DESIGN OF MULTIPORT RECTENNA FOR WIRELESS ENERGY HARVESTING IN WEARABLE APPLICATIONS

A PROJECT REPORT

(PHASE – II)

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BONAFIDE CERTIFICATE

Certified that this project report **"DESIGN OF MULTIPORT RECTENNA FOR WIRELESS ENERGY HARVESTING IN WEARABLE APPLICATIONS"** is the bonafide work of **"ELAKSHME DEVI C. [REGISTER NO: 21UEC046], DHARSHINI M.R. [REGISTER NO: 21UEC039], SINDUJA R. [REGISTER NO: 21UEC172]"** submitted to the Pondicherry University, Puducherry for the award of the degree of **Bachelor of Technology in Electronics and Communication Engineering**. The contents of this project, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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INTERNAL EXAMINER **EXTERNAL EXAMINER**

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ABSTRACT

The rapid advancements in wireless communication and wearable technologies have driven the need for efficient energy harvesting systems to power low-power devices sustainably. This project presents the design and implementation of a compact multiband rectenna system for wireless energy harvesting in wearable applications. The proposed system integrates a Complementary Split Ring Resonator (CSRR) antenna with a defected ground structure (DGS) and a rectifier circuit. The antenna is fabricated on a denim substrate with dimensions of $25 \times 25 \times 0.745\ mm^3$, the antenna exhibits linear polarization and omnidirectional far-field radiation, effectively capturing energy across targeted frequencies at 2.3 GHz, 3.5 GHz, and 5.4 GHz with respective gains of 1.04 dBi, 1.4 dBi, and 6.35 dBi. The rectifier circuit, utilizing an HSMS2852 diode in a half-wave configuration, achieves efficient RF-to-DC conversion with a 3 kΩ load. Furthermore, a 2 x 2 MIMO rectenna system is implemented on a larger denim substrate with layout of $60 \times 60 \times 0.745\ mm^3$, enhancing energy harvesting capacity and system reliability. The bending analysis has been conducted at angles of 15°, 30°, and 45° which demonstrates stable performance under mechanical deformation, while Specific Absorption Rate (SAR) compliance at 0.99 W/kg ensures safety for wearable applications. This rectenna system is well-suited for powering wearable electronics, IoT devices, and other low-power technologies, contributing to the development of sustainable and energy-efficient wireless systems.

Keywords**:** Multiband Rectenna, Wireless Energy Harvesting, Wearable Technologies, Defected Ground Structure (DGS), RF to DC Conversion.

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LIST OF ABBREVIATIONS

AC	Alternating Current
AR	Augmented Reality
CSRR	Complementary Split-Ring Resonator
dB	Decibels
DC	Direct Current
DGS	Defected Ground Structure
E-plane	Electric Field Plane
FCC	Federal Communications Commission
FR-4	Flame Retardant-4 (a common PCB substrate material)
FSS	Frequency Selective Surface
GHz	Gigahertz (frequency unit)
H-plane	Magnetic Field Plane
ISM	Industrial, Scientific, and Medical (radio band)
MIMO	Multiple Input Multiple Output
PCB	Printed Circuit Board
PCE	Power Conversion Efficiency
RF	Radio Frequency
RFID	Radio Frequency Identification
SAR	Specific Absorption Rate
VSWR	Voltage Standing Wave Ratio

Chapter-1

INTRODUCTION

1.1 OVERVIEW

Wearable technology plays a vital role in today's world, spanning diverse applications such as health monitoring, fitness tracking, and smart textiles designed to elevate the user experience. As the functionality of these devices continues to expand, powering them effectively presents a significant challenge. Traditional battery systems are often inadequate, requiring frequent recharging and adding unwanted bulk to the devices, compromising comfort and usability. This reliance on batteries limits the operational time of wearables, necessitating innovative solutions for sustainable power sources. Wireless energy harvesting has gained attention as an innovative approach, enabling devices to capture and make use of energy present in the surrounding environment.

Rectennas, or rectifying antennas, are considered one of the most efficient methods for converting ambient radio frequency (RF) energy into direct current (DC) power. A rectenna integrates both an antenna and a rectifier, enabling it to capture radio frequency signals and convert them into electrical energy with high efficiency.This proposed work aims to enhance the performance of rectennas by focusing on the design and optimization of a multi-port configuration with improved gain. Integrating multiple antennas allows the system to harvest energy from various RF sources simultaneously, significantly increasing the overall energy capture. This design improves efficiency and ensures reliable power generation, accommodating the dynamic nature of wearable devices. Through meticulous design adjustments and optimization, the proposed work seeks to develop a compact, efficient, and sustainable power solution that addresses the limitations of traditional battery systems, paving the way for more advanced and longer-lasting wearable technologies.

The benefits of this approach are manifold. Firstly, it significantly boosts the usage time of wearable devices, as illustrated in Fig 1.1, reducing the frequency of battery changes. Secondly, it improves power supply stability, ensuring consistent device performance. Additionally, the flexible design enhances user comfort by conforming to the body's contours, and its robust operation under bending conditions makes it ideal for dynamic, real-world environments.

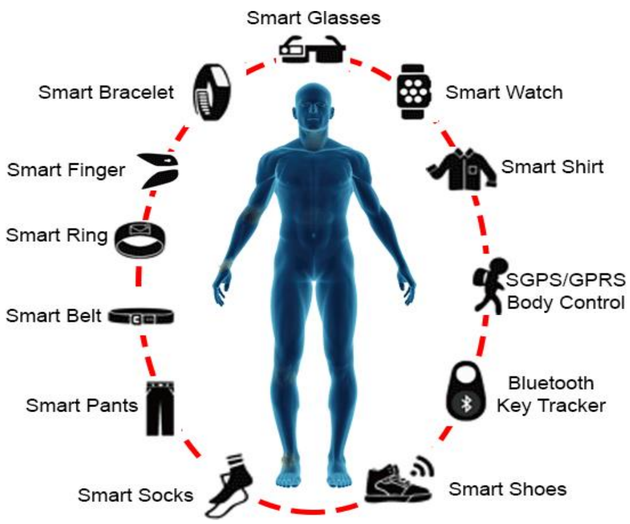


Fig. 1.1 Different Types of Wearable Technology

1.1.1 Wireless Power Transmission

Wireless Power Transmission (WPT) is a groundbreaking technology that promises to revolutionize the way we power our devices which is shown in Fig 1.2. By harnessing the principles of electromagnetic induction or radiation, WPT enables the transfer of electrical energy without the need for physical cables. This advancement holds the potential to transform various industries, from consumer electronics to automotive and medical fields.

A key promising application of WPT is in the field of wearable technology. By incorporating textile antennas into fabrics, it is possible to develop self-sustaining devices that can constantly gather energy from an adjacent power source. This removes the necessity for regular battery changes, improving the convenience and overall experience of using wearable devices. Textile antennas are engineered to be flexible, lightweight, and easily embedded into fabrics, making them perfect for various wearable applications. However, combining WPT with textile antennas comes with a number of challenges. A significant obstacle is achieving an efficient conversion of electromagnetic energy into usable electrical power. Textile materials typically have lower conductivity than conventional electronic components, which can affect the system's overall efficiency. Moreover, it is vital to guarantee the durability and dependability of textile antennas in different conditions, including washing and everyday wear.

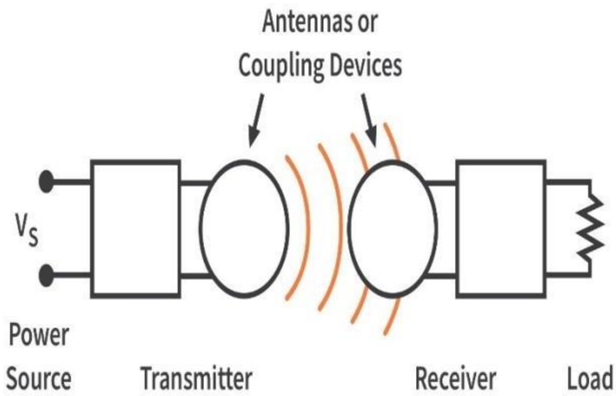


Fig. 1.2 Working of Wireless Power Transmission

Despite these obstacles, continuous research and development are aimed at overcoming these limitations. Researchers are exploring innovative materials and design techniques to improve the efficiency and durability of textile antennas. By optimizing the antenna's geometry, material selection, and integration methods, it is possible to achieve high-performance WPT systems that can power a variety of wearable devices. In conclusion, integrating wireless power transmission with textile antennas marks an important advancement in wearable technology. By addressing the technical challenges and utilizing progress in materials science and electronics, we can fully realize the potential of this technology, paving the way for a future where our devices are entirely wireless and self-sustaining.

1.1.2 Multiple Input and Multiple Output (MIMO)

The wireless communication system known as MIMO (Multiple Input numerous Output) uses multiple antennas at the transmitter and receiver to send and receive numerous data signals simultaneously over the same frequency channel, as seen in Fig. 1.3. This improves the overall capacity, speed, and reliability of the communication system without needing additional spectrum.

MIMO works by leveraging the spatial diversity of signals and the multiple antenna create different paths for data to travel, which the system can exploit to increase data throughput, reduce signal fading, and enhance overall performance. This technique enables better signal quality by mitigating interference and optimizing signal strength across multiple channels. Additionally, MIMO is widely used in modern wireless standards such as Wi-Fi, LTE, and 5G to support high-speed transmission.

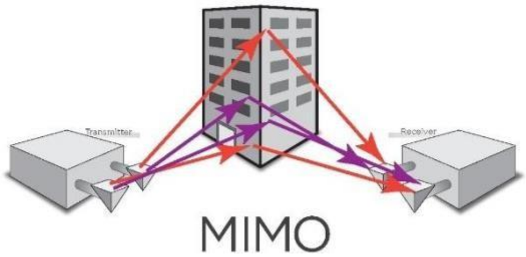


Fig. 1.3 Concept of MIMO

1.2 MONOPOLE ANTENNA

A monopole antenna is a type of radio antenna made up of a straight, vertical conductor placed above a conductive ground plane. Essentially, it is half of a dipole antenna, with the ground plane serving as a virtual image of the antenna element. This setup is akin to half of a dipole antenna positioned above a conducting ground plane. So the quarter- wave monopole antenna is the most common type where this antenna is around 1/4 of radio wave wavelength. These antennas are used in internet networks & mobile communications which is depicted in Fig 1.4.

A type of radio antenna that includes a straight rod-shaped conductor that is perpendicularly mounted above a ground plane is known as a monopole antenna. This antenna is a simple and single-wire antenna, mainly used for both transmitting & receiving signals, so broadly used in wireless communication systems. In a monopole antenna, the conductor rod functions as an open resonator for radio waves, oscillating through standing voltage and current waves along its length. The length of the antenna is easily determined based on the desired radio wave wavelength.

Monopole antennas exhibit strong directivity and minimal interference, which enhances signal strength and stability in communication networks. Their straightforward design, high efficiency, and wide bandwidth capabilities have made them an essential component in modern wireless communication, radar systems, satellite communications, and IoT-based applications. One of the key advantages of monopole antennas is their ease of design and construction. The length of the antenna can be adjusted based on the desired frequency of operation, making it highly adaptable for various applications. With ongoing advancements in antenna technology, modified monopole structures, such as loaded, helical, or fractal monopole antennas, are being developed to further enhance performance, miniaturization, and multi-frequency operation for advanced wireless systems. This makes monopole antennas cost-effective, compact such as radio broadcasting, cellular networks, vehicle-mounted antennas.

Fig. 1.4 Monopole Antenna

1.2.1 Monopole Antenna Design

A monopole antenna is essentially half of a dipole antenna, typically mounted above a ground plane. In this case, the antenna is positioned on an infinite ground plane with a length ‘L’, as illustrated below. Using image theory, the fields on the ground plane can be derived from the antenna in free space, as shown in the second diagram. This setup is effectively a dipole antenna, but with twice the length (2L) of the monopole antenna’s length (L).

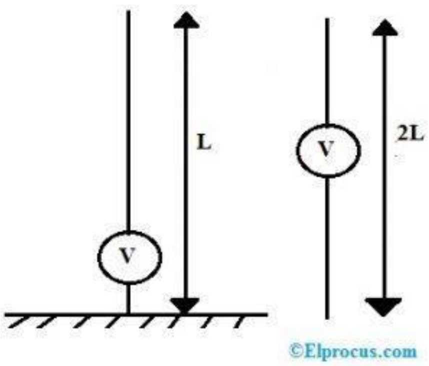


Fig. 1.5 Monopole Antenna Design

In Fig. 1.5, the fields on the ground plane are equal to the fields above it. The fields beneath the ground plane for the monopole antenna are zero. The directivity of the monopole antenna is closely related to that of a dipole antenna. If a dipole antenna with length 2L has a directivity of D1, the monopole antenna with length L will have a directivity of D1 + 3. This means that the monopole antenna's directivity is twice that of the dipole antenna. This increase in directivity is mainly due to the fact that no radiation occurs beneath the ground plane, making the antenna more efficient and "directive."

1.2.2 Monopole Antenna Working Principle

The working principle of a monopole antenna is that when the power is fed to a monopole then it is radiated similarly in all directions vertical to the antenna's length above the ground plane on which it is mounted. This antenna transmits in all directions at right angles to the antenna with equal strength because of its omnidirectional radiation pattern. Through the radiation falling off to zero at the antenna's axis peak, the radiated power from the antenna varies with elevation angle.

1.2.3 Monopole Antenna Types

Monopole antennas come in various types, including whip, helical, rubber ducky, random wire, umbrella, mast radiator, inverted-L, T-antenna, ground plane, folded unipole, and inverted-F.

1.2.3.1 Whip Antenna

As seen in Fig. 1.6, a whip antenna is a kind of monopole antenna that is renowned for its flexibility and resilience due to its resistance to breaking. The name of this antenna was derived from the whip-like motion that was exhibited once disturbed. This antenna includes a straight flexible rod or wire, and the bottom is simply connected to the radio transmitter or receiver. For portable radios, these antennas are frequently designed with a set of interlocking telescoping metal tubes, thus they can be pulled back once not in use. Longer whips are mainly designed to be mounted on vehicles as well as structures which are designed with a flexible fiberglass rod approximately a wire core & can be up to 11 m long. The perfect length of this antenna can be determined through the radio waves wavelength.

Fig. 1.6 Whip Antenna

1.2.3.2 Helical Antenna

A helical antenna includes a minimum of one or above conducting wires which are wounded in a helix form which is shown in Fig 1.7. When a helical antenna is designed with one helical wire then this antenna is known as monofilar whereas antennas designed with a minimum of 2 or 4 wires within a helix are then called quadrifilar/bifilar. These antennas are widely used for applications requiring circular polarization, such as satellite communications and GPS systems. The radiation pattern and impedance of a helical antenna depend on its dimensions, pitch angle, and operating frequency.

Fig. 1.7 Helical Antenna

1.2.3.3 Random Wire Antenna

A random wire antenna consists of a long wire suspended above the ground, which may be straight or zigzagged between walls or trees to ensure enough wire is elevated. Due to the wide range of possible antenna configurations, its efficiency can vary from one installation to another. As shown in Fig. 1.8, random wire antennas are commonly used as receiving antennas in short wave, medium wave, and long wave bands. These antennas are also utilized as transmitting antennas in these bands, especially for emergency or temporary transmission stations, small outdoor setups, or in locations where more permanent antennas cannot be installed.

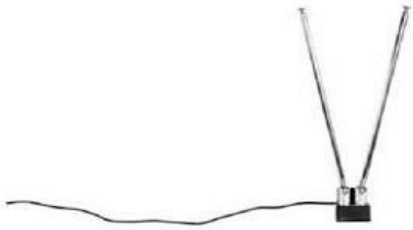


Fig. 1.8 Random wire Antenna

1.2.3.4 Rubber Ducky Antenna

The rubber ducky antenna, shown in Fig. 1.9, is a compact monopole antenna that functions similarly to a base-loaded whip antenna. It consists of a narrow, helix-shaped spring wire enclosed in a plastic or rubber casing to protect the antenna. These antennas are used in various portable radio devices like walkie-talkies, scanners portable transceivers where security and robustness take priority above electromagnetic performance. The flexible design helps prevent from physical impacts, making it ideal for rugged environments. Additionally, the rubber ducky antenna operates efficiently in the VHF and UHF frequency ranges, ensuring reliable communication.

Fig. 1.9 Rubber Ducky Antenna

1.2.3.5 Mast Radiator

A mast radiator, shown in Fig. 1.10, is a type of monopole antenna. It is a radiating tower or radio mast where the metal structure is energized to function as an antenna. Typically used for transmitting antennas operating at low frequencies in the MF and LF bands, it is commonly employed for AM radio broadcasting stations. The base of this antenna is usually mounted on a nonconductive support to isolate it from the ground.

Fig. 1.10 Mast Radiator

1.2.4 Benefits of Monopole Antennas

Monopole antennas are typically smaller and more compact than dipole antennas, making them easy to integrate into portable devices like mobile phones, GPS systems, and IoT devices. The monopole antenna consists of just a single conductive rod mounted above a ground plane, which simplifies the design and manufacturing process, reducing overall cost. Monopole antennas have an omnidirectional radiation pattern in the horizontal plane, meaning they radiate signals equally in all directions, providing broad coverage. This makes them ideal for mobile communications. With a ground plane, a quarter-wave monopole antenna impedance is around 37 ohms, which is close to the typical 50-ohm impedance of transmission lines. This reduces the need for complex impedance-matching circuits. The ground plane acts as a reflector, effectively doubling the length of the antenna (compared to dipole designs), and allowing a smaller physical antenna to achieve similar performance. Due to its small size and simple design, the monopole antenna can easily be integrated into compact electronic systems and portable devices without requiring significant space. Monopole antennas have a simple and robust structure, making them highly durable in harsh environmental conditions. They are commonly used in outdoor applications, including vehicles and military equipment. The simplicity of the monopole design, requiring fewer materials and less complex manufacturing processes, makes it cost-effective for mass production, especially for consumer devices like mobile phones. Monopole antennas naturally produce vertically polarized waves, which are advantageous for ground-based applications like mobile communication, where vertical polarization is preferred for efficient signal propagation over long distances.

1.3 WIRELESS ENERGY HARVESTING

Wireless energy harvesting is a groundbreaking technology that captures and converts ambient energy from the surrounding environment into usable electrical power, eliminating the need for traditional wired power sources or batteries, as shown in Fig. 1.11. This approach is especially important in today's technology landscape, where the growth of wireless devices, Internet of Things (IoT) applications, and wearable technology has increased the demand for efficient and sustainable energy solutions.

The primary sources of ambient energy that can be harvested include radio frequency (RF) signals, solar energy, thermal energy, and kinetic energy. Among these, RF energy harvesting has garnered significant attention because of the widespread availability of wireless communication systems, including Wi-Fi, cellular networks, and broadcast signals. Devices designed for wireless energy harvesting typically incorporate rectifying antennas (rectennas) that capture RF energy and convert it into direct current (DC) power. This conversion process allows the harvested energy to be either stored or used immediately to power low-energy devices, such as sensors, medical implants, or smart wearables.

By harnessing ambient energy, devices can operate independently of traditional power sources, reducing reliance on batteries that must be periodically replaced or recharged. This feature is especially advantageous in remote or difficult-to-access locations, where regular maintenance is not feasible.

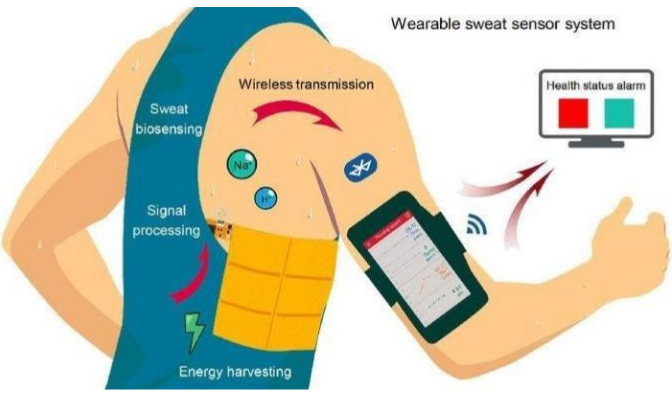


Fig. 1.11 Wireless Energy Harvesting

Wireless energy harvesting technologies also contribute to environmental sustainability by minimizing electronic waste and reducing the carbon footprint associated with battery production and disposal. As energy demands continue to rise in an increasingly connected world, wireless energy harvesting presents a promising avenue for powering the next generation of smart devices and applications. Wireless energy harvesting is a groundbreaking technology that captures and converts ambient energy into usable power, enabling the creation of self-sustaining electronic systems. By harnessing existing RF signals and other energy sources, it plays a crucial role in advancing sustainable and efficient energy solutions for a wide array of applications.

1.3.1 Key Characteristics of Wireless Energy Harvesting

Ambient RF signals from sources like Wi-Fi, cellular networks, and radio broadcast. Higher frequency radiation often used for specific applications. Although primarily not "wireless," solar panels can be combined with WEH technologies to create hybrid systems. A device that combines an antenna (for capturing RF signals) and a rectifier (for converting AC signals to DC). It effectively captures RF energy and transforms it into usable power. The conversion of the alternating current (AC) into direct current (DC) to charge batteries or power electronic devices. Systems often include energy storage to smooth out the energy supply, ensuring the device can operate continuously despite fluctuations in harvested energy.

1.3.2 Benefits of Wireless Energy Harvesting

Wireless energy harvesting significantly decreases reliance on traditional batteries, which can be harmful to the environment. Batteries contribute to pollution during their production, use, and disposal, often leaking toxic substances. By harnessing ambient energy, WEH promotes a more sustainable approach to powering electronic devices, contributing to a reduction in electronic waste. WEH taps into renewable energy sources, suchas radio frequency (RF) waves and solar energy, that are naturally occurring in the environment. This alignment with renewable energy principles supports global efforts to transition to greener energy solutions. Devices powered by WEH can operate indefinitely without the need for battery replacements. Devices situated in remote or difficult-to-reach locations, such ocean buoys or environmental sensors in forests, benefit greatly from this maintenance-free functioning. With no need for regular battery changes or maintenance, the overall operational downtime of devices is minimized. This reliability is crucial in applications such as industrial monitoring, where continuous data collection is essential. Over time, the savings associated with not having to purchase and replace batteries can be substantial, especially in large-scale deployments. This cost-effectiveness is significant for industries that require many sensors or devices, such as agriculture and smart cities. Maintenance tasks, such as battery replacement and disposal, require labour and resources. Wireless energy harvesting eliminates these costs, making it a more economically viable solution. Devices that do not require physical power connections can be more easily deployed in various locations. With the elimination of battery compartments, the design of electronic devices can be streamlined, allowing for more compact and lightweight products. This is especially beneficial for wearable technology and portable devices, where size and weight are critical factors. Wireless energy harvesting can be applied to various fields, including IoT, healthcare, agriculture, and smart infrastructure. This versatility makes it a suitable solution for powering sensors, monitoring devices, and communication systems across diverse industries.

1.4 RECTIFIER CIRCUIT

A rectifier is a crucial electronic component that converts alternating current (AC), which flows in both directions, into direct current (DC), which flows in one direction, as shown in Fig 1.12.This conversion is critical for many applications, including power supplies, battery chargers, and renewable energy systems. Rectifiers are utilized in everything from small electronic devices to large industrial applications, making them fundamental element of electrical engineering.

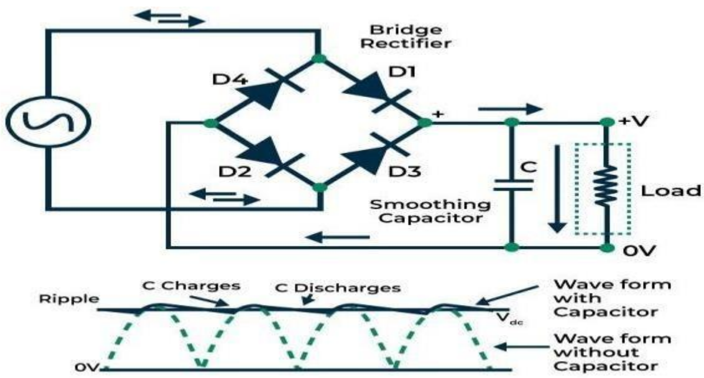


Fig. 1.12 Rectifier circuit

1.4.1 Working principle of rectifier

Rectifiers operate on the principle of controlling the direction of current flow. Semiconductor diodes are typically used in rectennas, as they allow current to flow in only one direction. This effectively blocks the negative portion of the AC waveform, producing a unidirectional output that forms DC.

1.4.2 Types of rectifiers

A half-wave rectifier uses a single diode to pass only one half of the AC waveform, blocking the negative half. It produces a pulsating DC output with a significant ripple, making it less efficient for power conversion. A full-wave rectifier, on the other hand, uses multiple diodes (typically arranged in a bridge configuration) to utilize both halves of the AC waveform. This results in a smoother DC output with reduced ripple, enhancing efficiency. The bridge rectifier is a specific type of full-wave rectifier that employs four diodes arranged in a bridge configuration. It converts the AC input into a unidirectional output, providing better performance than half-wave rectifiers.

1.4.3 Components of rectifiers

Diodes are the primary components that allow current to flow in only one direction, thereby enabling the conversion of AC to DC. Capacitors often used in conjunction with rectifiers to smooth the output voltage by filtering out the ripple, creating a more stable DC signal. Voltage Regulators are used to maintain a constant DC output voltage despite variations in the input voltage or load conditions.

1.4.4 Parameters of rectifiers

The maximum voltage a diode can handle in the reverse direction without conducting is essential for assessing its suitability for a specific application. The voltage drop across the diode occurs when it is conducting. Lower forward voltage drops lead to higher efficiency. A measure of the AC component present in the output DC voltage. Lower ripple factors indicate smoother DC outputs Efficiency is defined as the ratio of the output DC power to the input AC power. A higher efficiency indicates better performance in converting AC to DC. Load regulation refers to the rectifier circuit's ability to maintain a stable output voltage despite fluctuations in load current.

1.5 RECTENNA

A rectenna, which stands for rectifying antenna, is a device that integrates an antenna with a rectifier to convert radio frequency (RF) energy into direct current (DC) electricity. It functions by capturing RF signals from ambient sources like Wi-Fi and cellular networks through the antenna. This captured RF energy is then routed to a rectifier circuit, which converts the alternating current (AC) signal produced by the antenna into usable DC power. The captured RF energy is then fed into a rectifier circuit, which converts the alternating current (AC) signal generated by the antenna into usable DC power. Rectennas are designed for high efficiency, maximizing the conversion of captured energy, and many can operate across multiple frequency bands, enabling them to harvest signals from various sources simultaneously which is shown in Fig 1.13. Because of their small size, they can be integrated into wearable and portable electronics, which opens up a variety of uses, such as powering fitness trackers, smartwatches, and self-sustaining Internet of Things (IoT) sensors. By offering a sustainable energy source, rectennas play a key role in the advancement of self-powered electronic devices, decreasing dependence on conventional battery systems and fostering environmentally friendly technologies.

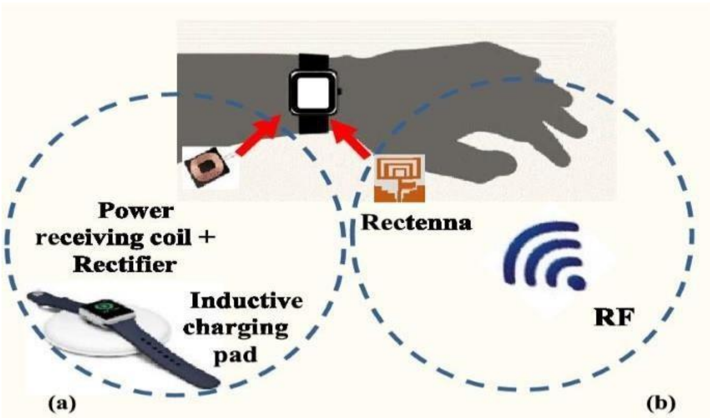


Fig. 1.13 Working of rectenna in wearables

1.5.1 Classification of Rectennas

Multi-Port Rectenna advanced design incorporates multiple antennas or ports, allowing simultaneous energy harvesting from various RF sources. It enhances efficiency by operating across multiple frequency bands. Single-Port Rectenna is a straightforward design featuring a single antenna connected to a rectifier, optimized for capturing energy from a specific frequency range. It is cost-effective but limited in energy capture compared to multi-port designs. Wideband Rectenna is designed to function over a broad frequency range, wideband rectennas can capture RF signals from multiple sources effectively. They utilize broadband matching networks for efficient energy harvesting across different communication standards. Microstrip Rectenna is characterized by a flat, printed circuit board design, microstrip rectennas are lightweight and suitable for integration into compact devices, making them ideal for applications in wearables and mobile technology. Planar Rectenna feature a planar design, often using thin-film technology, which allows for flexibility and conformability in applications such as smart textiles and flexible electronics. Array Rectenna comprises of multiple rectenna elements arranged in a grid formation, array rectennas enhance overall gain and directivity, improving energy capture from specific directions for higher efficiency. Textile Rectenna is integrated into fabric materials, textile rectennas are lightweight and flexible, making them perfect for wearable applications like smart clothing and health-monitoring devices.

1.5.2 Multiport Rectenna

Of these types of rectenna available, we choose multiport rectenna because of the following advantages, Multiport rectennas can capture energy from multiple sources or frequencies simultaneously, enhancing overall energy conversion efficiency. This is particularly beneficial in environments where RF signals are scattered across different bands. By integrating multiple rectifying ports, these rectennas can produce higher DC output power compared to single-port designs. Multiport rectennas can be designed to accommodate various operating conditions and applications which is depicted in Fig 1.14. They can be tuned to specific frequency bands or adjusted to optimize performance for different energy harvesting scenarios.

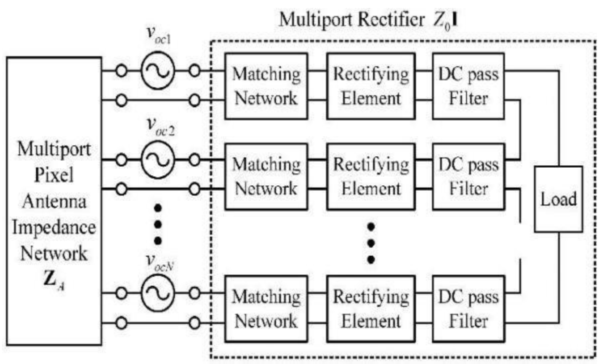


Fig. 1.14 Block diagram of Multiport rectenna

1.6 RECTENNA IN WEARABLE TECHNOLOGY

A rectenna (rectifying antenna) is an advanced device that seamlessly integrates an antenna with a rectifier to convert ambient electromagnetic energy into usable direct current (DC) electricity. In the realm of wearable technology, rectennas present a groundbreaking solution for energy harvesting, allowing devices to harness energy from their surroundings, such as radio frequency (RF) signals emitted by Wi-Fi networks, cell towers, and other wireless communication sources which is shown in Fig 1.15. This technology enhances the sustainability and efficiency of wearable devices by reducing reliance on conventional batteries, which not only diminishes environmental impact but also minimizes the frequency of battery replacements. The ability to convert harvested energy into DC power enables wearables—like smartwatches, fitness trackers, and smart textiles—to operate continuously without the constraints of limited battery life. Moreover, the compact and lightweight nature of rectennas allows them to be embedded within the design of various wearable products, maintaining comfort and aesthetic appeal while ensuring that devices remain powered for extended periods. The integration of rectennas into wearables significantly contributes to the development of Internet of Things (IoT) ecosystems, where continuous operation and connectivity are crucial for real-time data monitoring and communication. As the demand for sustainable and efficient energy solutions grows, rectennas are poised to play a vital role in the evolution of wearable technology. As the demand for self-powered and wirelessly charged devices continues to grow. Their ability to harvest energy efficiently, reduce dependency on batteries, and enable uninterrupted device operation makes them an essential component in the advancement of sustainable and smart electronics.

Fig. 1.15 Rectenna in wearable technology

1.7 SCOPE OF THE PROJECT

The project aims to design, develop, and test a novel textile antenna integrated with MIMO technology to enhance wireless energy harvesting efficiency and reliability for wearable electronic devices. This involves designing a textile antenna array, developing a WPT system, implementing MIMO signal processing, designing power management circuitry, and integrating and testing the entire system. The project will focus on core aspects like antenna design, WPT system optimization, MIMO signal processing, and power management, excluding large-scale production, in-depth material analysis, and long-term reliability testing. The final deliverables will include detailed design specifications, a fabricated prototype, comprehensive test results, and a technical report documenting the entire process.

1.8 MOTIVATION OF THE PROJECT

The growing demand for wearable electronic devices, combined with the constraints of battery technology, has driven the development of self-powered devices. Wireless energy harvesting (WEH) presents a promising solution to reduce the reliance on frequent battery replacements. However, traditional WEH systems often suffer from low efficiency and limited range. To tackle these challenges, combining MIMO technology with textile antennas offers a collaborative approach to boosting energy harvesting efficiency and reliability. By taking advantage of spatial diversity and multiplexing, MIMO can enhance the signal-to-noise ratio, expand the energy transfer range, and support both data communication and energy harvesting simultaneously. This project seeks to advance wearable technology by creating a self-sustaining and efficient solution capable of powering various wearable devices, ranging from smartwatches and fitness trackers to medical sensors and environmental monitors.

1.9 OBJECTIVES OF THE PROJECT

- To effectively capture ambient radio frequency energy from multiple sources, design and optimize a multi-port rectenna.
- Enhance the operating bands of the rectenna to maximize energy harvesting.
- To convert harvested RF energy into usable DC power with minimal loss, use high-efficiency rectifiers, impedance matching, filtering, MPPT, voltage regulation, and low-loss components.

1.10 ORGANIZATION OF THE REPORT

The Organization of the report is given as follows,

Chapter 1: Discusses overview of the wearable technology, monopole antenna, its characteristics and types. It also discusses the background of the project.

Chapter 2: Review of relevant scholarly papers and prior research related to energy harvesting for wearables design and development. Analysis of existing antenna designs and their performance based on specific parameters.

Chapter 3: Describes the proposed system design of the proposed antenna and rectifier circuit and its implementation.

Chapter 4: Explains the result and performance analysis of the proposed rectenna.

Chapter 5: Summarizes and concludes the proposed work, along with potential future extensions of the proposed methods in this project, are discussed.

Chapter – 2
LITERATURE SURVEY

2.1 OVERVIEW

The quest for advanced and efficient energy harvesting solutions is a vital endeavor within the rapidly evolving field of wearable technology. This project explores the exciting field of rectenna systems, with a particular emphasis on creating a small, multiport rectenna that can transform ambient radio frequency (RF) energy into useful direct current (DC) power. This project intends to meet the pressing demand for sustainable and independent power sources by incorporating state-of-the-art design concepts and materials to improve wearable devices' energy-harvesting capabilities.

The basic ideas of energy harvesting and the crucial function of antennas in obtaining radio frequency energy from various sources, including cellular networks, Bluetooth, and Wi-Fi, are covered first. This foundational overview highlights the limitations of conventional battery systems and emphasizes the necessity for innovative power solutions that can support the increasing demand for autonomous wearable technologies.

The discussion then transitions to the specifics of rectenna design, emphasizing the advantages of multiport configurations that enable simultaneous energy capture from multiple RF sources. By analyzing existing rectenna designs, we identify key strengths and challenges that inform our approach to developing a compact, efficient multiport rectenna. The core of this exploration lies in the unique characteristics of the proposed design, including its efficiency, adaptability, and potential for seamless integration into various wearable applications.

As the demand for self-sustaining wearable devices continues to grow, this project aims to contribute to the advancement of wireless power transfer technologies by offering a highly efficient and practical rectenna design. Future enhancements may include further miniaturization, improved frequency adaptability, and experimental validation under real-world conditions. By successfully implementing a multiport rectenna with superior energy-harvesting capabilities, this research paves the way for next-generation sustainable wearables, enabling continuous operation without the constraints of traditional power sources.

2.2 LITERATURE SURVEY

Mohmoud Waigh et al., (2022) [1] proposed is a novel dual-port wearable antenna that integrates an inductive coil and a broadband monopole to support both near- and far-field WPT. The coil functions as both an HF near-field receiver and a UHF resonator, allowing for a compact monopole design. Constructed from textile-based conductive materials, the antenna provides flexibility and adaptability for wearable applications. It achieves a 10 dB return loss over a 135% bandwidth while attaining 80% WPT efficiency in the near-field conditions. The antenna performs effectively on various textile substrates, ensuring wide applicability. SAR analysis confirms safe power absorption levels for both HF and UHF operations. Furthermore, the rectenna efficiently powers a BLE node using a BQ25505 DC-DC converter from minimal power inputs, demonstrating its potential in wearable energy harvesting.

Surajo Muhammad et al., (2021) [2] proposed is a long-range dual-band rectenna designed to harvest ambient RF energy from GSM/900 and GSM/1800 bands. A modified 5-section matching network (MN) is integrated to optimize impedance matching and enhance RF-to-dc power conversion efficiency (PCE). The rectenna employs a dual-band inverted-F monopole antenna, reducing circuit complexity while improving energy harvesting performance. Measurement results demonstrate a peak RF-to-dc PCE of 12.93% at 0.9 GHz and 8.0% at 1.8 GHz with an input power of -30 dBm. The harvester achieves an output dc voltage of 0.374 V, generating 0.747 V using a low-powered bq25504-674 evaluation module. This rectenna design enables efficient energy management for powering low-power electronic devices using harvested RF energy.

Giulia Battistini et al., (2024) [3] proposed is a compact rectenna system fully 3D-printed on low-cost polylactic acid (PLA) material, integrating a patch-like antenna with dual orthogonal excitation ports for UHF and UWB operation. The first port harvests multi-tone RF power at UHF, while the second backscatters intermodulation products to generate a quasi-UWB pulse. A single-diode rectifier is embedded within two subnetworks, optimizing both RF-to-dc conversion and backscattering efficiency. The 3D-printed substrate is engineered to achieve RF performance comparable to specialized materials. Full-wave and nonlinear simulations aid in minimizing footprint while ensuring UWB compatibility. Experimental results demonstrate a quasi-UWB pulse power peak of 80 nW with a received power of -15 dBm over eight tones.

Seong-Jin Kim et al., (2023) [4] proposed is a compact broadband stepped bow-tie antenna designed for ambient RF energy harvesting (RFEH) across entire cellular bands. The stepped structure ensures wide bandwidth, while the bow-tie shape enhances compactness for IoT sensor integration. Surface current distributions were analyzed through EM simulations to optimize impedance matching. A modified half-cut design further improved impedance characteristics, achieving a fractional bandwidth of 125% (0.85 GHz to 3.66 GHz) within a compact 68 mm x 107 mm form factor. The antenna was tested at various outdoor sites, identifying 0.9 GHz and 1.8 GHz as feasible bands for energy harvesting. An RFEH circuit, including a rectifier and power management unit (PMU), was integrated and experimentally validated, demonstrating potential for IoT sensor power solutions.

Zhen Li et al., (2023) [5] proposed is a two-port rectenna designed to harvest ambient RF energy from five commercial bands: 1.8, 2.1, 2.4, 2.65, and 3.5 GHz, covering GSM, LTE, WLAN, and 5G applications. The system integrates a hybrid half-wave rectifier and dual back-to-back slot antennas, enhancing multiband coverage with a single diode. The rectifier features series and parallel branches, achieving RF-to-dc power conversion efficiencies of up to 27.2% at 2.4 GHz and 43.7% under simultaneous five-tone input at −20 dBm. The slot antennas enable omnidirectional RF power reception at all target frequencies. Experimental validation confirms high efficiency and broad band coverage, demonstrating potential for powering sensors, wearables, and low-power applications.

Weihua Hui et al., (2023) [6] proposed is a novel rectenna utilizing a bifunctional double V-type metamaterial cover to enhance microwave energy harvesting efficiency. By adjusting the rotation angle of the metamaterial cover, the antenna achieves linear-to-circular polarization conversion at 5.8 GHz, making it suitable for complex electromagnetic environments. Experimental results demonstrate that the rectified dc power is 6.5 dB and 4.2 dB higher for linearly and circularly polarized waves, respectively, compared to conventional rectennas. The innovative design improves polarization adaptability, optimizing energy conversion. This metamaterial-integrated rectenna offers a promising approach for developing multifunctional and multipolarized energy harvesting systems.

Tu Tuan Le et al., (2024) [7] proposed is an all-textile broadband circularly polarized array antenna based on a metasurface (MTS), designed for high-performance, lightweight, and comfortable wearable applications. The 2 × 2 MTS array configuration includes a ground plane and a sequential feeding network, with miniaturized radiators incorporating diagonal slits. The antenna is fed through a microstrip line and cross-slot ground plane to achieve efficient radiation characteristics. A sequential series-feeding network ensures a 90° phase difference for enhanced performance. The antenna achieves a 72% impedance bandwidth and a 47.9% axial ratio bandwidth on a phantom head, with high broadside gain and moderate radiation efficiency. Simulated SAR values comply with US and European safety standards, demonstrating its suitability for wearable use.

Purna B. Samal et al., (2023) [8] proposed is a wearable textile multiband antenna with a full ground plane designed for wireless body area network (WBAN) applications. The antenna utilizes slots and multiresonant radiators with capacitive coupling to achieve broadband performance, including UWB and WLAN bands at 2.45 and 5 GHz. Characteristic mode analysis (CMA) is applied to enhance bandwidth by introducing independent resonances while maintaining spectral integrity. The antenna exhibits a directional radiation pattern with a compact size of $0.55\lambda_L \times 0.67\lambda_L \times 0.03\lambda_L$ at the lowest operating wavelength. It achieves an average maximum gain of 7.2 dBi across the operational range and maintains performance under on-body and bending conditions. This is the first wearable textile antenna with a full ground plane that supports UWB high-band and WLAN frequencies, making it highly suitable for WBAN applications.

Lan Yao et al., (2021) [9] proposed is a slotted full-textile microstrip antenna designed for miniaturization and electromagnetic reliability in wireless communication networks. Fabricated using the screen printing method, the antenna's measured return loss and radiation pattern were evaluated and compared with simulations. The adhesion of the silver paste radiation element to the textile substrate was tested using sticking tape and microscopic observation. To enhance on-body performance, an artificial magnetic conductor (AMC) was designed, optimized, and fabricated. Experimental results confirm that the AMC significantly reduces body coupling and antenna backward radiation, improving overall performance for wearable applications.

Gabriela Lachezarova Atanasova et al., (2022) [10] proposed is a fully textile dual-band logo antenna with an integrated reflector, designed for seamless incorporation into IoT wearable devices. The antenna's radiating elements mimic the logo of South-West University "Neofit Rilski" for unobtrusive integration into accessories. A reflector is incorporated to minimize radiation exposure and enhance robustness against loading effects from nearby objects. The fabricated prototypes were tested in free space and on various objects, including the human body, notebooks, and laptops. The antenna achieved a radiation efficiency of 25–38% and 62–90% across two frequency bands. Additionally, the reflector effectively reduced specific absorption rates (SAR) to safe levels, with a maximum of 0.5182 W/kg at 2.4 GHz and 0.16379 W/kg at 5.47 GHz. Real-world testing demonstrated high-quality off-body communication channels, confirming the antenna's potential for wearable IoT applications.

T. T. Le et al., (2024) [11] proposed Metasurface (MTS)-based all-textile broadband circularly polarized 2 × 2 array antenna for wearable technology. The design incorporates a metasurface radiator and a feeding network with a 90° phase difference, enabling high bandwidth and circular polarization. Diagonal slits are incorporated for miniaturization, enhancing adaptability. Performance tests in free space and on human body models demonstrate improved impedance bandwidth and compliance with SAR safety standards, contributing to lightweight, high-performance wearable technology.

Usman Ali et al., (2023) [12] proposed the work focuses on improving the performance of a dual-band textile antenna for wireless body area networks (WBAN).

It tackles issues related to backward radiation and Specific Absorption Rate (SAR) by using an Artificial Magnetic Conductor (AMC) as the ground plane, which enhances gain and radiation efficiency while reducing SAR by more than 98% at 2.45 GHz and 5.8 GHz. Built on a flexible felt substrate, the antenna remains stable when bent and performs effectively in both on-body and off-body conditions. The study demonstrates the AMC's potential to enhance safety and functionality in wearable WBAN devices, making it valuable for applications requiring low-profile, flexible antennas with low SAR.

Ilgvars Gorn et al., (2023) [13] proposed a wearable energy-harvesting system tailored for smart clothing applications, integrating electromagnetic and thermoelectric harvesters to capture energy from human motion and body heat. The system utilizes a shared energy storage capacitor, ensuring a continuous power supply for environmental sensors and wireless data transmission modules. Built with off-the-shelf components, the main electronic module offers compatibility and adaptability for various wearable devices. Their treadmill testing demonstrated sustained operation with up to 21% efficiency, showcasing the feasibility of energy-autonomous wearable electronics and supporting the development of stable and efficient power sources for smart textiles.

Madavarapu et al., (2024) [14] proposed the IoT Heterogeneous Energy Harvesting (IHEH) technique, which powers smart home appliances by utilizing multiple energy sources: thermal, piezoelectric, and light energy. The system comprises four layers—Energy Harvesting, Control and Sensing, Information Processing, and Application—achieving an overall energy efficiency of 90%. This approach ensures continuous operation, reduces reliance on conventional power sources, and enhances energy management, making it a promising solution for future IoT applications.

H. Y. Alkhalaf et al., (2024) [15] proposed an work on the design and development of a flexible meta-patch rectenna array aimed at powering low-power wearable medical sensors. The array features a meta-patch antenna operating at the 2.45 GHz ISM band, paired with a seven-stage Cockcroft-Walton Voltage Multiplier (CWVM) rectifier optimized for high DC output at low input power. Fabrication and measurement results show a power conversion efficiency (PCE) of 56%, providing a

DC output of 450 µW at an input power of -1 dBm. This research contributes to the development of efficient and sustainable power sources for wearable medical devices.

S.-J. Kim et al., (2023) [16] proposed a compact broadband stepped bow-tie antenna for RF energy harvesting has been introduced. The antenna uses straightforward stepped and bow-tie designs to achieve a broad bandwidth and compact size. Intended for use in the mobile communication frequency range, it offers a fractional bandwidth of 125%, high efficiency above 80%, and a maximum realized gain of 4.74 dBi. Additionally, the antenna is integrated with an RF energy harvesting circuit, illustrating its potential application in IoT systems.

D. R. Sandeep et al., (2023) [17] proposed a evaluation of a skin-contact wearable textile antenna's performance in a sweaty human environment.The antenna, constructed from natural jute fiber, is intended for on-body applications and tested under different sweat conditions, such as light spray, partial exposure, and full absorbency. The study highlights how sweat affects the antenna's resonating frequencies, gain, axial ratios, and efficiency, while maintaining circular polarization and functionality in the WLAN, Wi-Max, and ISM bands. This research supports the development of robust wearable antennas for harsh body sweat environments.

A. L. S. Giftsy et al., (2023) [18] suggested a thorough analysis of wearable and flexible antennas for use in biomedical applications. The paper emphasizes the significance of wearable technology in healthcare and the challenges of designing antennas that can function near the human body. Various techniques, including flexible substrates, conductive materials, and metamaterials, are discussed for antenna design. The key challenges of achieving high gain and a low specific absorption rate (SAR) are effectively addressed. The review provides insights into the current advancements and outlines future research directions in wearable antennas for biomedical use.

Rizwan et al., (2023) [19] proposed a compact textile monopole antenna for wearable devices designed to monitor bone fracture healing. Constructed from jeans fabric and copper, it ensures comfort, flexibility, and durability. The antenna complies with FCC SAR safety regulations while operating in the UWB range of 3.22–10.9 GHz, achieving an average gain of 3.83 dBi and 95.86% radiation efficiency. Using Principal Component Analysis (PCA), it analyzes signals for real-time fracture healing tracking. Validation on a bovine tibia demonstrated its capability to distinguish between fractured and healthy bones by detecting blood clots, offering a lightweight, non-invasive solution requiring no specialized technicians.

Gorn et al., (2023) [20] proposed a wearable energy-harvesting system for smart clothing that utilizes both human motion and body heat to generate power. The system combines an electromagnetic (EM) harvester with flat spiral coils and magnets and a thermoelectric (TE) generator to ensure continuous energy supply, even when stationary. Energy from both harvesters is stored in a shared capacitor to power a microcontroller that monitors parameters like temperature and humidity. An energy-aware algorithm optimizes power usage based on energy availability. Treadmill tests showed 38 mW peak power from the EM harvester and stable TE generator performance, offering reliable, battery-free operation with reduced power fluctuations.

Mohamed Aboualalaa et al., (2023) [21] suggested a new rectenna system for Internet of Things applications that combines a voltage doubler rectifier with a triple-band high-gain antenna. The design enables efficient RF energy harvesting while supporting simultaneous data transmission and reception, enhancing energy efficiency and reliability in power-constrained environments. The triple-band antenna provides operational flexibility across various frequency bands, adapting to diverse network requirements. Its high-gain properties optimize energy harvesting and communication reliability, even in challenging conditions. The voltage doubler rectifier ensures high power conversion efficiency, maximizing usable energy for IoT devices.

Yuchao Wang et al., (2022) [22] suggested a seven-band omnidirectional antenna for effective multi-band RF energy gathering. This design achieves excellent conversion efficiency and wideband operation to encompass GSM, LTE, Wi-Fi, and 5G bands by combining a revolutionary seven-band rectifier with a broadband omnidirectional antenna. It represents a significant advancement over three- and four-band rectennas, addressing the need for multiband energy harvesting to power self-sustaining devices. The study supports the development of rectennas capable of leveraging diverse wireless communication technologies for applications in various environments.

Hongcai Yang et al., (2022) [23] suggested a dual-band, dual-CP textile antenna that operates at the 3.5 GHz (WiMAX) and 5.8 GHz (ISM) bands for wearable applications .Utilizing PRAMC, it enables independent LHCP and RHCP radiation while ensuring flexibility and comfort through a textile substrate. The design is robust against human body effects, structural deformations, and substrate variations. Fabrication methods like laser cutting and screen printing were explored, addressing the need for wearable antennas with dual-band operation, circular polarization, and resilience for off-body communication.

Tu Tuan Le et al., (2023) [24] suggested an all-textile antenna for wearable technology in 5.8 GHz wireless body area networks (WBANs).The design employs a hexagonal slot radiator and a nonuniform metasurface (MS) to achieve broadband circular polarization by converting linear polarization to CP waves. The nonuniform MS, with a smaller center unit-cell, enhances bandwidth compared to uniform designs. SAR compliance satisfies US and EU safety regulations, and performance validation on a phantom head and in open space validates its appropriateness for wearable applications. This antenna offers a robust solution for WBAN applications.

Esra Çelenk et al., (2023) [25] proposed a novel all-textile antenna for military applications. The antenna is shaped like a military badge and operates in the X-band. It uses a SIW topology and has a bandwidth of 26% with low sidelobes. The antenna's measured gain and efficiency are high. It is designed to be worn on the body and performs well on conformal surfaces. The SAR values are within safety limits. The antenna is fabricated using standard textile techniques, making it suitable for mass production. This research presents a promising new antenna design for military applications.

Chengyang Luo et al., (2022) [26] proposed an embedding UHF-RFID antennas into surgical masks for healthcare applications. They tested three progressively designed antennas using a chip with lower sensitivity, all achieving good resonance. The final design (Design 3) demonstrated a maximum read range of 2.5 meters in air and maintained functionality when bent or worn on the face, with a read range of 1.1 meters. This design is suitable for tracking and social distancing alerts during epidemics and has the potential for adaptation with various textile sensors in the future.

Jie Cui, Feng-Xue Liu et al., (2022) [27] suggested a brand-new textile antenna design with pattern reconfigurability and no requirement for external power sources for wearable applications. Operating on a coupled-mode substrate-integrated cavity (CMSIC) topology, the antenna controls its radiation pattern using metallic snap buttons that function as switches. It can be adjusted to form two beams between the +z-axis and ±x axes for ON-body communication or to direct a main beam towards the +z-axis for OFF-body communication. It operates at a fixed frequency of 2.45 GHz. The design ensures flexibility, comfort, and seamless integration into wearable fabrics for practical use. Its passive switching mechanism enhances durability and energy efficiency, making it ideal for smart textiles and IoT applications.

Feng-Xue Liu et al., (2023) [28] suggested a half-mode substrate-integrated cavity (HMSIC) antenna with increased bandwidth for WLAN communications that is textile based. The antenna achieves a broader operational bandwidth by shifting the resonance frequency through the use of a V-slot. A prototype showed consistent coverage over the 5 GHz WLAN band, retaining functionality while bent and in close proximity to the human body. The antenna's high radiation efficiency and resilience make it appropriate for wearable applications, even though its bandwidth is marginally less than some designs because of a low-loss substrate.

Giovanni Andrea Casula et al., (2023) [29] introduced A novel design for wearable textile dual-band antennas using a substrate integrated waveguide (SIW) cavity was proposed. The study utilizes the eighth-mode of the SIW cavity to achieve substantial size reduction compared to conventional dual-band SIW antennas, making it more suitable for wearable applications. The antenna covers both the European and North American LoRa bands, ensuring flexibility for various regions. Focusing on low-cost fabrication and effective isolation from the human body, this design provides a compact and efficient solution for wearable LoRa applications. It leverages advancements in SIW technology and textile antenna design to enhance performance and practicality.

Haiyan Li et al., (2022) [30] introduced an innovative textile antenna designed for Wireless Body Area Network (WBAN) applications. This antenna operates across multiple frequency bands, including 2.45/5.8 GHz for ISM and 3.3-4.0 GHz for WiMAX and 5G. It incorporates a circular patch design with slots to tune high-order modes, enabling efficient multiband functionality. With a compact size of 60x60x1.17 mm and made from conductive fabric on denim, it offers flexibility and comfort. The design demonstrates good radiation patterns and low specific absorption rate (SAR).

2.3 COMPARISON OF THE EXISTING SYSTEM

The existing systems in wireless energy harvesting, particularly rectennas, have undergone significant advancements in design and functionality. Traditional single-port rectennas are commonly used to harvest and convert ambient RF energy into usable electrical power, with a focus on optimizing parameters such as gain, bandwidth, and conversion efficiency. However, limitations in energy capture from a single source led to the development of multi-port rectennas, which are capable of harvesting energy from multiple RF sources simultaneously. These advanced designs enhance energy conversion rates and provide redundancy, making them more effective for wearable and IoT applications where power availability from various RF signals is crucial. Additionally, research has focused on the use of novel materials and simulation techniques to further optimize rectenna performance, including increased efficiency and reduced size. These existing models which is depicted as a comparison table in Table 2.1 and Table 2.2 provides a solid foundation for the ongoing exploration of more efficient, versatile, and scalable wireless energy harvesting systems. The existing system for wireless energy harvesting, particularly in single-port rectennas, operates by capturing ambient RF signals through an antenna and converting them into usable DC power via a rectification circuit. The antenna captures radio frequency signals from sources such as Wi-Fi or cellular networks and transmits them to the rectifier, which converts the alternating current (AC) signals into direct current (DC).While effective, traditional single-port rectennas often suffer from limited gain and bandwidth, reducing their ability to efficiently capture and convert RF energy, especially from distant or weaker sources. Multi-port rectennas, an advancement in this field, address these limitations by using multiple antennas or ports to harvest energy from different RF sources simultaneously. This improves overall energy capture and conversion efficiency, making multi-port systems more suitable for environments with varying signal strengths and more reliable for applications like wearables and IoT devices. Despite these improvements, further optimization is needed to enhance gain and energy harvesting efficiency.

Table 2.1 Performance comparison of CSRR antenna with Existing works

R. No	TYPE OF ANTENNA	ANTENNA SIZE [L X W] (mm^2)	FREQUENCY OF OPERATION (GHz)	SUBSTRATE	GAIN (dBi)
[1]	Half – ellipse shaped	109 x 109	0.9	Felt	2.49
[2]	Inverted F monopole antenna	41.5 x 44	0.9, 1.8	FR4	0.62, 0.875
[3]	Dual port antenna	70 x 55	2.45	PLA	4.76
[4]	Stepped Bow Tie shaped antenna	68 x 107	0.9, 1.8	FR4	0.96, 4.74
[5]	E shaped slot antenna	75 x 75	1.8, 2.1, 2.4, 2.65, 3.47	F4BM-2	1.59, 3.18, 2.25, 2.41, 3.46
Proposed Work	CSRR antenna	25 x 25	2.3, 3.5, 5.4	Denim	1.04, 1.4, 6.35

Table 2.2 Performance comparison of rectifier with Existing works

R. No	FREQUENCY (GHz)	PCE (%) AT 0 dBm	SUBSTRATE	DIODE
[12]	5.8	66	S7136H	HSMS2850
[14]	0.12	77	FR4	SMS7630
[30]	1.84, 2.04, 2.36, 2.54, 3.3, 4.76, 5.8	44.4, 43.9, 45.4, 43.4, 36.1, 32.4, 28.3	Duroid 5880	BAT54
Proposed Work	2.3, 3.5, 5.4	52, 68, 71	FR4	HSMS2852

2.4 SUMMARY

From the above literature review, it could be understood that the published information on design of multiport rectenna for wireless energy harvesting technique is very much useful in terms of obtaining reference for this project. The previously proposed works, which are implemented at different domains and applications, are combined in order to build a new system which would stimulate the user about the rectenna designs in prior. The disadvantages of the existing systems designed by different authors acts as a base for the new proposal. Thus, the literature review gives more importance and very recent reviews among the researches and this indicates the high priority of researches towards this area.

Chapter – 3

DESIGN OF MULTIPORT RECTENNA FOR WIRELESS ENERGY HARVESTING IN WEARABLE APPLICATIONS

3.1 OVERVIEW OF THE PROPOSED SYSTEM

The proposed system is designed to enable efficient RF energy harvesting by integrating a circular ring monopole antenna with a rectifier circuit. The antenna, which is fabricated on a denim substrate, is specifically chosen for its flexibility, durability, and low dielectric constant (εr = 1.67). These properties make denim an excellent material for wearable electronics, as it ensures comfort while maintaining efficient RF performance. The antenna is structured as a circular ring monopole with concentric circular rings, which contribute to its multi-band functionality, allowing it to operate at 2.3 GHz, 3.5 GHz, and 5.4 GHz. This enables the system to capture ambient RF energy from commonly available sources such as Wi-Fi and Bluetooth. The design incorporates a microstrip feed, which ensures proper impedance matching, while the partial ground plane configuration enhances bandwidth and overall performance. Additionally, the use of a Defected Ground Structure (DGS) further optimizes impedance matching and bandwidth, improving the antenna's efficiency in wireless power transfer applications. To enhance performance and signal reception, the design extends into a 2×2 MIMO configuration, arranged in an orthogonal manner, which improves the system's ability to capture and utilize RF signals effectively.

The integration of the antenna with the rectifier circuit is a crucial aspect of the proposed system, ensuring that the captured RF energy is efficiently converted into usable DC power. The rectifier circuit is designed on an FR4 substrate, which provides mechanical stability and reliability. To maximize power transfer and minimize signal losses, an impedance matching circuit is implemented between the antenna and the rectifier. This impedance matching network plays a vital role in ensuring that the harvested RF energy is efficiently transmitted to the rectifier for conversion. The rectified DC output can then be used to power low-power wearable electronics, smart textile applications, and IoT devices, making the system highly practical for real-world applications. By leveraging the advantages of multi-band operation, enhanced bandwidth, and optimized impedance matching, the proposed system presents a highly efficient and sustainable approach to energy harvesting, paving the way for self-powered wearable electronics and wireless sensor networks. The flow chart of the proposed rectenna structure is illustrated in Fig 3.1.

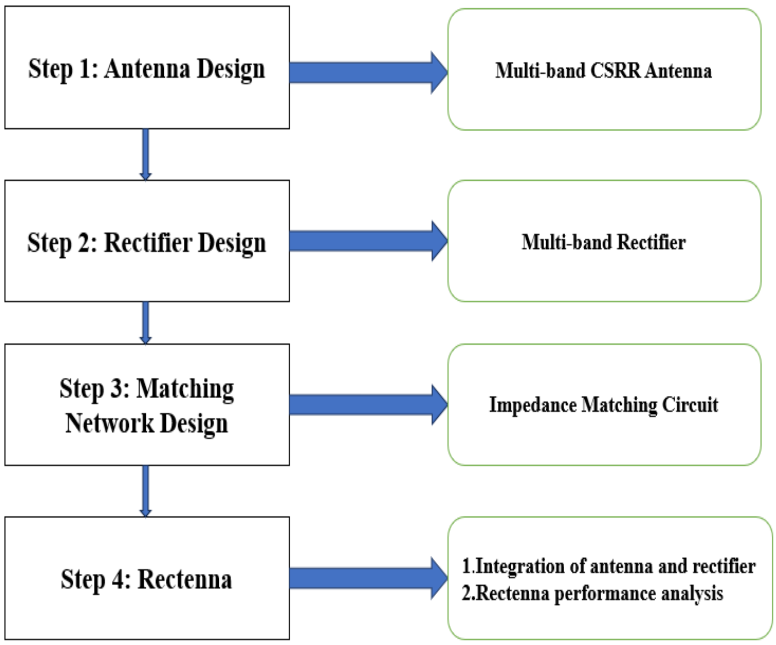


Fig. 3.1 Flow chart of the proposed rectenna design

3.2 DESIGN OF MULTI-BAND CSRR ANTENNA

The proposed antenna is the circular ring monopole antenna designed on a denim substrate, for efficient RF energy harvesting. The proposed antenna operates at 2.3 GHz, 3.5 GHz, and 5.4 GHz, making it suitable for capturing ambient energy from Wi-Fi, and Bluetooth sources. The overall schematic representation of the designed antenna is represented in Fig 3.2. The proposed antenna is structured as a circular ring monopole and has been designed using CST Microwave Studio. The design consists of concentric circular rings, which contribute to its multi-band functionality. The microstrip feed ensures proper impedance matching, with the partial ground plan configuration enhancing bandwidth and overall performance.

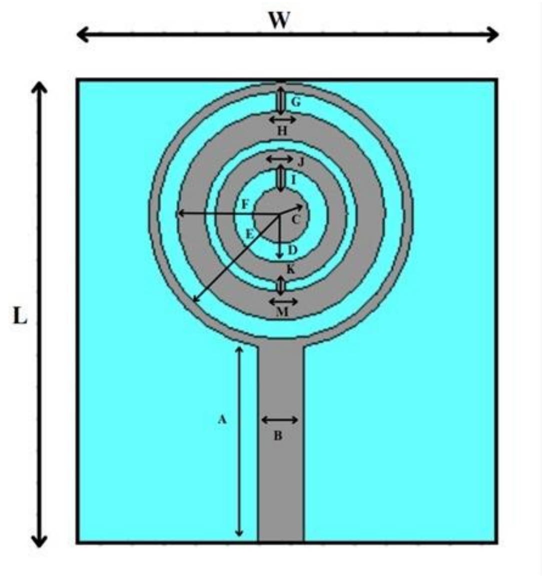


Fig. 3.2 Front view of multiband CSRR antenna

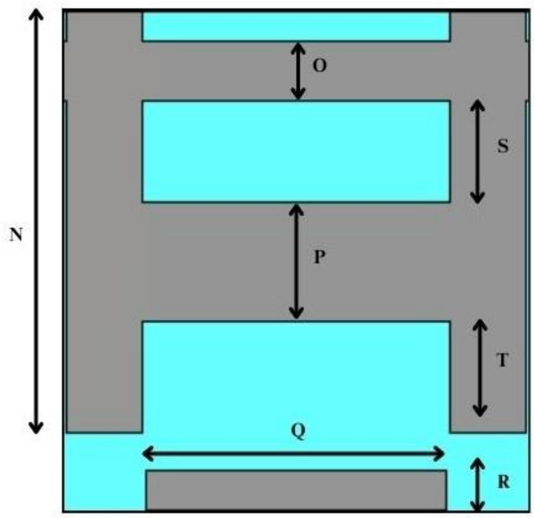


Fig. 3.3 Back view of multiband CSRR antenna

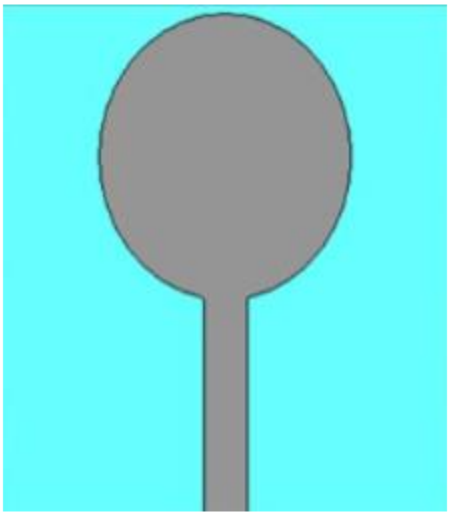
Denim is a flexible and durable fabric, making it an excellent choice for wearable antennas. It has a dielectric constant (εr) of 1.67, a thickness of 0.675 mm, and a loss tangent of 0.024, which enables low signal attenuation and efficient RF performance. Unlike rigid substrates such as FR4, denim provides superior comfort and flexibility, making it suitable for integration into smart textiles and wearable technology. The use of Defected Ground Structure(DGS) in the antenna design further enhances impedance matching and bandwidth performance, making it highly efficient for wireless power transfer and RF energy harvesting. The DGS ground structure is illustrated in Fig 3.3 and the dimensions of the antenna is illustrated in Table 3.1. The integration of DGS not only improves impedance matching but also reduces unwanted surface waves, enhancing radiation efficiency. This makes the proposed antenna design highly suitable for applications in wireless body area networks (WBAN) and energy-efficient communication systems.

Table 3.1 Multi-band CSRR antenna dimensions

Parameter	Dimensions (mm)	Parameter	Dimensions (mm)
L	25	J	0.5
W	25	K	0.5
A	10.6	M	0.5
B	2.4	N	21
C	1.5	O	5
D	2.5	P	6
E	6.5	Q	16
F	5.5	R	2
G	1	S	5
H	0.5	T	5.5

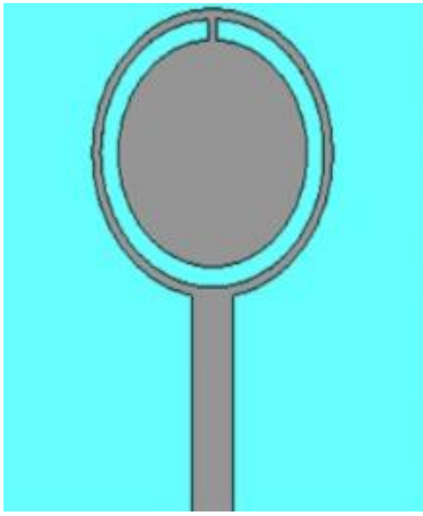
3.2.1 Evolution of the Multi-band Antenna

The proposed multi-band antenna evolution process is illustrated in Fig 3.4. The first iteration represents the basic monopole antenna with a circular patch and a microstrip feed. The design provides fundamental antenna characteristics but lacks multi-band capabilities. The second iteration introduces a single circular ring around the main monopole patch, enhancing the resonance properties and bandwidth performance. This modification begins the transition toward a multi-band structure by allowing additional resonances at different frequencies



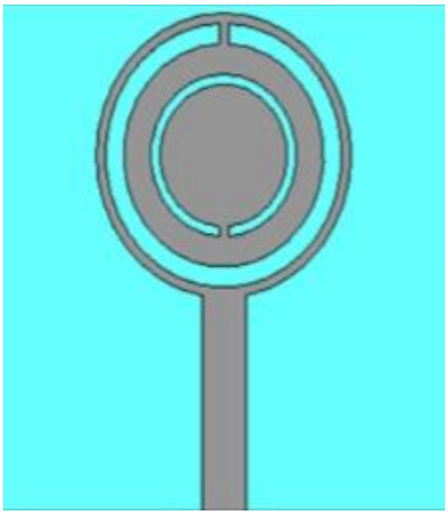
Iteration - 1

(a)



Iteration – 2

(b)



Iteration - 3

(c)

Iteration – 4

(d)

Fig. 3.4 Evolution of the multiband CSRR antenna: (a) Iteration – 1 (b) Iteration – 2 (c) Iteration – 3 (d) Iteration - 4

In the third iteration, an additional concentric ring is incorporated, further improving impedance matching and increase the number of resonant frequencies. This step significantly enhances the antenna's ability to operate efficiently at multiple frequency bands. Finally, the fourth iteration completes the design by adding a third concentric ring, fully optimizing the antenna for multi-band functionality. This final configuration ensures the antenna can efficiently capture ambient RF energy from sources like Wi-Fi and Bluetooth while maintaining stable radiation characteristics.

Through these iterative modifications, the proposed antenna evolves into a highly efficient energy-harvesting structure, offering improved bandwidth, impedance matching, and multi-band operation for wearable and IoT applications.

3.3 DESIGN METHODOLOGY OF PROPOSED CSRR ANTENNA

For a miniaturized antenna design, length and width play crucial roles and must be optimized to achieve the desired resonance frequency, efficiency, bandwidth, and radiation performance. The length and width of the conducting material have been calculated using the following formulas to ensure their better performance. Proper selection of these dimensions not only enhances impedance matching but also minimizes return loss, improving overall antenna efficiency.

3.3.1 Mathematical Calculations

a) Length of the conducting material

$$L = \frac{c}{4f\sqrt{\varepsilon_{eff}}} \quad \ldots (3.1)$$

The equation 3.1 calculates the length of the monopole planar antenna which is approximately a quarter of wavelength ($^{\lambda}/_{4}$). Where, c is the Speed of light, f is Operating Frequency in Hz and ε_{eff} is Effective permittivity of the substrate material.

b) Width of the Transmission line

$$\frac{w}{h} = \frac{2}{\pi}[B - 1 - \ln(2B - 1) + \frac{\varepsilon r+1}{\varepsilon r-1}\{\ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon r} \quad \ldots (3.2)$$

This equation 3.2 determines the width of the transmission line relative to the height of the substrate. It includes the factors like dielectric constant and a parameter BBB, accounting for the physical properties of the material.

c) Length of the Transmission lines

$$L=\frac{90(\frac{\pi}{180})}{\sqrt{eff}\ \times K_0} \qquad \text{...(3.3)}$$

This equation 3.3 calculates the length of the transmission line based on the effective dielectric constant and free space wave number.

d) Effective dielectric constant

$$eff = \frac{(\varepsilon r+1)}{2} + \frac{(\varepsilon r-1)}{2}\left(\frac{1}{\sqrt{1+\frac{12h}{w}}}\right) \qquad \text{... (3.4)}$$

The equation 3.4 determines the effective di-electric constant of the monopole planar antenna which influences the size, impedance, radiation characteristics and overall performance of the antenna.

e) Free space wave number in antenna

$$K_0 = \frac{2\pi f}{c} \qquad \text{... (3.5)}$$

The equation 3.5 is the free space wave number in monopole antenna which determines the spatial variation of the electromagnetic wave in free space. Where, f is the operating frequency in Hz and c is the Speed of light.

f) Ground

$$W_g = 6h + w \qquad \text{... (3.6)}$$
$$L_g = 6h + L_p + L_T \qquad \text{... (3.7)}$$

The equation 3.6 and 3.7 denotes the Ground plane width and Ground plane length of the monopole antenna which plays a vital role in extending sufficiently beyond the patch and ensuring proper radiation. Where, W_g is the Ground plane width, L_g is the Ground plane length, h is the Substrate height W is the Patch width and L is the Patch length.

3.4 DESIGN OF 2 x 2 MIMO ANTENNA

Fig 3.5 illustrates the MIMO antenna design and Fig 3.6 illustrates the ground structure, optimized for RF energy harvesting and wireless communication applications. The 2 x 2 MIMO antenna array, where four identical CSRR monopole antennas are arranged in an orthogonal configuration within a 60 mm x 60 mm substrate. The substrate used here is denim. Each antenna element is assigned a separate port (PORT 1, PORT 2, PORT 3, PORT 4), allowing independent signal excitation to enhance spatial diversity and improve overall system performance. The inter-element spacing, especially 11.7 mm horizontally and 7 mm vertically, ensures reduced mutual coupling and optimized impedance matching, which is essential for stable and efficient multi-band operation.

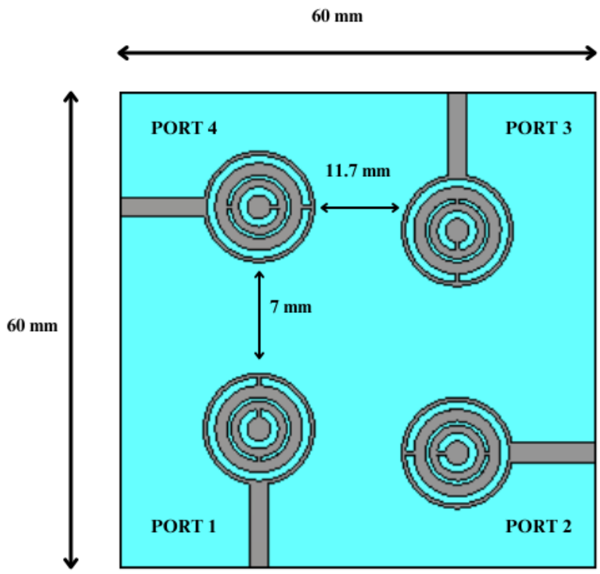


Fig. 3.5 Front view of MIMO antenna

Defected Ground Structure (DGS) is implemented in the antenna's ground plane. The DGS pattern consists of rectangular slots and etched shapes that introduce controlled perturbations in the current distribution, effectively improving impedance matching, bandwidth enhancement, and mutual coupling reduction. This structure plays a crucial role in fine-tuning the antenna's electrical characteristics, ensuring improved efficiency in RF energy harvesting and wireless power transfer applications. The combined effect of the MIMO configuration and the DGS allows the antenna system to achieve higher data rates, improved signal reception, and better performance in multipath environments, making it well-suited for wearable devices, IoT networks, and energy-efficient wireless communication systems.

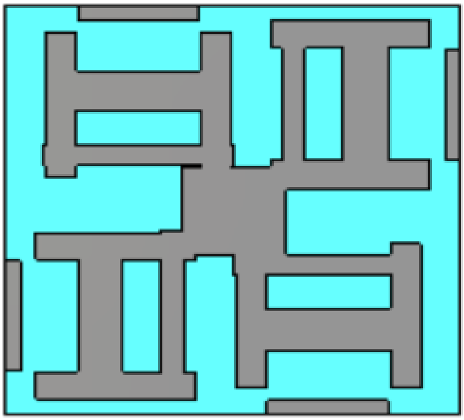


Fig. 3.6 Back view of MIMO antenna

3.5 DESIGN OF RECTIFIER CIRCUIT

The rectifier circuit presented is designed for efficient RF energy harvesting by converting ambient RF signals into usable DC power. The circuit consists of multiple inductors, capacitors, microstrip transmission lines, and Schottky diodes, all optimized for operation at 2.3 GHz, 3.5 GHz, and 5.4 GHz. The input section is matched to 50Ω impedance to ensure efficient power transfer from the antenna. The inductors and capacitors serve as impedance matching and filtering elements, ensuring that the incoming RF signals are efficiently rectified with minimal losses. The Schottky diodes, due to their low forward voltage drop and fast switching speed, effectively convert AC signals into DC. The rectified output is then filtered using capacitors and fed to a load resistor, providing a stable DC voltage suitable for low-power applications such as wearable devices and wireless sensors. The fig 3.7 illustrates the rectifier circuit. The rectified DC output, stabilized using capacitors and a load resistor, can be utilized for powering low-energy devices such as IoT sensors and wearable electronics.

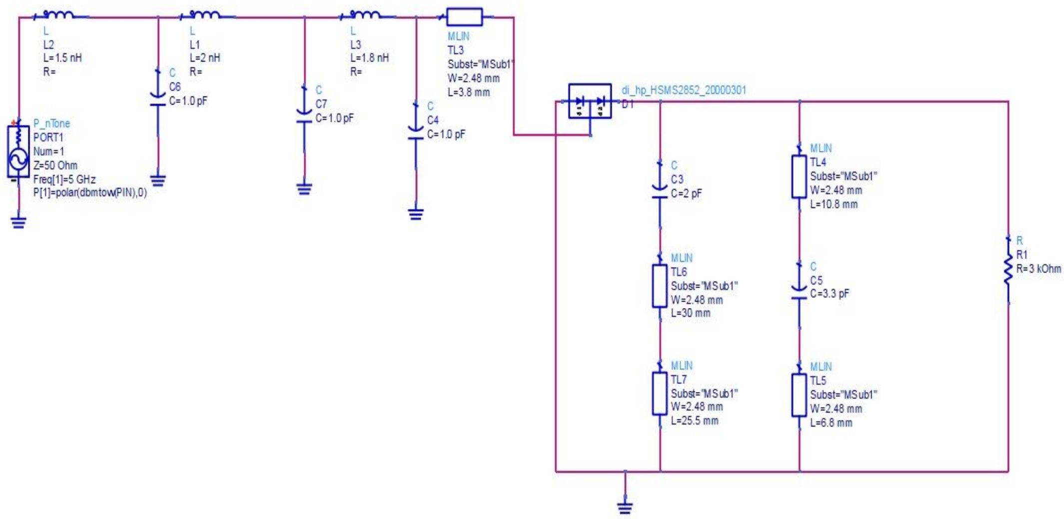


Fig .3.7 Proposed multi-band rectifier design

3.5.1 Mathematical Calculations

a) LC Network Calculation

The value of inductance can be calculated by considering the formula given as follows:

$$\mathbf{f} = \frac{1}{2\pi\sqrt{\mathbf{LC}}} \quad \Rightarrow \quad \mathbf{L} = \frac{1}{(2\pi\mathbf{f})^2\mathbf{C}} \qquad \dots (3.8)$$

The inductance values at different frequencies can be calculated as follows,

For **2.3 GHz**:

$$\mathbf{L} = \frac{1}{(2\pi \cdot 2.3 \times 10^9)^2 \cdot 1 \times 10^{-12}} \approx \mathbf{4.79}\,\mathrm{nH}$$

For **3.5 GHz**:

$$\mathbf{L} = \frac{1}{(2\pi \cdot 3.5 \times 10^9)^2 \cdot 1 \times 10^{-12}} \approx \mathbf{2.07}\,\mathrm{nH}$$

For **5.4 GHz**:

$$\mathbf{L} = \frac{1}{(2\pi \cdot 5.4 \times 10^9)^2 \cdot 1 \times 10^{-12}} \approx \mathbf{0.87}\,\mathrm{nH}$$

3.6 SOFTWARE AND HARDWARE TOOLS

3.6.1 CST Studio Suite

CST Studio Suite is a powerful electromagnetic simulation software widely used for designing and analyzing high-frequency components such as antennas, filters, and microwave circuits. It provides a range of solvers, including time-domain, frequency-domain, and integral equation solvers, allowing accurate analysis of electromagnetic behavior. The software is particularly useful in antenna design, enabling engineers to optimize parameters such as gain, impedance matching, and radiation patterns. One of its key advantages is its ability to model complex materials, including textile substrates like denim, which are commonly used in wearable antenna applications. CST allows users to define material properties such as permittivity and loss tangent, ensuring accurate simulation results.

3.6.2 Advanced Design System

Advanced Design System (ADS) is a leading electronic design automation (EDA) software developed by Keysight Technologies. It is widely used for designing, simulating, and optimizing RF, microwave, and high-speed digital circuits. ADS provides a comprehensive platform for engineers working in wireless communication, radar, satellite systems, and power electronics. For rectifier design, ADS allows users to model and optimize diode-based circuits for RF energy harvesting, wireless power transfer, and power conversion applications. Engineers can analyze important parameters like conversion efficiency, output voltage, power handling capability, and harmonic distortion. ADS also supports co-simulation with circuit and EM analysis, ensuring that the rectifier performs efficiently in real-world conditions. ADS remains a preferred tool for RF and microwave engineers. Its ability to simulate complex nonlinear behaviours and optimize circuit performance makes it essential for designing high-efficiency rectifiers and other power conversion systems.

3.6.3 Vector Network Analyzer

A Vector Network Analyzer (VNA) is a crucial tool in RF energy harvesting research, enabling precise characterization of the performance of RF harvesting systems, including rectennas. VNAs are utilized to measure key parameters such as impedance matching, reflection coefficients, and transmission coefficients across a wide range of frequencies. In the context of RF energy harvesting, VNAs are employed to evaluate the efficiency and effectiveness of rectennas in capturing and converting RF energy into usable electrical power. Researchers use VNAs to analyze the impedance matching between the antenna and rectifier components, ensuring maximum power transfer from the antenna to the rectifier. Moreover, VNAs enable the measurement of rectifier efficiency and conversion efficiency, providing insights into the overall performance of the RF energy harvesting system. By leveraging VNAs, researchers can optimize the design and configuration of rectennas to enhance energy harvesting efficiency and tailor them for specific frequency bands and environmental conditions, thus advancing the development of sustainable energy solutions.

VNAs play a crucial role in the development and validation of modelling and simulation techniques for RF energy harvesting systems. By comparing measured results with simulated data, researchers can refine and validate their mathematical models and simulation tools, ensuring their accuracy and reliability in predicting the behavior of complex RF energy harvesting systems. This iterative process of experimentation, measurement, and simulation enables researchers to gain deeper insights into the underlying principles governing RF energy harvesting and facilitates the optimization of system performance for real-world applications.

Chapter – 4

RESULTS AND DISCUSSIONS

4.1 PROPOSED CSRR ANTENNA PERFORMANCE ANALYSIS

The performance of the proposed rectenna structure, which includes a multi-band CSRR antenna and a multi-band rectifier circuit, is analyzed using CST Studio Suite and Advanced Design System simulation software. The evaluation assesses key performance metrics such as efficiency, gain, radiation pattern, and impedance matching across different frequency bands. Additionally, the rectifier circuit's ability to convert ambient radio frequency (RF) signals into usable DC power is examined.

4.1.1 Return Loss Characteristics

The return loss characteristics of the single antenna are shown in Fig. 4.1. The antenna maintains a return loss below -10 dB across its operating frequencies of 2.3 GHz, 3.5 GHz and 5.4 GHz respectively. It exhibits low reflection coefficients across the operating frequencies such as 2.3 GHz with a return loss of -12.02 dB, at 3.5 GHz with a return loss of -26.35 dB, and at 5.4 GHz with a return loss of -22.81 dB, demonstrating effective impedance matching and efficient signal transmission throughout the designated frequency bands.

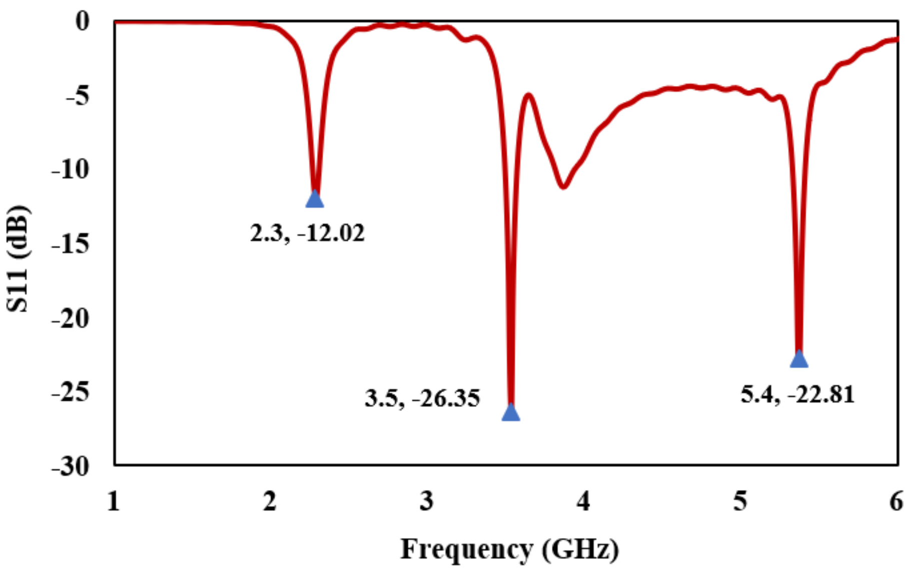


Fig. 4.1 Return loss characteristic of the CSRR antenna

4.1.2 Gain Characteristics

Fig. 4.2 illustrates the gain characteristics of the designed antenna at 2.3 GHz, 3.5 GHz, and 5.4 GHz. The antenna achieves a gain of 1.04 dBi at 2.3 GHz, 1.4 dBi at 3.5 GHz, and a peak gain of 6.35 dBi at 5.4 GHz. The increasing gain at higher frequencies indicates improved radiation efficiency. The antenna's enhanced performance at 5.4 GHz confirms its suitability for high-frequency applications. The gain variation signifies its potential use in wearable and wireless power transfer systems.

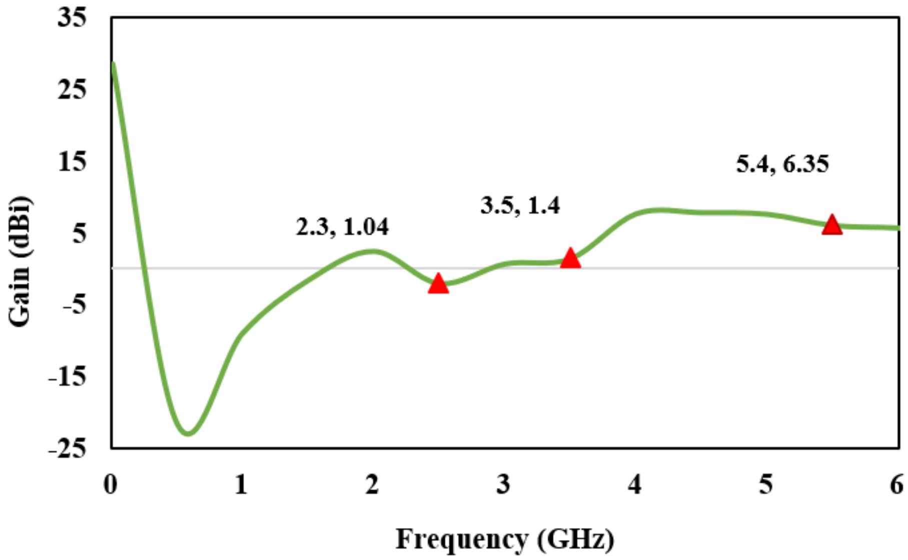


Fig. 4.2 Gain performance of the CSRR antenna

4.1.3 VSWR

Fig. 4.3 illustrates the Voltage Standing Wave Ratio (VSWR) characteristics of the designed antenna at its operating frequencies 2.3 GHz, 3.5 GHz, and 5.4 GHz. The measured VSWR values are 1.6 at 2.3 GHz, 1.13 at 3.5 GHz, and 1.18 at 5.4 GHz. A VSWR value close to 1 indicates good impedance matching, ensuring minimal signal reflection. The lowest VSWR of 1.13 at 3.5 GHz confirms excellent impedance matching at this frequency. The results validate the antenna's capability for efficient power transfer across multiple frequency bands. The overall low VSWR values across these frequencies demonstrate the antenna's efficiency in capturing ambient RF signals.

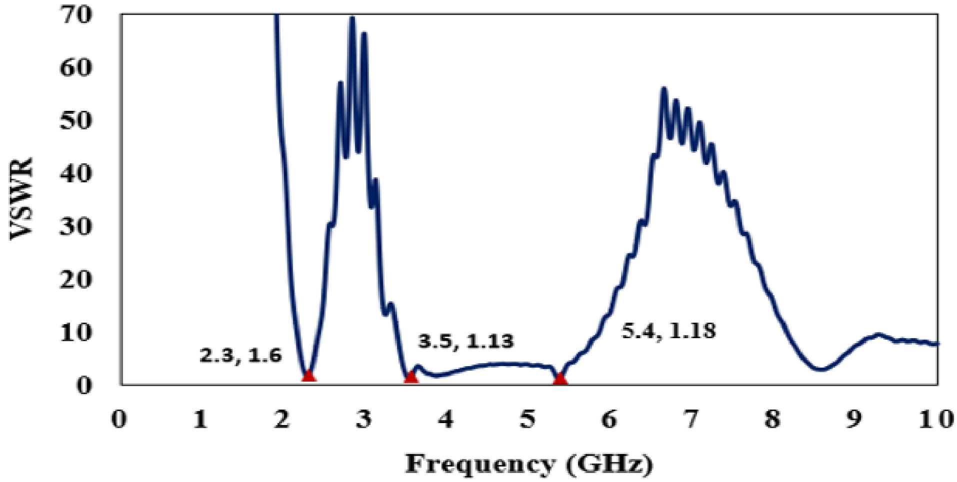


Fig. 4.3 VSWR of the CSRR antenna

4.1.4 Radiation Characteristics

Fig. 4.4 demonstrates the evolution of radiation performance across three configurations. From a symmetric dipole pattern to a more directional gain profile, the plots highlight how antenna design optimizations improve radiation directionality, suppress unwanted lobes, and enhance gain in the desired direction. These improvements are crucial for applications like wearable or embedded antennas in RF energy harvesting, where gain directionality ensures better energy capture from specific sources.

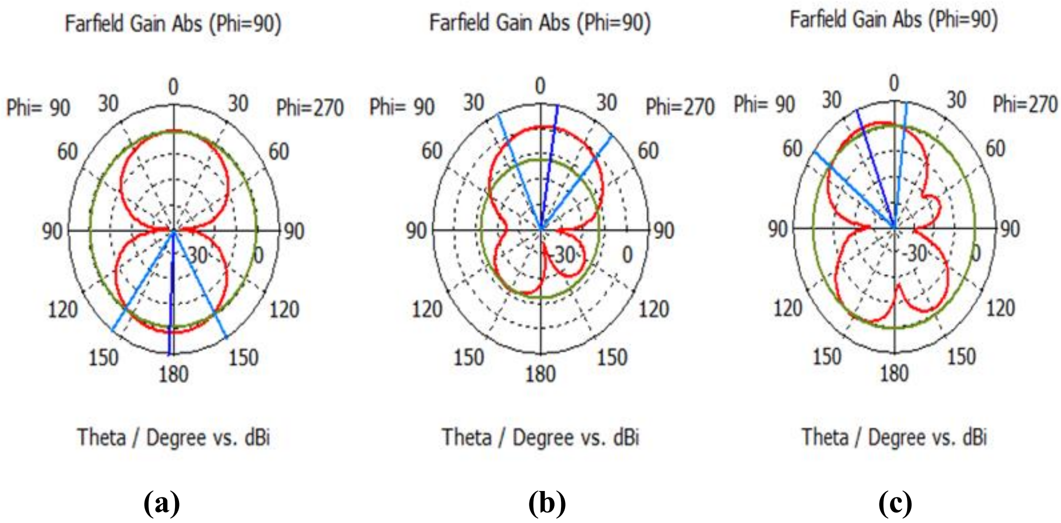


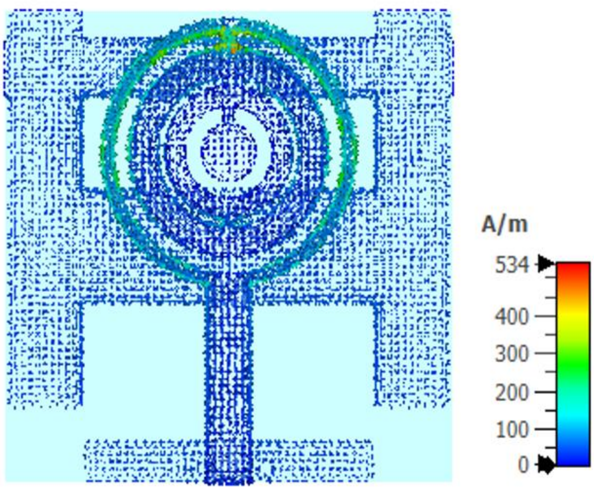
Fig. 4.4 Radiation characteristics of the CSRR antenna: (a) At 2.3 GHz (b) At 3.5 GHz (c) At 5.4 GHz

4.1.5 Surface Current Distribution

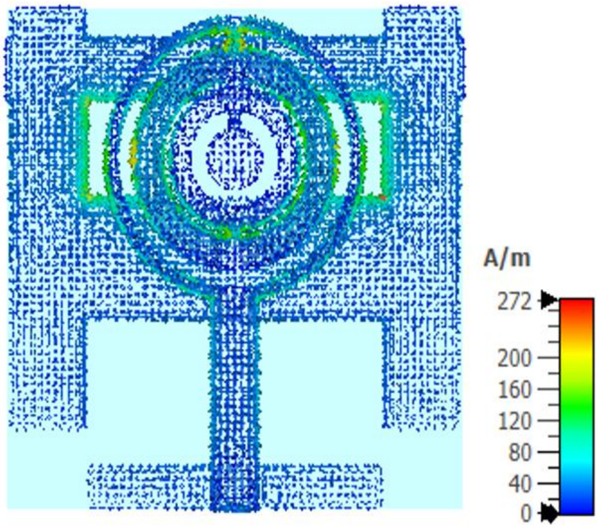
Fig. 4.5 demonstrates the surface current characteristics of the single antenna element at 2.3 GHz, 3.5 GHz, and 5.4 GHz, respectively. At 2.3 GHz, the surface current is strongly concentrated around the circular patch and the feedline, indicating effective excitation and resonance at the lower band. The current density peaks around 534 A/m, signifying strong radiation from the patch at this frequency.

At 3.5 GHz, the current distribution becomes more intense, especially around the inner circular ring and the adjacent structures, with a peak magnitude of 915 A/m. This reflects a higher resonance efficiency and tighter field confinement at the mid-frequency band.

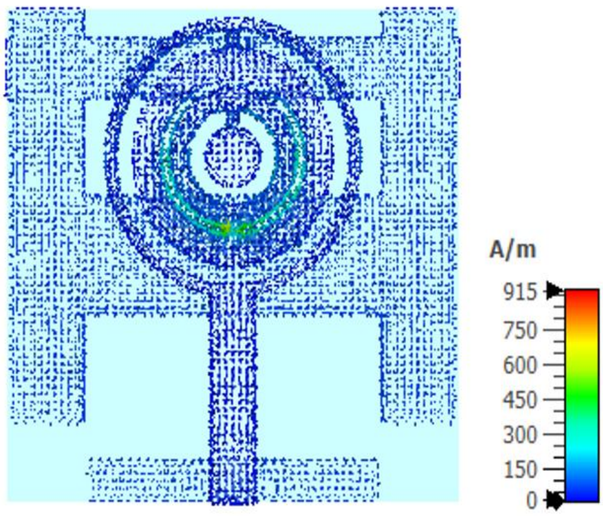
At 5.4 GHz, the surface current is more evenly distributed across the radiating structure but with a comparatively lower intensity of 272 A/m. This spread suggests that while the antenna maintains resonance at the higher frequency, the radiated power may be lower due to reduced surface current density. Overall, these current patterns confirm the multiband operation of the antenna and validate its capability to operate efficiently across the designated frequency bands. These variations in surface current intensity and distribution not only validate the antenna's resonance at each frequency but also reveal how the physical structure contributes differently to each band, ensuring the antenna effectively supports applications across the sub-6 GHz spectrum.



(a)



(b)

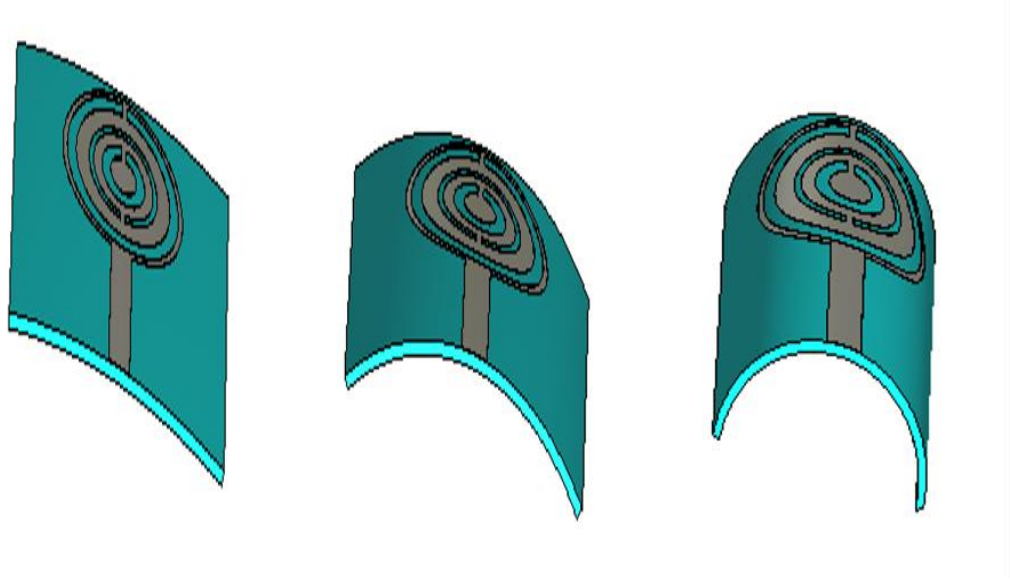


(c)

Fig. 4.5 Surface current characteristics of the CSRR antenna:
(a) At 2.3 GHz (b) At 3.5 GHz (c) At 5.4 GHz

4.1.6 Bending analysis of the antenna

The bending analysis of the proposed flexible antenna in Fig. 4.6, was conducted to evaluate its performance under mechanical deformation, which is crucial for practical applications in wearables. The antenna was bent at three different angles—15°, 30°, and 45°—to simulate realistic bending conditions. The 3D model shows the antenna structure under deformation, illustrating how the substrate and radiating elements adapt to curvature. The corresponding S-parameter (S11) results were analyzed over a frequency range of 1 GHz to 6 GHz for each bending condition.



(a) (b) (c)

Fig. 4.6 Bending analysis of the CSRR antenna: (a) At 2.3 GHz (b) At 3.5 GHz (c) At 5.4 GHz

The reflection coefficient plots in Fig. 4.7, demonstrates that the antenna maintains dual-band operation despite the physical distortion. At 15° bending, the antenna exhibits stable performance, and a return loss below -10 dB. When the bending angle increases to 30°, a minor shift in the resonant frequencies is observed along with a slight degradation in the return loss, particularly near the higher frequency band. At 45°, the deformation becomes more pronounced, leading to noticeable frequency shifts and a moderate increase in the reflection coefficient in some regions

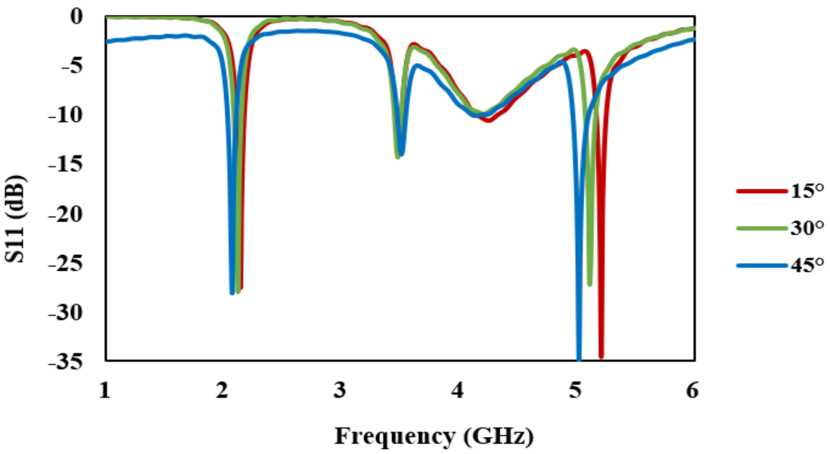
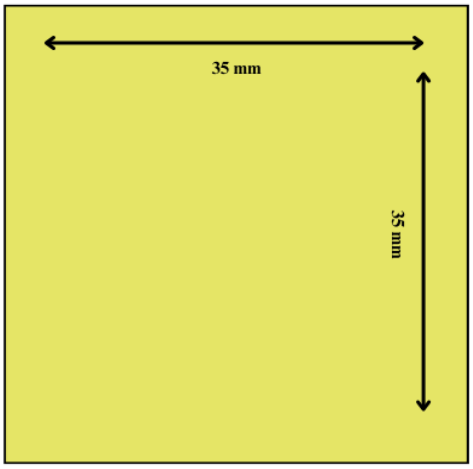


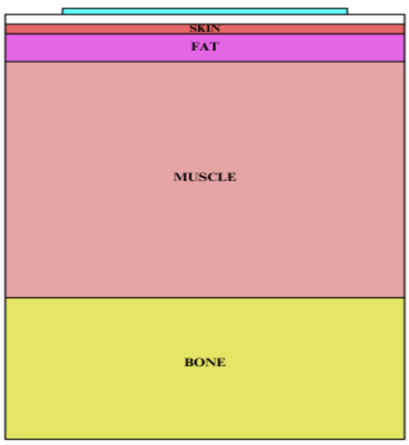
Fig. 4.7 S parameter of the CSRR antenna at different bending scenarios

4.1.7 SAR analysis of the antenna

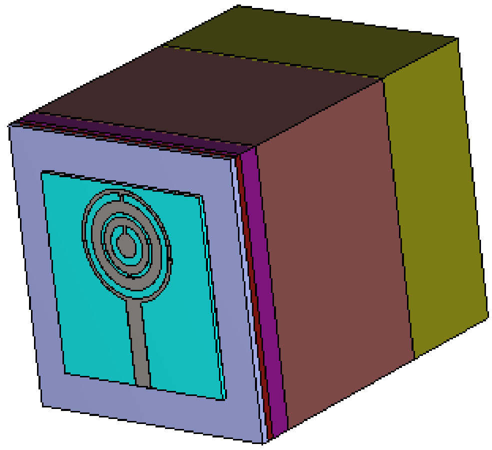
SAR (Specific Absorption Rate) measures the rate at which RF energy is absorbed by human tissue, with FCC standards limiting it to 1.6 W/kg averaged over 1 gram of tissue. In this analysis which is represented in Fig. 4.8, the SAR value was determined to be 0.99 W/kg, ensuring the design complies with safety regulations for electromagnetic exposure. The study also demonstrated that SAR values increase proportionally with input power, emphasizing the need for power optimization in device design.



(a)



(b)



(c)

Fig. 4.8 Simulated Model of a Cubic Biological Phantom: (a) Top view (b) Side view (c) Perspective view

4.2 PROPOSED 2x2 MIMO CSRR ANTENNA

The performance analysis of a 2×2 MIMO antenna involves evaluating several key parameters to ensure efficient and reliable wireless communication. The return loss (S11) should be less than -10 dB, indicating good impedance matching, while isolation (S21) between antenna elements should be below -15 dB to minimize mutual coupling. The antenna should exhibit high gain (typically 4–8 dBi) and efficiency above 70% for optimal radiation performance. Diverse and directional radiation patterns are essential to reduce signal correlation. The Envelope Correlation Coefficient (ECC) should ideally be less than 0.1, ensuring effective spatial diversity, and the diversity gain should be close to 10 dB to enhance signal robustness

4.2.1 Return Loss Characteristics

Fig. 4.9 presents the return loss (S-parameter) characteristics of the 2×2 MIMO antenna across a frequency range of 1 GHz to 6 GHz. The antenna exhibits resonances at multiple frequencies, with significant dips in the return loss, indicating effective impedance matching and efficient radiation at these points. The S11, S22, S33, and S44 parameters correspond to the reflection coefficients of the individual antenna elements, ensuring that minimal power is reflected back. The deep resonances in the graph confirm strong resonance at specific frequencies, making the antenna suitable for multi-band applications. The observed return loss values indicate low reflection The nearly identical behavior of all four parameters confirms mutual coupling reduction and stable MIMO performance.

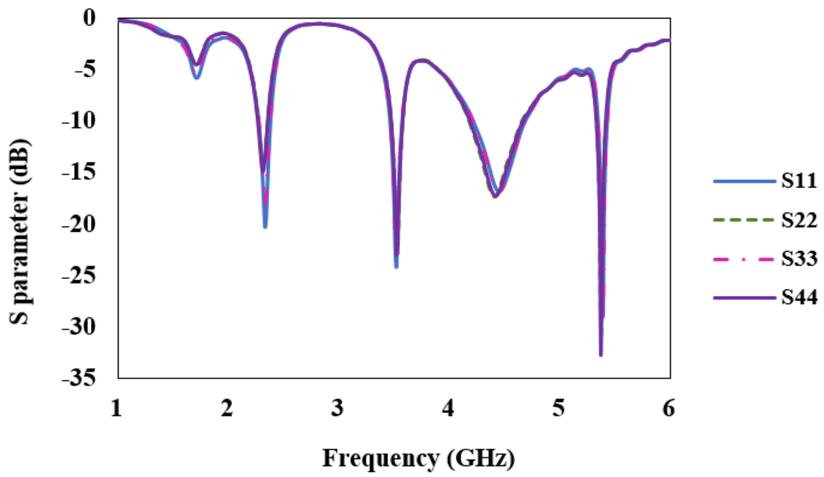


Fig. 4.9 Return loss characteristics of the MIMO antenna

4.2.2 Insertion Loss Characteristics

Fig. 4.10 presents the isolation (S-parameter) characteristics of the 2×2 MIMO antenna, illustrating the mutual coupling between the antenna elements over a frequency range of 1 GHz to 6 GHz. The parameters S12, S23, S31, and S42 represent the transmission coefficients between different antenna elements, indicating the level of isolation achieved. Lower values of isolation (below -15 dB) suggest minimal interference and improved MIMO performance. The graph shows that the isolation remains significantly low at various resonance frequencies, ensuring reduced mutual coupling and enhanced channel capacity.

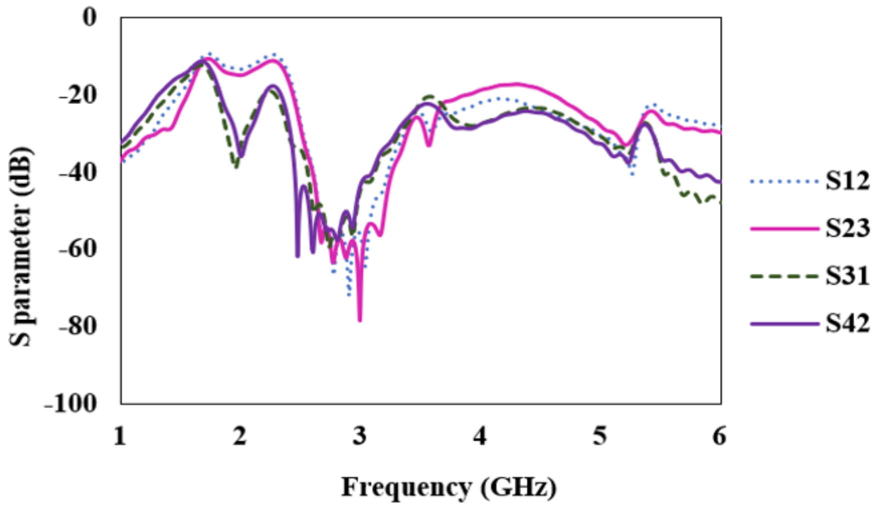


Fig. 4.10 Insertion loss characteristics of the MIMO antenna

4.2.3 Gain Characteristics

The gain performance of the proposed MIMO antenna is illustrated in Fig. 4.11, depicting variations across a wide frequency range (0–10 GHz). The antenna exhibits an initial sharp drop in gain at lower frequencies, which stabilizes as frequency increases. A peak gain of approximately 5 dBi is observed in the operational frequency band, ensuring reliable signal transmission and reception. The fluctuations in gain are attributed to impedance variations and mutual coupling effects among the antenna elements. The overall gain response demonstrates the antenna's capability to support wideband applications with stable radiation performance.

While the proposed antenna exhibits negative gain values at certain points within the operating frequency band, this can be considered acceptable in the context of compact, multiband, or wearable antenna designs, where trade-offs between size, bandwidth, and efficiency are common. The negative gain may result from factors such as mutual coupling, radiation leakage, or imperfect impedance matching, yet the antenna continues to maintain functional radiation characteristics. Additionally, in scenarios where omnidirectional or circularly polarized radiation is prioritized over directivity, slight negative gain values are tolerable. Therefore, despite these dips, the antenna remains suitable for low-power, short-range communication applications such as IoT and wearable energy harvesting, where stable connectivity is more critical than high-gain performance.

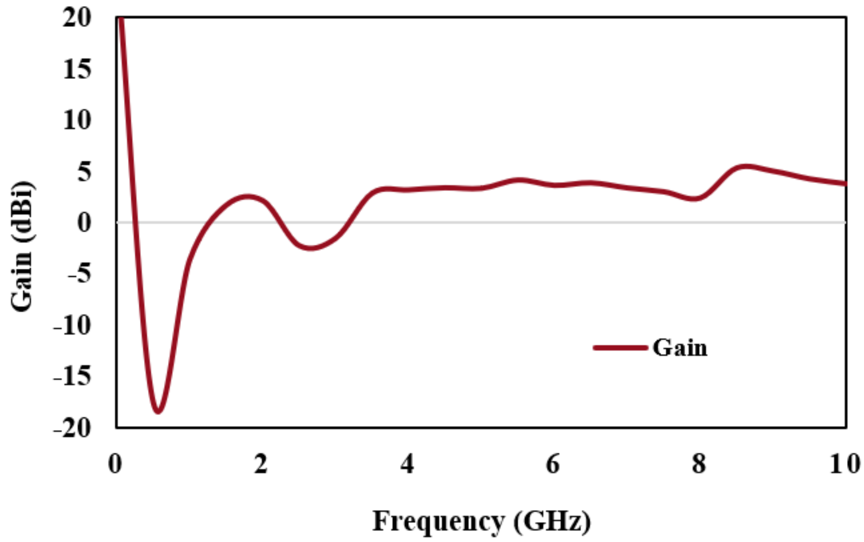


Fig. 4.11 Gain characteristics of the MIMO antenna

4.2.4 VSWR

The Voltage Standing Wave Ratio (VSWR) characteristics of the proposed MIMO antenna are presented in Fig. 4.12. The VSWR is analyzed for all four ports, showing similar trends across the operating frequency range. A lower VSWR value, close to 2 indicates good impedance matching and minimal reflection losses. The graph highlights that the antenna achieves acceptable VSWR values at certain frequency bands, ensuring efficient power transfer. However, the higher VSWR peaks at specific frequencies suggest some impedance mismatches, which could be optimized further for better performance.

The VSWR characteristics further confirm the effective impedance matching of the MIMO antenna at key resonant frequencies such as 2.3 GHz, 3.5 GHz, and 5.4 GHz, where the VSWR values drop below 2, indicating efficient power transfer with minimal reflection. The close alignment of the curves for all four ports demonstrates uniform performance and symmetry in the antenna structure, which is essential for MIMO systems to ensure consistent signal quality across multiple channels. Although some frequencies exhibit higher VSWR values, these occur outside the main operational bands and are common in broadband antenna designs. Overall, the VSWR behavior highlights the antenna's capability to support multiband applications while maintaining good impedance matching in its intended frequency ranges.

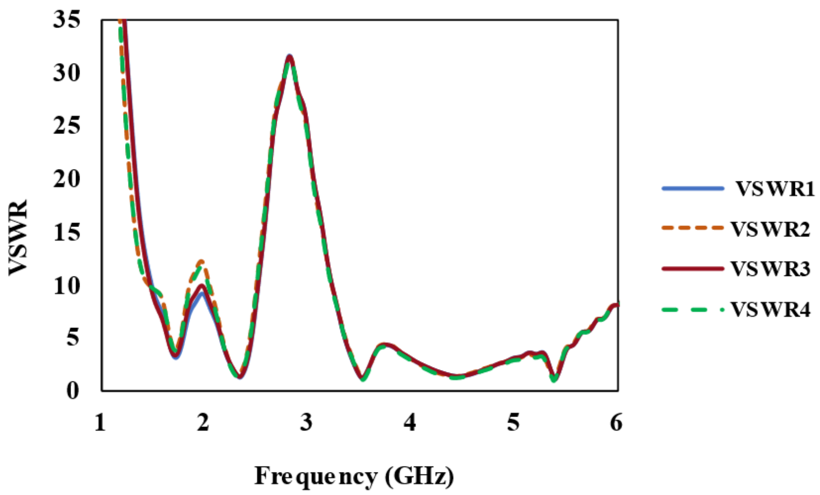


Fig. 4.12 VSWR of the MIMO antenna

4.2.5 Radiation Pattern

The radiation patterns at 2.3 GHz in Fig. 4.13(a) demonstrate that the proposed MIMO antenna exhibits directional radiation behavior with slight asymmetry across the four ports. The plots show significant radiated power concentrated in specific directions, which is a characteristic feature of patch-based antennas. Each port displays distinct yet consistent main lobes, ensuring spatial diversity and effective signal transmission. The clear separation of the lobes across the ports indicates low mutual coupling and good isolation, making the antenna suitable for reliable MIMO operations in the lower frequency band.

At 3.5 GHz, the radiation characteristics in Fig. 4.13(b) become more defined with improved symmetry and narrower beamwidths. The far-field directivity patterns indicate stronger directivity and more focused radiation, which is beneficial for minimizing interference and improving channel capacity in MIMO systems. The consistent coverage across all four ports at this frequency enhances the spatial multiplexing capabilities, which is essential for 5G and sub-6 GHz applications. The radiation patterns suggest good polarization diversity, with each port maintaining unique directional characteristics without significant overlap.

At 5.4 GHz, the antenna displays compact and more directive radiation patterns in Fig. 4.13(c) with enhanced gain. The lobes become sharper, and the null regions are more pronounced, indicating reduced back radiation and improved forward gain.

Such characteristics are highly favourable for high-frequency wireless communication systems where directionality and high efficiency are crucial. Despite the frequency increase, the radiation patterns remain stable across all four ports, showing the robustness of the antenna design. This confirms the antenna's suitability for wideband MIMO applications with consistent radiation performance across multiple bands.

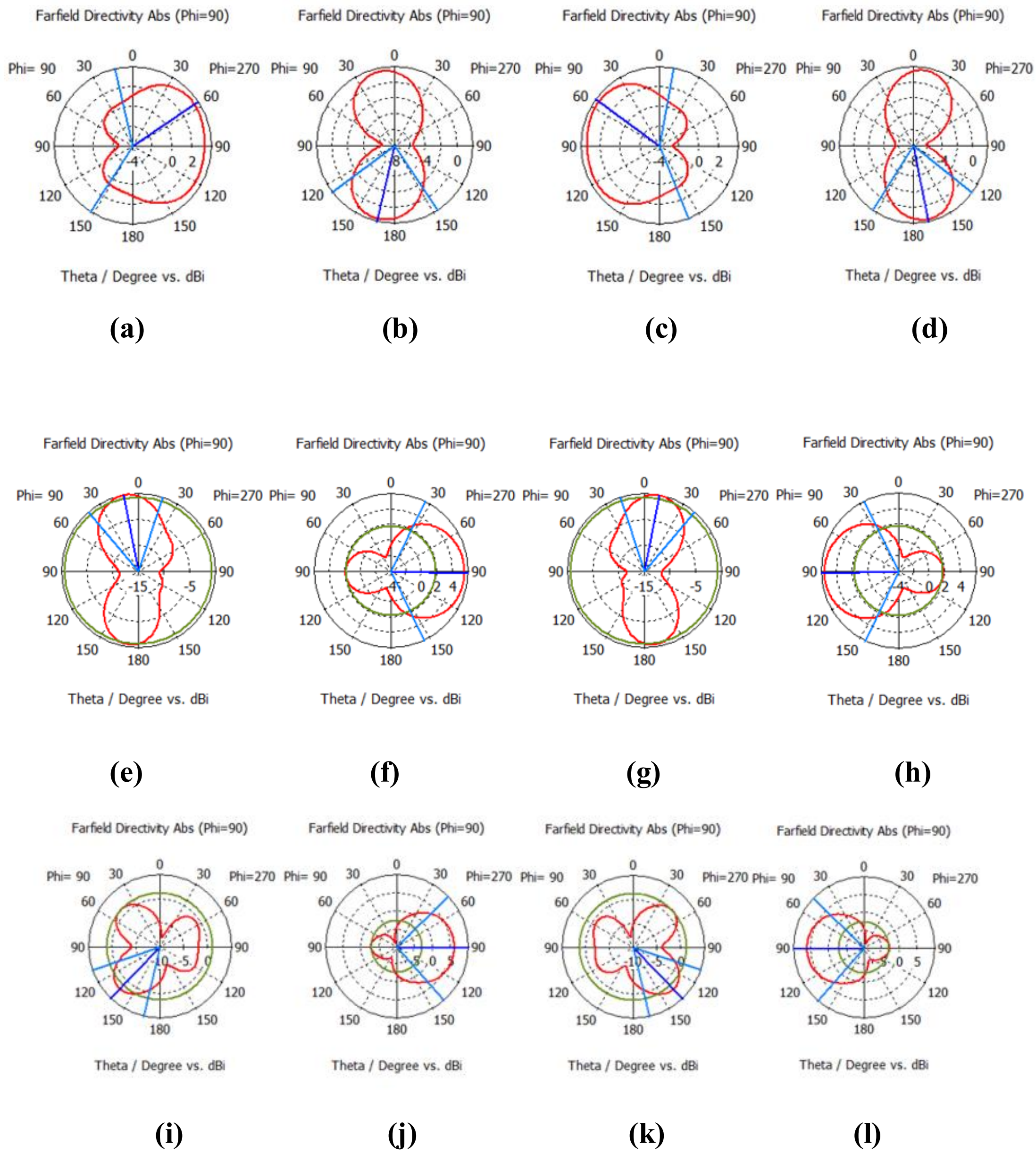


Fig. 4.13 Radiation characteristics of the MIMO antenna:
(a) At 2.3 GHz (port 1) (b) At 2.3 GHz (port 2) (c) At 2.3 GHz (port 3) (d) At 2.3 GHz (port 4) (e) At 3.5 GHz (port 1) (f) At 3.5 GHz (port 2) (g) At 3.5 GHz (port 3) (h) At 3.5 GHz (port 4) (i) At 5.4 GHz (port 1) (j) At 5.4 GHz (port 2) (k) At 5.4 GHz (port 3) (l) At 5.4 GHz (port 4)

4.3 PERFORMANCE ANALYSIS OF THE RECTIFIER

The performance analysis of the rectifier in the proposed rectenna system is crucial to evaluate its efficiency in converting captured RF energy into usable DC power. Key parameters considered include return loss, which ensures proper impedance matching and minimal reflection; output DC voltage versus input RF power, which illustrates the voltage response at varying power levels; and Power Conversion Efficiency (PCE), representing the ratio of the output DC power to the input RF power. These characteristics collectively determine the rectifier’s ability to operate effectively across the intended frequency range. The analysis confirms that the rectifier demonstrates consistent voltage output and reasonable efficiency within the operational band, making it suitable for wireless power harvesting applications.

4.3.1 Return Loss Characteristics

The Return Loss (S11) Characteristics of the proposed circuit illustrate its impedance matching efficiency across different frequency bands. As observed in the graph in Fig. 4.14, the circuit exhibits three resonance points at 2.39 GHz, 3.54 GHz, and 5.46 GHz, with corresponding return loss values of -14.210 dB, -14.515 dB, and -14.214 dB, respectively. A return loss below -10 dB indicates good impedance matching, minimizing reflections and maximizing power transfer. These results validate the circuit's suitability for multiband applications, ensuring effective signal transmission with minimal losses.

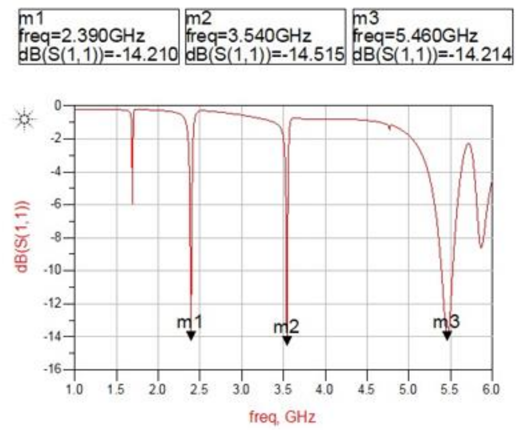


Fig. 4.14 Return loss characteristic of the rectifier

4.3.2 RF to DC Power Conversion Efficiency

The RF-to-DC power conversion efficiency (PCE) is a critical metric in evaluating the effectiveness of a rectifier circuit in a rectenna system as depicted in Fig. 4.15. It represents the percentage of the input RF power that is successfully converted into usable DC power. This efficiency is influenced by factors such as input power level, impedance matching, rectifying circuit design, and load resistance. A higher PCE indicates better energy harvesting capability, which is essential for powering low-power electronic devices in wireless applications. In the proposed design, the PCE analysis helps assess how efficiently the system converts ambient RF signals into DC output across different input power levels, ensuring optimal performance under varying environmental conditions.

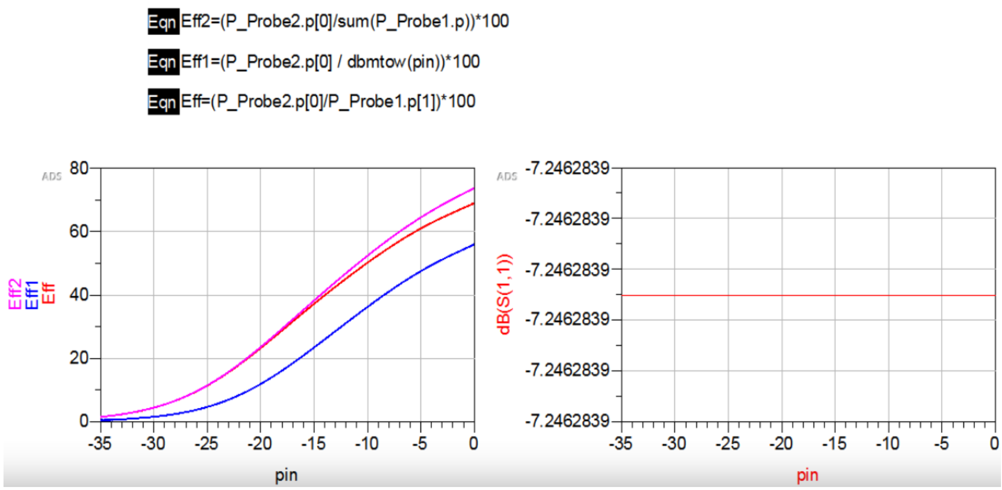


Fig. 4.15 RF to DC Power Conversion Efficiency

Return loss and RF-to-DC power conversion are critical parameters in the performance evaluation of a half-wave rectifier, particularly in wireless energy harvesting systems. Return loss indicates how effectively the rectifier matches the input impedance to minimize power reflection, ensuring maximum RF signal capture. A higher return loss signifies better impedance matching and efficient energy transfer. The RF-to-DC power conversion efficiency measures the rectifier's ability to convert incoming RF signals into usable DC power. In a half-wave rectifier, the design of the rectifying diode and the load impedance play vital roles in optimizing this efficiency.

Chapter – 5
CONCLUSION AND FUTURE SCOPE

5.1 CONCLUSION

Advancements in wireless communication and battery technology have enabled devices to function without physical connections. Most electronic devices in wireless systems rely on cable-based power supplies or battery sources, leading to challenges such as high maintenance costs, frequent charging, and battery disposal issues due to performance degradation over time. In critical applications like implantable biomedical devices and wireless sensor networks, these limitations can have serious consequences. Therefore, an alternative power source is essential to address these challenges. Wireless RF energy harvesting offers a promising solution by enabling efficient wireless power transfer. A rectenna is used to capture and convert RF energy from the surrounding environment. The key performance metric of a rectenna is its RF-to-DC conversion efficiency (η%), which depends on factors such as antenna design, input power density, rectifier efficiency, and impedance matching. Improving rectenna efficiency requires addressing these critical aspects to enhance overall energy harvesting performance.

The most important part of wireless RF energy harvesting is the rectenna. The performance of the rectenna is justified by RF to DC conversion efficiency, which determines the effectiveness of energy harvesting. This research work focuses on the design and analysis of textile-based rectenna structures for ambient RF energy harvesting. The antenna is designed using denim as the substrate, while the rectifier is implemented with FR4 as the substrate. The rectenna geometries are proposed for three different ambient frequencies, namely 2.3 GHz, 3.5 GHz, and 5.4 GHz, respectively. A complementary split-ring resonator (CSRR) antenna is designed and analyzed for efficient energy harvesting. The designed antenna resonates at 2.3 GHz with a return loss of -12.02 dB, at 3.5 GHz with a return loss of -26.35 dB, and at 5.4 GHz with a return loss of -22.81 dB. The peak gain of 6.35 dBi is achieved at 5.4 GHz, indicating good radiation performance. The proposed rectenna structures are optimized to enhance RF to DC conversion efficiency and improve overall energy harvesting capabilities.

The results demonstrate the feasibility of using textile-based rectennas for ambient energy harvesting applications.

5.2 SCOPE OF FUTURE WORK

The future research direction for RF energy harvesting focuses on its implementation in wireless-powered wearable electronics. The proposed rectenna will facilitate real-time wireless powering, eliminating the dependency on traditional batteries and reducing the need for frequent recharges. This will significantly enhance the lifespan and efficiency of wearable devices while improving user convenience. Further advancements in rectenna design will aim to improve RF to DC conversion efficiency through reconfigurable antennas. These antennas dynamically alter their radiation pattern and polarization using integrated switches, ensuring optimal energy capture. A promising research avenue is the development of reconfigurable rectennas, which can efficiently harvest RF energy from multiple sources such as Wi-Fi, Bluetooth, and cellular networks, maintaining a stable and high DC output voltage. In addition, multi-port rectennas offer an efficient solution for wearable applications by utilizing multiple antenna elements. Each antenna port captures energy from different directions and polarizations, ensuring a consistent power supply in dynamic environments. This is particularly useful for wearable devices such as smart textiles, health monitors, and fitness trackers, which require a continuous and reliable energy source. Another crucial area for future research is the design of advanced rectifier circuits. While the proposed system includes single-stage full-wave and half-wave rectifier circuits, future studies can explore multistage cascaded rectifier circuits. These can significantly boost conversion efficiency while ensuring a compact and low-complexity design suitable for next-generation self-sustained wearable electronic systems. With wearable technology advancing rapidly and increasing power consumption demands, developing high-efficiency RF energy harvesting rectennas is a highly recommended research area. A successful implementation would lead to self-sustaining wearable electronics, eliminating the need for traditional battery charging and enhancing user convenience while ensuring a sustainable and efficient power source for emerging technologies.

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