RF Energy Harvesting System

Project Phase I Report

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in

Electronics and Communication Engineering

by

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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 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.

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Declaration

I **P Pranav** 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.Semeeha Mumtaz V A .

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.

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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.

Acknowledgement

I take this opportunity to express our deepest gratitude and sincere thanks to everyone who helped us complete this work successfully.

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Chapter 1

Introduction

RF energy harvesting systems represent a groundbreaking leap in the quest for sustainable energy solutions, heralding a significant shift in how we power our electronic devices. These innovations capitalize on ambient radio frequencies, converting them into a valuable source of electricity. At the core of this revolutionary approach lie three pivotal components: the FR4 substrate-designed antenna, the meticulously optimized matching circuit utilizing S-parameters derived from the antenna's behavior, and the crucial RF-to-DC converter.

Functioning as the interface between the RF energy source and the harvesting system, the antenna assumes an indispensable role. Crafted with precision and leveraging the FR4 substrate, the antenna utilizes specific material properties such as 1.6 mm thickness, 4.4 permittivity, and a 0.02 loss tangent. Its primary task is to efficiently intercept RF signals from the surrounding environment. Being the initial point of contact in the energy harvesting sequence, the antenna sets the stage for effective energy extraction.

The matching circuit holds essential significance in maximizing the transfer of captured RF energy. This circuit ensures impedance alignment between the antenna and subsequent components, based on the S-parameters derived from the antenna's characteristics. This impedance matching functionality prevents signal reflections and significantly enhances the overall efficiency of the energy transfer process.

Completing the energy harvesting process, the RF-to-DC converter plays a pivotal role in converting the RF signals captured by the antenna into direct current (DC), a form usable for powering electronic devices. This converter stands as the final piece, underscoring the sustainability and self-reliance of RF energy harvesting systems by transforming collected energy into a usable form. Together, these components synergize to form a cohesive and efficient system, offering immense potential to shape future wireless, eco-friendly power solutions.

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

Objectives

The project aims to create a power solution that is both sustainable and efficient for portable electronic devices operating in the 0.8 GHz to 3 GHz frequency range. The system uses an RF-to-DC converter, a matching circuit optimized for impedance efficiency, and an antenna that is precisely designed in order to harness ambient radio frequency (RF) signals for energy generation. The RF-to-DC converter converts the harvested RF signals into useful electrical power, the matching circuit guarantees smooth energy transfer, and the antenna acts as the interface for capturing RF signals. By concentrating on these key elements and the designated frequency range, the goal is to develop a strong RF energy harvesting system that provides an efficient and wire-free substitute for electrical device powering.

Hence the main objectives are:

1.Determining the ambient frequencies from the surroundings, then the simulation of antenna followed by matching the impedance network using the s-parameters of the antenna simulated and RF DC converter to convert the RF to DC so as to operate low power devices.

2.Fabrication of the above antenna impedance matching circuit and the RF DC converter.

Chapter 4

Methodology

4.1 Antenna Design

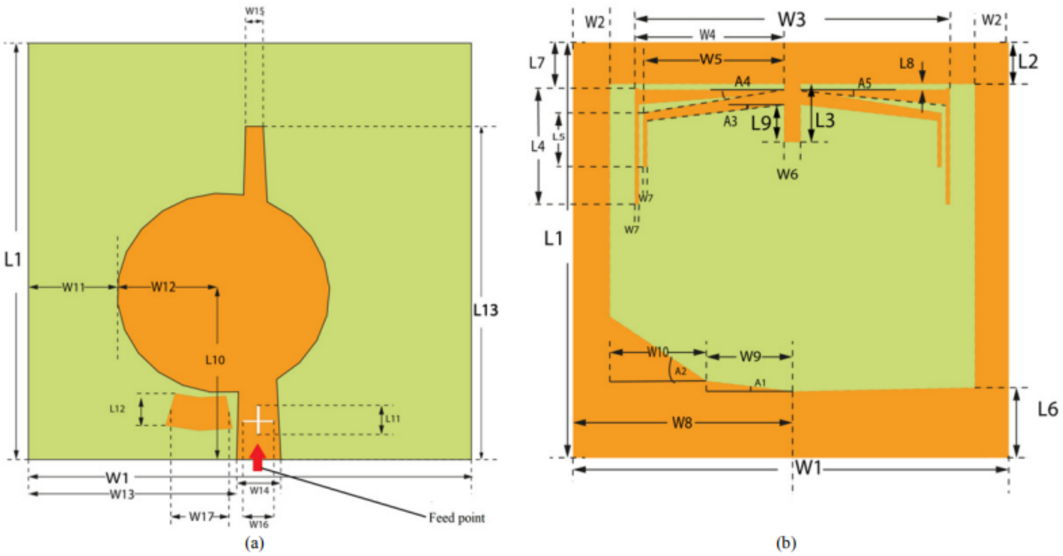

Figure 4.1: Proposed antenna structures: (a) top view, and (b) bottom view.

The antenna design process begins with the utilization of Ansys HFSS software, a powerful tool for electromagnetic simulation and analysis. The primary objective is to attain resonance within a defined frequency range spanning from 0.8 GHz to 3 GHz. Within this spectrum, specific resonant frequencies are meticulously targeted at 0.9 GHz, 1.8 GHz, and 2.4 GHz to meet the desired operational requirements. The fundamental architecture of the antenna revolves around a circular patch that serves as the radiating element. This circular patch is intricately fed by a trapezoidal-shaped microstrip line, forming the basis of the antenna's radiating structure.

To enhance the antenna's operational capabilities, additional spider arm-shaped resonators are strategically integrated into the slotted ground structure. These resonators play a crucial role in extending the antenna's operating frequencies, providing versatility beyond the primary resonances. This augmentation facilitates the antenna's adaptability to a broader range of frequencies, contributing to its utility in various applications. Moreover, the design incorporates advanced features for Ultra-Wideband (UWB) communication. An arc-shaped resonator and a cross-shaped slot are introduced on the feed line, further broadening the UWB bandwidth. These additional elements contribute to the antenna's efficiency in transmitting and receiving signals across a wide frequency spectrum.

In adherence to design principles, the overall antenna structure is crafted with a focus on simplicity and compactness. The dimensions are meticulously set at $50 \times 50 \times 1.6$ mm^3, ensuring a streamlined and space-efficient design. This compact form factor is advantageous for practical implementation in diverse electronic devices, where space constraints are often a critical consideration. The design prioritizes not only optimal electromagnetic performance but also practicality, making it well-suited for integration into modern compact wireless systems.

4.2 Matching Network

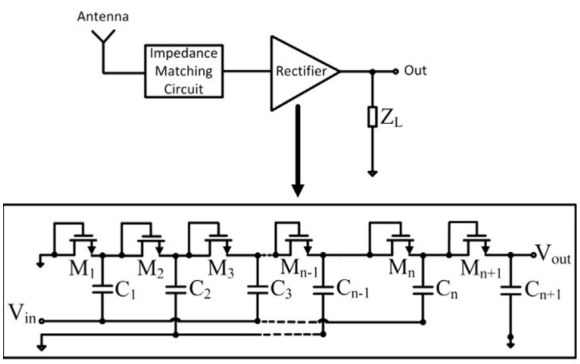

Figure 4.2: RF energy harvester with impedance matching circuit

The impedance matching circuit, a critical component in the energy harvesting system, is meticulously designed using Keysight Advanced Design System (ADS) software.

This software provides a comprehensive platform for RF and microwave circuit design, simulation, and optimization. The primary objective of the impedance matching circuit is to establish compatibility with the antenna, ensuring a smooth transition of signals and efficient power transfer throughout the system.

Configured to achieve a 50-ohm impedance match, the matching circuit is optimized to minimize signal reflections and losses, thereby enhancing power transfer efficiency. The 50-ohm impedance match is a standard in RF systems, and achieving it is crucial for minimizing signal degradation and ensuring maximum power transfer between components. The matching circuit is tailored to bridge any impedance mismatches between the antenna and subsequent components in the energy harvesting system.

A key aspect of the design process involves leveraging the Smith chart within the ADS software. The Smith chart is a graphical tool that aids in the visualization and analysis of complex impedance values. Through the iterative use of the Smith chart, the design of the matching circuit is refined to seamlessly align with the impedance characteristics of the antenna. This visual tool provides insights into the impedance transformation process, allowing designers to make informed adjustments and optimizations.

The iterative nature of the design process, facilitated by the Smith chart, ensures that the matching circuit is precisely tuned to the impedance profile of the antenna. By achieving an optimal impedance match, the goal is to maximize power transfer efficiency within the energy harvesting system. This meticulous design approach contributes to the overall effectiveness and performance of the system, allowing it to efficiently harvest and utilize RF energy for various applications.

4.3 RF DC Converter

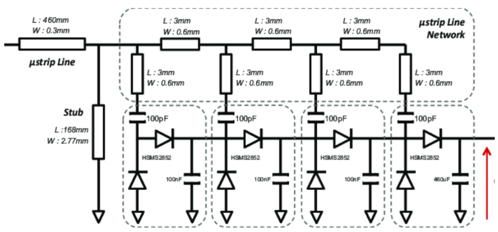

Figure 4.3: Architecture of the RF to DC converter

The simulation of the RF DC converter is a crucial phase in the energy harvesting system, conducted with precision in Keysight Advanced Design System (ADS) software. This simulation primarily aims at the efficient conversion of harvested RF signals into usable direct current (DC) voltage, a key aspect of the energy harvesting process. The design strategically incorporates Schottky diodes, known for their suitability in RF rectification applications, ensuring effective energy extraction from the RF source.

The configuration of the RF DC converter is fine-tuned to optimize energy conversion efficiency. This involves considering the varying input RF frequencies that the system might encounter during operation. Schottky diodes play a pivotal role in rectifying RF signals, allowing the extraction of DC voltage with minimal losses. The simulation in ADS allows for a detailed analysis of the converter's performance under different scenarios, providing insights into its efficiency, voltage output characteristics, and response to varying RF frequencies.

The ADS software facilitates a comprehensive examination of the RF DC converter's behavior, enabling designers to assess its performance metrics thoroughly. Parameters such as efficiency, voltage output levels, and the converter's response to different RF frequencies are scrutinized to ensure its effectiveness in transforming harvested RF energy into usable electrical power. This simulation step is instrumental in refining the converter design, identifying potential challenges, and validating its capability to meet the energy harvesting system's requirements.

This simulation phase helps the energy harvesting system function as a whole by utilizing the features of Keysight ADS software. In order to maximize the conversion of RF energy into a steady and usable DC voltage for powering electronics or charging energy storage units, it makes sure the RF DC converter runs as efficiently as possible.

4.4 Integration and Optimization

The final steps involve the seamless integration and optimization of the entire RF energy harvesting system. Outputs from the antenna design, impedance matching circuit, and RF DC converter are synchronized to ensure coherent functionality.

Iterative adjustments and optimizations are performed to enhance overall system performance. The interplay between the antenna, matching circuit, and RF DC converter is scrutinized for maximum energy transfer efficiency and operational effectiveness. The methodology encapsulates a systematic and iterative approach, guaranteeing that each component is fine-tuned to harmonize with the others, resulting in a cohesive and efficient RF energy harvesting system.

Chapter 5

Software Description

5.1 Proteus

Proteus is an advanced electronic design automation (EDA) software suite that facilitates the creation, simulation, and testing of electronic circuits. The software's schematic capture feature allows users to design circuits through a user-friendly graphical interface, placing and connecting various components such as resistors, capacitors, transistors, and integrated circuits. What sets Proteus apart is its powerful simulation capabilities, enabling users to virtually test the behavior of their circuits before physical implementation. This helps identify and address potential issues, ensuring a more efficient and error-free design process.

A notable feature of Proteus is its support for mixed-mode simulation, allowing the integration of both analog and digital components within the same circuit. This versatility is particularly beneficial for designing complex systems that involve a combination of analog and digital functionalities. Furthermore, Proteus boasts an extensive library of microcontroller models, making it a preferred choice for embedded systems design. Users can simulate and program microcontrollers using various languages, enhancing the software's utility for projects involving programmable logic and automation.

In addition to circuit simulation, Proteus provides tools for printed circuit board (PCB) layout design. Users can seamlessly transition from schematic design to PCB layout, placing components and routing connections for a production-ready design. The software's 3D visualization feature enhances the design process by allowing users to view their circuits and PCB layouts in a three-dimensional space, providing a more realistic representation and aiding in the identification of potential physical constraints. Overall, Proteus is a comprehensive solution that caters to the needs of both educators and professionals in the field of electronics, offering a robust platform for designing, simulating, and implementing electronic circuits and systems.

5.2 ANSYS HFSS Software

ANSYS HFSS (High-Frequency Structure Simulator) stands as a cornerstone in the realm of electromagnetic field simulation, offering engineers a robust platform for the analysis and optimization of high-frequency electronic components and systems. At its core, HFSS excels in modeling and simulating electromagnetic fields, providing engineers with insights into the behavior of diverse devices, antennas, and circuits across varying frequency spectrums. The software's 3D modeling and visualization capabilities empower users to create intricate representations of their designs, including complex structures like antennas, transmission lines, and electronic components.

HFSS is versatile, supporting both frequency domain and time domain analyses. This versatility enables engineers to comprehensively study the performance of devices, considering factors such as frequency response and transient behavior. Antenna design and analysis represent one of HFSS's pivotal applications, enabling engineers to model, simulate, and optimize antennas for diverse applications. The software's ability to conduct parametric analyses is invaluable, allowing for the exploration of different design parameters and their impact on component performance—a critical aspect of the optimization process.

With an extensive material database, HFSS ensures accurate modeling of the electromagnetic properties of various materials, contributing to the simulation of real-world conditions. Leveraging finite element methods (FEM) and finite element-boundary integral (FEM-BI) methods, HFSS employs advanced solver technology to provide precise results for complex electromagnetic challenges. Moreover, its integration with other ANSYS tools expands its capabilities, offering a comprehensive simulation environment for electromagnetic and multiphysics analyses. HFSS finds applications in antenna design, RF and microwave component analysis, signal integrity assessments, power integrity evaluations, and the development of wireless communication systems, making it an indispensable tool in industries where precise electromagnetic predictions are paramount.

5.3 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.

Chapter 6

Implementation

6.1 Antenna Simulation

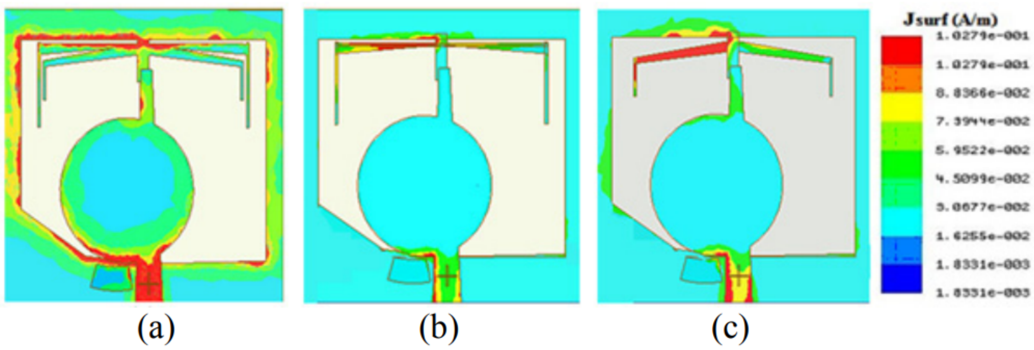

Figure 6.1: Surface current distributions at three resonant frequencies: (a) 900 MHz, (b) 1.8 GHz, (c) 2.4 GHz.

The primary component of the RF energy harvesting system is the antenna, designed and simulated using Ansys HFSS with an FR-4 substrate. The antenna is designed to cover the frequency range from 0.8 GHz to 3 GHz, resonating specifically at 0.8 GHz, 1.9 GHz, and 2.4 GHz. The substrate material FR-4 is chosen for its electrical properties. The simulation results include the S-parameters of the antenna, providing crucial information about its performance.

A critical aspect of the antenna design is the radiation pattern.The radiation plot obtained from the simulation offers insights into how the antenna radiates energy in free space. This information is valuable for understanding the antenna's directional characteristics.

Furthermore, a polar plot is generated to visually represent the radiation pattern in a specific plane. The polar plot is instrumental in conveying the directivity and beamwidth of the antenna from various viewing angles. It provides a clear illustration of how the antenna radiates energy in different directions.

The antenna design incorporates a trapezoidal shape and spider arm structures to enhance its performance. The S-parameters obtained from the simulation are significant for assessing the antenna's impedance characteristics. S11, in particular, reflects the amount of power reflected from the antenna, offering insights into impedance matching.

6.1.1 Radiation Pattern

The radiation pattern of an antenna is a graphical representation of the spatial distribution of radiated electromagnetic waves. It provides crucial insights into how the antenna directs and propagates signals in three-dimensional space. Understanding the radiation pattern is essential for optimizing antenna performance in various applications. Here's a detailed elaboration on the key aspects of a radiation pattern:

1.Angular Distribution: The radiation pattern illustrates how the radiated power varies with angle in both the azimuth (horizontal) and elevation (vertical) planes.It helps identify the main lobe, which is the primary direction of maximum radiation, and any additional lobes or nulls.

2.Main Lobe and Side Lobes:The main lobe is the region in the radiation pattern where the maximum power is concentrated, representing the primary direction of radiation.Side lobes are secondary, smaller radiation lobes that occur at angles away from the main lobe. Minimizing side lobes is crucial for optimizing the antenna's directional characteristics.

3.Beamwidth: Beamwidth is an important parameter derived from the radiation pattern. It is the angular width between points where the radiated power falls to half the maximum (3 dB) in the main lobe. Narrow beamwidth indicates a more focused, directional radiation, while wider beamwidth suggests broader coverage.

4.Directivity and Gain: Directivity is a measure that tells us how much an antenna focuses its radiation compared to what an isotropic radiator would do. An isotropic radiator emits energy equally in all directions, like a light bulb shining light in all angles. Gain is a way to measure how well an antenna concentrates its power in a particular direction. It's usually expressed in decibels (dB) and compared to what an isotropic radiator would achieve.

5.Polarization:The radiation pattern also provides information about the polarization of the antenna. It shows whether the electric field vector of the radiated wave is oriented horizontally, vertically, or elliptically.

6.Nulls:Nulls are regions in the radiation pattern where the radiated power is at a minimum. Avoiding or mitigating nulls is crucial in applications where consistent coverage is required.

7.Frequency Dependence:The radiation pattern may vary with frequency, impacting the antenna's performance across different parts of the spectrum. This information is vital for applications with specific frequency requirements.

6.1.2 Polar Plot

A polar plot is a graphical representation that displays data in a two-dimensional circular format. In the context of antennas and RF systems, polar plots are commonly used to visualize and analyze key characteristics of radiation patterns. Here's a detailed elaboration on the key aspects of a polar plot:

1.Representation of Azimuthal (Horizontal) Plane:A polar plot is particularly useful for representing the radiation pattern in the azimuthal plane (horizontal plane), providing a clear depiction of how the antenna radiates in different directions around its axis.

2.Angular Coverage: The circular format of the polar plot corresponds to a full 360-degree angular coverage around the antenna's reference axis. The angular positions on the plot represent different azimuth angles, starting from 0 degrees at the top and increasing in a clockwise or counterclockwise direction.

3.Visualization of Main Lobe and Side Lobes: The main lobe, which corresponds to the primary direction of maximum radiation, is represented by the prominent segment of the polar plot.Side lobes, if present, appear as additional segments extending from the center in various directions.

4.Beamwidth Indication:The width of the main lobe and any side lobes can be visually assessed, providing insights into the beamwidth of the antenna.Narrow beams result in concentrated lobes, while wider beams lead to broader coverage.

5.Nulls and Minima:Nulls, where the radiated power is minimized, are represented by gaps or reduced intensity in the polar plot.The absence of data in certain directions indicates regions of reduced radiation.

6.Directivity and Gain Visualization:Directivity and gain information, crucial for understanding the antenna's performance, can be inferred from the shape and intensity of the polar plot.Higher intensity in the main lobe suggests higher gain and directivity.

7.Polarization Orientation:The orientation of the polar plot segments provides information about the polarization of the radiated wave.The plot may indicate whether the antenna radiates in a horizontally, vertically, or elliptically polarized manner.

8.Application-Specific Analysis:Engineers and designers use polar plots to assess how well an antenna meets the requirements of specific applications.For example, in wireless communication, an omnidirectional antenna's polar plot should show a consistent radiation pattern in all directions.

9.Frequency-Dependent Characteristics:Changes in the polar plot across different frequencies can be observed, aiding in the analysis of the antenna's frequency-dependent behavior.

10.Comparison and Optimization: Engineers use polar plots to compare different antenna designs and optimize parameters to achieve desired radiation characteristics.Adjustments can be made to minimize side lobes, maximize gain, or tailor the pattern for specific applications.

6.2 Matching Network Simulation

The impedance matching circuit is designed in Keysight Advanced Design System (ADS) software to ensure compatibility with the antenna. Configured to achieve a 50-ohm impedance match, the circuit is optimized for efficient power transfer. Leveraging the Smith chart in ADS, the matching circuit's design is refined to facilitate seamless impedance matching. This visual tool aids in the iterative process, ensuring that the matching circuit aligns with the impedance characteristics of the antenna. The goal is to maximize power transfer efficiency, optimizing the overall performance of the energy harvesting system.

6.3 RF DC Converter Simulation

The RF DC converter simulation, conducted in Keysight ADS software, focuses on converting harvested RF signals into usable direct current (DC) voltage. Employing Schottky diodes strategically, the converter rectifies RF signals efficiently. The configuration is fine-tuned for optimal energy conversion efficiency, considering varying input RF frequencies. The ADS simulation provides a comprehensive analysis of the RF DC converter's performance, examining parameters such as efficiency, voltage output, and response to different RF frequencies. This step ensures the converter's effectiveness in transforming harvested RF energy into usable electrical power.

6.4 Integration Simulation

The final steps involve the seamless integration and optimization of the entire RF energy harvesting system. Outputs from the antenna design, impedance matching circuit, and RF DC converter are synchronized to ensure coherent functionality. Iterative adjustments and optimizations are performed to enhance overall system performance. The interplay between the antenna, matching circuit, and RF DC converter is scrutinized for maximum energy transfer efficiency and operational effectiveness. The methodology encapsulates a systematic and iterative approach, guaranteeing that each component is fine-tuned to harmonize with the others, resulting in a cohesive and efficient RF energy harvesting system.

Chapter 7

Results and Discussion

7.1 Antenna

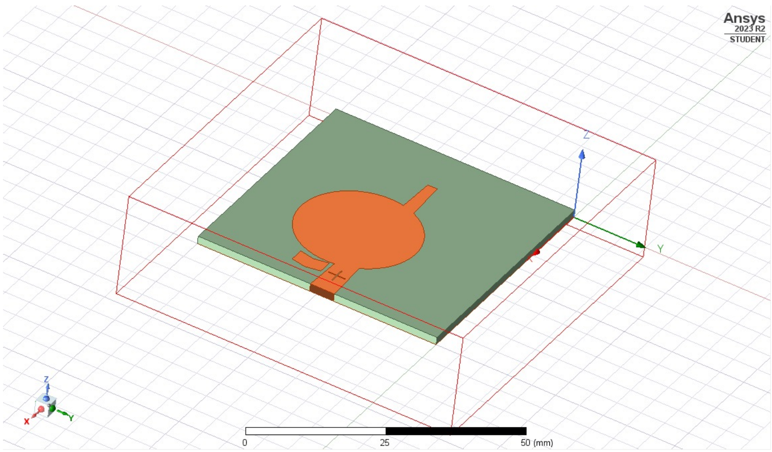

Figure 7.1: Antenna Simulated top view

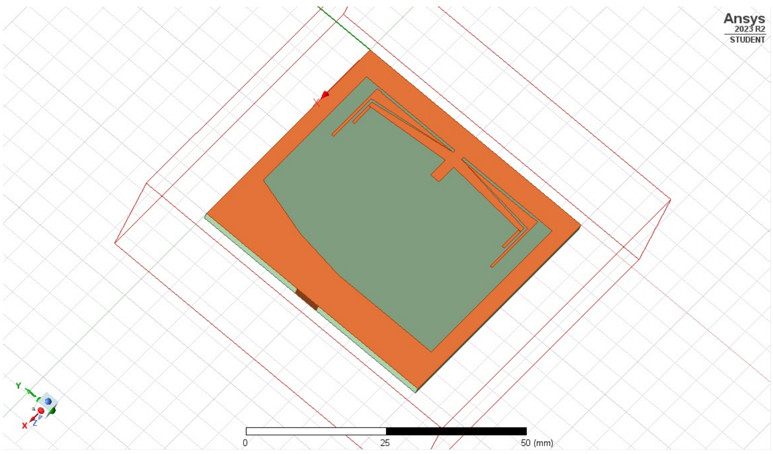

Figure 7.2: Antenna Simulated bottom view

Antennas play a vital role in the RF harvesting energy system. Antenna is used for receiving the ambient RF signal in the environment and transferring it to the continuing circuitry. And our aim was to design an antenna with a resonant frequency of 0.9, 1.8,and 2.4 GHz for efficient receiving of RF signals. Figs. 7.1 and 7.2 show the top and bottom views of our antenna design using Ansys HFSS software. The design provides the required resonant frequencies of 0.9, 1.8, and 2.4 GHz.

7.1.1 S-Parameter

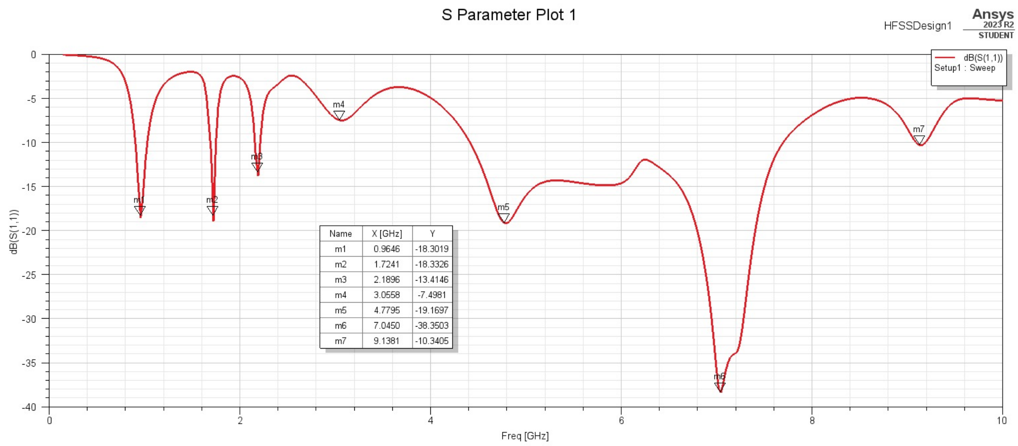

Figure 7.3: S-parameter plot1

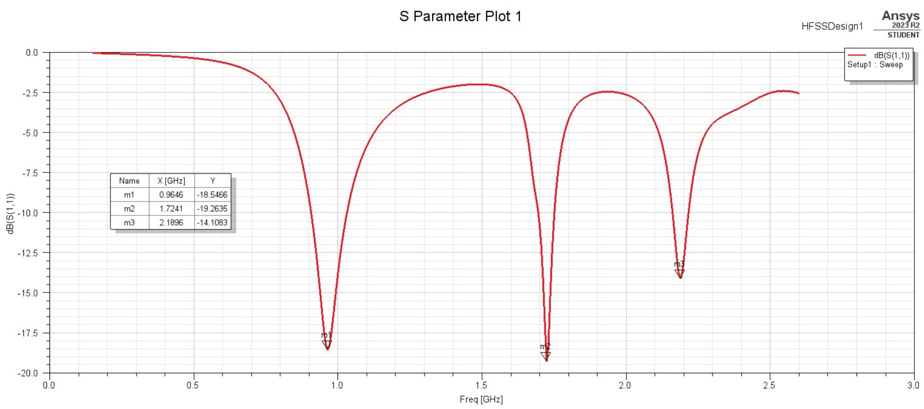

Figure 7.4: S-parameter plot 2

S-parameters offer a way to describe how waves behave within a device, using waves instead of traditional electrical measurements like voltage and current. S11, known as the reflection coefficient, specifically tells us how much of a wave is reflected back from the device. When an antenna is properly adjusted and matched, ideally, S11 should be as small as possible at its intended operating frequencies. This means minimal reflection of waves when sending signals into the antenna. The goal of the project is to minimize S11 at frequencies of 0.9, 1.8, and 2.4 GHz. Fig. 7.3 in the project's simulations, conducted using Ansys HFSS software, depicts the antenna's behavior across a wide frequency range, from 0.8 to 10 GHz. Meanwhile, Fig. 7.4 specifically focuses on the frequencies between 0.8 and 3.3 GHz, illustrating how well the antenna manages reflection at the targeted frequencies of 0.9, 1.8, and 2.4 GHz, aligning with the project's objectives.

7.1.2 Radiation Pattern

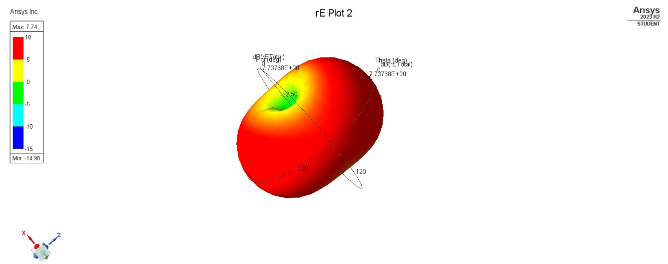

Figure 7.5: Radiation Pattern of the antenna

The radiation pattern serves as a visual depiction of how an antenna behaves in terms of emitting or receiving energy concerning its surroundings. It's like a graphical map that illustrates how the antenna sends out signals into space or captures incoming signals. This pattern essentially tells us about the antenna's behavior—how it spreads or focuses its emitted or received energy across different directions in space. It's a way of visually understanding how the antenna interacts with the surrounding environment, depicting the specific areas where its signals are stronger or weaker, akin to a map showcasing the antenna's energy distribution in space. Figure 7.5 shows the three-dimensional radiation pattern plotted in decibels in the Ansys HFSS software. It is an omnidirectional radiation pattern for our design. For the project, we need an isotropic pattern, but it will not be obtainted in a real-time scenario. The intensity of the color describes the energy level of the antenna.

7.2 Impedance Matching Circuit

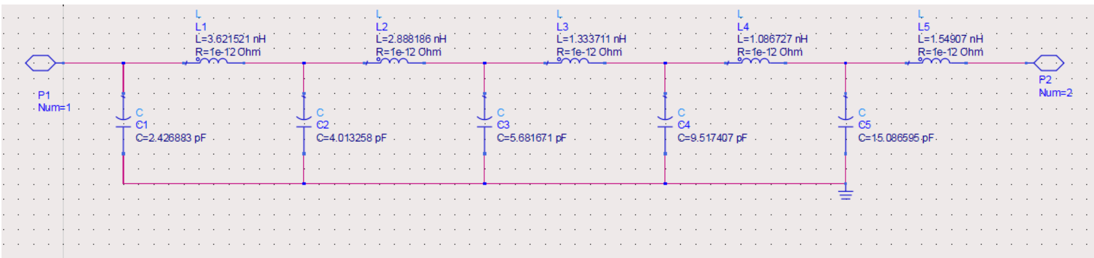

Figure 7.6: Circuit Diagram

The impedance matching circuit provides maximum efficiency for the RF energy harvesting system. It is a component or network of components designed to maximize power transfer between an antenna and an RF DC converter. Fig. 7.6 shows the schematic diagram of the circuit made in ADS using Smith chart analysis, as shown in Fig. 7.7. Pi topology was used in this circuit. The S parameter was exported from the HFSS software to the ADS, which drew the components according to impedance. A schematic diagram was generated automatically. Only one frequency can be analyzed through the simulation; Fig. 7.7 shows the Smith chart analysis for 0.9 GHz. The S parameter can also be seen in the figure. The project can't decide on this schematic diagram in the real case, so it may vary according to the behavior of the antenna. From the simulation part, the required schematic diagram was obtained, which is a matching circuit that transfers the maximum at frequencies of 0.9, 1.8, and 2.4 GHz.

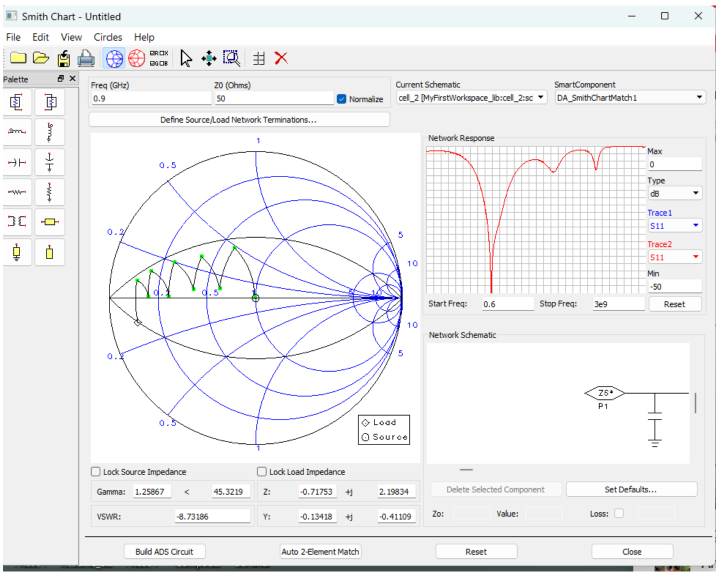

Figure 7.7: Smith Chart Analysis of 0.9 MHz

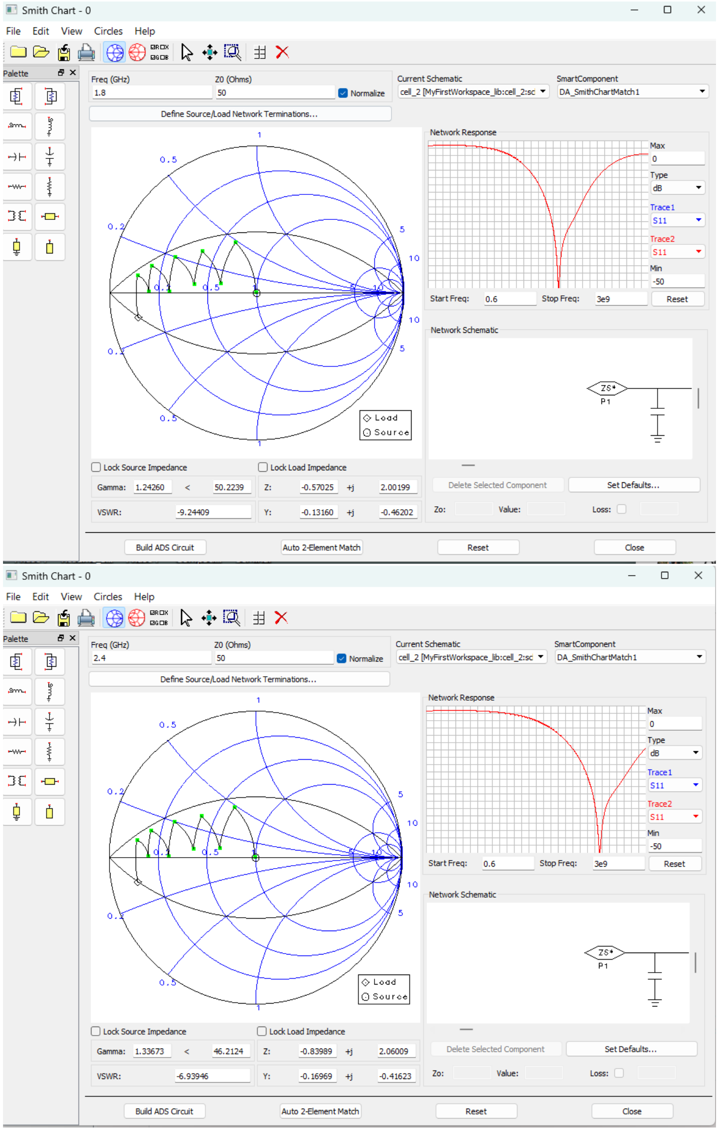

Figure 7.8: Smith Chart analysis of 1.8 and 2.4GHz

Fig 7.8 shows the individual s parameter for the circuit diagram,which implies the matching network shows maximum power transfer for 0.9,1.8 and 2.4GHz frequencies.

7.3 RF DC converter

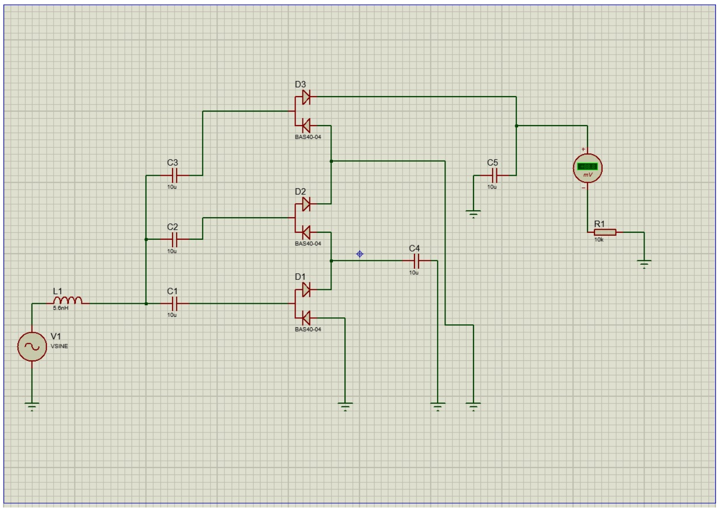

Figure 7.9: RF DC converter Circuit Diagram

The RF-DC converter converts the RF signal into an electrical signal. The aim was to design a circuit diagram using a Scottkey diode. And it is expected to achieve maximum power transfer from the matching, obtain a dc voltage of around 0.5 v, and produce an s parameter of the required frequency. Fig. 7.9 shows the schematic diagram of the circuit that was made in Proteus software. In the project we reached a circuit, expecting to get the answer. I have also added an inductor of 5.6 nH to get enhanced efficiency and voltage value. I did not reach our final answer, but I can detect the problem in the second phase through hardware implementation.

The simulation part of the first phase of the final project was completed, and we obtained the antenna model with a resonance frequency of 0.9, 1.8, and 2.3 GHz, as well as the rough schematic diagram of the RF-to-DC converter and impedance matching network, which may vary according to the antenna in the hardware setup. Finalization of the impedance matching network and RF-to-DC converter can be done only after the antenna.

Chapter 8

Conclusion

In conclusion, the RF energy harvesting system represents a promising technology that harnesses ambient radiofrequency (RF) signals to generate electrical power for various applications. The key components of this system—antenna, impedance matching circuit, and RF DC converter—work synergistically to efficiently capture, process, and convert RF energy into usable electrical power.

The antenna plays a crucial role as the initial receiver of RF (radio frequency) signals from its surroundings. Within this system, the antenna's construction is intricately refined using specialized Ansys HFSS software. It's meticulously crafted to function effectively across a wide frequency spectrum, spanning from 0.8 GHz to 3 GHz, and is specifically fine-tuned to resonate at distinct frequencies such as 0.9 GHz, 1.8 GHz, and 2.4 GHz. This design incorporates cutting-edge elements, including a circular patch that's connected by a trapezoidal-shaped microstrip line. Additionally, it features spider arm-shaped resonators integrated into the slotted ground, along with supplementary components like an arc-shaped resonator and a cross-shaped slot. These various design aspects synergistically contribute to several benefits: they expand the antenna's bandwidth, enhance its ability to match impedance, and crucially, they actively suppress interference by generating a unique stop band characteristic.

The impedance matching circuit, designed in Keysight ADS software, plays a crucial role in ensuring effective power transfer between the antenna and the subsequent stages of the energy harvesting system. Configured for a 50-ohm impedance match, the circuit is optimized using the Smith chart of the antenna, aligning with its impedance characteristics. This step is vital for maximizing power transfer efficiency and overall system performance.

The RF DC converter, simulated in Keysight ADS software and employing Schottky diodes, is responsible for converting the harvested RF signals into usable direct current (DC) voltage. The converter's efficiency is fine-tuned to accommodate varying input RF frequencies, ensuring optimal energy conversion. The comprehensive simulation analysis assesses parameters such as efficiency, voltage output, and response to different RF frequencies, validating the converter's effectiveness in transforming RF energy into electrical power.

The effective functioning of the RF energy harvesting system fundamentally relies on the meticulous planning and fine-tuning of its primary elements. Firstly, the antenna's role is pivotal—it adeptly gathers ambient RF signals, ensuring an efficient capture of available energy. Then, the impedance matching circuit steps in to enable smooth and efficient transfer of power, ensuring that the energy harvested by the antenna can be utilized optimally. Lastly, the RF DC converter plays a crucial role by efficiently converting the collected RF energy into a usable form. Collectively, these components showcase the considerable potential of RF energy harvesting. They demonstrate its capability to power wireless devices sustainably and efficiently, paving the way for a more environmentally friendly and self-sufficient approach to powering wireless technologies.

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