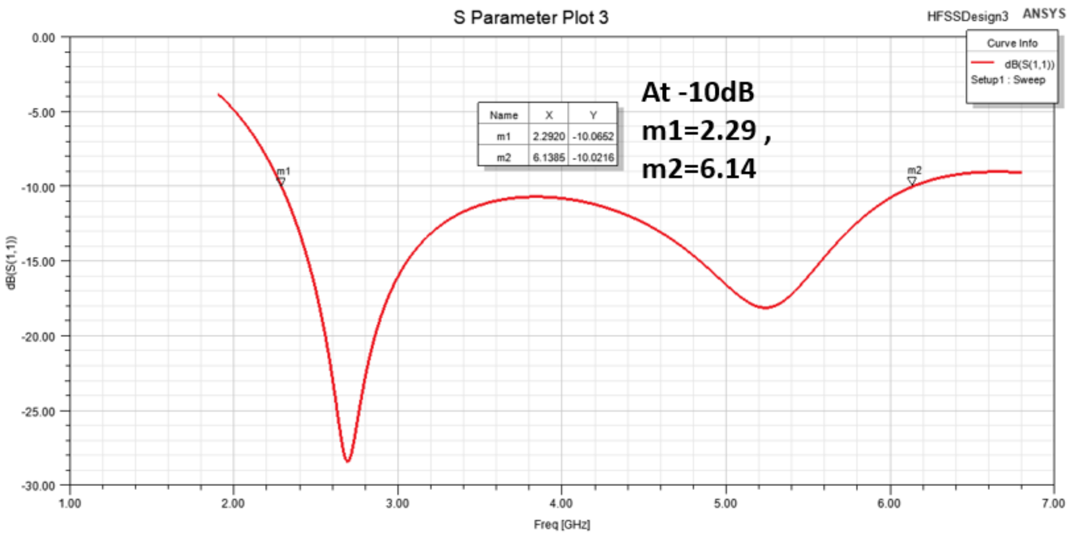


Figure 3-16: S-parameter of Wideband Antenna on Finalized values

3.4.3.2.6 Radiation Pattern of Wideband Antenna at 2.4GHz

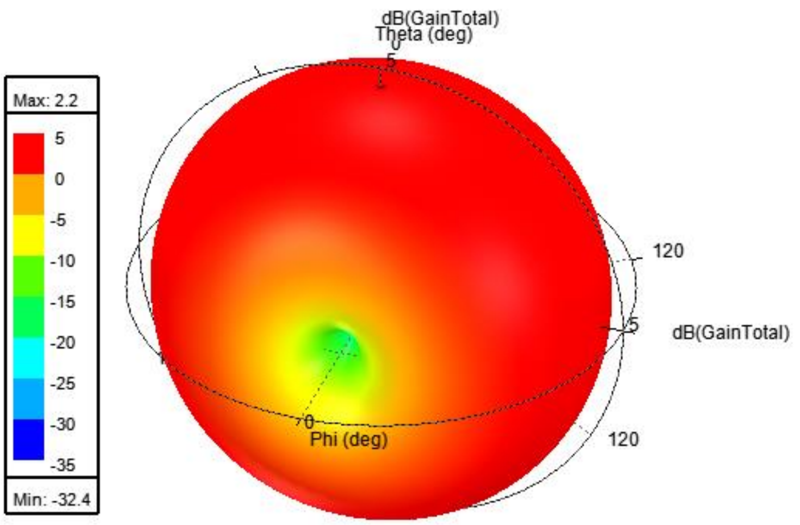


Figure 3-17: Radiation Pattern of Wideband Antenna at 2.4GHz point

3.4.3.2.7 Radiation Pattern of Wideband Antenna at 5.8GHz

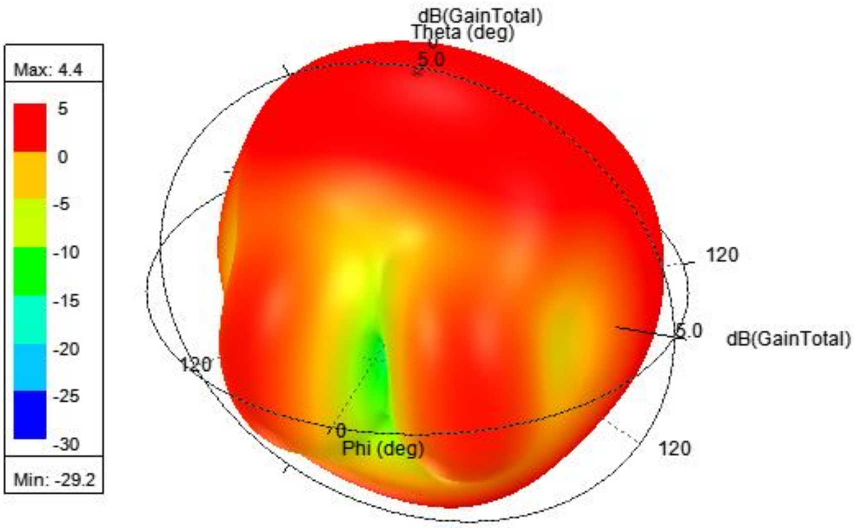


Figure 3-18: Radiation Pattern of Wideband Antenna at 5.8GHz point

3.4.4 Fabricated Antenna

3.4.4.1 Gerber File and Fabrication:

Including the Gerber file in the report allows for accurate representation of the PCB design. A Gerber file is a standard format used in the PCB manufacturing industry to convey information about the copper layers, solder mask, and other relevant details of the PCB design.

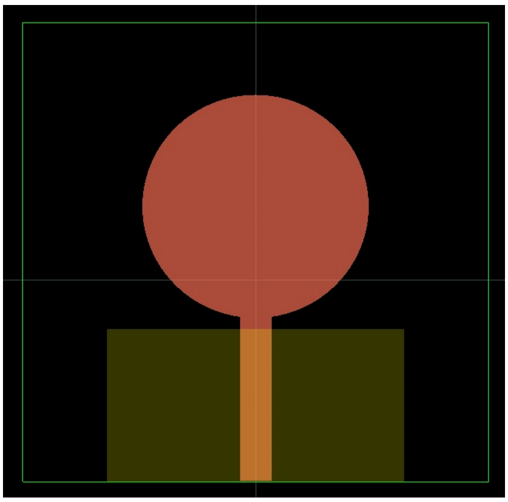


Figure 3-19: Gerber file of Wideband Antenna for Fabrication

The antenna is fabricated after the Gerber file prepared in ADS. The given Figure 3.20(A) and Figure 3.20(B) is the front and the backside of the antenna respectively.

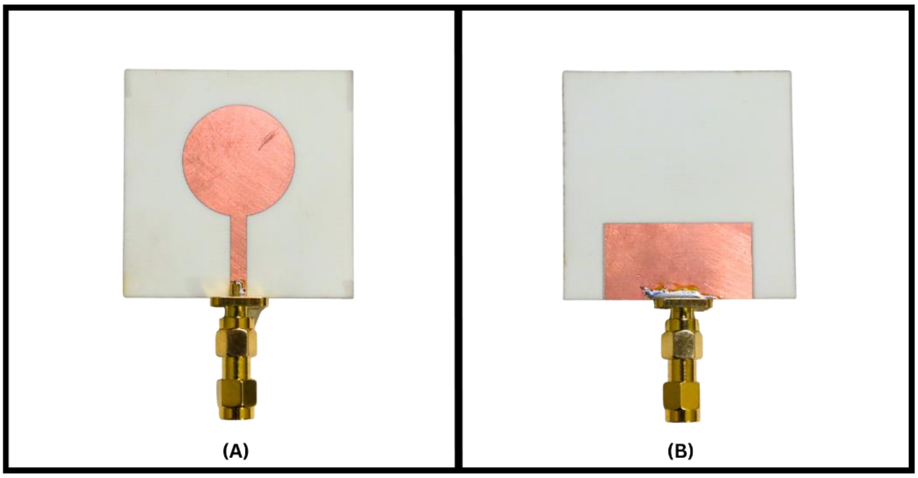


Figure 3-20: (A) Fabricated Wideband Antenna Front side (B) Fabricated Wideband Antenna Back side

3.4.5 Real Time S-parameters' Results:

Following Figure 3.21 demonstrate the real time s-parameter values of the designed antenna. In this photo it can be clearly seen that the antenna's bandwidth fulfills the all requirement whatever it gives in the simulations. It ranges is 2.4GHZ < freq < 6GHz.

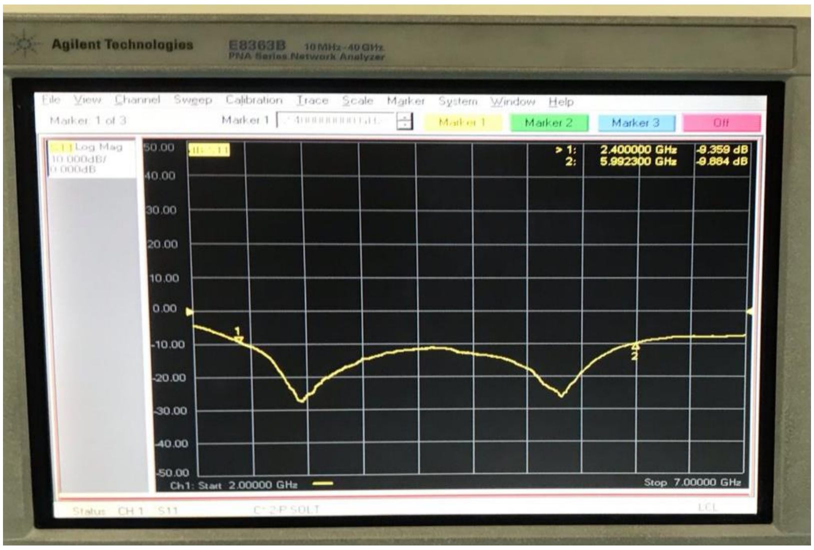


Figure 3-21: Real Time S-parameters of Fabricated Wideband Antenna

Chapter 4 : RECTIFIER DESIGN

4.1 What is rectification?

Rectification is the process of converting alternating current (AC) signals into direct current (DC) signals by allowing current flow in only one direction using diodes. This enables the extraction and utilization of the power contained within high-frequency RF signals for various applications.

4.2 Substrate Specifications

The substrate used in the project is RO4003C with a thickness of 20 mil. RO4003C is a high-frequency laminate known for its excellent electrical properties and low loss characteristics. The datasheet provides key numerical values such as a dielectric constant (εr) of 3.38 ± 0.05, a dissipation factor ($\tan \delta$) of 0.0027, and a copper-clad thickness of 1 oz (35 µm). These values are crucial for accurate design and analysis of RF circuits, ensuring optimal performance and signal integrity. [9]

4.3 Diode HSMS 2850

The HSMS 2850 diode is commonly used in high-frequency rectifier circuits due to its excellent performance characteristics. This diode offers low junction capacitance, high switching speed, and low forward voltage drop, making it suitable for efficient rectification of high-frequency signals. The numerical values associated with the HSMS 2850 diode include a forward voltage drop of around 0.5V, a maximum reverse voltage of 20V, and a capacitance of approximately 0.3pF. [8]

4.4 Diode Impedance Calculation

Using Advanced Design System (ADS), an equivalent model of the HSMS 2850 diode can be created to calculate its impedance at both frequencies (2.4 GHz and 5.8 GHz) with a 1k ohm load. The equivalent model can be based on the diode's S-parameters or its small-signal equivalent circuit.

By setting up the simulation in ADS and incorporating the diode model along with the 1k ohm load, the impedance values can be obtained for each frequency. The simulation results will provide the complex impedance values, including both the resistance and reactance components, at the specified frequencies.

These calculated impedance values are crucial for impedance matching network design and overall rectifier circuit optimization, ensuring efficient power extraction from the RF energy source while properly matching the load impedance for maximum power transfer. [8]

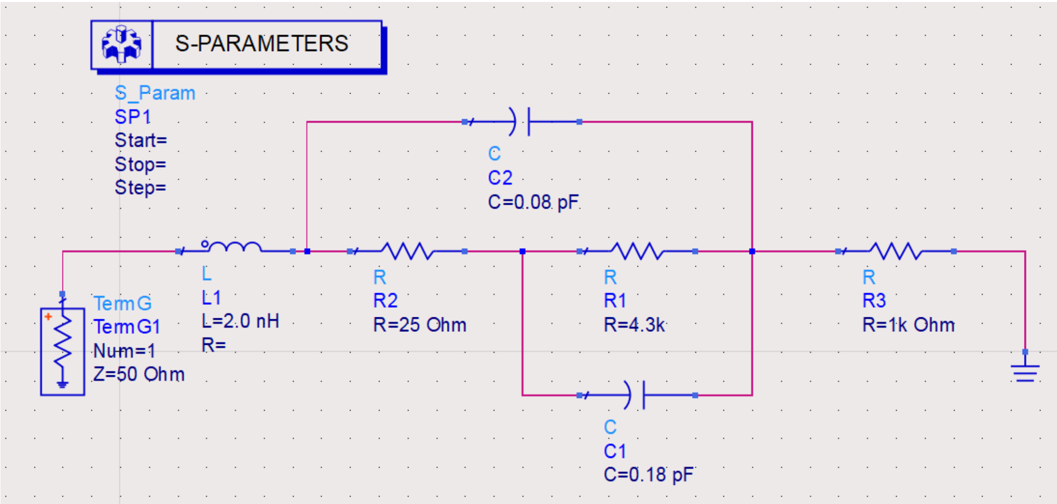


Figure 4-1: Equivalent Circuit of HSMS 2850 Diode in Schematic

4.4.1 Diode Impedance Calculation at 2.4 GHz

ADS simulation results for the HSMS 2850 diode with a 1k ohm load showed impedance values of X + jY ohms at 2.4 GHz frequency.

The impedance value is 1026.45-j219.1 Ohm.

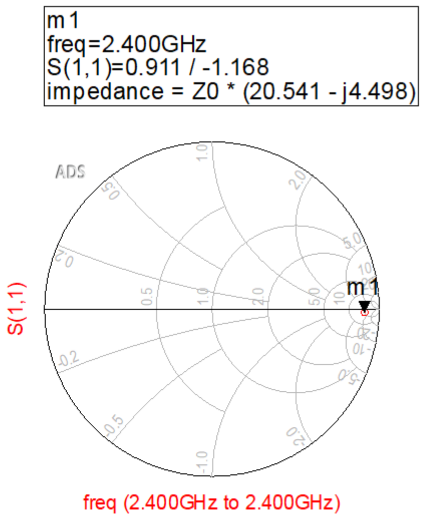


Figure 4-2: Diode Impedance Calculation at 2.4 GHz

4.4.2 Diode Impedance Calculation at 5.8 GHz

ADS simulation results for the HSMS 2850 diode with a 1k ohm load showed impedance values of X + jY ohms at 5.8 GHz frequency.

The impedance value is 1014.55-j33.45 Ohm.

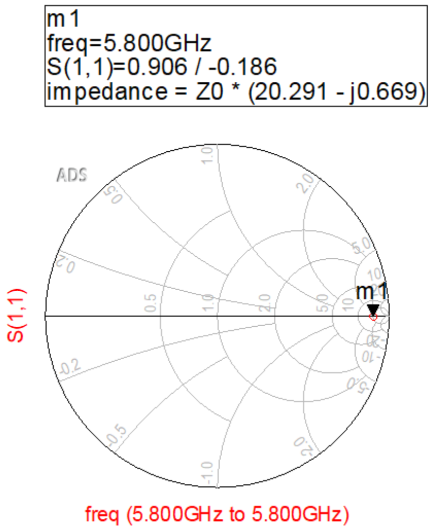


Figure 4-3: Diode Impedance Calculation at 5.8 GHz

4.5 Impedance Matching Networks

Impedance matching is a technique used in electronic circuits to ensure maximum power transfer between a source and a load by minimizing signal reflections and optimizing impedance characteristics. It is necessary to improve signal integrity, reduce loss, and enhance overall system performance.

Impedance matching involves adjusting the impedance of a load to match the impedance of a source. When the impedances are matched, there is efficient power transfer without significant signal reflections. This allows for maximum power to be delivered to the load. [5]

4.5.1 Importance of Impedance Matching:

i. Maximizing Power Transfer Efficiency: Impedance matching ensures that the maximum power available from the source is transferred to the load, minimizing power loss.

ii. Minimizing Signal Reflections: Reflections occur when there is a mismatch between the source and load impedances. Impedance matching reduces reflections, preventing signal distortion and improving overall system performance.
iii. Improving Signal Integrity and Quality: Impedance matching helps maintain signal integrity by minimizing signal distortions, such as attenuation and phase shifts.
iv. Enhancing System Performance and Efficiency: Proper impedance matching leads to improved system performance, reduced power loss, and increased efficiency.

4.5.2 Types of Impedance Matching

4.5.2.1.1 Single Stub Matching:

Single stub matching is a technique used for impedance matching using a transmission line with a stub section. It involves adding a stub of a specific length and impedance to the transmission line to cancel out the reactive component of the load impedance. The stub is connected at a specific distance from the load, allowing for impedance transformation and matching. [5]

4.5.2.1.2 Quarter Wave Matching:

Quarter wave matching is another common technique for impedance matching. It involves using a quarter-wavelength transmission line section connected between the load and the source. The characteristic impedance of the transmission line is chosen to match the load impedance. This technique provides a reflection less transition from the source to the load by transforming the impedance at a specific distance. [5]

4.5.3 Impedance Matching Network Design at 2.4 GHz

To design a single stub matching circuit at 2.4 GHz using an open circuit stub, the following steps were followed:

i. Using the Smith Chart utility in ADS, the load impedance and source impedance were plotted on the Smith Chart. The load impedance was ZL = 1026.45 – j219.1 ohms and the source impedance was ZS = 50 + j0 ohms.

ii. By locating the intersection point of the load impedance and the 2.4 GHz constant resistance circle on the Smith Chart, the normalized load impedance (ZL_norm) was determined.

iii. The distance from the normalized load impedance point to the center of the Smith Chart represents the normalized distance (d_norm) of the stub.

iv. Using the Transmission Line Calculator in ADS, the physical lengths of the stub were calculated based on the desired frequency (2.4 GHz) and the electrical lengths determined from the Smith Chart.

v. The calculated stub lengths were then used to draw the simulation structure of the single stub matching network in ADS.

vi. The simulation was performed to obtain the results, which include the reflection coefficient (S11), return loss, and impedance matching performance.

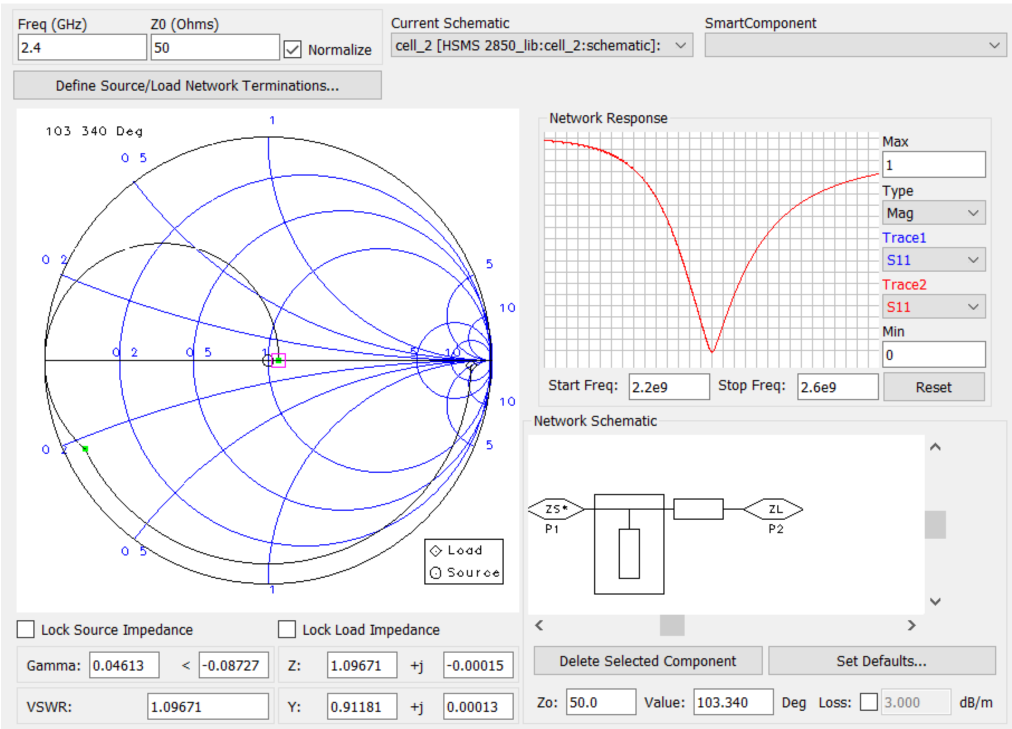


Figure 4-4: Stub Length Calculations using Smith Chart Utility in ADS for 2.4 GHz (A)

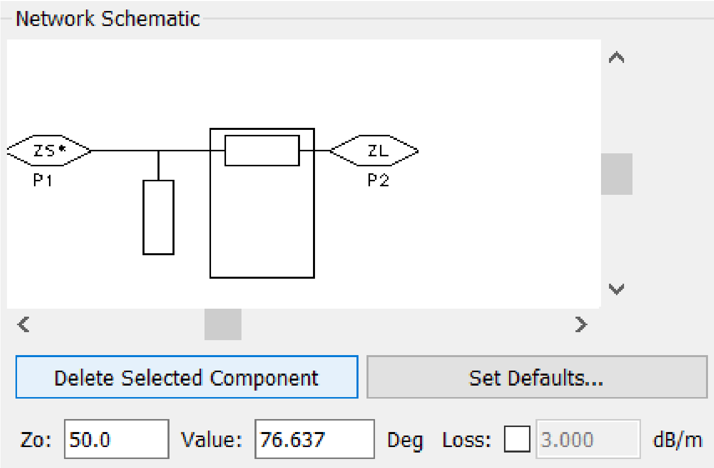


Figure 4-5: : Stub Length Calculations using Smith Chart Utility in ADS for 2.4 GHz (B)

4.5.3.1 Matching circuit in Schematic

Using the calculated values from TL calculator, circuit is implemented in ADS Schematic for the simulation. [5] Values are given below:

Distance d = 16.07 mm

Length L = 21.72 mm

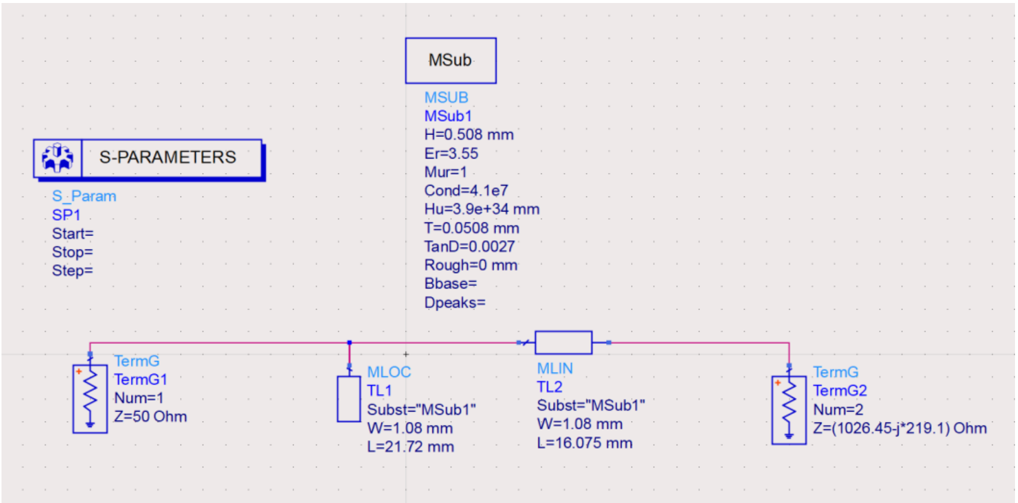


Figure 4-6: Impedance Matching Circuit at 2.4 GHz in Schematic

The simulation results for the schematic circuit are given below.

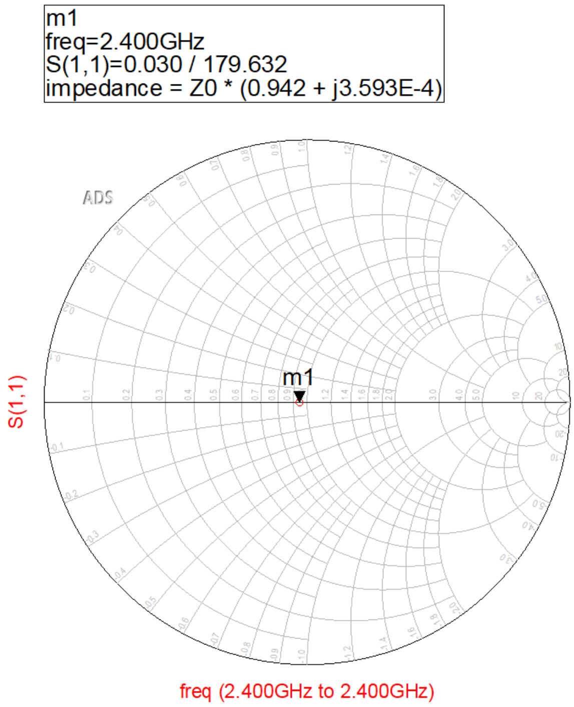


Figure 4-7: Schematic Simulation Result for Impedance Matching Circuit at 2.4 GHz

As the point is in the center of the circle, we have minimum reflection in our signals.

4.5.3.2 Matching circuit in layout

Values from schematic circuit are used to develop ADS Layout circuit for PCB implementation.

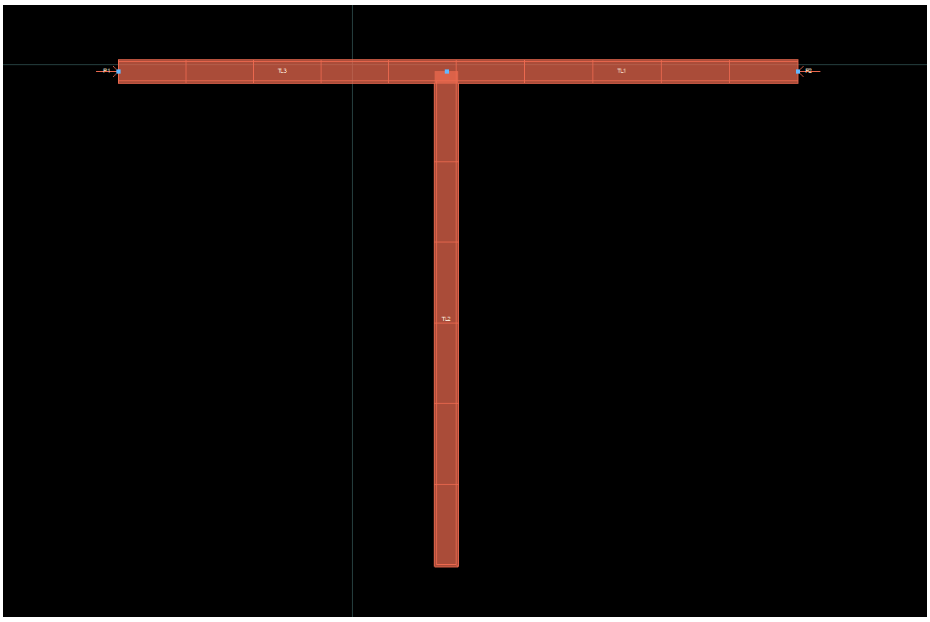


Figure 4-8: Impedance Matching Circuit at 2.4 GHz in Layout

Its results are given below.

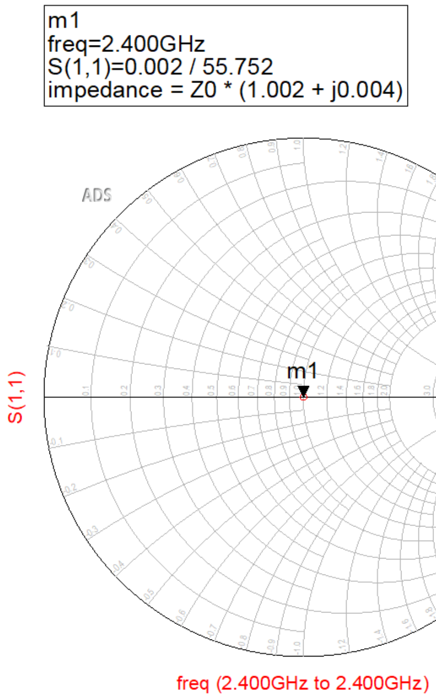


Figure 4-9: Simulation Results for Layout Impedance Matching Circuit at 2.4 GHz

4.5.4 Impedance Matching Network Design at 5.8 GHz

To design a single stub matching circuit at 5.8 GHz using an open circuit stub, the following steps were followed:

i. Using the Smith Chart utility in ADS, the load impedance and source impedance were plotted on the Smith Chart. Let's assume the load impedance was ZL = 1014.55 - j33.9 ohms and the source impedance was ZS = 50 + j0 ohms.

ii. By locating the intersection point of the load impedance and the 5.8 GHz constant resistance circle on the Smith Chart, the normalized load impedance (ZL_norm) was determined.

iii. The distance from the normalized load impedance point to the center of the Smith Chart represents the normalized distance (d_norm) of the stub.

iv. Using the Transmission Line Calculator in ADS, the physical lengths of the stub were calculated based on the desired frequency (5.8 GHz) and the electrical lengths determined from the Smith Chart.

v. The calculated stub lengths were then used to draw the simulation structure of the single stub matching network in ADS.

vi. The simulation was performed to obtain the results, which include the reflection coefficient (S11), return loss, and impedance matching performance.

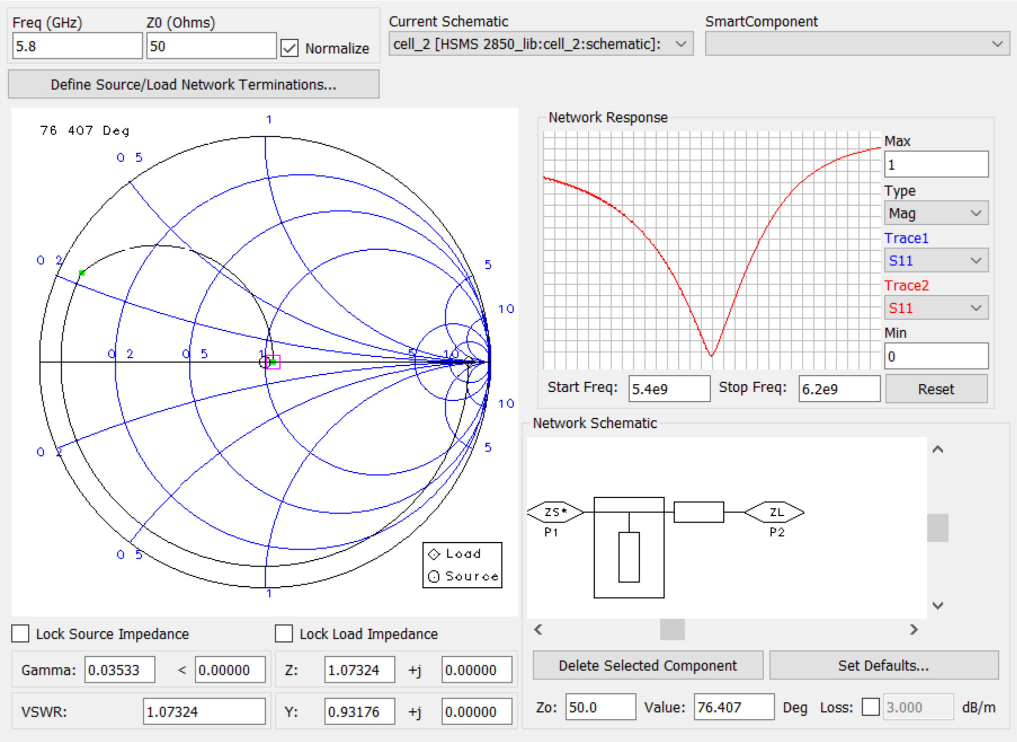


Figure 4-10: Stub Length Calculations for 5.8 GHz using Smith Chart Utility in ADS (A)

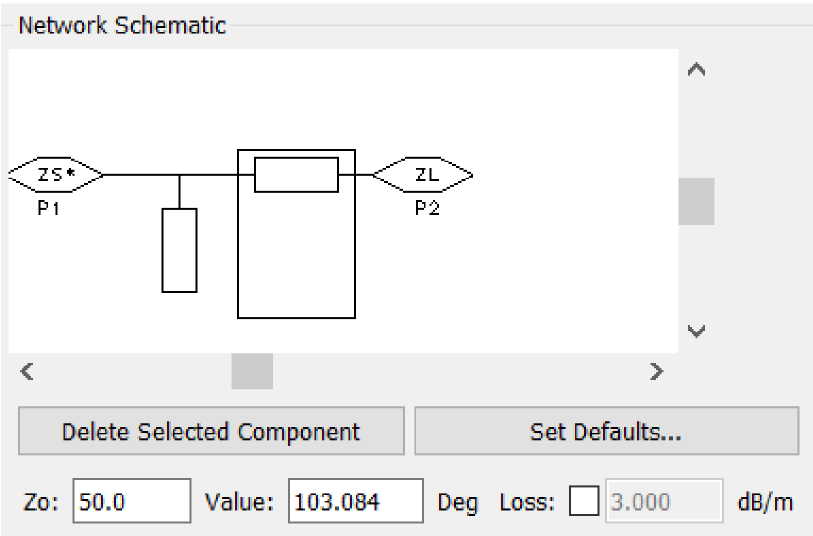


Figure 4-11: Stub Length Calculations for 5.8 GHz using Smith Chart Utility in ADS (B)

4.5.4.1 Matching circuit in Schematic

Using the calculated values from TL calculator, circuit is implemented in ADS Schematic and Layout for the simulation. [5] Values are given below:

Distance d = 6.635 mm

Length L = 9.02 mm

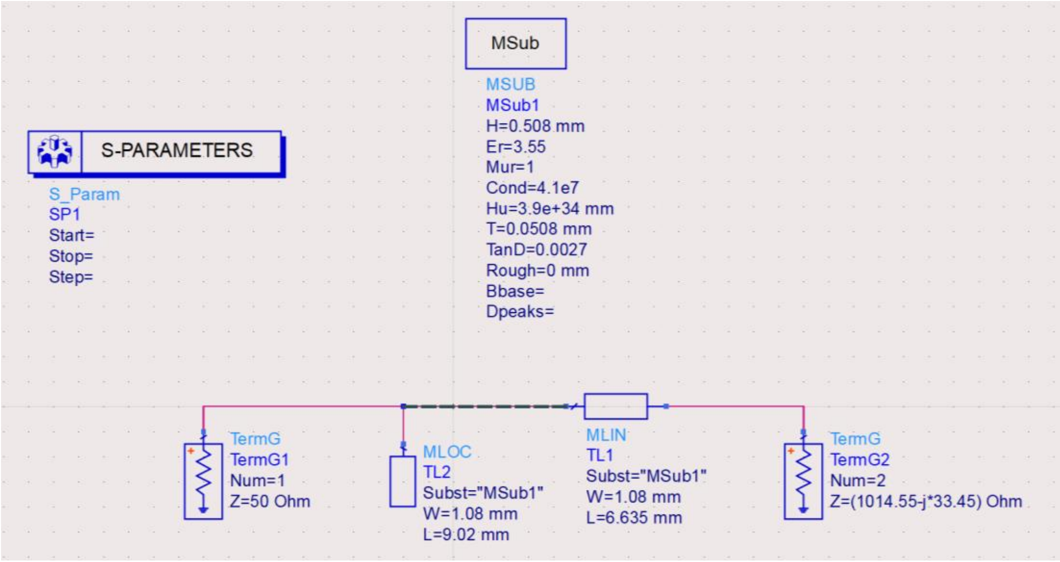


Figure 4-12: Impedance Matching Circuit at 5.8 GHz in Schematic

The simulation results for the schematic circuit are given below.

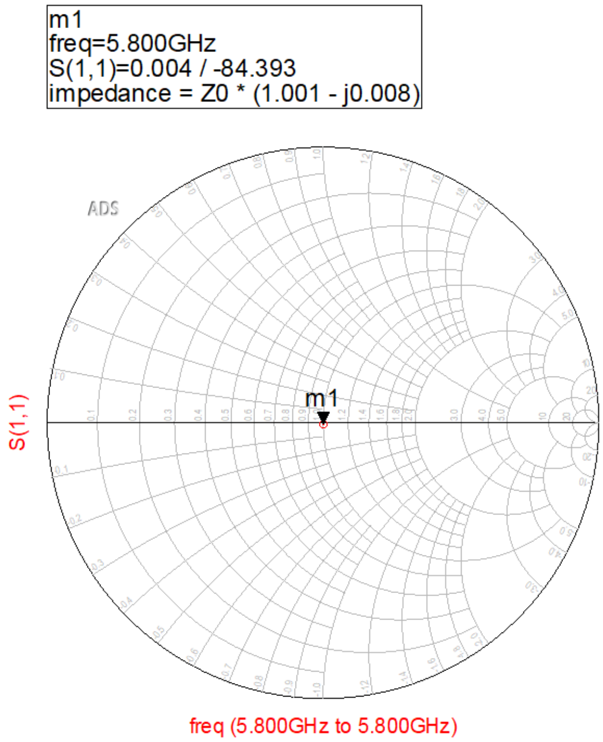


Figure 4-13: Schematic Simulation Results for Impedance Matching Circuit at 2.4 GHz

As the point is in the center of the circle, we have minimum reflection in our signals.

4.5.4.2 Matching circuit in layout

Values from schematic circuit are used to develop ADS Layout circuit for PCB implementation.

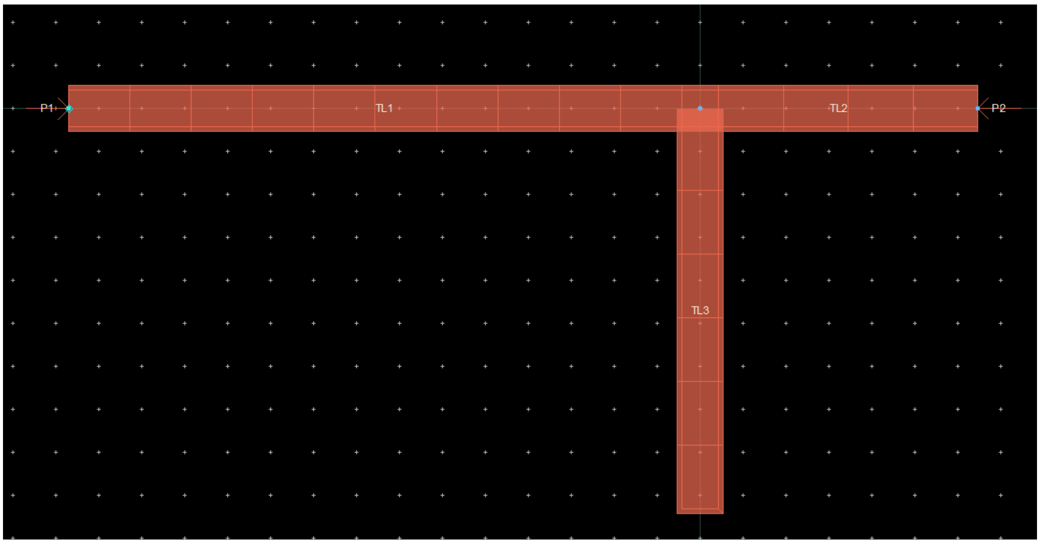


Figure 4-14: Impedance Matching Circuit at 5.8 GHz in Layout

Its results are given below.

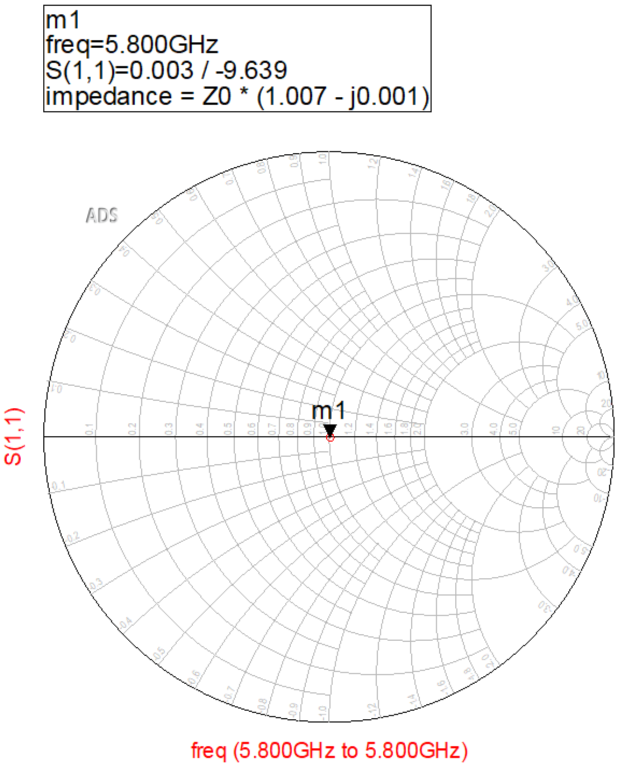


Figure 4-15:Layout Simulation Results for Impedance Matching Circuit at 5.8 GHz

4.6 Diode Padding

The thesis project involved the design and implementation of a diode pad in ADS layout for the HSMS 2850 diode, utilizing the information provided in the HSMS 2850 datasheet. The objective was to address the challenges associated with the diode's parasitic capacitance and enhance its performance. [8] The following steps were undertaken:

The ADS layout tool was employed to create a new layout design specifically for the diode pad. The appropriate substrate material (Ro4003C in this project) and layer stackup were selected to meet the design requirements. The HSMS 2850 diode was placed accurately within the layout, ensuring proper alignment and connectivity to other components. [8]

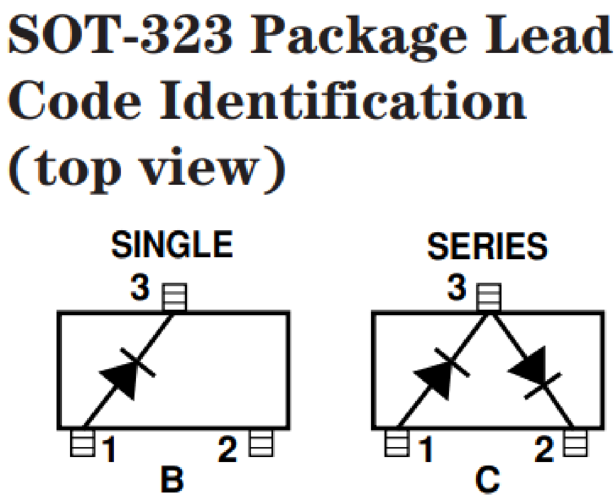


Figure 4-16: HSMS 2850 Diode Structure

Diode pad dimensions from the datasheet are given below in Figure 4.17.

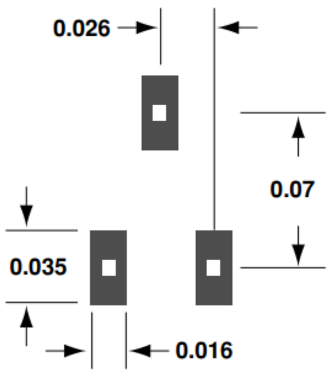


Figure 4-17: HSMS 2850 Diode Padding Dimensions

The same structure made in ADS Layout shown in Figure 4.18.

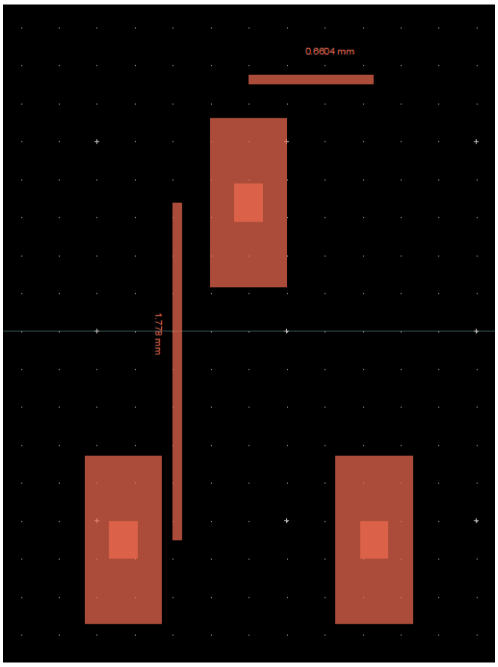


Figure 4-18: Diode Padding made in Layout

4.7 Rectifier Circuit Structures

The rectifier structure in this project involved connecting the impedance matching circuit, diode pads, and a 1k load pad using the RO4003C substrate. The goal was to design an efficient rectification system for RF energy harvesting. [5] The following steps were followed:

i. Impedance Matching Circuit: The impedance matching circuit, designed previously, was connected to the input of the rectifier structure. This circuit ensures optimal power transfer between the source and the rectifier.

ii. Diode Pads: The diode pads, designed using the HSMS 2850 diode, were integrated into the rectifier structure. These pads were placed in parallel with the diodes to compensate for the parasitic capacitance and improve overall diode performance.

iii. 1k Load Pad: A load pad with a resistance value of 1k was included in the rectifier structure. This load pad provides a suitable load impedance for the rectified output signal.

iv. RO4003C Substrate: The rectifier structure was implemented on the RO4003C substrate, known for its excellent RF performance and low loss characteristics. The substrate provides a stable platform for the rectifier components and helps minimize signal losses.

4.7.1 Rectifier Circuit Structure for 2.4 GHz

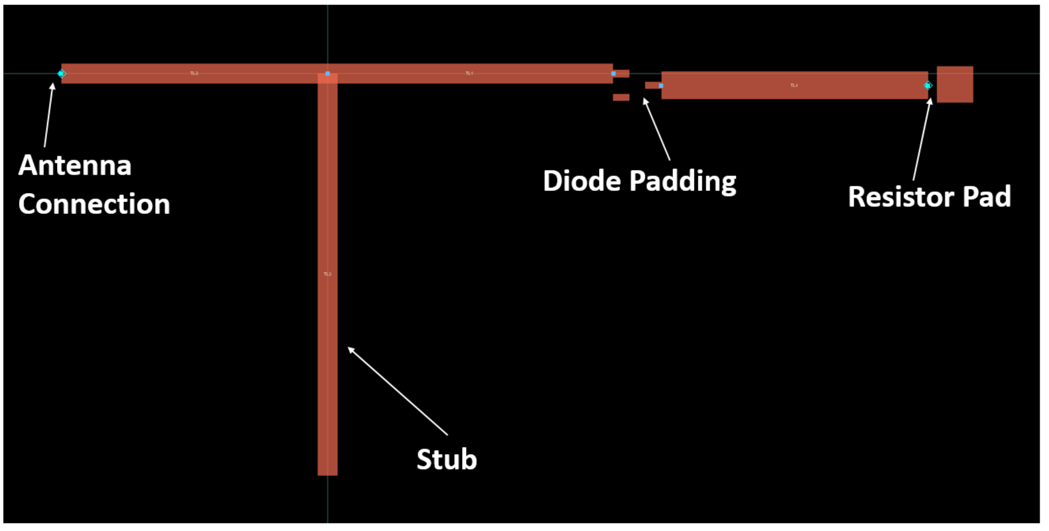


Figure 4-19: Rectifier Circuit Structure for 2.4 GHz

4.7.2 Rectifier Circuit Structure for 5.8 GHz

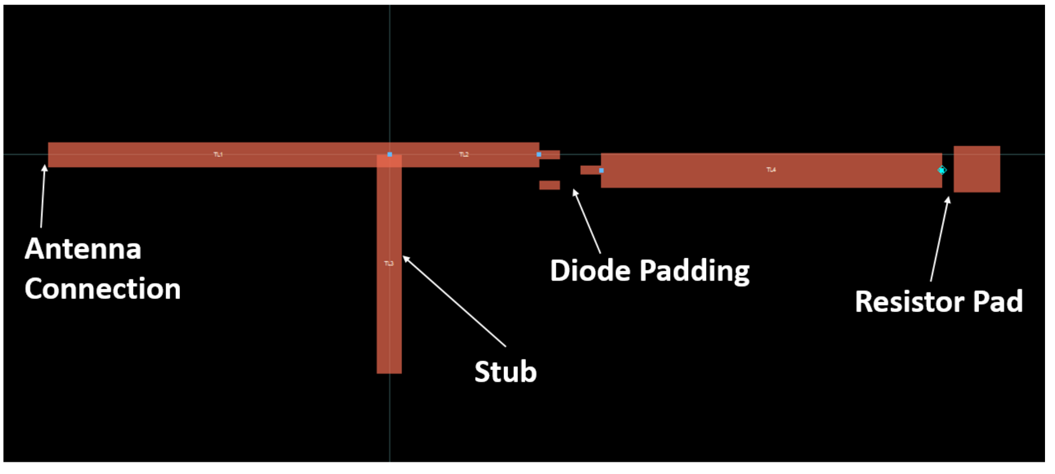


Figure 4-20: Rectifier Circuit Structure for 5.8 GHz

4.8 T-Junction: Connecting Both Frequency Matching Networks

The design of a T junction was necessary in order to connect the impedance matching networks for both the 2.4 GHz and 5.8 GHz frequencies. The main reasons for incorporating a T junction were to achieve wideband impedance matching and to combine the rectifiers designed for each frequency. [5] These decisions were motivated by the following factors:

i. Wide Band Impedance Matching: By utilizing a T junction, a wideband impedance matching circuit can be designed. This enables efficient power transfer across a broad frequency range, ensuring optimal performance for both the 2.4 GHz and 5.8 GHz frequencies. The T junction allows for seamless transition and impedance matching between the two frequencies.
ii. Integration of Rectifiers: As part of the project, rectifiers were designed separately for the 2.4 GHz and 5.8 GHz frequencies. The T junction provides a means to connect these rectifiers together. By combining the rectifiers, the overall system becomes capable of harvesting RF energy from both frequency bands, thereby enhancing the overall energy harvesting efficiency.
iii. Wide Band Omnidirectional Antenna: The T junction serves as the connection point between the wideband omnidirectional antenna and the impedance matching networks. This configuration allows the antenna to capture signals across a wide frequency range and channel them to the respective rectifiers through the T junction. It enables the antenna to effectively receive signals from both the 2.4 GHz and 5.8 GHz bands.

By incorporating a T junction in the design, a wideband impedance matching circuit is achieved, facilitating the combination of rectifiers for different frequencies. The T junction also enables seamless integration with a wideband omnidirectional antenna, leading to efficient RF energy harvesting from multiple frequency bands. [5]

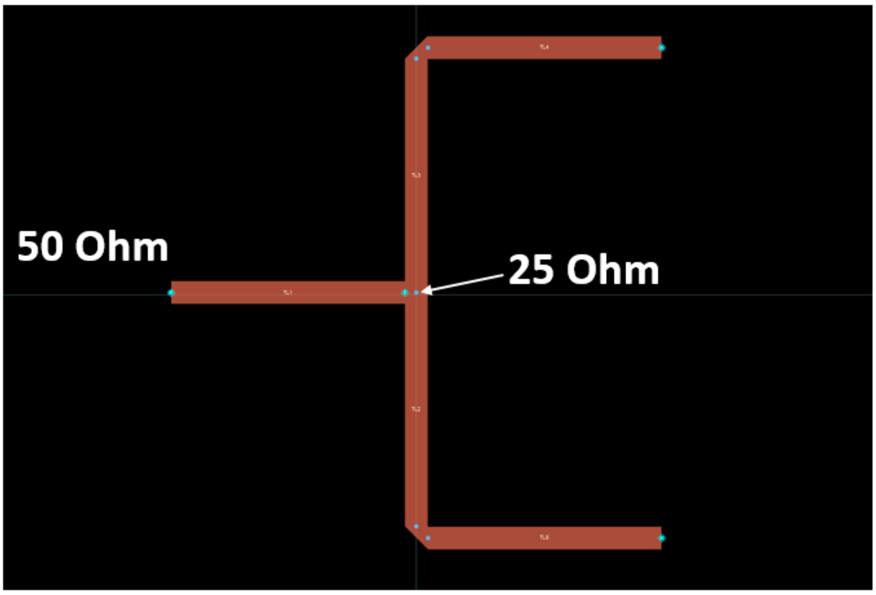


Figure 4-21: Initial Structure of T-Junction for Rectifier circuits' connection

4.8.1 Multi-Section Transformer for T Junction

The design of a multisection transformer, also known as a Chebyshev transformer or quarter-wave transformer, is required to achieve impedance matching between the 50-ohm impedance at the antenna side and the impedance of the rectifier structure sides. This transformer plays a crucial role in ensuring efficient power transfer and minimizing signal reflections. [5] The following steps can be followed to design the multisection transformer:

i. Determine the Desired Transformation Ratio: The transformation ratio of the multisection transformer needs to be determined based on the impedance ratio between the antenna side (50 ohms) and the rectifier structure sides.

ii. Calculate the Electrical Length: The electrical length of each section in the transformer can be calculated based on the desired transformation ratio and the operating frequency. The electrical length is typically a quarter-wavelength at the desired frequency.

iii. Determine the Number of Sections: The number of sections required in the multisection transformer depends on the desired transformation ratio. Each section contributes to the overall impedance transformation.

iv. Design the Transmission Line Sections: Using transmission line design techniques, such as microstrip or stripline, the physical dimensions of each section can be calculated based on the electrical length and the characteristic impedance of the transmission line used.

v. Connect the Sections: Connect the sections of the multisection transformer together, ensuring proper alignment and impedance continuity between each section.

vi. Verify Performance: Simulate the designed multisection transformer using simulation software like ADS to verify its performance in terms of impedance matching and power transfer efficiency. Adjustments can be made if necessary. [5]

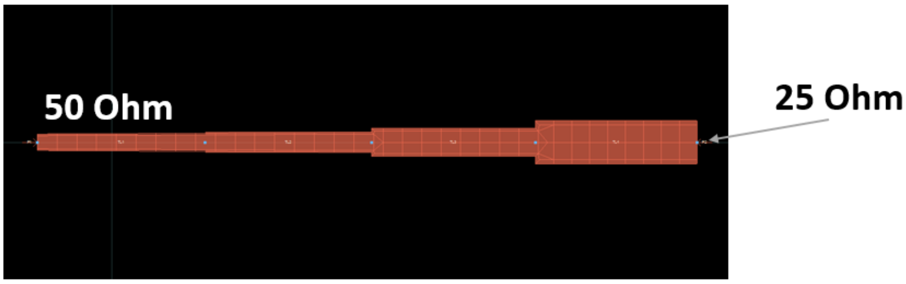


Figure 4-22: Multi-Section Transformer Initial Structure

Three section transformer is the made as its value of bandwidth percentage lies in the range of required bandwidth of the frequencies 2.4 GHz and 5.8 GHz. [5]

	$N = 3$					
	$\Gamma_m = 0.05$			$\Gamma_m = 0.20$		
Z_L/Z_0	Z_1/Z_0	Z_2/Z_0	Z_3/Z_0	Z_1/Z_0	Z_2/Z_0	Z_3/Z_0
1.0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1.5	1.1029	1.2247	1.3601	1.2247	1.2247	1.2247
2.0	1.1475	1.4142	1.7429	1.2855	1.4142	1.5558
3.0	1.2171	1.7321	2.4649	1.3743	1.7321	2.1829
4.0	1.2662	2.0000	3.1591	1.4333	2.0000	2.7908
6.0	1.3383	2.4495	4.4833	1.5193	2.4495	3.9492
8.0	1.3944	2.8284	5.7372	1.5766	2.8284	5.0742
10.0	1.4385	3.1623	6.9517	1.6415	3.1623	6.0920

$$\sec\theta_m = \cosh\left[\frac{1}{N}\cosh^{-1}\left(\frac{\ln Z_L/Z_0}{2\Gamma_m}\right)\right]$$

$$\frac{\Delta f}{f_0} = 2 - \frac{4\theta_m}{\pi}$$

Figure 4-23: Formulas for Multi-Section Transformer Sections

Using the above formulas, impedances of 3 three sections were calculated using TL calculator. Values are given below.

Impedance for Section 1: 43.35 Ohm

Impedance for Section 2: 35.35 Ohm

Impedance for Section 3: 28.68 Ohm

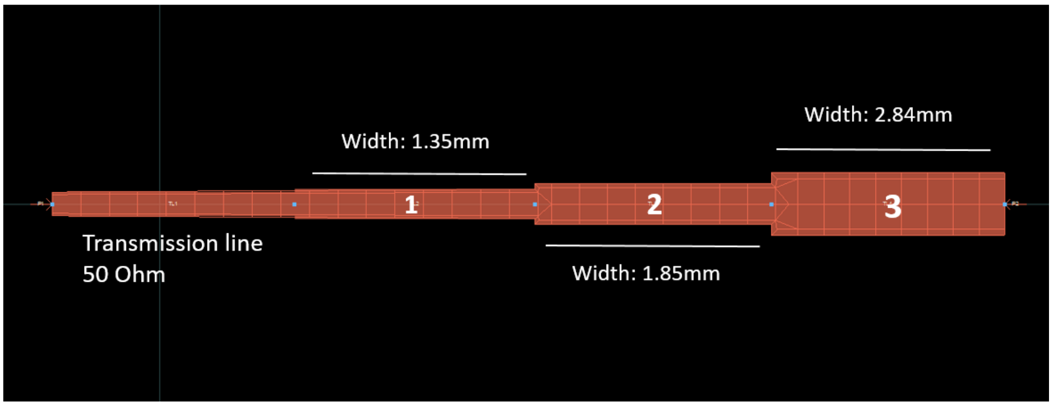


Figure 4-24: Multi-Section Transformer with Calculated values

The simulation results for the 3 section transformer are given below. It shows matching is perfectly done at both ends with minimum reflection or loss of signals.

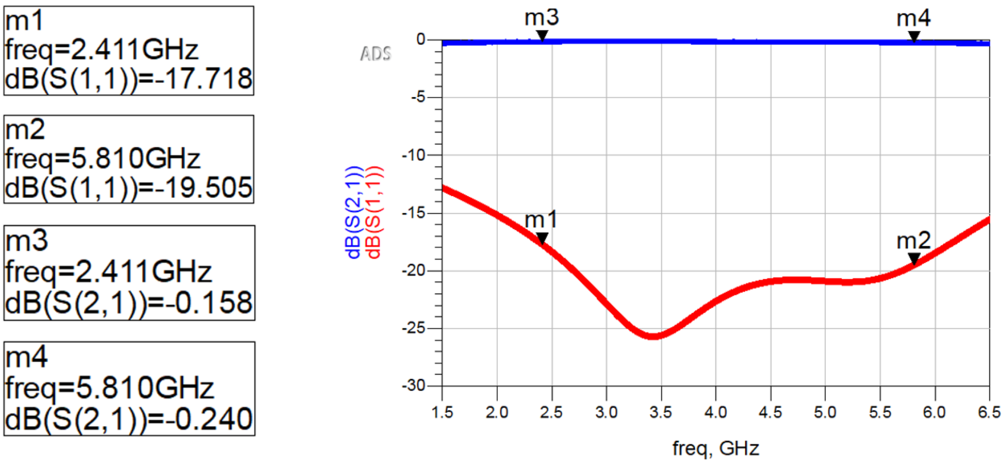


Figure 4-25: Simulation Results for Multi-Section Transformer

4.8.2 Connection of Multi-Section Transformer with T-junction

After connecting the multisection transformer to the T junction, the impedance matching is evaluated by measuring the results. Impedance measurements are performed at the antenna side, transformer input, and rectifier structure sides using measurement equipment. The transformer sections are adjusted iteratively based on the measured impedance values to optimize the matching. The goal is to achieve the best impedance matching by minimizing deviations and ensuring efficient power transfer throughout the system. [5]

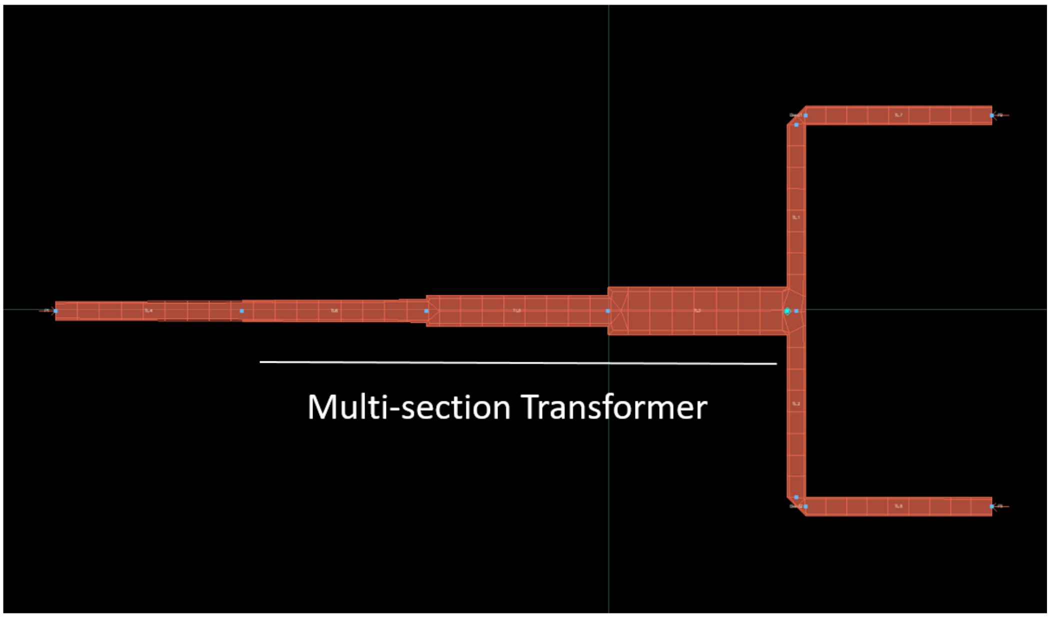


Figure 4-26: Structure of T-Junction with Multi-Section Transformer in Layout

Simulation results for the T-junction structure are given below. It shows matching is perfectly done at both ends with minimum reflection or loss of signals.

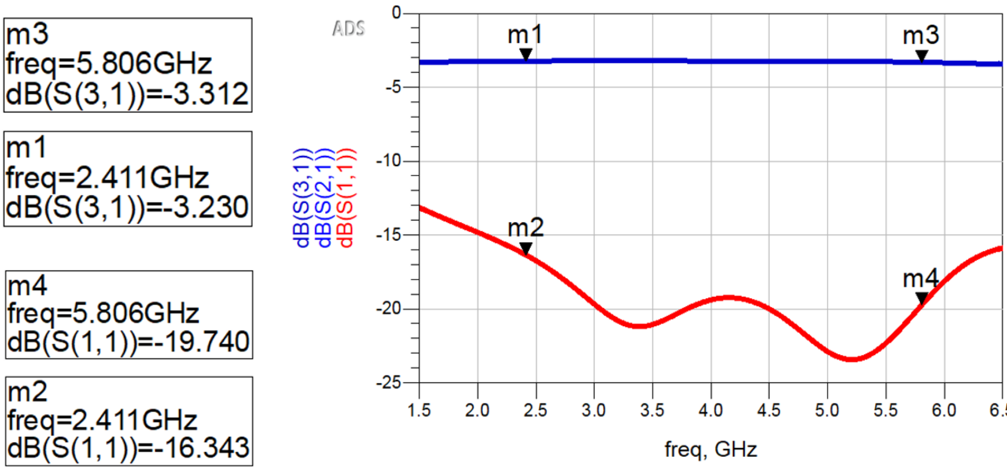


Figure 4-27: Simulation Results for T- Junction Finalized Structure

4.9 Finalized Structure of Rectifier

The final structure of rectifier is obtained after connecting impedance matching networks for both frequencies (2.4 GHz and 5.8 GHz) with diode pads and then connecting them to T-Junction with multisection transformer and at the end with a same 1k Ohm load.

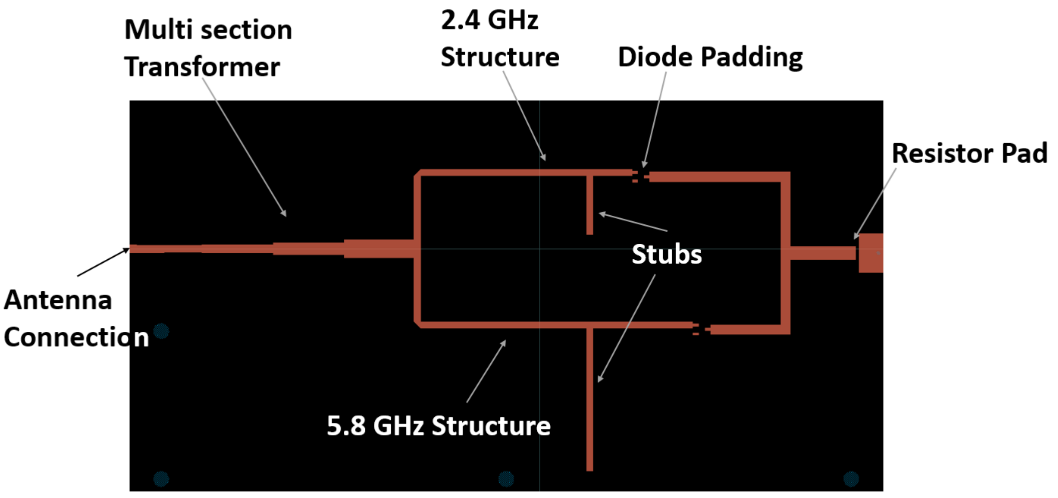


Figure 4-28: Finalized Rectifier Structure

4.10 Fabricated Rectifier Structure

4.10.1 Gerber file

Including the Gerber file in the report allows for accurate representation of the PCB design. A Gerber file is a standard format used in the PCB manufacturing industry to convey information about the copper layers, solder mask, and other relevant details of the PCB design. The Gerber file of rectifier has holes for placing it on the aluminum plate.

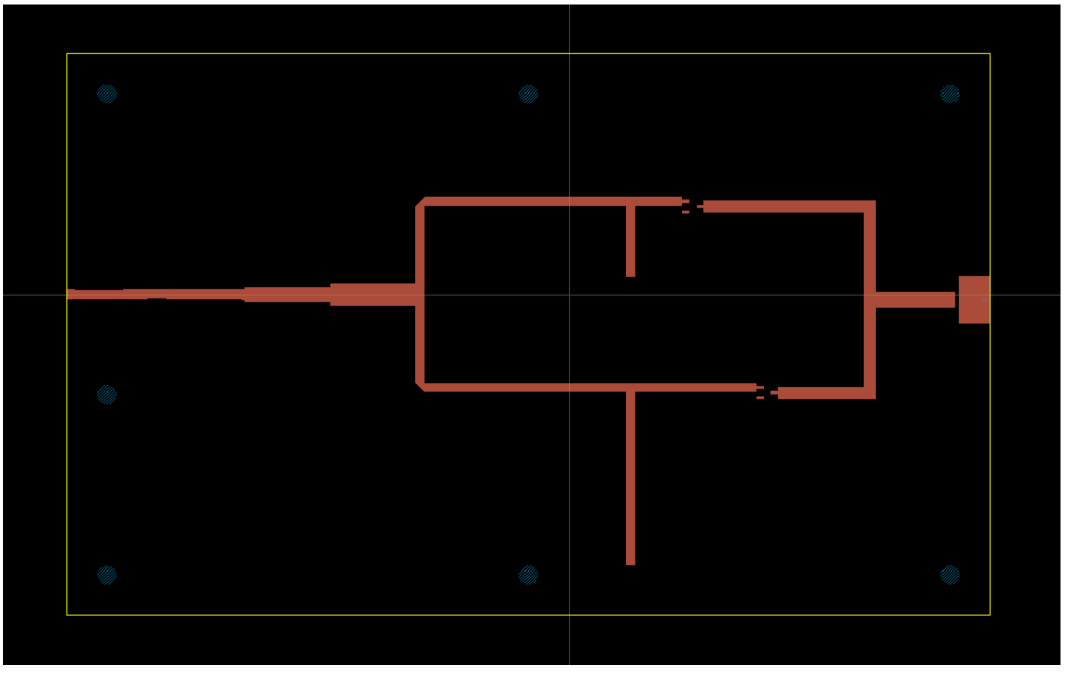


Figure 4-29: Gerber File for Finalized Rectifier Circuit

The fabricated rectifier structure is give below.

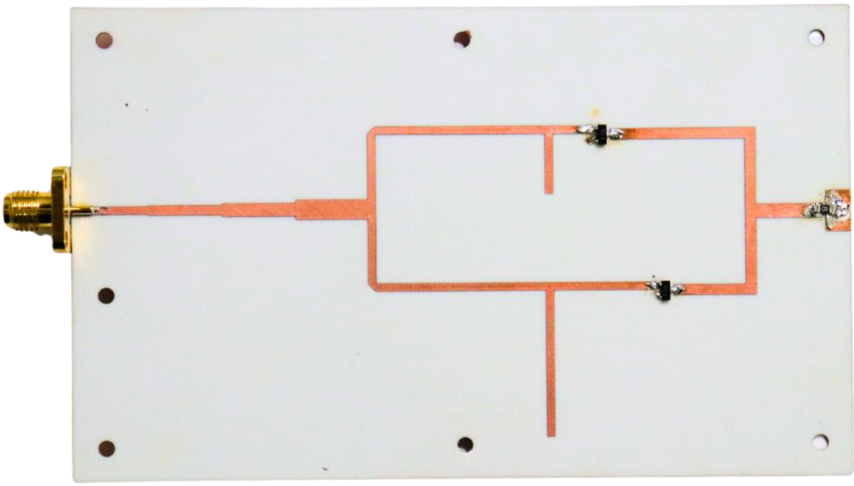


Figure 4-30: Fabricated Rectifier Circuit

4.11 Integrated Rectenna

After successfully design of Antenna and Rectifier in ADS, here comes the need for fabrication. The need for fabrication is to verify the designed results of ADS.

Fabrication is divided into the following parts:

- PCB Fabrication.
- Manufacturing of Aluminum Plate.
- Assembling.
- Testing.

4.12 PCB Fabrication

Using the parameters included in the design package, PCB fabrication is the process or operation that converts a circuit board design into a physical structure.

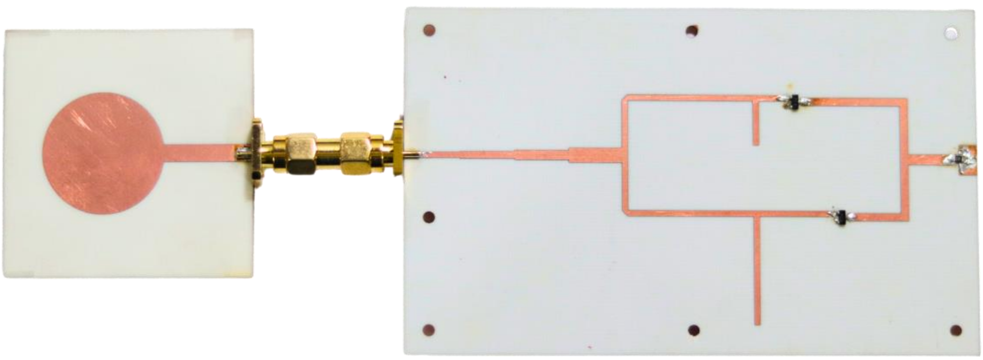


Figure 4-31: Antenna and Rectifier circuit connected

4.13 Manufacturing of Aluminum Plate

The purpose of the aluminum plate is to support the SMA connector and the PCB. It isn't easy to hold the soldered connectors in their place without this plate.

4.13.1 Designing of Plate

This plate is designed with precise measurements according to the need. It is designed in SolidWorks.

4.13.1.1 SolidWorks

SolidWorks is automated software and a CAD tool for designing 2D and 3D models. The plate used in this project has the following specifications:

- Length = 115.2 mm
- Width = 70 mm
- Height = 6mm
- Holes of M2x0.4

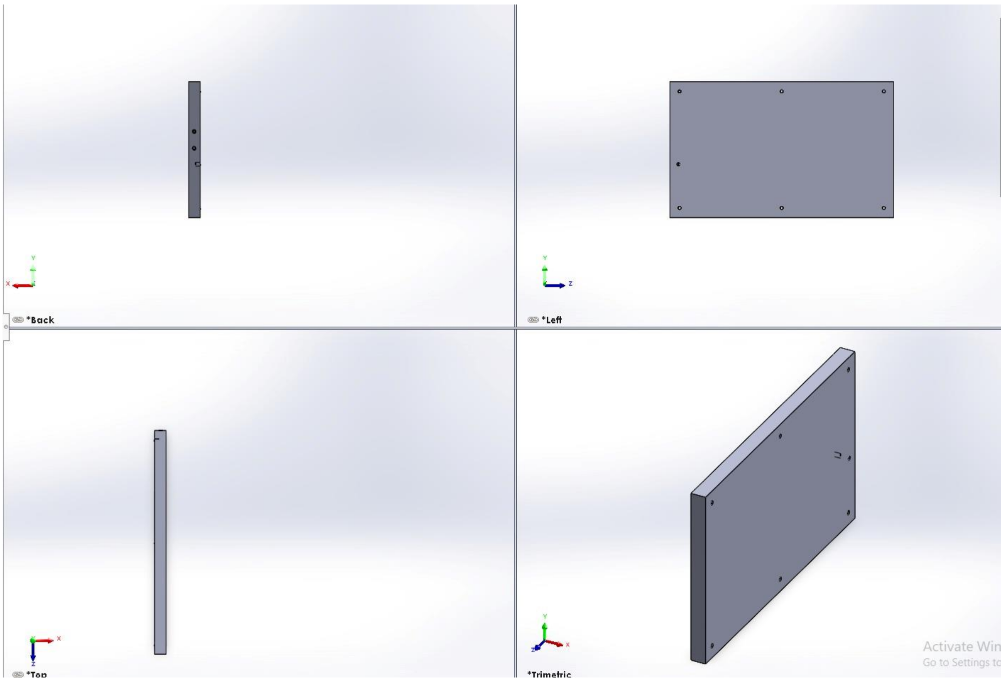


Figure 4-32: Aluminum Plate Structure in Solidworks

4.13.1.2 CNC (Computer numerically controlled) Process.

Computer Numerical Control (CNC) machining is a manufacturing process in which pre-programmed computer software dictates the movement of factory tools and machinery.

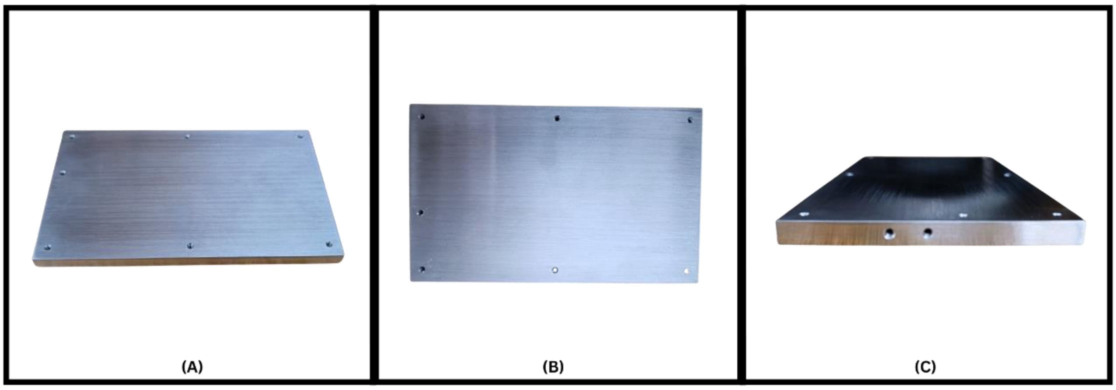


Figure 4-33: Manufactured Plate using CNC Machine

The file designed in SolidWorks is then sent for the CNC machining process. This process must be based on precise measurements, which is difficult to achieve with any other mechanical method, i.e., cutting metal by hand and putting threaded holes in a specific place.

4.14 Assembly

The following process is to assemble PCB onto the aluminum plate and connect the input port with the PCB. SMA Connectors are used as input port from Antenna side. PCB is adjusted on the plate using 7 screws of M2x0.4.

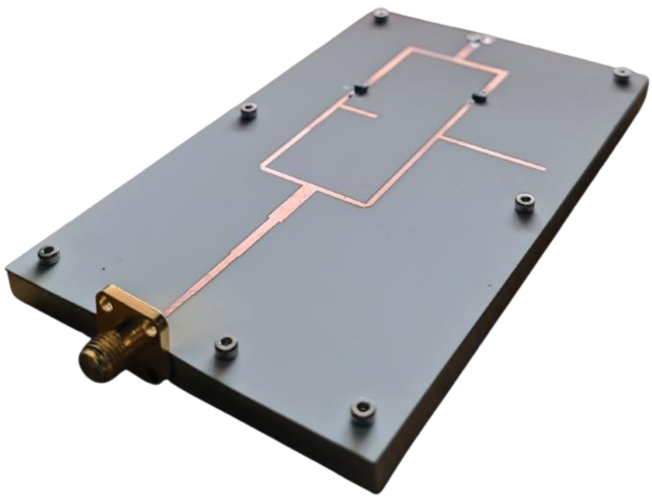


Figure 4-34: Rectifier PCB screwed onto Aluminum Plate

4.14.1 SMA Connectors

SMA connectors are 50 Ohm RF Coaxial connectors that operate up to 18 GHz. The center sleeve of an SMA Female connection is encircled by a barrel with threads on the exterior.

SMA Female connectors are also termed SMA Jack connectors. The connector has a 6.34 mm diameter in the thread region and an outside thread length of 4.32 mm. SMA connectors are shown in Figure 4.34 below.

Figure 4-35: Female SMA Connectors

Chapter 5 : FUTURE WORK

i. Design and Fabrication of High Gain Omnidirectional Antenna:
In future work, it is suggested to focus on the design and fabrication of a high gain omnidirectional antenna. This type of antenna plays a crucial role in RF energy harvesting systems as it enables efficient reception of signals from multiple directions. By optimizing the antenna's radiation pattern and gain, the system can achieve enhanced signal capture, resulting in improved energy harvesting performance. Advanced antenna design techniques, such as array antennas or metamaterial-based structures, can be explored to achieve higher gain and wider coverage. The fabrication process can involve using advanced materials and manufacturing techniques to ensure the antenna's mechanical stability, durability, and performance.

ii. Design and Fabrication of Wideband Impedance Matching Network:
Another avenue for future work is the design and fabrication of a wideband impedance matching network. While the current project focused on impedance matching for specific frequencies, a wideband matching network would enable compatibility with a broader range of frequencies. This would enhance the versatility of the RF energy harvesting system, allowing it to harvest energy efficiently across multiple frequency bands. The future work could involve exploring innovative matching network topologies, such as distributed matching networks or metamaterial-based matching structures, to achieve wideband impedance matching. The fabrication process would involve precision manufacturing techniques to ensure accurate implementation of the designed network and minimize signal losses.

By pursuing these future suggestions, researchers can further enhance the capabilities and performance of RF energy harvesting systems. The design and fabrication of a high gain omnidirectional antenna and a wideband impedance matching network will contribute to the development of more efficient and versatile energy harvesting solutions in various application domains.

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