RF ENERGY HARVESTING SYSTEM

PROJECT REPORT

Submitted by

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to

the APJ Abdul Kalam Technological University

in partial fulfillment of requirements for the award of the Degree

of

Bachelor of Technology

in

Electronics and Communication Engineering

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Mar Athanasius College of Engineering
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DECLARATION

I, **P PRANAV** undersigned hereby declare that the project report **RF ENERGY HARVESTING SYSTEM** , submitted for partial fulfillment of the requirements for the award of degree of Bachelor of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of Prof.Basil J Paul . This submission represents my ideas in my own words and where ideas or words of others have been included, I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University 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.

Kothamangalam

03-05-2024

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DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING

MAR ATHANASIUS COLLEGE OF ENGINEERING

KOTHAMANGALAM 2023-24

CERTIFICATE

This is to certify that the report entitled **RF ENERGY HARVESTING SYSTEM** submitted by **P PRANAV (MAC20EC090)** to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Bachelor of Technology in Electronics and Communication Engineering is a bonafide record of the project work carried out by him under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

Prof. Basil J Paul	**Dr. Jiss Paul**	**Dr. Aji Joy**
(Project Guide)	(Project Coordinator)	(Head of Department)

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P PRANAV

ABSTRACT

This project endeavors to design, implement, and evaluate an Radio Frequency (RF) energy harvesting system operating within the frequency range of 0.8 GHz to 3 GHz. The primary objective is to harvest ambient RF signals, prevalent in everyday environments through sources like Wi-Fi networks and cellular signals, and convert them into usable electrical power. The fundamental components of the system include a rectifying antenna (rectenna), an impedance matching circuit, and a robust RF-to-DC converter.

The rectenna serves as the cornerstone, strategically designed for compactness and efficiency to ensure optimal conversion of RF energy into direct current (DC) voltage. An impedance matching circuit plays a crucial role in facilitating efficient power transfer between the antenna and subsequent circuitry, thereby enhancing overall system performance. The RF-to-DC converter is tasked with transforming the captured RF signals into a stable DC voltage suitable for powering electronic devices.

Real-world experiments form an integral part of the project, providing empirical validation of the system's performance. Rigorous testing involves measurements of harvested energy and assessments of efficiency over varying conditions and time periods. This approach contributes valuable insights into the system's practical viability and effectiveness.

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LIST OF ABBREVIATIONS

RF	Radio Frequency
DC	Direct Current
IoT	Internet of Things
AC	Alternating Current
HFSS	High Frequency Structure Simulator
VNA	Vector Network Analyzer
DSO	Digital Storage Oscilloscope
ADS	Advanced Design System
PCB	Printed Circuit Model

CHAPTER 1

INTRODUCTION

1.1 GENERAL BACKGROUND

RF energy harvesting systems are a recent innovation that has emerged as a promising solution for generating electricity sustainably. Unlike traditional power sources like batteries or solar panels, RF energy harvesting systems utilize radio frequency (RF) waves present in the environment to produce electrical energy. These systems represent a significant advancement in the field of renewable energy and offer a novel approach to powering electronic devices.By using radio waves, which are everywhere in cities because of wireless technologies, these systems give us renewable and almost endless energy.The concept of RF energy harvesting involves using custom antennas to capture RF signals, converting them into electrical power, and then using this power to operate electronic devices.

1.2 OBJECTIVES

- Design and implement an RF energy harvesting system that captures ambient RF radiation and converts it into usable electrical power.
- Develop a wideband antenna operational within the 0.5 GHz to 5 GHz frequency range for efficient RF energy collection.
- Design an impedance matching circuit to optimize power transfer between the antenna and the RF energy source.

- Develop an RF-to-DC converter circuit to efficiently convert the harvested RF energy into DC voltage suitable for powering low-power electronics.
- Design a power storage unit using a supercapacitor to store the harvested DC energy.

1.3 SCOPE OF THE PROJECT

The aim of this project is to design and implement an RF energy harvesting system that harvests energy by collecting RF radiations from its surroundings through an antenna. The circuit when kept in the vicinity of RF emitting sources like Wi-Fi, cell phone, etc., collects RF energy from its surroundings and converts it into DC charge which is stored in super capacitor and then used for low voltage applications.

The scope of the project is :

1. Antenna Simulation and Optimization:
    - Conduct simulations to fine-tune antenna designs for optimal performance within the 0.5 GHz to 5 GHz frequency range.
    - Optimize antenna parameters such as size, shape, and materials to maximize energy harvesting efficiency.
    - Validate antenna performance through simulation software to ensure compatibility with a variety of RF signals.
2. Development of Efficient Matching Circuits:
    - Design and implement matching circuits that effectively interface with the antennas to enhance signal reception and energy transfer.
    - Optimize matching circuit parameters to achieve impedance matching between the antenna and the RF source.
    - Ensure that the matching circuits can operate over the entire 0.5 GHz to 5 GHz frequency range for consistent performance.
3. Design and Fabrication of RF-to-DC Converters:
    - Develop RF-to-DC converters capable of efficiently converting harvested RF

energy into usable electrical power.

- Implement efficient rectification and voltage regulation circuits to maximize power conversion efficiency.
- Ensure that the RF-to-DC converters are compact, reliable, and capable of handling the varying RF signal strengths across the frequency range.

CHAPTER 2

LITERATURE SURVEY

Numerous research projects have been undertaken concerning the RF energy harvesting sytem. This chapter provides an explanation of recent related work and their suggested methodologies.A comprehensive survey reveals a focus on crucial components like antennas and rectifiers, where researchers have strived to enhance the efficiency of converting ambient RF signals into usable energy. Explorations into frequency bands, energy storage strategies, and integration with IoT devices underscore the multidisciplinary nature of RF energy harvesting. Despite notable progress, challenges such as limited range persist, requiring ongoing research for refinements and innovative solutions.

[1]L.Paul et.al, introduced the prevalent use of portable electronic devices, all of which are reliant on battery power and necessitate periodic recharging. As the demand for extended battery life grows alongside the increasing ubiquity of these devices, the inconveniences associated with wired charging methods become more apparent. Sesk propounds the cutting-edge technology of Wireless Power Transmission (WPT), positioned at the forefront of electronic advancements. The proposal centers on a wireless battery charger designed specifically for mobile phones, aiming to alleviate the challenges inherent in current battery technologies. This innovative solution envisions a seamless and wire-free power transmission for devices like cell phones, PDAs, digital cameras, voice recorders, mp3 players, and laptops. By eliminating the need for wired connections, this wireless power solution not only promises greater efficiency but also addresses the practical challenges faced by users, providing a significant leap forward in the realm of electronic power management.

[2]A. Rajan et.al, introduced the growing importance of alternate energy sources, addressing the rising demand for power. Over the past decades, various external sources like thermal energy, solar power, wind energy, and RF energy have been utilized. Focusing on RF energy harvesting, this paper explores capturing RF energy from sources like mobile phones and WLANs through a receiving antenna. The rectification process converts this captured energy into usable DC voltage. The paper emphasizes the potential of RF energy harvesting to overcome power limitations in electronic devices and highlights microstrip patch antennas for their widespread use due to their low profile and lightweight design. It further discusses different methods for designing energy-harvesting devices based on available energy types and elaborates on microstrip patch structural rectennas as RF signal harvesters for powering low-consumption electrical devices.

[3]Z. Hameed et.al, developed a step-by-step approach to create better matching circuits for RF energy harvesters. These circuits help maximize the energy collected from various power levels. Unlike regular RF circuits, the circuits for these energy harvesters need special designs because of how the parts inside them work.Their research found that for these circuits to work best, you need to figure out how the part that converts the radio signals into energy behaves when it gets different strengths of signals. They suggested using a method that measures the part's behavior when it gets the strongest signal while also making sure it gets a stable power supply. This method helps get the most energy out of a set amount of input power.When the input power levels change, their paper suggests picking the right matching circuit using a strategy. This strategy considers how likely different input power levels are and helps choose the best matching circuit to get the most energy from these varying power levels. Essentially, they made a plan to build better circuits that can get the most energy out of different strengths of incoming signals.

[4]M.AMutalib et.al, introduced a special antenna that looks like an ice-cream cone. This antenna is designed to capture a wide range of signals and turn them into usable energy. They made it using a computer program called CST Studio Suite 2011 and put it on a type of circuit board called FR-4. They also made a part called a rectifying circuit, using a different program called Agilent Advanced Design System (ADS) 2011. This circuit takes the signals caught by the antenna and turns them into electricity. They

tested this system with different strengths of incoming signals and measured how much electricity it made. In their experiments, when they tested it with a signal that's equivalent to a certain level of strength (like turning up the volume on a radio), they found that the system produced 0.09 volts of electricity when using a specific setting called a 20k load. This amount of voltage could be useful for powering small sensors in networks of sensors, possibly doing away with the need for regular batteries.

[5]A. Das et.al, introduced a special kind of antenna that can work across a really wide range of frequencies, from 3 to 10.5 billion cycles per second (also called gigahertz). This range covers various wireless technologies like GSM (used in phones), Bluetooth, and more. They designed it to avoid picking up signals from WiMAX (a different wireless technology) between 3.27 and 4.02 gigahertz. Their design is quite straightforward: they used a simple circular patch connected to a specific kind of wire called a trapezoidal-shaped microstrip line. This setup covers the entire range of frequencies they were aiming for. They added extra parts called spider arm-shaped resonators to make sure it can work for even more frequencies.T hey made sure that the antenna doesn't get mixed up or confused between the WiMAX signals and the ones it's supposed to pick up by using certain tricks that help separate these different types of signals. The antenna they made is pretty small—about 50 by 50 by 1.6 millimeters in size—and it's really good at picking up a wide range of wireless signals. They tested it out, and both their computer simulations and real-life tests showed that it works really well for different wireless technologies.

[6]D. Lee et.al, introduced a device called an RF-to-DC converter. This device is designed to turn radio signals, like the ones used in 3G and 4G cellphones, into usable electricity over a wide range of frequencies. The converter has a few key parts: it uses a specific kind of technology called CMOS and has a component called an impedance matching network that can be adjusted to work with different frequencies. Inside, there's a part called a differential-drive cross-coupled rectifier and another component called a 4-bit capacitor array. By using a particular manufacturing process called a 130nm CMOS process, this converter managed to turn radio signals at frequencies like 700 MHz, 800 MHz, and 900 MHz into electricity with very high efficiency. For instance, with a specific setting (a load resistance of 10k), it reached efficiency levels of around 72.25%, 64.97%, and 66.28% for those frequencies. Essentially, it's a device that efficiently turns cell phone-like signals into power you can use.//// [7]M. Zarghami

et.al, introduced a device called a power divider. This device helps split power from one source into two different paths. They made it using a mix of a hybrid coupler and two special diodes called varactor diodes. These diodes are like switches that control how the power is split, making it easier to send the right amount of power to another part of the device that collects energy. They built this power divider using special lines on a common and affordable material called FR4. To check if it worked well, they used a computer to simulate how it would perform in different situations. The results showed that this power divider could split power in a specific range, kind of like adjusting a knob, from one to five parts. After that, they actually made the device and tested it out in real life. What they found when they tested it matched pretty closely with what the computer said it would do. It could split power into different ratios, from one to four parts, which is pretty useful for things like sending power wirelessly to devices such as sensors or medical implants. Essentially, it's a device that can control how much power goes where, which is handy for lots of wireless power transfer jobs.

[8]M.A Rosli et.al, introduced a way to power wireless devices without needing batteries, using radio signals around us instead. They created a special circuit using really tiny technology (about 0.13 micrometers) that can turn radio signals into electricity. Their circuit is made up of different parts: a rectifier, a ring oscillator, a charge pump, and a regulator. The rectifier changes the radio signals into a type of electricity called direct current (DC), which is what most devices need to work. Then, the charge pump and the ring oscillator work together to increase this low electricity to a higher level that devices can use better. After that, they make sure this electricity stays at a steady level of 1.2 volts, which is what many devices need to run smoothly. When they tested it on signals between 900 million cycles per second (megahertz) and 2400 megahertz, with a specific strength of -16.48 decibel-milliwatts, they found that their circuit could turn those signals into a steady 1.25 volts of electricity, which could power devices with a resistance of 50 kilo-ohms. Essentially, it's a circuit that turns radio signals into power that devices can use, even without batteries.

[9]R.Chandel et.al, introduced a small but powerful antenna meant for devices that need to wirelessly connect to lots of different things really quickly, like your phone talking to Wi-Fi, Bluetooth, and other devices. This antenna is only about 18mm by 34mm in size. They designed it using a special type of pattern that looks like a thin strip and has small cuts in it. These cuts help the antenna avoid certain types of signals, kind

of like how you might use earmuffs to block out noise. Specifically, these cuts help the antenna avoid signals from certain Wi-Fi and satellite bands. What's really impressive is that this antenna can connect to different devices without causing problems between them. It's really good at not letting signals meant for one device interfere with signals meant for another. They tested it across a wide range of frequencies, from about 2.93 billion cycles per second (gigahertz) to 20 gigahertz, and found it worked really well. The antenna manages to keep the connections strong while making sure different devices' signals don't mess with each other. Overall, it's a strong and versatile antenna that's great for many different types of devices needing fast wireless connections.

[10]J.D.Park et.al, introduced a way to connect devices together so they can share power more efficiently. They used something called a transformer, which has two coils of wire that are connected together magnetically. They figured out some important equations that help make sure that both the device sending power and the one receiving it match up perfectly. Matching them up perfectly means the power transfers smoothly between them without wasting any. They also came up with a new way to measure how well this setup works, which helps understand how much power is being transferred efficiently. They tested this idea using tiny transformers on a chip made using really small technology (about 0.18 micrometers). Their tests, both on the computer and in real life, matched up pretty closely with their calculations, especially for frequencies up to about 72% of the transformer's highest possible frequency. This work shows that their formulas are practical and useful for designing systems that share power effectively, especially for higher frequency devices like those used in microwaves and really fast data transfer.

CHAPTER 3

METHODOLOGY

3.1 WORKING

The RF energy harvesting system harvests ambient radio waves from the environment and converts them into usable DC voltage to power low-power devices.

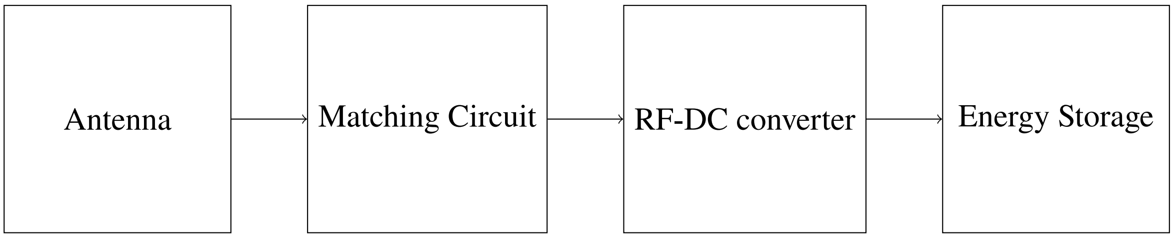
First, the trapezoidal microstrip antenna with its spiderarm shaped resonator efficiently captures radio waves within the desired frequency range of 0.5 GHz to 5 GHz. The trapezoidal design offers a good balance between size and efficiency, while the spiderarm resonator helps target specific frequencies within the band, maximizing energy collection.

Next, the captured radio waves encounter the impedance matching circuit. This circuit acts as a bridge, carefully tuning the antenna's impedance to match the input impedance of the RF-to-DC converter. This ensures optimal power transfer from the antenna to the subsequent stages.

The RF-to-DC converter plays a crucial role in transforming the high-frequency AC signal received from the antenna into a low-frequency DC voltage usable by the target device. This conversion process is further enhanced by a voltage multiplier section. The multiplier boosts the harvested DC voltage to a level that can effectively power the low-power device.

Finally, the harvested and potentially boosted DC voltage is stored in a supercapacitor. Supercapacitors, with their high capacitance, are ideal for storing this energy and delivering short bursts of power, perfectly suited for powering low-power electronics.

3.2 BLOCK DIAGRAM



The RF energy harvesting system, illustrated in the block diagram, efficiently converts ambient radio waves into usable DC power for low-power devices. The specially designed antenna captures radio waves, while a matching circuit optimizes power transfer. The RF-to-DC converter, with a voltage booster, transforms the AC signal to a suitable DC voltage. Finally, a supercapacitor stores the harvested energy for powering the device. Each component works together to harvest, convert, store, and ultimately power low-power electronics.

3.3 COMPONENTS

3.3.1 Schottky Diode

Figure 3.1: Schottky Diode

The 1N5819 Schottky Diode is a crucial component in electronic circuits, distinguished by its low forward voltage drop of 600mV and a forward current of 1A. Unlike conventional PN-junction diodes, the Schottky diode exhibits reduced forward voltage drop, especially noticeable when 1A of current is supplied, and offers fast switching speeds. These attributes make it indispensable in various applications, notably in protection circuits designed to mitigate reverse polarity issues and in high-frequency switching circuits.

Applications:

1. Reverse Polarity Protection: It effectively prevents issues arising from reverse polarity, safeguarding electronic devices from potential damage.

2. Inverters: Due to its capability to operate at high frequencies, the 1N5819 Schottky diode is frequently employed in inverters, ensuring efficient energy conversion.

3. General-Purpose Rectification: Acting as a rectifier, it converts alternating current (AC) to direct current (DC), serving as a power source for numerous electronic devices.

4. RF Applications: Its usage extends to radio frequency (RF) applications where polarity protection is critical for signal integrity.

5. Signal Detection and Power Supplies: It finds application in detecting signals and powering various electronic circuits.

6. Logic Circuits: Integrated into logic circuits, it aids in logical operations and signal processing.

7. Freewheeling Diodes: In freewheeling diode configurations, it facilitates the flow of current in specific circuit configurations.

3.3.2 Supercapacitors

Figure 3.2: Supercapacitor

Supercapacitors emerge as a vital energy storage solution, particularly in systems harnessing radio frequency (RF) energy. They possess the remarkable ability to rapidly store and release energy, making them well-suited for intermittent energy sources. With a high power density, they efficiently manage rapid power fluctuations commonly encountered in RF energy harvesting applications. Moreover, their extended cycle life and minimal self-discharge rates ensure prolonged efficiency in capturing and retaining RF energy.

The advantages of supercapacitors are:

1.Fast Energy Storage and Release: They swiftly capture and release energy, ensuring efficient utilization of intermittent RF energy sources.

2.High Power Density: With their high power density, they effectively manage rapid power fluctuations, contributing to the stability of RF energy harvesting systems.

3.Long Cycle Life: Supercapacitors endure a high number of charge and discharge cycles, ensuring longevity and reliability in energy storage applications.

4.Low Self-Discharge Rate: Their minimal self-discharge rate preserves captured RF energy efficiently over time, minimizing energy losses.

5.Efficient Energy Transfer: Low internal resistance enables high-efficiency energy transfer, complementing the dynamic power levels inherent in RF energy harvesting.

3.3.3 SMA Connector

Figure 3.3: SMA Connector

The SMA (SubMiniature version A) connector is a widely used coaxial RF connector known for its compact size and high performance. It features a threaded interface, which provides a secure and reliable connection, particularly suitable for applications where vibration or movement is a concern.

The SMA connector comprises a male and female version, with the male connector featuring external threads and the female connector featuring internal threads. This design allows for easy mating and demating of the connectors while maintaining a stable connection.

One of the key advantages of the SMA connector is its versatility. It supports a wide range of frequencies, typically from DC up to 18 GHz or higher, depending on the design and quality of the connector. This makes it suitable for various RF applications, including antennas, RF modules, test and measurement equipment, and RF energy harvesting systems, among others.

The SMA connector is available in different variants to accommodate various cable types and sizes, such as semi-rigid, flexible, and semi-flexible cables. Additionally, it comes in standard and reverse polarity versions, denoted as SMA and RP-SMA respectively, to prevent mismating in applications where polarization is critical.

In RF energy harvesting systems, the SMA connector serves as a crucial interface between the antenna and the RF circuitry. It allows for easy connection and disconnection of the antenna, facilitating testing, calibration, and maintenance of the system. Moreover, its robust construction ensures reliable performance even in challenging environmental conditions.

3.3.4 Cable 50 ohm

Figure 3.4: Cable 50 ohm

In the realm of RF (Radio Frequency) systems, the choice of cable impedance plays a pivotal role in ensuring optimal performance and energy transfer efficiency. In RF energy harvesting system, we have to carefully select a cable with a characteristic impedance of 50 ohms to facilitate seamless transmission of RF energy from the antenna to the harvesting circuitry.

The 50-ohm characteristic impedance is widely regarded as a standard in RF engineering, particularly in applications like ours that involve energy harvesting. This impedance value is not arbitrary; it's chosen strategically to match the impedance of various RF components commonly used in such systems, including antennas, amplifiers, and harvesting circuits.

One of the primary advantages of using a 50-ohm cable is its ability to minimize signal reflections. When the impedance of the cable matches that of the components it connects, there's less mismatch, reducing the likelihood of signal bouncing back and forth, which could lead to signal degradation or loss. This impedance matching ensures efficient power transfer, allowing us to harness as much energy as possible from the RF signals captured by the antenna.

Moreover, the 50-ohm impedance standard is well-established in the RF industry, meaning that components and devices designed to operate within this impedance range are readily available and widely compatible. This compatibility simplifies system integration and troubleshooting while offering a greater selection of off-the-shelf components for our energy harvesting system.

3.4 SOFTWARE DESCRIPTION

3.4.1 Ansys HFSS

Ansys HFSS (High-Frequency Structure Simulator) stands as a powerful electromagnetic simulation software utilized extensively for the analysis and design of high-frequency electronic components and systems. It employs advanced numerical techniques to accurately model electromagnetic fields, enabling engineers to predict the behavior of RF and microwave devices with exceptional precision.

HFSS enables engineers to create detailed 3D models of complex geometries, such as antennas, RF/microwave circuits, and interconnects, facilitating an in-depth analysis of electromagnetic fields and interactions within these structures. This capability provides valuable insights into their performance and behavior across a broad spectrum of frequencies, ranging from RF to microwave and millimeter-wave frequencies.

Engineers leverage HFSS to perform parametric sweeps and optimization studies, allowing them to explore design variations and identify optimal configurations. This capability streamlines the design refinement process, ensuring that devices meet performance specifications while maintaining efficiency and productivity.

Moreover, HFSS seamlessly integrates with various CAD (Computer-Aided Design) tools, enabling engineers to import existing designs and collaborate across different design environments effortlessly. This integration enhances workflow efficiency and collaboration, contributing to faster and more effective design iterations.

3.4.2 Vector Network Analyzer(VNA)

A Vector Network Analyzer (VNA) is a sophisticated electronic test instrument used to analyze and characterize the electrical performance of high-frequency and radio-frequency (RF) devices, components, and systems. VNAs are capable of measuring the magnitude and phase of RF signals transmitted through or reflected from the device under test (DUT), providing valuable insights into its impedance, transmission characteristics, and frequency response across a wide range of frequencies. These

Figure 3.5: Vector network analyzer

instruments typically operate across frequency ranges spanning from a few kilohertz to several tens of gigahertz, making them invaluable tools for testing RF and microwave circuits, antennas, filters, amplifiers, and other RF components. The VNA's ability to measure both amplitude and phase with high accuracy and resolution allows engineers to comprehensively characterize the performance of their designs, enabling them to identify issues, optimize designs, and verify compliance with specifications.

A key feature of VNAs is their capability to perform various types of measurements, including S-parameter measurements (S11, S21, S12, S22), impedance measurements, time-domain measurements (reflectometry), and noise figure measurements. These measurements provide valuable information about the behavior and performance of the DUT under different operating conditions, allowing engineers to diagnose problems, troubleshoot issues, and refine their designs.

Modern VNAs are equipped with advanced features such as frequency sweep capabilities, multiple channels, built-in calibration routines, and sophisticated data analysis tools. Additionally, VNAs may offer options for network analysis software that enable automated measurement setups, data processing, and reporting, enhancing productivity and efficiency in RF testing and characterization workflows.

3.4.3 Altium

Altium Designer offers a robust schematic design environment where users can create schematics using a vast library of components or by designing custom symbols. The software provides an intuitive interface for connecting components and defining electrical connections, ensuring clarity and accuracy in the schematic representation of the circuit.Once the schematic is finalized, Altium Designer facilitates the translation of the schematic into a physical PCB layout. Users can leverage powerful placement and routing tools to position components and route traces according to design constraints and requirements. The software's interactive routing capabilities enable efficient and precise trace routing, contributing to the overall integrity and performance of the PCB design.

Altium Designer offers advanced 3D visualization capabilities, allowing users to inspect and analyze their PCB designs in three dimensions. This feature provides valuable insights into the spatial arrangement of components and enables users to detect potential mechanical conflicts or interference issues early in the design process. By visualizing the PCB design in 3D, designers can ensure proper fit within the enclosure and optimize the overall mechanical design. Altium Designer includes built-in simulation tools that enable users to perform various analyses to validate and optimize their designs. These simulations cover a range of aspects, including signal integrity, power distribution, and thermal performance. By simulating circuit behavior under different conditions, designers can identify and address potential design issues, leading to improved performance and reliability of the final product.

Altium Designer offers features for seamless collaboration among team members working on the same project. The software supports concurrent design activities, allowing multiple users to work on different aspects of the design simultaneously. Additionally, Altium Designer provides version control, commenting, and design review tools to facilitate communication and ensure design integrity throughout the collaborative process.

Altium Designer streamlines the process of generating manufacturing output files required for fabricating and assembling the PCB design. The software supports industry-standard file formats, including Gerber files for PCB fabrication, NC drill files for drilling operations, and Bill of Materials (BOM) for component procurement. By seamlessly generating these manufacturing files, Altium Designer enables a smooth transition from design to production, reducing time to market and ensuring manufacturing success. Altium Designer is designed to integrate seamlessly with other software tools and platforms commonly used in the electronics industry. Whether it's integrating with MCAD software for mechanical design collaboration or connecting to PLM systems for managing design data and revisions, Altium Designer ensures interoperability and smooth data exchange across the design and manufacturing ecosystem. This integration capability enhances workflow efficiency and enables designers to leverage the best-in-class tools for each aspect of the design process.

3.4.4 Proteus

Proteus stands out as a versatile electronic design automation (EDA) tool with robust simulation capabilities. Its powerful simulation environment allows users to analyze both analog and digital circuits, including microcontroller-based designs, in real-time. With mixed-signal simulation capabilities, Proteus enables seamless integration of analog and digital components within the same design, facilitating comprehensive testing of entire systems before hardware prototyping.

In addition to simulation, Proteus offers integrated PCB design and layout tools, streamlining the transition from schematic capture to PCB development. Users can design and validate their circuits within the same software environment, ensuring design continuity and reducing the risk of errors. Proteus also provides interactive debugging features, including virtual instrumentation and logic analyzers, enabling users to troubleshoot and analyze their designs effectively.

Moreover, Proteus finds extensive use in educational settings, offering an intuitive platform for teaching electronics and circuit design. Its comprehensive simulation capabilities, coupled with extensive component libraries, make it an ideal tool for hands-on learning and experimentation. Whether for professional development or educational purposes, Proteus remains a go-to solution for electronic design, simulation, and prototyping needs.

3.5 Advanced Design System

Advanced Design System (ADS) is a powerful electronic design automation (EDA) software suite developed by Keysight Technologies. It is widely used in the design and simulation of RF, microwave, and high-speed digital electronic components and systems. ADS offers a comprehensive set of tools and capabilities that support the entire design cycle, from concept to implementation.

One of the key strengths of ADS is its versatility in handling various aspects of electronic design. It covers a wide range of applications, including the design of amplifiers, filters, mixers, oscillators, and other RF/microwave components. Additionally, ADS supports the design of communication systems, radar systems, and high-speed digital circuits, making it suitable for a broad spectrum of electronic design projects.

The software provides an intuitive and user-friendly environment for schematic capture, allowing engineers to create and simulate electronic circuits easily. It includes a vast library of predefined components and models, streamlining the design process. Furthermore, ADS supports the use of various simulation techniques, such as linear and nonlinear circuit simulation, harmonic balance, and system simulation, enabling engineers to analyze the performance of their designs under different conditions.

One notable feature of ADS is its emphasis on design optimization and tuning. The software includes optimization algorithms that allow engineers to automatically adjust design parameters to meet specified performance goals. This iterative optimization process is crucial for achieving optimal performance in RF and microwave designs.

Another strength of ADS is its integration with electromagnetic (EM) simulation tools. Engineers can seamlessly transfer designs between the circuit simulator and EM simulator, enabling accurate modeling of physical structures like transmission lines, microstrip traces, and antennas. This integration is essential for predicting the real-world behavior of RF components.

ADS also supports the co-simulation of different domains, allowing engineers to perform co-simulations with thermal analysis tools, signal integrity simulations, and more. This multiphysics approach provides a holistic understanding of the entire system.

In conclusion, ADS is a comprehensive EDA software solution that plays a crucial role in the design and simulation of RF, microwave, and high-speed digital circuits and systems. Its rich feature set, simulation capabilities, and optimization tools make it a go-to choice for engineers working on cutting-edge electronic designs.

3.6 DESCRIPTION

3.6.1 Antenna Design

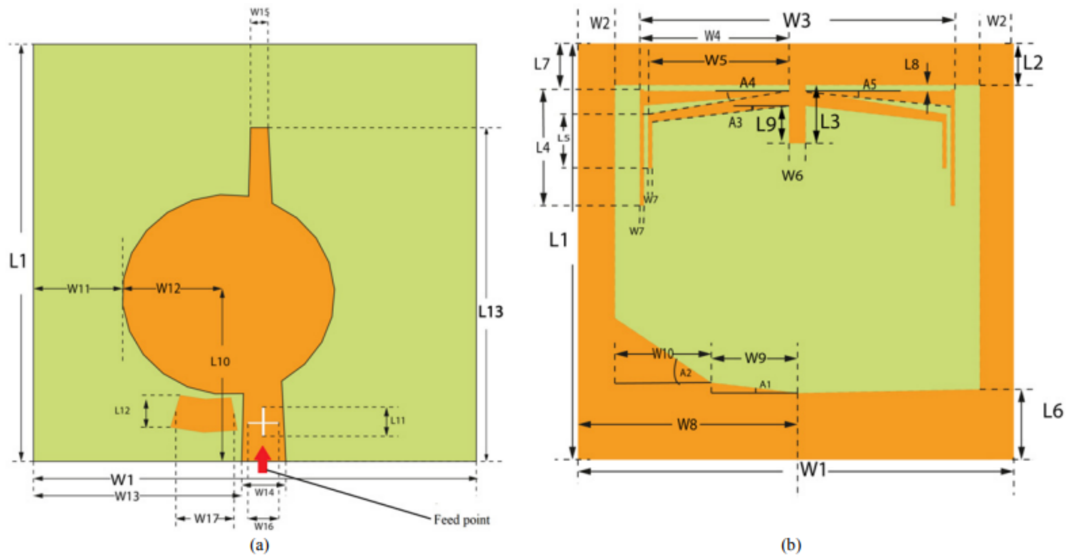


Figure 3.6: Proposed antenna structures: (a) top view, and (b) bottom view.

The antenna design process starts with using Ansys HFSS software for electromagnetic simulation, aiming to achieve resonance between 0.8 GHz to 3 GHz, focusing on specific frequencies like 0.9 GHz, 1.8 GHz, and 2.4 GHz. The core structure comprises a circular patch as the radiating element fed by a trapezoidal-shaped microstrip line. To enhance operational flexibility, spider arm-shaped resonators are added to the slotted ground structure, extending the operating frequencies for versatile applications and improved adaptability across a wider range of frequencies. Advanced features for Ultra-Wideband communication, including arc-shaped resonators and cross-shaped slots, further boost the antenna's performance in transmitting and receiving signals over a broad frequency spectrum.

In adherence to design principles, the antenna design emphasizes simplicity and compactness with precise dimensions of $50 \times 50 \times 1.6$ mm^3. This streamlined form factor ensures space-efficient integration, making it ideal for compact wireless systems where space constraints are crucial. The antenna's compact design not only prioritizes electromagnetic efficiency but also practicality, allowing for seamless integration into modern electronic devices.

The integration of spider arm-shaped resonators and advanced UWB features like arc-shaped resonators and cross-shaped slots enhances the antenna's operational capabilities. These additions enable the antenna to operate effectively across a wide frequency range, surpassing the primary resonances and expanding its utility in diverse communication scenarios. By focusing on practical implementation and electromagnetic efficiency, the antenna design successfully balances performance and compactness, making it a versatile and adaptable solution for modern wireless systems requiring reliable signal transmission and reception capabilities.

3.6.2 Matching Network

In the methodology for implementing the impedance matching circuit, the approach began with a comprehensive analysis of various impedance matching techniques suitable for the RF energy harvesting system. Considering factors such as the frequency range of operation and desired impedance matching specifications, different methods were evaluated to identify the most appropriate approach. After careful consideration, the T-match network emerged as the optimal choice due to its high Q and low ripple factor characteristics, which are essential for achieving efficient impedance matching.

Following the selection of the T-match network, the detailed design and optimization of the impedance matching circuit were pursued. This phase involved determining

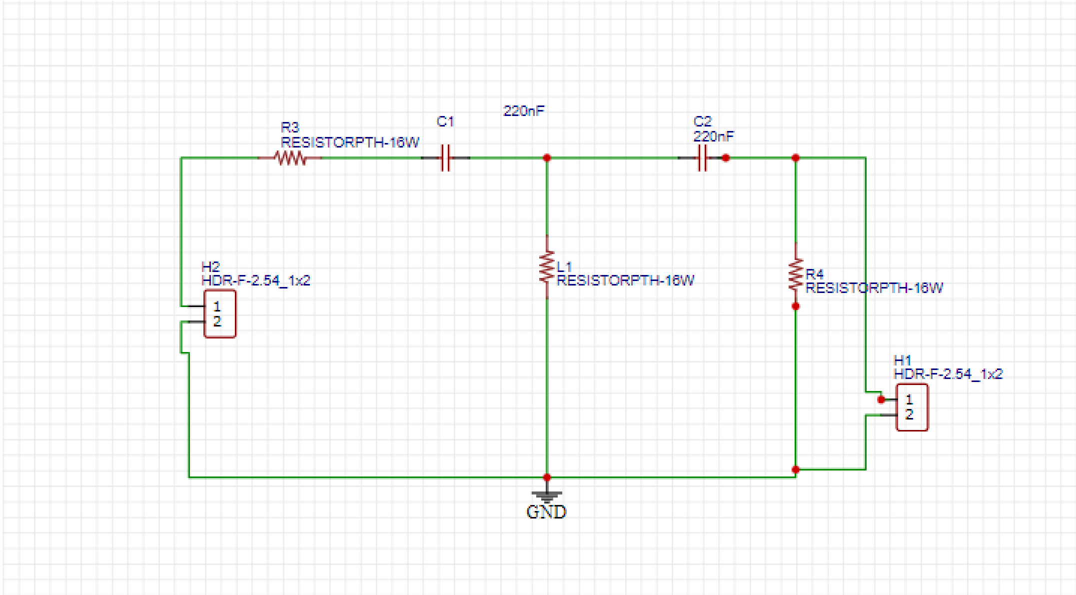


Figure 3.7: RF energy harvester with impedance matching circuit

the specific component values, circuit topology, and layout considerations necessary to meet the impedance matching requirements. Thorough simulations and analysis were conducted to refine the circuit design and ensure its effectiveness in minimizing return loss and maximizing power transfer efficiency.

Once the circuit design was finalized, the practical implementation of the impedance matching circuit commenced. This involved selecting and sourcing the necessary components and assembling prototypes of the T-match network

3.6.3 RF DC Converter

The process of converting Alternating Current (AC) to Direct Current (DC), known as rectification, is essential in many electronic applications. This transformation involves ”straightening” the direction of the current flow, which is achieved primarily through the use of diodes. Diodes, semiconductor devices that allow current to flow in only one direction, serve as the main components in rectifier circuits.

A voltage multiplier or doubler circuit is a specialized form of rectifier circuit that amplifies or boosts the DC voltage output. It consists of a network of capacitors and diodes arranged into multiple stages, typically denoted as ”n” stages. As the name suggests, the voltage multiplier circuit not only converts RF energy to DC but also increases the DC voltage level based on the number of stages employed. This amplification of DC voltage is particularly useful in applications requiring higher

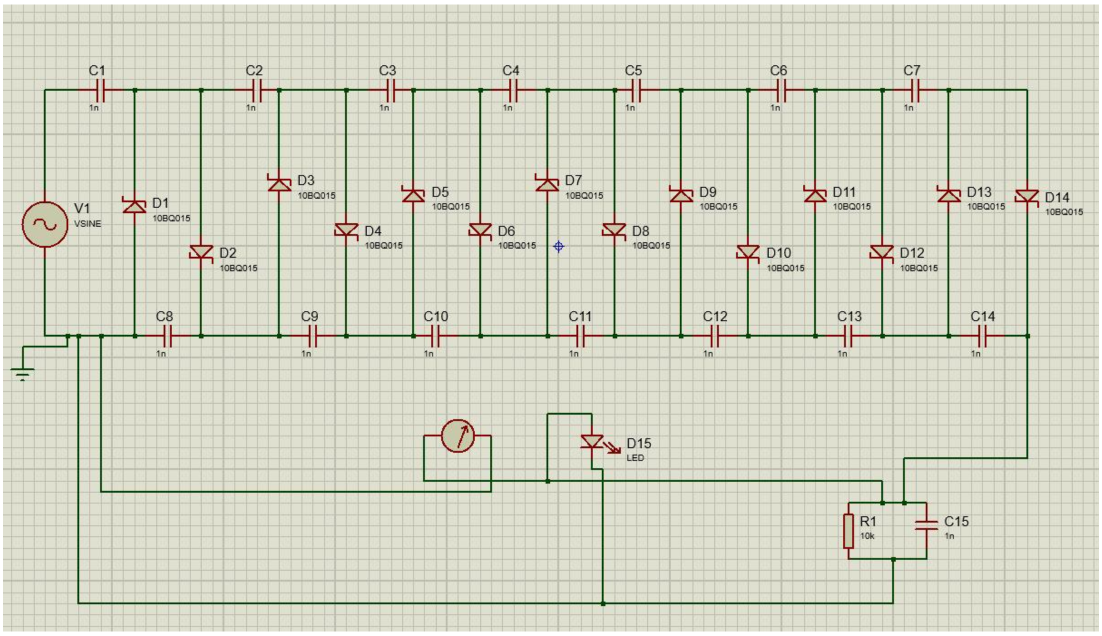


Figure 3.8: Architecture of the RF to DC converter

output voltages for powering electronic devices or charging energy storage systems.

The most commonly used diode for the rectenna is the silicon Schottky barrier diodes because of their fast switching time. RF energy harvester circuits operate in a high frequency so they require diodes with fast switching times to match them.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 ANTENNA SIMULATION I

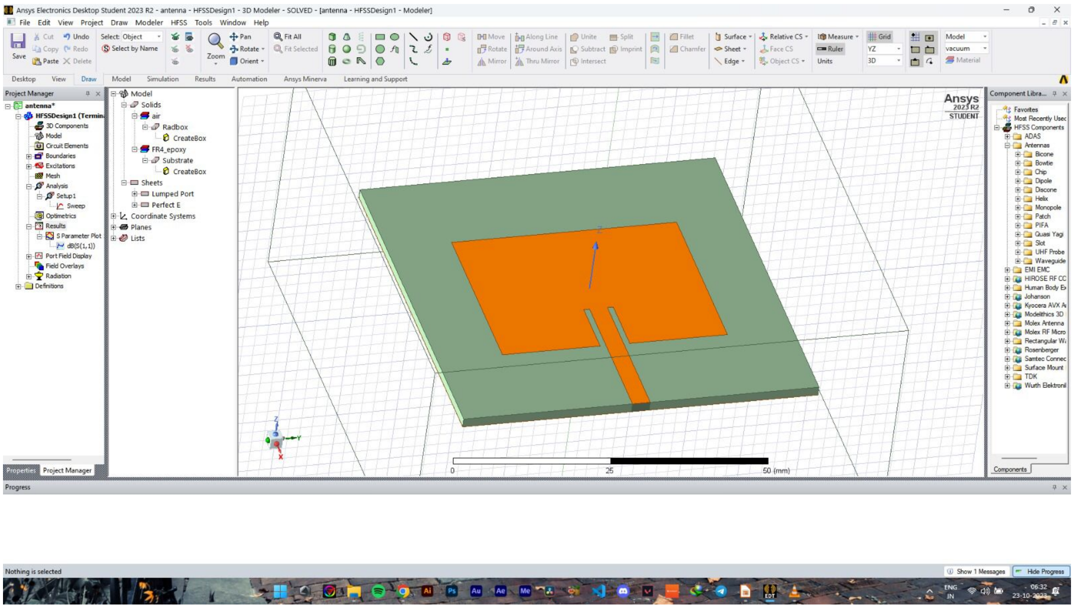


Figure 4.1: 2.4GHz Patch antenna

For the project, started by designing an inset feed microstrip patch antenna at 2.4 GHz using HFSS (High Frequency Structure Simulator) software. During the design process, it was crucial to adhere to specific specifications to ensure the antenna's functionality met our project requirements. This involved selecting a substrate with the appropriate properties, including FR4 Epoxy with a relative permittivity of 4.4, a loss tangent of 0.009, and a thickness of 1.6 mm. Additionally, the antenna was designed to have an impedance of 50 ohms, with precise dimensions set at Lg = 38.52mm, Wg = 47.01mm, Lp = 28.92mm, Lg = 37.41mm, a = 3mm, and b = 19mm.

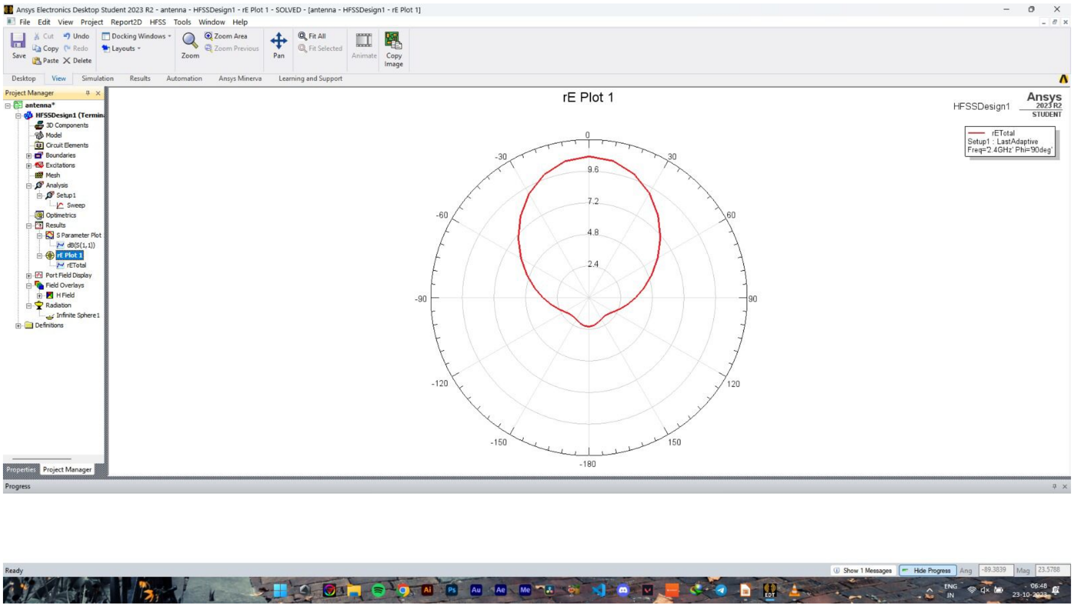


Figure 4.2: 2.4GHz Patch antenna radiation plot

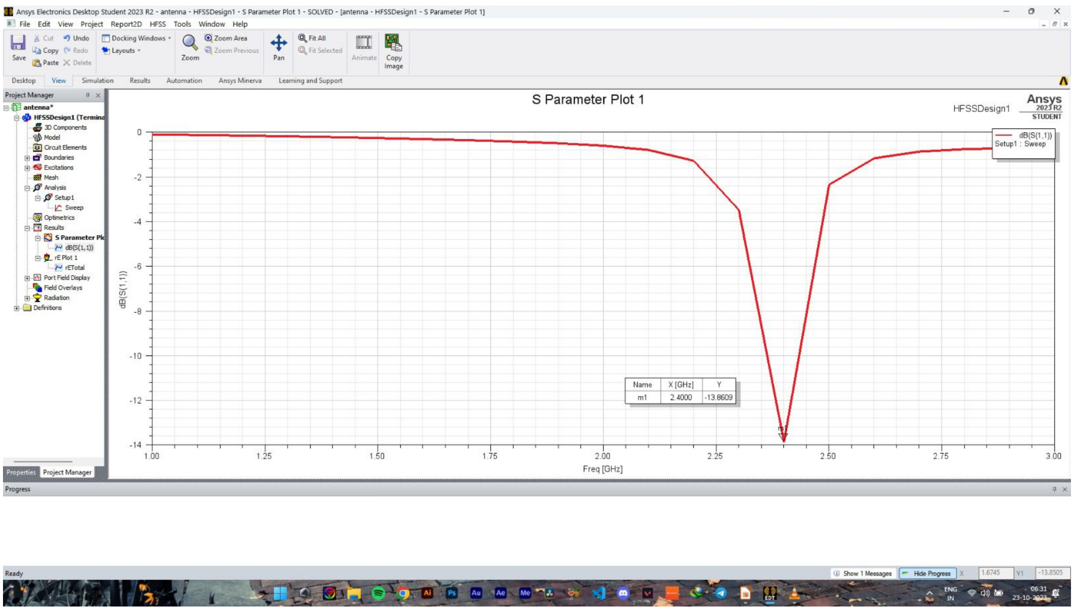


Figure 4.3: 2.4GHz Patch antenna S parameter

Figure 4.2 and Figure 4.3 illustrate the radiation plot and S-parameter analysis of the patch antenna. The radiation plot visually represents how the antenna emits or receives energy in its surrounding space. Meanwhile, the S-parameter analysis, specifically the S11 parameter, evaluates the antenna's reflection coefficient, indicating how efficiently it matches the impedance of the connected system. In this case, the respective matching of -13.48dB at 2.4GHz suggests that the antenna is effectively matched to its operating frequency, ensuring optimal performance in transmitting and receiving signals at that specific frequency.

Following the initial design, our guide recommended further optimization to enhance the antenna's performance. This involved modifying the design to resonate at three distinct frequencies: 0.9 GHz, 1.8 GHz, and 2.4 GHz. By incorporating resonant frequencies tailored to our project's specifications, we aimed to improve the antenna's responsiveness and overall effectiveness in receiving and transmitting signals.

4.2 ANTENNA SIMULATION II

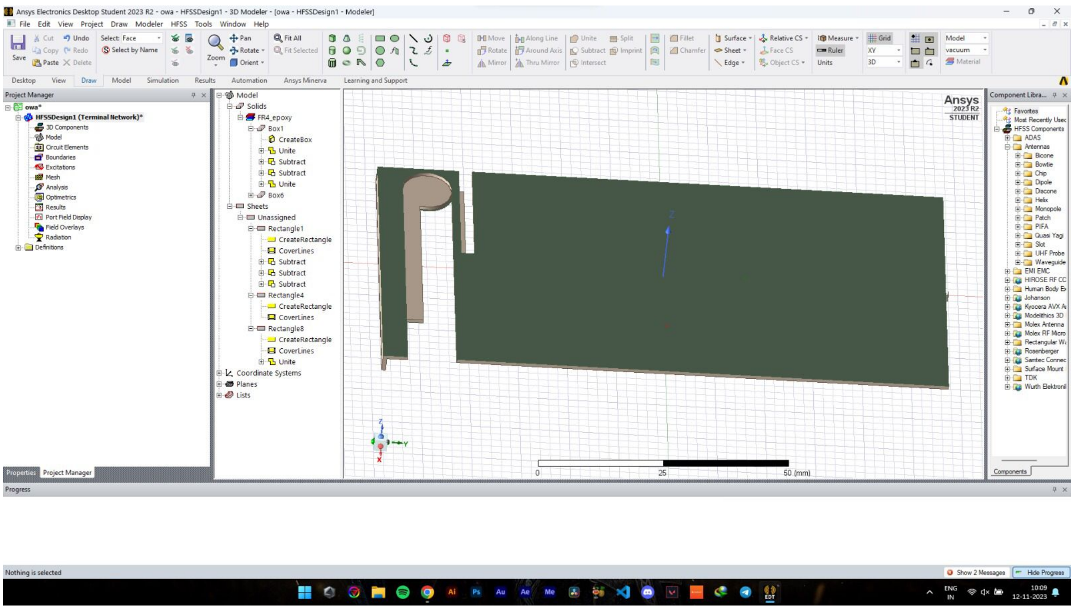


Figure 4.4: Antenna Front View

After conducting thorough research and consulting a research paper, a new antenna design has been developed. This antenna design features simulations covering a wide frequency band spanning from 0.8 GHz to 2.5 GHz, allowing for versatile performance across various frequency ranges. The antenna is constructed using FR4 material with dimensions of 150x60x1.6, featuring a dielectric constant of 4.4.

Figure 4.6 displays the S-parameter analysis of the antenna simulation. Upon analyzing the S-parameter data, it becomes evident that the antenna exhibits poor impedance matching. This mismatch could significantly impact its performance, leading to suboptimal functionality in practical scenarios. Additionally, the antenna's size may not be compatible with real-world applications, further limiting its usability. As a result, the overall project performance may be compromised. Consequently, a decision was made to redesign the antenna for the third time, aiming to address these shortcomings

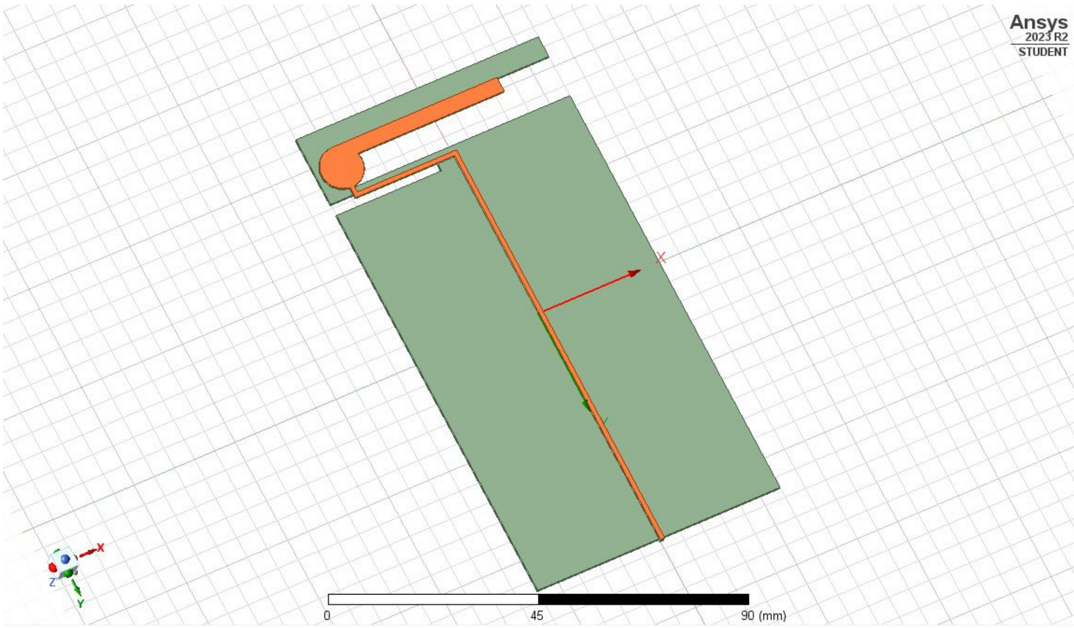


Figure 4.5: Antenna Back View

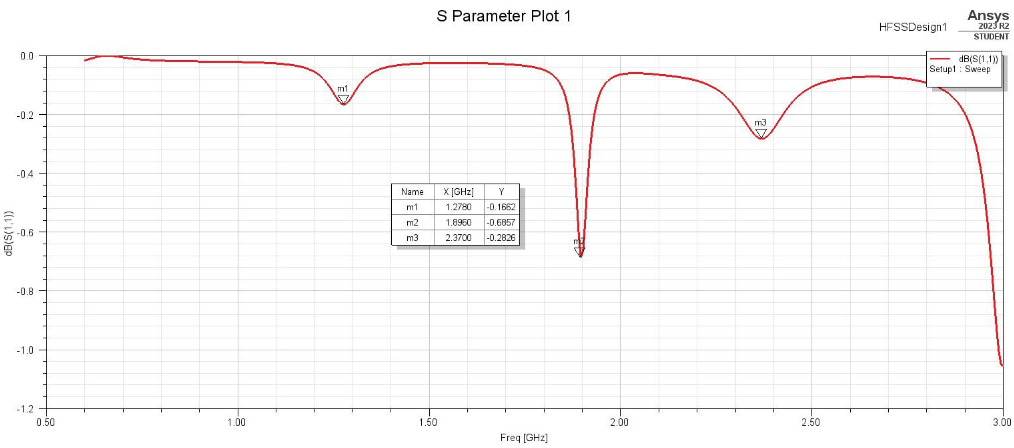


Figure 4.6: 2.4GHz Patch antenna s-parameter

and deliver improved performance. This iterative process underscores the importance of thorough testing and refinement to ensure the success of the antenna design in real-world applications.

4.3 ANTENNA SIMULATION III

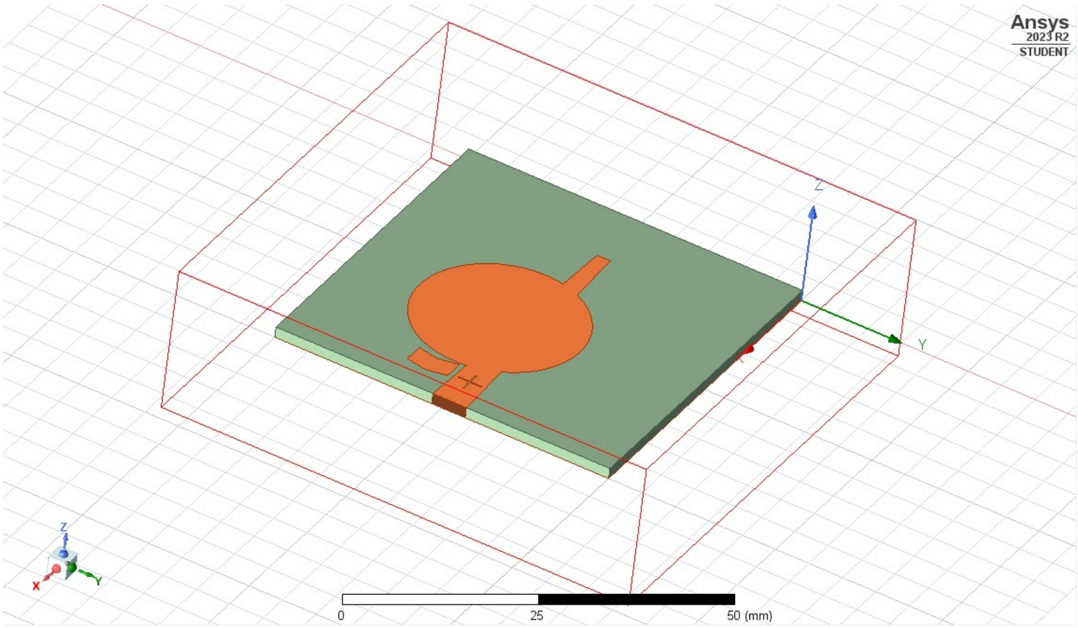


Figure 4.7: Antenna Simulated top view

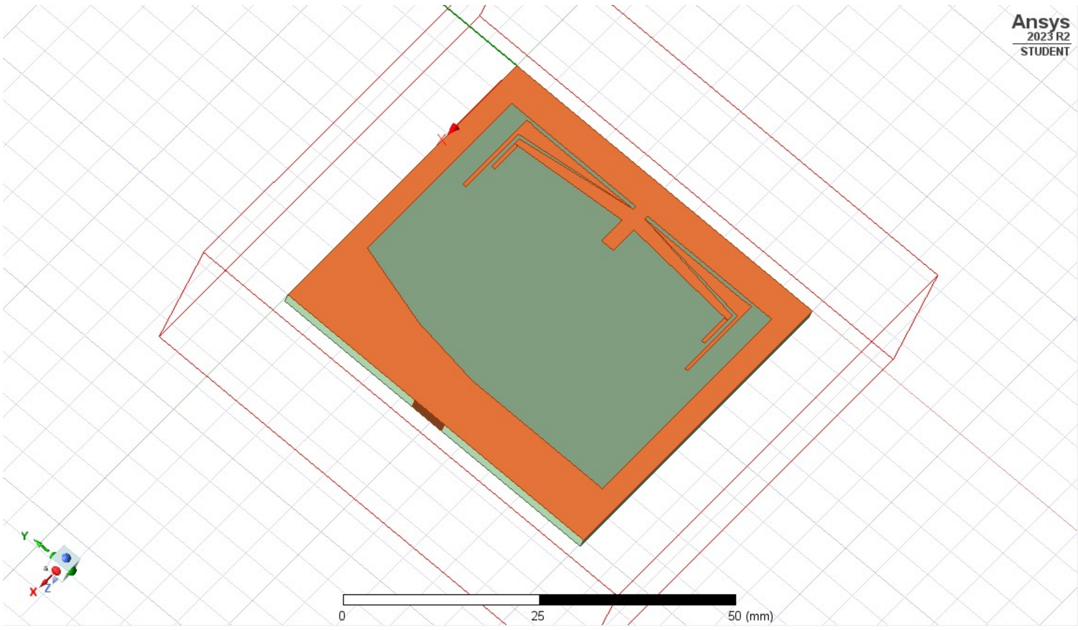


Figure 4.8: Antenna Simulated bottom view

Antennas indeed play a crucial role in RF energy harvesting systems, serving as the interface between the ambient RF signals and the energy harvesting circuitry. Designing an antenna with specific resonant frequencies, such as 0.9, 1.8, and 2.4 GHz, is essential for efficiently capturing RF signals at those frequencies.

Utilizing Ansys HFSS software for antenna design offers powerful capabilities for simulation and optimization. Figures 4.7 and 4.8 likely provide visual representations of the antenna design from both the top and bottom perspectives, showcasing its geometry, dimensions, and possibly other characteristics.

4.3.1 Antenna characteristics

4.3.2 S-Parameter

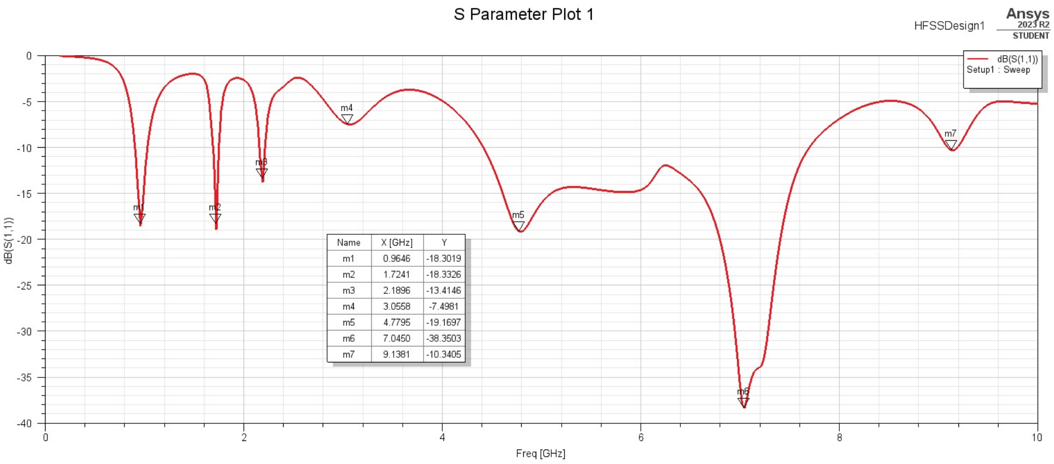


Figure 4.9: S-parameter plot 0.2GHz-10GHz

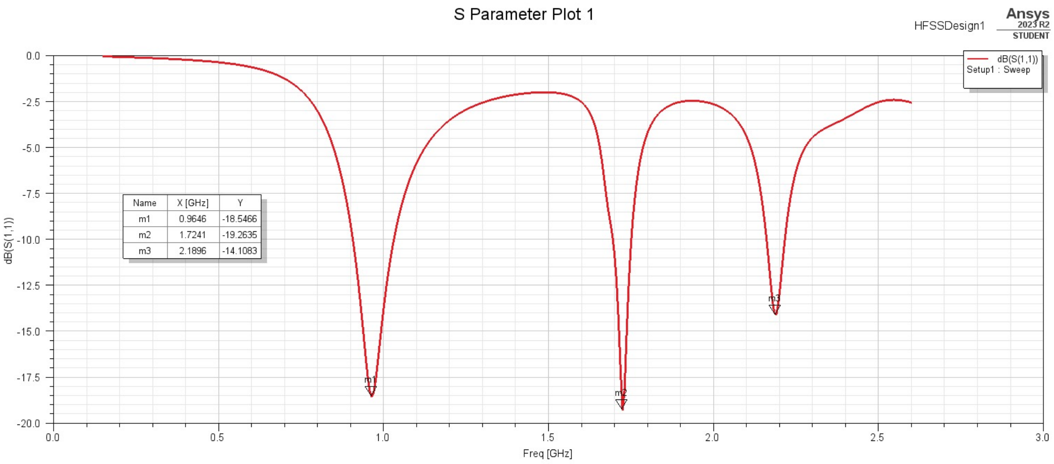


Figure 4.10: S-parameter plot 0.2GHz-2.6GHz

In antenna analysis, S11 parameter plays a significant role in characterizing the antenna's performance, particularly in terms of impedance matching and reflection coefficient at the antenna port.S11, also known as the reflection coefficient at port 1, represents the ratio of the power reflected from the antenna to the power incident on the antenna. In practical terms, S11 indicates how well the antenna is impedance-matched to the transmission line or the system it's connected to. A low S11 value (close to zero) suggests good impedance matching, meaning that most of the incident power is absorbed by the antenna, and minimal power is reflected back to the source. On the other hand, a high S11 value (closer to 1) indicates poor impedance matching, with a significant portion of the incident power being reflected.Analyzing the S11 parameter allows antenna engineers to optimize the antenna's design for better impedance matching, which is essential for maximizing power transfer efficiency, minimizing signal loss, and achieving desired radiation characteristics.

Figure 5.4 presents the S-parameter plot of the antenna used in this project, generated using Ansys HFSS software. The plot displays the dB (decibel) magnitude of the S-parameter S(1,1), representing the reflection coefficient at port 1. The x-axis indicates the frequency in gigahertz (Freq [GHz]), while the y-axis represents the dB magnitude of S(1,1). The frequency sweep ranges from 0 to 30 GHz. Analysis of the plot reveals resonance at three frequencies: 0.9 GHz with a reflection coefficient of -18.5466 dB, 1.7241 GHz with -19.2635 dB, and 2.1896 GHz with -14.1083 dB, aligning with project requirements. These values indicate minimal reflection coefficient, demonstrating effective impedance matching and optimized antenna performance for signal reception and transmission.

While the simulation results demonstrate favorable resonance and minimal reflection coefficient at the targeted frequencies, it's important to acknowledge certain limitations in the analysis. One limitation lies in the accuracy of the simulation model, which may not fully capture real-world environmental factors and manufacturing variations that could impact antenna performance. To address this limitation, additional validation through physical prototyping and testing is recommended.

4.3.3 3D Plot-Radiation Pattern

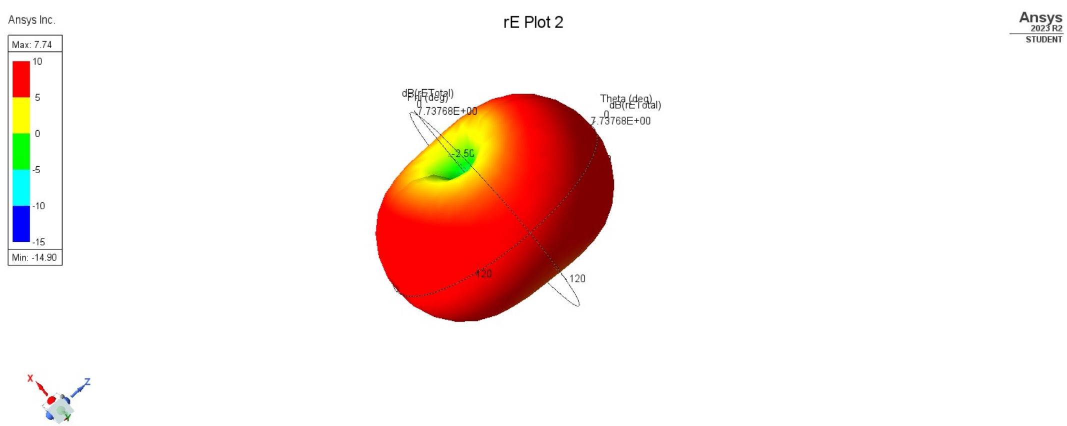


Figure 4.11: Antenna 3D Radiation Pattern

The 3D radiation plot serves as a visual representation of how an antenna behaves in terms of emitting or receiving energy concerning its surroundings.It illustrates how the antenna sends out signals into space or captures incoming signals, depicting the specific areas where its signals are stronger or weaker.The plot may showcase different types of radiation patterns, such as omni-directional, which radiates equally in all directions, or isotropic, which represents a theoretical uniform radiation in all directions. The achieved pattern informs about the performance and coverage of the antenna.The intensity of the plot's color corresponds to the energy level of the antenna. This provides a visual representation of the energy distribution, allowing for analysis of the spatial distribution of radiation intensity.

Figure 4.11 illustrates the 3D radiation plot for the project's antenna design. Analyzing the strength or intensity of the radiation pattern can be accomplished by examining the color mapping and legend provided with the plot. The legend, located on the side of the plot, presents a scale indicating the intensity levels mapped to different colors, ranging from weaker (lighter colors) to stronger (darker colors). Notably, regions colored in red denote the highest intensity or strongest energy levels, signifying areas where the antenna radiates with maximum power. Conversely, areas transitioning from blue to green, yellow, orange, and ultimately red suggest a gradient from weaker to stronger radiation intensity. By interpreting these color variations, insights into the directional characteristics and spatial distribution of electromagnetic energy emitted by the antenna can be gained.

However, while the 3D radiation plot provides valuable insights into the antenna's radiation characteristics, it's essential to acknowledge certain limitations in the analysis. One limitation lies in the accuracy of the simulation model, which may not fully account for real-world environmental factors, such as surrounding objects, terrain, and atmospheric conditions, that could affect the antenna's radiation pattern. Additionally, the simulation may not accurately capture the effects of mutual coupling between multiple antennas, which can distort the radiation pattern.

4.3.4 Radiation Pattern

A plane radiation pattern, also known as a 2D radiation pattern, is a graphical representation of how an antenna radiates or receives electromagnetic energy in a specific plane. Unlike a 3D radiation pattern, which shows radiation characteristics

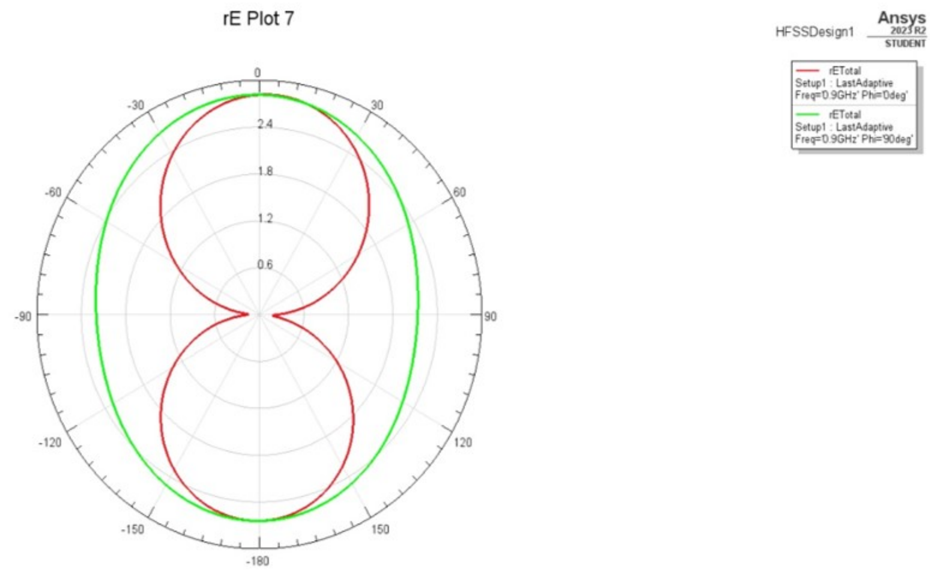


Figure 4.12: Antenna Plane Pattern for 0.9 GHz

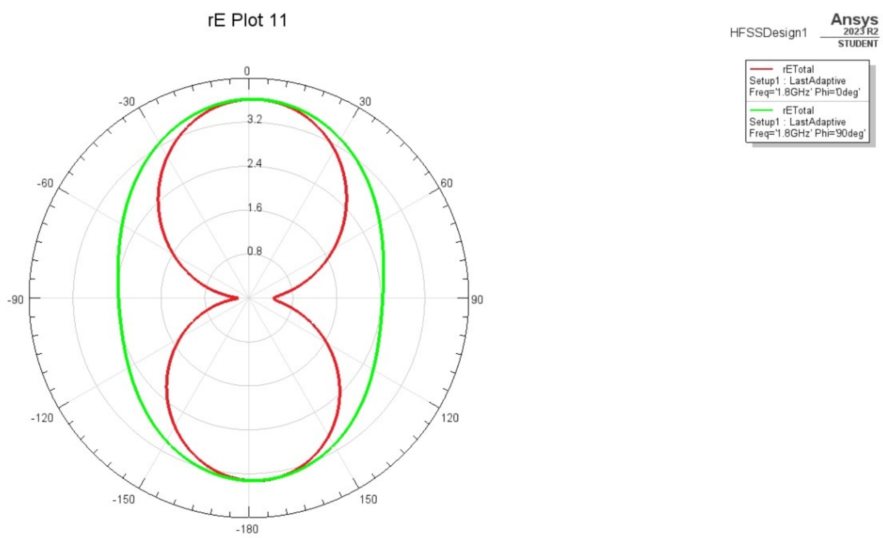


Figure 4.13: Antenna Plane Pattern for 1.8 GHz

in three dimensions, a plane radiation pattern focuses on a single plane, typically the horizontal (azimuthal) or vertical (elevation) plane.

Figure 5.6 illustrates the antenna radiation pattern in the plane of the project, displaying both azimuthal and elevation plane radiation patterns. The azimuthal plane radiation pattern, represented by 0 degrees azimuthal , depicts how the antenna radiates or receives energy in the horizontal plane, with angles measured in degrees relative to a reference direction. Similarly, the elevation plane radiation pattern illustrates the antenna's radiation or reception characteristics in the vertical plane, also measured in degrees relative to a reference direction. Each angle is represented by a different color,

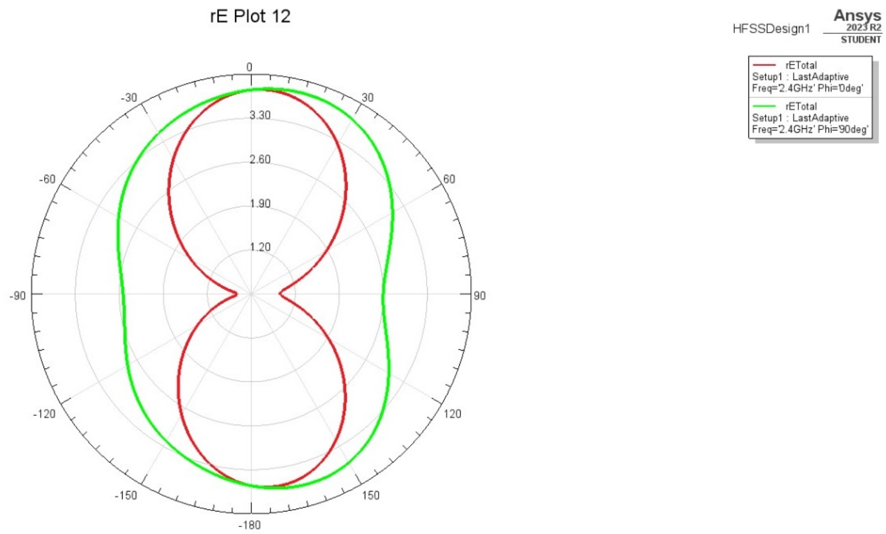


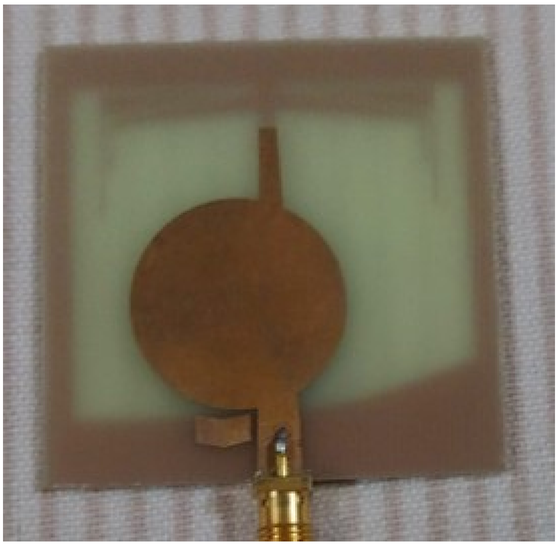
Figure 4.14: Antenna Plane Pattern for 2.4 GHz

with a legend provided on the side of the plot for reference. Analysis of the plot reveals that the antenna radiates in accordance with our requirements, exhibiting maximum radiation as expected. This visualization provides valuable insights into the antenna's directional characteristics and ensures alignment with project objectives.

4.3.5 Fabricated Antenna

The antenna design specifications encompass a 50mm length, 50mm width, and 1.6mm height, constructed from FR4 material. This multi-frequency antenna operates across distinct bands, with the ground leg resonating at 2.4 GHz, the main leg at 1.8 GHz, and the front portion at 900 MHz. Facilitating impedance matching, the antenna utilizes a trapezoidal-shaped micro-strip line for feeding, transitioning from 5mm width near the feed point to 2mm at the top, spanning a length of 40mm. The feed line strategically traverses a patch with a 12mm radius, centrally located at (22, 20, 1.6). Incorporating dielectric material with a permittivity of 4.4 and a loss tangent of 0.02, meticulous design considerations ensure optimal performance across the desired frequency bands.

To broaden the antenna's bandwidth and enhance its performance, modifications to the ground plane are introduced. These modifications include a substantial slot with precise dimensions, featuring side walls measuring 3mm, a top wall of 5mm, and a protruding triangle with a height of 8mm and base width of 39.3mm. Furthermore, the design integrates pairs of spider arm-shaped resonators atop the slotted ground to



(a) Front view

(b) Back view

achieve additional frequency bands. An arc-shaped resonator, 3mm in width, extends strategically from coordinates (16, 6, 1.6) to (20, 20, 1.6) at an angle of 26.5 degrees. These enhancements are meticulously engineered to broaden the antenna's bandwidth and ensure robust performance across various frequencies.

The feeding mechanism of the antenna is carefully tailored to optimize impedance matching and signal transmission efficiency. Employing a trapezoidal-shaped microstrip line for feeding, the antenna achieves better impedance matching by tapering from 5mm width near the feed point to 2mm at the top. This configuration facilitates efficient energy transfer between the feed line and the radiating element. Routing the feed line through a patch with a 12mm radius, centered at (22, 20, 1.6), minimizes signal loss and maximizes energy transfer. These design considerations, combined with precise feed line dimensions and strategic placement, ensure that the antenna operates with optimal performance and reliability across a range of frequencies.

4.3.6 S-Parameter

The experimental testing of the fabricated antenna using a Vector Network Analyzer (VNA) and output analysis revealed notable resonance frequencies and their corresponding reflection coefficients.

The analysis indicated resonance frequencies at 1.062 GHz with a reflection coefficient of 24.59 dB, 1.737 GHz with -14.48 dB, 2.202 GHz with 8.91 dB, and 3.110 GHz with

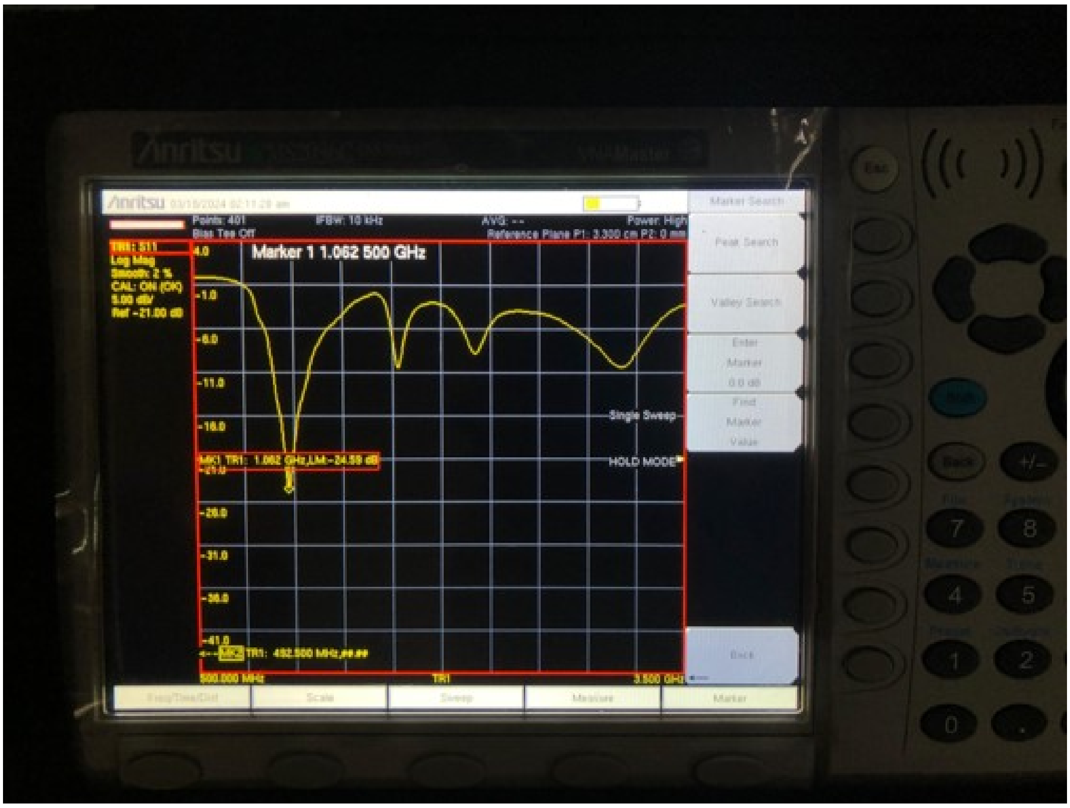


Figure 4.16: VNA Result at 1.062 GHz

10.50 dB.

Comparing these results with the antenna simulation showed close agreement, except for the resonance frequency at 2.202 GHz, which exhibited a mismatch. To address this discrepancy and achieve better impedance matching, further investigations are required. This may involve conducting parametric analysis to identify the factors influencing the impedance mismatch at 2.2 GHz. Alternatively, designing and implementing a matching circuit specifically tailored to the 2.2 GHz frequency can help optimize the antenna's performance and ensure efficient energy transfer. By resolving the impedance mismatch, the antenna can operate more effectively across the desired frequency bands, enhancing its overall performance and applicability in practical applications.

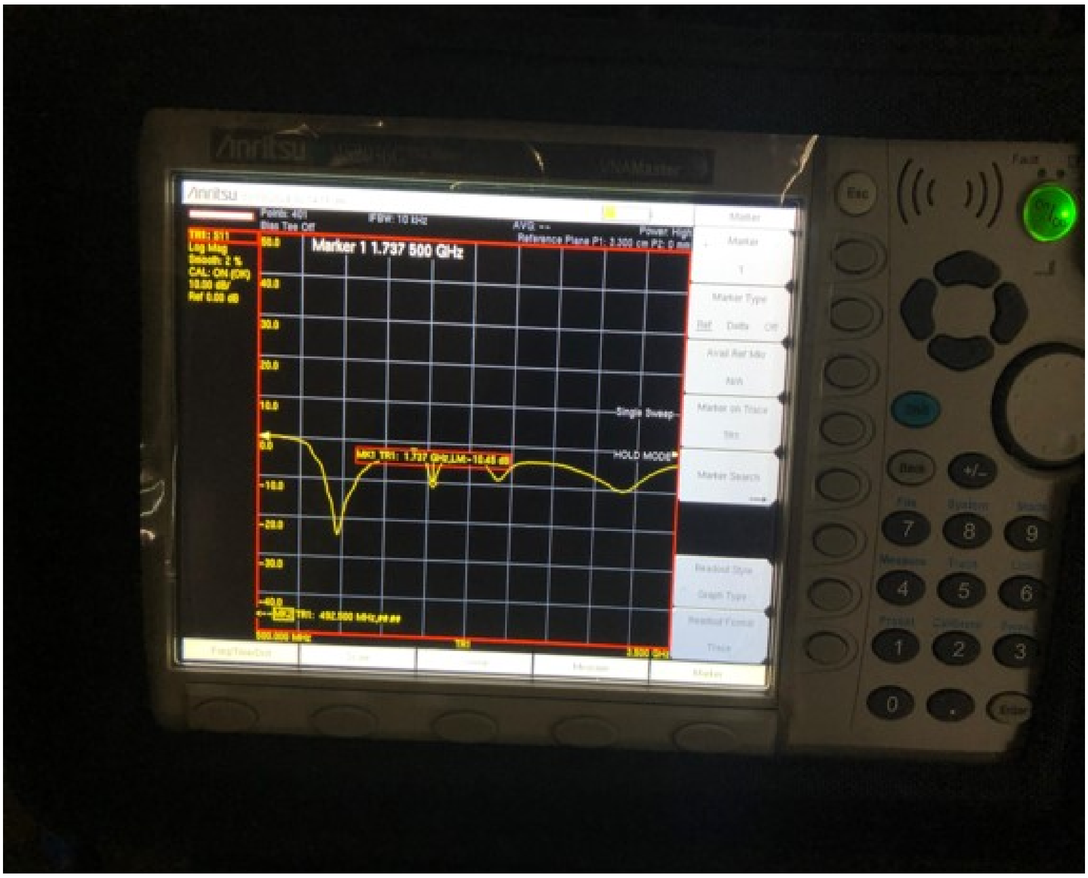


Figure 4.17: VNA Result at 1.737 GHz

4.3.7 Parametric Analysis

Parametric analysis in antenna design refers to the systematic study and evaluation of how changes in various parameters affect the performance and characteristics of the antenna. These parameters can include dimensions, materials, geometries, feed structures, and operating frequencies. The goal of parametric analysis is to optimize antenna performance by identifying the most influential parameters and determining their optimal values.

The optimization process involved varying the patch radius (R) of the antenna within the range of 11 mm to 13 mm. The corresponding reflection coefficients (S11) were measured and plotted. Through this experimentation, it was observed that the best impedance matching across the entire Ultra-Wideband (UWB) spectrum was achieved when the patch radius was set to 12 mm.

Adjusting the width of the side walls (W2) within the slotted ground structure is crucial for fine-tuning the placement of the antenna's primary operating band, which targets coverage of the GSM-900 band. Through a systematic variation of W2 ranging from 2

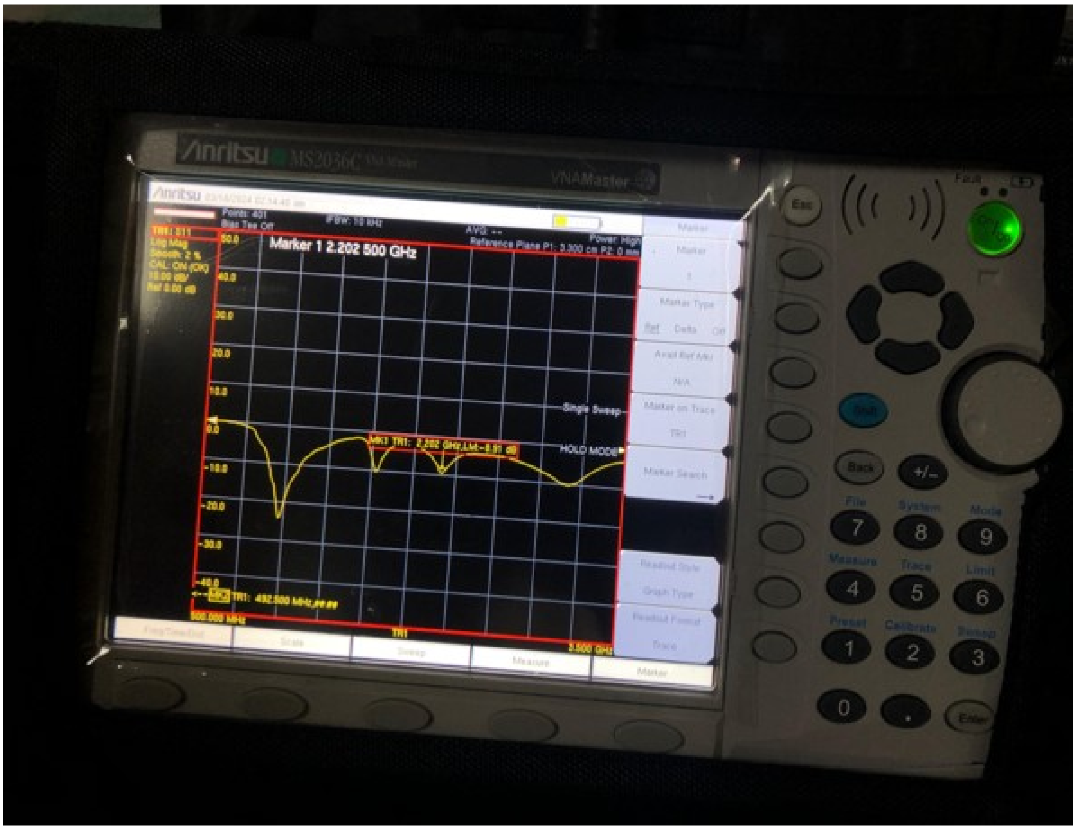


Figure 4.18: VNA Result at 2.202 GHz

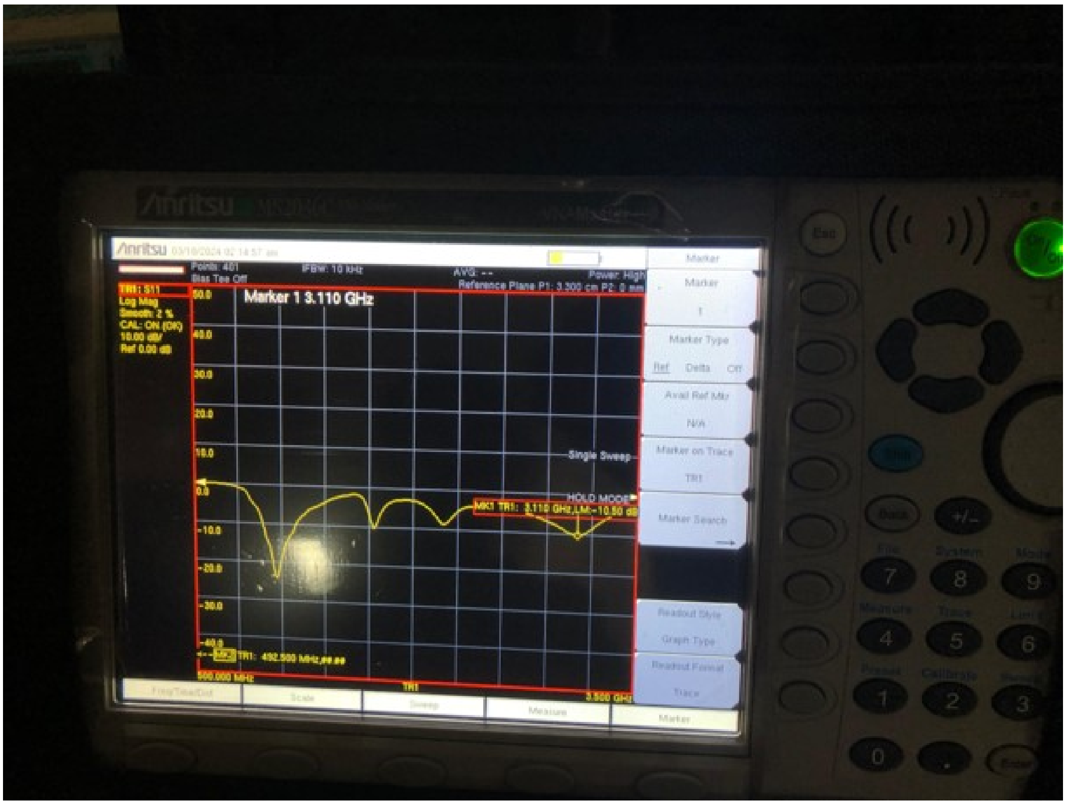


Figure 4.19: VNA Result at 3.3 GHz

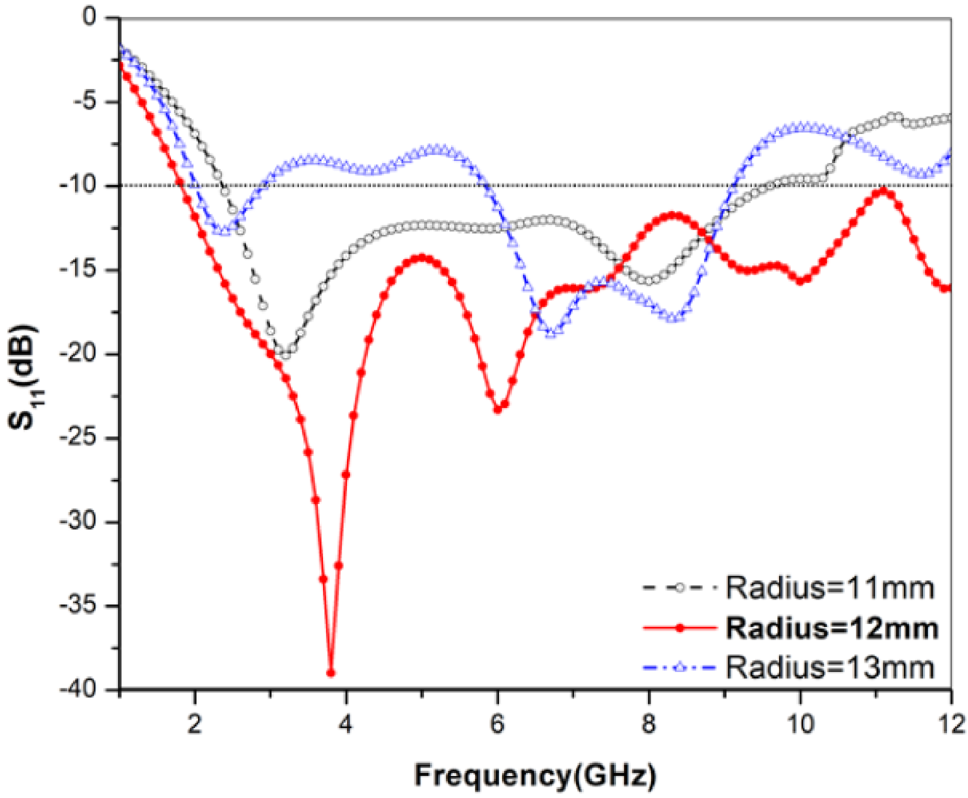


Figure 4.20: Change in S11 characteristics due to radius variation of circular patch.

mm to 4 mm, the resulting S11 parameter (specifically for the first band) was analyzed and presented. The analysis revealed that when W2 is set to 3 mm, the operating band effectively encompasses the entirety of the GSM-900 band, with a resonant frequency precisely at 900 MHz. This observation underscores the importance of optimizing W2 to achieve resonance and comprehensive coverage across the desired frequency band.

The optimization process also extended to the overall length of two spider arm-shaped resonators, aiming to precisely position two additional operating bands to cover the entire GSM-1800 and Bluetooth bands. By varying the length of the larger resonator arms from 64 mm to 68 mm, a variable operating band centered at 1.8 GHz was achieved. Similarly, adjusting the length of the smaller arm from 56 mm to 58 mm resulted in resonance at 2.4 GHz. These adjustments are visually depicted.

The optimal lengths for the larger and smaller arm resonators were determined to be 66 mm (corresponding to /2.6) and 57 mm (corresponding to /2.48) respectively, where represents the wavelength corresponding to each resonance frequency. The dimensions of the resonators were carefully chosen to align their resonance frequencies closely with those of the modified ground structure. This strategic coupling among

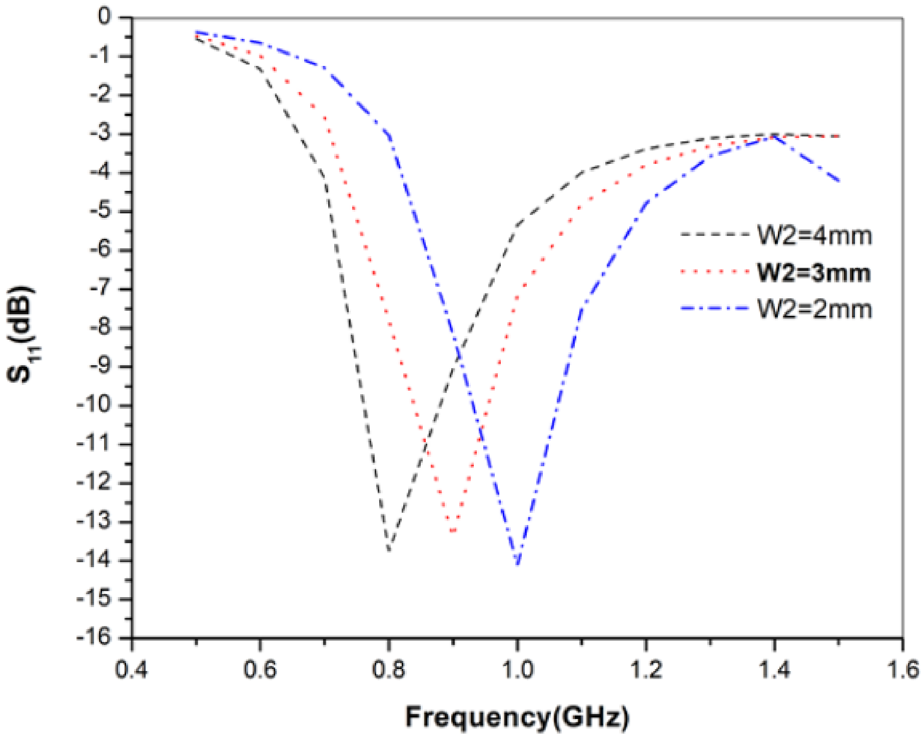


Figure 4.21: S11 characteristics for the GSM-900 band due to side wall width variation of the ground plane.

multiple resonances contributed to a wide bandwidth (¿500 kHz) for each additional operating band, including the GSM-900, GSM-1800, and Bluetooth bands. Figure below depicts the surface current densities at three resonant frequencies corresponding to the extra bands. The analysis reveals that specific components of the antenna structure are responsible for generating resonance in the GSM-900, GSM-1800, and Bluetooth bands. Specifically, the two side walls of the ground, along with the larger and smaller spider arm-shaped resonators, correspond to these respective frequency bands.

The asymmetric design of the patch, inclined more towards the left-hand side, leads to increased mutual coupling with the left arm of the ground plane. Consequently, the surface current density is higher on the left arm compared to the right arm of the ground plane. This asymmetry in current distribution is an important aspect to consider in understanding the antenna's behavior and performance characteristics across different frequency bands. The inner spiderleg structure located at the ground of the antenna is strategically designed to capture frequencies in the 2.4 GHz range, while the outer spiderleg is optimized for capturing frequencies at 1.8 GHz. This segmentation ensures that the antenna can effectively operate across multiple frequency bands, catering to different communication standards or protocols.

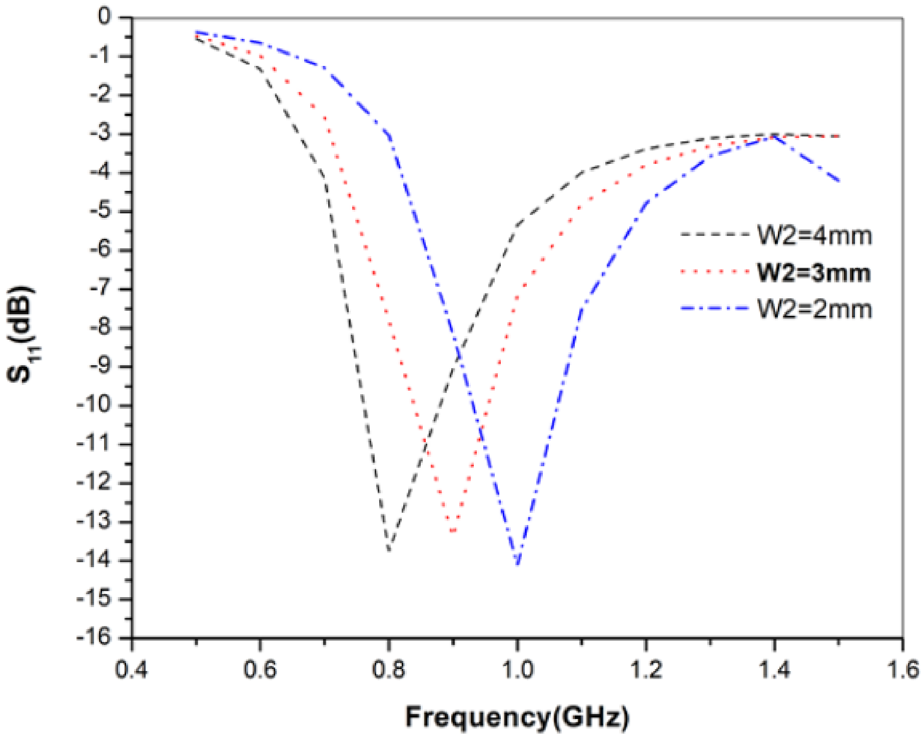


Figure 4.22: S11 characteristics for the (a) GSM-1800, and (b) Bluetooth bands, due to length variation of the spider arm-shaped resonators.

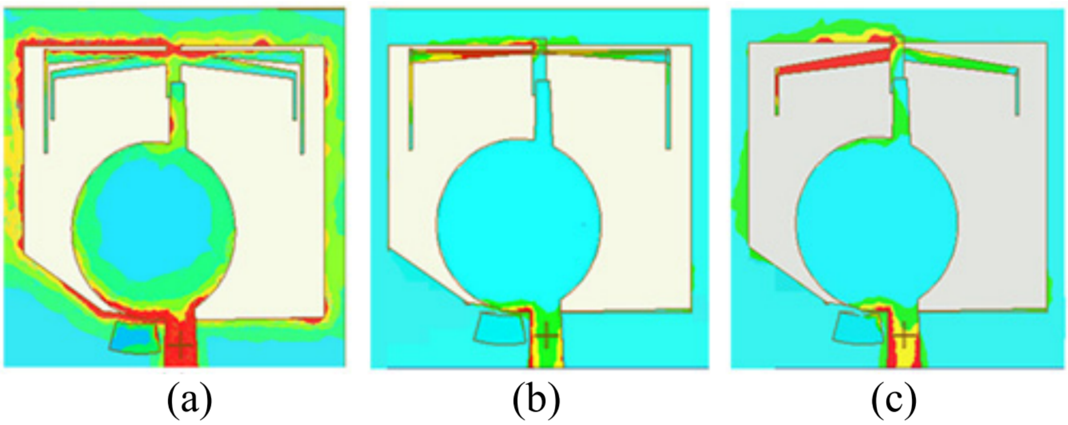


Figure 4.23: Surface current distributions at three resonant frequencies: (a) 900 MHz, (b) 1.8 GHz,(c) 2.4 GHz

Additionally, a circular region positioned at the front of the antenna serves the purpose of implementing better impedance matching. Impedance matching is critical for optimizing the transfer of power between the antenna and the connected system or device. By fine-tuning the geometry and dimensions of this circular region, impedance matching can be enhanced, leading to improved overall performance and efficiency of the antenna system.

To enhance impedance matching for the 2.4GHz frequency range in the antenna design, two modifications are made: Firstly, a slot measuring 1mm x 8.5mm is introduced

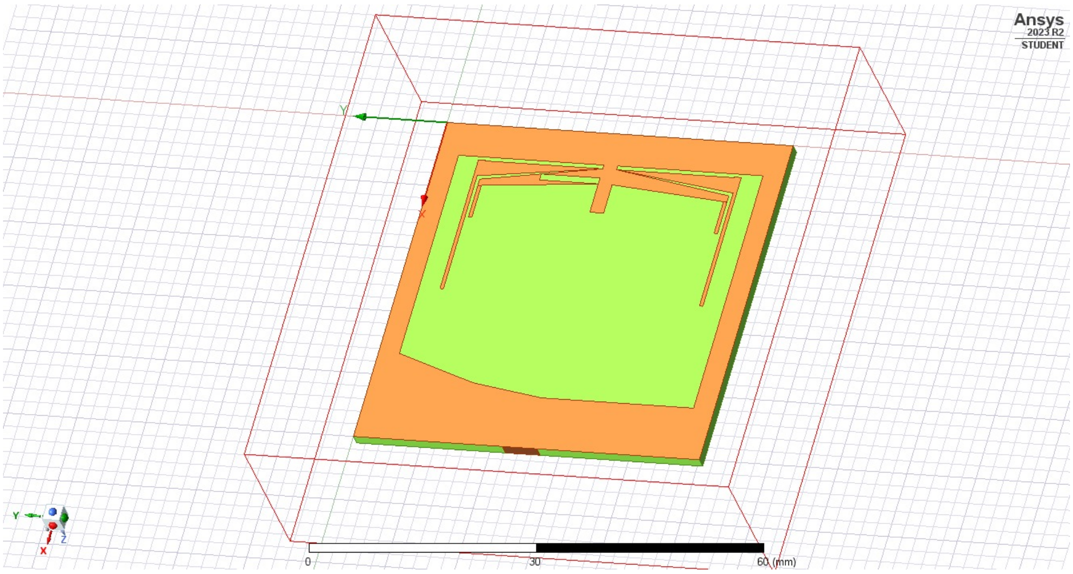


Figure 4.24: Antenna Simulated bottom view

into the left inner spider leg at the antenna's ground. This addition aims to shift the S-parameter response towards the 2.4GHz frequency range, specifically optimizing impedance matching for this band.

Secondly, a slot is integrated into the circular structure at the antenna's front. Positioned towards the bottom left corner of the circle, this slot measures 1mm x 5mm. Its purpose is to further refine impedance matching, especially targeting the 2.4GHz frequency range.

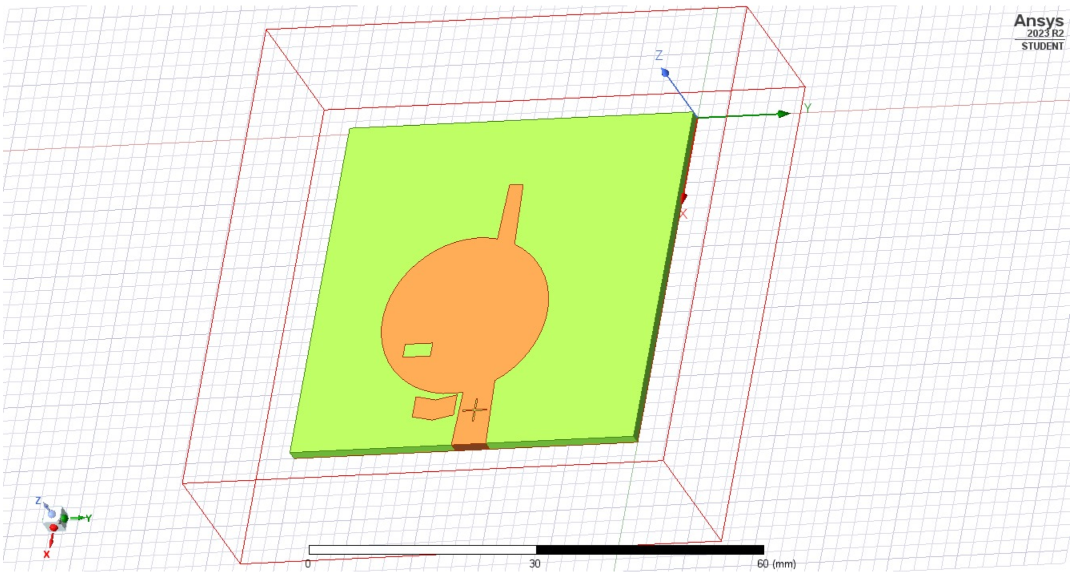


Figure 4.25: Antenna Simulated top view

These strategic slot implementations are key adjustments to the antenna's design, tailored to fine-tune impedance characteristics for optimal performance and efficient power transfer within the 2.4GHz frequency band. By carefully incorporating these slots into the design, the antenna can achieve superior impedance matching, thereby improving overall functionality and effectiveness in communication applications operating at 2.4GHz.

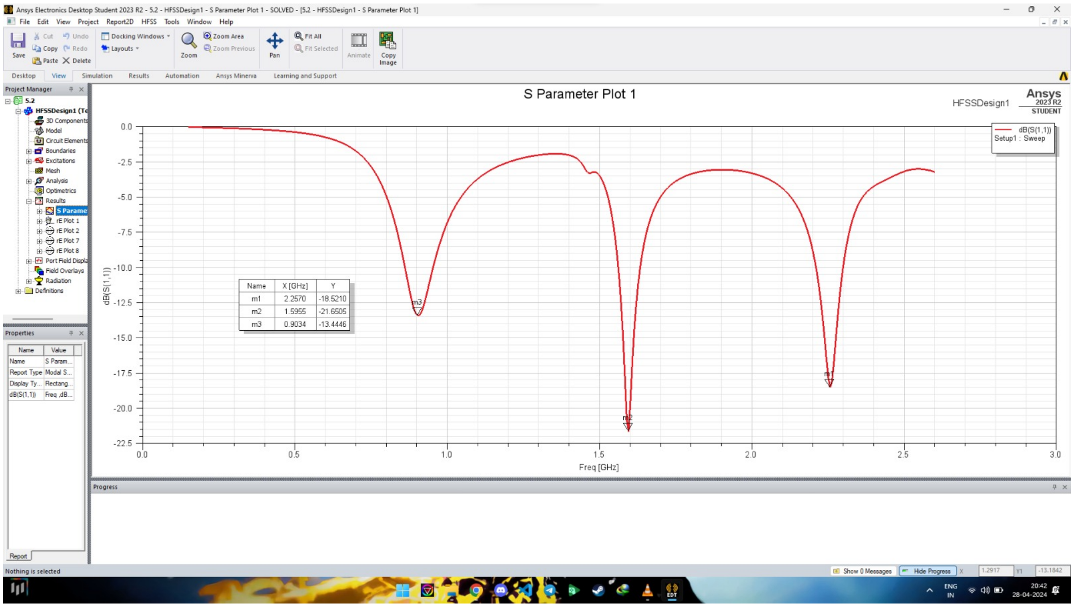


Figure 4.26: S-Parameter plot

After simulating the S-parameters of the modified antenna design, a noticeable improvement in impedance matching is observed compared to the previous design. Specifically, at the 2.4GHz frequency, the impedance measures -18.52dB, indicating a better match between the antenna and the connected system or device. Similarly, at 1.8GHz, the impedance improves to -21.65dB, and at 0.9GHz, it measures -13.45dB.

This improvement in impedance matching is a positive outcome of the design modifications, such as the inclusion of slots in strategic locations. The measured impedance values indicate that the antenna is better aligned with the desired frequency bands, leading to enhanced performance and more efficient power transfer. These results validate the effectiveness of the design adjustments in achieving improved impedance matching across multiple frequency ranges.

4.3.8 Matching Circuit and RF-DC Converter

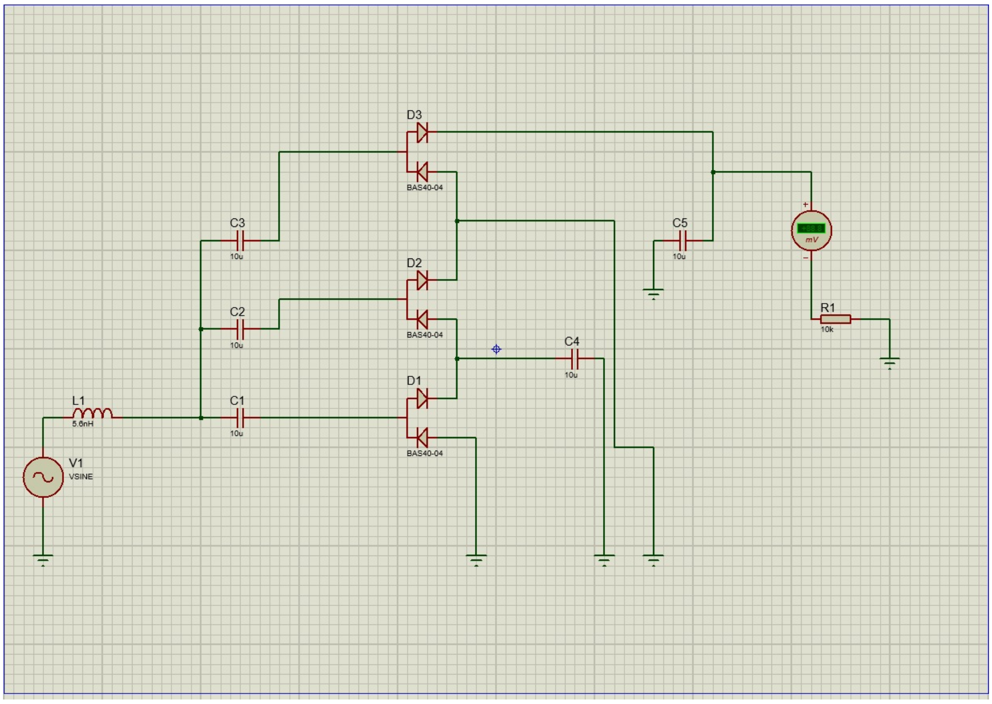


Figure 4.27: Simulated circuit

In the next stage of our project, we used computer simulations to test a circuit that connects two devices. from the circuit understand that the out got was 88mv Unfortunately, the results were much worse than we expected.

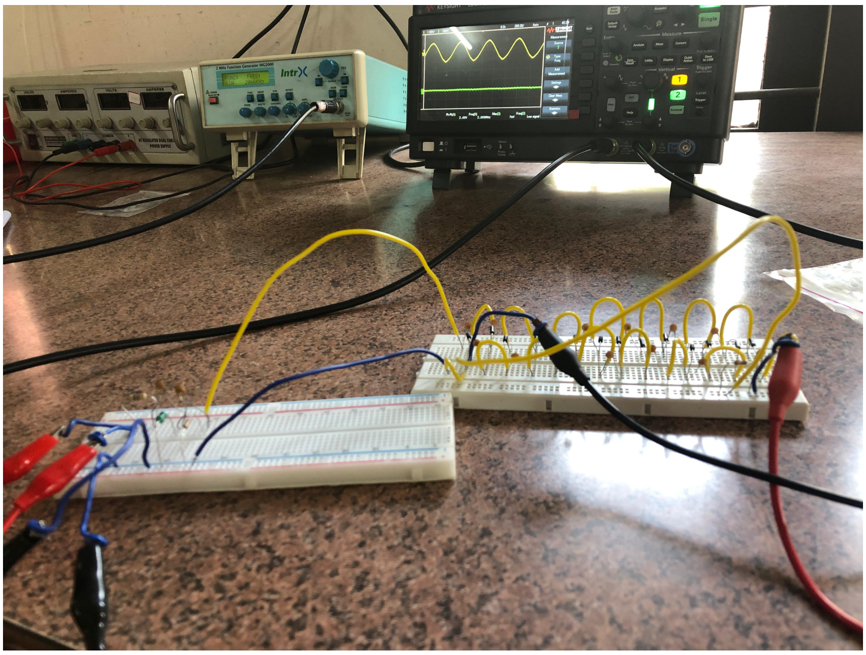


Figure 4.28: Integration

When we tested the circuit in the lab, it give 11 mv and the results were just as bad as

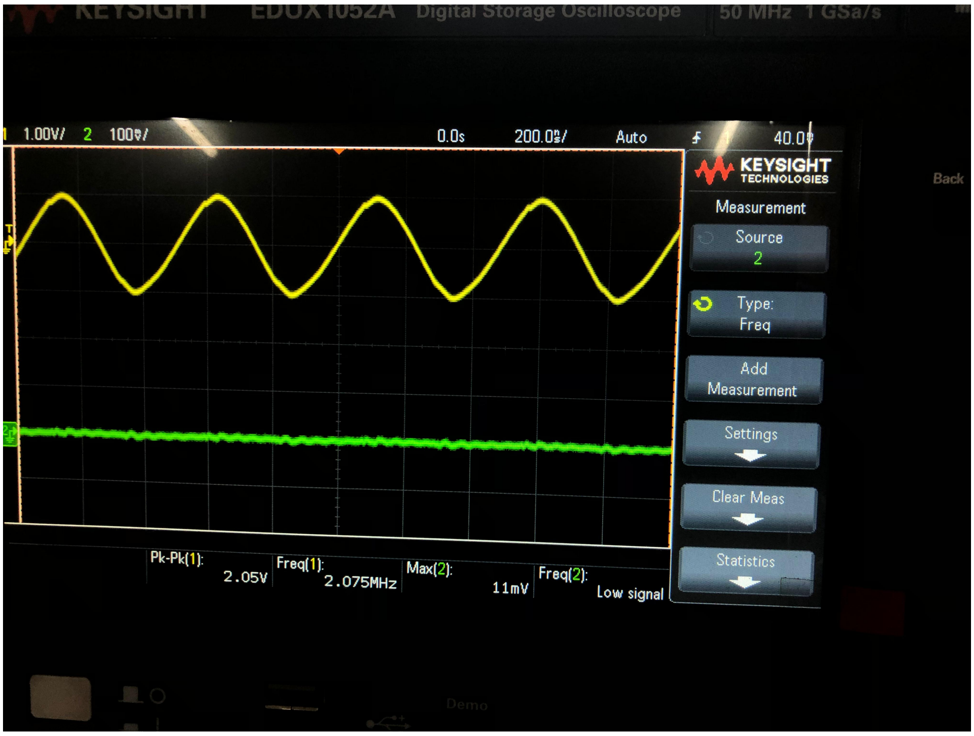


Figure 4.29: Result in DSO

the simulations. This means the circuit doesn't work well for what we need.

So, we decided to completely change both the circuit and one of the devices it connects to. We made this decision after doing a lot of research and finding other ways to build the circuit. We hope that by making this big change, we can use what we learned from our research to build circuits that not only work well but work even better than we hoped. This will make sure our project is successful.

4.3.9 Impedance Matching Circuit

To ensure our antenna works efficiently, we explored various impedance matching circuits using ADS software. By analyzing the S parameters of the antenna, we could determine the best matching circuit for different frequencies. using s parameter got impednece and drwaing smith chart it directly generate matching circuitUsing the Smith chart, we visualized the impedance characteristics and designed three matching circuits for frequencies of 0.9 GHz, 1.8 GHz, and 2.4 GHz. However, our analysis revealed that the antenna's impedance didn't match well at 2.4 GHz. To address this, we focused on creating a specific matching circuit tailored for the 2.4 GHz frequency. This approach allowed us to optimize the antenna's performance across the desired frequency range.

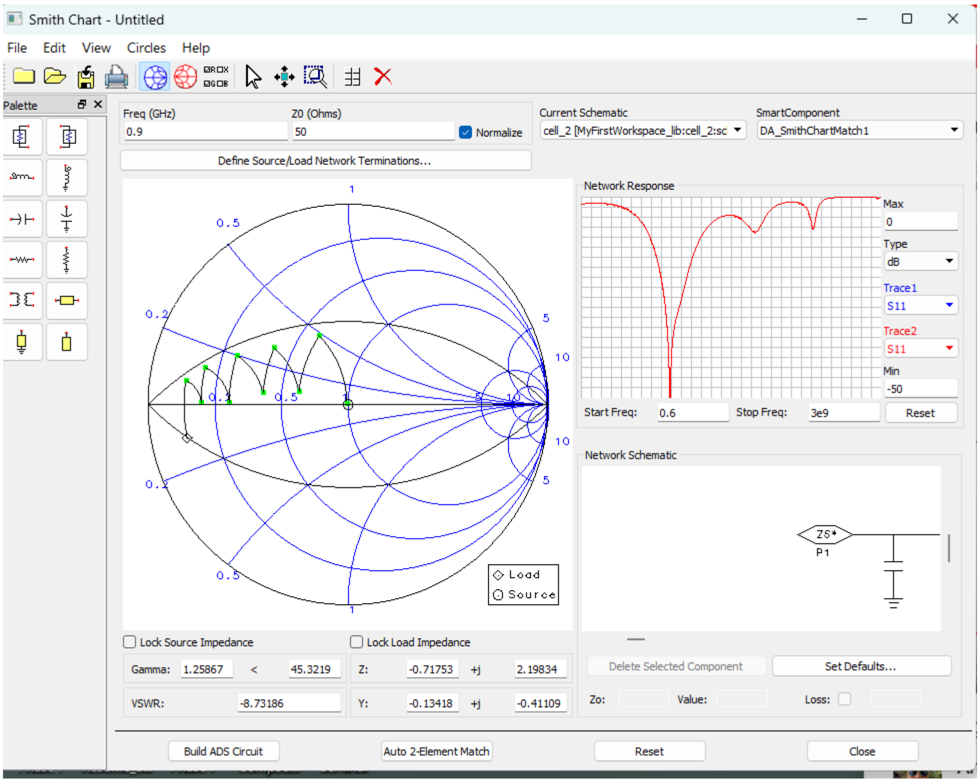


Figure 4.30: Analysis for 0.9 GHz

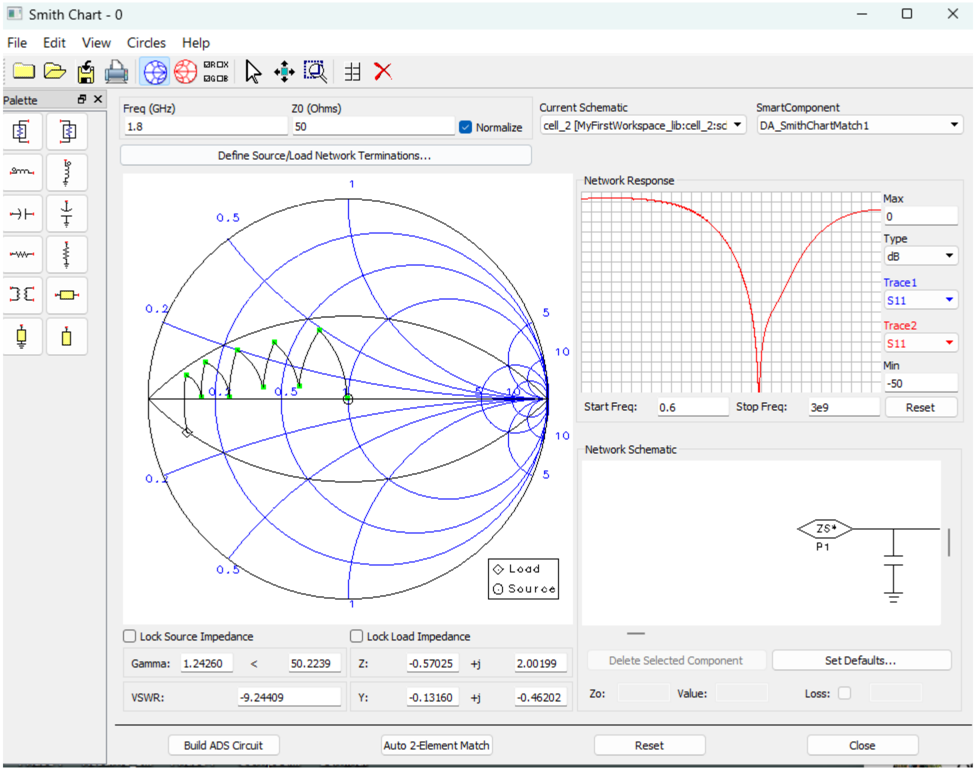


Figure 4.31: Analysis of 1.8 GHz

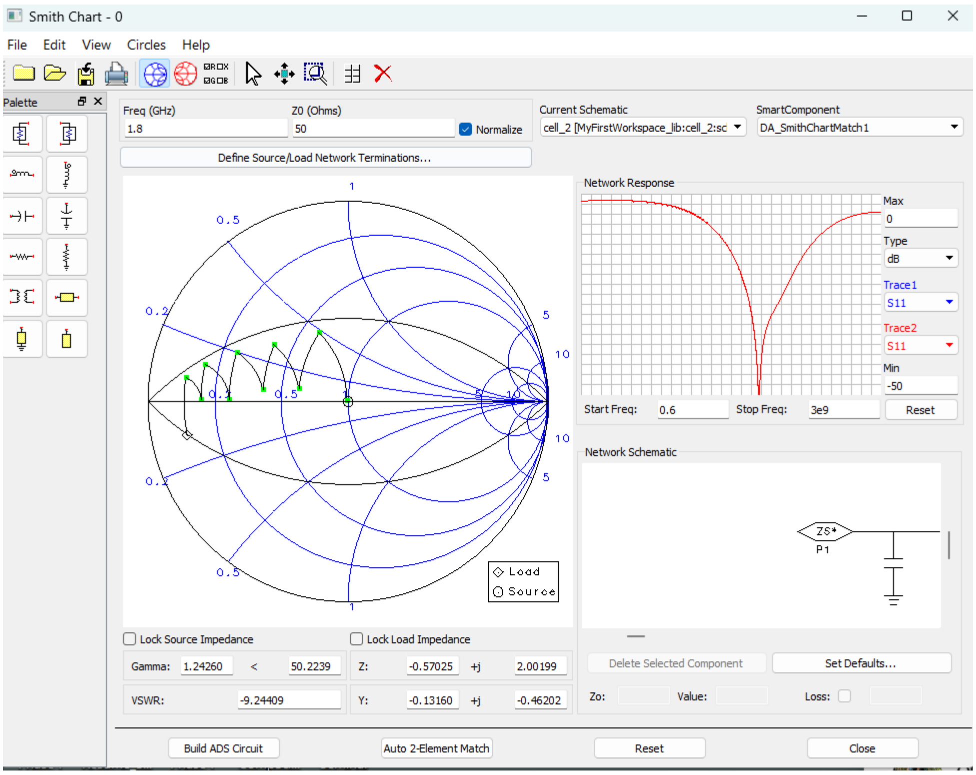


Figure 4.32: Analysis for 2.4 GHz

Figure 4.33 show the PCB layout for the impedance matching circuit was created using Altium Designer software. Once the layout was finalized, a laser print of the design was obtained to serve as a reference during the fabrication process. The design was then transferred onto a copper-clad board using techniques such as photochemical etching. Ultimately, this process resulted in the development of a high-quality impedance matching circuit, contributing to improved performance and efficiency of the antenna system.

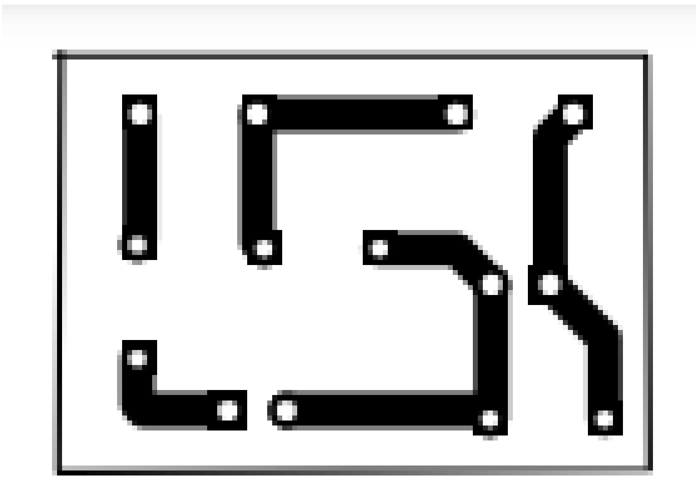


Figure 4.33: PCB layout of matching circuit

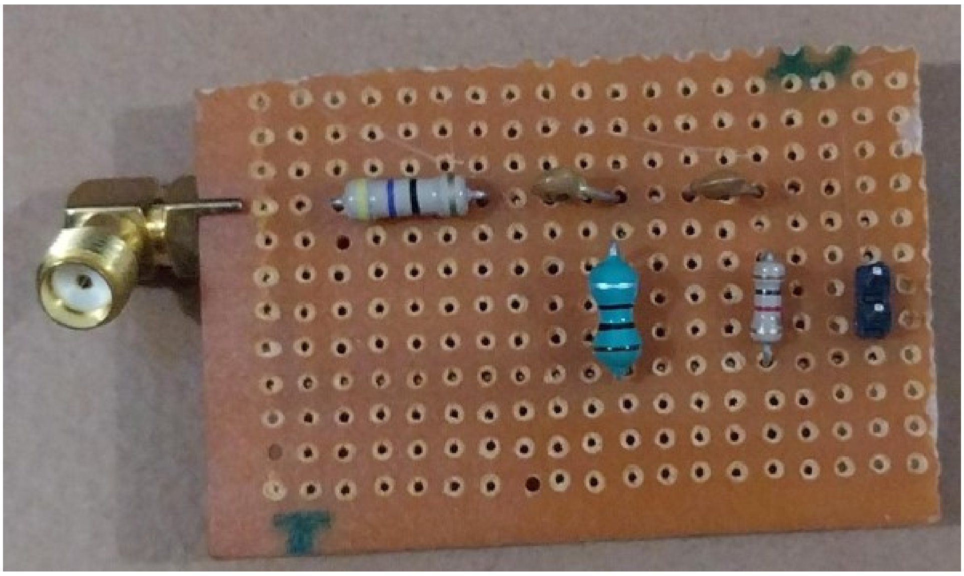


Figure 4.34: PCB Fabrication of Impedance Matching Circuit

Following the design phase, the PCB undergoes meticulous fabrication using precision manufacturing techniques and high-quality materials to accurately translate the layout design into a physical PCB. Components are then soldered onto the board according to the layout specifications to ensure proper alignment and connectivity. Rigorous testing is conducted to validate the PCB's performance and functionality, including measuring parameters such as impedance matching, insertion loss, and return loss. The output signals are also analyzed to evaluate the circuit's behavior and response using specialized equipment like a Vector Network Analyzer and Digital Storage Oscilloscope.

SMA connectors are integrated into the PCB to facilitate seamless integration into the RF energy harvesting system. These standardized connectors provide a user-friendly interface for connecting the matching circuit to other system components, ensuring compatibility and ease of use. In summary, the matching circuit PCB layout undergoes a comprehensive process from design to fabrication and testing, ensuring optimal performance, reliability, and compatibility within the RF energy harvesting system.

4.3.10 Testing the Impedance matching Circuit

Figure 4.35: Function Generator

To ensure the matching circuit's functionality under different conditions, a comprehensive testing approach was employed.figure 4.35 and 4.36 shows the testing process of impedance matching circuit. Using a function generator, a 5Vrms sine wave was generated with the frequency set to its maximum limit, covering a wide range of frequencies. This signal was carefully fed into the matching circuit to assess its performance across various frequency ranges. The output voltage from the circuit

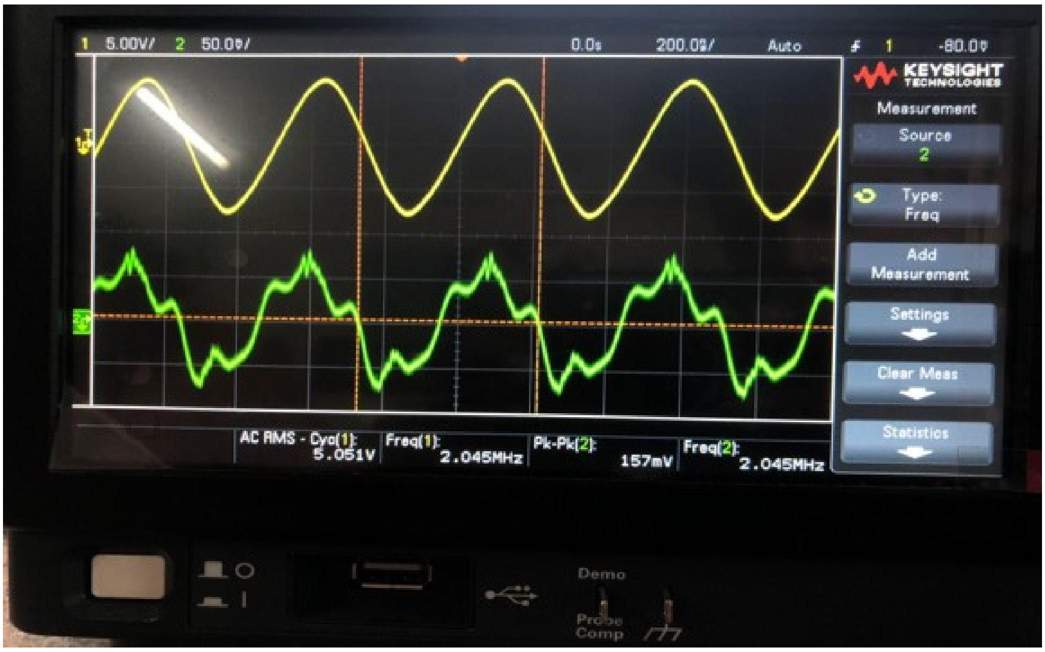


Figure 4.36: Result in DSO

was then measured using the DSO to evaluate its response. Remarkably, the output voltage obtained was 1570mV, indicating efficient power transfer and optimal circuit operation. This thorough testing process provided valuable insights into the matching circuit's behavior and confirmed its ability to maintain consistent performance across different frequency ranges. Additionally, it ensured that the circuit was capable of delivering maximum power transfer, validating its reliability and suitability for practical applications.

4.3.11 RF DC converter

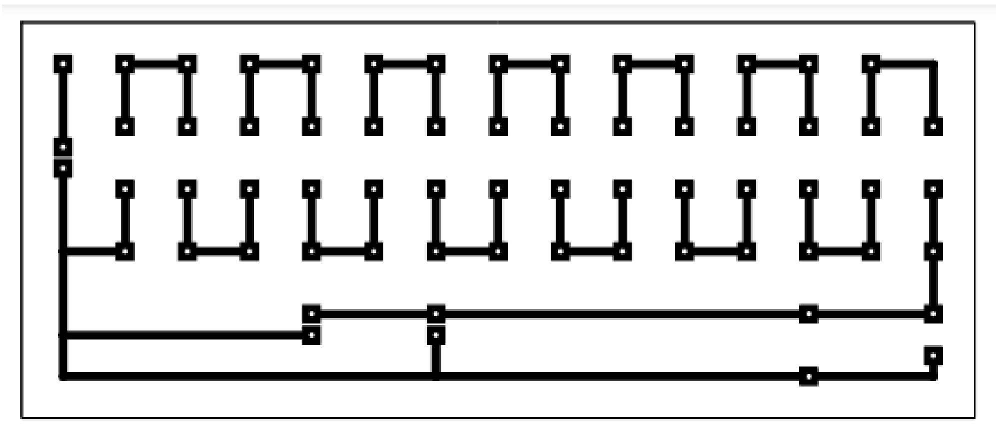


Figure 4.37: PCB Layer of RF DC Converter

In the same way, we designed the PCB layout for the RF to DC converter using Altium

Designer software. Once the layout was finished, we transferred it onto a copper plate to make the actual PCB. We did this by using methods like toner transfer or photochemical etching. After etching, we checked the PCB carefully to make sure all the lines and connections were good. If we found any mistakes, we fixed them right away. This ensured that the PCB was well-made and ready for use in the RF to DC converter.

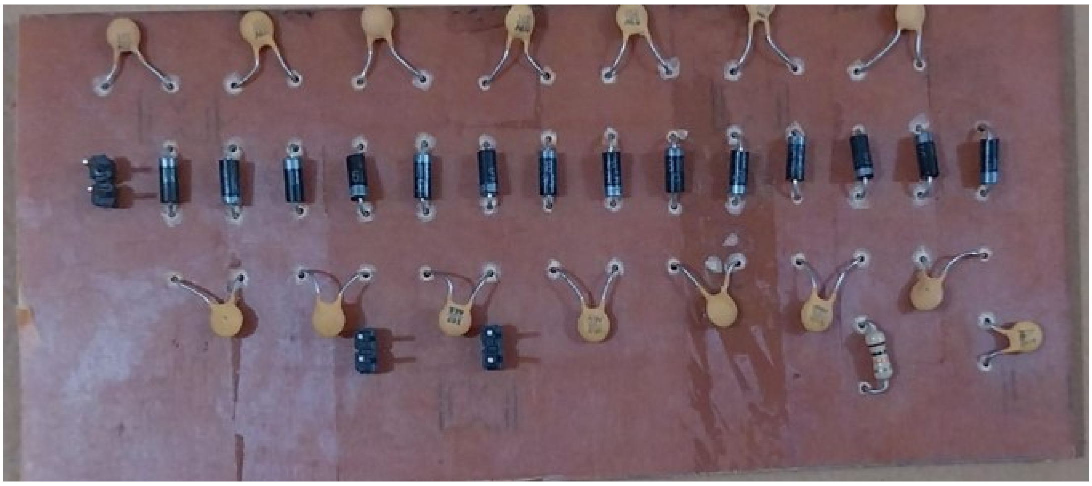


Figure 4.38: RF DC voltage multiplier

Following the implementation of the PCB for the matching circuit, the next crucial component in the RF energy harvesting system is the RF-to-DC converter, specifically utilizing a voltage multiplier configuration. This converter, employing Schottky diodes, plays a pivotal role in transforming RF signals into usable direct current (DC) voltage.

The fabrication of the RF-to-DC converter involves assembling the circuit components, including Schottky diodes, capacitors, and other necessary components, onto the PCB board. Precision soldering techniques are employed to ensure proper connections and alignment of components according to the circuit design.

Once the fabrication is complete, the RF-to-DC converter undergoes testing to verify its functionality and performance. A Digital Storage Oscilloscope (DSO) is utilized to measure and analyze the corresponding output signals generated by the converter. This analysis provides insights into the converter's efficiency, voltage output characteristics, and response to varying RF input signals.

The use of Schottky diodes in the converter circuit is particularly crucial for their fast switching times, which are essential for matching the high-frequency operation of RF energy harvesting systems. These diodes enable efficient rectification of RF signals, ensuring optimal energy extraction and conversion.

4.3.12 Testing the RF-DC Converter

Figure 4.39: RF DC Output in DSO

The testing process for the RF to DC converter yielded a maximum DC output voltage of 200mV when a 2V input voltage was provided. This result was obtained through rigorous testing and analysis, confirming the converter's functionality and performance under specified conditions.

4.3.13 Integration

After individually fabricating and testing the PCBs for the matching circuit, RF-to-DC converter (utilizing a voltage multiplier with Schottky diodes), and the antenna, the next phase involves integrating these components into a cohesive system.

First, the individual PCBs are interconnected according to the system design. Connections between the antenna, matching circuit, and RF-to-DC converter are carefully established to ensure proper signal flow and compatibility. SMA connectors used to facilitate easy and secure connections between the components.

Additionally, the system is connected to a supercapacitor, which serves as an energy storage device for storing the harvested energy. The supercapacitor is connected in parallel with the output of the RF-to-DC converter to efficiently capture and store the obtained energy.

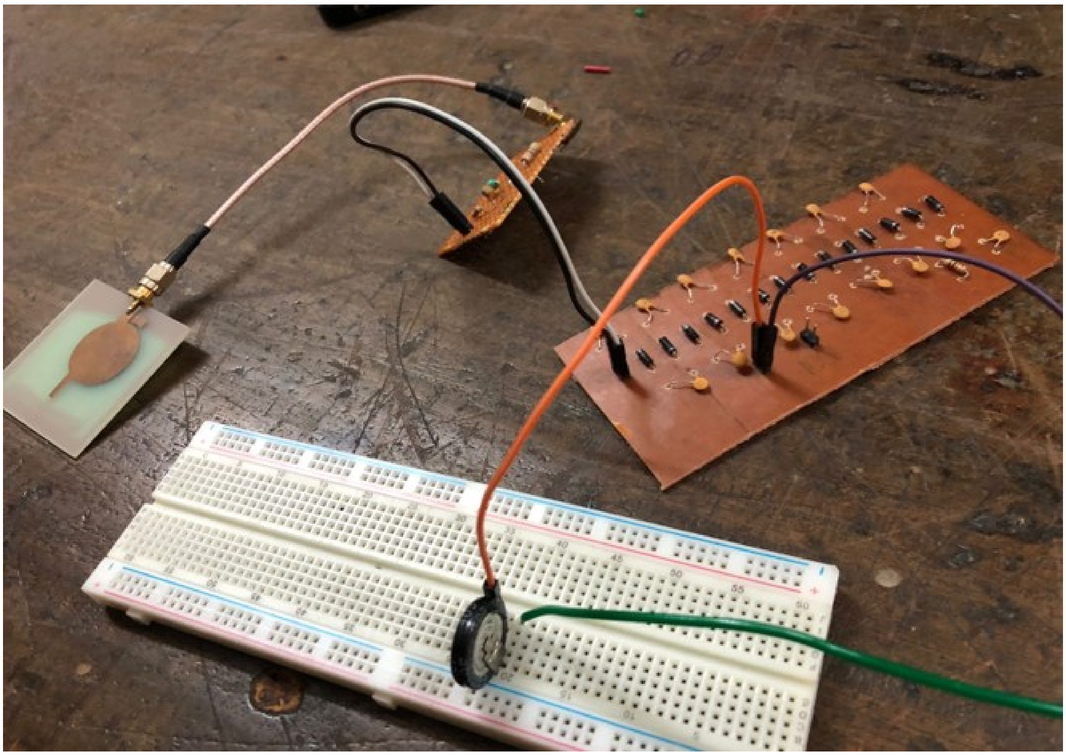


Figure 4.40: RF Energy Harvesting System

To facilitate testing and validation of the system, an additional LED is incorporated into the circuit. The LED serves as a visual indicator, illuminating when the system successfully harvests and stores RF energy. This allows for real-time monitoring of the system's performance and provides immediate feedback on its functionality.

Once the components are interconnected and the system is assembled, thorough testing is conducted to verify its performance and functionality. This testing include measuring the voltage output of the RF-to-DC converter, assessing the charge/discharge behavior of the supercapacitor, and observing the illumination of the LED in response to RF energy harvesting.

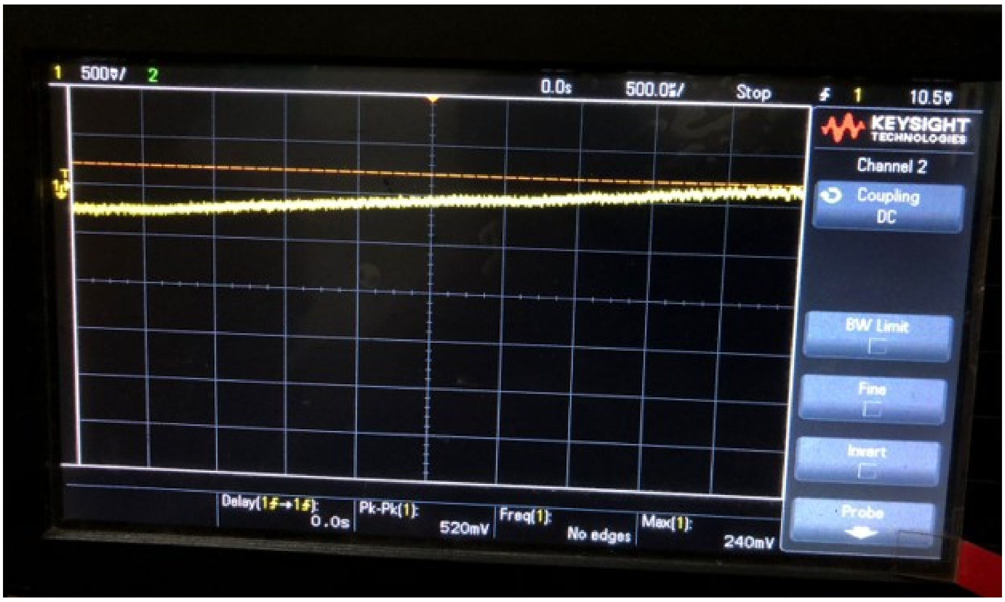


Figure 4.41: Output from the DSO

Upon observation on the oscilloscope, we found that the final output closely matched the expected values from the given input by the function generator. Notably, the output, measured in millivolts, mirrored the input voltage, indicating a consistent relationship between the two. It's important to recognize that the output of the RF to DC converter is not static but fluctuates based on the intensity of RF energy waves. Consequently, the output may vary between millivolts and volts, reflecting the dynamic nature of RF energy absorption.

To amplify the output DC voltage, additional voltage doubler circuit stages can be integrated into the RF to DC converter. By increasing the number of stages, the signal can be further boosted, enhancing its effectiveness in powering various electronic devices or systems. This approach allows for greater flexibility and adaptability in utilizing RF energy for practical applications, catering to a wide range of voltage requirements.

4.3.14 Testing With Super Capacitor As Load

After a period of charging, the supercapacitor connected to the circuit's output terminals was evaluated using a digital multimeter to measure the charge accumulation. Figures 4.42 and 4.43 depict the multimeter readings at various time intervals, showcasing the progression of charge accumulation over time. These readings provide valuable insights into the charging dynamics of the supercapacitor, demonstrating its ability to store electrical energy efficiently. However, despite the successful charging process, attempts to illuminate an LED using the charged capacitor were unsuccessful. The LED's forward voltage requirement, starting at 1.4 volts, posed a challenge, revealing a limitation of the prototype for low voltage applications. This highlights the need for further enhancements to expand the circuit's utility.

Figure 4.42: Capacitor value in multimeter 1

Addressing the limitation of the circuit for low voltage applications, a viable remedy involves integrating a DC voltage booster into the circuit. By incorporating a booster, the output voltage of the circuit can be elevated to meet the requirements of higher voltage devices, such as LEDs. This enhancement extends the circuit's applicability to a broader range of applications, enabling it to effectively power devices with higher voltage thresholds. Additionally, optimizations in the design and configuration of the circuit may be explored to improve efficiency and performance, ensuring compatibility with various voltage requirements in practical applications.

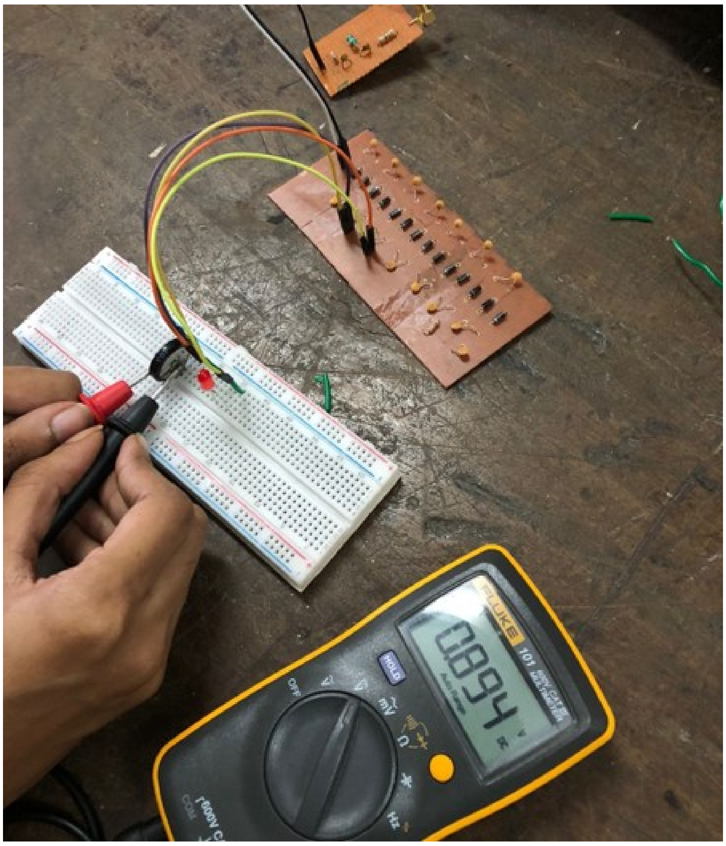
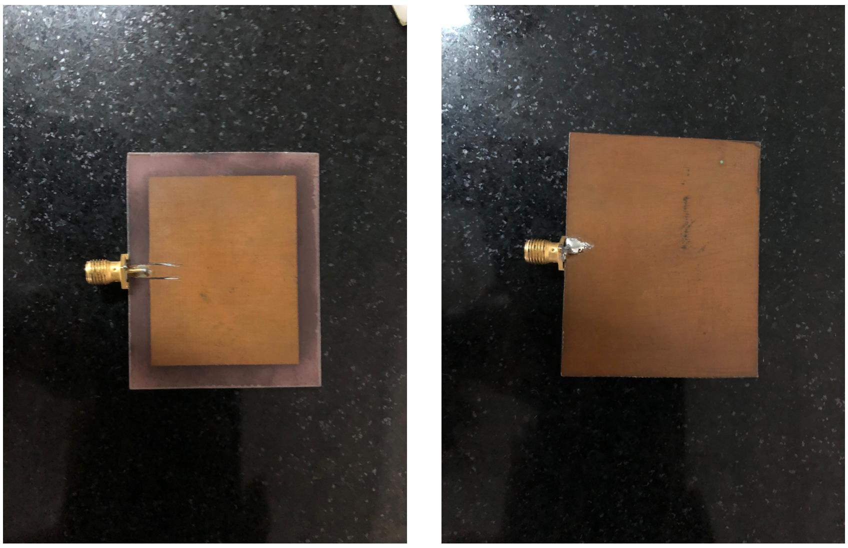


Figure 4.43: Capacitor value in multimeter 2

4.3.15 Additional Testing



(a) Antenna front view (b) Antenna back view

In our effort to make sure our antenna works well, we compared it to another antenna. We chose a common 2 GHz patch antenna and checked how well it performed using a VNA. The results showed a reflection coefficient of -27.68dB, giving us a good idea of how well antennas usually work at this frequency. Figure 5.28 in the figure 2.9 shows pictures of the 2 GHz patch antenna, both from the front and back, focusing on the ground structure at the back.

This comparison helped us understand how good our antenna is compared to a standard one like the 2 GHz patch antenna. By doing this, we figured out where our antenna is doing well and where it needs improvement. This will help us make our antenna work even better in the future, ensuring it performs reliably and effectively.

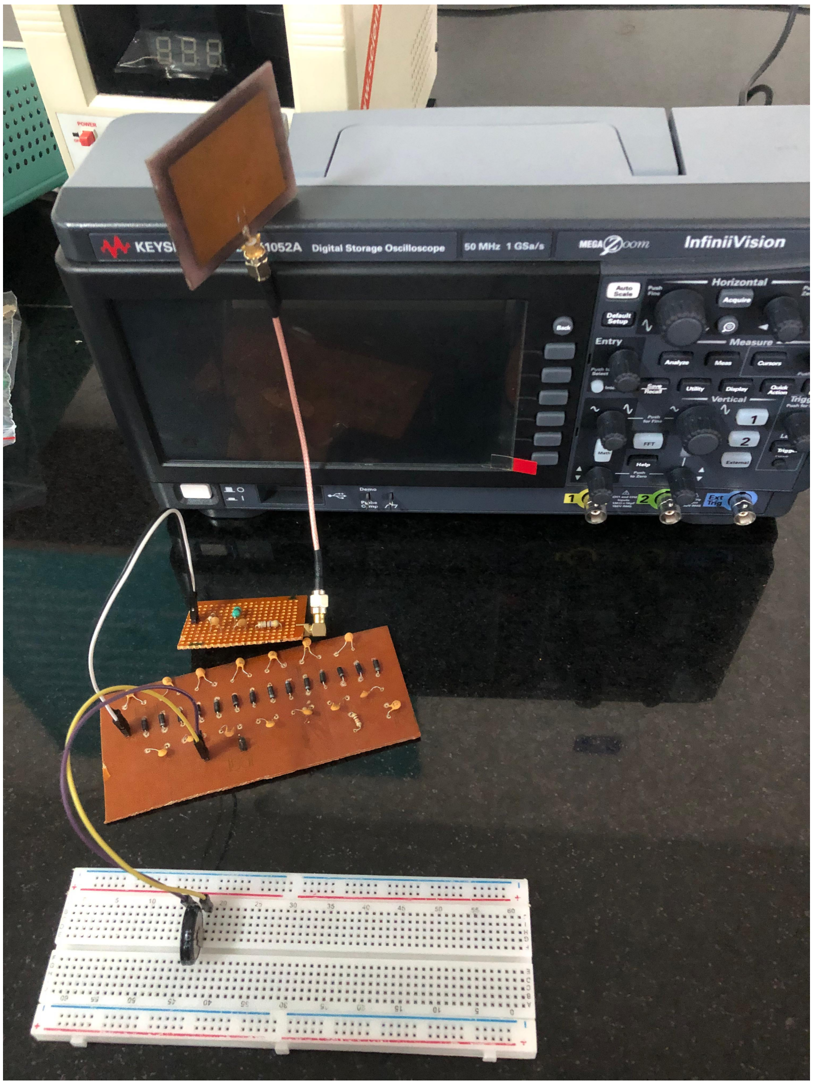


Figure 4.45: RF Energy Harvesting System with 2 GHz patch antenna

When we added the 2 GHz patch antenna to our system, it gave us 200mV as output. But when we used our own antenna, the output jumped to 500mV. This means our antenna is better at making electricity than the 2 GHz patch antenna. The reason for this difference is because our antenna is designed to work with three different frequencies. This helps it gather more energy from different sources, giving us more electricity to store or use.

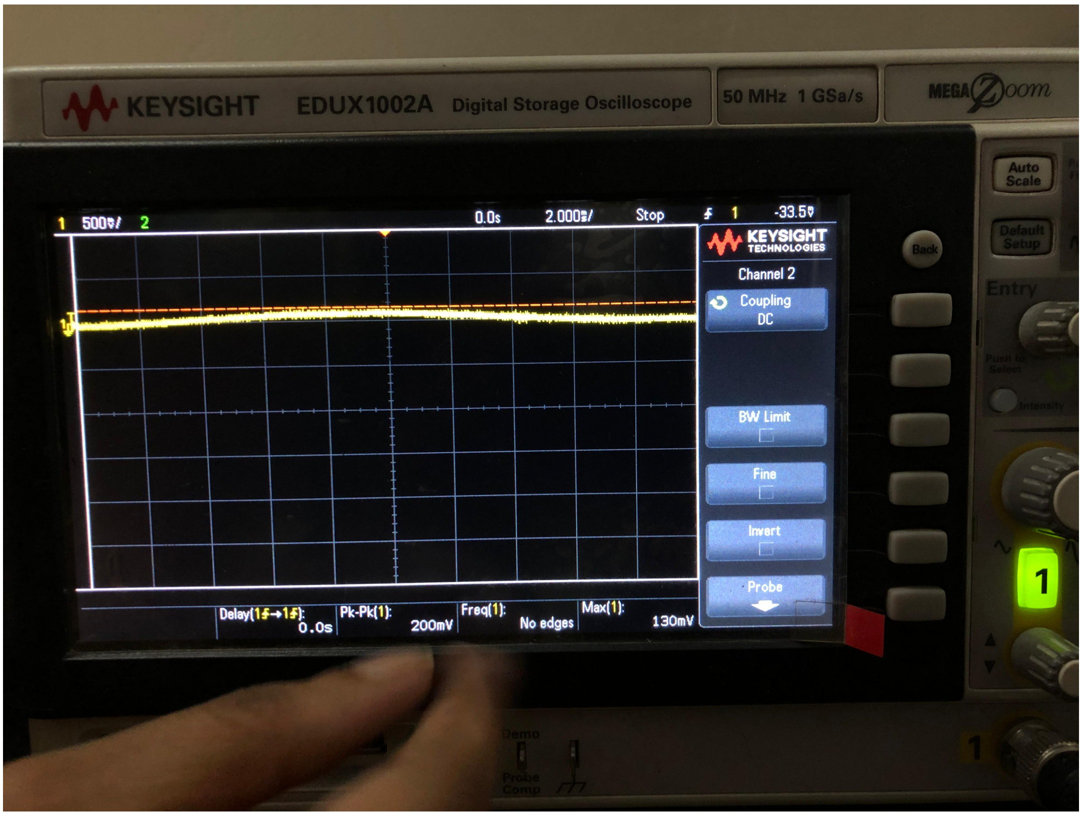


Figure 4.46: RF Energy Harvesting System with 2 GHz patch antenna result

This comparison shows that our antenna is really good at turning radio waves into usable power. By giving us a much higher voltage output than the 2GHz patch antenna, our antenna proves its effectiveness in converting radio signals into electricity. This improvement not only boosts our system's ability to collect energy but also makes it useful in more situations where we need more power. Overall, our antenna is a promising solution for powering electronics in various places with different radio signal strengths and frequencies

CHAPTER 5

CONCLUSION

In summary, the RF energy harvesting system represents a significant stride in sustainable energy technology, harnessing ambient radiofrequency signals to generate electrical power for diverse applications. The system's core components—namely, the antenna, impedance matching circuit, and RF DC converter—operate synergistically to efficiently capture, process, and convert RF energy into usable electrical power.

The meticulously engineered antenna, refined using Ansys HFSS software, assumes a pivotal role in adeptly receiving RF signals across a broad frequency spectrum. Its intricate design, featuring innovative elements like circular patches and spider arm-shaped resonators, not only enhances bandwidth and impedance matching but also actively mitigates interference.

The impedance matching circuit, meticulously crafted with Keysight ADS software, ensures seamless power transfer between the antenna and subsequent system stages. By meticulously aligning with the antenna's impedance characteristics, this circuit optimizes power transfer efficiency, facilitating the optimal utilization of harvested energy.

Simultaneously, the RF DC converter, simulated with Keysight ADS software and incorporating Schottky diodes, efficiently converts harvested RF signals into usable DC voltage. Rigorous simulation analyses confirm the converter's efficacy in accommodating variable RF frequencies and maximizing energy conversion.

The integration of these components in the hardware phase of the project, culminating in a Multimeter reading of approximately 900mV, underscores the system's capacity to generate electricity sustainably. However, it is pertinent to acknowledge that the system currently supports low-power devices.

In conclusion, the RF energy harvesting system presents a promising avenue for powering wireless technologies in an environmentally conscious and self-sustaining manner. Continued advancements in efficiency and power output hold the potential to broaden its utility to higher power devices, thereby catalyzing the widespread adoption of sustainable energy solutions.

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