

CRANFIELD UNIVERSITY

EZEKIEL DARLINGTON NWALIKE

ENHANCEMENT OF RADIO FREQUENCY ENERGY
HARVESTING USING EMBROIDERY CONDUCTIVE THREAD
AND IMPROVED POWER MANAGEMENT CIRCUIT DESIGN

SCHOOL OF WATER, ENERGY AND ENVIRONMENT, CRANFIELD
UNIVERSITY, CRANFIELD

PhD in Energy and Power

DOCTORATE PROGRAM IN ENERGY AND POWER
ENGINEERING

Academic Year: 2019 - 2023

Supervisor: Dr Jerry Luo
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This thesis is submitted in partial fulfilment of the requirements for
the degree of PhD.

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based solely on examination of the thesis)***

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ABSTRACT

The global demand for remotely powering electronic devices without batteries, particularly for low-power electronics, through ambient RF (Radio Frequency) energy harvesting is increasing. However, several challenges must be addressed for Radio Frequency energy harvesting to achieve its full potential in wearable technology. These challenges include: 1. Maintaining continuous and steady conductivity of the antenna patch in RF energy harvesting (RFEH) devices. 2. Enhancing the efficiency of current rectification and power management circuits at extremely low power levels. This PhD project aims to overcome these obstacles by employing innovative embroidery conductive thread technology, which offers more uniform conductivity compared to traditional ink-based fabrication techniques. Additionally, the project focuses on designing an improved rectifier for the power management circuit. The proposed rectenna patch antenna is based on a 50-ohm impedance matching network. The design, simulation, optimization, and efficiency results of the rectenna patch antenna were recorded. The fabrication involved creating an efficient patch on both a textile substrate using conductive threads and a plastic substrate using liquid metal alloys. An embroidery machine was used for the textile design, while an inkjet printer was utilized for the plastic substrate. The harvested energy results were documented, demonstrating an improvement in the current wearable RF power harvesting system. This study provides valuable insights into materials, antenna design, and power management systems, advancing the state-of-the-art in RF energy harvesting and paving the way for further research and development.

Keywords:

Radio Frequency, power harvesting, power efficiency, rectifiers, radiation pattern, antenna fabrics, rectenna, boost converter.

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LIST OF ABBREVIATIONS

AC	Alternating Current
AEH	Ambient Energy Harvesting
AMC	Artificial Magnetic Conductor
DC	Direct current
EBG	Electromagnetic Damping and Energy Harvesting
EH	Electronic Band Gap
EMDEH	Energy Harvesting
IT	Information Technology
LC	Linear Circuit
MPPT	Maximum Power Point Tracker
PBG	Photonic Band Gap
PCB	Printed Circuit Board
RF	Radio Frequency
RFEH	Radio Frequency Energy Harvesting
RFID	Radio Frequency Identification
SRR	Split Ring Resonator
WPT	Wireless Power Transfer
WSN	Wireless Sensors Network

1 INTRODUCTION

1.1 Background

Energy Harvesting (EH) is the process through which energy is derived from external sources, captured, and for small, wireless autonomous devices, such as those used in wearable electronics and wireless sensor networks. EH can refer to energy harvesting, which is the process of capturing and converting ambient energy into electrical energy for immediate use or storage. It can also refer to energy storage, particularly in certain contexts or industries where EH may be shorthand for energy harvesting and storage systems. The sources of EH include wind energy, thermal energy (mechanical load), salinity gradients (temperature gradients), kinetic or ambient energy (vibrations), and solar energy (light). Among them, Radio Frequency Energy Harvesting (RFEH) system has been developed to wirelessly power and enable device operation harnessing the RF signals from environment. RFEH is an energy conversion technique employed for converting energy from the electromagnetic field into the electrical domain. That is, into voltages and currents. The RFEH system captures and convert electromagnetic energy into a usable direct current (DC) voltage. The antenna and rectifier circuit that allows the radio frequency power or alternating current (AC) to be converted into DC energy are the key units of radio frequency harvesting system. Tran. et al., (2017). RFEH technique circumvents the need for rigid and dense batteries and has been authenticated through design, simulation, optimization, and experimental results. However, the development of effective and efficient RF electronics for off-body and on-body communications in applications still poses significant challenge (Adami et al., 2018; Nepa and Rogier, 2015; Ojha, Singhal and Thakare, 2022).

Radio frequency (RF) refers to the oscillation rate of an alternating electric current or voltage, as well as the electric, magnetic, or electromagnetic field associated with it. The electromagnetic radiation spectrum encompasses a range of frequencies, spanning from 3 kHz up to 300 GHz. These frequencies are utilised for wireless communications or radar signals. RF waves are generated when an alternating current passes through a conductive material (Rao et al., 2022). They

prove advantageous for wireless energy harvesting, enabling the wireless powering and operation of devices even in scenarios with limited RF energy available. The characteristics of RF include the following: its ability to penetrate walls, its lack of requirement for a direct transmission route, low power consumption (less than 1mW of power), a good operating range (3 to 30 meters), and support for data rates up to 1 to 2 Mbps. The applications of RF technology encompass telemetry, wireless meter reading, remote control, vehicle monitoring, wireless data terminals, access control systems, robot remote control, biological signal acquisition, wireless home security systems, Negra, et al., (2016), Tran, et al., (2017). Currently, RF transmission from hundreds of thousands of radio transmitters is prevalent worldwide, including mobile base stations, cellular phones, and television broadcasting terminals (Saraerel, et al., 2020). In fact, RF is helpful in wireless energy harvesting because it is used to directly power up battery less systems and for battery activation purposes. Also, for remotely battery recharging, waking up sensors in sleep mode.

To integrate wearable electronics and RF wireless power transfer is not an easy task, and currently faces some challenges for apparent reasons, which includes: the steadiness efficiency and radiation pattern of the antenna on the moving body must be accounted for, also the interconnections between rigid and flexible subsystem should be considered, and the power management of the circuits to maximize the power output of the device (Visser, et al., (2012)).

It is significant that radio frequency energy harvesting technique and wireless power transfer (WPT) are potential alternatives in generating clean and renewable power source, which definitely presents a promising scheme in battery-less self-sustaining applications for future (Zhang, et al., 2019). The T shape LC matching network are designed between the antenna and the rectifying circuit to obtain more power transmission. Then the designed antenna array improves the received RF power effectively and also can harvest RF power in multi-frequency bands. With the measured results indicate that these systems can be used to power electronic. Besides, energy harvesting via radio frequency (RF) signals reduces the reliance on the supply of power grid, which makes it

suitable for deployment in cooperative networks given that RF signals can concurrently carry wireless energy and information (Ojo, et al., (2019). The wireless energy harvesting, and information transfer (WEHIT) enables energy constrained cooperative communication nodes to harvest the energy needed for information transmission from electromagnetic radiation sources. Also, the paper deliberated on the challenges to concurrently accomplish wireless information and power transfer (SWIPT) approach, advantages, disadvantages, and solutions to challenges for further research.

Hassan, et al., (2018) carried out research on improving the performance of many radio frequency harvesting device designs, especially in the microwave range area. Using a split ring resonator (SRR) and other metamaterial structure in antenna network applications. They focus on the following performance: the techniques used, dimension, return loss, material of substrate and the resonant frequency of the antenna. The SRR is compared with other metamaterial structure such as photonic band gap (PBG), electronic band gap (EBG) and artificial magnetic conductor (AMC). It was observed that the SRR structure is a good candidate for energy harvesting because it can increase the conversion efficiency. Dieff et al, (2020) demonstrated flexible and light-weight textile-integrated rectenna arrays for powering wearable electronic devices. This method exploits large clothing-areas to integrate arrays consisting of 2×2 and 2×3 rectenna elements. Each element comprises a patch antenna and a rectifier which are fabricated using embroidery of conductive thread on the textile substrates. The rectifier used single-diode circuit configuration and showed a radio frequency (RF)-to-dc conversion efficiency of 70% for an applied input RF-power of 8 dBm at its input port. They also present several tests to demonstrate the applicability of the rectenna array. Specifically, in boosted-Wi-Fi modality. Boosted Wi-Fi modality likely refers to a scenario where the Wi-Fi signal is amplified or enhanced to increase its range or strength. In this context, the rectenna array is designed to capture ambient Wi-Fi signals and convert them into usable electrical power. When the Wi-Fi signal is boosted, it becomes stronger and can potentially provide more energy for harvesting by the rectenna array. Therefore, the term "boosted Wi-Fi modality" in this case is that the Wi-Fi

signal being harvested is not just regular Wi-Fi but has been enhanced or boosted in a way to increase the power available for harvesting by the system. a dc power of 600 μ W was collected at 10 cm from the source and 80 μ W was collected at 60 cm from the source. The demonstrations show a better system's applicability for charging and powering low-power wearable electronic devices.

Adami et al. (2018) have shown that developing a system requires careful design considerations, such as the use of appropriate antennas, rectifiers, and boost converters. Moreover, researchers have been working on developing flexible energy harvesting devices that can be integrated into wearable electronics and other flexible devices. The flexibility of these devices is achieved through the use of materials and manufacturing techniques that enable them to maintain their functionality even when bent or stretched. This could involve using flexible substrates, such as plastics or textiles, and employing novel fabrication methods that accommodate flexibility without sacrificing performance. This technique circumvents the need for rigid, dense, and potentially toxic batteries and has been authenticated through measurement of individual components, simulation, optimisation, and experimental results.

In summary, Energy Harvesting has enormous potential to extend the lifetime of wireless sensors and wearable electronics, which require small amounts of power to operate. Lifetime of wireless sensors and wearable electronics in the context of energy harvesting, it typically refers to how long these devices can remain functional and operational using the harvested energy from their surroundings, without the need for external power sources. Thereby improved an effective and efficient RF electronics for off-body and on-body communications for healthcare applications.

1.2 Problem Statement

The problem of RFEH which demands a viable solution is identified as listed below and will be addressed in detail:

1. The difficulty in maintaining the continuous conductivity of the antenna for RFEH device. To ensure optimal operation and efficient performance of RF power harvesting systems, it is essential to consider the consistent and steady conductivity of the material.

2. The current design rectification and power management circuit cannot operate efficiently at the extremely low power levels. Design rectification" implies that there are issues or shortcomings in the current design of these circuits that need to be addressed in order for the power management system to function effectively at low power levels. This may involve redesigning the circuit layout, optimizing component selection, or improving the efficiency of the rectification process to ensure that the system can efficiently manage and utilize the harvested energy for powering electronic devices. For a low-power electronic device system to advance its functionality from input to output terminals, power management circuit needs to improve.

We looked at RFEH and its upgrades for the energy harvesting (EH) approach. The radiant energy harvesting scenario was examined, including the working environment, adaptable antennas and circuits, constraints of the antenna, fabrication process, and simulation study of the antenna, impedance matching circuit, and needs. The kind of thread, needle, etc., used to create rectenna for needlework was also investigated. Additionally, research was done on the surface impedance of inkjet printing and embroidery patterns.

1.3 Aim and Objectives

The aim of the research is to develop a novel antenna's fabrication to improve its conductivity, as well as improve the net DC output from the RF input source for wearable device applications. To maximize the performance of the device, the materials, antenna, and rectifying circuit have been optimized. Thereby, improving the power efficiency of the device achieved. The outcome was verified between the simulated and manufactured rectenna patches. Additionally, a comparison of the rectenna patch's precise design using two different

manufacturing processes was done. The objectives to achieve this are as followings.

- ❖ Develop a novel antenna material and fabrication technique using a programmable embroidery machine.
- ❖ To design an improved antenna and an improved rectifier circuit of RF power harvesting system for wearable device.
- ❖ Investigate methods to enhance the robustness and flexibility of the antenna material and fabrication technique, ensuring suitability for wearable applications where durability and flexibility are critical.
- ❖ Validate the system design through comprehensive simulations and real-world experiments to ensure optimal performance, efficiency, and reliability of the RF power harvesting system in diverse wearable environments.

1.1 Research Novelty.

The proposed systems use programmable embroidery conductive thread-based material for its technology. Which is flexible, washable, ironable, robust, cost-effective, durable and have uniform continuous conductivity compared to the conventionally used ink-based fabrication technique.

This material development on embroidery antenna is a novel technique developed very recently and has been adapted into this work with several improvements. The previous work in 2020 (Dieff et al., 2020) was focusing on the embroidery technique but no evident on comparing the embroidery antenna to conventional ink-based printed antenna. In this PhD project the technique has been improved with more systematic and comprehensive new approach with evidence to compare performances and to optimise the density of threads, pattern, tension of stitching for high conductivity of the device. Conductive inks are mostly used for antenna in research, However, the method utilized in the project offers enhanced, consistent, and uninterrupted conductivity compared to conductive inks. Additionally, it comes at a lower cost as there is no requirement for bespoke screens and expensive silver inks. Challenge/limitation associated

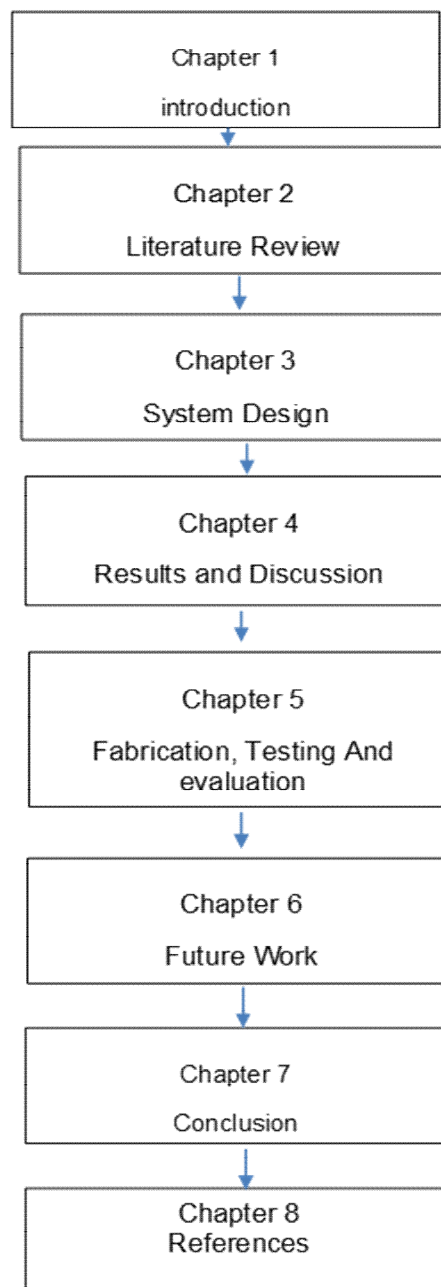
with this method is the selection of material and diode is taken care of. Presently, at the course of printing the designed rectangular microstrip patch antenna with silver ink-printer, it is observed that the single ink print does not conduct while the double printing does conduct. But the single stitching by the embroidery conductive thread conducts perfectly based on its high stitching-density.

In terms of power management, the use of single-diode rectifier to integrate components to achieve fully textile rectenna arrays achieved efficiency up to 70% because single diode can only rectify a single half cycle and reject the other half cycle (Valenta & Durgin, 2014; Hemour et al., 2014; Dieff et al, 2020). Thus, the competence of power handling can be disturbed. Therefore, we have designed a voltage multiplier circuit for energy harvesting and we have also chosen a high frequency diode HSMS 2852 from Skyworks efficient performance. A maximum efficiency of 75% was achieved which is better than that reported (Dieff et al,2020). Another improvement is the limited breakdown voltage which cannot be achieved with a half wave rectifier topology is overcome using this voltage multiplier circuit and matching network in this work.

1.2 Organization of Thesis

This research work is structured in seven (7) chapters to give detailed knowledge on the design and implementation of a wearable device for RF wireless energy harvesting. Introduction to the research background has been discussed in Chapter 1. A concrete background of the research topic will be proffered. Contextual background about the topic area will be expressly provided within the research circumference. In Chapter 2, a review of literature related to the work will be given with relevant concepts to the topic area. Antenna design has been analysed in Chapter 3; this chapter will demonstrate the design of the regular patch antenna by utilizing the proposed software tools and other related designs for device subsystems in general. In Chapter 4, results and discussion will be provided, presenting the findings from the design and simulations. Chapter 5 will cover the fabrication, testing, and evaluation of the device. Test results will be obtained and a comparative analysis with previous work carried out in this area will be made. Detailed

procedures will also be outlined. Chapter 6 will discuss future work, suggesting areas for further research and improvement. Chapter 7 will provide a summary and detailed achievement of the research aims and objectives, conclude the findings, and make necessary and relevant recommendations based on the obtained research results. References will be listed at the end of the thesis.



2 LITERATURE

1.1 Literature Review

These sections provide a comprehensive literature review on radio frequency (RF) energy harvest. It begins with an introduction to energy harvest, and radio frequency. It then discusses material, designs, challenges, and future research in RF energy harvest.

2.1 Introduction

Energy Harvesting (EH) is the process through which energy is derived from external sources, captured, and stored for small, wireless autonomous devices, such as those used in wearable electronics and wireless sensor networks. The sources of EH include wind energy, thermal energy (mechanical load), salinity gradients (temperature gradients), kinetic or ambient energy (vibrations), and solar energy (light). Among them, RFEH system has been developed to wirelessly power and enable device operation harnessing the RF signals from environment. This technique circumvents the need for rigid and dense batteries and has been authenticated through design, simulation, optimization, and experimental results. However, the development of effective and efficient RF electronics for off-body and on-body communications in applications still poses significant challenges (Adami et al., 2018; Nepa and Rogier, 2015; Ojha, Singhal and Thakare, 2022).

RF waves are generated by the flow of alternating current through a conductive material. This generation process is fundamental to various wireless systems, including those used in telecommunications and data transmission. As RF waves travel through space, they carry the information embedded within them, allowing for the exchange of data between wireless devices and networks (Rao et al., 2022). Furthermore, RF technology supports data rates ranging from 1 to 2 Mbps, enabling the transmission of moderate to high volumes of data. This capability is essential in applications requiring real-time communication or the exchange of large data sets, such as video streaming, sensor data transmission, and remote monitoring. The versatile applications of RF technology have led to its widespread

adoption in various industries and domains. For instance, telemetry systems utilize RF technology to collect and transmit data from remote locations, facilitating data acquisition and analysis in various fields such as environmental monitoring and scientific research (Negra, Jemili and Belghith, 2016; Tran, Cha and Park, 2017). The widespread prevalence of RF transmission is evident in the global presence of hundreds of thousands of radio transmitters. These transmitters serve diverse purposes, including mobile base stations, cellular phones, and television broadcasting terminals, forming the backbone of modern communication systems (Saraereh et al., 2020a). Additionally, RF technology plays a vital role in remote battery recharging, enabling devices to be powered up without the need for direct physical connections. This capability is particularly useful in applications where constant access to power sources is impractical or challenging.

Energy harvesting has gained significant attention in recent years as a promising field for capturing and converting ambient energy into usable electrical power. This approach offers distinct advantages, especially in applications where conventional battery-based power sources are not feasible or have limitations in terms of lifespan and power density. By harnessing energy from sources like light, heat, vibration, and radio frequency (RF) signals, energy harvesting technologies provide a sustainable and self-sufficient solution for powering various devices and systems. This growing interest in energy harvesting stems from its potential to address challenges in renewable energy, wireless sensor networks, Internet of Things (IoT), and wearable electronics.

Zhang et al. conducted research on the design of a radio frequency (RF) energy harvesting for battery-less self-sustaining applications. To enhance power transmission, an antenna and rectifying circuit were designed, utilising a T-shape LC matching network in between. The designed antenna array facilitates the harvesting of RF power in multiple frequency bands, and the received RF power is improved and utilised for powering electronic devices. The study demonstrates the potential of RF energy harvesting for powering low-power devices and highlights the importance of optimizing the antenna design and matching circuit

for maximum power transfer efficiency (Zhang et al., 2019). This research is relevant for the development of sustainable and energy-efficient wireless communication systems for the Internet of Things (IoT) and other applications.

Adami et al. emphasized the importance of the material used in the fabrication of antenna designs, as it directly impacts the amount of RF energy that can be harvested and wirelessly transferred to power electronic devices (Adami et al., 2018). Fabric antennas, which are made of textile materials, are gaining popularity due to their flexibility and comfort in wearable technology applications (Shen et al., 2022; Singh et al., 2022a; Visser et al., 2012a). On the other hand, rectenna arrays are used to convert electromagnetic energy into direct current (DC) electricity. These arrays consist of multiple dipole elements and are useful in harvesting RF energy from various sources such as ambient radiation, Wi-Fi signals, and cellular networks. The size and arrangement of rectenna elements affect the overall efficiency of energy conversion, making it an important consideration in the design of energy-harvesting systems. Figure 2.1 further Shows the components for the RF power harvesting system.

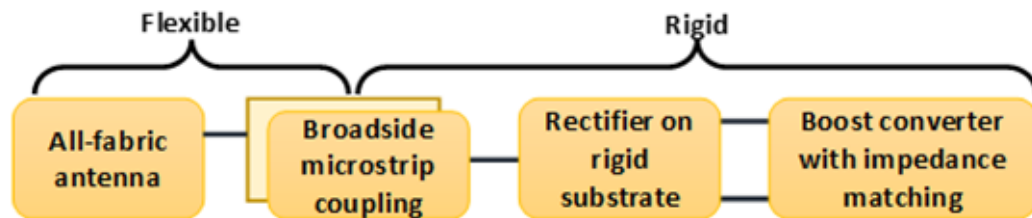


Figure 2.1 Block diagram of the radio frequency (RF) power harvesting system as reproduced from (Adami et al., 2018).

Integrating wearable electronics with RF wireless power transfer is not an easy task and currently faces several challenges for obvious reasons. These challenges include accounting for the stability, efficiency, and radiation pattern of the antenna on the moving body (Shen et al., 2022). According to (Singh et al., 2022a), the main challenge in the RF powered dual hop relay system is achieving high energy harvesting is compounded by the inherent nature of RF propagation,

which is associated with very high transmission path losses. Additionally, the interconnections between the rigid and flexible subsystems are taken into consideration, along with the power management of the circuits, to maximise the power output of the device (Visser et al., 2012b). Broadside and omnidirectional antennas have been employed to fabricate textile rectennas operating in the UHF to millimeter-wave (mmWave) frequency range (Bharti et al., 2019; Li et al., 2019; Tan et al., 2019; Xu, 2018)]. However, the rectennas described above have only been studied and characterised as steady-state continuous power sources. In the past, rectennas coupled with energy storage devices have been the subject of system-level experiments. For example, rectennas were connected to a Power Management Integrated Circuit (PMIC) boost converter in a commercial setting (Adami et al., 2015; Akhtar and Rehmani, 2015; Bahk et al., 2015; Nawale and Zope, 2015). In (Akhtar and Rehmani, 2015), a sensor node was charged for 8 minutes by an incident RF power density of 12.6 W/cm^2 before being powered by a 7mF commercial supercapacitor. In (Tan et al., 2019), a 1.3 mF electrolytic capacitor was charged while a textile-based rectifier was described. In (Haagenson et al., 2015), a rectenna integrated with an electrolytic capacitor and a buck converter with a range of up to 2 m was presented as a sensor node for railway monitoring. For sub- W/cm^2 power densities, a 3D-printed enclosure incorporating RFEH, and a solar cell was employed to charge an electrolytic capacitor through a boost converter IC.

Currently, electromagnetic waves are utilised to power implantable biomedical devices, enable wireless charging, support WSN (Wireless Sensor Network) nodes, and power other devices. Radio frequency recording is especially important in biomedical devices, especially when implanted in the body, to extend the life of the batteries in their structure. RF has become an important energy source due to the abundance of 300 MHz to 3 GHz RF waves in various wireless applications such as broadcast, mobile, satellite and Wi-Fi communications (Lu et al., 2019). This abundant energy can be harvested and stored in batteries for IoT applications.

In summary, the integration of wearable electronics and RF wireless power transfer poses significant challenges due to various reasons (Lu et al., 2019). Firstly, the interconnections between rigid and flexible subsystems must be carefully designed to ensure reliable and contactless electrical connections. Secondly, the stability and efficiency of the antenna on a moving body must be considered to ensure continuous power transfer. Lastly, effective power management strategies must be employed to maximize the power output of the device while minimizing power losses. So, while efficiency is undoubtedly a key consideration in power management, the statement may have chosen to highlight the broader goal of maximizing power output alongside minimizing losses to underscore the importance of effectively utilizing the available energy. Despite these challenges, the potential benefits of RF wireless power transfer for wearable electronics, such as self-sustainability, convenience, and safety, make it a promising technology for future applications. This thesis reviews the state-of-the-art for RFEH in the three main areas of materials, antenna design and power management, to provide an overview of the technology and its future trend.

2.2 Materials

In (Xu, 2018), a review is conducted on textile applications in antenna design, with an emphasis on developments in e-textiles, including surface resistivity. The use of textiles in antenna design aids in collecting health-related data and communicating data with devices. This application of textiles in electrical engineering, known as smart clothing or e-clothing, dates back to 1993.

The efficiency of the antenna in transmitting wirelessly available energy is determined by the RF power harvested. Additionally, the resistivity of a material is important as it enables the use of suitable materials in the appropriate places in electrical and electronic components. Textile-based antennas demonstrate potential in wearable devices for communicating various information with other electronics or computers. Integrating wearables directly into clothing (smart or e-clothing) is more convenient than attaching them to the body (Hasni et al., 2021; Ramesh Varma et al., 2023). The surface resistivity and non-conducting textiles. Surface resistivity is used to evaluate insulative materials where high resistance

characteristics are desirable (Chouhan et al., 2023). Non-conductive materials, also known as insulators, either prevent or block the flow of electrons. This aspect affects the wireless energy transfer to devices, as it bridges the connectivity to the flow of electrons.

Therefore, there is a demand for using materials with the lowest loss and thicker structures (Boyes et al., 2012). Thicker materials with high resistivity help reduce the electric fields on the body, thus lowering the antenna performance itself for the same input power. Variation in distance also aids in minimising harm to the user's body. The use of multi-band antennas is also beneficial in assessing the performance of textile devices. Hence, it is necessary to choose or select suitable materials, as shown in Tables 2-1. The choice of material in fabricating the antenna design is of utmost importance. It determines the amount of RF energy that can be harvested and transferred wirelessly to power system devices, as depicted in Figure 1. Thus, it enhances the efficiency and widens the frequency range of the RF energy harvesting system. The focus on fabric materials in this selection is to cater to a wide range of device applications and improve the efficiency of the RF devices. The selection of cotton fabrics and polyester materials is due to their extensive use in the industry, as detailed in Table 1.

Table 2-1 Surface resistivity of some commercial e-textiles and permittivity of commonly used fabrics (Xu, 2018).

Surface resistivity affects the electrical conductivity of the material, which in turn influences the efficiency of energy conversion in PV cells. The basic equation for the power output of a PV cell can be expressed as:

$$P = V_{oc} \times I_{sc} - I^2 \times R_{Loss}$$

Where:

P is the power output of the PV cell,

V_{oc}

is the open-circuit voltage,

I_{sc}

is the short-circuit current,

I

I is the operating current, and

R_{loss}

are the total resistance losses in the PV cell.

The impact of surface resistivity on energy harvesting can be indirectly inferred through its influence on these resistance components. Lower surface resistivity typically leads to lower series resistance and higher shunt resistance, which can result in reduced overall resistance losses and improved power output efficiency in PV cells.

E-Textile	Surface Resistivity (Ω^2)
Silver jersey Knit fabric	2
Silverell fabric	5
Nickel Copper ripstop fabric	0.03
Pure copper polyester taffeta fabric	0.05
Ripstop silver fabric	0.25
Commonly Used Fabrics Permittivity (ϵ)	
Fabrics	Permittivity ($\times 10^{-2}$)
Wash cotton	151
Curtain cotton	147
Polyester	144
Polycot	156
Jeans cotton	167
Floor spread	146

The selected materials discussed above focus solely on fabric materials for a wide range of applications. The topmost materials are polyester and cotton fabrics, widely used in the garment industry. Additionally, there is an UV-curable polyurethane acrylate-based standard interface material and a waterproof interface material from Smart Fabric Inks limited. In this work, the two-line method, as shown in the above Table 2-2, is used to characterise various flexible materials and textile. It provides an estimation of the material characteristics over a relatively wide frequency range. It was observed that the loss tangent for these

materials is estimated to have better or similar accuracy than that obtained with FR4.

Table 2 2 RF harvester system

Parameters	Dedicated RF Harvester System	Ambient RF Harvest Systems
Sources	Dedicated RF Sources	Ambient RF Sources
Energy Cost	Cost of Dedicated Source	Cost Free Source
Compatibility	Suitable for devices with QoS (Quality of Service) constraints and fully controllable.	Not controllable
Reliability	Predictable energy supplier	Unpredictable energy supplier

Furthermore, in (Paracha et al., 2019a), a research review is conducted on materials, structure, and innovative features in communication and sensing. It is noted that flexible materials in a low-profile structure are required when used on different parts of the human body for wearable antenna design. The low-profile antenna structure can also be mounted on buildings and cars. These antennas

often have high input impedance and maintain small height and width, mostly in the form of microstrip patch antennas (Xu, Flandre and Bol, 2023). An antenna system comprises a source, destination, and relay, where the source generates and transmits the signal, the destination receives and processes the signal, and the relay acts as an intermediary for enhanced communication (Singh et al., 2022b). The relay in an antenna system acts as a vital intermediary by performing various functions to enhance communication reliability, range, and efficiency between the source and destination. Its role is to overcome challenges and optimize signal transmission, ensuring seamless connectivity in wireless communication networks.

Moreover, according to [statista.com/statistics](https://www.statista.com/statistics) that approximately 28 billion smart devices will be connected worldwide using legacy technologies in 2021. This connection will be highly advantageous for applications in consumer electronics, building security, and automation. Once accomplished, RF energy will provide improved value for wireless energy harvesting globally.

Additionally, surface resistivity is utilised to evaluate insulative materials, where high resistance characteristics are desirable, as indicated in Table 2.2 Overall, high resistance characteristics in insulative materials are desirable because they contribute to the safety, reliability, and performance of electrical and electronic systems. They help ensure effective electrical insulation, minimize leakage currents, and provide stability in various operating conditions, making them essential for a wide range of applications in consumer electronics, building security, automation, and beyond. wireless energy harvesting plays a vital role in ensuring the harvest and storage of RF energy to power electronic devices remotely, while also promoting self-sustainability and environmental friendliness by harnessing RF energy from the surrounding environment as shown in Figure 2-2. With the advancements in broadcasting technologies, the availability of ambient RF power density has exponentially increased. Sources of RF power density include wireless fidelity (Wi-Fi) signals (Bharti et al., 2019; Du et al., 2018; Habibzadeh et al., 2018; Li et al., 2019; Xu, 2018), AM/FM radio (Kursheed and Budyal, 2018; Wang et al., 2018), mobile base stations (Adami et al., 2018;

Agiwal, Roy and Saxena, 2016; Ibrahim, Karami and Jafari, 2017; Ur-Rehman et al., 2017; Wen et al., 2018; Yang et al., 2017), television (TV), and digital television (DTV) (Akhtar and Rehmani, 2015; Bahk et al., 2015; Lakshmanan and Sukumaran, 2016; Nawale and Zope, 2015), as illustrated in Figure 2.

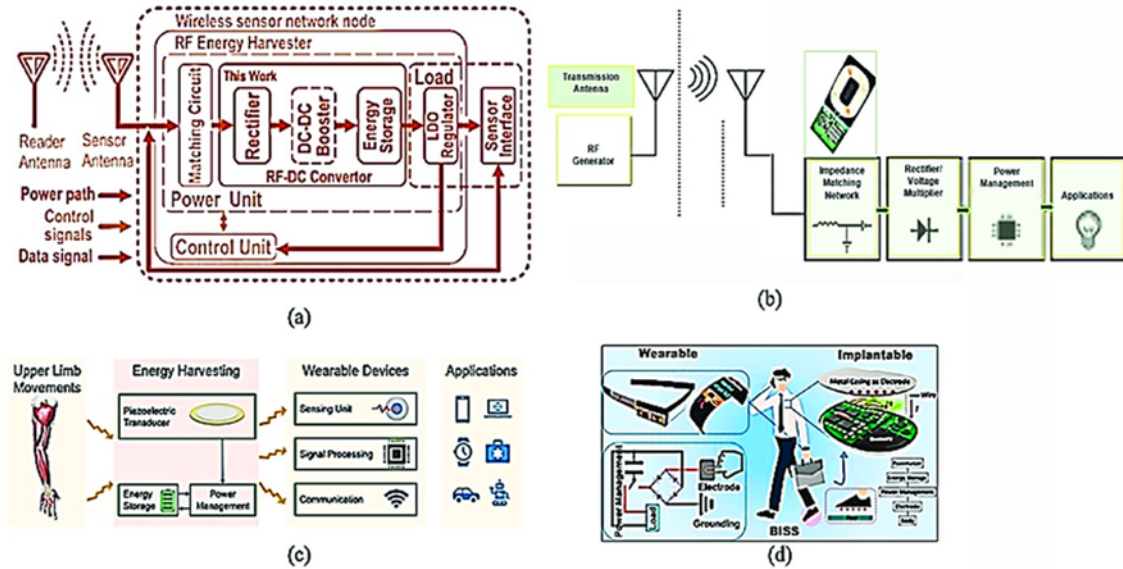


Figure 2-2 (a) Radiofrequency (RF) energy harvester block diagram (Moghaddam et al., 2017). (b) An overview of RF energy harvesting (IoT Design Pro, 2021). (c) Piezoelectric energy harvesting for applications involving wearable, self-powered upper limbs (Liu et al., 2021). (d) Devices that harvest energy include the reintroduction of device power. By reintroducing harvested energy back into the device, it becomes more self-sustaining and less reliant on external power sources such as batteries or charging stations. This can enhance the device's autonomy, convenience, and usability, especially in scenarios where frequent battery replacements or recharges are impractical or inconvenient, such as in wearable applications.

A self-powered triboelectric tactile sensor with metallised nubs, which enables the sensor to generate its own power is shown in Figure 2.3. The flexible printed circuit plays a crucial role in the system. This flexible printed circuit features a grating slider. The grating slider likely serves to improve the flexibility and durability of the flexible printed circuit, ensuring that it can withstand bending and flexing motions while maintaining its electrical conductivity and structural integrity.

That enhances its flexibility, as well as a microfluidic-based sweat sensor diagram that is seamlessly integrated with the flexible circuitry, as illustrated. These components work together to enable the ultra-thin epidermal piezoelectric sensor to accurately monitor arterial pulses in real-time while ensuring comfort and flexibility for the wearer (Song et al., 2020).

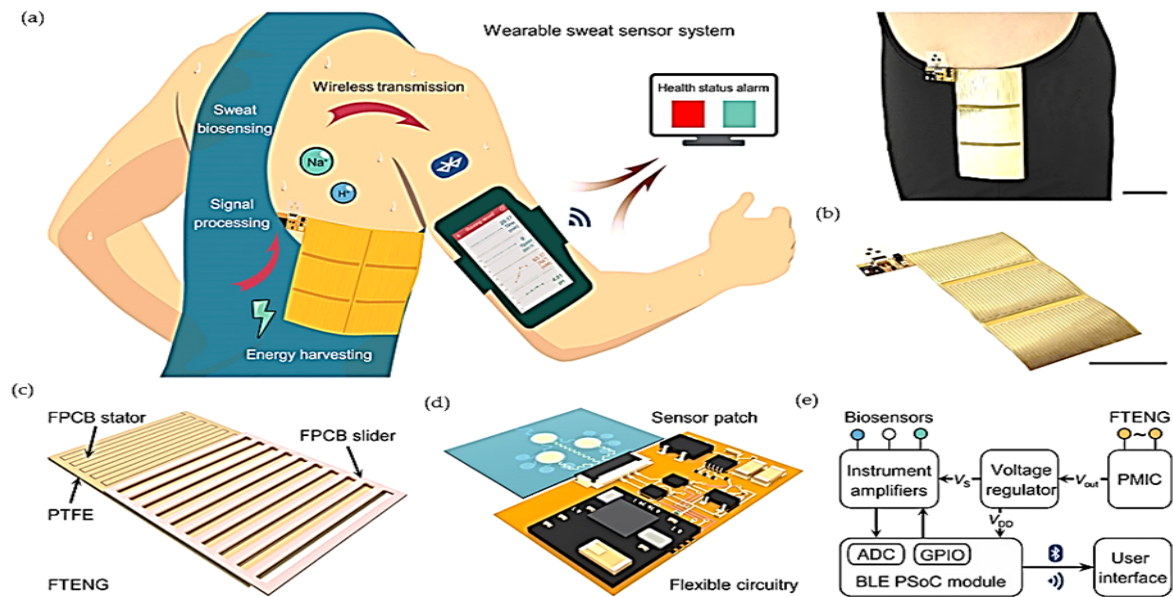


Figure 2.3 Ultra-thin epidermal piezoelectric sensor for self-powered, real-time arterial pulse monitoring (Song et al., 2020). **(a) Triboelectric tactile sensor with metallised nubs that is self-powered. (b) 4cm optical image of a flexible printed circuit (c, d, and e) Flexible printed circuit with grating slider, microfluidic based sweat sensor diagram integrated with flexible circuitry, and clock diagram of overall system.** PIO: GPIO stands for General-Purpose Input/Output. It refers to pins on a microcontroller or other digital device that can be configured to serve as either inputs or outputs. GPIO pins are commonly used to interface with external sensors, actuators, and other peripheral devices in embedded systems. They can be programmed to read digital signals from sensors or to control the state of connected devices by toggling their output voltage levels.

BLE PSoC: BLE stands for Bluetooth Low Energy, which is a wireless communication protocol designed for low-power, short-range applications such

as wearable devices, IoT sensors, and smart home appliances. PSoC stands for Programmable System-on-Chip, which is a family of microcontroller units (MCUs) developed by Cypress Semiconductor (now part of Infineon Technologies). A BLE PSoC device is a microcontroller unit that integrates Bluetooth Low Energy capabilities along with programmable digital and analog peripherals, allowing for flexible and customizable designs for Bluetooth-enabled applications.

FTENG: FTENG stands for Flexible Triboelectric Nanogenerator. Triboelectric nanogenerators (TENGs) are devices that convert mechanical energy, such as motion or vibrations, into electrical energy through the triboelectric effect and electrostatic induction. FTENG specifically refers to a type of TENG that is designed to be flexible, allowing it to conform to curved or irregular surfaces. FTENGs have applications in energy harvesting from human motion for wearable electronics, self-powered sensors, and other flexible electronic devices.

Figure 2.4 (a) illustrates commonly used configurations for RF energy harvesting setups. The depicted setup demonstrates the viability of powering multiple wearable devices through RF energy harvesting, thereby enabling self-sustainability and eliminating the need for external power sources in various applications including healthcare monitoring, sports, and IoT devices (Shi et al., 2018). In Figure 4 (b), the illustration demonstrates the contact of both signal and ground electrodes of the transmitter and receiver with the skin, facilitating energy harvesting from this contact area (Celik, Salama and Eltawil, 2022; Yoo et al., 2023).

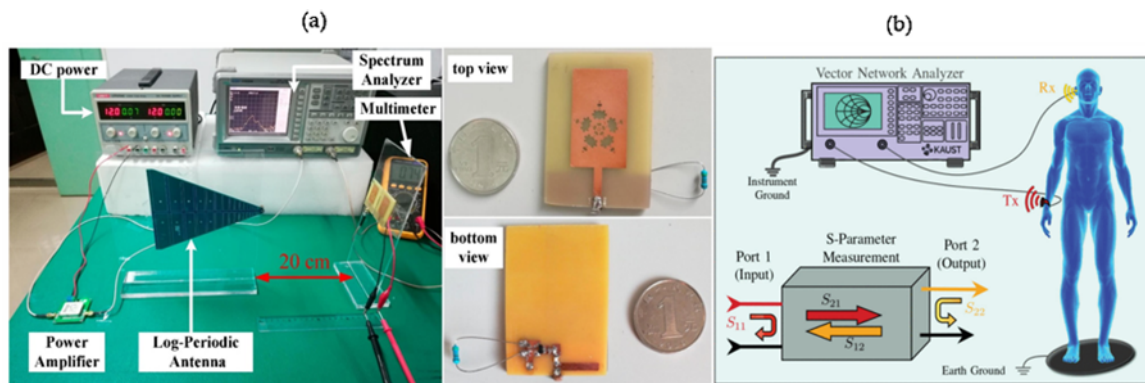


Figure 2-4 (a) Complete measurement setup for RF energy harvesters (Shi et al., 2018). **(b) Multiple wearable devices can be powered by body-coupled energy harvesting** (Celik, Salama and Eltawil, 2022).

RFEH technology has many advantages over other energy sources such as thermal, solar and vibration. The popularity of radio frequency energy makes it suitable for providing stable power for many biomedical devices. Stable power in the context of RFEH technology for biomedical devices means consistent and reliable electrical energy supply, ensuring the continuous and uninterrupted operation of these devices, thereby contributing to their reliability, accuracy, and effectiveness in medical applications. RFEH is a low energy technology (other than solar) that can be used to power IMDs. IMDs stands for Implantable Medical Devices. These are medical devices that are implanted inside the body to monitor physiological parameters, deliver therapeutic treatments, or perform other medical functions. Examples of IMDs include pacemakers, implantable cardioverter-defibrillators (ICDs), neurostimulators, drug infusion pumps, and implantable glucose monitors, among others. Unlike solar (Photovoltaic), and solar thermal methods, RFEH is not affected by light, physical motion, or heat. The working distance of the cutting machine depends on the operating frequency. It defines the DC output power performance of the RFEH system. The performance of the RFEH system can be clearly explained by monitoring it with an open load, as the load voltage and current are dependent on the load impedance. In some applications, such as measuring equipment, voltage is more important than current. In contrast, in others, such as LEDs, current is most important. The sensitivity of an RPEC system is defined as the minimum power required for operation. Sensitivity trade-offs are affected by the input impedance of the Complementary Metal Oxide Technology (CMOS), and efficiency is negatively affected by the leakage current of the high-performance node.

2.2.1 Flexible and Rigid Material

Flexible materials are characterised by their ability to bend or compress easily without cracking under normal conditions. One example of such material is graphene, which is the thinnest and strongest existing material. In its carbon form,

graphene can conduct electricity and heat more effectively. Flexible materials are often used in packaging applications, such as pouches, liners, and seals. On the other hand, non-flexible (rigid) materials are those that cannot be easily bent without breaking. These materials maintain their shape and can support their own weight when rested upon parallel edges.

In (Bosso, Magelli and Zampieri, 2021), the focus was on safety and reliability monitoring systems for railway transportation. To ensure the device's proper functioning, sensors and electronic components requiring electric power supply are necessary. Energy harvesting techniques from primary sources are employed to achieve widespread distribution of electrical energy. The study explored different concepts of energy harvesters for both on-board and wayside applications, discussing their advantages and disadvantages and identifying the most promising solutions.

(Wang et al., 2018) conducted research on flexible electrically resistive-type strain sensors, with a particular emphasis on polymer fibrous mats for monitoring human movement. The demonstrated results showed that flexible strain sensors have a wide range of applications in smart wearable devices. Table 3 present flexible conductive materials along with their thickness and conductivity.

Table 2-2 The flexible conductive materials with their thickness and conductivity (Paracha et al., 2019a).

Conductive material	Thickness t(mm)	Conductivity σ (Sm)
EgaIn liquid fillet	0.08	2.5×10^5
Polyleurethane-nanopartical composite sheet	0.0065	1.1×10^6
Zoflex + copper	0.175	1.93×10^5
Silver flakes+ Fluorine rubber	N. A	8.5×10^4
AgNWPDMS	0.5	8.1×10^5
Copper coated taffeta	0.15	3.4×10^6
PANI/CCO composite material composed of polyaniline (PANI) and carbon nanocoils (CCo).	0.075	7.3×10^3
Meshed fabric	0.057	2×10^5

Furthermore, (Bharti et al., 2019) investigated on scalable free-standing polypyrene films for wristband-type flexible thermoelectric power generators aimed at energy harvesting. The study revealed the granular morphology of the films and suggested that reducing the thickness of the device while increasing the concentration of p-toluene sulphuric acid (PTSA) could be beneficial. The films also demonstrated good potential for harvesting heat from hot-curved surfaces. Additionally, (Ur-Rehman et al., 2017) focused on the small and flexible structure of the antenna, highlighting its excellent impedance matching, good efficiency, broad bandwidth, and high gain, which make it suitable for simultaneous data transmission and reception in 5G body-centric applications.

Furthermore, (Ibrahim, Karami and Jafari, 2017) conducted an investigation and developed a programmed sensor using an Arduino board. The sensory data collected by the sensor were uploaded to cloud storage for access by connected devices in a smart home. The results demonstrated that online monitoring and analysis of sensory data stored remotely in the cloud were successful.

2.3 Summary

Energy Harvesting (EH) is a process that captures energy from external sources such as wind, thermal gradients, kinetic vibrations, and solar energy, storing it for use in small, autonomous devices like wearable electronics and wireless sensor networks. Among these methods, Radio Frequency Energy Harvesting (RFEH) is notable for utilizing ambient RF signals to power devices wirelessly, eliminating the need for traditional batteries. While RFEH systems offer significant advantages, developing efficient RF electronics for both off-body and on-body applications remains challenging.

RF waves are generated by the flow of alternating current through conductive material, essential for telecommunications and data transmission. As these waves travel through space, they carry embedded information, enabling data exchange between wireless devices and networks. RF technology supports

moderate to high data rates, crucial for applications requiring real-time communication or large data set exchanges, such as video streaming and remote monitoring. Its versatile applications have led to widespread adoption across various industries, including telemetry systems for environmental monitoring and scientific research, as well as mobile base stations, cellular phones, and television broadcasting.

Energy harvesting technologies provide sustainable power sources for devices by capturing ambient energy from light, heat, vibrations, and RF signals. This approach is particularly beneficial for wireless sensor networks, the Internet of Things (IoT), and wearable electronics, offering a solution where conventional batteries fall short due to limitations in lifespan and power density. Research efforts have focused on optimizing antenna designs and rectifying circuits to improve RF power harvesting efficiency. For example, Zhang et al. designed an antenna array with a T-shape LC matching network to enhance power transmission across multiple frequency bands, highlighting the potential for powering low-power devices.

The choice of materials for antenna fabrication significantly impacts the amount of harvested RF energy. Flexible fabric antennas are gaining popularity in wearable technology due to their comfort and adaptability. Rectenna arrays, consisting of multiple dipole elements, convert electromagnetic energy into direct current (DC) electricity, with design factors like element size and arrangement affecting conversion efficiency. Previous studies have integrated rectennas with energy storage devices and power management circuits to optimize performance, demonstrating the feasibility of powering devices through harvested RF energy.

Integrating RF wireless power transfer into wearable electronics faces challenges, such as ensuring stable and efficient antenna performance on a moving body, designing reliable interconnections between rigid and flexible subsystems, and implementing effective power management strategies to maximize power output. Despite these challenges, the potential benefits of RF wireless power transfer, including self-sustainability, convenience, and safety, make it a promising technology for future applications.

RF energy is crucial for powering implantable biomedical devices, extending battery life, and supporting wireless sensor network nodes. The abundance of RF waves in various applications, ranging from broadcast and mobile communications to satellite and Wi-Fi, provides a plentiful energy source for IoT devices. The integration of wearable electronics and RF wireless power transfer, while challenging, holds significant promise for advancing the technology and addressing power needs in various fields.

In summary, the chapter reviews the state-of-the-art for RFEH in materials, antenna design, and power management, providing an overview of current technology and future trends. By addressing existing challenges and optimizing system components, RF wireless power transfer can offer significant advantages in wearable electronics and other applications, paving the way for sustainable and efficient wireless communication systems.

3 System Design

An antenna is a device that can transmit and receive electromagnetic signals and convert them into electrical signals. These signals can be transmitted or received in several directions depending on the antenna capacity, allowing communication between distant locations. Antennas are classified into three main categories: directional antennas, characterised by a narrow beam; semi-directional antennas that operate at a certain angle; and omnidirectional antennas that radiate signals in all directions. For example, microwave antennas can transmit signals from one space to another and coordinate transmission lines in free space between two or more targets. Below are the basic parameters of the antenna:

Polarisation: polarization is a fundamental property of electromagnetic waves, describing the orientation of the electric field vector. While polarization itself is not measured in units, various parameters and techniques are used to characterize and quantify polarization in optical systems. This refers to the formation of electric field fluctuations in a plane [50] and the region where wave radiation occurs (Balanis, 2016).

Radiation pattern: Describes the radiation of field intensity in different angular directions on a plotted graph (Osaretin, 2012). The antenna radiation pattern can also be explained as a function of spatial coordinates (Ingale, Ingale and Trikolikar, 2013).

Bandwidth: In (Manrique et al., 2010), the bandwidth is defined as the percentage deviation of the narrow band frequency of the antenna in relation to its lower and upper limits or its ratio to the centre frequency. (Balanis, 2016) also states that it is a measure of antenna performance relative to a certain characteristic.

Impedance matching: The impedance matching can be defined by the maximum power transfer theory, as stated in Equation 3.1

$$Z_e = Z_x \quad (3-1)$$

Here, Z_e and Z_x represent the source impedance and the impedance load. Maintaining constancy in this context likely refers to ensuring that the impedance matching condition is maintained across different operating conditions or variations in the circuit parameters. By adhering to Equation (2.1), the system ensures that the power transfer remains optimized regardless of changes in the load or source characteristics, thereby maximizing the efficiency of the system. Equation (1) ensures maximum power transfer between impedance load and impedance source while maintaining constancy. Real and Reactive Power: In practical applications, both the real power (actual power consumed) and reactive power (power stored and released by reactive components) are considered. Matching impedances ensures that the real power is maximized. Circuit Design: Impedance matching is crucial in high-frequency circuits, such as RF and microwave circuits, where even small mismatches can result in significant power loss. Equation 1 shows the mathematical expression of this theorem, which is fundamental in ensuring that maximum power is transferred from the source to the load. Maintaining this impedance matching ensures that the power transfer remains constant and at its maximum possible value.

Return loss: This refers to the ability of an antenna to release power from its source (Mansour and Kanaya, 2019). Mathematically, return loss is defined as:

$$P_{RL} = 10 \times \log_{10} \frac{P_{in}}{P_r} \quad (3-2)$$

Where P_{in} and P_r represent incident power and reflected power. P_{RL} represent return loss.

Directivity: This represents an antenna's ability to focus its radiation at a targeted point (Serra, Nepa and Manara, 2012). Alternatively, it is the

ratio of the average radiation intensity of the antenna to the radiation intensity in all directions at the focus.

Power gain: Power gain, also known as radiation efficiency, is the isotropic ratio of the antenna output power to the power of the reference antenna in the focused area. The receiver power can be expressed as given by equation (3.3):

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2} \quad (3-3)$$

Where P_R represents the antenna received power, G_R represents the receiving antenna gain, P_T represents the transmitted power, G_T represents the transmitting antenna gain, R represents separation distance between transmitting and receiving antenna, and λ^2 wavelength of transmitting wave (Divakaran, Krishna and Nasimuddin, 2019). The path loss due to free space is given by Equation (4)

$$P_L = \frac{(4\pi f R)^2}{G_T G_R c^2} \quad (3-4)$$

Furthermore, (Thakar et al., 2020) conducted a study on antenna systems for RF energy harvesting using radio frequencies. RF signals are transmitted from various sources such as base stations, Wi-Fi routers, cell towers, TV, and radio broadcast stations. The goal of RF energy harvesting is to power low-power devices without the use of batteries. The article focused on the different frequency ranges that can be used, the parameters for system model design, and the circuitry required to convert the low voltage output to a high voltage output for efficient RF power harvesting in various applications. This concept is consistent with the law of conservation of energy which states that "Energy can neither be

created nor destroyed, it can only be converted or transformed from one form to another". RF energy is currently transmitted from a variety of sources, including telephones, televisions, and radio stations (Thakar et al., 2020).

In (Karampatea and Siakavara, 2019a, 2019b), research was conducted to address the need for continuous power support in wireless sensor networks without using batteries. The antenna device designed in this study is suitable for rectenna applications at the universal mobile telecommunication System (UMTS) frequency range from 1.92 GHz to 2.17 GHz. This device captures the power of impinging RF signals, rectifies it, and stores it using rectenna grades. The antenna consists of planar dipoles with a specific layout printed on a dielectric substrate with double negative (DNG) electromagnetic properties. This hybrid structure allows for a larger amount of RF power to be gathered compared to ordinary dielectrics, making it suitable for RF power harvesting known as the rectenna.

Furthermore, (Adami et al., 2015) worked on screen-printed patch antennas and rectennas for RF power transfer and harvesting on textiles. The two-line method on a planarised polycotton substrate was used. The results showed that the substrate performed better than a third of standard FR4. The paper recommends improvements in resistance to chemicals and increased electrical and mechanical robustness performance of the textile device.

Similarly, (Said et al., 2019) studied a high-gain rectenna at 2.45 GHz using a two-layer low-cost FR4 substrate with air-gap technology. The design includes an antenna and open stub rectifying circuits with a feedline. This technique aims to increase the antenna gain. The rectenna design achieved an output voltage of 0.46 V with an input power of 0 dBm, and a maximum input power of up to 6V. The device offers advantages such as low cost, easy integration, high gain, low profile, and simplicity in design, making it applicable in various wireless communication and RF energy harvesting applications.

Moreover, (Afridi, 2015) examined the application of patch antennas in various fields, including civil engineering, military, mobile and GSM (Global System for

Mobile Communications) Communication sectors, and the healthcare sector, for communication purposes. After investigation, a gain of 8.27 dB and a VSWR (Voltage Standing Wave Ratio) of 1.18 were obtained, which is commendable and close to the calculated resonance frequency. The research indicates that the resonant frequency and dielectric constant are dependent on the patch antenna.

Additionally, (Nawale and Zope, 2015) conducted experimental work on antenna design, mainly modifying the ground plane of an antenna using DGS structures allows for the optimization of various antenna parameters, including frequency response, size, radiation characteristics, and mutual coupling. This flexibility in design is crucial for developing antennas that meet the requirements of specific applications and performance criteria. Known as defected ground structure (DGS). The parameters used and optimised in the study included reflection coefficient, bandwidth, DGS, VSWR Voltage Standing Wave Ratio), and gain.

Similarly, (Suhail, 2014) investigated coating design for helical and loop antennas at varying refractive indices and angles. The study used a copper substrate, and the incidence angle on the reflectance spectrum was investigated. The results showed that reflectance increases at shorter wavelengths, shifting towards the wavelength. It was also observed that a shift in incidence angle affects the wavelength's function. This study aligns with previous research, indicating that adjustments made to certain parameters can positively or negatively affect the variation of angle positions, thereby impacting antenna efficiency.

Furthermore, (Wen et al., 2018) studied the use of high-impedance surfaces (HIS) to design a compact and low-profile multi-in multi-out (MIMO) antenna for wearable applications. The MIMO antenna achieved good port-to-port isolation without increasing its geometric size. The antenna design employed a pair of degenerated characteristic modes of a circular loop antenna, and four elements of high-impedance surface were chosen to match the antenna profile, resulting in improved antenna gain. Simulation results aligned with the measurement results, demonstrating the antenna's robust performance against the human phantom and a low specific absorption rate.

Likewise, (Dutta, Guha and Kumar, 2017) conducted two investigations: one on the aperture field for different solid geometries and another on a typical radiator of a printed microstrip patch antenna dipole. The analyses showed that a higher compact shape of the Radiating Circular Aperture (RCA) was obtained, leading to improved lightweight feed for large reflector gains. This finding enhances the compatibility of the device in terms of antenna performance.

In (Agiwal, Roy and Saxena, 2016)], research was focused on the vision of next generation 5G wireless communications, including improved data rate, latency, quality of service (QoS), capacity, radio access network (RAN) design, air interfaces, smart antennas, cloud, and heterogeneous RAN. Simulation experiments were conducted to explore possible future research works, demonstrating the functionality of the antenna device.

In summary, antenna design plays a crucial role in checking the specific of. The RF absorption rate energy harvesters absorption rate of RF (Radio Frequency) energy harvesters refers to the efficiency with which these devices convert ambient RF energy into usable electrical power. RF energy harvesting is a promising technology for powering low-power electronic devices, such as wireless sensors and IoT (Internet of Things) devices, by capturing and converting ambient electromagnetic energy from sources like Wi-Fi, cellular signals, and broadcast TV/radio. Planar multilayer-fabric patch antennas with a ground plane are particularly suitable for fabric wearable antennas, offering improved efficiency compared to designs without a ground plane.

3.1.1 RF Energy Harvesting for Antenna Design and Characteristics

It serves to capture the RF signal received from the extended source and has a significant effect on the conversion efficiency. Antenna resonance optimisation can be achieved in single or multiple frequency bands. High-gain receive antennas are needed to meet the high-power input requirements of software packages such as remote charging of mobile phone batteries, wake-up sensors, and powering wireless sensor networks (Saha et al., 2020a). The antennas must provide sufficient power for these applications, even with limited ambient signals.

Desirable characteristics in RFEH antenna design include power amplification, wide bandwidth, miniaturisation with maintained efficiency, and circular polarisation to minimise mismatch losses. When designing antennas for biomedical applications, such as wearable and Implantable antennas, factors such as flexibility, durability, light weightiness, and safety are crucial considerations. Therefore, this section discusses the design, characterisation, and configuration of implants and wearable antennas used in the RFEH system. A wireless battery-free sweat sensor system designed to detect sweat composition in real-time is shown in Figure 5 (Li, Zheng and Wang, 2019). A multi-functional sweat sensor, as illustrated in the schematic diagram, is worn as a monitoring film and connected to an electrochemical analyser. The collected data is then transmitted wirelessly to a smartphone via Bluetooth for analysis and monitoring (Bandodkar et al., 2019; Lei et al., 2019; Li, Zheng and Wang, 2019).

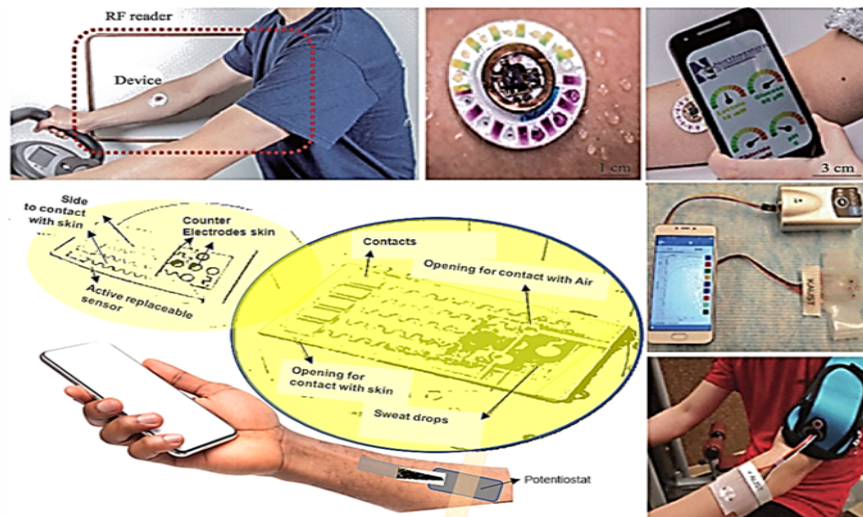


Figure 3-1 Wireless battery-free sweat sensor system for RF energy harvest with a smartphone bluetooth wirelessly transmitter for analysis and monitoring (Bandodkar et al., 2019; Lei et al., 2019).

3.1.2 RF Wearable Energy Harvesting Antenna Design

Antenna integration in wearable medical equipment necessitates conformal and nonobtrusive designs. Mechanical deformations of wearable antennas can significantly impact bandwidth and centre frequency, particularly when operating in limited areas where even minor changes can detune the optimised frequency.

The ground plane plays a crucial role in isolating the wearable antenna from anatomical and physiological loads, as well as absorptive losses. Wearable antennas are constructed using various dielectric and conductive materials, chosen for their ability to withstand mechanical deformations such as twisting, bending, and wrapping, while also providing protection from electromagnetic radiation. Fabric and non-fabric materials have been utilised to fabricate wearable antennas, but proper characterisation of fabric materials is essential prior to use (Liew et al., 2020). Textile materials, including felt cloth, polyester cotton, and cordura, are commonly used in wearable antennas for RF energy harvesting due to their widespread availability (L. Li et al., 2020; Shearer et al., 2006; Zareei et al., 2019). These textile antennas can adopt different topologies such as monopole and patch antennas and operate in single or dual bands. Non-fabric flexible thermoplastic materials with secure dielectric properties are also employed in many RFEH wearable antennas. For instance, (Luo et al., 2019) proposed a double dipole antenna printed on Kapton, and (Babayo et al., 2017) suggested a monopole antenna printed on a polyethylene terephthalate (PET) film. (Din et al., 2012) described a dual-band patch antenna built on a polydimethylsiloxane (PDMS) substrate.

Furthermore, wearable antennas for RFEH need to be flexible enough to accommodate stretchable skin deformations or human motions (Sidhu et al., 2019). Stretchable antennas experience a decrease in resonant frequency when stretched (Muncuk et al., 2018), thus limiting their use for strain sensing integrating them with commercially available chips presents challenges as well. Moreover, the lossy nature of human tissues significantly reduces the radiation efficiency of flexible antennas (Anika et al., 2018; Ojo et al., 2019; F. Yang et al., 2020a). Therefore, for communication and radio broadcasting, an extended antenna with high characteristics and insensitivity to resonance frequencies is required (Z. Li et al., 2013; Loubet et al., 2019; Munir & Dyo, 2018; Ostfeld et al., 2016; Szarka et al., 2012; J. wei Zhang et al., 2019). Because of their unique electromagnetic properties and high electrical efficiency, tensile and plain steels are suitable for the manufacture of radiating elements. In published work (H. Sun et al., 2022), a laser stretchable wideband dipole antenna was proposed using

resistive laser-induced graphene (LIG) patterns selectively coated with metal, mounted on an elastomeric substrate.

During radiation performance measurements of the bendable antenna, both mechanical and electromagnetic properties were considered using a customised stretcher. The stretchable multiband dipole antenna maintained its performance under various deformation modes, including stretching, twisting, and bending.

3.1.3 RF Energy Harvesting with Implantable Antenna Design

Whether for RF energy harvesting (RFEH) or data transmission in IMDs (Implantable medical devices), implantable antennas are an essential component in electromagnetic energy transformation (Saha et al., 2020b). Designing Implantable antennas presents additional challenges compared to wearable antennas due to their placement inside the body. The primary limiting factor affecting the performance of Implantable antennas is dielectric loading from fluids and body tissues. To maximise the chances of successful integration, miniaturisation techniques play a crucial role in configuring implanted antennas by reducing their size to the minimum possible. Researchers have proposed various types of miniaturised Implantable antennas for RFEH, each tailored to a specific scenario. To improve power transmission, a circular dual-band implantable antenna with a radiating slotted overlay supplemented by an external metal reflector positioned behind the human hand has been developed (Alkurt et al., 2020). The radiating metallic patch had a size of 10.8mm, matching the material and the superstrate to ensure contact with the surrounding tissue. For enhanced efficiency of the wireless power link, a portable planar inverted F-antenna (PIFA) with a matching layer on the arm was developed specifically for RFEH (Gu et al., 2020).

3.1.4 RF Wearable Inkjet-Printed Energy Harvester

Additive manufacturing has grown in industrial importance due to its environmental friendliness and economy in manufacturing processes such as 3D printing and inkjet printing. These emerging technologies aim to significantly reduce the number of re-necessary machining steps, including the elimination of

etching mechanisms, thereby increasing manufacturing efficiency. In environments where disposable or disposable items need to be hygienically maintained, such as hospitals, wearable sensor devices are often the preferred choice. Additive manufacturing makes it possible to build many circuit components into a device, leading to a reduction in the overall cost of the device. Recent advances in manufacturing and performance have made inkjet technology suitable for sensor and RF applications. Consequently, (Hariyawan, Darwis and Posma, 2016) proposed a design enabling near-field RF energy harvesting (RFEH) for wearable sensors through an additive manufacturing process. The study builds circuit prototypes by combining conductive traces made using conductive inkjet printing and masking technology solutions with integrated circuit components.

Additionally, S-parameters were used to estimate the input power for RF to DC conversion circuits. The circuit achieved a peak output power of 0.146 W for the H-field harvester and 0.0432 W for the E-field harvester. To verify the functionality of two-way radio powered harvesters, they underwent a battery of tests using a microcontroller communication module and LEDs, both in bottle and body bending conditions. The results of these analyses confirm the flexibility of inkjet energy harvesting devices, making them suitable for use in wearable biosensors. In addition, the work presented in (Zorbas et al., 2018) used 3D printing and inkjet technology to develop a flexible and wearable energy-autonomous body-based sensor network fully operational for RFEH using a hand-held two-way radio in the 464.5 MHz UHF band. Both the backscatter RFID tags capable of sensing and the wearer's hands are equipped with an energy harvester, with one harvesting the energy of the 464.5 MHz signal to power the tags and the other converting the same signal into direct current. Compared to conventional ambient energy harvesters, this alternative device shows higher efficiency. The system utilised energy harvesting designs, utilising the rectifier's DC and second resonance frequencies to support two additional functions. Traditional 3D printing methods often require significant time and material to fabricate desired structures. Therefore, (Hameed and Moez, 2014) proposed a fabrication method to develop an origami RF harvester system employing the same principles of origami folding

as those used in low-frequency applications. This ingenious method eliminates the need for support materials and significantly reduces fabrication time.

3.1.5 RF Textile-Based Wearable Energy Harvester

The integration of miniature electronics and conductive materials into wearable devices holds the potential to establish the paradigm of wearable technology (Assimonis et al., 2018). Fabric rectennas can be employed in battery-free, body-centric wireless communication systems.

Numerous antennas for wireless communication have been reported to be fabricated using textile materials (Al-Shidaifat et al., 2020; Sun, Huang and Wang, 2022). Some studies have combined a textile antenna with a rectifier circuit built on a printed circuit board (PCB) to create a wearable device for power harvesting (Zareei et al., 2019). Rectennas can operate at a single frequency or two different frequencies. In the 4.65 GHz textile rectenna described in (Cavalheiro, Moll and Valtchev, 2017), jeans cotton was utilised as the substrate, while copper tape was employed for the radiating element. An input power of 5 dBm was applied to generate a DC output voltage of 400 mV from the textile rectenna, achieving a maximum power conversion efficiency (PCE) of 55%. By combining a sub-1 GHz broad-beam rectenna with an off-body antenna operating at 2.4 GHz, (Ahmed et al., 2021) developed a textile rectenna that operates simultaneously at both frequencies. This rectenna demonstrated a PCE of 63.9% and a DC output of 650 mV at a power density of less than 0.8 Wcm². Subsequently, a comprehensive textile rectenna system was presented in (Chen, Sun and Tsai, 2022). This rectenna utilises RF power harvesting to establish an innovative power management platform. The rectenna is designed to operate with wireless networks that utilise the 900 MHz, 1800 MHz, and 2.4 GHz frequency bands. Nonlinear methods are employed to test the RF properties of the textile rectenna, while electromagnetic simulations are utilised to numerically characterise the textile equipment and antenna layout. The system does not require a battery and can operate on a weak RF signal (15 dBm) due to its inherent autonomy.

3.1.6 RF Flexible and Stretchable Energy Harvester

Mechanical deformations such as stretching or bending have a significant detuning effect on the frequencies of wearable rectennas, resulting in reduced performance. While the miniaturised thin film rectifying circuit design and matching network can provide robust mechanical properties, the size of the antenna within the rectenna is limited to a specific range for the target radio frequencies of ambient wireless energies. Additionally, the conversion efficiency of existing rectennas operating at a single frequency is greatly diminished for low-power RF energies under dim lighting conditions (less than 1 mW) (Alkurt et al., 2020; Gu et al., 2020; Saha et al., 2020b). This reduction is partly attributed to the characteristics of the limiting diode and increased losses in the transmitter and impedance matching circuits. To address the need for integrating received RF energy across a wider bandwidth during deformations, it is crucial to design and demonstrate a high-performance stretchable wideband antenna based on previous experience. In this context, (Beato-López et al., 2020) presented a design for a stretchable wideband rectenna that exhibits resilience to mechanical deformations, operates efficiently, and integrates external RF power across the entire frequency spectrum. The proposed design combines magnetic resonance techniques with laser-based fabrication to create a highly effective stretchable wideband rectenna with compatible mechanical properties. This integration of the rectenna with various laser-induced graphene (LIG) sensors enables the development of expandable all-LIG devices for remote sensors and wearables.

Furthermore, a comprehensive rectenna system based on textiles was presented in (Chen, Sun and Tsai, 2022). This rectenna utilises RF power harvesting to establish an innovative power management platform and is designed to operate with wireless networks that utilise the 900 MHz, 1800 MHz, and 2.4 GHz frequency bands. Nonlinear methods are employed to test the RF properties of the textile rectenna, while electromagnetic simulations are used to numerically characterise the textile raw material and antenna layout. The system does not require a battery and can operate on a weak RF signal (15 dBm) due to its inherent autonomy.

To mitigate the inefficiency of a flexible RFEH system, the utilisation of multipath and antenna diversity to achieve quasi-omnidirectional RF reception enhances the system's ability to successfully receive energy in its natural environment. In order to leverage the advantages of plastic wrapping form and ambient RFEH operation in indoor settings, the study by (Lee, Jung and Park, 2018) proposes a 3D flexible antenna diversification approach that can be incorporated into rectangular packaging. By employing a Rogers 4003 substrate in the design of the angle and polarisation diversity antenna, the issue of poor substrate performance is addressed while maintaining small antenna size, high isolation, and high radiation efficiency. Rectenna measurements were conducted in various realistic scenarios. Scenario S1 involved the use of a standard antenna patch to measure ambient power in all directions and locations. Scenario S2 employed a regular antenna patch and rectifying circuit A to calculate absorbed power in all directions and at all points (Rectenna 1A). In Scenario S3, a packing box connected to Rectifier B was utilised, incorporating four patch antennas oriented in opposite and perpendicular orientations (Rectenna 1B). Scenario S4 involved physically separating the rectifier from the antenna (Rectenna 2), while in Scenario S5, the rectifier was physically integrated into the antenna (Rectenna 3). The efficiency of both the flexible rectenna diversity configuration and regular patch diversity was evaluated in these scenarios.

3.2 Power Management

Power management is a feature of computing devices that allows users to control the amount of electrical power consumed by the underlying device, minimising usage. Examples of devices that incorporate power management include copiers, computers, CPUs, GPUs, and computer peripherals such as monitors and printers, which turn off the power or switch to a low-power state when inactive.

In (Saraereh et al., 2020b), a hybrid energy harvester is presented to enhance the network lifetime of Internet of Things (IoT) devices. This device model utilises both RF energy harvesting and thermal energy harvesting to increase the lifespan of the devices. To further enhance the device's performance, a supercapacitor is employed to store the harvested energy at a sufficient level to power the devices.

The study observes that the network lifetime of the hybrid energy harvesting network is significantly extended compared to a network without any energy harvesting. Further exploration of other sources of energy harvesting can be incorporated to study this device. The core energy subsystem module comprises the energy harvester, energy storage, and energy manager.

Furthermore, [(Shearer et al., 2006)] introduces a radio frequency-based powering device that aims to convert RF energy into usable energy. The harnessed energy can directly power untethered devices or supplement batteries and other storage components. Additionally, the paper suggests that power management devices for energy harvesting can be simplified, as depicted in Figure 6 (Dostal and Nast, 2015).

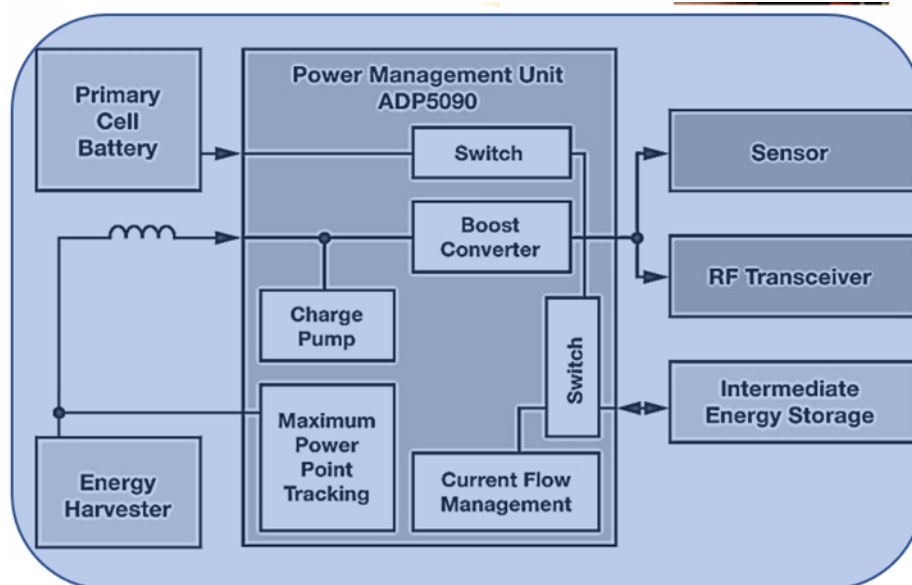


Figure 3-2 Power management device for energy harvesting applications (Dostal and Nast, 2015)

Figure 5 above depicts the power management diagram for an energy harvesting device and its applications. The setup includes start-up circuitry with a charge pump that enables a start-up voltage of 380 mV on the input. The internal circuitry is powered from the output voltage, which serves as the node that powers the load of the energy harvesting system.

In (Colaiuda, Ulisse and Ferri, 2020) the development of simple and effective devices that can be used as energy efficient autonomous sensors that outperform existing state-of-the-art solutions is being explored. Acceptable voltage levels for the load. The device uses a microstrip line discrete component board with a bulk device and is optimised for two different power sources for RF energy harvesting. The phase rectifier consists of two different Schottky diodes in two different topologies using a diode and a 2-phase Dixon charge pump. Offering better performance than commercial products and reaching a maximum range of up to 22 meters with its high RF power, D-Wise collects energy, making it suitable for IoT applications.

In addition, (Farrar et al., 2007) reviews the development of energy harvesting for low power embedded structural health monitoring (SHM) sensing systems. The research focuses on transitioning the concept of energy harvesting for embedded SHM sensing systems from laboratory research to field-deployed engineering prototypes. The paper also discusses current energy harvesting applications and system integration, concluding with defining future research directions and concepts of energy harvesting technology methods.

Condition monitoring has the potential to reduce machine breakdown losses, enhance productivity and operational safety, and deliver significant benefits to various industries (Ball et al., 2018). Energy harvesting technologies have garnered attention from engineers due to their ability to convert microwatt or milliwatt level power from the environment, enabling the implementation of maintenance-free machine condition monitoring systems with wireless sensor networks. Additionally, (Dostal and Nast, 2015) introduces an interesting energy system setup, as illustrated in Figure 7. It illustrates the energy harvesting system for wireless environmental sensors. The sensor is utilised to detect various gases such as CO₂, humidity, and temperature. The harvester plays a crucial role in energy harvesting, with solar energy being the most common type. The harvester generates electricity, which is then converted into useful voltage or current to power the system or charge intermediate energy storage devices like batteries and supercapacitors.

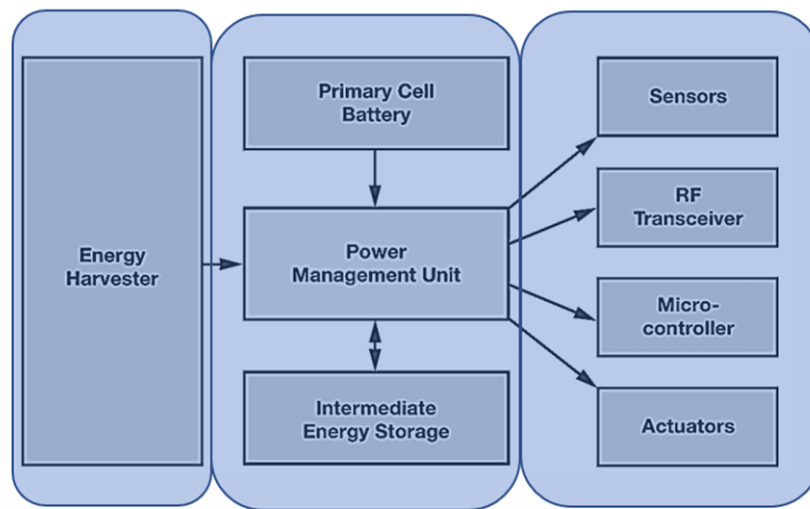


Figure 3-3 Energy harvesting system setup (Dostal and Nast, 2015)

In (Gholikhani et al., 2020), a critical review of energy harvesting technologies in roadway applications was conducted. The focus was on harvesting principles, prototype development, economic considerations for each harvesting technology, and implementation efforts. Roadway harvesting is categorised into three groups based on the energy harvesting source: solar radiation, mechanical energy from vehicles, and pavement heat. This technology generates green renewable energy that can be utilised in roadside applications to power LED lights, sensors, and microprocessors for various data collection purposes. In conclusion, these harvesting technologies have reached a sufficient level of development to generate self-sustainable roadside electrical power.

Furthermore, (Liew et al., 2020) conducted a feasibility review of wind turbine technology for highway energy harvesting. The aim was to utilise natural wind energy in the most effective manner to achieve maximum electric output. Therefore, the government can consider implementing a suitable type of wind turbine configuration on highways at a low cost, taking advantage of the moving vehicles on both sides of the road. In renewable energy sources, solar energy and wind energy can be combined and used to generate electricity. The combination of solar panels and wind turbines will be beneficial in cases of non-functioning or when supported by other sources, ensuring continuous power supply without being affected by day and night or any emergency breakdown.

Other sources of energy and the energy requirements for different applications are detailed in Figure 8 (Dostal and Nast, 2015). It depicts a 10cm² harvester that generates energy from various types of harvesting. The left side shows the energy generated, while the right side displays the energy consumption for different tasks. The logarithmic power scale is positioned at the center. A comparison of the RF energy harvesting based on parameters studied is shown in Table 4.

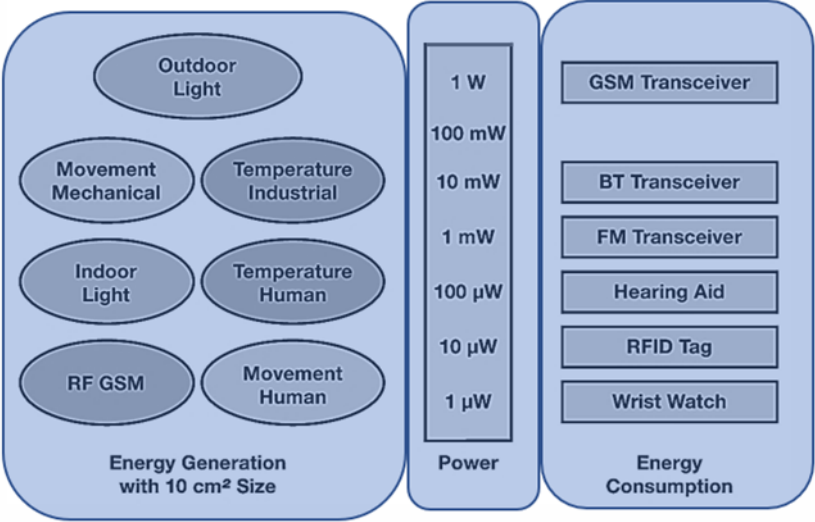


Figure 3-4 Different sources of energy and the required energy requirements of different applications (Dostal and Nast, 2015).

Table 3-1 Comparison of the RF energy harvesting (Fan et al., 2019)

Parameter	2019 Transact ions on Microwa ve Theory and Techniq ues	2018 Transact ions on Microwa ve Theory and Techniq ues	2016 Transacti ons on Microwav e Theory and Technique s	2018 Antennas and Wireless Propagati on Letters	2013 Internati onal Microwa ve Worksho p Series	2013 Internati onal Microwa ve Sympos ium
Frequency (GHz)	2.45	2.45	0.85, 1.85	2.45, 5.5	1.8, 2.45	0.9, 1.8, 2.45
Rectifier Architecture	Rectifier Bridge Rectifier	Half-wave	Greinacher	Greinacher	Half-wave	Dickson
Number of Stages	4	1	2	2	1	4
Peak PCE (dBm)	37% at 13	56.0% at -10	44.2% at -10	36.0% at 5	75.1% at 12	43% at 16
Load Resistance at Peak PCE (k Ω)	20	3	9.53	12	0.917	0.012
Output Voltage at -10 dBm (V)	1.70	0.41	0.65	0.49	0.50	0.24
Voltage Improvement (%)	315	0	58	20	22	42

Each of these stages plays a crucial role in the rectification process, and the overall performance of the rectifier circuit depends on the design and implementation of each stage. By designing and optimizing each stage, can achieve the desired output voltage and current characteristics, as well as efficiency and reliability, in various applications.

3.2.1 Impedance Matching Network

Power loss can be reduced or completely eliminated through the utilisation of an impedance matching network, which ensures efficient transfer of energy from the generator to the load. While impedance matching is essential for achieving

maximum power transfer from the generator to the load in RF energy harvesting systems, it does not guarantee maximum efficiency. Efficiency depends on various factors, including losses in components and conversion processes, and optimizing efficiency requires minimizing these losses in addition to impedance matching. Maximum power transfer is achieved when the impedance of the output antenna matches that of the load. If there is an impedance mismatch, the incident wave will be reflected at the load. In the RFEH system, the rectifier acts as the load, while the receiver antenna captures radio frequency (RF) energy. To minimise unnecessary loss caused by the re-radiation of higher-order harmonics produced by the bridge rectifier, the impedance matching network also functions as a low-pass filter (Al-Absi and Al-Batati, 2020). Achieving impedance matching between the source and the load is crucial for optimal performance of the RFEH, irrespective of the input power, frequency, or load resistance. The architecture of a WLAN energy harvest system is shown in Figure 9.

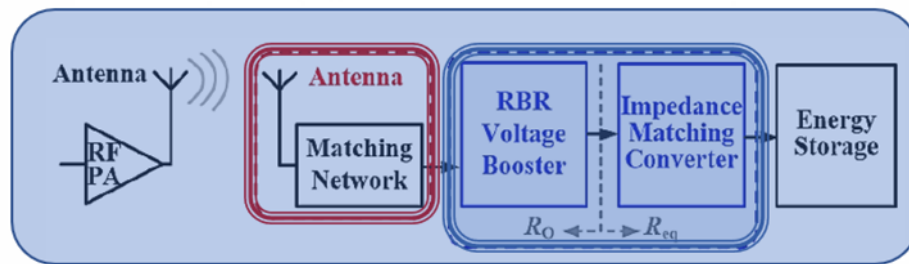


Figure 3-5 Architecture of the WLAN energy harvesting system (Fan et al., 2019).

Furthermore, (Cansiz, Altinel and Kurt, 2019) conducted a comprehensive review on the efficiency of RF energy harvesting systems. They noted that RF energy serves as an alternative means of acquiring energy for wireless devices directly from RF sources in the environment. The study also presented various components such as energy storage devices, voltage multipliers, rectifiers, transmission mediums, impedance matching circuits, antennas, and more. The primary focus was placed on analysing the input and output power ratios at each block. The researchers thoroughly characterised the system parameters and

identified the RF configuration that achieved the highest efficiency, resulting in maximum output power.

3.2.2 Rectifier Circuit Design and Topologies

The rectifier plays a crucial role in converting the RF voltage collected by the receiving antenna into a DC voltage suitable for various electronic circuits. The main design limitation of the rectifier lies in the challenge of generating DC voltage from a relatively weak input power (Basim et al., 2022). There are two primary categories of rectification circuits: diode-based rectifiers and metal-oxide-semiconductor field-effect transistor (MOSFET) rectifiers. Diode-based rectifiers are more popular in practical applications due to their smaller forward voltage drop compared to MOSFET circuits. Optimal diodes with low forward voltage are preferred for their increased Power Conversion Efficiency (PCE). In rectenna applications, Schottky barrier diodes are commonly employed (Sun et al., 2020).

The half-wave rectifier, consisting of a single diode (D1), represents the most basic rectifier topology. However, its use is often inadequate for most applications. On the other hand, the full-wave rectifier, showcased in Figure 10, is the preferred choice due to its superior performance. In comparison, the bridge rectifier offers higher power efficiencies, lower output ripples, and lower reverse breakdown voltages compared to its counterparts (Sarma and Sarma, 2019). The conversion efficiency of RF energy to DC current is given by equation 5. where, P_{RF} is the input RF power and P_{DC} is the output DC power.

$$\eta_{RF} = \frac{P_{DC}}{P_{RF}} \quad (3.5)$$

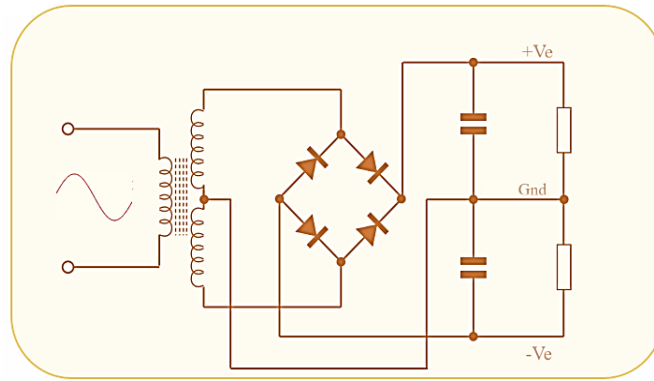


Figure 3-6 Circuit layout of a full-wave rectifier (Sarma and Sarma, 2019)

The power management circuit plays a crucial role in matching the output load of the RF device to an optimal impedance, thereby maximising the rectification efficiency of the device. The storage capacitor is also utilised to assess the converter efficiency and boost the output voltage, contributing to the overall efficiency improvement of the RF energy harvester.

3.3 Challenges and Research Gap

Wearable sensors face limitations in size, highlighting the challenges in RF wearable energy harvesting such as efficiency improvement, limited RF power density, integration into wearable devices, miniaturization, and materials/fabrication techniques. Future work includes exploring multi-band energy harvesting, integrating energy storage and power management systems, developing hybrid energy harvesting systems, and designing adaptable solutions for different environmental conditions. Implementing RF harvesters in wearable medical devices poses challenges related to connectivity, power conversion, radiation efficiency, and mechanical deformations. Advancements are needed in lightweight and flexible rectenna designs for efficient RF energy harvesting. Additionally, considerations for power density, energy storage, and network-based design are crucial in wearable energy harvesting. The challenges and future directions in RF wearable energy harvesting have been summarized and presented in Table 5 for comprehensive understanding and guidance in this field. It guides researchers in identifying areas of improvement and motivates them to contribute towards advancing the field. It also provides readers with insights into

the potential future directions and areas that require attention, fostering collaboration and knowledge exchange.

Table 3-2 Challenges and future directions in RF wearable energy harvesting

Challenges	Future Directions
Efficiency Improvement	<ul style="list-style-type: none"> • Multi-band energy harvesting approach by exploring methods to harvest energy from multiple RF bands simultaneously. • Enhancing the energy conversion efficiency of RF energy harvesting.
Limited RF Power Density	<ul style="list-style-type: none"> • Power management systems by developing advanced power management systems to optimize energy harvesting and utilization. • Addressing the limited availability and variability of RF power in the environment.
Integration and Design	<ul style="list-style-type: none"> • Energy Storage Integration by integrating energy storage solutions for efficient energy utilization and extended device operation. • Designing compact and comfortable RF energy harvesters for seamless integration into wearable devices.
Miniaturization	<ul style="list-style-type: none"> • Hybrid energy harvesting systems combining RF energy harvesting with other complementary energy sources for enhanced overall energy harvesting efficiency. • Overcoming size constraints while maintaining performance and comfort.
Materials and Fabrication Techniques	<ul style="list-style-type: none"> • Environmental adaptability by developing adaptable energy harvesting systems to accommodate varying environmental conditions. • Exploring new materials and fabrication methods for efficient and scalable RF energy harvesting devices.

Table 3-3 provides a concise summary of important research studies in the field of RF energy harvesting. It highlights the research focus and key findings of each study. This table serves as a valuable reference for researchers and practitioners, offering an overview of significant advancements and contributions in RF energy harvesting research.

Table 3-3 Research on RF energy harvesting

Study	Research Focus	Key Findings
(Sharma and Singh, 2023)	Lifetime enhancement of wireless sensor networks (WSNs) through energy harvesting and efficient RF to DC conversion	<ul style="list-style-type: none"> - RF energy is abundant but has low power density, making RF energy harvesting an attractive solution for WSNs. - Designing RF energy harvesting systems involves challenges such as achieving maximum power conversion efficiency (PCE) at low input power and optimising rectifier circuit and antenna topologies. - Recent antenna designs are featured, considering their structure, attributes, and materials.
(Divakaran, Krishna and Nasimuddin, 2019)	Review work on rectifier circuits and matching networks	<ul style="list-style-type: none"> - Developed a framework for designing ambient RF energy harvesting systems. - Identified challenges in conversion efficiency, bandwidth, and form factor. - Emphasised the importance of achieving high conversion efficiency under varying load and input power conditions.
(Kursheed and Budyal, 2018)	Investigation on enhancing energy efficiency in 5th generation IoT	<ul style="list-style-type: none"> - Investigated an integrated model with combined control unit components. - Delaying the select and sleep mechanism (SSM) resulted in reduced power consumption. - Compared with the Traditional Zooming Scheme to demonstrate improved energy efficiency.
(Boussetta et al., 2019)	The development of a sophisticated control system that proficiently governs the power generation and consumption dynamics within the microgrid.	<ul style="list-style-type: none"> - Focused on maximising efficiency in the electricity distribution of a microgrid. - Employed an off-grid hybrid renewable energy system with a power management controller. - Validated the application through a case study of an isolated mosque in Morocco.
(Yang et al., 2020)	Investigation of magnetic and electric energy harvesting technologies in power grids	<ul style="list-style-type: none"> - Reviewed energy harvesting methods for electric and magnetic fields in power grids. - Aimed to address power supply issues through energy harvesting techniques. - Highlighted the potential for low-power sensing of simple parameters within a wider serviceable range.
(Zareei et al., 2019)	Enhancing the performance of	<ul style="list-style-type: none"> - Utilising clustering and transmission power adjustment improves power distribution and network performance.

	energy harvesting sensor networks for environmental monitoring applications	<ul style="list-style-type: none"> - It resulted in a 20% improvement in packet delivery ratio, a 10% increase in network lifetime, and reduced delay by minimising hop count.
(Luo et al., 2019)	RF energy harvesting for wireless communications (RF-EHWC)	<ul style="list-style-type: none"> - Harvesting RF energy from the environment makes wireless sensor networks self-sustaining. - The study explores hardware design, RF energy distribution, implementation, and applications in smart healthcare services for animals, 5G-assisted RF-EHWC, and wirelessly charging wearable devices.
(Imran et al., 2019)	Energy harvesting technology roles in 5G networks by providing sustainable power sources.	<ul style="list-style-type: none"> - Energy harvesting plays a crucial role in extending device and network battery life by harnessing energy from environmental sources and ambient radio frequency signals. - The study covers energy conversion methods, models, propagation, and requirements in 5G networks.
(Saffari, Basaligheh and Moez, 2019)	Wide input range, voltage compensated RF-to-DC power converter.	<ul style="list-style-type: none"> - The design efficiently converts RF signals to DC voltages by applying optimum compensation voltage produced by subthreshold auxiliary transistors. - The compensated rectifiers achieve higher efficiency over a wider input power range. The design demonstrated a measured power conversion efficiency (PCE) above 20% while driving a resistive load.
(Visser et al., 2012a)	Optimisation of RF energy transfer through modelling	<ul style="list-style-type: none"> - RF energy transfer is subject to path loss, resulting in low RF power available on the rectenna and low RF-to-DC conversion efficiency. - Optimisation is crucial for both the subsystem and rectenna to balance efficiency and boost converter performance.
(Xiang et al., 2019)	Circuit conversion design for ambient energy harvesting at ultra-high frequency (UHF)	<ul style="list-style-type: none"> - The study investigates power conversion efficiency and output voltage theoretically for ambient energy harvesting at UHF. - Specific circuit design considerations are explored.
(Yahya Alkhalaf, Yazed)	Wearable and Implantable medical devices (IMDs) and their	<ul style="list-style-type: none"> - Identified system elements for enabling optimised device operation. - Characteristics required for efficient RFEH implementation.

Ahmad and Ramiah, 2022)	power supply challenges	<ul style="list-style-type: none"> - Identification of gaps in RFEH implementation - Exploration of future research opportunities in the field.
(Yu et al., 2022)	Flexible and wearable hybrid RF and solar energy harvesting system for powering wearable electronic devices	<ul style="list-style-type: none"> - Compared to a single solar cell, the hybrid system provides an additional 35.6%-769.5% output power when RF source power varies from 4 to 10 dBm. - The proposed flexible and wearable RF-solar energy harvester has the potential for practical use in powering various devices
(Noghabaei et al., 2022)	Harvesting radio frequency energy (RFEH) for self-powered micro-systems	<ul style="list-style-type: none"> - Improved sensitivity and input power range of the converter. - Better performance compared to previously reported results. - Enables self-powered micro-systems with efficient energy harvesting.
(Liu, Wu and Li, 2022)	Wearable RF energy-localised harvester for powering a Bluetooth sensor module	<ul style="list-style-type: none"> - Shows potential for powering small electronic devices in wearable applications. - Harvested power density of $2.75 \mu\text{W}/\text{cm}^2$ and supports battery-free Bluetooth temperature and humidity sensor.
(Mohammed et al., 2022)	Challenges with on-device batteries in ultra-low power wearable devices and the emergence of wireless power transmission technologies	<ul style="list-style-type: none"> - Batteries in wearable devices pose constraints in usability and functionality, including periodic charging and e-waste generation. - Wireless power transmission technologies offer a potential solution for unobtrusive and seamless charging of wearable devices. - Existing solutions, such as RF signals, lasers, and electromagnetic fields, face challenges related to infrastructure requirements and power transmission magnitude. - Further research is needed to develop wireless power transmission technologies that overcome these challenges for wearable devices.
(Liu, Wu and Li, 2022)	Development of a wearable RF energy-localised harvester for powering a Bluetooth sensor module	<ul style="list-style-type: none"> - The harvester was made of flexible materials for a compact and low-profile design. - The harvested power supports a battery-free Bluetooth humidity sensor and temperature with a power density of $2.75 \mu\text{W}/\text{cm}^2$. - The system demonstration of RF energy harvesting showcases the potential to power small electronic devices for wearable applications.

(Zhang and Lin, 2023)	Feasible study of wearable energy neutral operation (ENO) while maintaining robustness in wireless textile body area network (TBAN)	<ul style="list-style-type: none"> - Reliability and energy issues are challenges faced by TBAN. - Numerical results show stable power levels and improved packet error rate and battery power with the proposed optimisation algorithms. - DQN-based optimisation performs better than Q-Learning, achieving 14% improvement in PER and 56% improvement in battery Power
		<p>Innovative Antenna Materials and Fabrication Techniques: There is a gap in developing novel antenna materials and fabrication techniques that can be produced using programmable embroidery machines. Current methods may lack the precision, scalability, or adaptability required for creating efficient and flexible antennas for wearable devices.</p> <p>Enhanced Antenna and Rectifier Circuit Design: Designing improved antenna and rectifier circuits for RF power harvesting systems tailored to wearable devices presents a research gap. Existing designs may not optimize power conversion efficiency, miniaturization, or integration with wearable technology.</p> <p>Robustness and Flexibility of Antenna Materials: Investigating methods to enhance the robustness and flexibility of antenna materials is crucial. The current materials used may not withstand the mechanical stresses and deformations experienced during typical wearable use, necessitating research into more durable and flexible alternatives.</p> <p>Suitability for Wearable Applications: Ensuring that antenna materials and fabrication techniques are suitable for wearable applications where durability and flexibility are critical is a significant gap. This involves developing and testing materials that can maintain high performance despite the dynamic conditions associated with wearables, such as bending, stretching, and exposure to various environmental factors.</p>

4 Results and discussions

4.1 Introduction

This chapter presents, the details on the design are focused and presented regarding the RF energy harvesting rectenna patch antenna description of parameters and calculated values that are displayed with tables to show each of the actual values and parameters that match alongside using equations to calculate the values accurately. Furthermore, this chapter also in depth provides information on the structures of the antenna, by describing the dielectric medium or substrate along with other features such as the radiator and the ground plane. This chapter also will demonstrate the experimentation deployed to achieving the research aimed result. This is where the design of the regular patch antenna will be demonstrated by utilising the proposed software tools and other related designs for device subsystems in general. This chapter finally provides additional details covering over the understanding of the geometrical dimension which are presented in a diagram to clearly identify each dimension that was found through the calculated values.

4.2 Design of the Rectenna Patch Antenna

4.2.1 Research Methodology

Simulation – CST (Computer Simulation Technology) and HFSS (High-Frequency Structure Simulator) was used for simulating the antenna model. A fabric antenna with dimensions 72mm by 68mm by 1.5 structured on rigid organza dielectric material. The simulation output is quantified with previous measurement as discussed in (Dieff et al, 2020) to assure the results. This outlines the process of simulating an antenna model using CST and HFSS software, with a focus on ensuring the accuracy and quality of the simulation results through comparison with previous measurements.

Power management – ADS (Advanced Design System) software was used to simulate power management circuit. To improve efficiency, multiple diode rectifier has been adopted for the design with the following lumped components, capacitors, resistors, rectifying diodes, length of the transmission line. The

lumped component values that were placed in the circuit are $C1=2\text{pF}$, $C2=0.4\text{pF}$, and $R=1\text{kilo ohms}$ respectively. This highlights the use of ADS software to simulate and optimize the power management circuit, with a focus on improving efficiency through the use of a multiple diode rectifier design and tuning of component values and transmission line lengths. The position of the diode is optimized by tuning the lengths $L1=18\text{mm}$, and $L2=6\text{mm}$ to increase the efficiency. The idea is to utilize the power stored in a standing wave, which causes higher voltage across diode terminals. As expected, standing wave amplitude could be up to twice the propagating wave.

4.2.2 Research Methodology

This research work has been executed using CST microwave studio design, calculate the antenna properties by using transient solver. ADS Momentum, HFSS and other advanced software's to better understand the performance of the antenna. Experimental tests have been conducted using computer simulations and fabricated prototypes. Equipment's used includes programmable embroidery machine, an oscilloscope to determine the RF antenna signal to achieve a wideband performance of the device. The dimensions and the calculated parameter values of the antenna is simulated and optimised. Testing includes scattering parameter measurements, radiation patterns, gain analyser using Vector Network Analyser and other modern software modelling tools for effective simulation and optimization. The results obtained from the experimental measurements is analysed, and discussed intensively with comparison and as well, used to develop an improved antenna design for the device power efficiency performance.

Methodology of the Design

The methodology for designing, modelling, and validating an RF energy harvesting system for wearable devices includes several stages: software installation, patch model structuring, prototype rectenna modelling, iterative testing, and rectification network integration. The process ensures optimized

performance through repeated iterations and validations using simulation software. The key stages and steps are as follows:

- **Software Installation and Setup:** Install standard RF model design software such as CST, HFSS, and ADS on a PC.
- **Patch Model Structuring:** Create and structure various patch model samples to test the performance of the software.
- **Prototype Rectenna Modelling:** Initiate the modelling process of the prototype rectenna, followed by an iterative process to meet predefined performance thresholds.
- **Threshold Evaluation:** After each iteration, evaluate if the predefined threshold has been met. If not, repeat the iteration process.
- **Rectification Network Integration:** Once the threshold is satisfied, incorporate the rectification network and continue with iterations until the overall system performance is optimized.
- **Conversion and Fabrication:** Convert the simulated model into a digital format and proceed to the embroidery fabrication stage.
- **Final Testing:** Test the fabricated model to ensure it meets the required specifications.

Optimization Objectives and Constraints

Optimization Objectives:

Maximize RF-dc Conversion Efficiency: Aim to achieve high conversion efficiency by optimizing the rectifier circuit and antenna design.

Enhance Power Management: Improve the efficiency of the power management circuit using a voltage multiplier design.

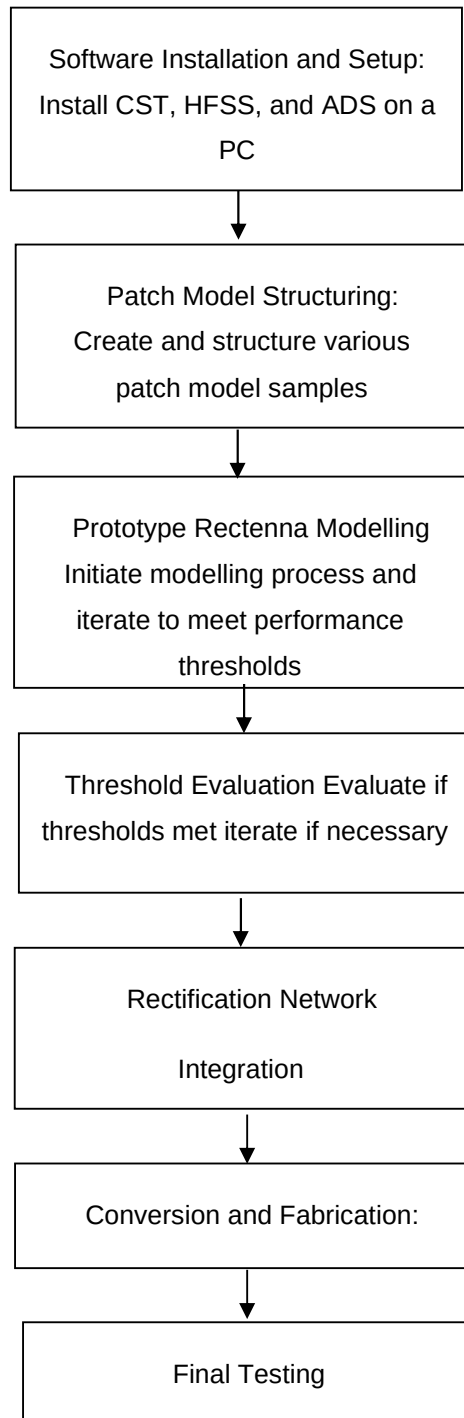
Achieve Impedance Matching: Ensure optimal impedance matching to maximize the power transfer from the antenna to the rectifier circuit.

Constraints:

Material and Fabrication Limitations: Ensure the materials used are flexible and suitable for wearable applications.

Size and Form Factor: Maintain a compact design to integrate seamlessly with wearable devices.

Power Density and Incident Power: Consider the limitations in power density of incident RF signals and design the rectifier circuit to operate efficiently under these conditions.



4.2.3 Experimentation Design

The dimensions of the patch antenna for this research as illustrated in fig 4-1 microstrip patch antenna, fig 4-2 is the geometrical dimensions of the microstrip patch antenna. While table 4-1 is the measurement parameters values for the antenna design. Which is of essential with parametric symbols to aid the calculations of the patch antenna values. It contains the width and the length of both the patch and the substrate of the antenna design respectively.

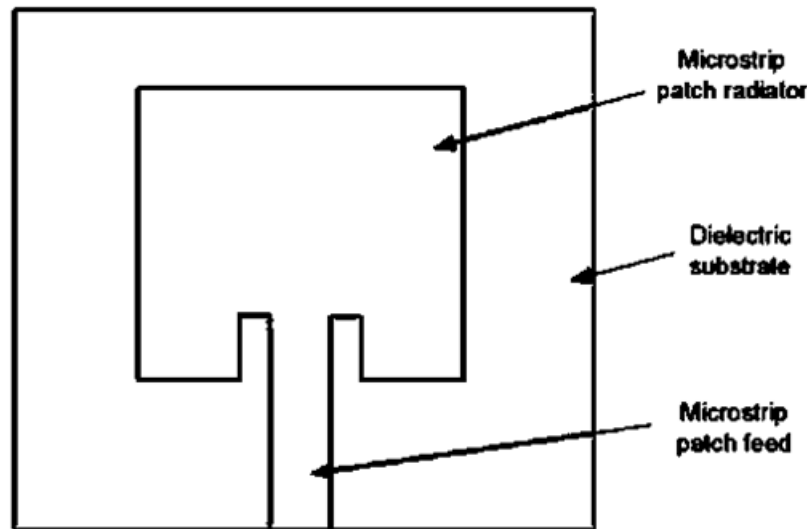


Figure 4-1 Microstrip patch antenna

A microstrip patch antenna is a type of antenna widely used in various applications due to its compact size, low profile, and ease of fabrication. It consists of a metallic patch (typically rectangular or circular) printed or etched on one side of a dielectric substrate, with a ground plane on the other side. The patch and ground plane are usually separated by a dielectric material, creating a microstrip transmission line.

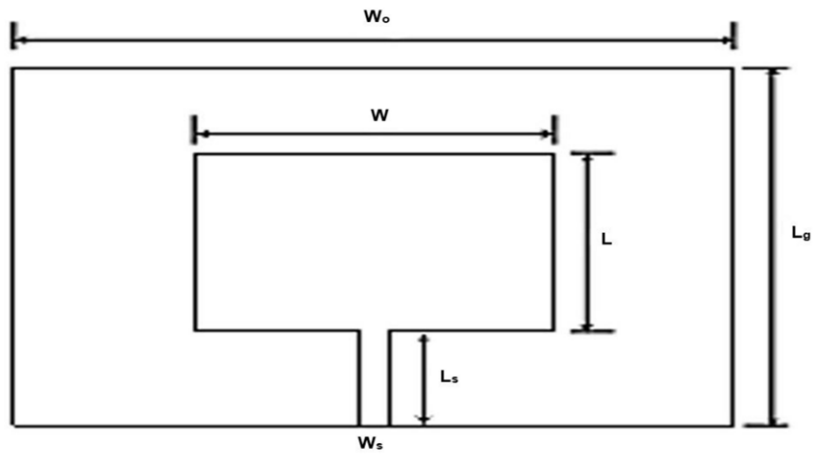


Figure 4-2 Geometrical dimensions of the patch antenna

Table 4-1 Measurement parameters values for the antenna design

Dimension	Value (mm)
Antenna	
PatchX	44.7
PatchY	36.25
Substate	
SubH	1.5
SubX	76
SubY	109.6
Feed	
InsetD	11.42
Inset	2
Feed	4
FeedL	34.03

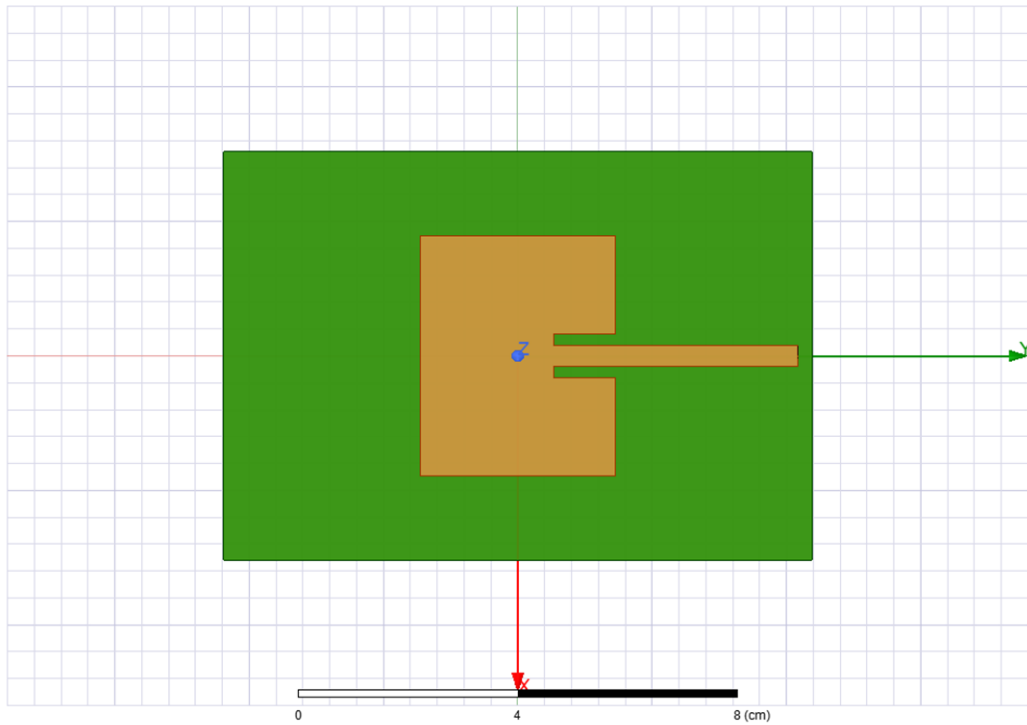


Figure 4-3 Patch antenna on woven polyester substrate $\epsilon_r = 2.75$ and loss tangent=0.003

In order to find a better energy source for wearable technology, this section looks into several energy sources. Since researchers want results that require little to no human intervention, batteries are typically used in these devices, which is not the best option. Because of this, batteries have a finite lifespan and need to be continuously recharged or replaced.

The objective of the design is to develop a sustainable and maintenance-free energy source for wearable devices. This is achieved by creating a 2 x 2 rectenna array that can harvest ambient energy, thereby reducing or eliminating the need for traditional batteries that have a finite lifespan and require continuous recharging or replacement. This innovative energy harvesting solution aims to enhance the practicality and longevity of wearable technology by providing a reliable and long-lasting power source and analysed a 2 x 2 rectenna array. Unlike batteries, the rectenna array can potentially harvest ambient energy to power the wearable devices, reducing or eliminating the need for recharging or replacing batteries. This approach aims to provide a more sustainable and

maintenance-free energy source, addressing the limitation of finite lifespan associated with traditional batteries. The elements of the proposed antenna array are composed of rectangular patch antennas. The patch antennas were chosen due to low profile and better performance. The dimension of the antenna element was calculated based on the dielectric permittivity of the organza substrate. The permittivity of organza is taken from (Dieff et al, 2020). The length of the patch (L_p) was estimated with the following relation.

$$L_p = \lambda / 2\sqrt{\epsilon_r} \quad 4.1$$

L_p : Length of the patch

λ : Wavelength in free space

ϵ_r : Relative permittivity of the substrate material

Using the relation, the permittivity of 2.75 for organza substrate was used at the frequency of 2.45 GHz. The patch length of 36.9 mm was estimated in which we excluded the fringing fields due to thinner substrate of 1.5 mm. Further, the width of the radiating patch (W_p) was analysed based on the equation 3.2

$$W_p = \frac{c}{2fr\sqrt{\epsilon_r + 1/2}} \quad 4.2$$

Using the dielectric constant of 2.75 at frequency of 2.45 GHz, the width of 44.7mm was determined. Based on the calculated value, the rectangular patch antenna was designed in high frequency simulator (HFSS). By adjusting the length of the patch, the design was fine-tuned to achieve a better match, minimizing the reflection coefficient and enhancing the antenna's efficiency. This iterative process of adjustment and simulation is common in antenna design to ensure optimal performance, which was optimized by slightly decreasing the L_p to 36.2 mm. The rectangular patch antenna based on fabric material organza is

shown in Fig. 3-3. In the initial simulations, the PEC boundaries were assigned to the patch and ground of the antenna. The reflection coefficient of the designed antenna is shown in Fig. 4-4

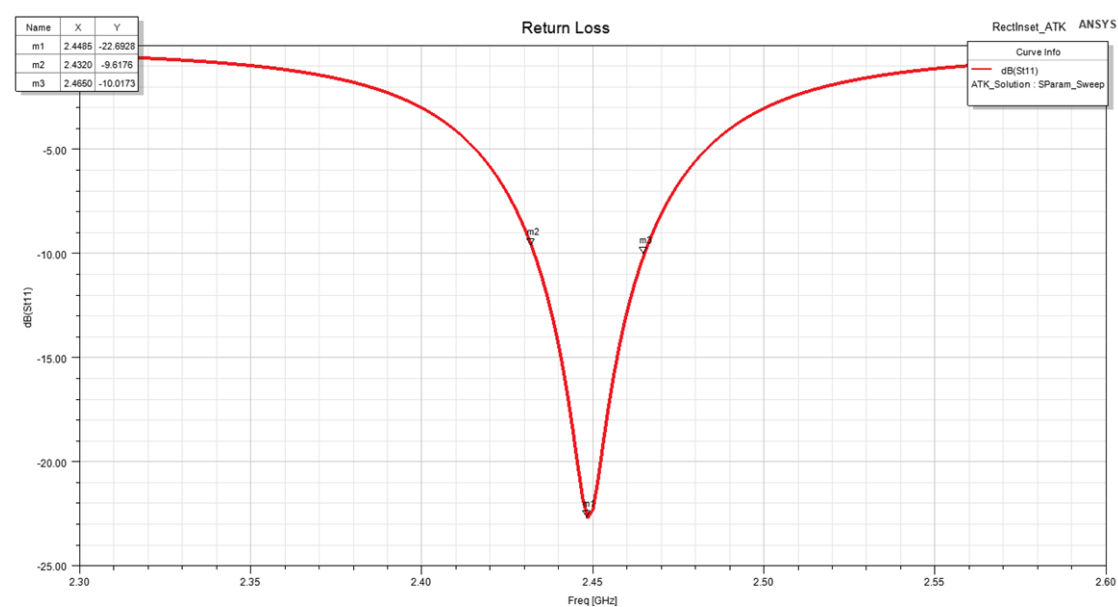


Figure 4-3 Reflection coefficient with PEC patch and ground

The antenna is resonating at 2.45 GHz frequency with S11 depth of -22dB. These metrics indicate that the designed rectangular patch antenna has excellent performance characteristics, with efficient power radiation at the desired frequency and a good directional gain, making it suitable for wearable technology applications. S11 parameter, often expressed in decibels (dB), represents the reflection coefficient of an antenna. It indicates how much of the signal sent to the antenna is reflected back towards the source, rather than being radiated outward. A lower S11 value (closer to 0 dB or less negative) indicates better matching between the antenna and the transmission line or the surrounding environment, implying less signal loss due to reflection.

Given Data and S11 Depth:

The data states that the antenna resonates at 2.45 GHz with an S11 depth of -22 dB. An S11 depth of -22 dB means that the reflection coefficient is -22 dB. This value signifies that only a small fraction of the incident power (about 0.63%) is

reflected back towards the source, while the remaining power is effectively radiated by the antenna.

Implications of S11 Depth:

A deeper (more negative) S11 value such as -22 dB indicates good impedance matching and efficient transmission of RF energy from the source to the antenna. It suggests that the antenna is effectively absorbing and radiating energy at its resonant frequency of 2.45 GHz. This efficiency is crucial for maximizing the antenna's performance in terms of power reception and transmission. A well-matched antenna can achieve higher gain and broader bandwidth, as less energy is lost due to reflections.

Comparative Performance:

The discussion highlights that the antenna's performance, including its gain of 7.1 dB and directional characteristics, is superior to existing textile rectennas. This superiority can be partly attributed to its efficient impedance matching as indicated by the S11 parameter. The directional gain of 7.1 dB suggests that the antenna focuses its radiation pattern in a specific direction, which is advantageous for applications requiring targeted energy harvesting or communication.

S11 depth of -22 dB indicates that the antenna efficiently absorbs and radiates RF energy at its resonant frequency, contributing to its overall performance metrics such as gain and bandwidth. Efficient impedance matching, reflected by a low S11 value, is essential for optimizing an antenna's effectiveness in various RF applications.

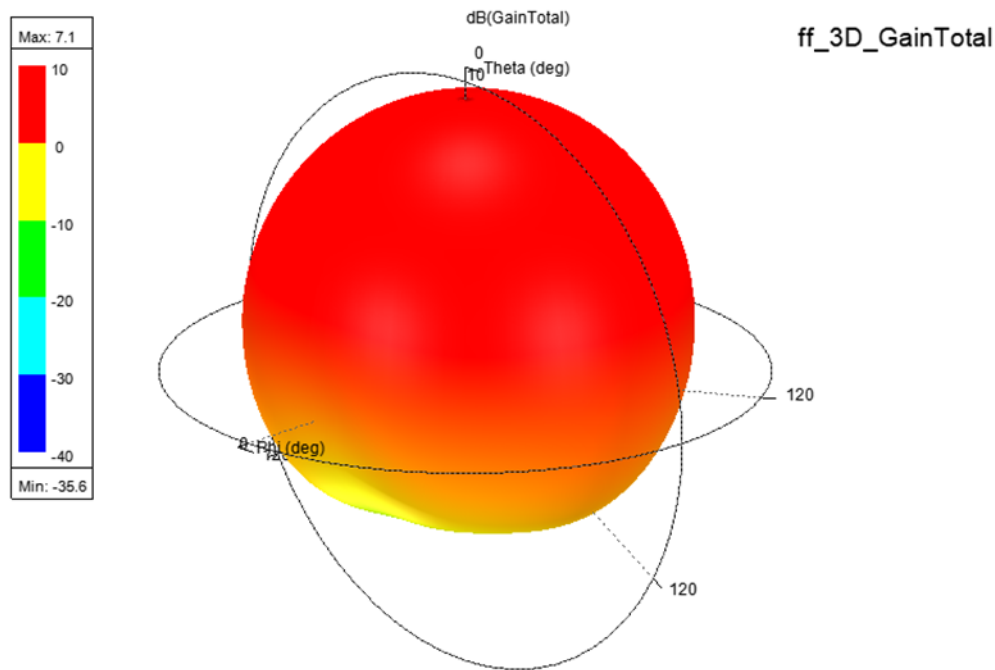


Figure 4-4 Gain with PEC boundaries for patch and ground.

- The Bar at the left side shows the minimum and maximum value of gain in dB so for designed antenna maximum gain of 10 dB is achieved.
- PEC Boundaries: Idealized assumption of perfect conductivity for the patch and ground plane.
- Simulation Impact: Provides an idealized performance measure, ignoring real-world material imperfections.
- Gain Measurement: Represents the best-case directional radiation efficiency of the antenna.

By using PEC boundaries, designers can understand the potential maximum performance of their antenna design and then make adjustments to account for real-world materials and conditions.

For the experiment, a capacitive rectifier circuit was linked to the patch antenna to convert the Rf energy into a useful DC voltage. Additionally, the signal generator was 20 cm away from the antenna.

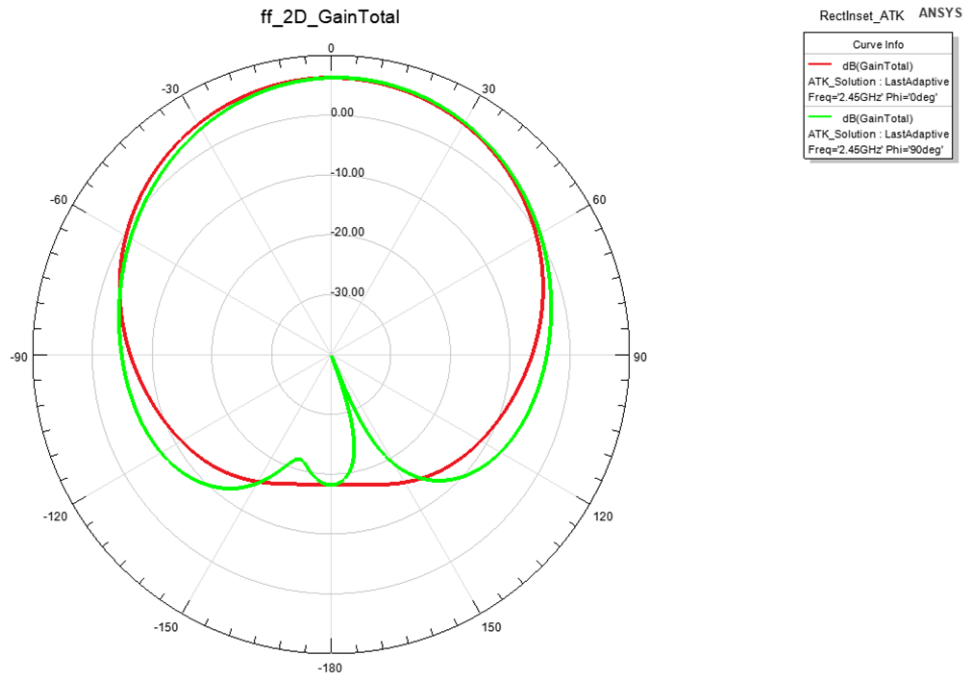


Figure 4-5 Polar radiation pattern of the antenna when PEC boundaries were applied to conductive surfaces.

The phrase "Polar radiation pattern of the antenna when PEC boundaries were applied to conductive surfaces" refers to the idealized simulation setup used to analyse the antenna's radiation properties. By applying PEC boundaries, the simulation ensures efficient reflection of electromagnetic waves from conductive surfaces, resulting in a clear and accurate depiction of the antenna's directional radiation pattern. This pattern, alongside the antenna's resonant frequency, S11 depth, and gain, provides a comprehensive understanding of its performance and effectiveness in RF energy harvesting applications.

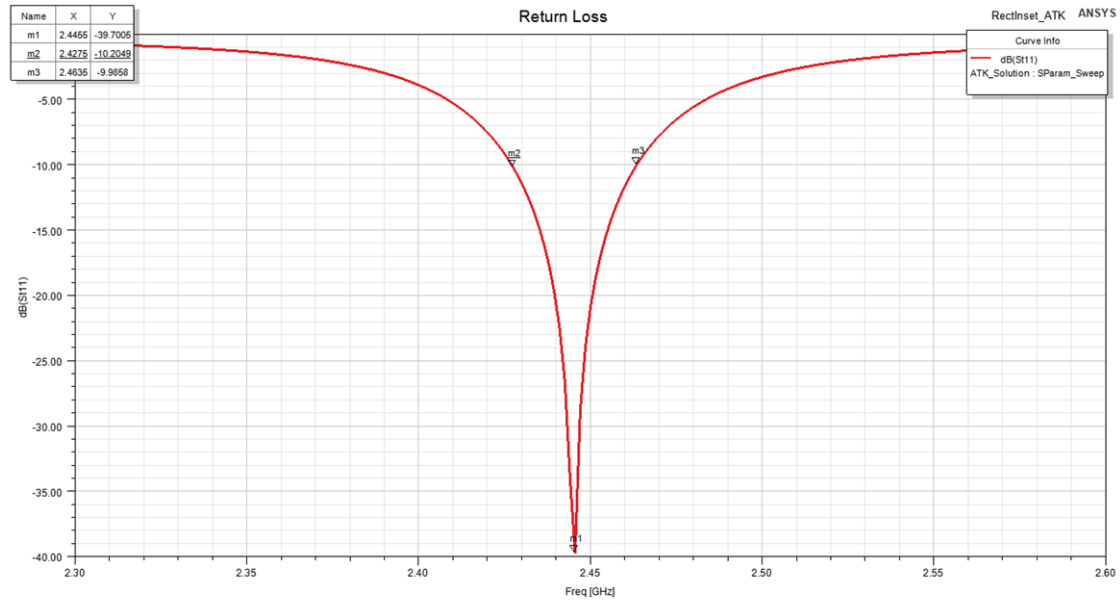


Figure 4-6 Reflection coefficient with conductivity of 6.1×10^6 S/m for patch and ground planes

The aforementioned analysis was based on PEC boundaries for patch and ground planes, which have no losses. However, in reality, the conductive thread used in the textile-based antennas has less conductivity and included losses. Therefore, we have assigned the conductivity of conductive thread as 6.1×10^6 S/m for patch and ground plane. We have excluded the dielectric losses and assumed only some small losses in the conductive thread. The S11 of the antenna when the embroidered surface conductive was 6.1×10^6 S/m is shown in Fig. 4-7. The S11 depth increased to -39.7 dB at the resonance frequency, which increased the bandwidth to 181 MHz. This is due to the stability of the currents on the conductive surfaces. However, a slight reduction in the peak gain was observed as shown in Fig. 3-8 the peak gain of the antenna when the embroidered surface conductive of 6.1×10^6 S/m is 6.29 dBi, as depicted in Fig. 4-8.

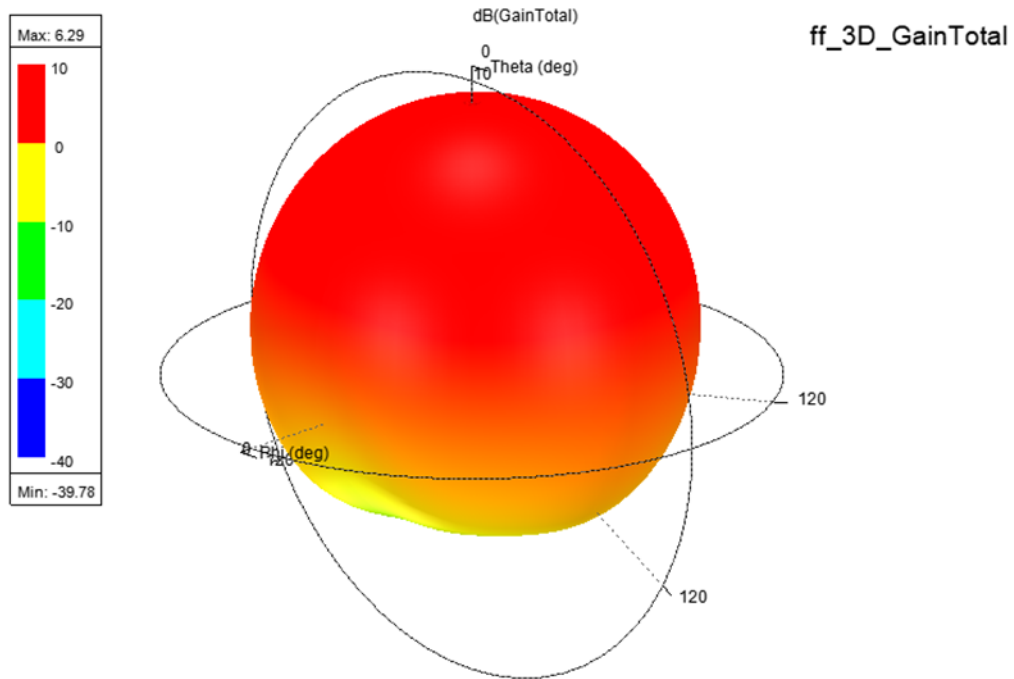


Figure 4-7 Gain with conductivity of 6.1×10^6 S/m for patch and ground planes.

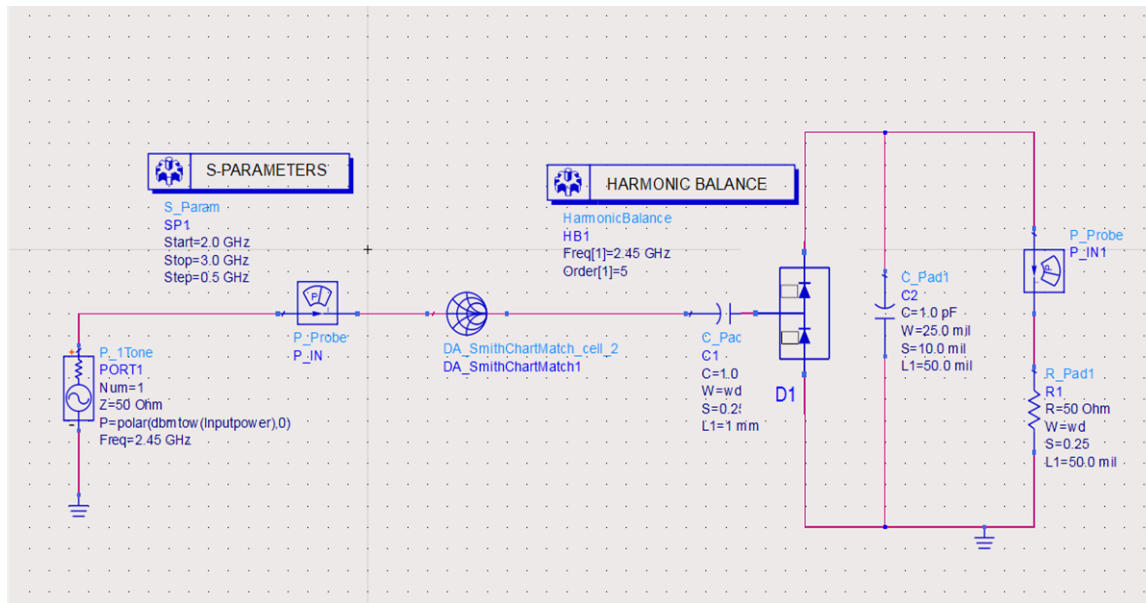


Figure 4-8 Voltage multiplier design for energy harvesting

Fig. 4-9 shows the voltage multiplier circuit for efficient energy harvesting. The voltage multiplier circuit described in the given context is a more efficient and robust solution for RF energy harvesting compared to the single diode rectification circuit. It effectively addresses issues related to low incident power density and limited breakdown voltage, leading to better power handling and energy conversion efficiency. The S11 parameter of -44 dB at 2.45 GHz further indicates excellent impedance matching and minimal power reflection, ensuring optimal performance of the circuit. A single diode-based rectification circuit was designed for energy harvesting application. Which can only rectify a single half cycle and reject the other half cycle. Further due to low incident power density, this topology cannot fulfil the requirements of RF energy harvesting. Another main reason is the limited breakdown voltage can be achieved with a half wave rectifier topology. Breakdown Voltage: A critical parameter that defines the maximum voltage a component can handle. The voltage multiplier circuit design helps manage this by spreading the voltage across several stages, thus avoiding the limitations of a single diode rectifier. Thus, the competence of the power handling can be disturbed. Therefore, we have designed a voltage multiplier circuit for energy harvesting as shown in Fig. 4-9 The S11 of the voltage multiplier circuit is

shown in Fig. 4-10, which has a deep resonance depth of -44 dB at 2.45 GHz ISM band. The designed circuit contain two parts: voltage multiplier and matching network.

For the conversion of RF to DC, we have chosen a high frequency diode HSMS 2852 from Skyworks due to its efficient performance. To match the voltage multiplier, we used the smith chart utility in ADS simulator. The load impedance was matched with a source impedance of 50 ohm at desired ISM band of 2.45 GHz by utilizing shunt and a series inductor. The RF to DC efficiency was calculated based on the following equations.

$$\eta(\%) = \frac{DCpower}{RFpower} \times 100 \quad 4.3$$

is a key measure of the conversion efficiency of RF energy harvesting systems, but it is not the only parameter to consider when evaluating efficiency performance. Other important parameters include radiation efficiency, total efficiency, gain, and VSWR. Stability, both in terms of frequency and environmental conditions, is also critical for ensuring consistent and reliable performance in real-world applications.

Figure 4-11 shows the RF to DC efficiency of the designed voltage multiplier circuit at the input power from -30 dBm to 30 dBm. A maximum efficiency of 75% was achieve at the input power of 10 dBm, which is better than (Dieff et al, 2020) rectifier topology. signed voltage multiplier circuit achieves a maximum RF to DC conversion efficiency of 75% at an input power of 10 dBm, which is a notable improvement over the previous rectifier topology by Dieff et al. (2020). This high efficiency means that the circuit can effectively convert a large portion of the input RF power into usable DC power, making it more suitable for practical energy harvesting applications. Additionally, the ability to generate an output voltage of greater than 3.5 V further highlights the effectiveness of the proposed design. Furthermore, the output voltage was also analysed and showed in Fig. 4-12. A maximum voltage of greater than 3.5 V was achieved for the proposed voltage multiplier circuit.

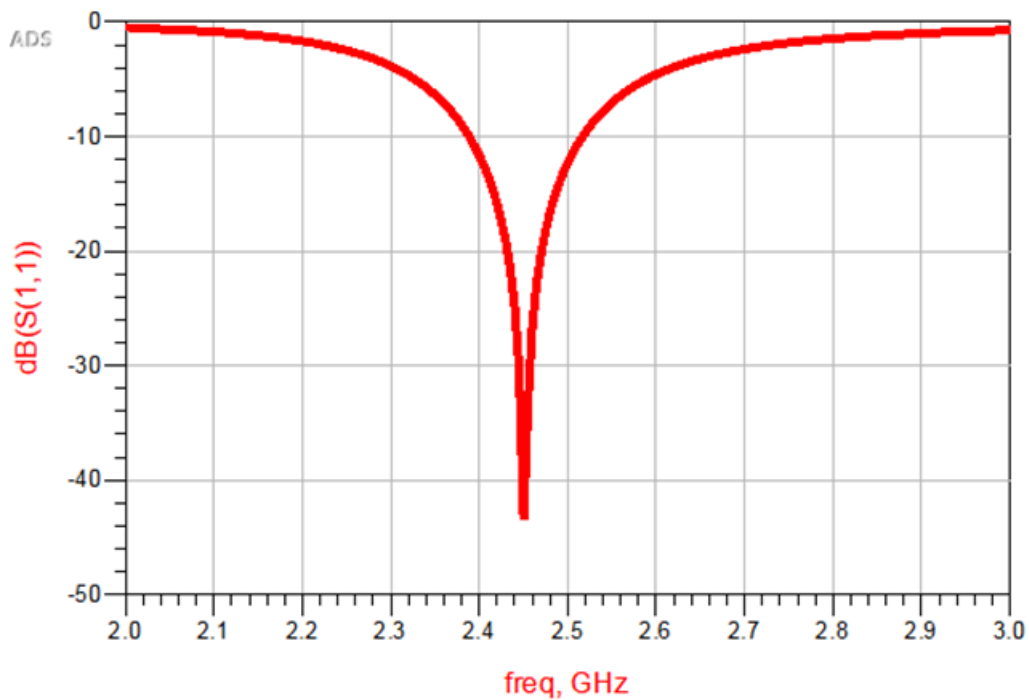


Figure 4-9 Reflection coefficient of the designed voltage multiplier circuit

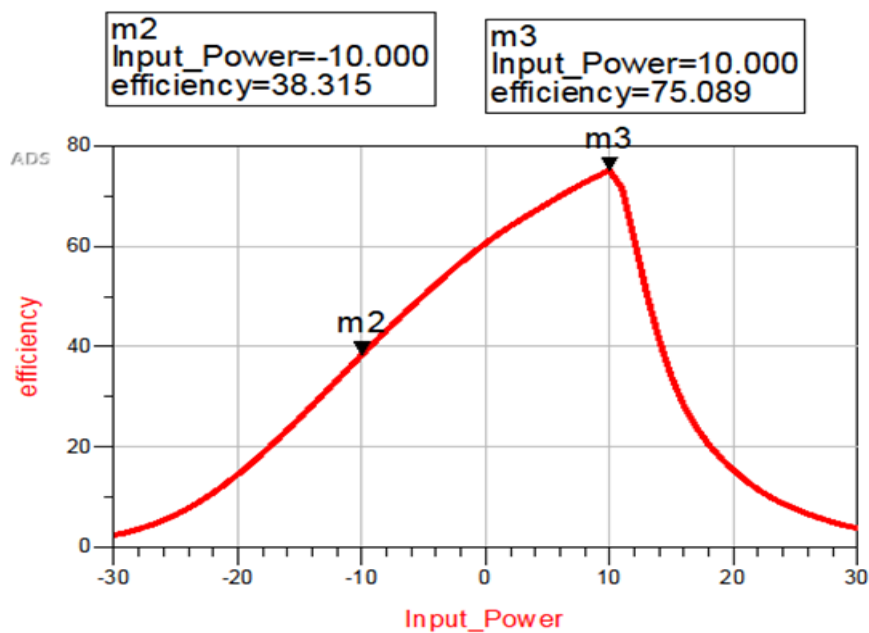


Figure 4-10 RF to DC efficiency of the designed voltage multiplier circuit

A negative input power vs. efficiency graph in HFSS is used to illustrate how the efficiency of an antenna or RF circuit varies with different levels of input power, including very low power levels typical of ambient RF energy sources. Negative values on the input power scale represent these low power levels, providing

crucial insights into the performance and optimization of energy harvesting systems under realistic operating conditions.

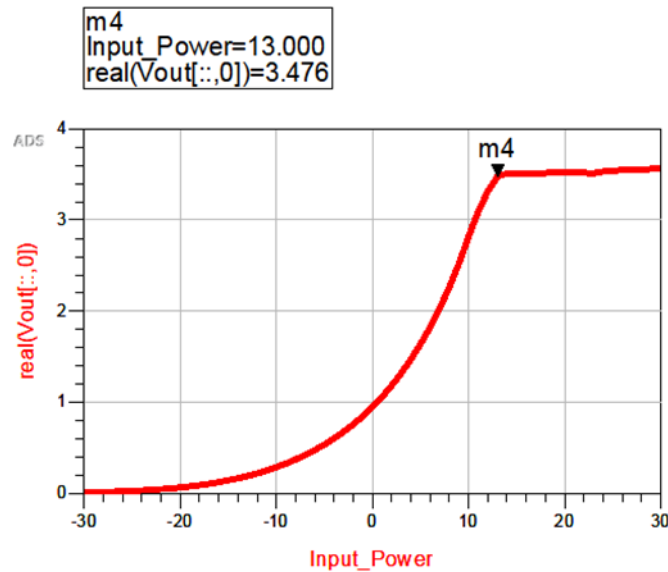


Figure 4-11 Output DC voltage of the designed voltage multiplier circuit

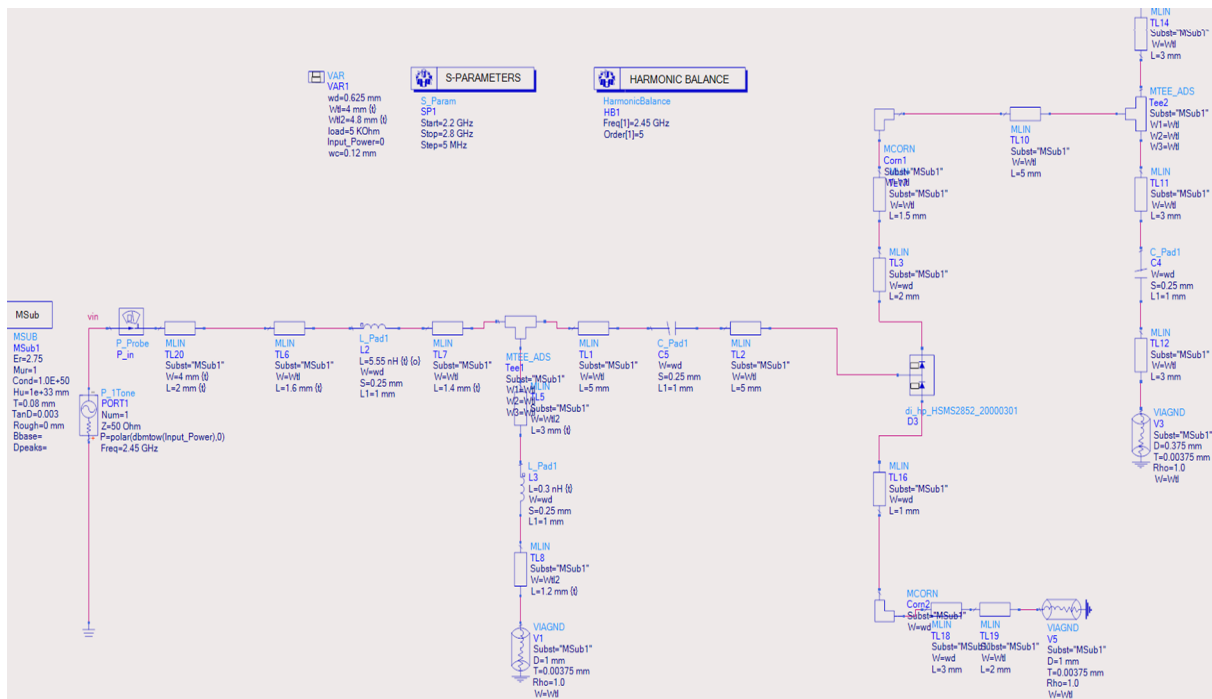


Figure 4-12 Transmission line model of the designed voltage multiplier circuit

To fabricate the designed circuit on Organza fabric, I need to include transmission line model to the proposed circuit. I have included transmission line with same

width of the antenna microstrip line for optimum impedance matching. The inclusion of transmission lines in the voltage multiplier circuit on Organza fabric is necessary for connecting components and maintaining impedance matching. However, this addition initially deteriorated the S11 parameter, indicating poor impedance matching. Through re-optimization, which involved tuning the values of inductors and adjusting the lengths of the transmission lines, the impedance matching was significantly improved, resulting in an S11 depth of -37.5 dB. This re-optimization ensures efficient energy transfer and satisfactory performance of the circuit across the desired frequency band. The transmission line model of the voltage multiplier circuit is shown in Fig. 4-13. After adding the transmission lines, the S11 was deteriorated which was re-matched by tuning the inductors values and lengths of transmission lines. The final layout of the voltage multiplier circuit is shown in Fig. 4-14. After re-optimization the S11 is shown in Fig. 4-15. The inclusion of transmission lines in the voltage multiplier circuit on Organza fabric is necessary for connecting components and maintaining impedance matching. However, this addition initially deteriorated the S11 parameter, indicating poor impedance matching. Through re-optimization, which involved tuning the values of inductors and adjusting the lengths of the transmission lines, the impedance matching was significantly improved, resulting in an S11 depth of -37.5 dB. This re-optimization ensures efficient energy transfer and satisfactory performance of the circuit across the desired frequency band. At the desired frequency band, the S11 depth of -37.5 dB with a satisfactory impedance bandwidth was achieved.

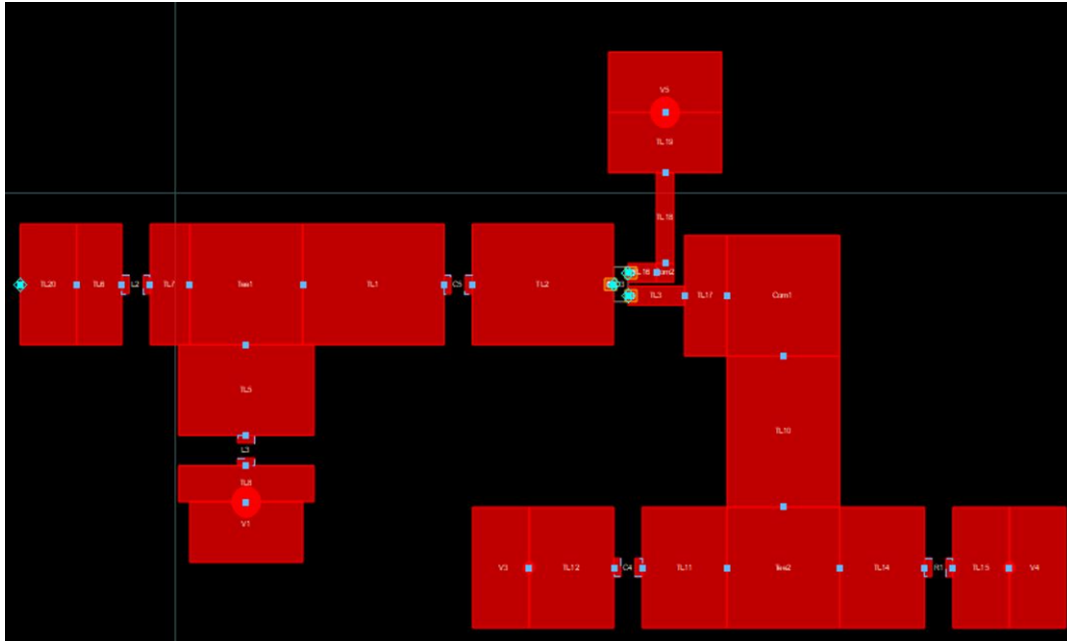


Figure 4-13 Final layout of the designed voltage multiplier circuit

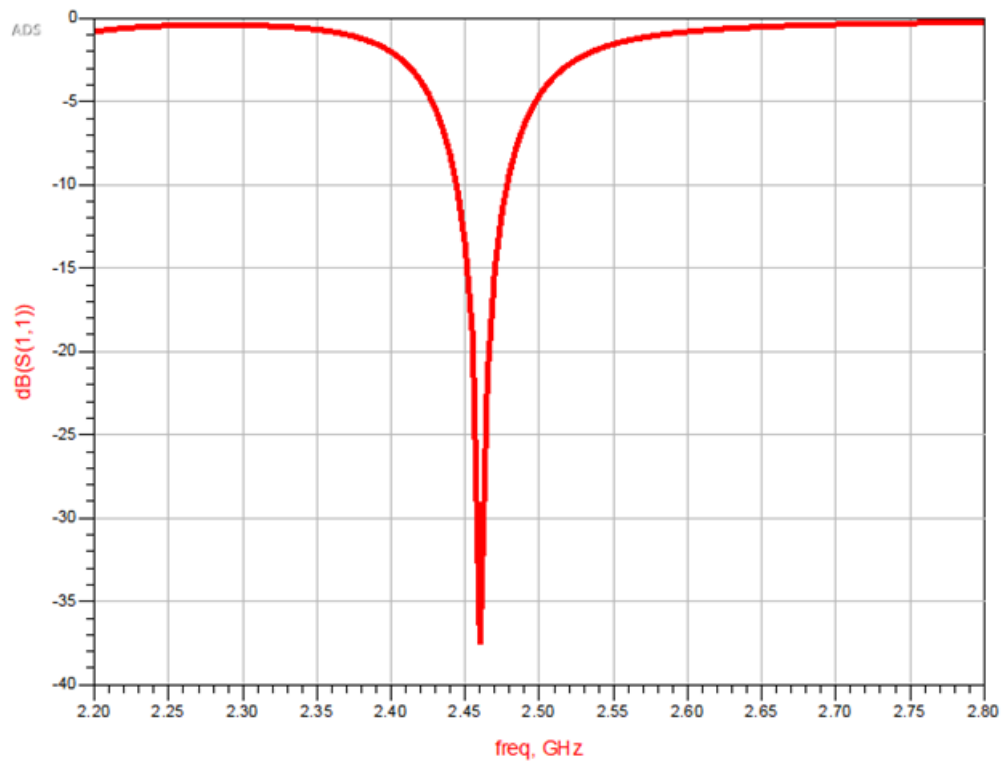


Figure 4-14 Reflection coefficient of the of the designed voltage multiplier circuit when transmission lines are added.

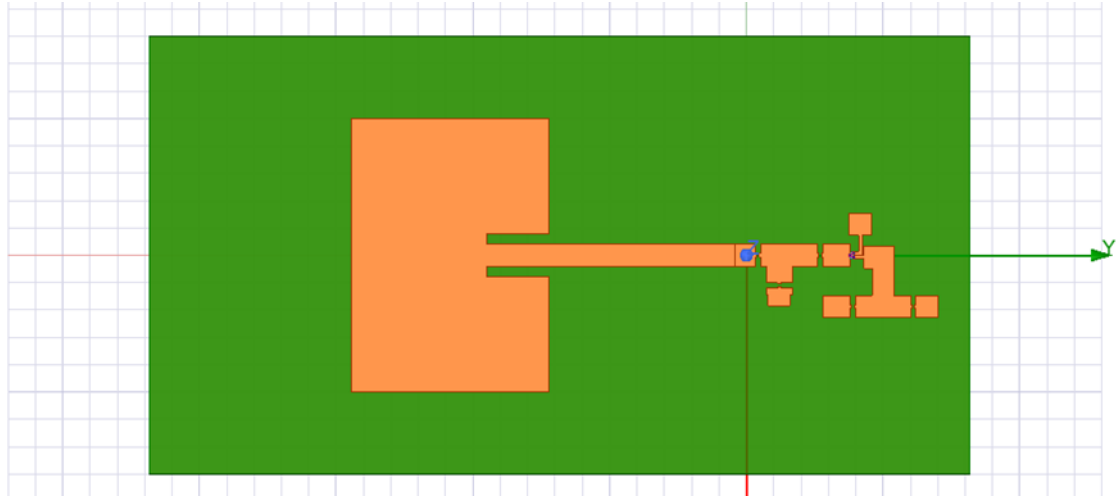


Figure 4-15 Designed antenna integrated with a designed voltage multiplier circuit.

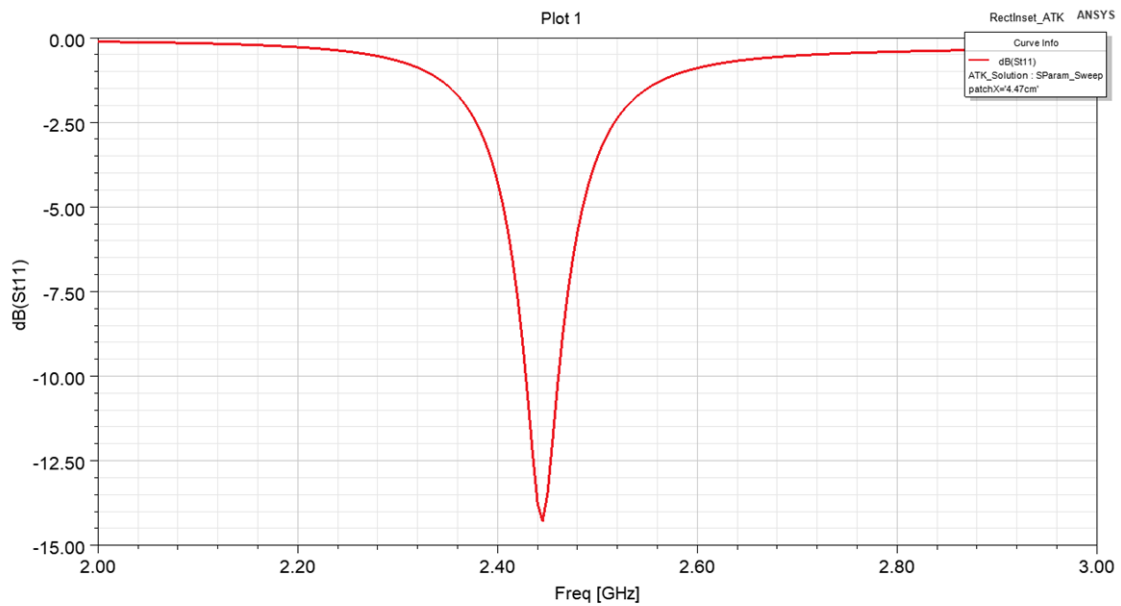


Figure 4-16 The reflection coefficient of the antenna integrated with a designed voltage multiplier circuit.

The layout of the proposed circuit was exported from ADS software and imported to HFSS. We have integrated the circuit layout to the antenna as shown in Fig. 4-16 the impedance matching was deteriorated by adding the circuit layout to the

antenna microstrip line. A S11 depth of -14 dB was observed and the bandwidth was reduced, as shown in Fig. 4-17. Thus, we retuned the antenna parameters for getting optimum performance. The processes described involves integrating the circuit layout with the antenna structure, which initially led to impedance matching issues. However, through antenna retuning and optimization, the impedance matching was significantly improved, resulting in better performance for energy harvesting applications. The observed gain of 6.2 dBi demonstrates the effectiveness of the optimized antenna-circuit system in efficiently converting RF energy into usable electrical power. The S11 of the optimized antenna with the circuit layout is shown Fig. 4-18 the depth was increased to -28 dB from -14 dB at the operating frequency of 2.45 GHz, which is much better for energy harvesting applications. Gain of 6.2 dBi was observed for the optimized antenna when integrated with a designed voltage multiplier circuit, as depicted in Fig. 4-19.

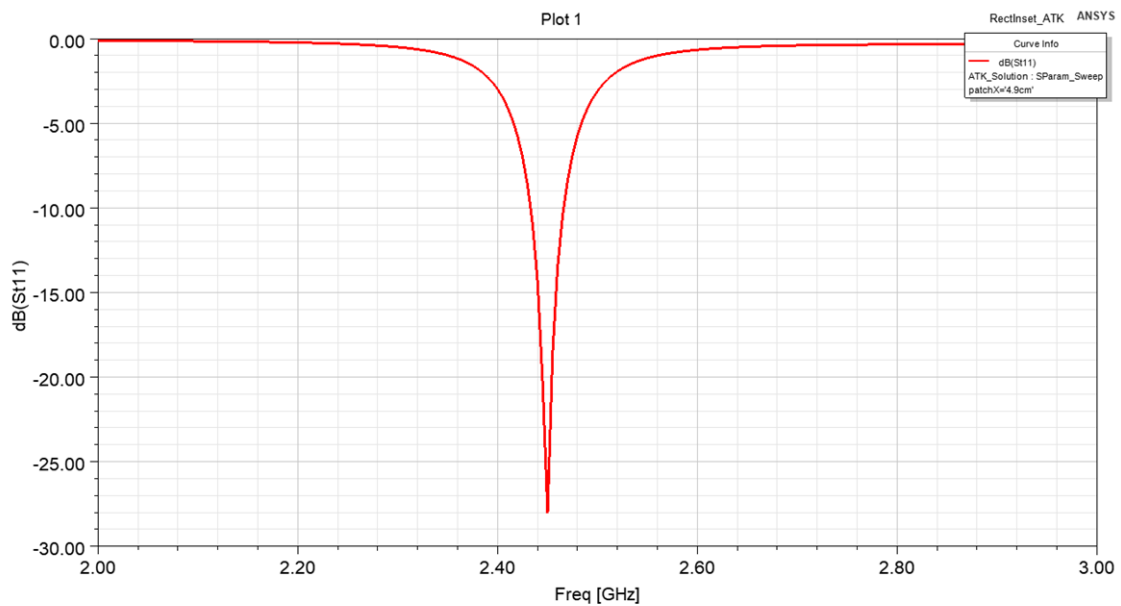


Figure 4-17 The reflection coefficient of the optimized antenna when integrated with a designed voltage multiplier circuit.

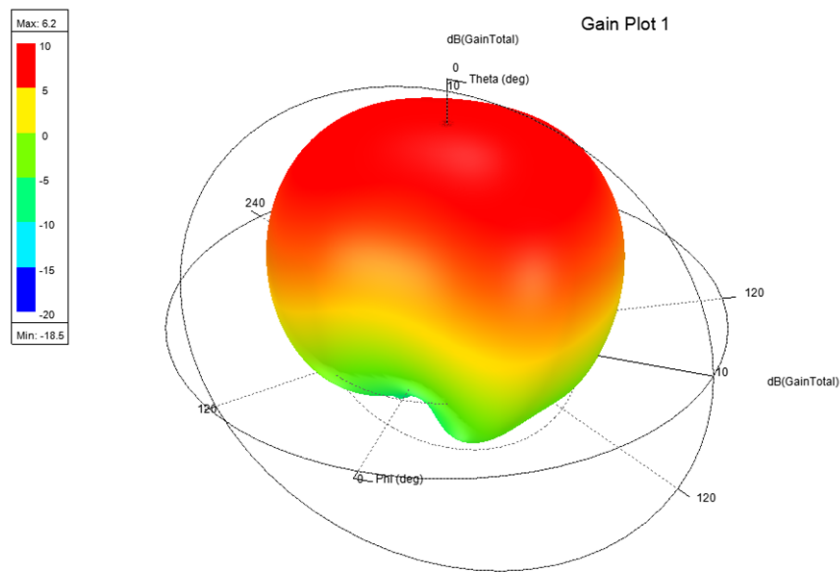


Figure 4-18 The gain of the optimized antenna when integrated with a designed voltage multiplier circuit.

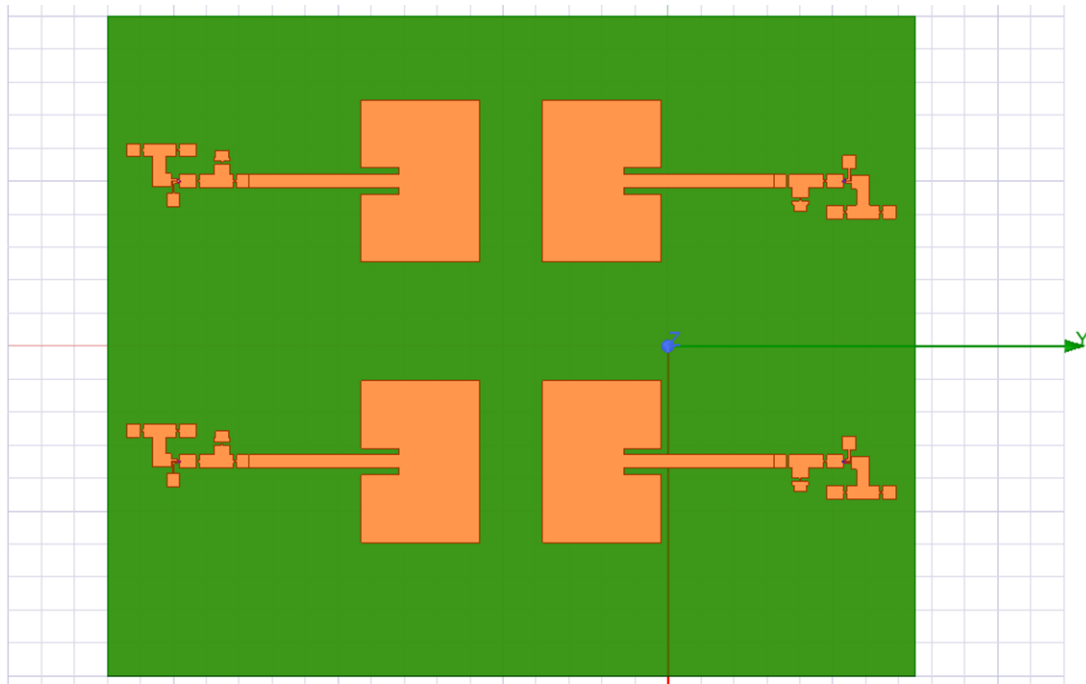


Figure 4-19 The 2 x 2 antenna array with the integrated voltage multiplier circuit

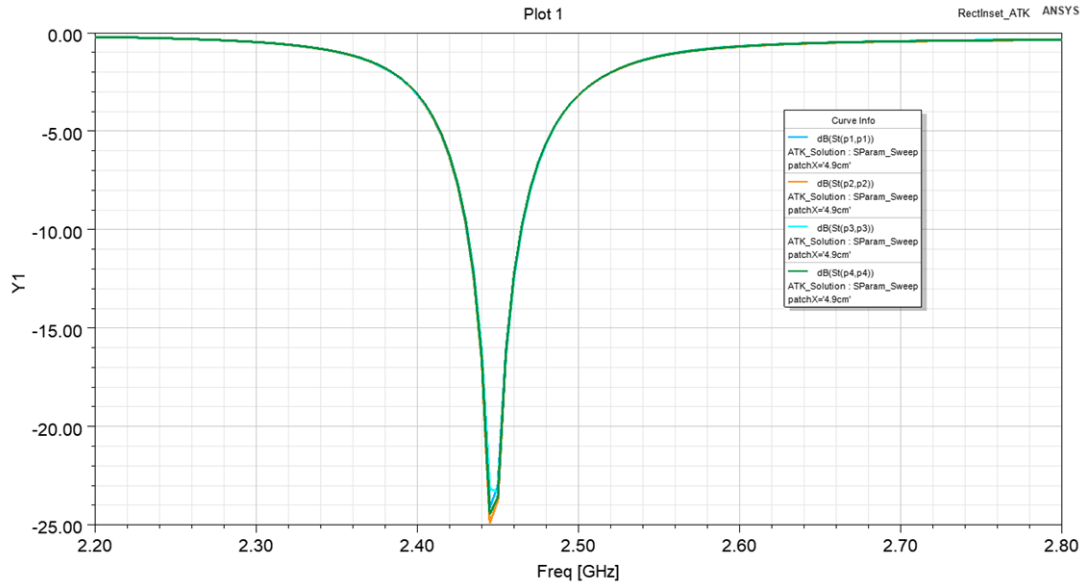


Figure 4-20 S11, S22, S33, and S44 of the 2 x 2 antenna array with the integrated voltage multiplier circuit

The 2 x 2 antenna array configuration was formed with the array integrated with a voltage multiplier circuit. Same material as organza was used for the substrate of the antenna array. In order to get optimum isolation, we have kept the horizontal distance between two elements as 85 mm and vertical distance as 55 mm. The total size of the 2 x 2 antenna array is 245mm x 200 mm. The 2 x 2 antenna array configuration is shown in Fig. 3-20. The S11, S22, S33, and S44 of the 2 x 2 antenna array is shown in Fig. 3-21. Due to identical structures and very low coupling, identical response was observed for all elements. The S11 depth of -25 dB was observed for all antenna elements. Furthermore, we have shown the S-parameters plots in Fig. 3-22. As can be seen from the figure, more than 15 dB isolation was achieved between the closest antenna elements. A maximum peak gain of 10.5 dBi was achieved for the 2 x 2 antenna array configuration. Based on the performance of the proposed 2 x 2 antenna array configuration, this can be used for the low power energy harvesting applications.

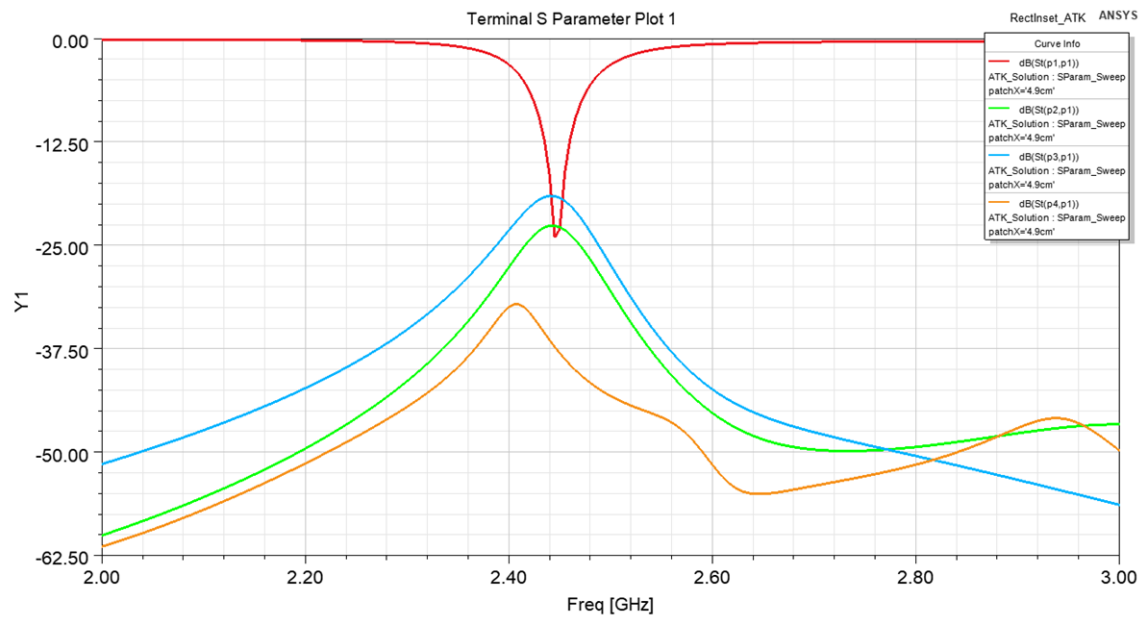


Figure 4-21 S-parameters of the 2 x 2 antenna array with the integrated voltage multiplier circuit

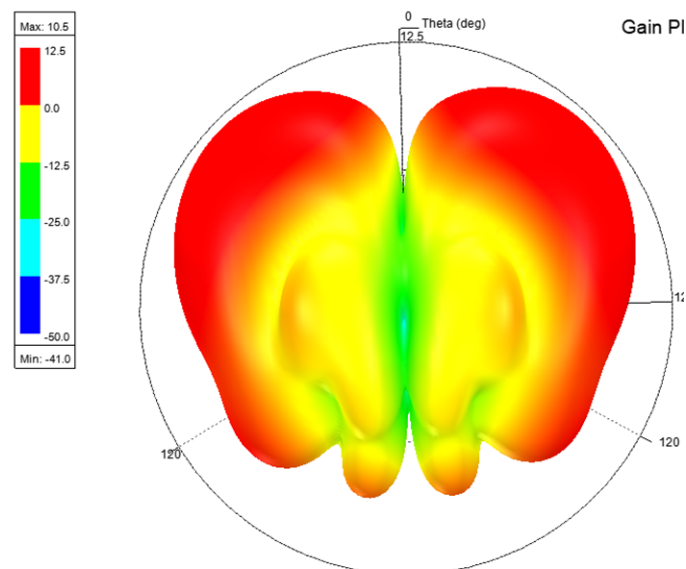


Figure 4-22 A combined gain of the 2 x 2 antenna array with the integrated voltage multiplier circuit.

4.3 Summary of Design, Modelling and Validation

In order to find a better energy source for wearable technology, this section looks into several energy sources. Since researchers want results that require little to no human intervention, batteries are typically used in these devices, which is not the best option. Because of this, batteries have a finite lifespan and need to be continuously recharged or replaced.

❖ Design Methods

The process begins by installing and setup of the standard RF model design software such as CST, HFSS and ADS on PC after that, then structure various patch model samples to test the performance of the software. Subsequently, initiate the modelling process of the prototype rectenna. At this stage, commence the initial following establishing the patch model. Upon completing each iteration, evaluate if the predefined threshold has been met. In the event that the threshold remains unfulfilled, repeat the iteration process. However, if the threshold is satisfied, proceed to incorporate the rectification network, and initiate a subsequent iteration. The iterative cycle continues until the threshold is successfully attained. Next, the conversion process transforms the simulated model into a digital format, which is then forwarded to the embroidery fabrication stage. Once the fabrication process is completed the model proceeds to the final testing stage.

❖ Simulation setup for rectenna patch antenna design

Higher frequency simulation software (HFSS), and Computer Simulation Technology (CST) were used to model the antenna conductive circuitry. They are industrial and commercial standard software for modelling RF applications such as antenna circuitry, low-pass filters, and rectifiers.

The CST is only applied for modelling the antenna model as it is inefficient for rectifier extension or matching network. Meanwhile, HFSS can simulate both the antenna and rectifier circuitry. Figure 3 and table 1 is the simulation environment of HFSS and measurement parameters values for the antenna design respectively. A fabric antenna with dimensions 72mm by 68mm by 1.5 is

structured on rigid organza dielectric material simulated on CST and HFSS respectively. The output included is quantified with the previous measurement as discussed by (Dieff et al, 2020) to ensure the quality of the results.

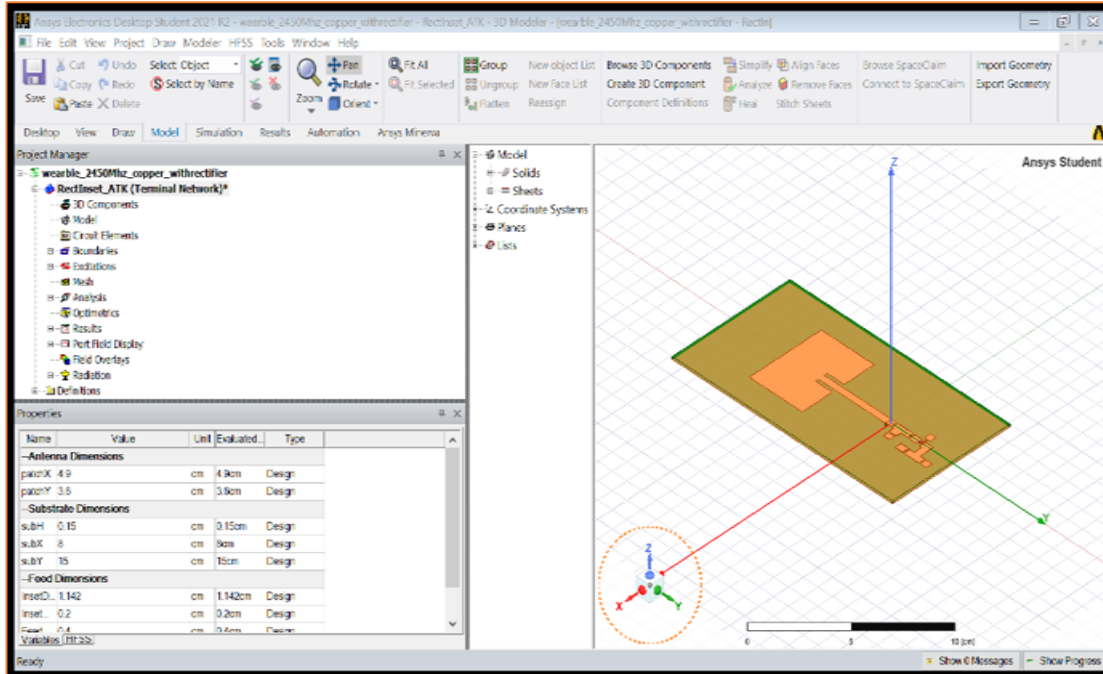


Figure 4.24 Simulation in HFSS Environment.

❖ Power Management (voltage multiplier circuit design)

Advanced design system (ADS) software is used to simulate the power management circuit. In order to enhance efficiency, a design approach utilising multiple diode rectifier has been implemented. This design incorporates various lumped components such as capacitors, resistors, rectifying diodes, and the length of the transmission line. These components collectively contribute to improving the overall efficiency of the system. The voltage multiplier circuit uses the following lumped components to enhance the RF ambient signal. The capacitor acts as an energy storage element, accumulating surface energy and supplying it to the load. In the event of voltage overflow, the resistor performs a step-down function to mitigate excessive voltage levels. Simultaneously, the diode amplifies the voltage, ensuring uniform and continuous conductivity, thus enabling efficient power transfer to the load.

The lumped component values placed in the circuit are $C1=2\text{pF}$, $C2=0.4\text{pF}$, and $R=1\text{kilo ohms}$ respectively. The position of the diode is optimised by tuning the lengths $L1=18\text{mm}$, and $L2=6\text{mm}$ to increase the efficiency. The idea is to utilise the power stored in a standing wave, which causes higher voltage across diode terminals. As expected, standing wave amplitude could be up to twice the propagating wave. This allows RF-dc conversion efficiency to improve on 50% limit threshold of single-diode half-wave rectifiers. Furthermore, the capacitors $C1$ and $C2$ are added and optimized for impedance matching with incoming RF power. A single diode-based rectification circuit is designed for energy harvesting application that can only rectify a single half-wave and reject the other half cycle (Valenta & Durgin, 2014; Hemour et al., 2014; Dieff et al, 2020). However, this topology cannot fulfil the requirements of RF energy harvesting due to low incident power density. Furthermore, a half wave rectifier topology can achieve limited breakdown voltage. Thus, the competence of the power handling can be disturbed. Hence, a voltage multiplier circuit has been designed for energy harvesting. The S11 parameter of the voltage multiplier circuit exhibits a profound resonance depth reaching -44 dB at 2.45 GHz ISM band. The power versus frequency graph in figure13 presents the design has a return loss at approximately -44dBm.

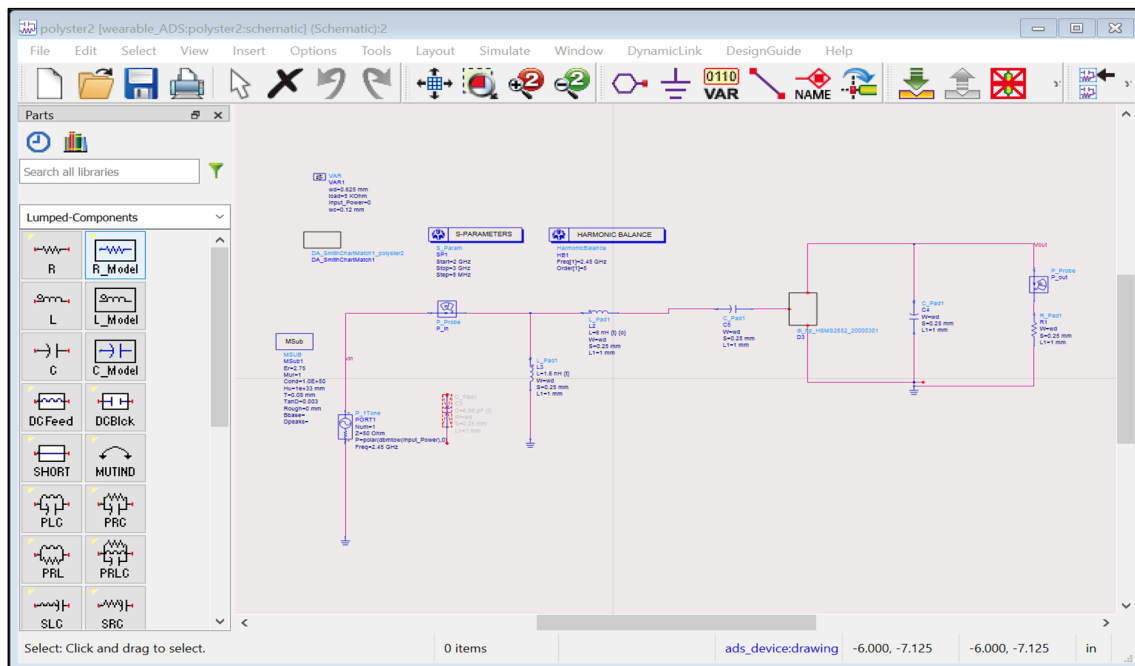


Figure 4.25 Voltage multiplier simulation in ADS environment.

5 FABRICATION, TESTING AND EVALUATION

5.1 Introduction

This chapter presents fabrication methods, testing and evaluation of the obtained research result. A comparative analysis of the result with previous work carried in this area will be made in this chapter as well. Also, the detailed procedure will be outlined. Furthermore, this research work will showcase the technical knowledge of the analytical performance of the system as related to RF wireless sensor. Then coupled with the system testing and discussion. The artefacts experimental results from this research with the stages undergone for the actualise the device will be provided also.

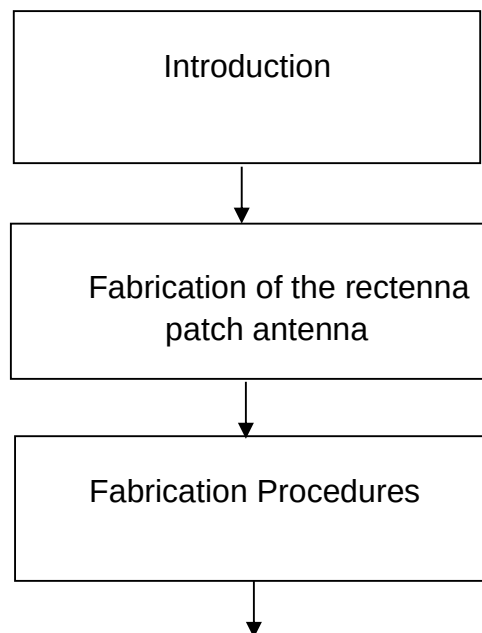
5.2 Fabrication of the rectenna patch antenna

Fabrication – use programmable embroidery machine to embroider conductive thread into textile substrate. The optimized CAD design from simulation is fed into the embroidery machine to fabricate antenna samples. Apart from the materials

of substrate and conductivity of the thread, other parameters such as density of threads in stitching (stitching-density), pattern and orientation of thread in stitching (stitching-pattern), and thread tension used during the stitching are also considered.

5.3 Fabrication Procedures

The intended systems use embroidered conductive thread-based conductive surface, which is washable, flexible and robust. The conductive thread technology performs better when compared with conductive ink technology, as it provides a uniform continuous metallic phase provided by metal-coated threads, as opposed to conductive inks, which merely contain metal nanoparticles. In contrast, embroidery method performs well with any off-the-shelf sewing machine. And, thus, does not need additional technological improvements, which could allow cost-effective manufacturing. We first present an embroidered patch antenna and a single-diode rectifier and then integrate these components to achieve fully textile rectenna arrays. The fabrication of the rectenna patch antenna was carried out using the following processes, inkjet printing and embroidery machine.



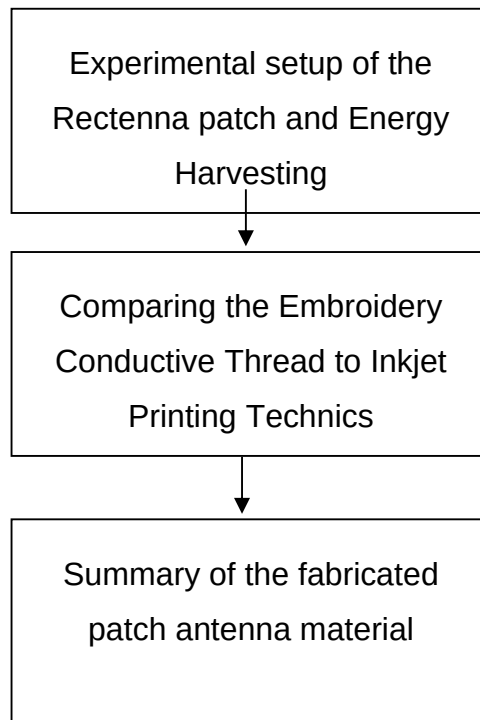
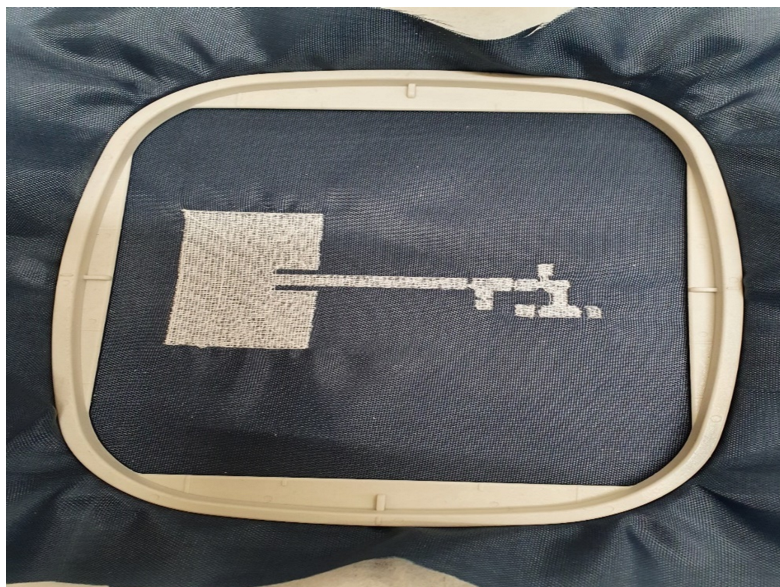


Figure 5-1 The fabricated patch antenna on the embroidery frame.

5.3.1 Using Inkjet Printer

The dimensions of the rectenna patch made by inkjet printing were identical to the simulations. Inkscape was used to digitalize the CAD model obtained by AutoCAD and exported in SVG format for manufacturing. The DPI It is a measure of the resolution of an image, specifically indicating the number of individual dots

that can be placed within a linear inch of the image. Of the image was increased before printing the rectenna patch to ensure fidelity. Also, the pet plastic was loaded inside the printer. Moreover, the printer was set to photo quality for printing the rectenna patch antenna.

Metalon JS-B25P silver ink. The value of the ink's desired sheet resistance is 60-70 milli-ohms/square. Sheet resistance was measured at the first and second layer with values of 120 milli-ohms/square and 90 milli-ohms/square respectively. The ink was cured in a vacuum oven at 100 degrees centigrade for 50 minutes before the printed rectenna patch. Figure 5-2 Connection of rectenna inkjet print to oscilloscope for output.

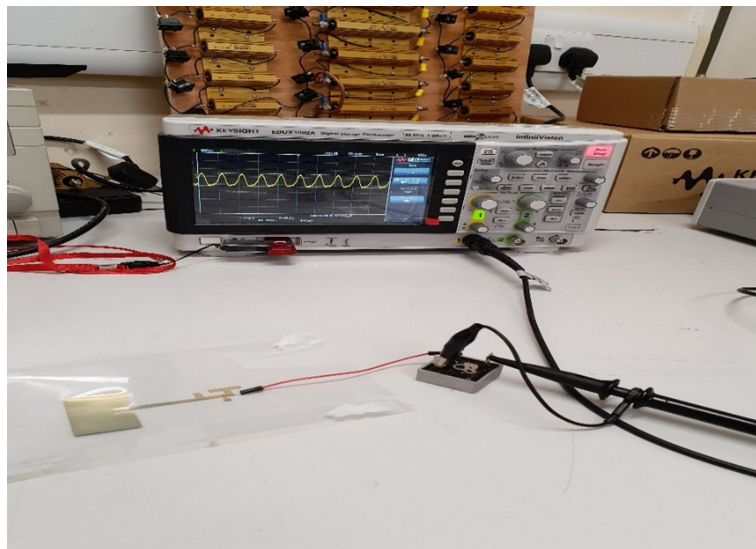


Figure 5-3 Connection of rectenna inkjet print to oscilloscope for output.

To monitor and examine the output of the rectenna circuit, it can be interesting to connect an inkjet print with a rectifying antenna to an oscilloscope. In order to transform electromagnetic waves, such as radio frequency (RF) or microwave signals, into direct current (DC) energy, a rectenna is a device that combines an antenna with a rectifier. Inkjet print of a rectangle This should be a printed

rectenna circuit made with conductive inkjet printing on a suitable substrate. A digital oscilloscope with the ability to gauge DC voltages and frequencies within the rectenna's output range. The usage of coaxial cable or a suitable connection the rectenna's connection to the oscilloscope. A rectenna inkjet print should be properly constructed and prepared for testing. For the purpose of converting RF or microwave signals into DC voltage, the printed rectenna should feature a rectifying diode and matching network. Find the rectenna's output terminals. Two terminals are typically present: one for the positive output (the anode of the rectifying diode), and the other for the negative output (the cathode of the rectifying diode). Set the oscilloscope to measure DC voltage and turn it on. Use one channel to measure the positive output and another for the negative output if the oscilloscope has many channels available. Opt for a dual-channel oscilloscope as an alternative. Connect the output terminals of the receiver to the oscilloscope probes. Once the oscilloscope is attached, you can begin viewing the output of the rectenna. Make that the positive probe is linked to the positive output terminal and the negative probe is connected to the negative output terminal. The rectenna should transform any RF or microwave signals existing in the surroundings into a DC voltage, which you can see on the oscilloscope. You might need to change the oscilloscope settings, such as the time scale and voltage scale, to get a clear picture of the output waveform, depending on the frequency and amplitude of the RF or microwave waves. Pay attention to the output waveform's frequency and amplitude. The strength of the received signal will be connected to the amplitude, while the frequency will rely on the incoming RF or microwave signal. Figure 5-4 Printed rectenna with inkjet printer.

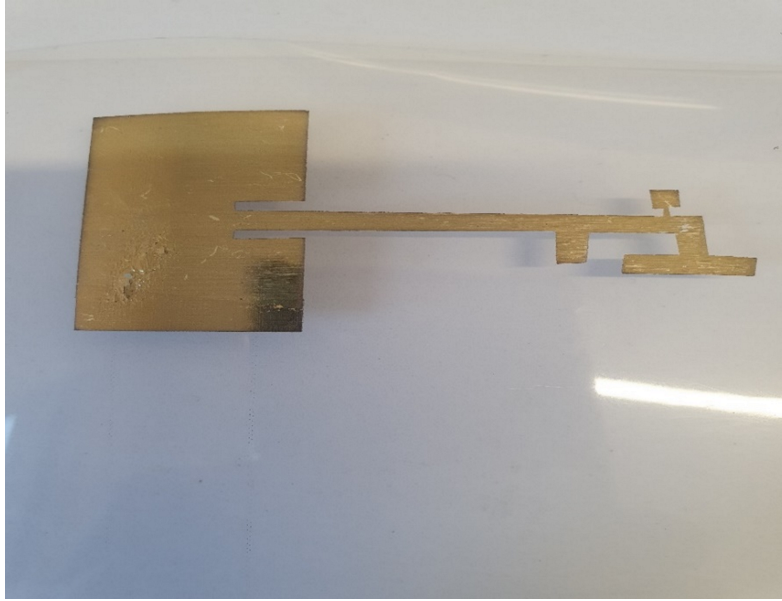


Figure 5-5 Printed rectenna with inkjet printer.

The dimensions were taken, much like in needlework, and an AutoCAD model was created. The model was then converted to digital form using Inkscape. After digitization, the model was exported as an SVG file. The DPI of the image was raised before printing. The printer was then loaded with the PET material. For printing, the printer was set to photo quality. A basic surface conductivity test was also carried out.

5.3.2 Using Embroidery Machine

Like the Inkjet printer, the dimension was also taken from the simulations and optimizes results. The simulated and optimized rectenna patch that resonates mostly at 2.45 GHz frequency was drawn in AutoCAD. Then the file was exported to Inkscape via ink stitch addon. Also optimized were the number of threads, sizing, patterns, etc. After words, the digitalized model was exported to the embroidery machine. To know the kind of conductive thread to purchase and the properties of the embroidery machine, the standard thread was used to fabricate the rectenna patch antenna. At fabrication of the patch rectenna, various setbacks were confronted. For the overall fabrication, the following processes were carried out, exploring in institch for the overall pattern of the rectenna,

adjusting the tension, tweaking the auto threader, needle, size of the thread among others.

The conductive thread make used was Madeira HC40 and 40 milli-ohms/square of sheet resistance. This process does not require curing of the thread (Vital et al; 2020). The conductive shapes are optimised using full-wave or circuit simulations were generated into CAD models imported to a Brother Innovis VM5100 embroidery software. Moreover, a pattern of needle paths is generated for the embroidery process. The pattern is then fed to the automated embroidery machine for fabrication.

In all, the following specifications were chosen for the fabrication a tension of 4 (out of 8), spacing of 0.25mm, maximum fill stitch length of 3.0mm, and 1.5mm for the running stitch length. The conductive thread make used was Madeira HC40 and 40 milli-ohms/square of sheet resistance. This process does not require curing of the thread (Vital et al; 2020)

Concisely, the conductive shapes are optimized by the use of full-wave or circuit simulations and then are converted to respective CAD models. The CAD models are then imported to a Brother Innovis VM5100 embroidery software, where a pattern of needle paths is generated for the embroidery process. The pattern is then fed to the automated embroidery machine for fabrication.

5.4 Experimental setup of the Rectenna patch and Energy Harvesting

To simplify the circuit design, a KBPC5010 bridge rectifier of 1000V 50A AC to DC full wave single phase rectifier was chosen. Also, a 2.0 K Ω resistor used for the circuit. The resistor specified is a 2.0 k Ω resistor. The lowercase "k" represents the prefix "kilo," which denotes multiplication by 1000. Therefore, 2.0 k Ω is equivalent to 2000 Ω , or 2.0 kilohms. Refer to the experimental setup depicted in Figure 4.4. The RF signal generator is placed left side of the fabricated patch antenna. Then the antenna fabricated conductive thread is connected to rectifier, which is finally connected to Oscilloscope for testing, display and analyze

the waveforms as voltage signals. Hence shows how voltage changes over time in seconds. The RF power harvested from the rectenna was plotted in the oscilloscope as shown in figure 4.4.

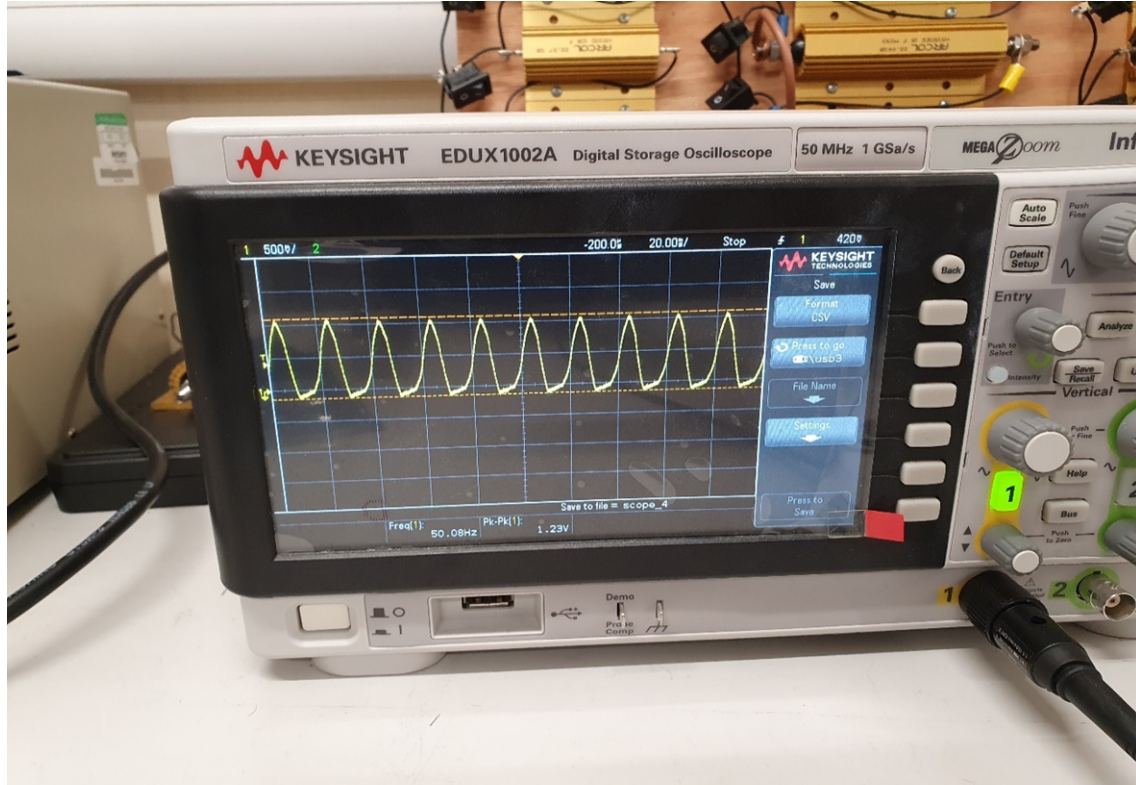


Figure 5-6 Connection of rectenna fabrication to oscilloscope for output

In the thesis implementation on RF or microwave transmissions, it's imperative to observe necessary safety precautions. While the equipment remains connected and powered on, I ensure to maintain a safe distance from any exposed metal components on the oscilloscope probes or the antenna. It's important to note that variations in the amplitude and frequency of surrounding RF/microwave signals can significantly impact the rectenna's behavior. To ensure accurate findings, I conduct experiments under diverse conditions and manipulate different variables. Utilizing the oscilloscope, I analyze the DC output voltage generated by the rectenna in response to the incoming electromagnetic waves.

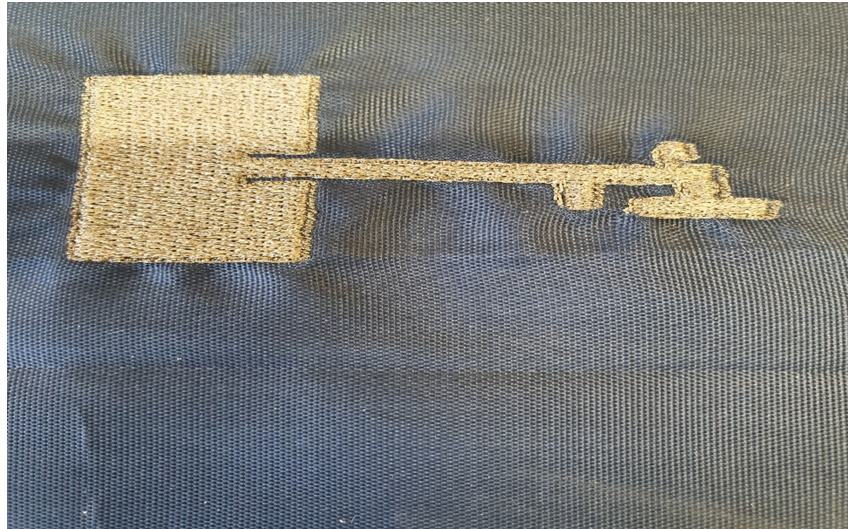


Figure 5-7 Fabricated rectenna with embroidery machine.

The electrical signals generated as data from the Oscilloscope is exported and saved via USB which is then imported to laptop system for a graph plot and electrical signal analyses.

The chosen KBPC5010 bridge rectifier converts the RF signal received by the antenna into a DC voltage. This rectifier is capable of handling high voltages and currents, making it suitable for efficiently converting the harvested RF power.

The 2.0 K Ω resistor acts as a load for the rectified DC output, allowing for a stable voltage measurement.

Waveform Analysis:

The oscilloscope is connected to the output of the rectifier and resistor combination. It displays and analyzes the DC voltage signal over time, showcasing how the voltage changes as the RF energy is harvested. The observed waveform on the oscilloscope represents the rectified DC voltage. The stability and amplitude of this waveform are influenced by the efficiency of the antenna (as indicated by the S11 parameter) and the effectiveness of the rectifier in converting the AC signal to DC.

Experimental Insights:

The oscilloscope's waveform provides visual confirmation of the RF energy harvesting process. It demonstrates how the harvested RF power is converted into a usable DC voltage, which can then be analyzed for its stability and efficiency. The low S11 value, coupled with the rectifier and load, ensures that the voltage signal displayed on the oscilloscope is a reliable representation of the rectenna's performance in harvesting RF energy.

The efficient design of the antenna (as evidenced by its S11 performance) and the use of the KBPC5010 rectifier allow for effective conversion of RF energy to DC voltage. The oscilloscope displays this voltage over time, providing a clear picture of the system's efficiency and stability in real-world conditions.

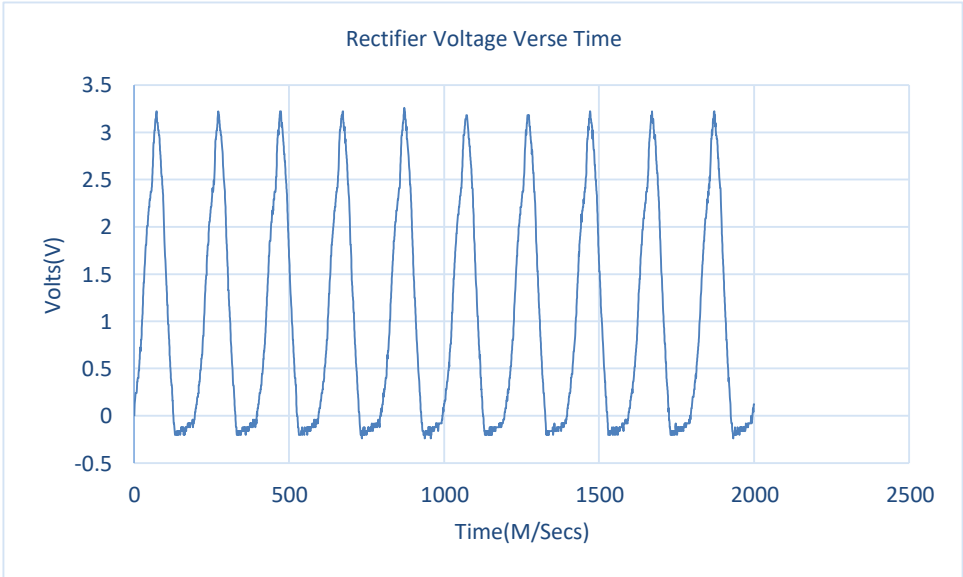


Figure 5-6 Graph of conductive thread

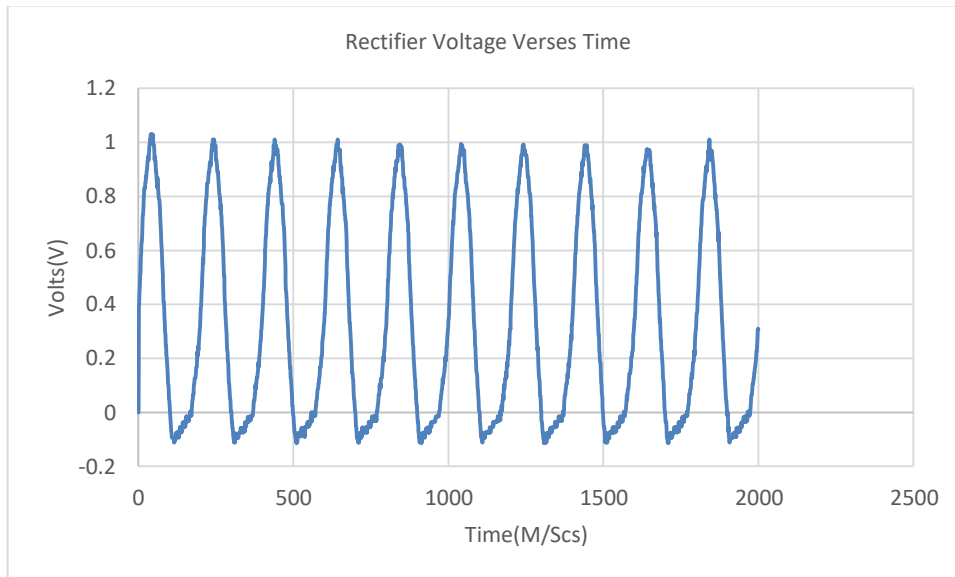


Figure 5-7 Graph of inkjet print

Figure 5.5 depicts the maximum peak electrical signal of 3.37 volts (equivalent to 0.002769 watts) obtained as the harvested output power for the conductive thread fabricated through embroidery. Conversely, Figure 4.6 illustrates the maximum peak electrical signal of 1.12 volts (equivalent to 0.0003059 watts) recorded as the output power harvested for the silver ink-print. These findings indicate that the conductive thread fabricated through embroidery exhibits greater conductivity compared to the silver ink-print

5.5 Discussion of results of Embroidery Conductive Thread to Inkjet Printing Technics

The improved system design in this PhD work use programmable embroidery conductive thread-based material for its technology. Which is flexible, washable, ironable, robust, cost-effective, durable and have uniform continuous conductivity compared to the conventionally used ink-based fabrication technique (W.G. Whittow et al...2014; B. S. Cook and A. Shamim 2012; J. Kimionis et al... 2015; J. Bito et al. 2015; S. E. Adami et al. 2015)

his material development on embroidery antenna was initially published in 2020 (Dieff et al., 2020). Hence, it had not been published when I commenced my literature review in 2019. This represents a novel and innovative research

advancement. The previous work was focusing on the embroidery technique but no evident on comparing the embroidery antenna to conventional ink-based printed antenna. In my Ph.D. project I have been improving it with more systematic and comprehensive new approach with evidence to compare performances and to optimise the density of threads, pattern, and tension of stitching for high conductivity of the device. Conductive inks are mostly used for antenna in research, however, the method used in this project provide improved, uniform and continuous conductivity than conductive inks, also lower cost since no need to use bespoke screen and expensive silver inks (S. E. Adami et al. 2015). However, one challenge/limitation associated with this method is the selection of material and diode is taken care of. By exploring these options and conducting further experimentation, it may be possible to overcome the challenges associated with material selection and conductivity enhancement in the fabrication of microstrip patch antennas. Presently, at the course of printing the designed rectangular microstrip patch antenna with silver ink-printer, we observed that the single ink print does not conduct while the double printing does conduct. But the single stitching by the embroidery conductive thread conducts perfectly based on its high stitching-density. Meanwhile, a comparison of the ink-printing of the designed patch antenna with silver ink-printer is conducted. We observed that the single ink print is not conductive while the double printing could improve. But with sample of conductive thread from embroidery machine do conduct at a single stitching based on its high stitching density.

Table 5.1 results and discussion

S/N	Parameters	Inkjet Printing	Embroidery
1	Fabrication	Fast to fabricate	Takes longer time fabricate due to its shape and process
2	Wearability	High surface resistivity due to prone to scratches	Low surface resistivity due to surface firm, no scratches.
3	Curing	Curing time required for the ink to dry up	Curing is not required

4	Materials	Nano silver ink printer needed	Threads and needles needed
5	Maximum Peak Voltage Value	1.12V	3.37V
6	Setup	Standard Method	Standard Method

High resistance during wearing" refers to the potential issue of increased electrical resistance encountered when a wearable device is worn or used. This resistance can arise from various factors such as body movement, sweat, or environmental conditions, which may affect the conductivity of the device's materials or connections. The Maximum Peak Voltage Value refers to the highest voltage reached during a specific period or cycle of an electrical signal. In an alternating current (AC) waveform, such as a sine wave, the voltage fluctuates between positive and negative values. The maximum peak voltage represents the highest positive value attained by the waveform.

Setup refers to the arrangement or configuration of equipment, materials, and conditions necessary to carry out a particular task, experiment, or procedure. In scientific or technical contexts, "setup" typically involves assembling and organizing various components and instruments according to a specific plan or protocol to achieve a desired outcome.

5.7 Summary of the fabricated patch antenna material

This current fabricated patch antenna material and its fabrication technique by embroidery machine using conductive thread are washable, cheap, ironable, bendable and have more uniform conductivity compared to the conventionally used ink-based fabrication technique.

Furthermore, these systems use programmable embroidery conductive thread-based material for its technology. It is favourable because of its uniform continuous conductivity, washable, durable, cost-effective, flexible. The material development on embroidery was first published in 2020 (Dieff et al.,2020). It is a relatively new technique used for fabricating antenna.

The fabricated patch antenna using embroidery techniques with conductive thread offers significant advantages over traditional inkjet printing methods. Here is a comparative summary of key parameters:

Fabrication Time:

Inkjet Printing: Fast to fabricate.

Embroidery: Takes longer to fabricate due to the complexity of the shape and process.

Wearability:

Inkjet Printing: High surface resistivity and prone to scratches.

Embroidery: Low surface resistivity with a firm surface that resists scratches.

Curing:

Inkjet Printing: Requires curing time for the ink to dry.

Embroidery: Curing is not required.

Materials:

Inkjet Printing: Requires a nano silver ink printer.

Embroidery: Uses threads and needles.

Maximum Peak Voltage Value:

Inkjet Printing: Achieves a peak voltage of 1.12V.

Embroidery: Achieves a higher peak voltage of 3.37V.

Setup:

Both methods use a standard setup.

Advantages of Embroidered Antennas

The current fabrication technique using an embroidery machine with conductive thread has several benefits over the ink-based fabrication method. These include:

Washable: The embroidered antennas can be washed without degrading performance.

Cost-Effective: The materials and process are cheaper compared to inkjet printing.

Ironable and Bendable: The antennas can withstand ironing and bending, adding to their durability and flexibility.

Uniform Conductivity: Provides more consistent conductivity compared to ink-based methods.

Material Development and Technology

Programmable Embroidery: The technique uses programmable embroidery machines with conductive thread, making it a modern and efficient method for antenna fabrication.

Durability and Flexibility: The embroidered materials are durable, flexible, and maintain uniform continuous conductivity, making them suitable for various applications.

Innovation: This technique, first published by Dieff et al. in 2020, represents a relatively new approach to antenna fabrication, showing promise for future advancements in wearable and flexible electronics.

The fabricated patch antenna using an embroidery machine and conductive thread presents several significant advantages over traditional inkjet printing methods. Although the embroidery process takes longer due to the complexity of the shapes and steps involved, it results in a more durable and wearable product. Unlike inkjet-printed antennas, which are prone to scratches and exhibit high surface resistivity, embroidered antennas boast low surface resistivity and a firm surface that resists damage. Moreover, the embroidered antennas do not require a curing period, unlike their inkjet counterparts, which need time for the ink to dry.

In terms of materials, inkjet printing relies on nano silver ink printers, while embroidery utilizes standard threads and needles, making the setup more

accessible and cost-effective. The embroidered antennas also demonstrate superior electrical performance, achieving a maximum peak voltage value of 3.37V compared to the 1.12V observed in inkjet-printed antennas.

The use of conductive threads in embroidery results in antennas that are washable, ironable, and bendable, enhancing their practical applications. These materials offer uniform conductivity, which is crucial for consistent performance. The programmable nature of embroidery machines enables precise and repeatable fabrication, making this method favorable for mass production.

First introduced in 2020 by Dieff et al., the technique of using conductive thread for antenna fabrication is relatively new but shows great promise. It provides a cost-effective, durable, and flexible solution for creating wearable electronics. Overall, the embroidered patch antenna is a robust alternative to traditional inkjet-printed antennas, offering enhanced performance and versatility in various applications.

6 DISCUSSION AND FUTURE WORK

6.1 Future Work

A developing technique called RF (Radio Frequency) power harvesting makes it possible to transform ambient radio frequencies into electrical power. The ability to continuously and wirelessly power low-power electronics requiring the use of conventional cable connections makes this technology extremely promising for wearable devices. In this post, we offer advice for the development of wearable technology's RF power harvesting systems.

Enhanced Energy Conversion Efficiency: For RF power harvesting systems, increasing energy conversion efficiency is essential. To maximise the amount of power transferred from the RF waves in the environment to the wearable device, researchers should concentrate on creating sophisticated circuit designs and perfecting the matching networks. By absorbing more RF energy, investigating novel materials, and developing cutting-edge antenna designs can also boost efficiency.

Integration and downsizing: Further miniaturisation and integration are required to make RF power harvesting systems more appropriate for wearable technology. The goal should be to make the power harvesting modules smaller and lighter without sacrificing performance. The functionality and practicality of wearable technology can be improved by integrating the power harvesting circuits with other parts, such as antennas, sensors, and energy storage units.

Multi-Band and Wideband Operation: Wearable technology operates in a variety of settings with diverse RF signal properties. Therefore, to ensure effective energy harvesting in a variety of settings, RF power harvesting devices should be built to operate over several frequency bands. The capabilities of wearable devices to harvest energy from a wider variety of frequencies will also be improved by the development of wideband RF power harvesting systems.

Adaptive Power Management: Optimising the use of energy in wearable devices can be accomplished by implementing adaptive power management algorithms in RF power harvesting systems. According to the power needs of

various components, these algorithms can effectively distribute and allot the captured energy, extending the device's overall working time. During low-power settings, adaptive power management can also aid in prioritising power allocation to crucial functionalities.

Integration of Energy Storage Technologies: Wearable technology must incorporate effective energy storage methods even though RF power harvesting offers a constant energy supply. During times of high-power demand or low RF energy availability, this integration assures a steady power supply. The total performance and usefulness of wearable technology can be considerably improved by investigating developments in energy storage, such as flexible batteries, super capacitors, or materials capable of harvesting energy.

Standardization and Interoperability: The RF power harvesting technologies for wearable devices need to be standardised in order to encourage their widespread use and interoperability. In order to facilitate the seamless integration of diverse RF power harvesting methods with different wearable devices, standardisation efforts should concentrate on developing common specifications, protocols, and interfaces. Interoperability between various devices will be possible as a result, helping an extensive ecosystem to grow.

6.2 Publications to date

1. Nwalike, E.D.; Ibrahim, K.A.; Crawley, F.; Qin, Q.; Luk, P.; Luo, Z. Harnessing Energy for Wearables: A Review of Radio Frequency Energy Harvesting Technologies. *Energies* **2023**, *16*, 5711. <https://doi.org/10.3390/en16155711>
2. Nwalike, E.D.; Ibrahim, K.A.; Crawley, F.; Qin, Q.; Luk, P.; Luo, Z. *Radio Frequency Power Harvesting System for Wearable Device*. *Energies* 2023, (manuscript in preparation).

7 Conclusion

7.1 Conclusion

Rectennas are a crucial part of an RFEH system that defines how well it performs and has a big impact on its overall efficiency. They may operate in various RF power and frequency bands. Rectennas can be made out of inexpensive, flexible, and printable materials, proving that material-induced losses can be reduced with the right antenna design and impedance matching methods. This has been shown with different manufacturing techniques and architectures up to mm Wave bands. The main conclusions and contributions of this thesis are outlined, along with an evaluation of the work that has been done and recommendations for future research based on the findings. Rectennas can be created utilizing affordable, flexible printed materials, as demonstrated. The RF to DC efficiency of the designed voltage multiplier circuit at the input power from -30 dBm to 30 dBm. A maximum efficiency of 75% was achieved at the input power of 10 dBm, which is better than (Dieff et al., 2020) rectifier topology. Furthermore, the output voltage was also analyzed. A maximum voltage of greater than 3.5 V was achieved for the proposed voltage multiplier circuit. An impedance matching circuit can be used to compensate for material losses, or the design can be improved. The manufactured rectenna patch were coupled to a capacitive rectifier circuit. Additionally, 1.12V via inkjet printing and 3.37V via embroidery were used to achieve the highest peak voltage for the frequency of the rectenna patch antenna. Also, the output power harvested for both inkjet printing and embroidery are (0.0003059 watts) and (0.002769 watts) respectively.

Concisely, the intended systems use embroidered conductive thread-based conductive surface, which is washable, flexible, and robust. Conductive thread technology outperforms conductive ink technology due to the ability of metal-coated threads to provide a uniform and continuous metallic phase. In contrast, conductive inks rely on metal nanoparticles, resulting in a less consistent performance. In addition, the embroidery method, which is compatible with commercially available sewing machine, exhibits outstanding performance and requires no additional technological advancements. This feature enables the

implementation of cost-effective manufacturing processes. Embroidered patch antenna and a single-diode rectifier are presented, followed by the integration of these components to achieve fully textile rectenna arrays.

Rectennas are a crucial part of an RF energy harvesting (RFEH) system, significantly impacting overall efficiency. These devices can operate across various RF power and frequency bands, and can be made from inexpensive, flexible, and printable materials, demonstrating that material-induced losses can be minimized with proper antenna design and impedance matching techniques. This versatility has been proven with different manufacturing techniques and architectures up to mm Wave bands. The key findings and contributions of this thesis are summarized as follows:

Conversion into Percentage

The RF to DC efficiency of the designed voltage multiplier circuit ranged from -30 dBm to 30 dBm input power, achieving a maximum efficiency of 75% at 10 dBm input power. This performance surpasses the rectifier topology presented by Dieff et al. (2020).

The output voltage analysis showed that the proposed voltage multiplier circuit achieved a maximum voltage greater than 3.5V.

The highest peak voltage achieved for the rectenna patch antenna was 1.12V via inkjet printing and 3.37V via embroidery, which represent increases of approximately 220% for embroidery compared to inkjet printing.

The output power harvested was 0.0003059 watts for inkjet printing and 0.002769 watts for embroidery, indicating that the embroidery method produces about 800% more power than inkjet printing.

The embroidered conductive thread-based antennas are washable, flexible, and robust. Conductive thread technology outperforms conductive ink technology due to the ability of metal-coated threads to provide a uniform and continuous metallic phase. In contrast, conductive inks, which rely on metal nanoparticles, offer less

consistent performance. Additionally, the embroidery method, compatible with commercially available sewing machines, exhibits excellent performance without requiring additional technological advancements. This compatibility enables cost-effective manufacturing processes. This work demonstrates the integration of

embroidered patch antennas and single-diode rectifiers to achieve fully textile rectenna arrays.

Summary of the Conclusion in Bullet Points

- **Efficiency:** Achieved a maximum RF to DC efficiency of 75% at 10 dBm input power, surpassing previous designs.
- **Voltage Output:** The proposed voltage multiplier circuit achieved a maximum output voltage greater than 3.5V.
- **Peak Voltage:** Embroidered antennas achieved approximately 220% higher peak voltage (3.37V) compared to inkjet printed antennas (1.12V).
- **Power Harvesting:** Embroidered method harvested about 800% more power (0.002769 watts) compared to inkjet printing (0.0003059 watts).
- **Material Advantages:** Embroidered conductive thread-based antennas are washable, flexible, and robust, outperforming conductive ink technology.
- **Manufacturing:** The embroidery method is compatible with commercially available sewing machines, facilitating cost-effective manufacturing processes.
- **Integration:** Successful integration of embroidered patch antennas with single-diode rectifiers to create fully textile rectenna arrays.

Beneficiaries of the Research:

Wearable Electronics Sector: Enhanced durability, flexibility, and washability make embroidered antennas ideal for wearable technology.

Healthcare Industry: Improved performance and reliability of wearable health monitoring devices.

Smart Textiles: Manufacturers benefit from cost-effective, flexible, and durable components for smart textiles.

Consumer Electronics: Companies developing flexible and portable electronic devices can utilize these antennas for improved performance.

Military and Défense: Durable and flexible antennas suitable for integration into military uniforms and equipment.

Overall, this research provides significant advancements in the development and application of embroidered antennas for RF energy harvesting, benefiting multiple sectors with improved performance, durability, and cost-effectiveness.

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