

Development of RF Energy Harvesters for Low Power Wireless Sensor Networks

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<https://doi.org/10.15017/2534463>

出版情報 : Kyushu University, 2019, 博士 (工学) , 課程博士
バージョン :
権利関係 :





九州大学

KYUSHU UNIVERSITY

Development of RF Energy Harvesters for Low Power Wireless Sensor Networks

A THESIS

Submitted to the Graduate School of
Information Science and Electrical Engineering
Kyushu University

In Partial Fulfillment of the Requirements for the Degree
of

Doctor of Philosophy

in

Electronics and Communication Engineering

By

Mohamed M. Mansour

2019

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To Whom It May Concern, We hereby certify that this print is a typical copy of the original Dr. Eng. (Doctor of Engineering) thesis of **Mr. Mohamed Mansour**

Dissertation Title:

DEVELOPMENT OF RF ENERGY HARVESTERS FOR LOW POWER WIRELESS SENSOR NETWORKS

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2019

Summary

The environment represents a relatively good source of available energy compared with the energy stored in batteries or supercapacitors. In this prospective, energy harvesting, also known as power harvesting and energy scavenging, is an alternative process for primary batteries, where energy is obtained from the ambient environment. An energy harvester typically captures, accumulates, stores, and manages ambient energy in order to convert it into useful electrical energy for autonomous wireless sensor networks. The use of energy scavenging minimizes maintenance and cost operation; therefore, batteries can be eventually removed in the wireless sensor networks (WSN) as well as in portable electronic devices.

RF energy is currently broadcasted from billions of radio transmitters around the world, including mobile telephones, hand-held radios, mobile base stations, and television radio broadcast stations. The ability to harvest RF energy, from ambient or dedicated sources, enables wireless charging of low power devices and has resulted benefits to product design, usability, and reliability. Battery-based systems can eliminate the battery replacement. Battery-free devices can be designed to operate upon demand or when sufficient charge is accumulated. In both cases, these devices can be free of connectors, cables, and battery access panels, and have freedom of placement and mobility during charging and usage. The obvious attraction of harvesting ambient RF energy is that it is essentially "free" energy. The number of radio transmitters, especially for mobile base stations and handsets, continues to increase. It is estimated that the number of mobile phone subscriptions has recently surpassed 5 billion users around the globe.

Mobile phones represent a great source of transmitters from which to harvest RF energy, and will potentially enable users to provide power on-demand for a variety of close range sensing applications. Also, consider the number of WiFi routers and wireless end devices such as laptops. In some urban environments, it is possible to detect hundreds of WiFi access points from a single location. At short range, such as within the same room, it is possible to harvest a tiny amount of energy from

a typical WiFi router transmitting at a power level of 50 to 100 mW. For longer range operation, larger antennas with higher gain are needed for practical harvesting of RF energy from mobile base stations and broadcast radio towers. Alternatively, energy can be generated and broadcasted in unlicensed bands such as 868MHz, 915MHz, 2.4GHz, and 5.8GHz when more power or more predictable energy is needed than what is available from ambient sources. At 915MHz, government regulations limit the output power of radios using unlicensed frequency bands to 4W effective isotropic radiated power (EIRP), as in the case of radio frequency identification (RFID) interrogators.

The main theme of this thesis is to introduce the recent advancement in the energy harvesting research field and develop a new improved performance rectifier circuits. Different topologies were suggested and implemented and the conversion efficiency of each technique was derived and plotted to show the incremental improvement compared with other published works. Three major rectifier circuits were studied based on the operating bandwidth and the impedance matching bandwidth. They are, single-band rectifier, broad-band, and differential rectifier topology. Each chapter in the thesis is discussing certain type of the previous configurations. The final chapter provides a practical application for the energy harvesting in the real life. The developed rectifier circuit along with the antenna find an application in the WSN and WBSN.

To my parents, my brother, my sisters, my beautiful wife, and my lovely daughter
Rofyda and Lujain who have always been my support in life
I dedicate this work.

Acknowledgements

First and foremost, I would like to thank **ALLAH** Almighty for giving me the strength, knowledge, ability and opportunity to undertake this research study and to persevere and complete it satisfactorily. Without his blessings, this achievement would not have been possible.

In my journey towards this degree, I have found a teacher, a friend, an inspiration, a role model and a pillar of support in my Guide, Prof. Haruichi Kanaya, Dr. Eng, Senior Member, IEEE. He has provide me with his heartfelt support and guidance at all times and has given me invaluable guidance, inspiration and suggestions in my quest for knowledge. I would like to express my sincere gratitude to him for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Ph.D study.

Besides my advisor, I would like to thank the rest of my thesis committee: Prof. Yoshitomi, Prof.Xavier, and Dr. Elsayed, for their insightful comments and encouragement, but also for the hard question which incented me to widen my research from various perspectives.

It would be inappropriate if I omit to mention the names of my dear friends Yasura Oiwa, Hayashi, Murakami, Kenji Kajiwara, Guan Chai Eu, who have, in their own ways, kept me going on my path to success, assisting me as per their abilities, in whatever manner possible and for ensuring that good times keep flowing.

Last but not the least, I would like to dedicate this work to my parents whose dreams for me have resulted in this achievement and without their loving upbringing and nurturing; I would not have been where I am today and what I am today. Also I would like to thank my lovely wife for her spiritual support and my child Rofyda and Lujain for their beautiful smile. They are my soul in this life without them I can not breath, survive, and sustain.

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Chapter 1

Introduction

1.1 Background

Nowadays, the explosion growth in the electronic industry and the technology trend to design and implement a much reduced footprint device has led engineers to devise a reliable and effective technique for energy power supply. Consequently, the energy harvesting was evolved as alternative method for the bulky batteries currently used in several electronic product in the market. The batteries not only is a bulk and hazard unit but it provides a hard and difficulties during maintenance and replacement. Therefore, the ability to wirelessly charge or entirely avoid the battery use is a future trend for engineer and research teams around the world.

Energy harvesting devices provide many benefits over conventional grid-powered and non-rechargeable battery-powered devices [1]. These advantages encompass energy self-sufficient, energy self-sustaining operation with lifetimes limited only by the lifetimes of their hardware. These devices utilize the energy harvested from alternative natural resources such as solar, vibrational, electromagnetic, thermoelectric, etc. As such, their widespread adoption will reduce the use of conventional energy and the accompanying carbon footprint, and benefit the environment. In addition, these devices do not require conventional recharging, enabling untethered mobility, and deployment of these devices in hard-to-reach places such as remote rural areas, within structures, and within the human body. Wireless power transfer (WPT) has emerged

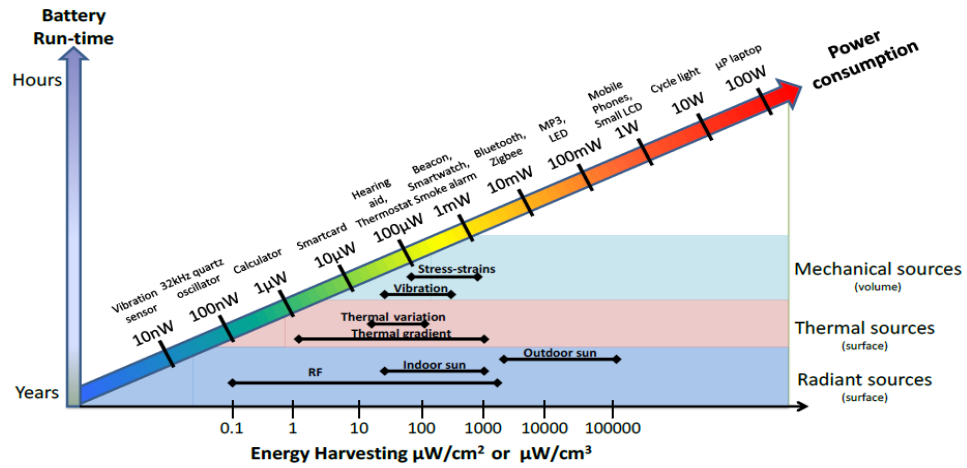


Figure 1.1: Overview of the power densities from various energy sources and average power consumption of electronic devices and systems [2].

as one of the most promising solutions to achieve self-sustainable electronic device operation for Internet of Things (IoTs) applications. With the increasing number of pervasive and connected WSN together enhanced capacity for data management, it enables intelligent monitoring on many practical fronts such as environmental, and weather forecast. Rapid development of low-power wireless electronic systems has resulted in many research activities focused on the feasibility of a remote powering of these systems. Therefore, RF and microwave power transmission has become a focal point of interest for many years as a promising technique for powering electronic devices over distance. Harvesting tiny levels of ambient RF energy from various energy sources has been proven to be suitable for powering low energy devices and can extend the battery lifetime in such devices. Depending on the energy prerequisite of the device it is possible, in some cases, to constantly power the device so that the battery or energy storage unit never needs to be replaced or charged via a cable. Although the RF energy is very low - RF power densities up to $300 \mu\text{W}/\text{cm}^2$ have been measured - power density does vary by location. Overall, the energy that can be harvested with the ambient RF energy harvester has been validated as sufficient to eliminate the charge of an energy storage device.

1.1.1 Ambient Energy Sources

Energy harvesting (EH) may be defined as the process of transforming ambient energy into electrical energy. Radiant (solar, infrared, radiofrequency), thermal, mechanical and biochemical are examples of the different forms of ambient energy. The energy harvesting efficiency can be defined as the ratio between the converted DC power and the available source of energy. Among the different energy sources available around us, outdoor photovoltaic energy is the most powerful source of ambient energy, as shown in Fig. 1.1, but the conversion efficiency presents very low values of energy harvesting, (around 10% [3]). Moreover, the photovoltaic panels will only be able to provide this efficiency during a few hours per day depending on solar incidence. Thermoelectric energy harvesting needs a constant temperature gradient to achieve the peak of efficiency. For a temperature gradient of 10°C, the efficiency would typically be 3% and even for a 100°C temperature gradient, an efficiency of 20% is expected [4]. Piezoelectric energy harvesting requires a specific and constant vibration frequency to have medium-high conversion efficiency [5]. Radio frequency (RF) energy harvesting requires sufficient levels of ambient RF energy density to be effective. In contrast to many other energy sources, RF signals are purposely generated and regulated. Due to the development of new radio technologies, the radio spectrum is becoming heavily populated: television, radio, cellular, GPS, WiFi, satellite and radar, among many others. Each of these frequency bands has an associated standard, which stipulates how it is used and the amount of RF authorised power to be transmitted. Depending on the location the RF power, energy densities can vary from 0.01 $\mu\text{W}/\text{cm}^2$ to 100 $\mu\text{W}/\text{cm}^2$, and in some cases, where a dedicated RF transmitter is available, the RF power density can reach 300 $\mu\text{W}/\text{cm}^2$.

1.2 Motivation

Thanks to the progress in sensor technology, many low-power-consumption devices have been made available, enabling the possibility of powering the sensors using environmental ambient energy. An alternative energy harvesting approach is needed if ambient RF energy

harvesting is to be considered a widely applicable power source for the 26 billion Internet of Things (IoT) devices and the anticipated \$300 billion industry being predicted by 2020. Photovoltaic, thermoelectric, and piezoelectric energy harvesting systems have been developed as technologies that can power Low Energy Internet of Things devices (LE-IoT). These technologies have their own inherent limitations, such as moving parts, fragility, and most importantly the constant presence of the energy source: solar energy harvesting only being available during daylight hours for example. Harvesting ambient RF energy, from WiFi, cellular networks and broadcast masts, offers an alternative solution to powering LE-IoT devices and could provide enough energy to extend the lifetime of these devices.

1.3 Research Objective

RF energy harvesting has been under development for many years but it has so far been limited in its application and commercial deployment. One of the main limiting factors has been the ability to design an RF energy-harvesting system that can operate at a high enough efficiency to harvest ambient RF energy from the very low power densities that are present in most city, home and office locations. As a result, current commercial systems require the use of a dedicated transmitter to boost RF power density levels to provide sufficient harvested power to undertake useful work.

RF energy is one example of the environmental free-energy. Multitude of radio devices are emitting electromagnetic energy into space and this energy is propagating every where and could be harvested using simple circuit called the rectenna, rectifying antenna. The rectennas are the most important elements in long-range wireless power transmission. The efficiency of rectenna mainly depends on their rectifiers. Therefore, to design a high-efficiency rectenna that guarantees the quality of a wireless power transmission system, more focus needs to be concentrated on the investigation and design of rectifiers with reference to high RF-to-dc conversion efficiency. In rectifier circuits, the rectifying component is also the core element that determines the overall efficiency of the circuits and is normally realized with a diode or a transistor.

In this dissertation, we focus on the energy harvesting technology using electromagnetic energy captured from multiple available ambient RF energy sources, such as TV and radio transmitters, mobile base stations, and microwave radios. This technique is very useful for sensors located in harsh environments or remote places, where other energy sources, such as wind or solar sources, are impracticable. In this context, this work presents an overview of advances achieved in RF harvesting field.

1.4 Contribution

Energy harvesting refers to the autonomously and simultaneously power feeding to multitude of sensors arranged in wide environment. Wireless power transfer tends to significantly attenuate once it transmitted from the power source. Consequently, the amount of power received at the far-field region is considered at the range of few micro watts. This puts constraint in the design of the receiver side, it should be more efficient, wide-bandwidth, compact, and simple design.

In this regard, the objective of this work is to design and implement a high-efficient energy harvesting system that meets the prescribed criteria. Several approaches have been proposed for the design of a high-efficient single band rectifiers. Indeed these rectifiers were combined with an antenna to realize the energy harvesting power feeding unit. Indeed a wide-band, simple, and optimum operated rectifier was developed to harvest power from across broadband spectrum ranging from the current broadcasting service bands, cellular bands, and the ISM 2.4 GHz and 900 MHz frequency allocated spectrum. Moreover, a balanced-output differential rectifier configuration was suggested to obtain a direct feeding connection to the electronic devices. The differential rectifier provides an output voltage that could be directly used for the transistor biasing as it needs $\pm$ DC voltage. To achieve the system verification, the proposed prototypes were integrated with a real-applications, and it was tested for continuous operation over long time period.

To summarize, the developed rectifier architectures offer an important progress in the current

research belonging to the RF energy harvesting technology. The outcomes of this research can be considered among the latest advancement of the wireless power transfer research area. This research has come up with more than five international journal articles as well as many national/international conference papers.

1.5 Thesis Organization

In this study, we introduce an investigation of the recent advancement in the RF energy harvesting techniques. Besides, we developed a new rectifier circuit topologies for improving the overall conversion efficiency, minimize the circuit footprint, maximize the circuit performance, deploy with a real application like WSN, and simple circuit design technique so facilitate procedures of the circuit implementation. These features offer a great advantages to the proposed design. The rest of the thesis is arranged according to the following order:-

- The different rectifier circuit configurations either based on the CMOS or the Schottky diode are discussed in chapter 2. Both the analysis and characterization of each circuit are conducted and a full comparison is made between them to get out the most efficient circuit. Moreover, it summarizes various concepts and equations that are particularly useful in the analysis of the energy harvesting circuit structures. In addition, the impedance matching network design procedures are described and the different mathematical analysis is conducted in this chapter.
- After analyzing the performance of the different rectifier architecture, an energy harvesting circuit based on the Schottky diode elements operating at 2.45 GHz is designed, evaluated, and characterized. In chapter 3, a single band rectifier is illustrated.
- Broadband rectifiers are essential to extend the efficient operating response over a wide frequency band. A compact and 1.5 Octave bandwidth rectifier is demonstrated in chapter 4.
- All modern electronic devices should be supplied with a balanced DC voltage. Therefore

the majority of power supply circuit should be followed by a conditioning circuit that convert from an unbalanced DC voltage to a balanced form. This will add a circuit complexity and increased large size. To eliminate such issue, we developed a a differential energy harvesting circuit that could provide the power directly to the electronic devices without the need for any conditioning circuit. The design of differential rectifier is introduced in chapter 5.

- A rectifier circuit based on 180nm CMOS technology is explained in chapter 6. The proposed circuit is designed and tested at operating frequency 2.45 GHz.
- A real application for the different proposed energy harvesting circuits is demonstrated in chapter 7. The deployment of an energy harvesting circuit is achieved with a Bluetooth low energy unit (BLE) which is attached with multitude of environmental sensors to measure vaious physical phenomenon.
- A future plan is considered in chapter 8. The theme of the forthcoming research work will further improve the harvesting circuits to maximize the efficiency for the micro-power input levels.

1.6 Conclusion

This chapter presented an introduction about the energy harvesting technology. Moreover, it indicated the purpose, and motivation of the current dissertation by demonstrating the objectives of each chapter.

Chapter 2

Different Rectifier Architectures

Recently, there has been an interest of research interests in radio frequency (RF) energy harvesting/scavenging technique, or RF harvesting in short, which is the capability of converting the received RF signals into electricity. This technique becomes a promising solution to power energy-constrained wireless networks. Conventionally, the energy-constrained wireless networks, such as wireless sensor networks, have a limited lifetime which largely confines the network performance. In contrast, an RF energy harvesting network (RF-EHN) has a sustainable power supply from a radio environment. Therefore, the RF energy harvesting capability allows the wireless devices to harvest energy from RF signals for their information processing and transmission. Consequently, RF-EHNs have found their applications quickly in various forms, such as wireless sensor networks, wireless body networks, and wireless charging systems. In RF energy harvesting, radio signals with frequency range from 300GHz to as low as 3kHz are used as a medium to carry energy in a form of electromagnetic radiation. RF energy transfer and harvesting is one of the wireless energy transfer techniques. The other techniques are inductive coupling and magnetic resonance coupling. Inductive coupling is based on magnetic coupling that delivers electrical energy between two coils tuned to resonate at the same frequency. The electric power is carried through the magnetic field between two coils. Magnetic resonance coupling utilizes evanescent-wave coupling to generate and transfer electrical energy between two resonators. The resonator is formed by adding a capacitance on an induction coil. Both of the

above two techniques are near-field wireless transmission featured with high power density and conversion efficiency. The power transmission efficiency depends on the coupling coefficient, which depends on the distance between two coils/resonators. The power strength is attenuated according to the cube of the reciprocal of the distance, specifically, 60 dB per decade of the distance, which results in limited power transfer distance. Besides, both inductive coupling and resonance coupling require calibration and alignment of coils/resonators at transmitters and receivers. Therefore, they are not suitable for mobile and remote replenishment/charging. In contrast, RF energy transfer has no such limitation. As the radiative electromagnetic wave cannot retroact upon the antenna that generated it (by capacitive or inductive coupling) at a distance of above $\lambda/(2\pi)$, RF energy transfer can be regarded as a far-field energy transfer technique. Thus, RF energy transfer is suitable for powering a larger number of devices distributed in a wide area. The signal strength of far-field RF transmission is attenuated according to the reciprocal of the distance between transmitter and receiver, specifically, 20 dB per decade of the distance.

2.1 Rectifier configurations

RF energy extracted from free space usually possesses low power density since the electric field power density decreases at the rate of $1/d^2$, where d is the distance from the RF source [6]. Therefore, a power amplifier circuit is required that yields enough DC energy from the electromagnetic waves to drive the loads. This gives rise to two possibilities, if the power consumption of the load is lower than the average power harvesting, the electronic devices at the load may work continuously; otherwise, if the load consumes more energy than the power harvesting circuit can generate, the devices cannot work continuously [7]. Rectifying is the most popular application of diodes, which refers to the conversion of AC current to DC current. In terms of power harvesting application, the RF signal retrieved in the antenna has a sinusoidal waveform. The signal after transformation through impedance matching network(IMN) would be rectified and boosted to meet the power requirements of the application. The most fundamental topology

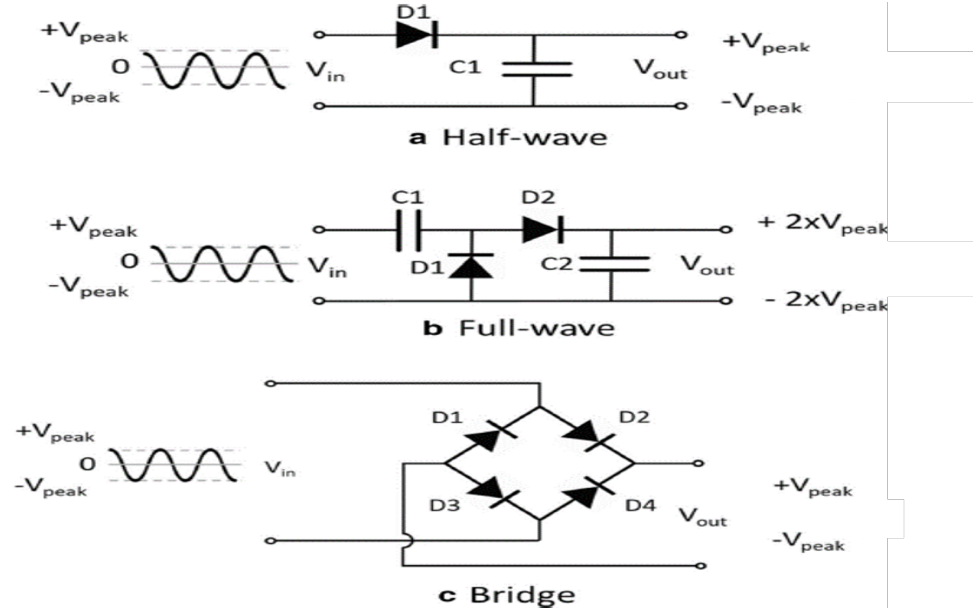


Figure 2.1: Some common topologies of a rectifier [8].

of the rectifier is the half-wave rectifier that comprises of a single diode $D1$ (Fig. 2.1(a)). When AC voltage transfers through $D1$, only the positive cycle remains and the negative cycle is cut-off; thus, it diminishes half of the AC power. Moreover, the output V_{out} is discontinuous since the negative cycle is cutoff. Despite its simplicity, a half-wave rectifier is usually inadequate for common applications. Hence, a full-wave rectifier is more preferable. The circuit design of the full-wave rectifier is shown in Fig. 2.1(b). During the first negative cycle of AC input, diode $D1$ is conductive and capacitor $C1$ is charged to the corresponding energy level of V_{peak} of the input. Then, at the next positive cycle, diode $D1$ is blocked, diode $D2$ is conductive so that capacitor $C2$ is also charged. In consequence, the output V_{out} would see two capacitors in series (each one is storing a voltage of V_{peak}). Thus, V_{out} is twice V_{peak} . Therefore, this topology is more stable and efficient than the half-wave rectifier. There is also a bridge rectifier that rectifies both positive and negative cycles of the AC input but retains $V_{out} = V_{peak}$ by alternatively blocking pairs of diodes $D1, D4$ and $D2, D3$ (Fig. 2.1(c)).

Voltage multiplier is a special type of rectifier circuit that converts and boosts AC input to DC output. In some case where the rectified power is inadequate for the application, there is

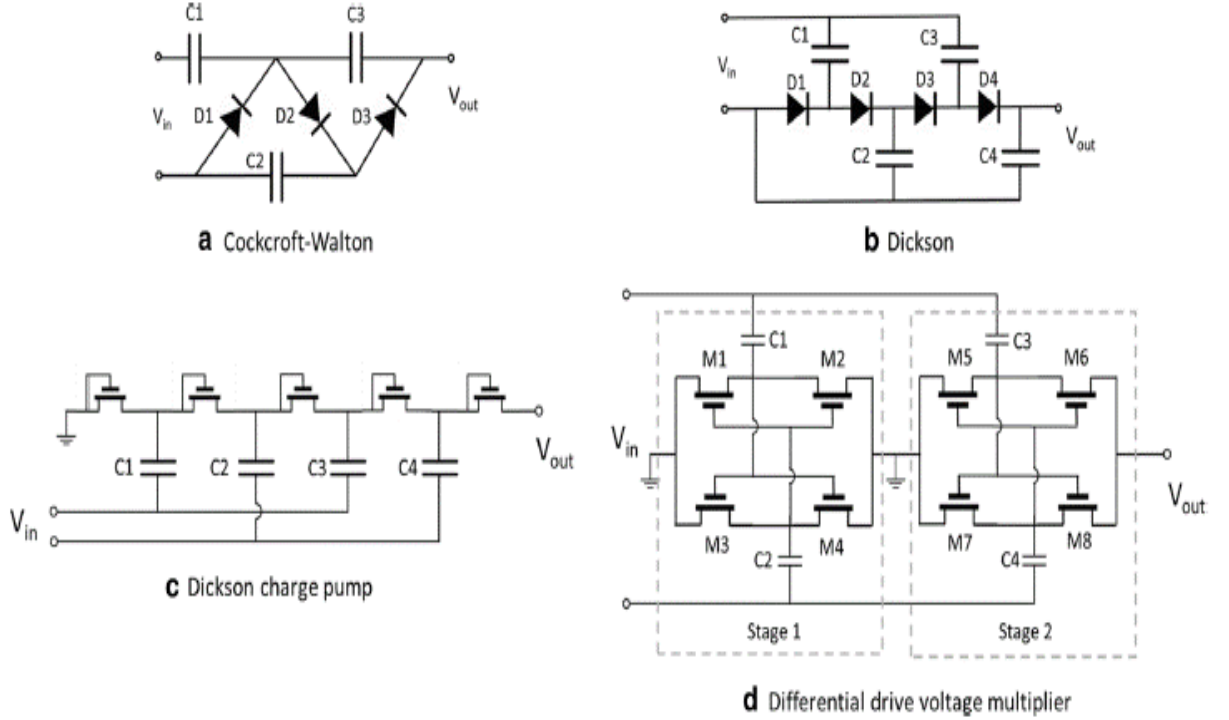


Figure 2.2: Common voltage multiplier configurations: (a) Three stages CockcroftWalton voltage multiplier, (b) Four stages Dickson voltage multiplier, (c) Four stage Dickson voltage multiplier using CMOS technology, (d) Two stages voltage multiplier comprised of differential drive unit [8].

a need for boosting the output DC by stacking single rectifiers into series, forming the voltage multiplier [9]. Several configurations of the voltage multiplier are shown in Fig. 2.2. The most fundamental configuration is the CockcroftWalton voltage multiplier (Fig. 2.2(a)). This circuits operational principle is similar to the full-wave rectifier (Fig. 2.1(b)) but has more stages for higher voltage gain. The Dickson multiplier in Fig. 2.2(b) is a modification of CockcroftWaltons configuration with stage capacitors being shunted to reduce parasitic effects. Thus, the Dickson multiplier is preferable for small voltage applications. However, it is challenging to obtain high power conversion efficiency (PCE) due to the high threshold voltage among diodes creating leakage current, thus reducing the overall efficiency. Additionally, for high resistance loads, output voltage drops drastically leading to low current supply to the load. The MOSFET (metal oxide semiconductor field effect transistor) technology is overcoming the limitations of diodes and becoming an alternate solution for rectifying and boosting. Owing to MOSFET

technology, Dickson multiplier can be integrated together in integrate circuits (IC) by replacing diodes with NMOS as shown in Fig. 2.2(c). Relatively low threshold voltages and high PCEs are features of this design. Moreover, differential drive voltage multiplier (Fig. 2.2(d)) is widely used because of its low leakage current and potential for further modification for specific applications. A detail explanation and analysis is presented in [10, 11]. As the number of stages getting increase, there is more loss across each added stage. However, the tradeoff is higher voltage multiplication and small threshold voltage at the first stage. On the other hand, a voltage multiplier with a few stages has less voltage drop between its stages but requires higher threshold voltage for all stages to work simultaneously. For this reason, a voltage multiplier becomes more sensitive when a large number of stages are present and becomes more efficient at fewer stages. This tradeoff feature was analyzed in several researches [12, 14]. Therefore, the optimal number of stages should be considered depending upon the application targets.

2.2 Impedance Matching Network

IMN is a critical circuit design for an efficient rectifier. To ensure maximum power transfer between the signal source and the terminal load, an IMN should be introduced between it. Bode [15] first showed what the physical limitations were on the broadband impedance matching of loads consisting of a reactive element and a resistor in either series or parallel configuration. Later, Fano [16] presented the general limitations on the impedance matching of any load. Fano's work show the efficiency of transmission and bandwidth are exchangeable quantities in the impedance matching of any load having a reactive component.

To illustrate the theoretical limitations which exist on broadband impedance matching, consider the example shown in Fig. 2.3 where the load to be matched consists of a parallel RC connection capacitor C_1 and resistor R_o . A lossless impedance-matching network is inserted between the generator and the load, and the input reflection coefficient between the generator

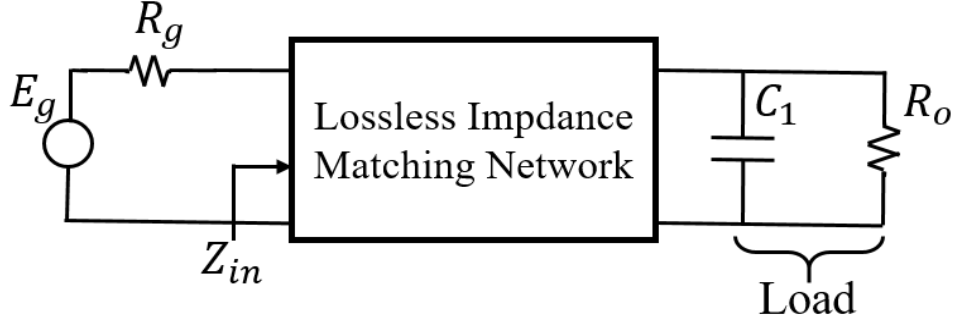


Figure 2.3: Example of an impedance matching problem.

and the impedance matching network is given by 2.1.

$$\Gamma = \frac{Z_{in} - R_g}{Z_{in} + R_g} \quad (2.1)$$

The work of Bode-Fano shows that there is a physical limitation on what Γ can be as a function of frequency. The best possible results are limited as indicated by the following relation:-

$$\int_0^\infty \ln \left| \frac{1}{\Gamma} \right| dw = \frac{\pi}{R_o C_1} \quad (2.2)$$

Recall that for a passive circuit $0 \leq |\Gamma| \leq 1$, for total reflection $|\Gamma| = 1$, and that for perfect transmission $|\Gamma| = 0$. Thus, the larger $\ln |1/\Gamma|$ is the better the transmission will be. But Equation 2.2 indicates that the area under the curve of $\ln |1/\Gamma|$ vs w can be no greater than $\pi/R_o C_1$.

If a good impedance match is desired from w_a to w_b , best results can be obtained if $|\Gamma| = 1$ at all frequencies except in the band from w_a to w_b . Then $\ln |1/\Gamma| = 0$ at all frequencies except in the w_a to w_b band, and the available area under the $\ln |1/\Gamma|$ curve can all be concentrated in the region where it does the most good. With this specification, Equation 2.2 becomes:-

$$\int_{w_a}^{w_b} \ln \left| \frac{1}{\Gamma} \right| dw = \frac{\pi}{R_o C_1} \quad (2.3)$$

and if $|\Gamma|$ is assumed to be constant across the band of impedance match, $|\Gamma|$ as a function of

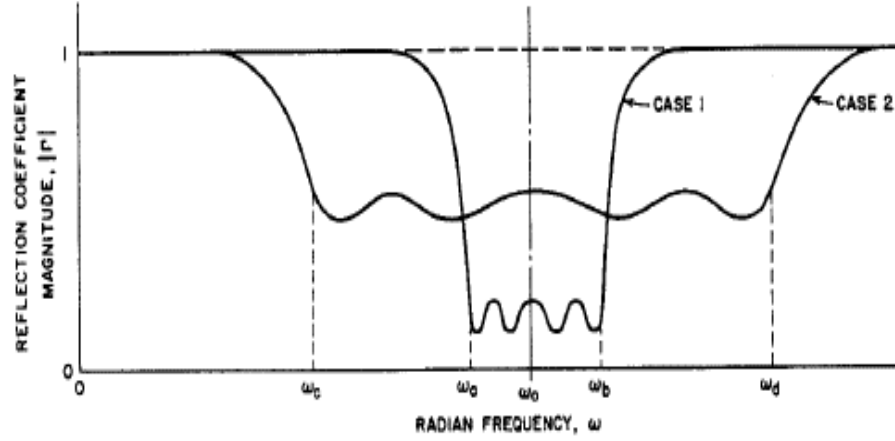


Figure 2.4: Curves illustrating relation between bandwidth and degree of the impedance match possible for a given load having a reactive component. [17]

frequency becomes

$$\Gamma = \exp[-\pi/(w_b - w_a)R_oC_1] \quad \text{for} \quad w_a \leq w \leq w_b \quad (2.4)$$

$$\Gamma = 1 \quad \text{for} \quad 0 \leq w \leq w_a \quad \text{and} \quad w_b \leq w \leq \infty \quad (2.5)$$

Equation 2.5 says that an ideal impedance-matching network for the load in Fig. 2.4 would be a band-pass filter structure which would cut off sharply at the edges of the band of impedance match. The curves in Fig. 2.4 show how $|\Gamma|$ vs w curve for practical band-pass impedance matching filters might look. The curve marked Case 1 is for the impedance matching of a given load over the relatively narrow band from w_a to w_b , while the curve marked Case 2 is for the impedance matching of the same load over a wider band from w_c to w_c using the same number of elements in the impedance matching network. The rectangular $|\Gamma|$ characteristic indicated by Equation 2.5 is that which would be achieved by an optimum band-pass matching filter with an infinite number of elements.

2.3 Chapter Summary

In this chapter, different rectifier architectures were extensively discussed. Each architecture was introduced and compared for the desired performance. The maximum power transfer between the source and a load terminal is achieved using an impedance matching network so the impedance matching network investigation was considered in the chapter. Moreover, a comparative study was made between the CMOS and Schottky diode as rectifier.

Chapter 3

2.45 GHz Single Band RF Rectifier

3.1 Introduction

This chapter looks into the underlying RF energy harvesting issues at low input ambient power levels below 0 dBm where efficiency degradation is severe. The chapter illustrates two different designs for improving the conversion efficiency.

The first design aims to improve the rectenna sensitivity, efficiency, and output DC power. In the same manner, we are using a straightforward and compact size rectenna design. The receiving antenna is a coplanar waveguide (CPW) slot monopole antenna with harmonic suppression property and a peak measured gain of 3 dBi. Also, an improved antenna radiation characteristics, e.g. radiation pattern and gain covering the desired operating band (ISM 2.45 GHz), is observed. The rectifier is a voltage doubler circuit based on microstrip (MS) structure. Two architectures of rectenna were carefully designed, fabricated and tested. The first layout; antenna, and rectifier were fabricated separately and then connected using a connector. The peak efficiency (40% at -5 dBm) achieved is lower than expected. To improve the efficiency, a high compactness and simple integration between antenna and rectifier are achieved by using a smooth CPW-MS transition. This design shows improved conversion efficiency measurement results which typically agree with the simulation results. The measured peak conversion efficiency is 72% at RF power level of -7 dBm and a load resistance of $2\text{ k}\Omega$.

The second design presents the implementation of a compact, reliable, effective, and flexible energy harvesting (EH) rectenna design. It integrates a simple rectifier circuit with a circularly polarized one-sided slot dipole antenna around 2.45 GHz ISM frequency band for wireless charging operation at low incident power densities, from 1 to $95 \mu W/cm^2$. The rectenna structure is printed on a single layer, low cost, commercial FR4 substrate. The integration of the rectifier and antenna produces a low-profile and high performance circularly polarized rectenna. In order to maximize the system efficiency, the matching circuit introduced between the rectifier and antenna is optimized for a minimum number of discrete components and it is constructed using multiple of L-slot defects in the ground plane. For a given input power of -6 dBm intercepted by the circularly polarized antenna with 3 dBi gain, the peak RF-DC conversion efficiency is 59.5%. The rectenna dimensions are $41 \times 35.5 mm^2$. It is demonstrated that the output power from the proposed rectenna is higher than the other published designs with a similar antenna size under the same ambient condition. Thanks to its compact size, the proposed rectenna could found a range of potential applications for wireless energy charging.

3.2 Literature Review

Recently, many rectennas have been reported, including a rectenna using a reconfigurable patch resonator [25, 26], a multiband frequency rectenna [27, 28], and rectenna with various patch antenna configurations [29]. Normally, the DC conversion efficiency, minimum detectable RF input power, and loading effect become one of the important considerations for rectenna designs. Most of the implemented rectennas are based on deploying either MS line or CPW design. For our best of knowledge, no rectenna combine both formats has been reported. The most recent advancement in RF EH is discussed in next sections.

In [32], authors propose an energy-harvesting IC fabricated in $0.25 \mu m$ CMOS that can charge a 3.3 V lithium battery with a delivered power ranging 0.5–5 mW utilizing up to four different energy sources have simultaneously efficiency up to 73.3%. A 900 MHz RF energy harvesting system is proposed for a far-field wireless power transfer application in [33]. Two

tuning techniques are employed and the power conversion efficiency is higher than 30% over an input power range -10 to 12 dBm with a peak value of 47% at 0 dBm for a 1.5 V output voltage. The maximum output voltage of the system is 2.45V with a sensitivity of -15 dBm. The design of a flexible hybrid printed low-cost RF energy harvester has been demonstrated in [34]. The performance of the designed far-field RF energy harvester has been verified through wireless experiments demonstrating output voltages above 2.9 V for input power levels above 0 dBm from 0.8 GHz $\sim$ 1.15 GHz. Authors in [35] introduces a wireless receiver system operating at 900 MHz band and fabricated in CMOS 180 nm, the proposed RF receiver system architecture can operate at the presence of unavoidable high out-of-band blockers (0 dBm) yet consumes 534 μ W. Moreover, 46% of this dc power is extracted from existing blockers via RF energy harvesting techniques. Although the previous studies offered numerous benefits to the energy harvesting technology, it still suffers from several practical issues like high fabrication cost, large size, power consumption,..etc.

The interfacing techniques between CPW and MS structures is realized using either electrical contact or electromagnetic (EM) coupling [36] Although the surface-to-surface EM coupling techniques offer advantages like via-free structure and low-loss, it suffers from design complexity, narrow bandwidth, and large size.

In this study, the electrical connection is selected for the interconnection between CPW and MS structure. Electrical connection provides broadband operation and compact size. It could be realized using via holes, bonding wires, or abrupt steps in the conductor. For the proper connection between CPW and MS structures, a via interconnection is selected. The placement of these vias is critical to achieving the desired impedance and low loss characteristics through parasitic wave modes suppression.

Diode nonlinearities may result in some high-order harmonics that may be radiated by the antenna. Serious nonlinearities noticed at the second (2nd), and third (3rd) harmonics almost have an adverse effect on the rectifier efficiency. Therefore, the proposed slot antenna has notched bands for the 2nd, and 3rd harmonics suppression of the fundamental frequency of 2.45 GHz.

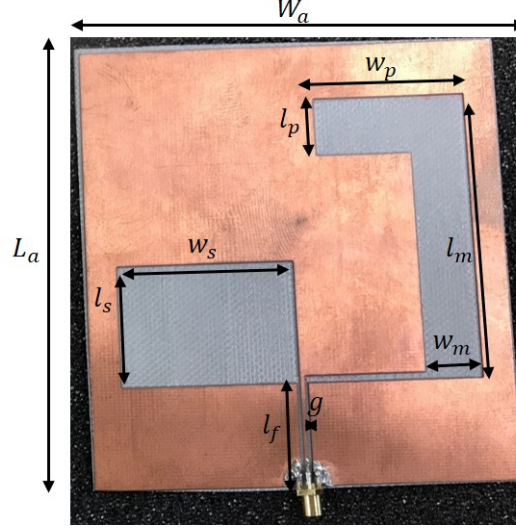


Figure 3.1: Photograph of the fabricated antenna with the structure parameters are given on the layout.

3.3 Antenna-Rectifier Direct Connection

We started our discussions by describing the designs of CPW slot antenna and the rectifying circuit. They are fabricated separately and assembled using micro-miniature coaxial (MMCX) connectors. This configuration represents the direct connection of Case 1 which will be discussed in Sec. 3.5.1.

3.3.1 CPW Slot Antenna

Slot antenna is a good candidate for energy harvesting applications owing to its wide impedance bandwidth, simple structure, low profile, and easy fabrication. Slot antennas can have a relatively large impedance bandwidth, especially antenna with a wide slot. The proposed antenna geometry along with the fabricated antenna photograph is illustrate in Fig. 3.1; the antenna is printed on single metal FR4 substrate of thickness 0.8 mm (h) and relative permittivity 4.4 (ϵ_r). The antenna structure consists of L-section (constituted by $L_p \times W_p$ and $L_m \times W_m$) and rectangular slot (constituted by $L_s \times W_s$). It is fed by 50 Ω CPW transmission line having a metal strip of width W_f , and coupling gap distance of g . The total dimensions of the antenna

Table 3.1: Parameters' values of the antenna design.

l_p	w_p	l_m	w_m	w_s	l_s	w_f	l_f	g
10	23	39	13	32	21	1.15	18	0.3

All units are given in mm.

are $78 \times 76.9 \times 0.8$ mm³. The fabricated prototype of the CPW slot antenna mounted with an MMCX female connector is shown in Fig. 3.1(b). The approximate resonant frequency can be estimated by the slightly modified equations 3.1 [37]:

$$f_r = \frac{300}{(l_s + w_s) \times \sqrt{\epsilon_{eff}}}, \epsilon_{eff} = \frac{2 \times \epsilon_r}{1 + \epsilon_r} \quad (3.1)$$

In the empirical formula, f_r is the resonant frequency of the fundamental mode in GHz, l_s and w_s are the inner width and length of the rectangular slot, respectively in millimeters and ϵ_{eff} is the effective dielectric constant. To achieve the desired broadband impedance bandwidth and harmonics suppression, a rectangular slot and L-slot are used respectively. The bandwidth of the asymmetrical slot antenna can be obtained with a proper impedance matching and $VSWR < 2$ by changing the antenna design parameters. A commercially available simulation software HFSS was used for the electromagnetic and numerical analysis simulations of the antenna.

A parametric study of the rectangular slot and L-section dimensions is carried out in order to obtain an efficient excitation and good impedance matching over the desired frequency band. To accurately determine the influence of these parameters, only one parameter is varied at a time while others are kept constant. The antenna return loss dependent on the rectangular slot and L-section slot dimensions is shown in Fig. 3.2.

As the rectangular slot width (W_s) increases, the response (return loss) moves toward low-frequency region. Changes in L-slot dimensions (W_m) affect the 2nd and 3rd harmonic components. The L-slot notched on the antenna structure provides a suppression feature of 2nd and 3rd harmonics (4.9 GHz and 7.35 GHz respectively). Therefore, the effect of spurious resonance is minimized.

It is noted that the input impedance of the antenna at the fundamental frequency 2.45 GHz,

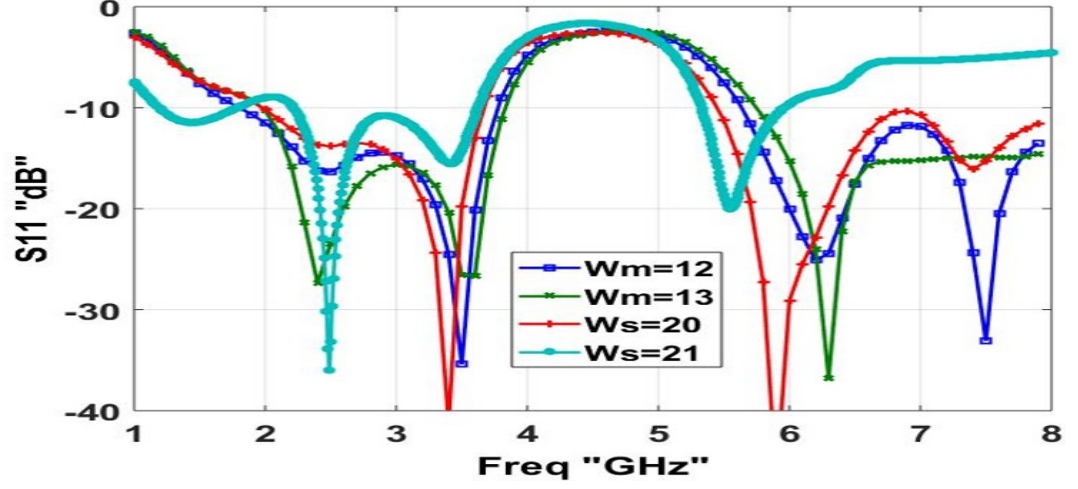


Figure 3.2: Parametric study of antenna dimensions, Return loss S_{11}

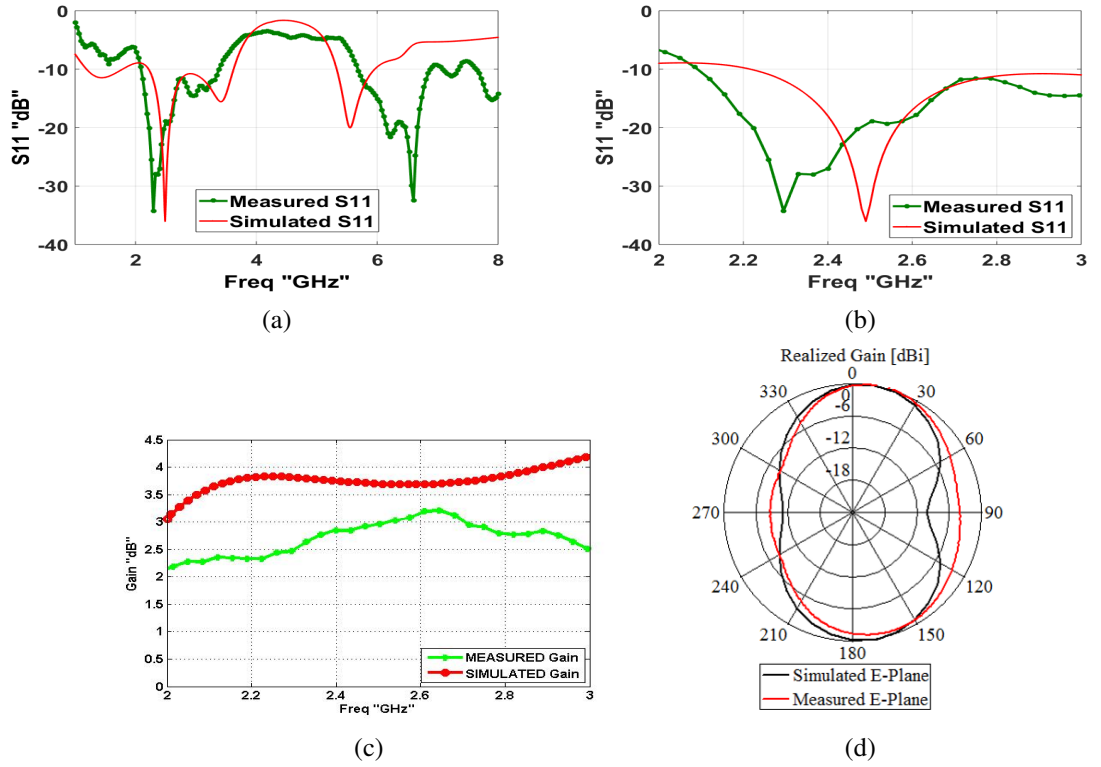


Figure 3.3: Comparison between the antenna experimental and simulation results (a) Return loss S_{11} over a wideband (1-8 GHz) to account for the 2nd and 3rd harmonics, (b) Return loss S_{11} over the band of interest, (c) Realized gain, (d) Normalized radiation pattern (XZ plane).

second harmonic frequency 4.9 GHz, and the third harmonic frequency 7.35 GHz are $39-j2.98 \Omega$, $131-j49 \Omega$, and $30+j47 \Omega$, receptively. Thus, the desired antenna performance has been achieved. After completing a thorough parametric study on the antenna geometry, the optimum design parameters of the antenna are set and summarized in Table 3.4.

Antenna measurements were carried out in an anechoic chamber. From the measured result in Fig. 3.3, it is observed that both measured and simulated return losses (Fig. 3.3(a)) are coinciding well around the fundamental resonant frequency 2.45 GHz, but it is slightly shifted at the higher frequencies above 5.2 GHz. Furthermore, the antenna is found to be matched to the input port of rectifier at 2.45 GHz and mismatched at high-order harmonics. The measured actual antenna gain is reasonable agreeing with the simulated gain as shown in Fig. 3.3(c). The measured gain is varying between a peak value of 3.2 dB and minimum 2.2 dB in the frequency range from 2 to 3 GHz. The normalized radiation pattern of the proposed antenna was measured at frequency 2.45 GHz, the measured far-field and simulated results are plotted in Fig. 3.3(d). As illustrated in the figure, the asymmetrical slot antenna produces the main lobe radiations in both the forward (+z) and backward direction (-z). Therefore it is considered as a bidirectional antenna with the side lobes entirely attenuated. The measured results are found to agree well with the simulated ones.

3.3.2 Rectifier Circuit Design

Radio frequency signal captured by the antenna is an alternating current (AC) signal. In order to convert AC signal to DC signal, a rectifier circuit is used. The most popular rectifier used is Greinacher circuit or voltage doubler [38]. The topology of this circuit (described in Fig. 3.4) is typically used for most of the reported rectenna, but the selection of transmission line model is different from one design to another. MS transmission lines are selected for the rectifier design due to its simple design, low cost, and low loss at moderately high frequencies. The 50Ω impedance matching is depending on the values of the L-matching circuit parameters L, C and the width of impedance transformer. Values of L and C are chosen as 5.6 nH and 1 pF, respectively. The width of the $\lambda/4$ impedance transformer is selected to be 7 mm. The rectifier

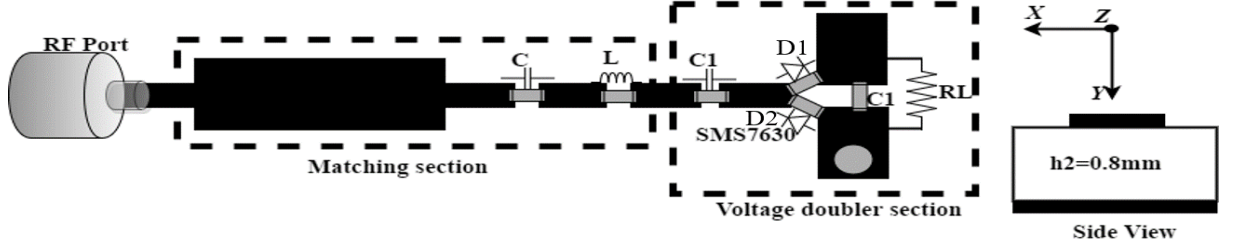


Figure 3.4: The layout of the MS rectifier circuit.

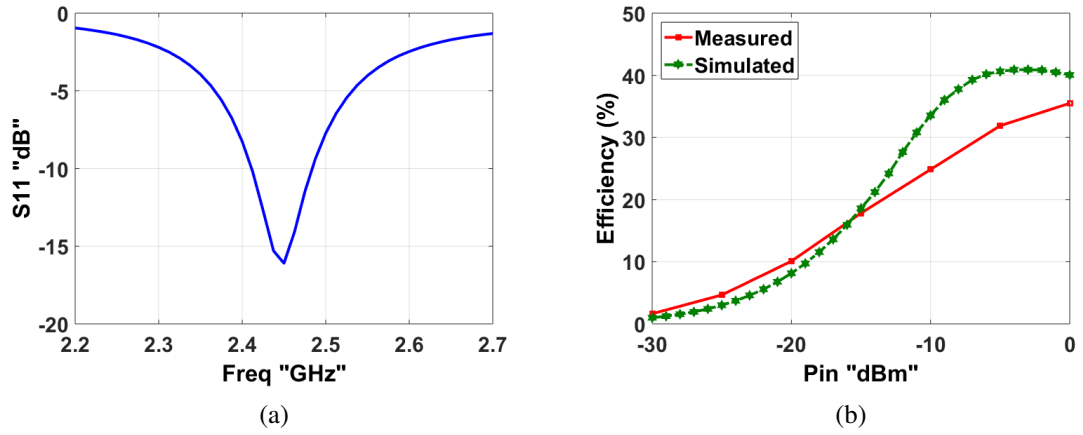


Figure 3.5: The analysis of the rectifier circuit performance (a) Return loss S_{11} , (b) Efficiency versus input signal frequency at $P_{in}=-20$ dBm, (b) Efficiency versus input signal power

circuit is printed on a two side FR4 substrate of thickness 0.8 mm (h) and relative permittivity 4.4 (ϵ_r). The simulations were carried out using schematic, momentum and co-simulation tools of ADS Keysight Tech.

The most important figure of merit of a rectifier is the efficiency. RF-DC conversion efficiency is given by: -

$$\eta(\%) = \frac{P_{DC}}{P_{RF}} = \frac{V_{out}^2}{R_L \times P_{RF}} \quad (3.2)$$

where P_{DC} is the output DC power, R_L is the resistive load, V_{out} is the output DC voltage, and P_{RF} is the RF received power. As shown in Fig. 3.5(a, b), the rectifier return loss is properly matched at the desired frequency so that a significant increasing of the efficiency has achieved as well. Both the simulated and measured results of rectifier efficiency are shown with the variation of P_{in} as depicted in Fig. 3.5(b). However the simulated maximum efficiency of 72%

was obtained at RF input power of -11 dBm and load resistance $2\text{ k}\Omega$, the measured efficiency is 25% only at the same constraints. The maximum measured efficiency 33% was achieved at -5 dBm. To account for the fabrication losses, series resistive element of $2\text{ }\Omega$ is connected in replace of the soldering pads, afterwards the simulation conducted again. This shows that measurement and the parasitic simulated results are slightly matched.

3.4 Rectenna Integration

The simplest way to connect the CPW slot antenna with the MS rectifier circuit is using an MMCX connector which will be introduced in Sec. 3.5.1. The main disadvantages of this approach are that it couldn't be integrated with the applications based on wireless power transfer, and it contributes to the ohmic losses of the system caused by MMCX connector. Consequently, a novel CPW-MS smooth transition is presented for improving the conversion efficiency, and reducing the size of the proposed rectenna. This configuration represents the second rectenna design architecture (Case 2 in Sec. 3.5.2). For any transmission line with discontinuities caused by impedance transitions [39], these will result in: -

- Some amount of energy reflected back to the source at the point of impedance transition. For example, the transition of the RF energy from the connector to the PCB often causes reflections.
- When the energy of the RF signal has two different modes of transitions, reactance is created. Parasitic reactance will contribute to the detuning of the desired design frequency.

Based on the aforementioned reasons, particular design procedures must be followed to construct a smooth transition between a CPW and MS structures. Such transition is implemented using a single via electrically connected between the CPW antenna feedline and MS feed point. Moreover, the ground of CPW slot antenna could be used as the ground for MS. In order to keep similar antenna performance as discussed in Section (2.1). The same asymmetrical slot antenna is used with minor changes, but the rectifier circuit configuration is developed. The antenna

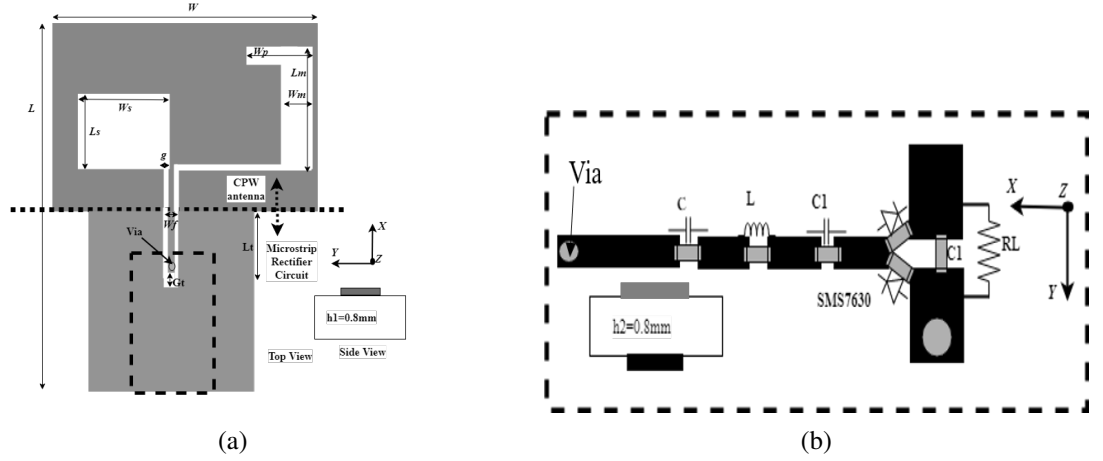


Figure 3.6: Case 2 antenna layout and the corresponding rectifier circuit (a) Case 2 antenna layout, (b) Case 2 rectifier layout mounted on the backside of (a) in the area specified by the dashed line.

ground plane is extended to cover the rectifier circuit dimensions. The antenna feed-line is increased to length L_t , and at the end of the feed-line, a via is inserted for linking the input of the rectifier circuit to the antenna as illustrated in Fig. 3.6(a). After precise optimization (using the HFSS electromagnetic software) of the transition structure dimensions (L_t , G_t , and the position of the via along the feed line), the correct values were obtained. The length is selected as $L_t = 5$ mm and the gap to the planar ground $G_t = 0.5$ mm.

To validate the design of CPW-MS transition, the antenna response of Case 2 was compared to that of Case 1. In Fig. 3.7(a), the return loss for both cases (Case 1, i.e. CPW slot antenna with no transition, and Case 2, i.e. CPW slot antenna with CPW-MS transition) are given. It is observed that the S_{11} curve of the proposed designs is in good agreement. In this way, broadband impedance matching over the desired frequency range and the harmonic suppression property without any changes at 2nd and 3rd harmonics characteristics are maintained. Also, gain comparison of Case 1 and Case 2 is presented in Fig. 3.7(b). As expected, the gain of both cases approximately is in agreement over the desired bandwidth. The radiation pattern characteristics are quite different from the previous case as shown in Fig. 3.7(c). This is due to the presence of a ground plane behind the antenna feed. This metal sheet acts as a reflector, so

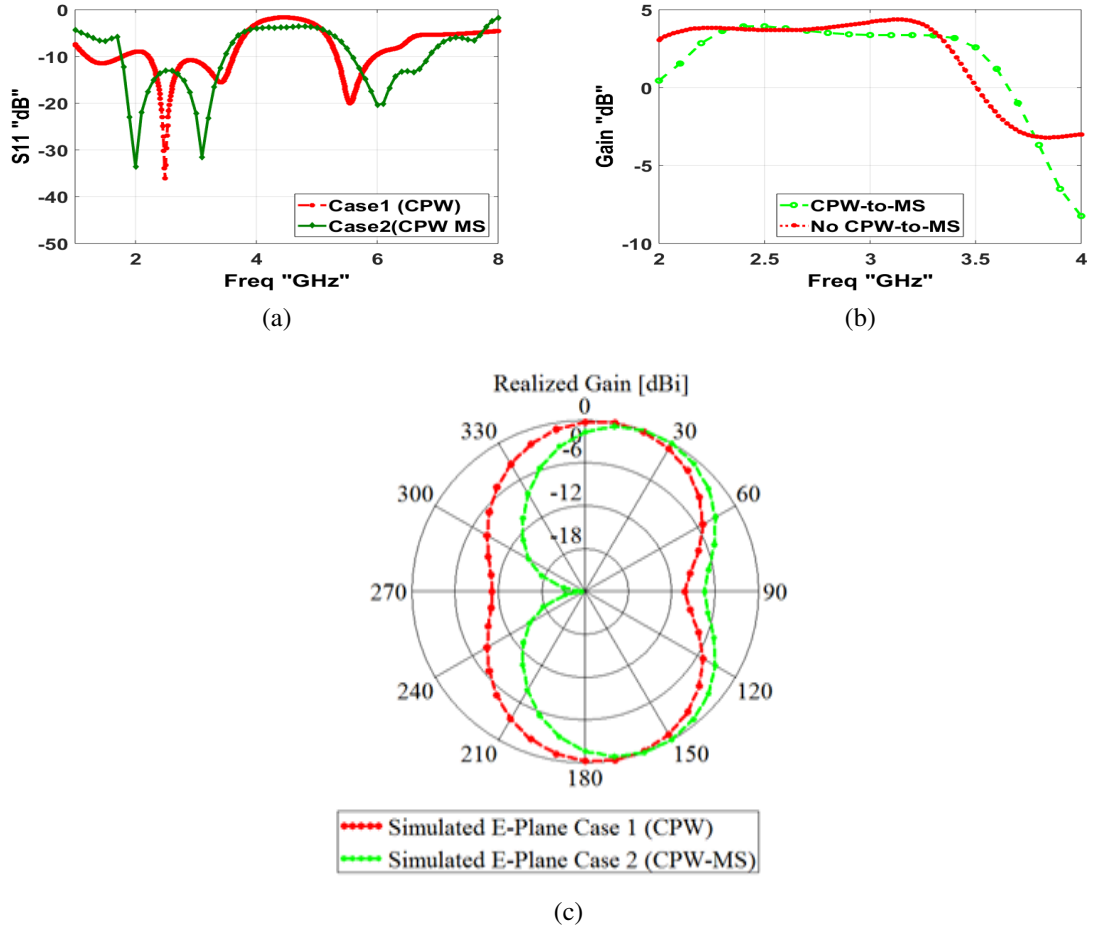


Figure 3.7: Comparison between the simulated results of Case 1 and Case 2 antenna response (a) Return loss S_{11} , (b) Realized gain, (c) Normalized radiation pattern (XZ Plane).

most of the radiations are reflected back in the opposite direction.

On the other hand, the rectifier circuit is developed, instead of using 0.8 mm double side substrate, the rectifier circuit is fabricated separately on the bottom side of a 0.8 mm double layer FR4 substrate as depicted in Fig. 3.6 (b). Then, a via hole is drilled for connecting the antenna feed to the input of the rectifier circuit. This will be discussed clearly in the next section. Since the the rectifier circuit substrate configuration has slightly changed, the input impedance has to be optimized for maximum power transfer. The co-simulation between antenna and rectifier was done by exporting Z-parameter file of the antenna with CPW-MS transition from

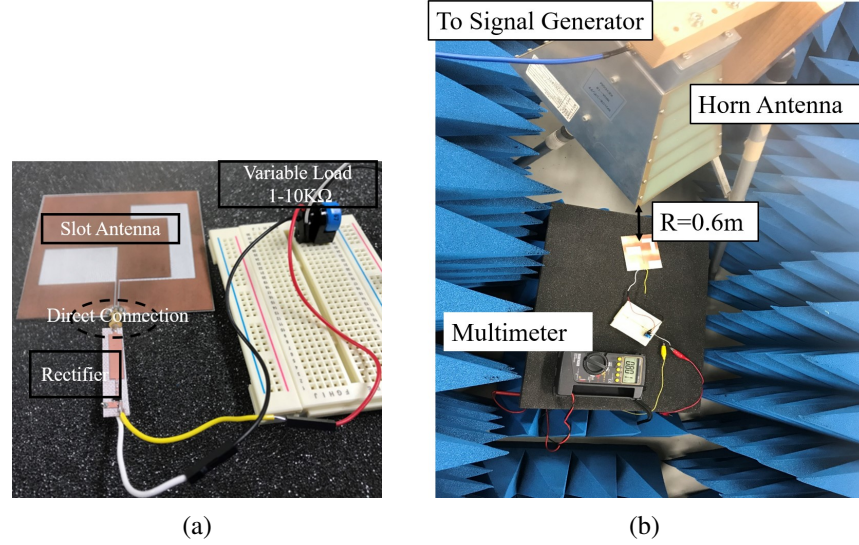


Figure 3.8: The connection and measurements of case 1 rectenna (a) antenna-rectifier interfacing, (b) Photograph of the measurement setup.

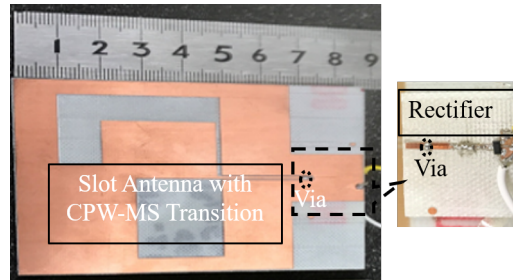


Figure 3.9: Case 2 antenna-rectifier integration .

HFSS and importing it into ADS software as input impedance of the rectifier circuit power source. This was done to ensure the optimum matching between the CPW-MS antenna and the rectifier. In this case, the impedance transformer is removed because the resistive part of input impedance of rectifier ($40-j8 \Omega$) is almost identical to that of the antenna ($38+j11 \Omega$). Thus the circuit dimensions are shrinking down. The imaginary part of the slot antenna (capacitive) is compensated by changing the LC series components. Therefore, only the value of inductance L has changed to 8.2 nH and C is kept constant.

3.5 Experimental Work and Measurements

The experimental work was conducted in two ways as suggested in the previous sections. Case 1 is the direct connection between CPW slot antenna (Sec. 3.3.1) and the MS rectifier circuit (Sec. 3.3.2) using MMCX connectors. Case 2 is obtained using CPW-to-MS transition described in Sec. 3.4.

3.5.1 Case 1 Experimental Results

At first, the experimental investigation of Case 1 is introduced. The straightforward connection between antenna and rectifier is shown in Fig. 3.8(a). For DC power measurement at the output of the rectifier circuit, the rectenna and horn antenna were set inside an anechoic chamber for eliminating any reflections from the surrounding objects as given in Fig. 3.8(b).

Next, the measured data are recorded and plotted versus the received power. The conversion efficiency at various input power levels is evaluated and depicted in Fig. 3.10(a). From the curve, it is noted that measured results follow the simulated results but with efficiency reduction of about 30%. The maximum measured efficiency is 40.3% at RF input power -5 dBm but the simulated is 72% at -11 dBm. Fig. 3.10(b) illustrates the output DC voltage with respect to RF input power. As can be seen, a maximum DC voltage level of 0.52 V was obtained. Fig. 3.10(c) explains the variation of rectenna efficiency with different load resistance values at a fixed RF input power of -5 dBm. It shows that the efficiency is greater than 30% over output load resistance from 1 to $4k\Omega$. The decreasing in efficiency is due to the connector and soldering losses which were estimated about -2.5 dB. The generated losses significantly attenuate the low RF input signal (in the order of few microwatts) intercepted by the antenna. In the next section, we will show how to improve the efficiency by reducing the losses associated with the connectors.

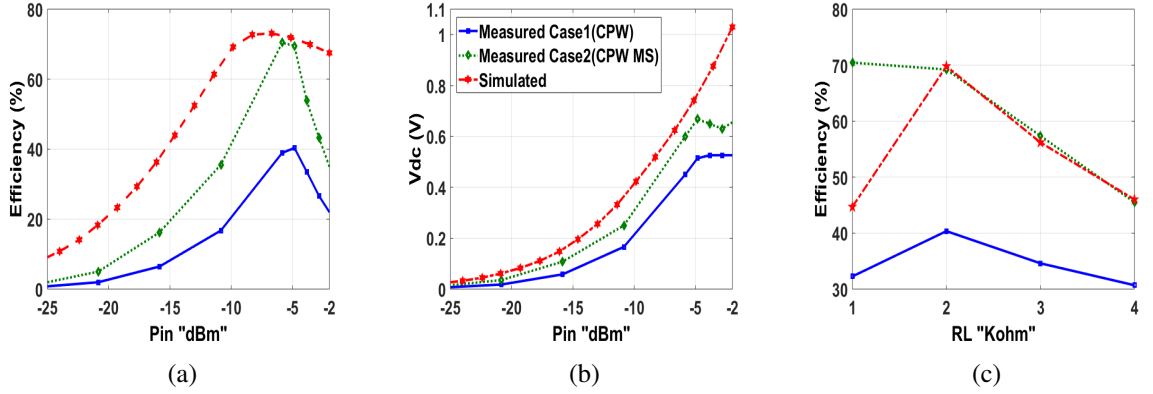


Figure 3.10: Comparison of various connected topology of rectenna (Case 1 and Case 2). (a) Efficiency versus input power P_{in} at fixed frequency 2.45 GHz and terminated load $R_L=2\text{ k}\Omega$, (b) DC output voltage versus input power P_{in} at fixed frequency 2.45 GHz and terminated load $R_L=2\text{ k}\Omega$, (c) Efficiency versus input power R_L at fixed frequency 2.45 GHz and terminated load $P_{in}=-5\text{ dBm}$.

Table 3.2: Comparison between case 1 and case 2.

	Case1 (Direct Connection)	Case2 (CPW-to-MS)
Size	$104 \times 76.9\text{ mm}^2$	$88 \times 76.9\text{ mm}^2$
Sensitivity	-25 dBm with output voltage of 3mV	-25dBm with output voltage 6mV
MMCX connection	Yes	No
Efficiency	40%	72%

3.5.2 Case 2 Experimental Results

In order to maximize the conversion efficiency, an integrated rectenna (Case 2) without any interconnections between the rectifier and antenna is used (shown in Fig. 3.9). The top layer consists of both the antenna and CPW-MS transition structure. The rectifier circuit is printed on the other side (bottom layer) and connected with a via to the top layer. The measurement procedures are typically similar to the previous case. The rectenna was loaded with the same resistance value, and the corresponding output voltage was measured. Fig. 3.10 shows a comparison of measurement results between Case 1, and Case 2. As depicted in Fig. 3.10(a), the maximum measured efficiency is about 72% at -7 dBm . Furthermore, the rectenna can detect very low input power signal (around -7 dBm) with higher efficiency compared to the conventional rectenna due to the elimination of MMCX connector. The decreasing of efficiency be-

Table 3.3: Comparison of our work with other rectenna in relevant literature.

	This work	[29]	[30]	[31]	[34]
Freq.	2.45GHz	2.45GHz	2.45GHz	2.45GHz	0.9GHz
Sens. dBm	-20	N/A	-30	-5	-7
Size mm^2	88×76.9	100×100	87×80	35×30	144×89
Sub.	FR4	FR4	RT 6002	FR4B-2	Melinex
Diode	SMS7630	HSMS-282c	HSMS-2862	HSMS-2852	SMS-7621
Eff.%@dBm	72@-7	82@22	50@-17	72@13	N/A
R_L, Ω	2000	1000	1400	900	N/A

tween simulated and measured curve at low input power levels lower than -10 dBm is caused by the stray capacitance produced from the via connection. This stray capacitance results in slight impedance mismatching between CPW and MS structure of Case 2 particularly at low received power levels. According to Fig. 3.10(c), the DC output conversion efficiency is approximately constant over 45% for load termination from 1 to 4 k Ω and a fixed RF input power of -7 dBm. The differences between Case 1 and Case 2 is summarized in Table 2. Case 2 has more merits than Case 1. The size of Case 2 design is 23.5% smaller than Case 1. Moreover, the efficiency and output DC voltage at the same input RF power for Case 2 is almost doubled that of Case1. Since the integrated rectenna has a compact size and high efficiency, it is preferred for many wireless applications that use RF energy harvesting.

At last, we summarize and compare the performance of the developed rectenna with the relevant architectures reported in the literature as shown in Table 3. The proposed rectenna greatly improves the EH performance in terms of efficiency and sensitivity compared to published work in [29], [30] and [31]. In [30], authors show a rectenna design characteristics of low detectable signal and high efficiency at -17 dBm, but the design was based on RT/Duriod 6002 which has a considerable small tangent loss. As a result, the dielectric losses are significantly reduced. Also, the measurement setup avoided the use of Friis transmission equation where the received power was measured through a spectrum analyzer. On the other hand, the proposed design in this paper has been constructed on a low-cost FR4 substrate where the tangent loss is large. Moreover, the proposed circuit provides an accurate measurement data and a approximately

constant efficiency with the load resistance from 1 to 4 k Ω , which is appropriate for wireless sensor node networks.

3.6 Second Design

This section provides an efficient rectifier operating at 2.45 GHz for wireless energy harvesting applications with low input power levels. In order to minimize the number of discrete components and hence the conduction losses, a single series diode topology is adopted for operation with low input power level. Indeed, the coplanar waveguide (CPW) configuration is selected for the rectifier and antenna configuration. This topology is chosen due to the high-frequency performance, ease of implementation, it reduces the coupling effect and allows for easy inclusion of series and shunt elements. The analytical approach is discussed to evaluate the rectifier performance in conjunction with the effect of matching circuit. The equivalent circuit model is predicted and compared with both the experimental and the EM model. The entire experimental performance of the rectenna is characterized and compared to the simulation results.

3.6.1 RF Rectifier Design

The key components of a rectifier are the diode(s), a lowpass filter and a resistive load. The diode is the most considerable components because it should convert the limited available RF power into an exploitable dc energy. A good rectifier must have a low power consumption, good power sensitivity, and good power handling capability [43]. The diode chosen for the present application is a Schottky diode SMS7630-061F [44]. It is chosen because of its low turn-on voltage and small junction capacitance which enables it to work at the required high frequencies.

The selection of rectifier topology design is critical for efficient power harvesting. A single matched low-power diode in series configuration is selected for the rectifier topology because it uses few lumped components, reduced sized, introduce low losses and ease of fabrication. The rectifier topology is based on a very simple and attractive CPW configuration given in Fig.

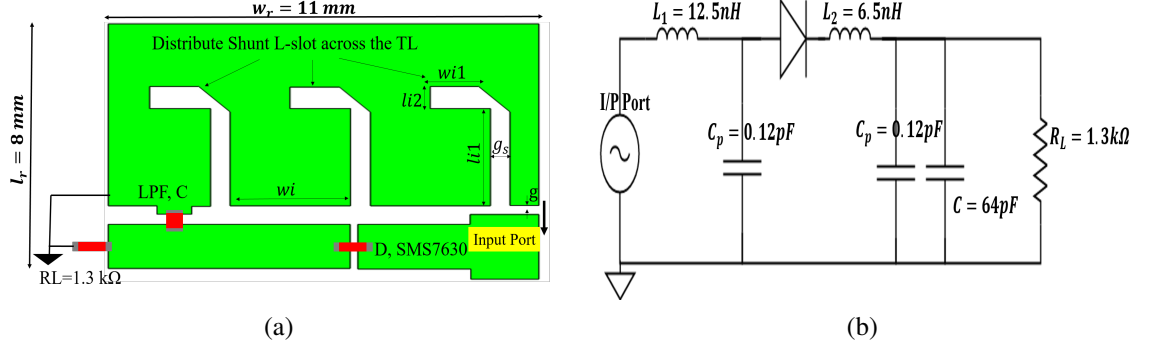


Figure 3.11: The RF rectifier circuit (a) Rectifier layout and the dimensions are as follow $w_{i1} = 1.7 \text{ mm}$, $l_{i1} = 3.14 \text{ mm}$, $l_{i2} = 0.74 \text{ mm}$, $w_i = 3.25 \text{ mm}$, $g_s = 0.53 \text{ mm}$, $g = 0.3 \text{ mm}$ (b) Equivalent circuit model.

3.11(a), the proposed circuit topology employs only single Schottky diode and a capacitor that behaves as LPF for smoothing the DC voltage at the rectifier output. Therefore, the design is very interesting in the aspect of deploying few lumped elements.

The impedance matching circuit is a crucial for maximum power transfer between the antenna and the rectifier input. Implementation of the matching circuit is not simple since the rectifier is a nonlinear load with complex impedance that varies with frequency, input power level and the built-in characteristics of the diode. In order to obtain the optimum diode performance, the rectifier circuit is optimized in conjunction with the matching circuit.

The matching circuit is simply formed by inserting defects in the ground plane. The defects are multiple of L-slots distributed along the transmission line. Single L-slot is $\lambda_g/10$ short-ended transmission line at the frequency of interest. To ensure the optimum DC power output, the number of slots were optimized using the ADS software. The effect of cascading the number of slots on the rectifier input characteristics will be investigated later.

The rectifier circuit is analyzed using the circuit model approach and the electromagnetic (EM) approach as well. The analytical circuit model derived from the rectifier layout is shown in Fig. 3.11(b). To illustrate, each slot has inductance $L(\text{nH})$, this inductance is derived from the input impedance (Z_{in}) of a shorted lossless transmission line has characteristic impedance Z_o and propagation constant β . The inductance estimated using the well-known equations [46] is $L = 6.5 \text{ nH}$.

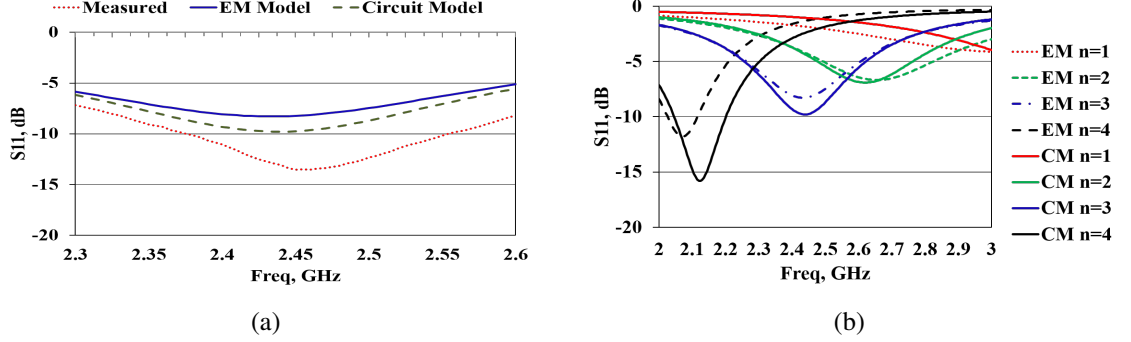


Figure 3.12: The simulation characteristics of the RF rectifier circuit , (a) Return loss S_{11} , (b) Effect of cascading L-slot along the transmission line (EM: stands for EM model simulation, CM: Circuit model simulation, and n represents the number of slots).

The first two slot comprise a series pair of inductance so they can be estimated as $2 \times L$. In order to consider the coupling inside the slot gap, a shunt capacitor is introduced between the main transmission line and the ground. After full optimization of such components, the circuit model parameters are given by ($L_1 = 12.5$ nH, $L_2 = 6.5$ nH and $C_p = 0.12$ pF).

The simulations were carried out in the ADS software and the typical comparison between EM-model simulation, circuit model and measurements are shown in Fig. 3.12(a). The curves demonstrate the exact results agreement between EM and the extracted circuit model along the operating band. To show the rectifier design flexibility, a cascading number of slots were considered and simulated using both EM and circuit model. The number of slots can significantly changing the resonance frequency as shown from the EM and circuit simulation in Fig. 3.12(b). The circuit model of each case was derived based on the previous discussion. The optimum number of slots selected for the current design are equal three as it produces a good matching along the desired frequency band.

3.6.2 Antenna Design Architecture

Both the rectifier and antenna structure is constructed using CPW configuration with removing one of the ground on either side of the signal strip line. Some of the advantages of CPW arise from the fact that the mounting of lumped (active or passive) components in shunt

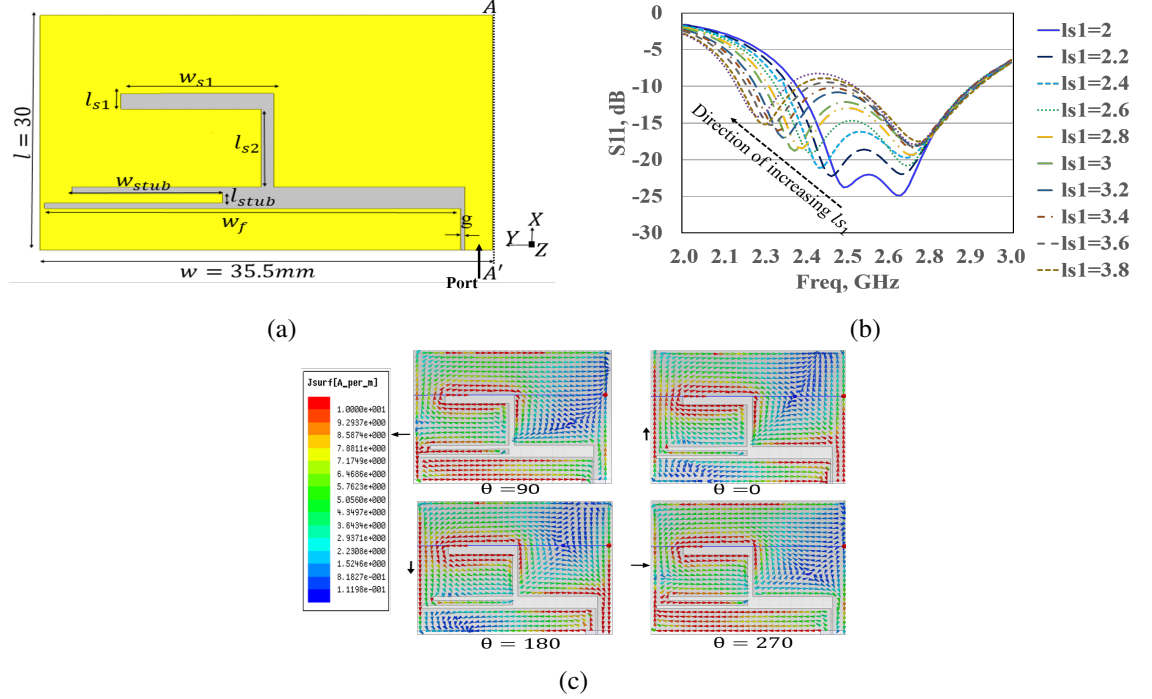


Figure 3.13: The antenna configuration and parametric study. (a) The CPW antenna layout, the dimensions are as follow $w_{s1} = 12$ mm, $l_{s1} = 2$ mm, $l_{s2} = 9.9$ mm, $w_{stub} = 11.84$ mm, $l_{stub} = 1.2$ mm, $w_f = 32.7$ mm, $g = 0.3$ mm, (b) The effect of changing the L-slot width l_{s1} (c) Surface current distribution on the antenna structure for different phase excitation at frequency 2.45 GHz.

or series configuration is much easier, drilling of holes through the substrate is not needed, and transition to slotline is less cumbersome, thereby allowing greater flexibility in the use of mixed transmission media [46].

The slot antenna (shown in Fig. 3.13(a)) consists of a radiator formed by cutting a narrow slot in a large metal surface given by $l \times w$ where l is the length, and w is the width of the antenna. The slot is formed by L-section slot with length of approximately in the order of half wavelength at the desired frequency and the width is optimized (using HFSS simulation software Ansys Co.) for proper impedance matching as given in Fig. 3.13(b). The surface current distribution on the antenna geometry is shown in Fig. 3.13(c) for different input phase excitation. From the plots, the current is rotated anti-clockwise. Consequently, it shows a left-handed circular polarization (LHCP). The antenna is printed onto FR4 substrate using CPW transmission line configuration. It is fed by a 50Ω -CPW feeding line, where the signal strip and

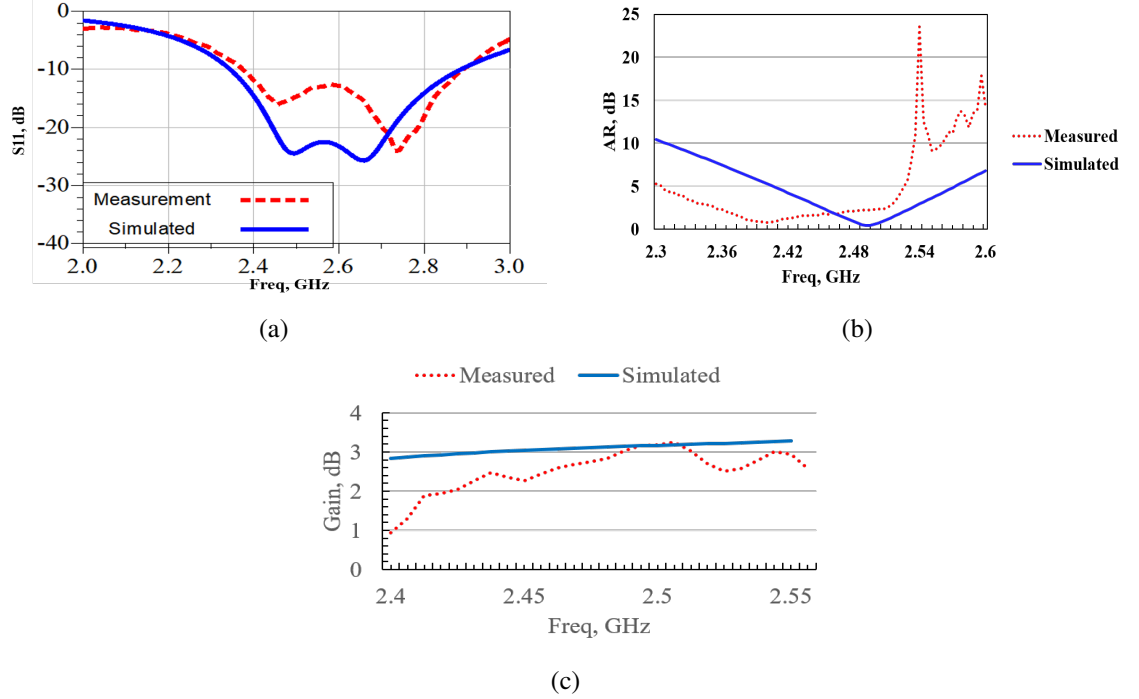


Figure 3.14: The measurement and simulation characteristics of the slot antenna (a) Return loss S_{11} , (b) Axial ratio AR , (c) Antenna gain.

the gap have 2.16mm and 0.3mm , respectively.

The radiation and matching characteristics of the antenna is illustrated in Fig. 3.14. The antenna return loss (S_{11}) across the operating band is shown in Fig. 3.14(a). It is noted that both measured and simulated results are well matched across the operating band with more than -10 dB around the center frequency 2.45 GHz. The proposed design also has $VSWR < 2$ with matching impedance bandwidth 600 MHz ($2.3 - 2.9$ GHz) which is approximately 25% relative to the center frequency of 2.45 GHz. To prove the CP of the proposed antenna, the axial ratio AR is plotted in Fig. 3.14(b). The measured 3 dB AR bandwidth can reach as large as 100 MHz ($2.4 - 2.5$ GHz) which is about 4% (relative to the center frequency of 2.45 GHz) to cover the Wi-Fi band $2.4 - 2.5$ GHz (IEEE 802.11 standards) which meet the prior design specifications. The antenna gain is explained in Fig. 3.14(c). As shown, the maximum realized gain (3 dBi) is slightly shifted from the resonance frequency. This is attributed to the tolerance during the measurement setup.

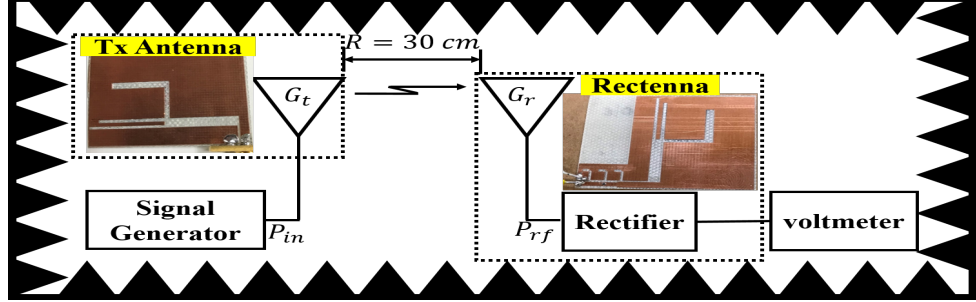


Figure 3.15: Rectenna measurement setup and the prototype of both the rectenna and antenna is embedded in the figure.

3.6.3 Rectenna, the integration of rectifier and antenna

The rectenna is fabricated on FR4 substrate with thickness $h = 0.8mm$ and dielectric constant $\epsilon_r = 4.4$. To accurately model the rectenna simulation characteristics, the Theveinin equivalent circuit, which is represented by input impedance matrix of the antenna $[Z_A]$, is used to simulate the presence of the antenna in the ADS simulation. The impedance matrix is exported from the HFSS EM simulator software. The rectenna characteristics are defined using Friis equation to determine the received RF power. The measurement setup (shown in Fig. 3.15) is done as follow, a CP antenna (same as used for the rectenna fabrication) connected to a function generator is used as the RF transmitter, the signal source generator power is set to 22 dBm.

The received RF power P_{rf} is calculated using Friis equation. A suitable definition of the RF-DC conversion efficiency is the ratio of the amount of DC power at the load to the RF input power collected by the antenna, and is given by equation 3.2.

The calculated efficiency includes the antenna efficiency, mismatch, coupling from antenna to the rectifier and rectification efficiencies. The rectenna efficiency for different constraints is plotted in Fig. 3.16. From the data shown, it is obvious that the results obtained for measurement, EM and circuit model is typically agreed over the desired band with a maximum efficiency at frequency= 2.4 GHz. The variation of conversion efficiency with frequency is shown in Fig. 3.16(a). The efficiency is still more than 45% over the band of interest and slight

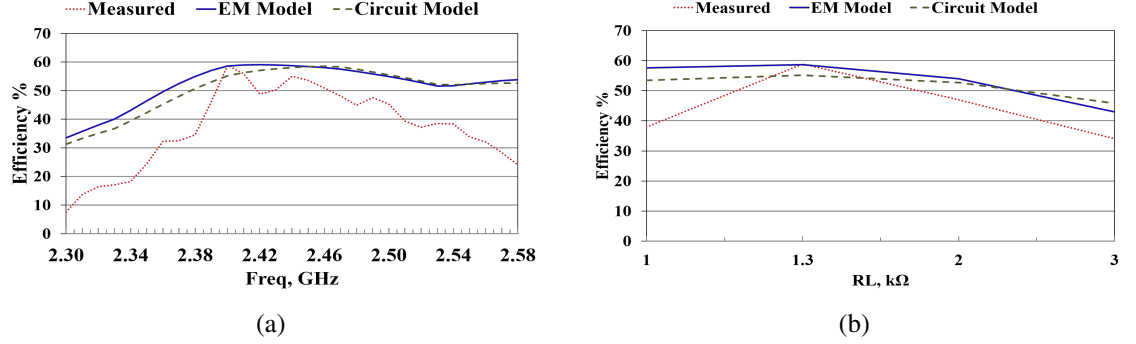


Figure 3.16: Rectenna simulation and measurement performance characteristics (a) Efficiency versus frequency at a fixed measured input power -6 dBm, simulated input power -4.5 dBm and $R_L = 1.3$ kΩ, (b) Efficiency versus terminal load at defined measured input power -6 dBm, simulated input power -4.5 dBm and frequency 2.4 GHz.

Table 3.4: Comparison of this study with the relevant research work in literatures.

REF	f , GHz	P_{rf} dBm	η , %	Polarization	Size, mm^3	Sub.
[40]	2.45	$\cong -1.5$	37.8%	LHCP	$60 \times 60 \times 1.6$	FR4
[41]	2.45	-15	28%	HP	$49 \times 54 \times 0.37$	Paper
[42]	2.45	22	82.3%	RHCP and LHCP	$100 \times 100 \times 3.8$	FR4
This work	2.45	-6	59.5%	LHCP	$41 \times 35.5 \times 0.8$	FR4

reducing from the simulation results. The slight reduction of the measured efficiency for the higher frequencies inside the operating band is due to the resultant mismatching in the rectifier circuit. The effect of terminal load is explained in Fig. 3.16(b). The peak measured and simulated conversion efficiency is achieved at $R_L = 1.3$ kΩ.

A comparison between the current design and the relevant work is explained in Table. 3.4. The comparison reveals the significant merits of the current study in terms of low power, high efficiency, and compact size features of the proposed design. For instance, the current design is 60%, 47%, and 85.5% smaller than the topologies given in Ref. [40], [41], and [42], respectively. The most important thing should be noticed is the high efficiency improvements at power levels

less than 0 dBm.

3.7 Conclusion

In conclusion, an efficiency-enhanced energy harvester at a frequency of 2.45 GHz has been demonstrated through simulation and measurement. Our design objective was to obtain the highest possible DC conversion efficiency corresponding to RF input power level below 0 dBm using Schottky diode. The maximum simulated and measured efficiencies of 72% have been obtained at -7 dBm RF input power and a load resistance of $2k\Omega$. Different design typologies were explained, and a comparison study of each architecture was performed to demonstrate the effectiveness of the design. Improvements in the conversion efficiency, DC output power, and sensitivity have been achieved using CPW-MS transition. Finally, a comparison between our proposed rectenna design and the rectennas reported in literature was made to show the contribution of this work. In order to increase the conversion efficiency beyond -20 dBm, it is possible to use low-loss dielectric materials, high Q-factor resonant circuits, high-gain antenna, minimal turn-on voltage Schottky diode, etc. All such ideas are applicable but with the cost of increasing the circuit complexity, fabrication cost, and large circuit footprint.

Moreover a new method to design compact, circular-polarized, high-efficient rectenna that can work at low input power less than 0 dBm, typically -6 dBm. A high-efficiency 2.45 GHz rectenna with simple structure, low-cost fabrication, and single-feed network has been proposed and investigated. The configuration of the proposed antenna design is very simple and provides a high flexibility in the operating frequency of the antenna design and fabrication. It is demonstrated that the overall efficiency of the proposed rectenna can achieve 59.5% with RF input power of -6 dBm. Since the RF-to-dc conversion efficiency has evolved as an important research topic for low-power RF energy harvesting, this work can be considered as a successful attempt in this respect.

Chapter 4

Design of a Broadband RF Rectifier

This chapter proposes two wideband rectifier circuit design for RF energy harvesting. The proposed circuit can collect signals efficiently over broad bandwidth spanning from 0.87 to 2.7 GHz, which includes UHF ISM 900 MHz, GSM 900 and 1800 MHz, wireless communication, PCS, and ISM 2.4 GHz. In order to obtain sufficiently large rectifier bandwidth, a matching circuit based on high-pass type L-section for lower-band impedance matching and inductive L-section for higher-band impedance matching is proposed. The rectifier circuit is constructed using voltage doubler configuration with Schottky diode SMS7630-005LF. The circuit is optimized and re-fabricated to compensate the undesired parasitic and obtain the required rectifier performance. Two prototypes were simulated, fabricated, and characterized. The rectifier has a measured conversion efficiency exceeding 30% from 870 MHz to 2.5 GHz at 0 dBm input power and a load terminal of $2k\Omega$ and a DC output voltage equal to 1 V. The circuit sensitivity may reach up to -20 dBm with DC output voltage 8 mV and 8% conversion efficiency. The maximum measured efficiency is 63% from 1.1 GHz to 1.35 GHz.

4.1 Introduction

Energy harvesting is among the latest technologies that have much of interest during the last decade. An increasing number of wireless applications are in operation in daily life, such

as Wi-Fi, Bluetooth, 3G and 4G communications, Wireless LAN as well as GSM 900 or 1800 MHz [47]. Consequently, the environment includes a substantial amount of electromagnetic energy situated over a wide frequency range.

High-efficiency rectennas for RF energy harvesting have been studied for decades, but most prior work in ambient RF harvesting has focused on a single ambient sources of energy [48]–[50] or multiband RF harvesting [51, 52]. One common aspect across both harvester topologies is that what if the intercepted RF signal source is not available at the moment of energy harvesting. Therefore, it is better to design a rectifier to detect the RF signal efficiently over a wide operating frequency band. Several challenges when developing either multiband or broadband EH circuits were covered in [53]. For example, the nonlinear nature of the rectifying devices affects the performance of rectifier circuits in terms of RF-DC conversion efficiency with variations in the input power level and also in the output load.

To extend the rectifier performance over a broad bandwidth, several literatures had offered different design architecture. There are various previous studies on diode detectors [54], and theoretical estimation of the efficiency of diode rectifiers [55], as well as more recent publications such as [56, 57] addressing the performance as RF-DC power conversion circuits in low-power far-field wireless power transfer or RFID applications.

In [58, 59], authors introduced one octave bandwidth rectifier that is based on a non-uniform transmission line. The overall efficiency is as low as 5% over a frequency range from 470 MHz to 990 MHz for a given RF input power of -20 dBm. The main issues were, the efficiency degradation along the band and the dimensions were very large compared to the wireless device size. A wideband class-F1 amplifier is reconfigured as a wideband rectifier by adding feedback to the amplifier to provide a gate drive signal from the RF input port of the rectifier. The measured efficiency remains above 60% over a frequency range from 600 MHz to 1150 MHz [60]. Despite the achieved high efficiency over the desired band, this efficiency requires relatively high input power of 8 W (40 dBm). In [61], two-branch impedance matching circuit is introduced to enhance the performance and efficiency of the rectenna. The proposed structure had a maximum conversion efficiency of around 55% for 10 dBm input power from 1.8 to 2.5 GHz.

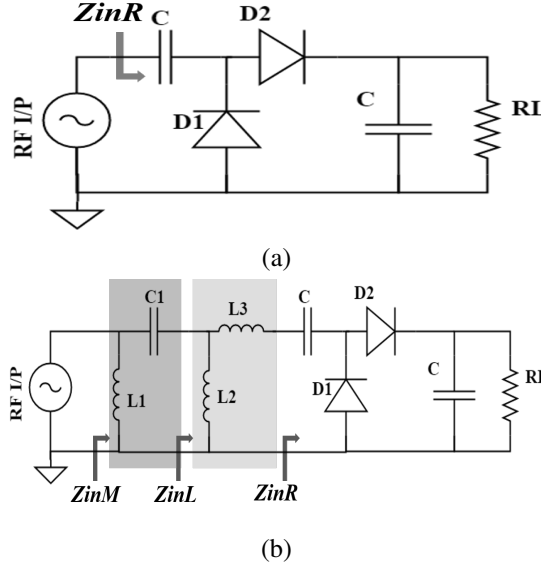


Figure 4.1: Rectifier circuit topology (a) and voltage doubler rectifier circuit (b) Voltage doubler rectifier circuit with the cascaded two L-section stages.

Most of the previously proposed broadband rectifiers not only demand a large footprint but also doesn't greatly improve the efficiency so far especially at low RF input power. In this paper, a novel compact broadband rectifier using straight forward design of two-cascaded L-section is proposed (shown in Fig. 4.1). In order to minimize the rectifier size, the two L-sections were constructed using surface mount lumped elements. A four reactive elements $L1$, $L2$, $L3$, and $C1$ was used as shown in Fig. 4.1(b). The total rectifier circuit dimensions are $17.8 \times 6.4 \times 0.8 \text{ mm}^3$.

4.2 Rectifier Circuit Analysis

Many topologies had been considered for rectifier circuit design. One of the most efficient rectifier topology is the voltage double configuration shown in Fig. 4.1. It consists of two branches of diode-capacitors

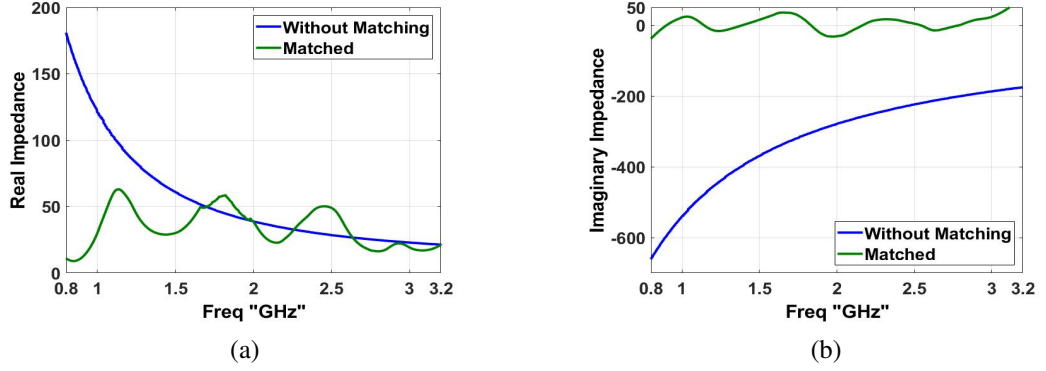


Figure 4.2: Simulated rectifier input impedance of the real part (a) and the imaginary part (b).

4.2.1 Rectifier Input Impedance

The most critical rectifier parameter is the input impedance, Z_{inR} where its value is depending on RF input power P_{in} , operating frequency $freq$, nonlinear impedance of the diode R_d and terminated load R_L .

$$Z_{inR} = f(P_{in}, freq, R_d, R_L). \quad (4.1)$$

The circuit diagram of the rectifier circuit is shown in Fig. 4.1(a). The rectifier input impedance for this arrangement when $C = 64$ pF, $R_L = 2k\Omega$ and $P_{in} = 0$ dBm is shown in Fig. 4.2(a). As illustrated, by increasing the frequency, the real part is decreasing from a few of hundreds ohms at 800 MHz to few tens of ohms at 3 GHz. In the same manner, the capacitive input impedance component reduces from 700Ω at 800 MHz to 200Ω at 3 GHz. Therefore, it is preferable to remove the capacitive component encountered at the rectifier input and matching the real part of the rectifier by inserting the proposed matching configuration.

4.2.2 Broadband Impedance Matching

In order to realize a wideband matching network, a cascaded pair of L-section is chosen. An L-section reactive elements (L , C) are traditionally used for narrowband impedance matching consideration. However, a modified pair of L-section has developed in this communication for

Table 4.1: Reactive Elements Values.

	L1	L2	L3	C1	BW(GHz)	$\eta\%$
Initial	16	4	5.5	2	1.1 – 3.05	>50
Optimized	10	8	7	1.5	0.837 – 3.12	>40

Inductance and capacitance values are given in (nH) and (pF).

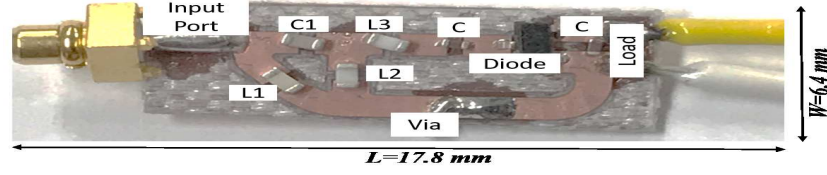


Figure 4.3: The fabricated prototype of the proposed wideband rectifier circuit.

achieving a wideband performance. A high-pass type L-section comprised of $L1$, $C1$ is used for tailoring the impedance matching at the low frequency band spanning from 800 MHz to about 1.5 GHz. On the other hand, an inductive L-section consisting of $L2$, $L3$ is used for high-frequency impedance matching at frequency above 1.5 GHz. The impedance matching circuit model is shown in Fig. 4.1(b). Using SPICE simulation (ADS, Keysight tech.), we conducted the optimization of the cascaded L-sections parameters ($L1$, $L2$, $L3$, $C1$). The optimized values are given in Table 4.1. After introducing the matching network prior to the rectifier input, both the real and imaginary input impedance is almost constant to acceptable levels from 0.8 to 3.2 GHz as demonstrated in Fig. 4.2(b).

4.3 Fabrication and Measurement Results

The rectifier circuit is fabricated on 0.8-mm low-cost commercial FR-4 substrate with $\epsilon_r = 4.4$ and $\tan\delta = 0.02$. Fig. 4.3 shows the fabricated prototype circuit. The characteristic impedance of the feed line is 50Ω . The measurements were carried out using vector network analyzer, function generator and multimeter.

The measured reflection coefficient S_{11} (Fig. 4.4 and the efficiency of the rectifier (Fig. 4.5) were measured experimentally under different power levels from -20 dBm to 0 dBm with interval of 5 dBm over the operating frequency band. Also, the input impedance was estimated

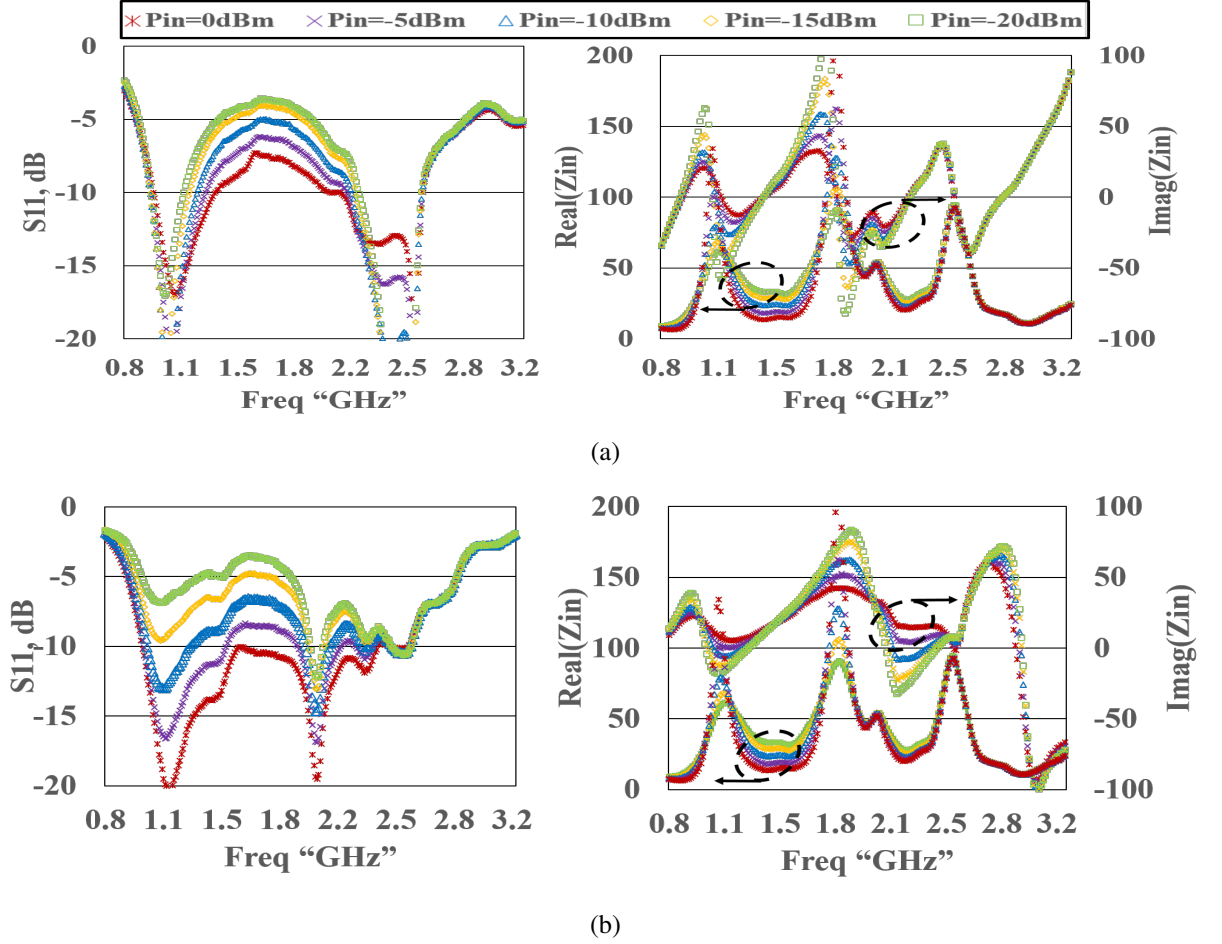


Figure 4.4: Sweeping of P_{in} and the corresponding measurement data (a) Initial design measurement characteristics S_{11} , Z_{in} , (b) Optimized design measurement characteristics S_{11} , Z_{in} .

from the S_{11} and is given in Fig. 4.4.

From Fig. 4.5(a), the rectifier could keep a practical efficiency exceeding 40% from 870 MHz to 2 GHz for input power of 0 dBm. Also, it is noted that the simulated efficiency has a bandwidth larger than the measured efficiency. For instance, the measured 40% efficiency bandwidth is 1.13 GHz while the simulated 50% efficiency bandwidth is 2 GHz, with about 43.5% reduction ratio. This is attributed to diode inaccurate model reported in the datasheet, soldering losses, chip-component tolerances, interconnecting transmission lines, and the SMA connector. As the frequency increases, the lumped component will have distributed effects or added phase

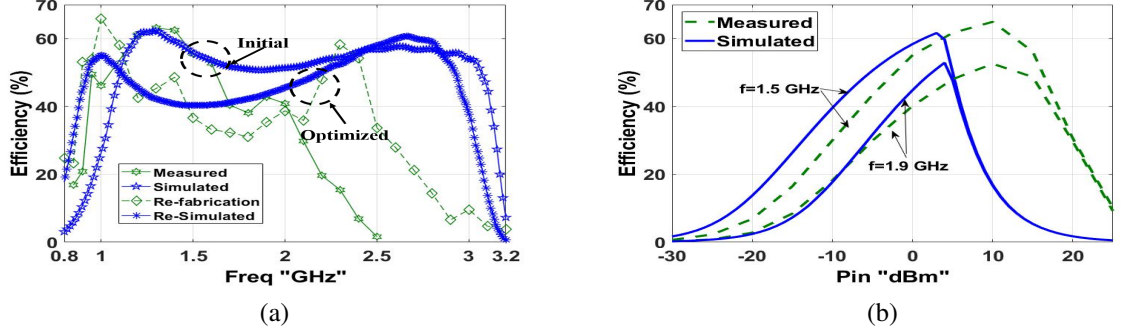


Figure 4.5: Simulation and measurement results. (a) Efficiency vs. Frequency with $P_{in} = 0$ dBm (a) and efficiency vs. input power with different frequencies.

shift which must be accounted for in the analysis. Consequently, at high frequencies additional parasitic effects must be included in the component model. All of these issues contribute to the main sources of parasitic and the cause for discrepancy between measured and simulated results as given in Fig. 4.5(a).

To accurately demonstrate these problems, we extracted the input reactive elements (L , C) in the transmission line from both the measured and simulated data, the difference between corresponding values were compensated by the optimization of chip component, as given in Table I, till matching the simulated and measured results. The parasitic components are consisting of series-connected LC in shunt with shunt-connected LC section introduced in front of the measured s-parameter data of the initial design data given in Fig. 4.4(a), and its values are given as $L_p = 50$ nH, $C_p = 30$ pF, $L_s = 68.4$ nH and $C_s = 6.12$ pF. The simulations were done with the account of parasitic and the results show that the measured and simulated results are in reasonable agreement.

A new prototype was re-fabricated to overcome the parasitic and the measured results are shown in Fig. 4.5(a). It demonstrates the rectifier is performing well over a wider frequency band with efficiency more than 30% from 0.87 GHz to 2.5 GHz for 0dBm input power. Fig. 4.5(b) depicts the efficiency against input RF power at different frequencies (1.5, 1.9GHz), both measurements and simulated conversion efficiency are in good agreement. Table 4.2 summarizes this work along with previously published works. The performance of the proposed circuit

Table 4.2: Comparison of this study with the relevant research work in literature.

REF	BW(GHz)	Frequency range(GHz)	η_{max}	Size mm^2
[58]	0.46	0.4 – 0.86	60%@10 dBm	1900
[60]	0.55	0.6 – 1.55	80%@39 dBm	N/A
[61]	0.7	1.8 – 2.5	55%@–10 dBm	1400
This work ⁺	1.13	0.87 – 2.0	40%@0 dBm	114
This work*	1.63	0.87 – 2.5	30%@0 dBm	114

⁺ Initial * Optimized

is very attractive in terms of efficiency, frequency bandwidth and the overall size compared with the relevant work in [58, 60, 61].

4.4 Second design

In this design, the implementation of a compact, wide-band, single layer, and simple RF rectifier design is discussed. The proposed rectifier configuration is based on the co-planar waveguide (CPW) transmission line. The rectifier is constructed using the voltage doubler circuit in conjunction with a broadband matching network. To obtain a small circuit size, the matching circuit is constituted with a series dual-inductive lumped elements. The overall rectifier dimensions are very compact $22.5 \times 31 mm^2$. In order to accurately characterizing the rectifier performance, the electromagnetic and harmonic balance simulations are conducted using the Agilent, ADS software. The comparison shows good agreement between the simulation and measurement results. For instance, the peak measured efficiency is 74.8% at 10 dBm RF input power and the corresponding simulated value is 75% with a terminal load of 1 k Ω . The efficient frequency range is extending from 0.1 to 2.5 GHz, with an efficiency of more than 45% at input power 10 dBm.

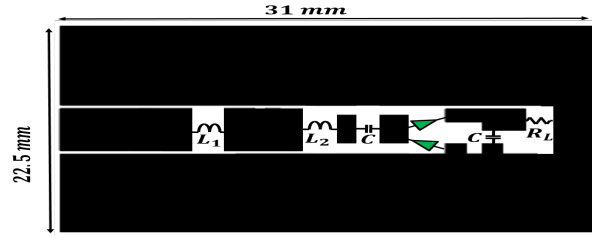


Figure 4.6: The rectifier circuit layout

4.4.1 Rectifier Circuit Architecture

The rectifier circuit topology is composed of a voltage doubler connected in series with a series two inductive lumped elements $L_1=1.2$ nH and $L_2=3.9$ nH, as shown in Fig. 4.6.

The rectifier is consisting of diode and capacitor. There are different types of rectifier (i) Basic rectifier (ii) Voltage doubler (iii) Voltage multiplier. In the basic rectifier circuit, the diode is connected in series with load. In this case, the capacitor is used for smoothing the DC output voltage. In the voltage doubler, two diodes and two capacitor are used for approximately double up the DC voltage. In the voltage multiplier, cascaded connection of diodes and capacitors are used to obtain higher voltage order. For typical 50Ω antenna, the received RF signal power is generally smaller than the diode threshold. So diode with the lowest turn on voltage are preferable for the energy harvesting circuit. A series pair of Schottky diode (SMS7630-005LF) is suitable for the RF energy harvesting schemes.

The investigation of the matching circuit performance is shown in Fig. 4.7. The equivalent circuit for both cases is illustrated in Fig. 4.7(a). The VSWR is given in Fig. 4.7(b) which quantify that the inductive matching circuit is widely resonant out the reactive part of the input impedance of the voltage multiplier. Therefore, it achieves a broadband operation.

A prototype circuit has been realized on FR4 substrate with dielectric constant $\epsilon_r = 4.4$ and thickness $h = 0.8$ mm and was fabricated using a milling machine. The fabricated rectifier circuit layout is shown in Fig. 4.8. The total size of the rectifier circuit is 22.5×31 mm².

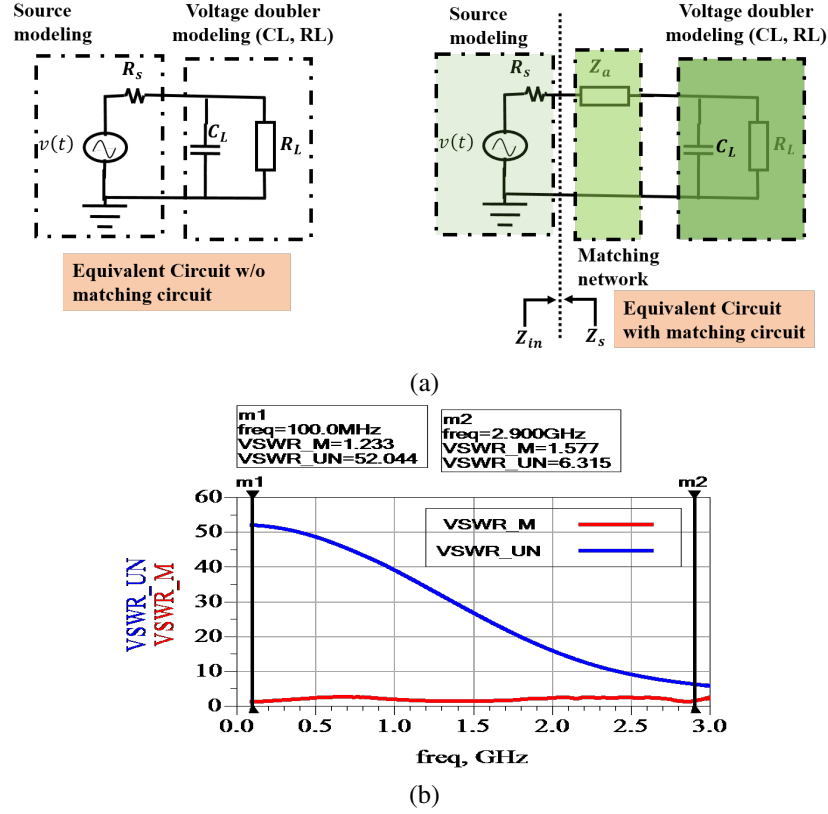


Figure 4.7: Demonstration of the matching circuit, (a) Equivalent circuit for the rectifier topology with and w/o the matching circuit, Z_a represents the equivalent impedance of the inductive matching circuit, (b) Voltage standing wave ratio (VSWR). M: stands for matched condition, UN: stands for unmatched condition.

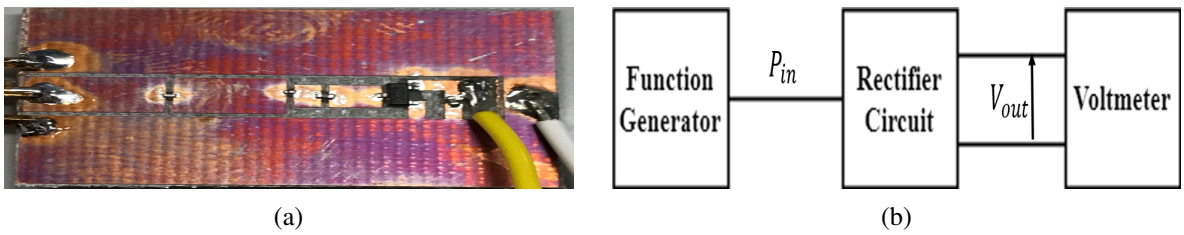


Figure 4.8: Photograph of the (a) fabricated rectifier circuit and (b) the measurement setup.

4.4.2 Experimental Rectifier Characterization

In this section the characterization and results for the rectifier of the harvesting system are discussed. As the performance of the circuit depends on the input frequency, input power, and load conditions, three separate cases are considered for the rectifier evaluation. The input signal

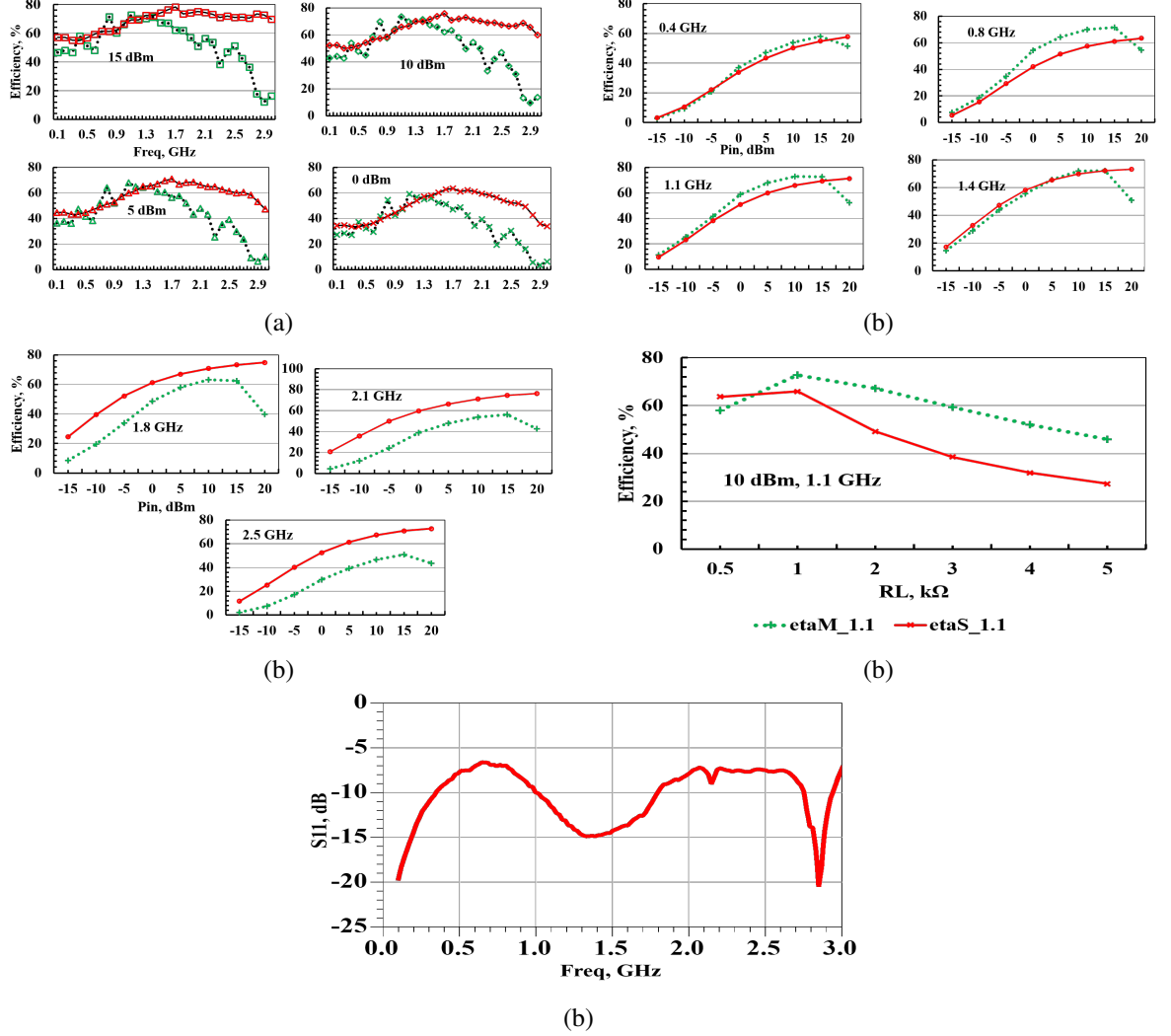


Figure 4.9: The measured and simulated rectifier performance comparison (a) Efficiency variation with the input frequency taken at different input power P_{in} =15, 10, 5, and 0 dBm, and R_L =1 kΩ (c) Efficiency changes with the input power at some selected in-band frequencies 0.4, 0.8, 1.1, and 1.4 GHz, and at R_L =1 kΩ (d) Efficiency changes with the input power at some selected in-band frequencies 1.8, 2.1, and 2.5 GHz, and at R_L =1 kΩ (e) Efficiency changes with the load terminal at different RF input power P_{in} =10 dBm, and at frequency 1.1 GHz, (e) Input reflection coefficient, S_{11} . M: stands for measurements and is given in dotted green line, and S: stands for simulations and is given in solid red line.

is produced by a function generator and then fed to the rectifier circuit using a 50 Ω connector. The output DC voltage is taken across the terminal load and measured using voltmeter. The measurement setup block diagram is demonstrated in Fig. 4.8(b).

The measured input reflection coefficient is introduced in Fig. 4.9(e). As can be noted, at

least 75% of the input power could be transmitted to the rectifier input when reflection coefficient is around 6 dB. In that case, the impedance matching performance is achieved at the desired frequency range from 0.1 to 2.7 GHz. In order to evaluate the rectifier performance, first the terminal load, and the input power are set to 1 k Ω , and 15 dBm, respectively. On the other hand, the frequency is changing from 0.1 to 2.9 GHz. The output voltage is estimated and the output conversion efficiency is calculated using the following equation:-

$$\eta = \frac{P_{dc}}{P_{rf}} \times 100\% = \frac{V_{dc}}{R_L^2 \times P_{rf}} \times 100\% \quad (4.2)$$

where P_{dc} is output DC power, P_{rf} is the RF input power signal, and V_{dc} is the output DC voltage. Next, to evaluate the rectifier frequency response at several input power level, the power is changed to 10, 5, and 0 dBm and the measurements are repeated again at the same output load value. The measurement and simulated results comparison is shown in Fig. 4.9(a).

Second, the signal input frequency is kept constant at 0.4 GHz, the terminal load is set to 1 k Ω , and the input power level is changed from -15 to 20 dBm. This is done for various signal input frequencies 0.8, 1.1, 1.4, 1.8, 2.1, and 2.5 GHz. The simulated and measured data is plotted in Fig. 4.9(b), (c). From the list of curves it could be observed that as the frequency is increasing, the measured rectifier efficiency is deteriorated from the simulation curves. For example, at 15 dBm RF power input the measured efficiency at the low frequency band (0.4 GHz) is about 60%, but at 2.5 is 50% at the same constraints. Moreover, the RF-DC conversion efficiency is slightly constant over the dynamic power range from 10 to 15 dBm.

Last, the effect of terminal load changes is given in Fig. 4.9(d). The given data were plotted at input signal frequency 1.1 GHz and input power 10 dBm. The RF-DC conversion efficiency exhibit more good results in the vicinity of 1 k Ω .

4.5 Conclusion

Two topologies for the implementation of a wide-band rectifier was proposed in this chapter. First, a broadband rectifier with almost flat measurement conversion efficiency over 30% from

870 MHz to 2.5 GHz was presented based on a cascaded two L-section reactive elements. The ideal simulation value is over 50% from 970 MHz to 3.1 GHz. The rectifier circuit was optimized for maximal performance operation for low power levels below 0 dBm which is suitable for low power wireless sensor applications. The main contribution in this article is the compact size, and broadband feature of the proposed rectifier design. Also, the narrowband signals have good performance at a specific frequency. Future research includes designing a broadband antenna for rectifier integration. The most challenging point was to maintain the efficiency over a wideband disregarding the RF input frequency.

Second, an efficient broadband RF energy harvesting rectifier has optimized for the maximal performance to drive power to a wireless sensor network. The proposed circuit could efficiently harvesting power from a dedicated microwave source, that emits a signal with input power from -15 to 20 dBm and has a dynamic frequency range from 0.1 to more than 2.7 GHz. The proposed system produces a DC output voltage of 4 V for the load resistance of 1 k Ω . The power conversion efficiency of the proposed system is kept above 45% over the desired frequency range. In order to maximize the output DC voltage, a multistage of the proposed rectifier is connected together to form a cascaded rectifier chain.

Chapter 5

Wide-band Efficiency Improved RF Differential Rectifier

This chapter presents a novel design of radio-frequency (RF) differential rectifier (DR) for harvesting power as low as 0 dBm . The proposed configuration aims to improve efficiency over extended bandwidth of operation, and further size reduction for low profile RF rectifier circuit. The developed design introduces a balanced output voltage which is suitable for biasing most of the analog integrated circuits, e.g, all circuits based transistor requires $\pm V_{dc}$. In addition, the proposed topology provides a measured RF-DC efficiency more than 30% over a relatively wide bandwidth (550 MHz) from 0.95 GHz to 1.5 GHz . Commercial balanced-unbalanced (BALUN) component is used for port transformation. Experimental results show that the system can work with different carrier frequencies and the proposed converter can provide a regulated output voltage of $\pm 1\text{ V}$ over the proposed frequency band at RF input power $P_{in} = 5\text{ dBm}$. The peak conversion efficiency of the whole system is 57.5% at 1.1 GHz .

This work addresses the design and implementation of a broadband differential rectifier (DR) combined with an Archimedean spiral dipole antenna (ASDA) for wireless power harvesting at low incident power densities below $200\text{ }\mu\text{W}/\text{cm}^2$. The proposed design exhibits an improved RF-DC conversion efficiency over a wide frequency range from 1.2 to 5 GHz. This frequency band is associated with several wireless communication services, for instance, ISM,

WLAN, 5G, LTE, and GPS applications. The receiving planar ASDA exhibits circular polarization and has an average measured gain of 4.5 dBi from 1.2 to 5 GHz. To enable a wide operating bandwidth, the rectifier circuit is constituted by two architectures, designated A and B. Each scheme is designed to harvest power efficiently across a specific bandwidth. The optimal performance of both rectifiers are obtained using the nonlinear harmonic-balance simulations. The antenna–rectifier integration yields a compact rectenna with a high-efficiency performance over the intended bandwidth from 1.2 to 5 GHz for an input power of 9 dBm and terminal load resistance of 1 k Ω . The total measured RF-DC conversion efficiency is maintained above 30% across the entire frequency range with a peak value of 61% achieved at 1.2 GHz. In comparison with similar architectures, the proposed rectenna maintains a stable output efficiency despite the wide fluctuations in the input frequency and also has a minimum footprint size (58 $\times$ 55 mm²).

5.1 Introduction

Nowadays, Wireless Power Transfer (WPT) is among the latest technologies for the implementation of low-power electronic devices specifically for deploying in the Wireless Sensor Networks (WSN). It has numerous wireless applications from RFIDs, wireless sensors, and biomedical devices to wirelessly powered electric vehicles [62]–[64].

Recently, extensive research [65]–[67] has been conducted on developing WPT implementation techniques. Despite these research efforts, WPT devices still face many unsolved problems concerning issues such as power transfer efficiency, threshold sensitivity, and the unpredicted values of the RF power. WPT is classified according to the method of extracting power from the environment, for example near-field electromagnetic radiation, far-field electromagnetic radiation and ambient RF energy harvesting. Each method has its benefits and limitations [68].

The idea of exploiting the surrounded radiated electromagnetic energy as power source for wireless devices is very attractive, mostly due to the widespread propagated energy in the environment. Unfortunately, the received power strength is typically very small and unpredictable.

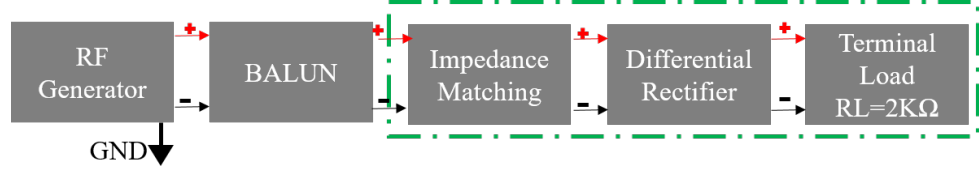


Figure 5.1: Block diagram of the DR architecture

Therefore, it is better to implement a multi-carrier signal reception RF rectifier. Differential output voltage is a crucial for electronic circuit power supply. Therefore, it is important to design a balanced output port using the DR configuration. Advances in integrated RF circuit technology and expansion of differential RF building blocks allow differential architectures to be applied for high-performance receiver designs. Differential based circuit has several benefits over their counterparts(single-ended), for instance it provides a reduced susceptibility to supply noise: a good chunk of supply noise appears as common-mode, so a fully-differential circuit will reject (ignore) it

With the advent of Internet of Things (IoT), many researchers are currently focused on the challenging task of recharging ubiquitous devices and machines wirelessly to allow truly perpetual wireless-powered communication. The RF rectifier design is the most important stage for efficient energy harvesting system performance. The rectifier topologies have been introduced in literature [69]– [71].

Several solutions were adopted for energy harvesting to overcome the intercepted received power limitations. In [72], authors present a steady-state model rectifier with high conversion efficiency for an electronic product-code Gen2-compatible RFID tag. A two DR at GSM 1800MHz was introduced in [73], it improves the overall circuit RF-DC efficiency by suppressing the odd harmonics with the using of radial stubs in series prior to the output. A quasi-isotropic RF rectifier for autonomous long distance IoT operation was suggested in [74]. Despite the previous rectifier circuit development, none of them were able to introduce a full-wave DR with considerable high efficiency over a wide bandwidth and compact size. A detailed mathematical analysis of the proposed balanced rectifier using the Ritz-Galerkin method has been introduced in [75].

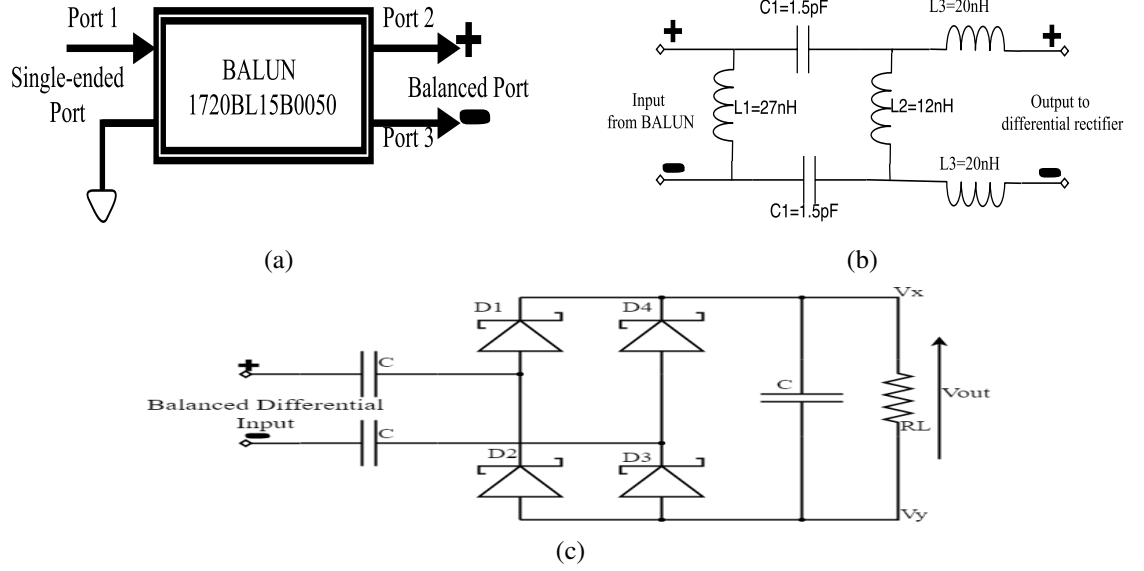


Figure 5.2: Block diagram of (a) BALUN, (b) Matching network, (c) DR circuit

5.2 Differential Circuit Configuration

The proposed circuit is composed of various building blocks as shown in Fig. 5.1. The function of each element will be clearly illustrated in the next subsections. The signal generator is a single-ended RF source which supply the RF input power to the circuit. The BALUN is used for port transformation. The impedance matching network is implemented based on cascaded pair of L-section reactive elements.

5.2.1 BALUN

For valid operation of the DR, a BALUN is used to convert unbalanced input port (RF signal generator) into balanced output port as shown in Fig. 5.2(a). The BALUN ensures 180° phase shift for the input voltage excitation in both branches of the circuit. A BALUN forces an unbalanced transmission line to properly feed a balanced component. The selected BALUN has Operating frequency range $625MHz - 2815MHz$, transformation impedance $50 \rightarrow 50\Omega$, and maximum insertion loss $1.5dB$ [77]. The BALUN performance is characterized using the full-wave S-parameter simulation. The output is a differential signal so the mixed-mode

Table 5.1: Matching Component Values and its Part Number

Component	Initial	Optimized	Part number
L_1 (nH)	27	33	LQG15HH27NG02
C_1 (pF)	1.5	1.5	GCM0334C1E1R5CA01
L_2 (nH)	12	12	LQG15HH12NG02
L_3 (nH)	20	18	LQG15HH18NG02

s-parameter [78] is used for port description.

The simulated mixed-mode s-parameters of the BALUN is derived based on the model available from the manufacturer [77]. The BALUN has insertion loss $1dB$ over the desired bandwidth, these losses were considered during the estimation of the conversion efficiency.

5.2.2 Matching Circuit

Two stages of L-section matching circuit is used as depicted in Fig. 5.2(b). The first stage (L_1, C_1) employs a high-pass frequency for lower-band impedance matching. In contrast, the inductive second stage (L_2, L_3) is assigned for higher-band impedance matching. Both are constructed using chip lumped elements L_1, L_2, L_3 and C_1 . Each series components is halved to meet the balanced conditions of the differential input. The chip elements were provided from Murata electronics manufacturing company. Both value and part number (Murata) is given in Table 6.1.

5.2.3 Differential Rectifier

As given in Fig. 5.2(c), the DR is constructed with a two stages of voltage-doubler configuration [72]. The rectifier is arranged like a full wave AC rectifier, the input capacitor C is used for RF coupling and two-double diode configuration employs for RF-DC conversion. The used diode package is from SKYWORKS and has part number of SMS7630-061. While diodes D1 and D3 are operating together during the positive cycle, D2 and D4 are conducting during the negative cycle. the output capacitor C is acting like low pass filter for reducing the DC voltage ripples. The output voltage appears a the terminal load is measured as $\pm V_{out}$. This

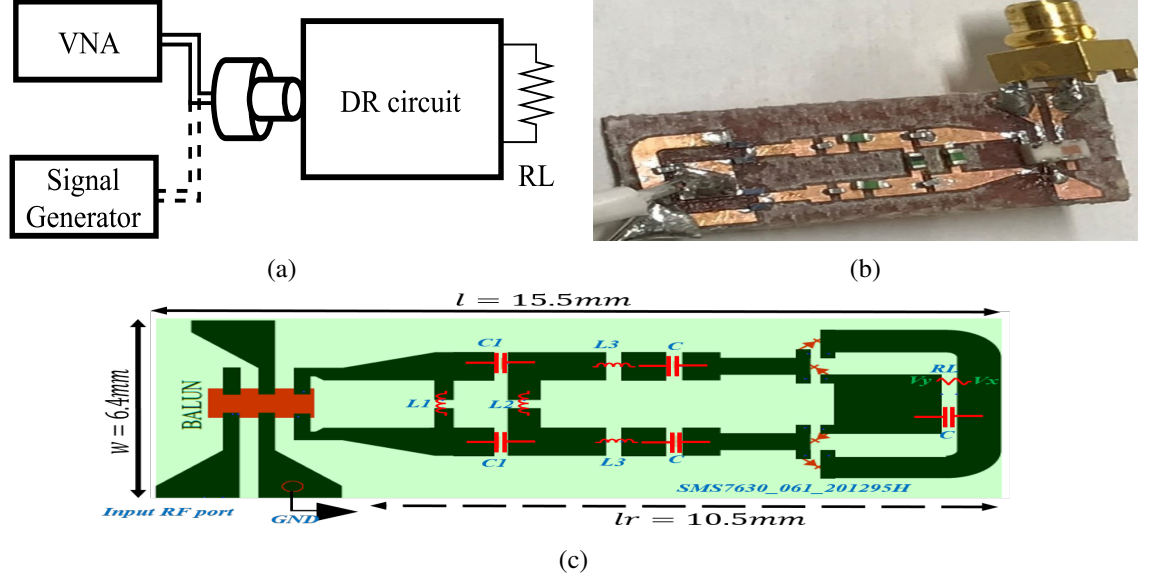


Figure 5.3: The circuit prototype and layout of the DR (a) Measurement setup (b) Fabricated prototype (c) Circuit layout

value represents the balanced output voltage required for electronic equipment biasing.

5.3 Fabrication and Measurement Results

A prototype circuit has been realized on FR4 substrate with the dielectric constant $\epsilon_r = 4.4$ and thickness $h = 0.8mm$ and was fabricated using a milling machine. The total size of the rectifier circuit is $15.5 \times 6.4 mm^2$. The single-ended input port impedance is set to 50Ω , and the impedance transformation is accomplished using the BALUN stated in the previous section. The architecture layout and the fabricated prototype circuit are shown in Fig. 5.3 (a, c). The fabricated prototype has a ground plane shown by the bottom metal layer. The ground (green rectangle) is connected to the excitation RF source. The upper layer (black) represents the transmission line traces connecting all surface mount components. The interfacing cable used for RF-generator connection is a miniature microwave coaxial (MMCX) cable.

We characterized the performance of the rectifier including the BALUN by measuring the output voltage and the overall conversion efficiency at different RF input frequency. Such mea-

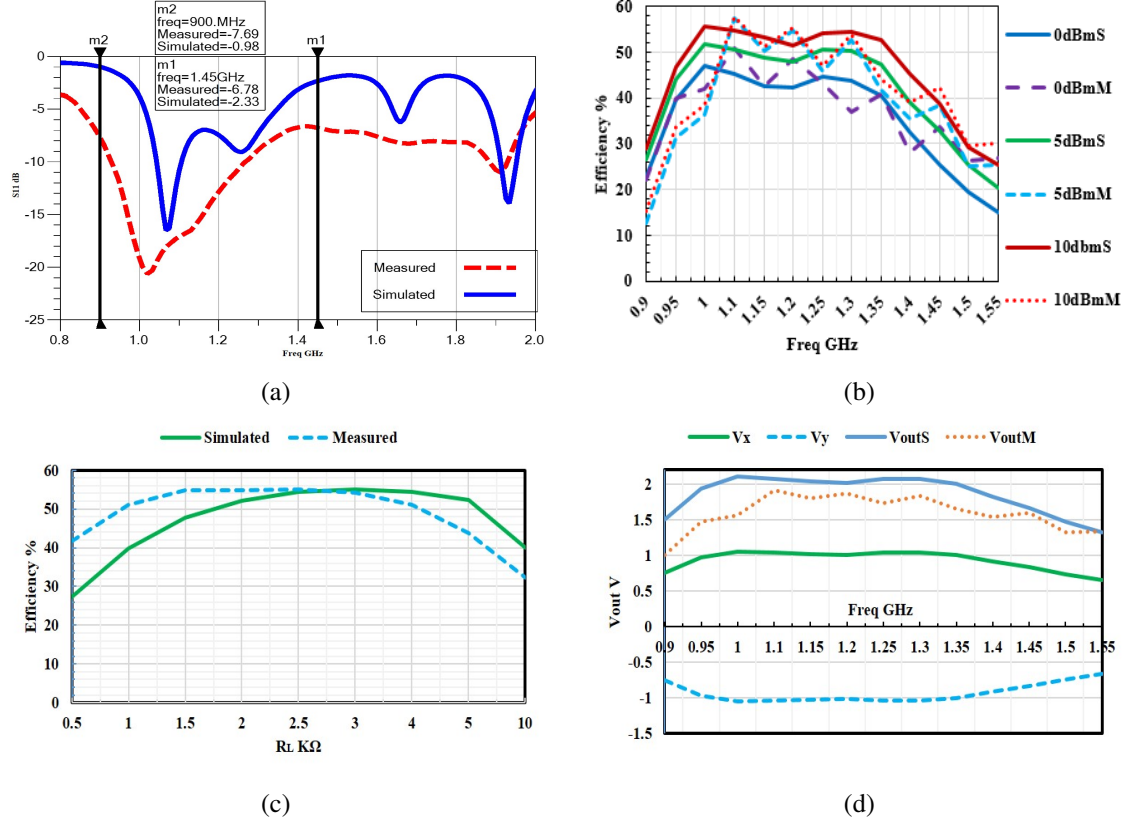


Figure 5.4: Measurement and simulated results.(a) Return Loss S_{11} (b) Efficiency versus frequency at $P_{in} = 0$ dBm , 5 dBm , 10 dBm respectively (c) Variation of the efficiency with R_L (k Ω) (d) Output voltages (V_x , V_y , V_{out}) versus frequency for $P_{in} = 5$ dBm and $R_L = 2$ k Ω .

measurements have required (i) Vector network analyzer for measuring the input reflection coefficient S_{11} . (ii) Function generator port to supply the RF input power for the rectifier over the desired operating frequency band. (iii) Terminal load, $R_L = 2$ k Ω , for measuring the accumulated DC output voltage. Such measurement setup is given in Fig. 5.3 (a).

The measured input reflection coefficient S_{11} is coinciding well with the simulation results as shown in 5.4(a). The bandwidth is marked as the vertical lines (m1 and m2), the measured 6 dB BW is equal to 550 MHz. The BALUN losses (1 dB) were considered during the estimation of the measured efficiency. In Fig. 5.4(b), S:- refers to simulation results and M:- stands for measurement results. Figure 5.4(b) shows the output conversion efficiency over the frequency band 900 MHz to 1.55 GHz at $P_{in} = 5$ dBm. The expected measurement results are in good

agreement with the simulated efficiency obtained from ADS Agilent tools. The peak efficiency 57.5% is achieved at 1.1GHz. The bandwidth is obtained in the vicinity from 0.95 GHz to 1.5 GHz where the efficiency is more than 30%. The changes of efficiency versus output terminal load R_L is given in 5.4(c). As noted, the efficiency could keep unchanged for terminal loads from $1k\Omega$ to $4k\Omega$. The balanced output voltage over the operating frequency is depicted in 5.4(d). The voltages V_x and V_y represent the node voltage at the load terminal. Both has the same value but out of phase. The total output simulated voltage is in good matching with the measured DC voltage.

5.4 Differential Rectenna Design

Many wireless communication systems require antennas to operate across a broad bandwidth. As energy harvesting tends to collect much spectrum power, it is preferable to design a wideband antenna. A broadband antenna usually requires a structure that does not have abrupt changes in the geometry but instead have a smooth geometry [82]. In this section, we are going to focus on the design of the ASDA and its feeding topology. The feeding architecture is implemented using a wideband-tapered microstrip BALUN microwave component.

5.4.1 BALUN Design

A wideband transition from the coaxial line to the parallel strip line is designed to feed the antenna. In practical applications, low-profile spiral antennas suffer from the lack of suitable feeding methods. A vertical BALUN is the most used technique for improving the matching of the antenna input impedance to an excitation source impedance of 50Ω . The BALUN was designed by using electro-magnetic (EM) simulator (ADS, Keysight).

An integrated BALUN is a microstrip-tapered transmission line [83], as shown in Fig. 5.5a. The impedance transformation is performed by a step decay in the transmission line width from the source (50Ω) to the load (140Ω). The 140Ω -impedance represents the input real resistance of the ASDA.

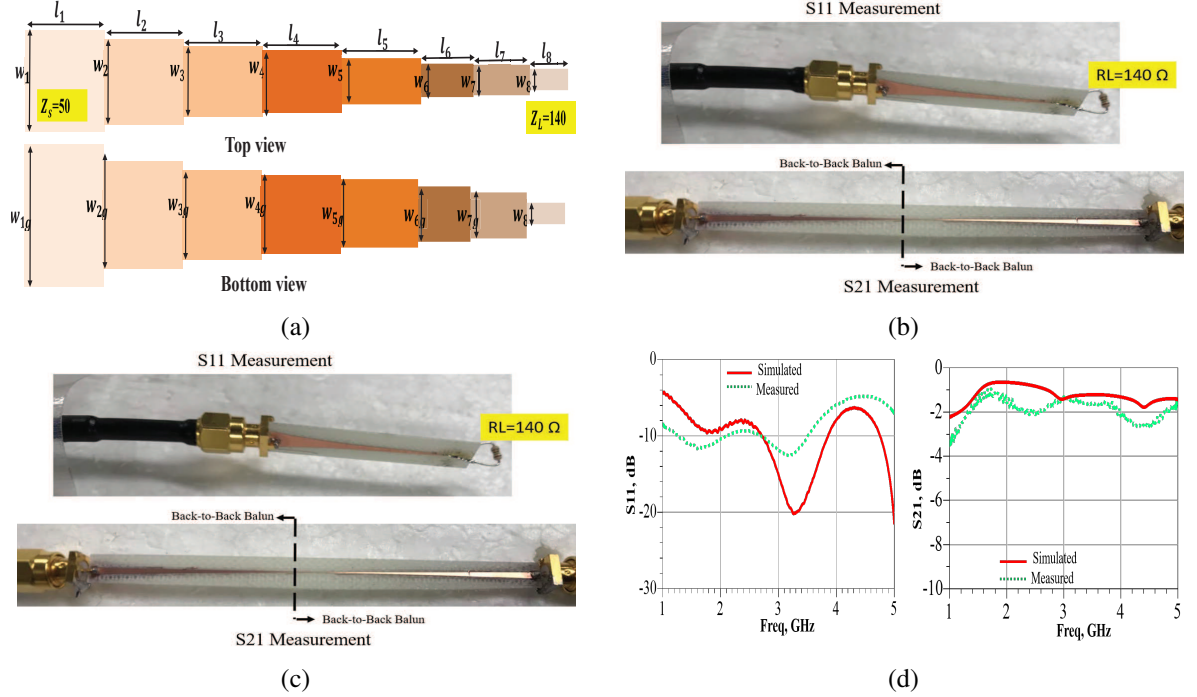


Figure 5.5: Fabricated balun layout and the measurement set-up for the performance characterization. (a) Photograph of the top and bottom view of the Balun layout, (b) Measurement set-up for S_{11} and S_{21} , (c) Comparison between the measured and simulated data.

The experimental measurement set-up is demonstrated in Fig. 5.5b. For S_{11} evaluation, a single BALUN is terminated with 140Ω and its port is connected to a coaxial cable (50Ω). Then, a single-port measurement is computed. The insertion loss measurement is slightly different owing to the requirement of a two-port calibration. Consequently, another BALUN is connected back-to-back to constitute a balanced two-port network. The resultant BALUN is connected with a $50\text{-}\Omega$ -coaxial cable from each side. The S_{11} - S_{21} simulation and measurement comparison are plotted in Fig. 5.5c. From the figure, it is noticed that the BALUN is well matched from 1.2 to 5 GHz with S_{11} less than -10 dB. The measured S_{21} curve has a difference of approximately -0.3 dB from the simulated curve, and this is caused by the additional connected BALUN. Generally, the BALUN frequency response is adequate for appropriate feeding of a spiral antenna.

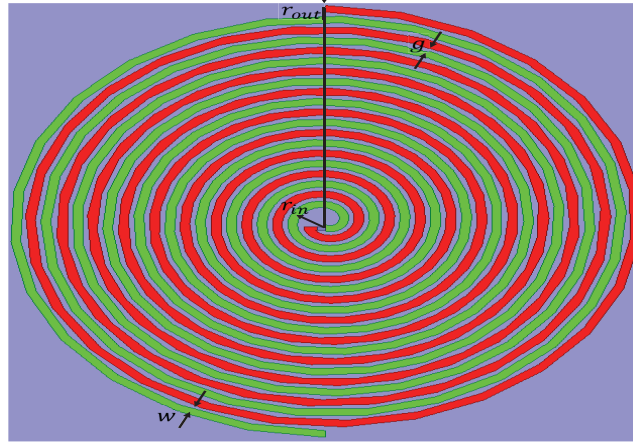


Figure 5.6: Layout of the antenna structure.

5.4.2 Archimedean Spiral Antenna Design

A two-arm Archimedean spiral antenna can be considered as a dipole, the arms of which are wrapped into the shape of an Archimedean spiral (Fig. 5.6). An Archimedean antenna is a planar broadband-frequency-independent antenna structure and constructed easily using printed circuit-board techniques. The antenna is based on the classical geometry equation that describes the Archimedean structure [84] and is given by,

$$\begin{aligned} r &= r_o \times \phi + r_{in} \\ r &= r_o \times (\phi - \pi) + r_{in} \end{aligned} \quad (5.1)$$

Each arm of the ASDA is linearly proportional to angle ϕ and has a proportionality factor (defined the flare-out angle), the flare ratio r_o is given by

$$r_o = \frac{g + w}{\pi}, \quad (5.2)$$

where g is the inter-spacing between adjacent lines, and w is the strip width. The r_{in} is the inner radius of the spiral antenna.

The antenna geometry is determined based on the lower- and higher-band frequency bound-

Table 5.2: Spiral antenna parameters.

Antenna Param.				Balun Param.			
Param.	Value	Param.	Value	Param.	Value	Param.	Value
f_U	10	w_1	2	w_{1g}	5	l_1	4
f_L	0.8	w_2	1.3	w_{2g}	3.5	l_2	8
r_{in}	3	w_3	1.1	w_{3g}	2	l_3	4
r_{out}	28	w_4	0.9	w_{4g}	1.5	l_4	10
g	0.65	w_5	0.8	w_{5g}	1	l_5	5
w	1	w_6	0.7	w_{6g}	0.8	l_6	5
r_o	0.64	w_7	0.5	w_{7g}	0.7	l_7	5
		w_8	0.4	w_{8g}	0.4	l_8	5

All units are given in mm except f_U and f_L in GHz.

aries. The antenna radiates from an active region where the circumference of the spiral equals one wavelength. Each arm of the spiral is constituted, based on (5.1), 180 out of phase, so that the currents at complementary or opposite points on each arm of the spiral add in phase in the far field when the circumference of the spiral is one wavelength. The low- and high-frequency operating points are determined theoretically by the outer and inner radius, respectively (given in (5.3)). In practice, the low-frequency point is slightly shifted from the value predicted by (5.3) owing to the reflections from the end of the spiral. Moreover, the high-frequency limit is less than what can be found by using (5.3) owing to the feed region effects [85].

$$\begin{aligned}
 r_{out} &= \frac{c_o}{2 \times \pi \times f_H \times \sqrt{\varepsilon_{eff}}} \\
 r_{in} &= \frac{c_o}{2 \times \pi \times f_L \times \sqrt{\varepsilon_{eff}}}
 \end{aligned} \tag{5.3}$$

In (5.3), c_o represents the speed of the electromagnetic signal in free space and is equal 3×10^8 m/s, and ε_{eff} is the effective dielectric constant of the substrate. The dimensions of the antenna geometry are listed in Table 5.2, with total number of turns = 17.

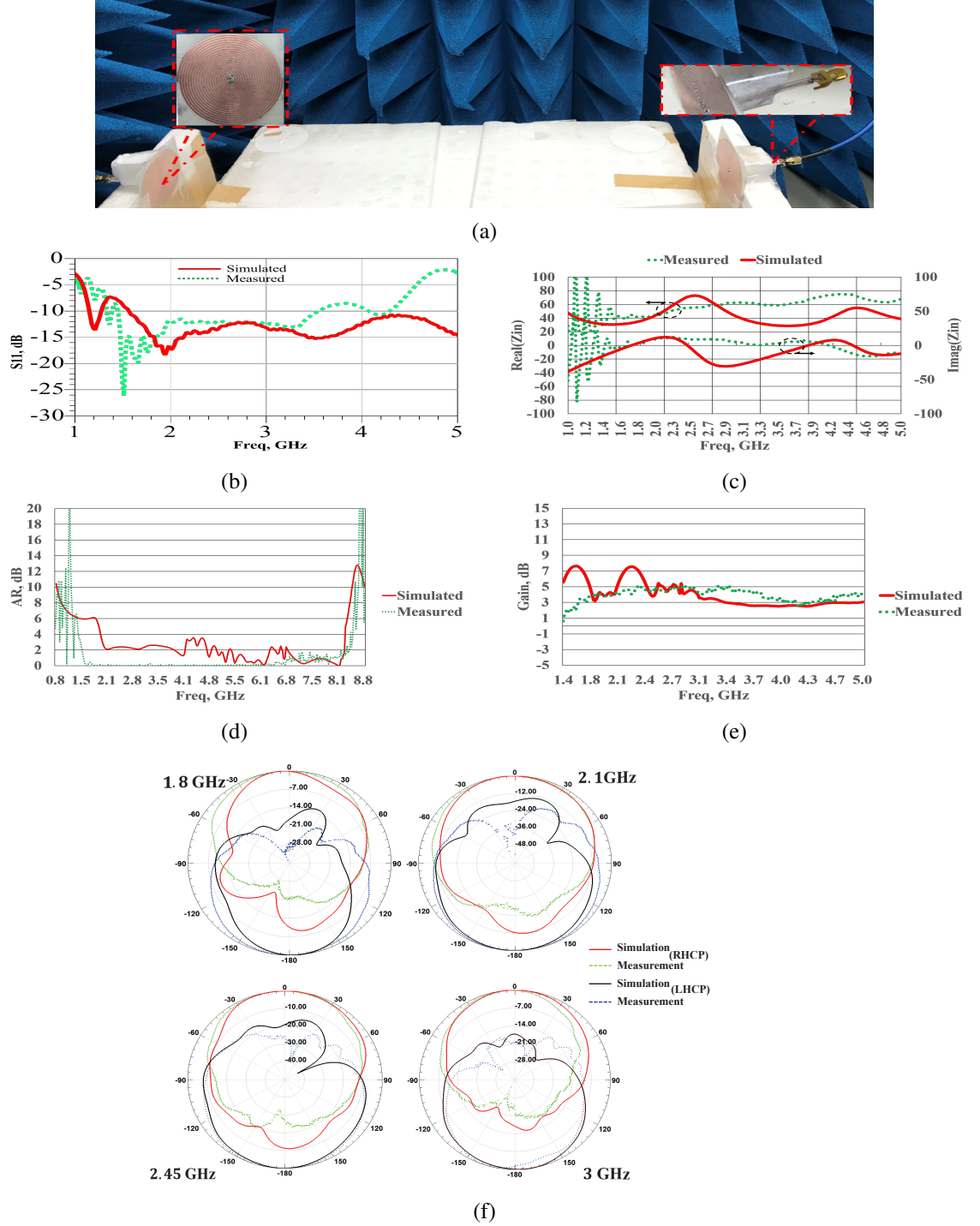


Figure 5.7: Antenna simulation and measurement performance characteristics, (a) Measurement set-up, (b) Input reflection coefficient S_{11} , (c) Impedance matching, Z_{in} , (d) Axial ratio AR, (e) Realized gain, and (f) E-plane radiation pattern.

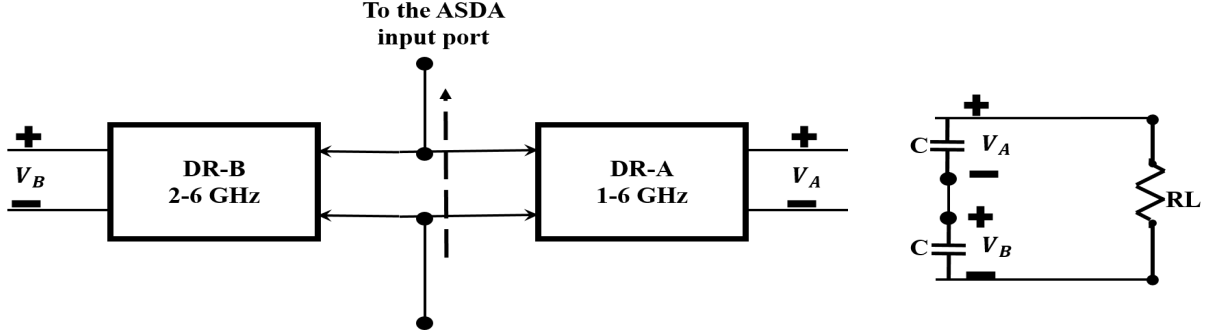


Figure 5.8: (Left) Block diagram of the two DRs adopted for the maximization of the rectifier operating frequency bandwidth. (right) Timing of V_A and V_B for the connection of the terminal load.

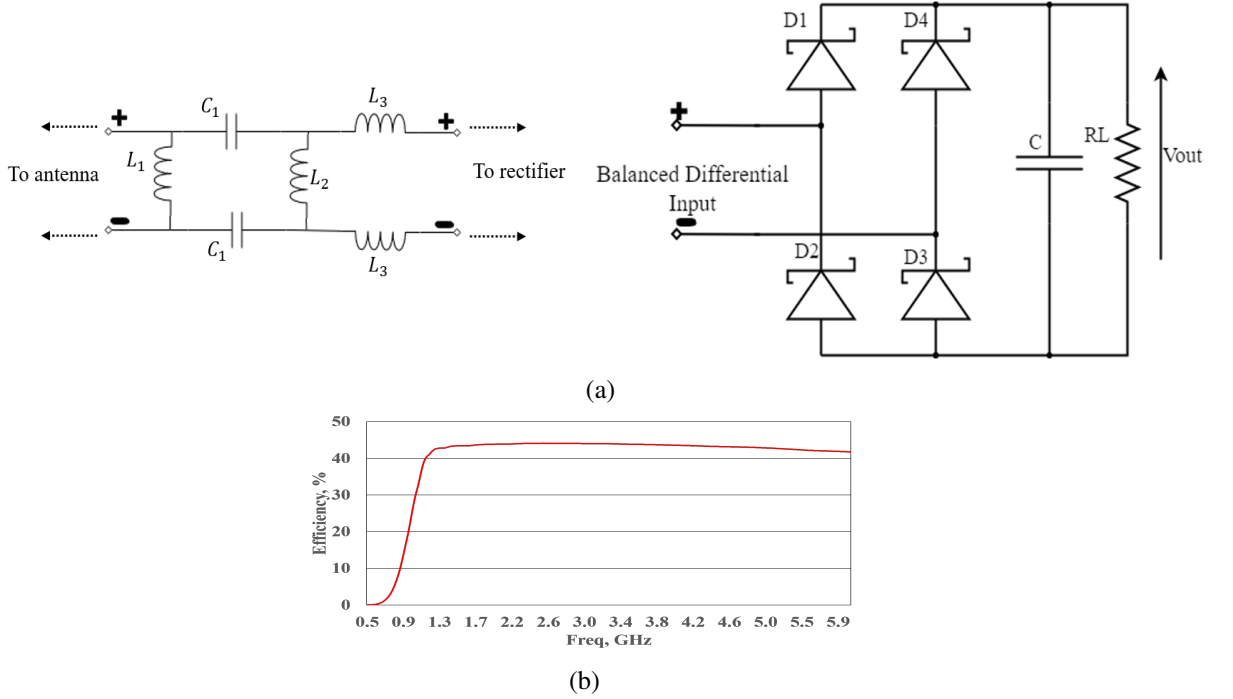


Figure 5.9: Balanced differential rectifier. The configuration and the simulation performance of the dual rectifier (a) Block diagram of right and left rectifier, (b) Efficiency versus frequency simulation response.

5.4.3 Antenna Experimental Results

The ASDA is fabricated on a commercial low-cost substrate with relative dielectric constant $\epsilon_r = 4.4$, loss tangent 0.02, and thickness 0.8 mm. The proposed antenna has a compact size of $58 \times 55 \times 0.8 \text{ mm}^3$. Both the simulation and measurement results are presented, demonstrating

the UWB characteristics of the proposed antenna for wireless communication applications. A prototype of the proposed antenna is fabricated and tested. The antenna measurement set-up is given in Fig. 5.7a. The measurement is performed inside the anechoic chamber.

The simulated and measured reflection coefficients and the matching impedance are shown in Fig. 5.7b, d. The overall -10 dB impedance band is from 1 to 5 GHz and above. It can be observed that the input impedance has real value 50Ω and an imaginary part of approximately 0Ω . Thus, it indicates a well impedance matching condition to the coaxial input port.

Fig. 5.7d displays the simulated and measured axial ratio results of the antenna. It is noted that from 1.5 to 8.5 GHz, the antenna axial ratio is below 1 dB, and this implies that the cross-polarization ratio is below -30 dB. The gain versus frequency variation is illustrated in Fig. 5.7e. It has an average value of 4.5 dBi with a maximum measured value of 5 dBi. The gain deteriorates at frequencies above 5 GHz owing to the mismatch with BALUN. Fig. 5.7f shows the normalized radiation patterns of the antenna. Good right-handed circular polarization (RHCP) and left-handed circular polarization (LHCP) patterns with low cross polarization are obtained. The simulated and measured results are in good agreement. The radiation patterns are plotted at different in-band frequencies, namely, 1.8, 2.1, 2.45, and 3 GHz.

5.5 DR Design

Because the diode nonlinearity, input power levels, input signal frequency, and output load resistance are leading to performance degradation of the rectifier over a wide operating frequency band, a pair of DRs (DR-A and DR-B) is used for maximizing the operating bandwidth as shown in Fig. 5.8. The most common rectifier structure used for energy harvesting applications is the voltage doubler. Although this topology offers twice the input voltage, it does not provide a balanced output voltage. Therefore, this architecture is modified to realize a DR as shown in Fig. 5.9. The closed-form mathematical equation of the DR was accurately deduced and analyzed in [75]. This circuit is composed of four diodes (D1, D2, D3, and D4), and each pair is conducting during one half cycle of the input signal. While diodes D1 and D3 are

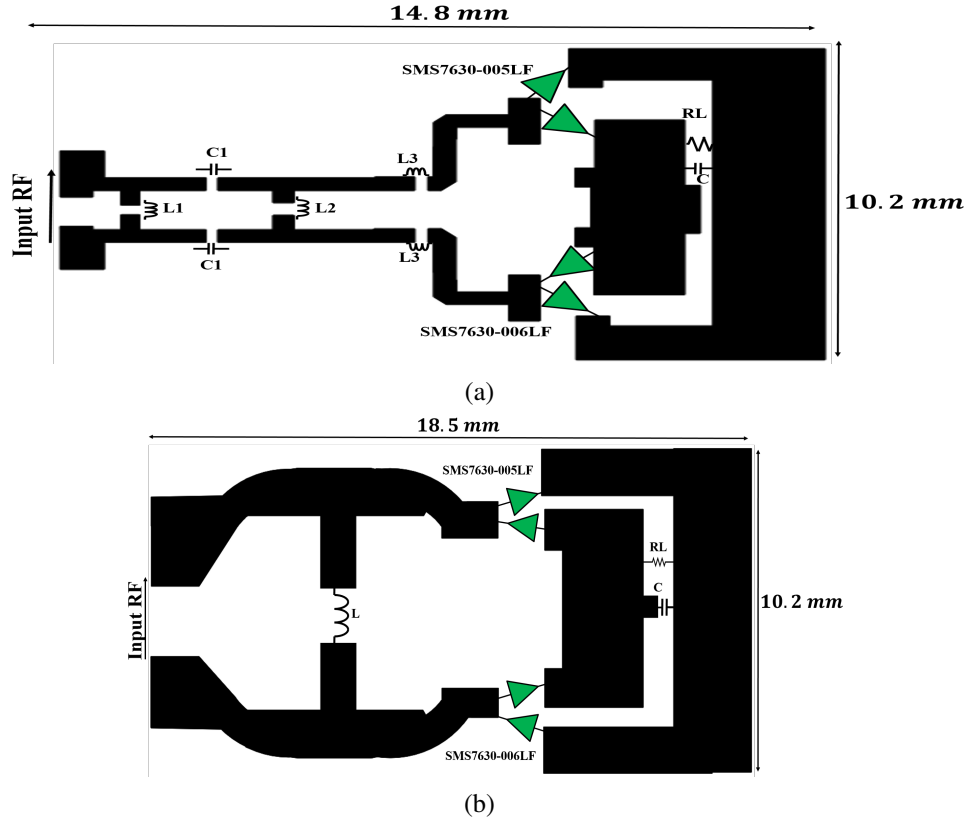


Figure 5.10: Topology of both the DR-A and DR-B rectifier circuits. (a) Layout of rectifier DR-A, (b) Layout of rectifier DR-B.

conducting during the positive half cycle of the input signal, diodes D2 and D4 are conducting during the negative half cycle. The pumped voltage is stored in output capacitor C, with the load connected across it. The Skyworks SMS7630 Schottky diode is used, and the package parasitics are considered during the simulation. A parasitic inductance value of $L_p = 1.15$ nH and parasitic capacitance value of $C_p = 0.25$ pF provided by the manufacturer are added to the design schematic.

To achieve a broad bandwidth, two DRs are linked together. They are designated as DR-A and DR-B, as shown in Fig. 5.10. DR-A is designed to operate across the band from 1–6 GHz. DR-A is manufactured using lumped elements L1, L2, L3, and C1, purchased from Murata Manufacturing Co. Ltd., and connected to two cascaded L-sections to provide broadband

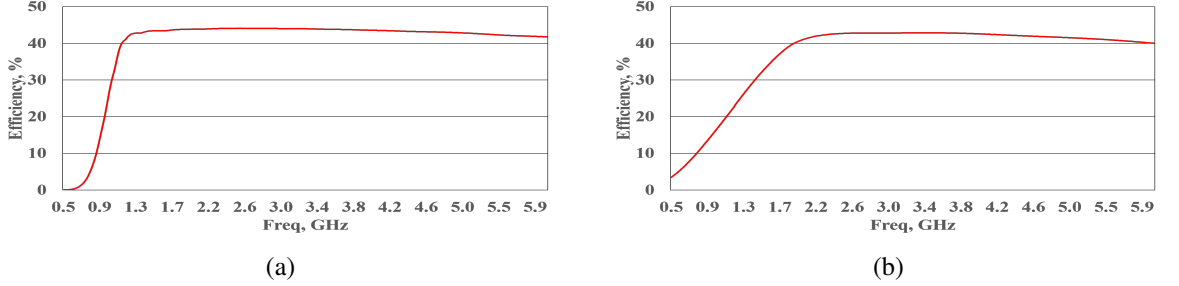


Figure 5.11: Harmonic balance simulation performance of the DR-A and DR-B rectifiers (a) DR-A response, (b) DR-B response. Both simulations were conducted at $P_{in} = 9$ dBm and $R_L = 1$ k Ω .

Table 5.3: List of the DR-A and DR-B parameters.

Param.	L1	L2	L3	C1	L	C
Value.	33 nH	18 nH	2.7 nH	1 pF	17 nH	100 pF

impedance matching. The value parameters (presented in Table 5.3) are obtained following a thorough optimization using the nonlinear harmonic balance simulation in the Agilent, ADS software. The input impedance of each rectifier is set as the ASDA input impedance Z_{in} . This impedance is obtained from the electromagnetic HFSS simulation of the ASDA without considering the BALUN connection. Z_{in} is exported from the HFSS and introduced as the input port impedance of the rectifier circuit. The simulated rectifier performance of DR-A is exhibited in Fig. 5.11a. As noted from the figure, DR-A has 40% conversion efficiency over the band from 0.95–6 GHz. These results are obtained at $P_{in} = 9$ dBm and $R_L = 1$ k Ω .

In comparison, DR-B is implemented using a single lumped element, L, connected in parallel to the DR circuit. This inductor offers good input matching characteristics from 2–6 GHz, as shown in Fig. 5.11b, with more than 40% RF-DC conversion efficiency. The total output DC voltage obtained from both the schemes is given by,

$$V_{dc} = V_A + V_B \quad (5.4)$$

where V_A and V_B are the balanced output voltages of DR-A and DR-B, respectively.

5.6 Experimental Measurement Results

The rectenna is built on a double layer FR4 substrate with thickness $h = 0.8$ mm and dielectric constant $\varepsilon_r = 4.4$ by using the print broad making equipment (MITS; FP-21T model 40).

The rectenna prototype is displayed in Fig. 5.12a. The conventional definition of the RF-DC conversion efficiency is the ratio of the amount of DC power at load P_{dc} to RF input power collected by the antenna P_{rf} , and is given by,

$$\eta = \frac{P_{dc}}{P_{rf}} = \frac{V_{dc}^2}{R_L \times P_{rf}} \quad (5.5)$$

The measurements were performed to satisfy the far-field conditions. They were made with variation in the transmitted power and frequency, so that the received incident power changed according to the transmitted signal frequency, with the free-space losses being frequency dependent. The absorbed received input power was estimated using an antenna connected to a signal network analyzer. The measurement set-up is presented in Fig. 5.12b. The measurements were done inside an anechoic chamber represented by the triangles on the side walls. The power transmitter is emitting power into space with RF-power value of P_{in} . At the receiver side, we employed an antenna to measure the received power P_{rf} and at the same time the rectenna is mounted on the same reception plane. The output characteristics of the rectenna is measured using a voltmeter. The rectenna output performance is calculated using (5.5), and the efficiency for different constraints is plotted in Fig. 5.13. The response of the rectenna conversion efficiency with frequency is shown in Fig. 5.13a. From the data shown, it is obvious that the results obtained from the measurements and EM model are in good agreement over the desired band with a maximum simulated efficiency at frequency 2 GHz. The measured efficiency is still more than 30% over the band of interest (1.2 to 5 GHz) and slightly reduced relative to the simulation results. The slight reduction in the measured efficiency for the higher frequencies inside the operating band is due to the resultant mismatching in the rectifier circuit at those frequencies. Indeed, the results deviation is coming from the inaccurate diode modeling over the suggested

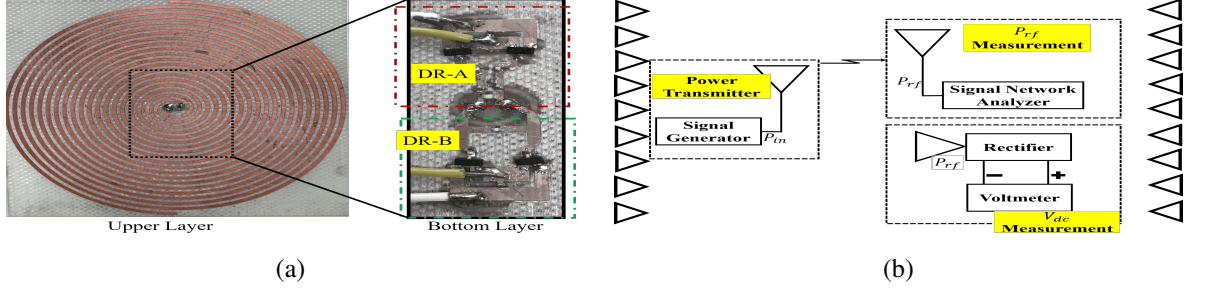


Figure 5.12: Photograph of the fabricated rectenna prototype and measurement setup, (a) Rectenna prototype showing both the upper layer (antenna) and bottom layer (rectifier); the rectifier is combined with two circuits DR-A and DR-B. (b) Measurement set-up with an antenna to determine the expected received power.

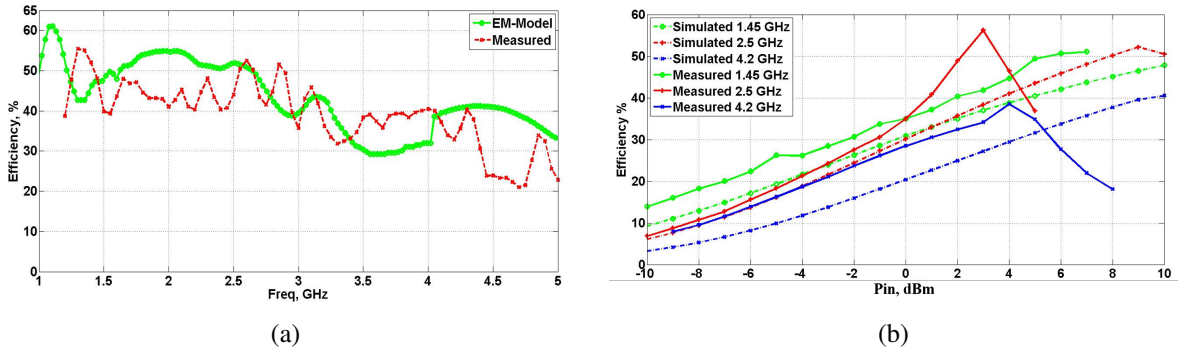


Figure 5.13: Rectenna measurement and simulated results. (a) Efficiency versus frequency at simulated $P_{in}=9\text{dBm}$, $R_L = 1 \text{ k}\Omega$. (b) Efficiency versus input power for $R_L=1 \text{ k}\Omega$ and at different input frequencies.

wideband of frequencies. To precisely model the diode over that broadband frequency, a circuit should be fabricated separately with only the diode and measure the real S-parameters along the desired band and then consider it during the simulation. Although such method is accurate, it would be time-consuming. In the manuscript, I supposed the model introduced in the datasheet. The efficiency versus input power is exhibited in Fig. 5.13b. The curve is plotted at various input frequencies and fixed output load $R_L = 1 \text{ k}\Omega$.

To fulfill the impact and contribution of the proposed rectenna design, a detailed comparison with state-of-the-art literature that discussed similar performance is presented in Table 5.4. The selected parameters for comparison are frequency bandwidth f , incident input power P_{rf} , achieved RF-DC conversion efficiency η , polarization type, circuit size, and the substrate used for the rectenna fabrication. In comparison with similar rectifiers, the rectenna presented in this

Table 5.4: Comparison of this study with the relevant research reported in the literature.

REF	f , GHz	P_{rf}	η , %	Polarization	Size, mm ²	Substrate
[79]	2–18	1–100 $\mu\text{W}/\text{cm}^2$	N/A	Dual CP	2800 $\times$ 2200	RO3850
[80]	0.25–3	10dBm	33%	No antenna	150 $\times$ 10	Kapton
[81]	1–3.2	15dBm	> 50%	N/A	228.6 $\times$ 304.8	RO4003C
This work	1–5	9dBm	> 30%	Dual CP	58 $\times$ 55	FR4

paper achieves a very compact size that facilitate the integration with wireless sensor nodes. As an example, the current design provides a much reduced size than the circuit and rectenna presented in refernces [79]– [81], respectively. Moreover, the proposed topology can offer a balanced output voltage suitable for supplying the integrated electronic circuit.

5.7 Conclusions

This chapter presented several broadband RF energy harvester circuits that exhibit efficient power conversion over the entire band from 1.2 to 5 GHz and has a simple two-layer design. First, a new DR architecture composed of a pair of voltage double stages has been suggested. The proposed configuration can supply a balanced output voltage ($\pm V_{out}$) which is a demand for electronic devices. The main achievement of the proposed design is compactness and the wide-band feature. As mentioned in the paper, the DR performance has been well characterized over the operating frequency band. The measurement and simulation results were agreeing well over the operating bandwidth. The peak efficiency is achieved at 1.1GHz. The compactness of this work could be integrated with a low-profile antenna to realize the entire wireless energy harvesting system.

Furthermore, the operating principles of the spiral antenna, rectifier, and matching network were presented in detail. The complete rectenna prototype was fabricated and tested by radiated measurements. More than 30% power conversion efficiency was measured across the desired frequency band, which represented the combined efficiency of the receiving antenna, impedance matching, and conversion by the rectifier into DC power at the load. Compared with a typical

rectifier topology, the proposed DR exhibited improved RF-DC conversion efficiency, compact size, wider frequency range, and reduced sensitivity to the input received frequency. Further improvements in the rectenna could be realized by integrating the rectifier and antenna on the same metal plane. This could be obtained by the optimum design (strictly defining the minimum and maximum operating frequencies) of the antenna to save space for mounting the rectifier.

Chapter 6

CMOS RF Rectifier Design

Wireless energy harvesting has promised to completely change the conventional wired technology for powering the wireless sensor nodes. In the current study, we introduce a high efficient, wideband, and compact RF rectifier for batteryless wireless communication applications. We propose an improved energy harvester which maximizes the efficiency over a wide input frequency range. The proposed design relies on integrating a differential broadband matching circuit with a CMOS rectifier. In order to widen the operational bandwidth of the cross coupled CMOS rectifier architecture, T-Matching circuit composed of inductive and capacitive elements is suggested. The rectifier along with the matching circuit is fabricated using the standard 180-nm CMOS technology. The proposed design was analyzed, simulated, measured. The functionality of the rectifier design, which operates from 1.8 to 4.2 GHz, is studied through simulation in Agilent, ADS and implementation using Cadence, Virtuoso. The simulation and measurement results reveal that the harvester could provide a 2.1 VDC with 5 dBm input power and the efficiency is maintained above 30% over the frequency band of interest. The peak efficiency obtained from the rectifier architecture is 51% at excitation frequency 2.6 GHz, input power 5 dBm and a terminal load of 3.5 k Ω .

6.1 Introduction

RF power can simply be delivered to the targeted applications when required using a huge RF transmitter. There are a multitude of wireless services that radiating RF signals into the environment in the vicinity above 1.8 GHz range. These signals could be intercepted by an antenna and feed to an RF rectifier for DC energy conversion. The targeted frequency range is starting from 1.8 to 4.2 GHz, which include dozens of wireless communication applications, for instance, GSM1800, GSM1900, UMTS 2100, WiFi, ISM 2450, LTE 2600, Satellite communication, WiMAX, WiLAN, and many other services. Small input power level to the rectifier means slight input voltage amplitude across the integrated switching devices (diodes or MOS transistors). When the amplitude becomes so small, below the transistor threshold, the rectifier will unable to convert the RF input into DC voltage.

Numerous technical contributions have been reported to suppress the MOS transistors threshold voltage of the rectifier [86]– [88]. In the same manner, in order to increase the received power and to extend the operational bandwidth CMOS rectifier, several impedance matching circuit compensation techniques have been proposed [89]. In this study, the cross coupled differential rectifier configuration (CCDR) connected with a wideband matching circuit is investigated. For proper connection between the rectifier differential input port and the feeding source, a balanced-unbalanced (BALUN) component was inserted for port conversion.

6.2 CMOS Circuit Configuration

Generally, charge pump circuit is capacitor based, where voltage is pumped up at each stage depending on each stage voltage gain. Charge pump circuits are mostly based on Dickson charge pump circuit [90]. Pumping capacitors and diode connected nMOS are major elements of this type of charge pump circuits. Since there are body effect of the nMOS and threshold voltage, the circuit needs to sustain large voltage loss, which leads to low voltage gain per stage. To develop higher pumping efficiency, a CCDR [91] rectifier is proposed to reduce the threshold voltage and leakage current simultaneously. In the following sections, CMOS topology and

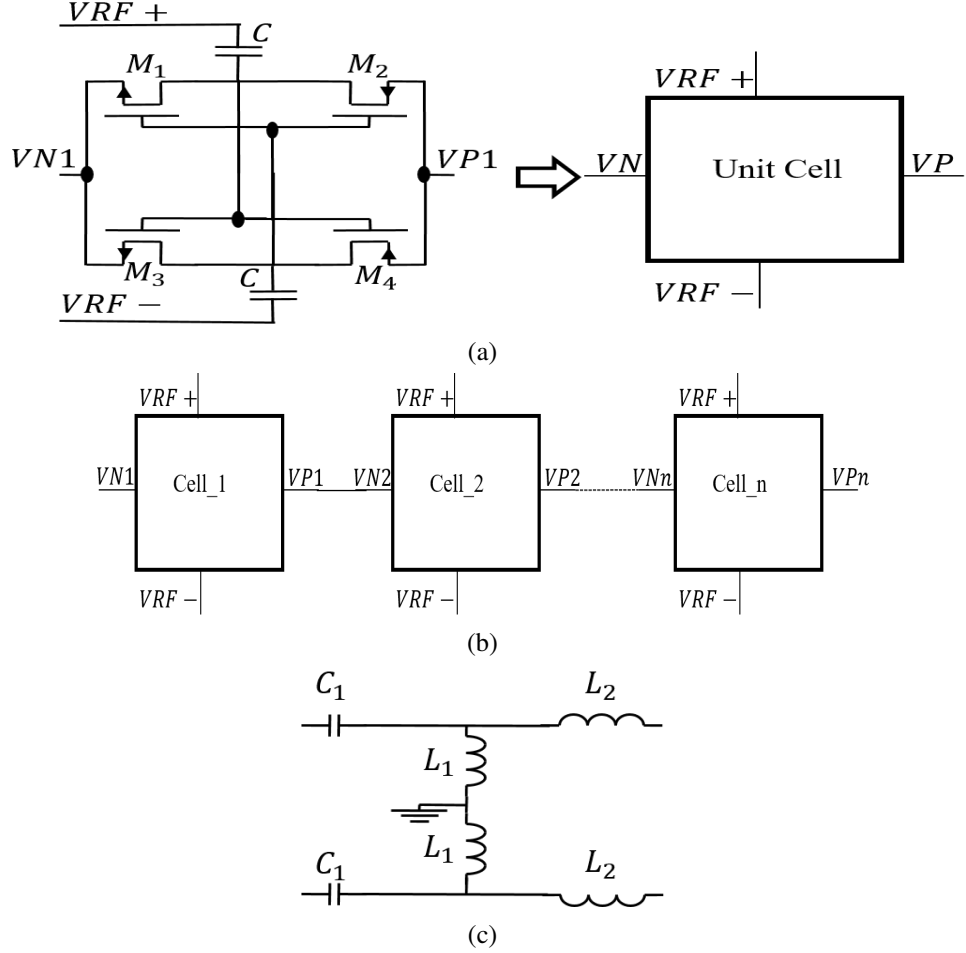


Figure 6.1: CMOS rectifier architecture based on cross-coupled dual transistor (a) Unit cell composed of two NMOS (M1, M3) and two PMOS (M2, M4) transistors, (b) Multistage CMOS rectifier configuration, (c) T matching circuit comprising a balanced connection.

BALUN performance will be explained.

6.2.1 CMOS Circuit Design

Instead of using the discrete Schottky diodes, CMOS compatible MOSFET diodes with zero threshold voltage V_{TH} , were employed. However, using the low V_{TH} transistors resulted in an inferior performance, because the trans-conductance of the MOS transistors in the sub-threshold region is less than that of a diode. The detailed analysis and design strategy for a rectifier with

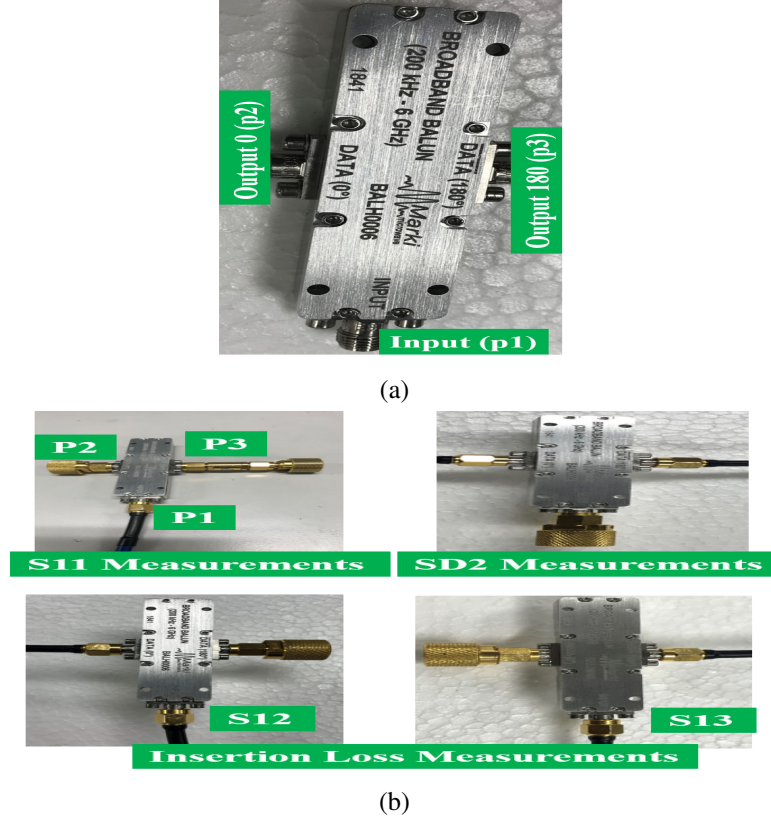


Figure 6.2: Photograph of the broadband BALUN and the measurement setup characterization (a) BALH0006 component, (b) characterization of the BALUN performance using 2-port VNA analyzer.

zero V_{TH} MOS diodes were introduced in [93]. The DDCC transistor architecture can correct the voltage drop using a transistor as a switch instead of diode. The structure is depicted in Fig. 6.1(a) and composed by four MOSFETs (two nMOS, M1, M3 and two pMOS, M2, M4) and two capacitors in each stage. The typical connection of the multistage CMOS rectifier is given in Fig.6.1(b). In this study, two stages of the rectifier were selected. The impedance matching circuit is constituted by a T-topology. In order to fulfill the balanced connection, each component is halved into two sections. The optimized component's value of the matching circuit is $L_1=3.47$ nH, $C_1=0.45$ pF, and $L_2=5.5$ nH. They were realized using the standard 180-nm CMOS technology.

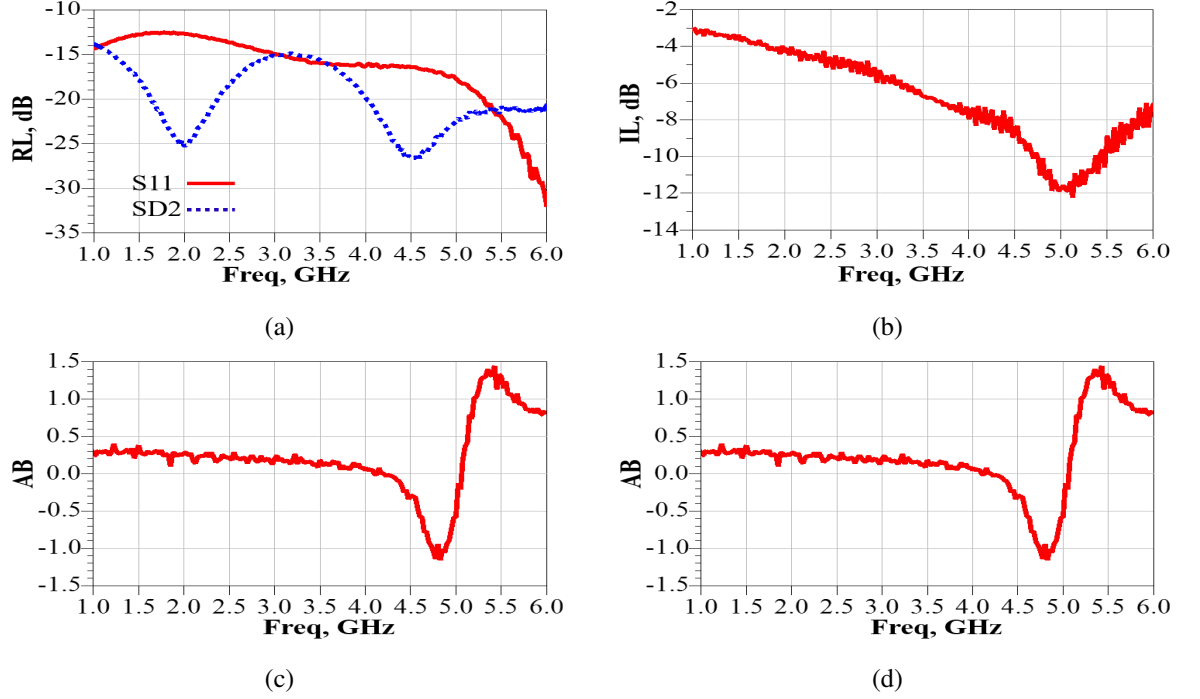


Figure 6.3: Measurement results of the BALUN (a) Return loss at both the unbalanced port, S11, and the balanced port, SD2, (b) Insertion loss of the signal transmission between the unbalanced port (P1) and the balanced port (P2, P3), (c) The amplitude balance (AB) between the balanced ports (P2, P3), (d) The phase balance (PB) between the balanced ports (P2, P3).

6.2.2 BALUN

A balun consists of an "unbalanced" port (P1, input) and two "balanced port" (P2 designated as output 0, P3 identified as output 180) as shown in Fig. 6.2(a). The selected BALUN has Operating frequency range from 200 kHz to 6 GHz, transformation impedance $50 \rightarrow 50\Omega$, and maximum insertion loss $8dB$ [92]. The BALUN performance is characterized using the full-wave S-parameter measurements. The procedures for BALUN measurements is given in Fig. 6.2(b). The balanced output two ports (p2, p3) were converted into 1-port unbalanced port (SD2). The measurement results is depicted in Fig. 6.3. Both input and output ports are well matched and the insertion loss is increasing up to -12 dBm along the entire frequency band. The amplitude imbalance (AB) and phase imbalance (PB) are given in Fig. 6.3 (c), (d), respectively.

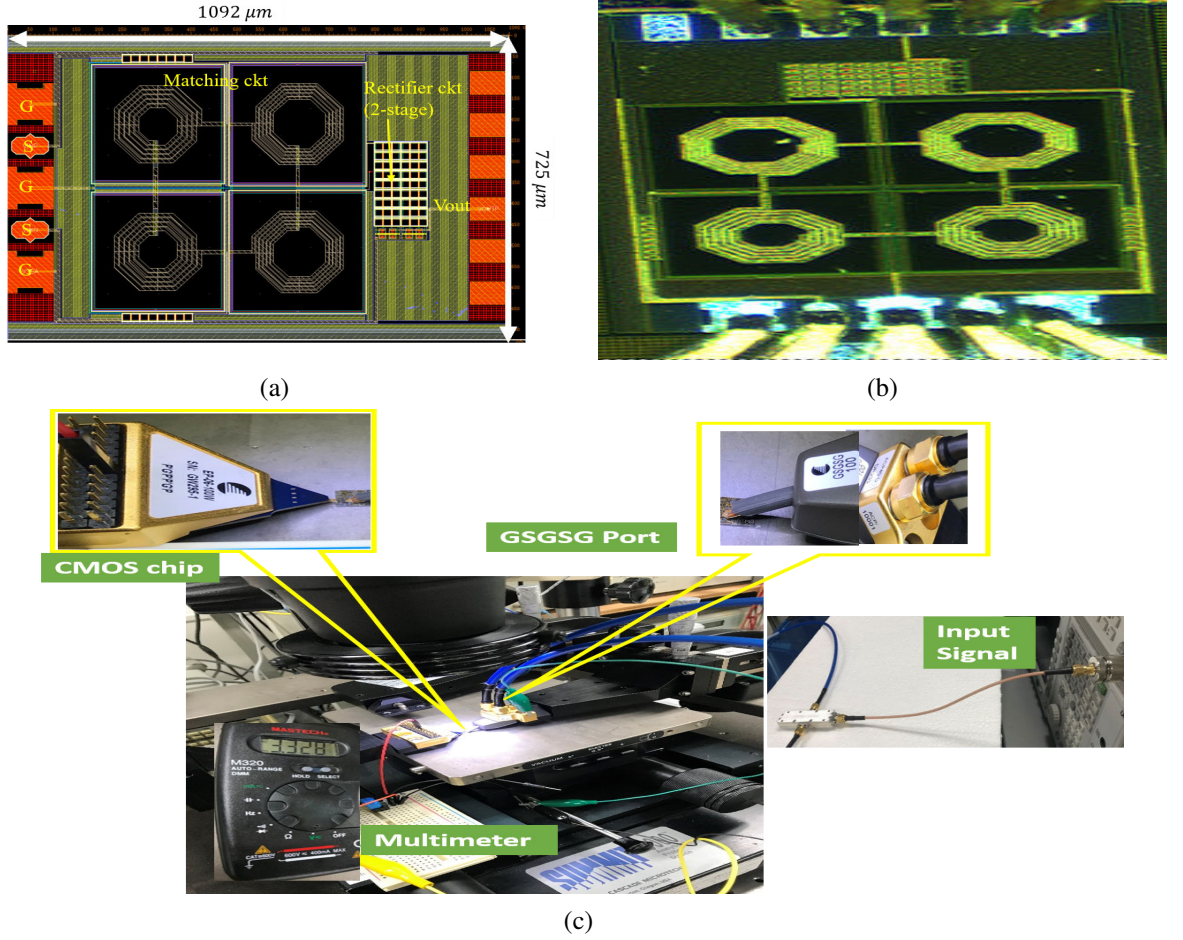


Figure 6.4: The circuit prototype and layout of the fabricated circuit (a) Circuit layout (b) Fabricated prototype (c) Measurement setup.

Table 6.1: Component values of the circuit architecture

Component	Value
L_1	3.47 nH
C_1	450 fF
L_2	5.5 nH

6.3 Fabrication and Measurement Results

A prototype circuit has been realized using 180-nm TSMC technology. The total layout dimensions are $1092\mu\text{m} \times 725\mu\text{m}$ as shown in Fig. 6.4(a). The photograph of the fabricated die

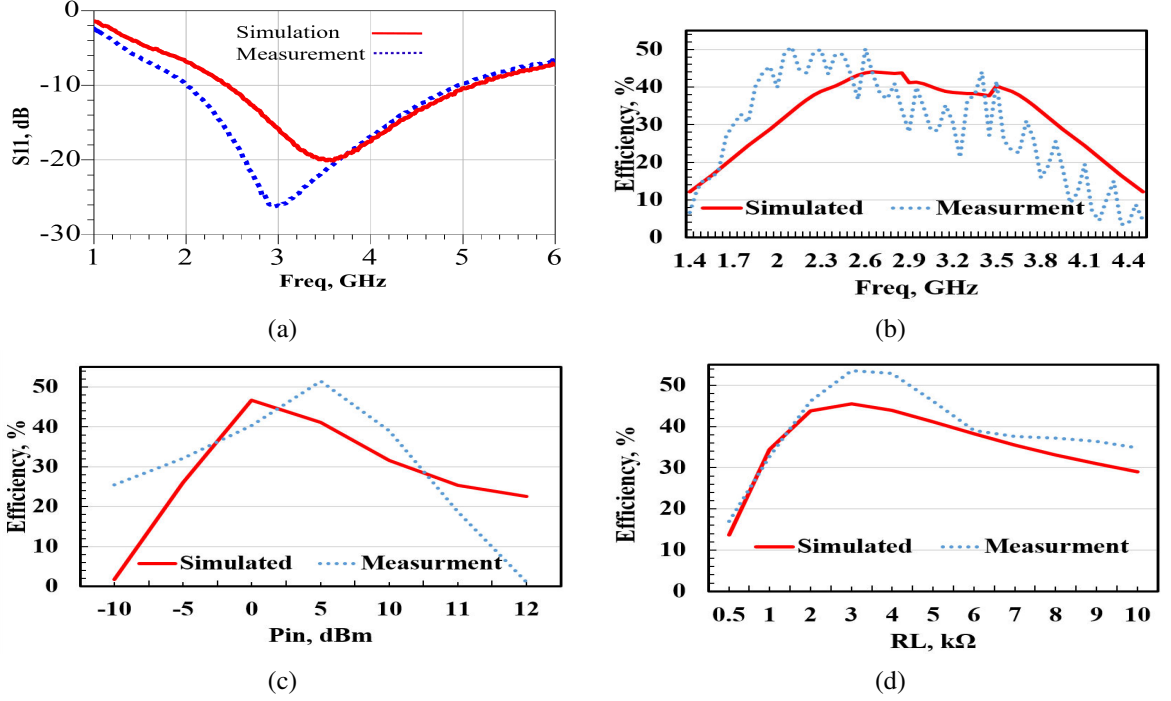


Figure 6.5: Measurement and simulated results.(a) Return Loss S_{11} , (b) Efficiency versus frequency at $P_{in} = 5$ dBm, $R_L = 3.5$ kΩ, (c) Variation of the efficiency with P_{in} at frequency 2.6 GHz, (d) Efficiency versus R_L at $P_{in} = 5$ dBm and frequency 2.6 GHz.

is illustrated in Fig. 6.4(b). The rectifier were designed in a two-stage configuration with total transistor width of $6\mu\text{m}$ and $18\mu\text{m}$ for NMOS and PMOS, respectively. The length of 180 nm is chosen for both transistor types. This aspect ratio approximate the ON-resistances be almost identical. Metal-Insulator-Metal (MIM) type with value 335 fF was selected for coupling and smoothing capacitors.

6.3.1 Measurement Setup

The experimental results were obtained using GSGSG probe and the probe station existing in our laboratory. The experimental setup is shown in Fig. 6.4(c). First, the input reflection coefficient is derived using mixed s-parameter balanced mode. For the correct performance calculation of the S_{11} , the balanced s-parameters were measured and converted into single-ended input port based on the well-known mathematical equations. The input reflection coefficient

of the circuit is depicted in Fig. 6.5(a), It can be observed that both the measurement and the simulation results are consistent. The 10 dBm S11 bandwidth extends from 2 to 5.5 GHz. The rectifier performance is identified by the conversion efficiency, injected input power, excitation frequency, output DC voltage, and the terminal load. Consequently, the study of each parameter on the rectifier performance has been carried out. From the data shown in Fig. 6.5(b), it is observed that the rectifier circuit could maintain a conversion efficiency more than 30% over the band 1.8 to approximately 4.2 GHz. Indeed, a 51% maximum efficiency is obtained at 2.6 GHz. The demonstration of conversion efficiency versus input power for different input signal frequency is given in Fig. 6.5(c). Moreover, the conversion efficiency for different output terminal loads with a fixed input power and frequency is shown in Fig. 6.5(d). From the above illustration, we could conclude that the proposed design is able to feed a constant DC voltage over a wide-spectrum input signal frequency. This serves as a good candidate for mobile wireless communication services existing in the frequency band from 1.8 to 4.5 GHz.

6.4 Conclusion

An enhanced wideband differential CMOS rectifier was proposed. The improved architecture enables the rectifier operation for dynamic range of various signal frequency excitation. The fabricated circuit offers a small footprint and could be integrated with different wireless applications. As mentioned in the paper, the rectifier performance was accurately characterized over the operating band of interest. The measurement and simulation results were agreeing well over the operating bandwidth. The peak efficiency is achieved at 2.6 GHz.

Chapter 7

Experimental Investigation of Wireless Energy Harvesting with a Bluetooth Low Energy Sensing Unit

In this chapter, we introduce an experimental demonstration for wireless energy harvesting application. Bluetooth low energy (BLE) unit connected to an array of sensors is used in conjunction with the proposed RF wireless rectenna. Two applications are proposed, the first application is feeding an array of sensors connected to the BLE unit. In this scenario, the rectenna is composed of a circularly polarized spiral antenna and a microstrip RF voltage doubler rectifier. The scheme shows a constant voltage charge of a super-capacitor (0.1pF) within the voltage limits of optimum BLE operation. The temperature and humidity sensing system was tested in real operation for more than 20 hours. The delivered voltage was maintained over 2.7 V that corresponds to the proper operating voltage of the BLE.

Wireless Body Sensor Network (WBSN) is used for communication of the sensor nodes operating on or inside the human body in order to monitor the human activities. Wearable sensors can monitor and record real-time information about one's physiological condition and motion activities. Wearable sensor-based health monitoring systems may comprise different types of flexible sensors that can be integrated into textile fiber, clothes, and elastic bands or

directly attached to the human body. In this context, wearable technology has been addressed to make humans (his clothes) able to communicate with, and be part of the interconnected network. The proposed rectenna architecture is designed to harvest energy efficiently in the vicinity of low intercepted power around 0dBm . The rectifier is composed of voltage doubler circuit with LC matching circuit. The antenna is commercially available from flexible conductive film, COCOMI[®], Toyobo Co., Ltd. The overall rectifier dimensions are very compact $19.5 \times 9.7\text{mm}^2$. There are a good agreement between the simulation and measurement results. For instance, the peak measured efficiency is 52% at -5dBm RF input power and the corresponding simulated value is 61%. The 63% peak measured efficiency is achieved at 5dBm with a terminal load $5k\Omega$.

7.1 Introduction

There has been an increased demand for wireless sensors for data gathering and transmission where running wires to power a device or changing/recharging batteries is difficult. According to the emerging of Internet of Things (IoT) paradigm, electronic apparatuses will be deployed almost everywhere. The next generation of sensors and circuits will be literally embedded in the items, so their maintenance will be hindered by the fact that they will be difficult to reach or even to localize [94]. This means that the battery replacement will be difficult or even impractical, so, in most of the cases, batteryless devices will be the only option. Intensive industrial and academic activities have been devoted to improving the efficiency performance of energy harvesting (EH) systems. Several techniques and circuit solutions have been concurrently proposed and tested to ensure sufficient and non-intermittent WPT with the lowest possible received power density. For instance, multiband, single band and broadband rectifiers [95]– [96] were adopted for improving the system reliability. The most stringent requirement of the rectifier is the compactness to be easily integrated with the wireless sensor nodes, and low sensitivity orders to harvest the ambient RF energy lower than -20dBm . From the perspective of the antenna, several configurations were introduced to increase the intercepted power and eliminate

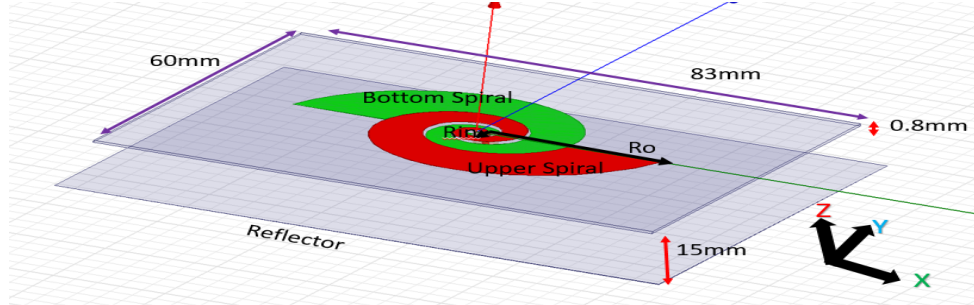


Figure 7.1: Antenna configuration layout

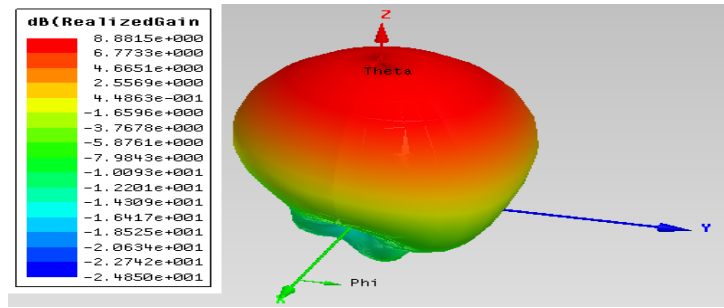


Figure 7.2: Simulated realized gain at frequency=2.45GHz

the misalignment with the transmitting antenna. Therefore, a circularly polarized antenna is an adequate antenna arrangement for a typical EH system. In this research, rectenna is demonstrated for experimental arrangement with BLE unit. The proposed rectenna is decomposed of circular-polarized antenna and a wideband voltage doubler RF rectifier introduced in 4.

7.2 Antenna

For a freestanding spiral antenna, it is known that bi-directional radiation with opposite polarizations is achieved. But in most applications, a unidirectional pattern is needed to block radiation on the other side. So far, some investigations have been devoted to the realization of low profile unidirectional equiangular spiral antennas (ESAs) [98]– [100], all of which have used absorbing materials. The dimensions of a log-periodic dipole antenna (LPDA), when expressed in terms of wavelength, vary with frequency, it usually exhibit different radiation

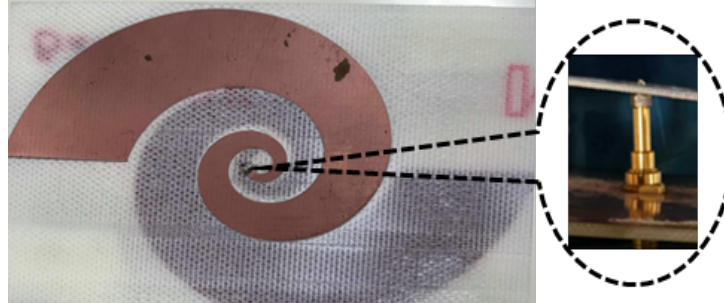


Figure 7.3: Simulated realized gain at frequency=2.45GHz

properties at different frequencies. The LPDA consists of a system of driven elements, but not all elements in the system are active on a single frequency of operation. Depending upon its design parameters the LPDA can be operated over a range of frequencies.

In Fig. 7.1, the LPDA spiral antenna is shown with two antipodal metal strips. In Z-direction, an upper spiral metal strip is mounted on the substrate and another 180-degree bottom spiral is put on Z-direction. The two spiral constitute antipodal antenna. The coaxial feed is taken between the upper and lower patch. A ground plane reflector is set at a distance 15mm below the substrate. It reflects all back-radiation into the forward direction, therefore the gain is improved by about 3dB. The realized simulated gain is shown in Fig. 7.2. The maximum gain (8.89dB) direction is in the broadside (+ Z-direction, Theta=0). As noticed also, all the field radiations are propagated in the + Z-direction. Fig. 7.3 shows the layout of the proposed PLDA. The simulated return loss characteristic is compared with the measured results and given in Fig. 7.4(a). The antenna has a wideband nature from 1 to 3 GHz with S11 less than 6dB. The axial ratio is a very important parameter that helps to quantify the polarization of an antenna. The axial ratio of a wave elliptically polarized, is the relationship between major and minor axes of the ellipse, and it can take values among one and infinity. The antenna axial ratio (AR) is illustrated in Fig. 7.4(b), the AR is less than 2 dB around 2.45GHz with a measured bandwidth 270MHz. The measured and simulated gain versus the frequency is depicted in Fig. 7.4(c). Both results are well-matched with the maximum gain achieved around 2.45GHz.

7.3 Technical Approach AND Experimental Procedures

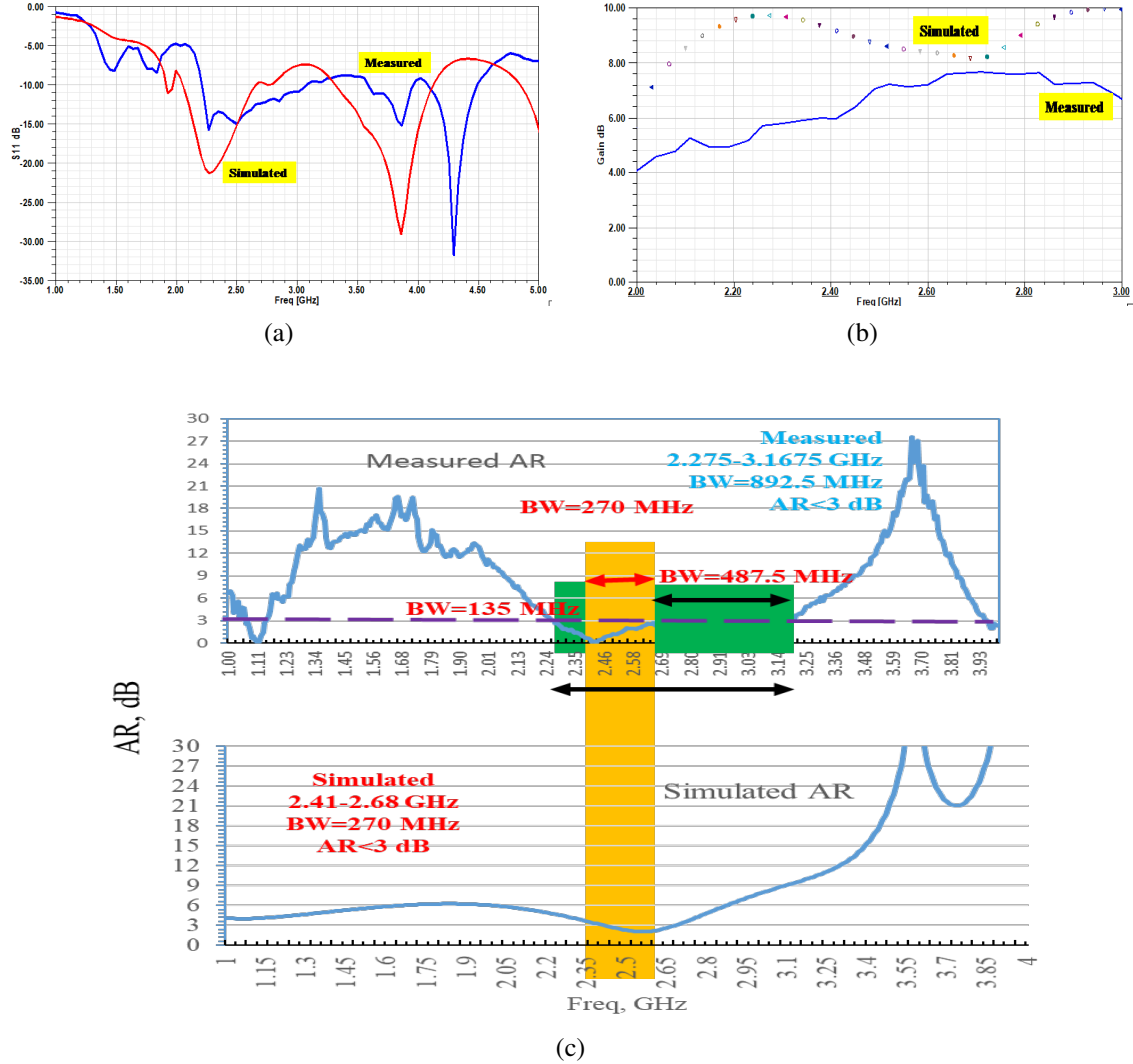


Figure 7.4: The simulated and measured antenna performance over the operating frequency band 1-4GHz, (a) S₁₁, (b) AR, and (c) Gain

7.3 Technical Approach AND Experimental Procedures

A complete rectenna unit is implemented and tested in practical operation. The entire block diagram is shown in Fig. 7.5(a). The transmitting antenna and rectenna unit is given in Fig. 7.5(b), where the super-capacitor is connected to wirelessly charging. The BLE sensing unit is depicted in Fig. 7.5(c), respectively. The rectenna efficiency at 1.52GHz is shown in Fig. 7.6(a). The maximum received RF input power from the transmitting antenna is about 0.5dB. Based

7.3 Technical Approach AND Experimental Procedures

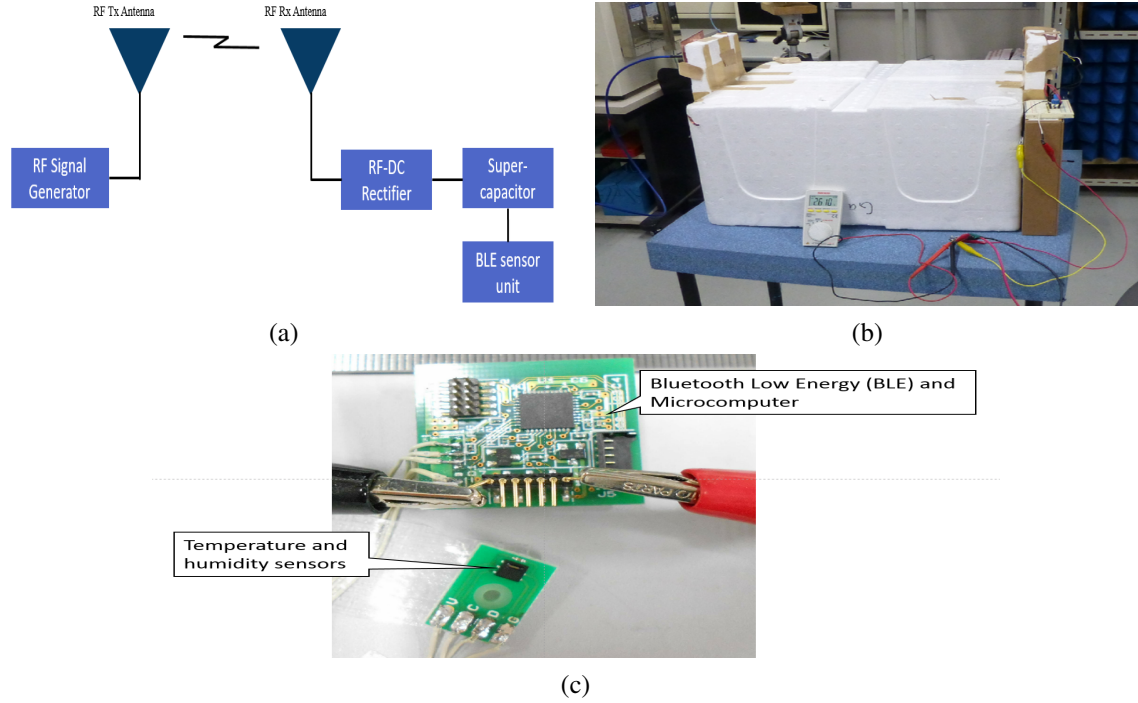


Figure 7.5: Measurement setup and experimental verification of the proposed EH-BLE application. (a) The system block diagram, (b) Rectenna transmitting and receiving unit, (c) BLE wireless module and the sensors.

on the previous discussion, the expected measured efficiency is more than 50%. The efficiency is gradually degraded with the decreasing of intercepted power.

A BLE unit connected to a super-capacitor (0.1pF) was experimented for about one day of continuous operation. The capacitor charging voltage over time, and capacitor discharging voltage over time during the measurement and BLE communication were accomplished as shown in Fig. 7.6(b) and 7.6(c). Besides the constant functionality of the BLE unit, the super-capacitor voltage remains almost fixed around the initial charge voltage 2.7 V. This implies the proper wireless charging of the super-capacitor. The BLE module is transmitting the sensed temperature and humidity data to a laptop computer every 1 min interval.

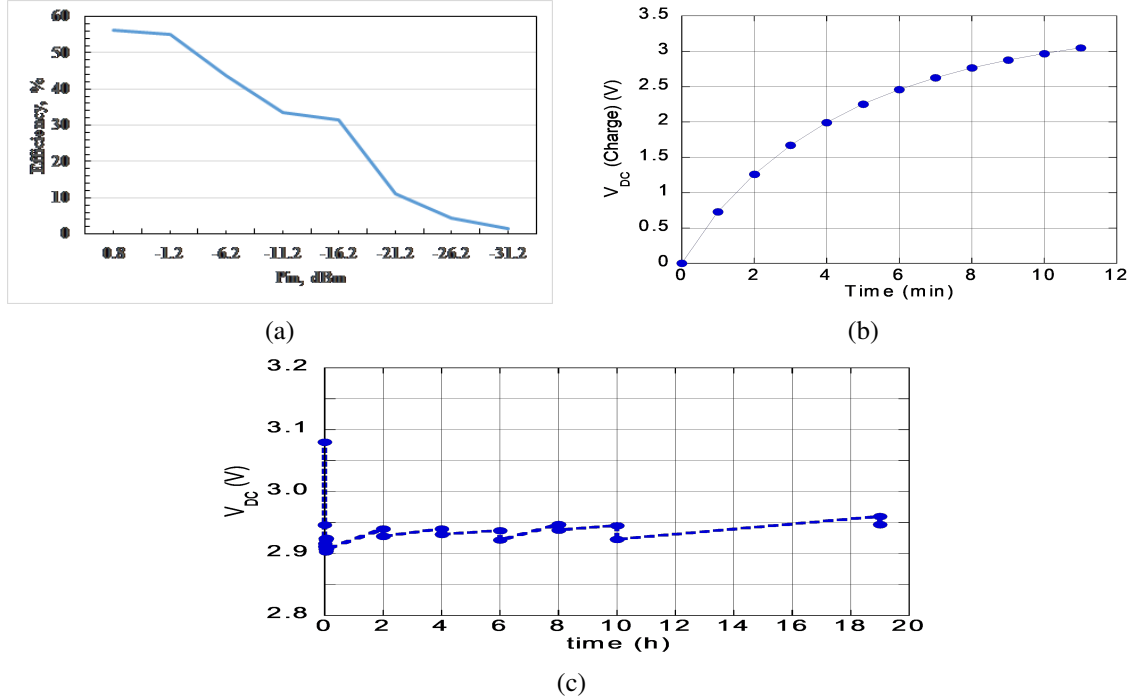


Figure 7.6: Super-capacitor charging discharging mechanisms. (a) Rectenna efficiency versus the intercepted RF power, (b) capacitor charging voltage over time, and (c) capacitor discharging voltage over time.

7.4 Wireless Bio-medical Sensor Application

As many wearable technology products rise, companies are consolidating around the aspects of wearable products that add the most value. In many cases, these value propositions come from the sensor data. Fitness tracking and smartwatches have been built around biometric and activity data. The sensor data can be routed over a Wireless Body Sensor Network (WBSN), that is used to monitor the daily life activities of a person, to a remote location using the internet network. WBSN consists of intelligent sensor nodes which do not obstruct the daily life activities and are useful in detecting chronic diseases like heart attack, asthma, diabetes etc. and to warn the patients in case of emergency conditions [101]– [103]. With the help of WBSNs we can monitor activities, movements and vital human body signals from a remote location by the means of internet. Due to the limited resources such as memory, battery power and varying bandwidth, WBSN still need much research effort to become a full-independent wireless

network.

Powering of such tiny devices is a challenge due to the compactness of personal biomedical devices and the need for sustainability of power supply. Energy harvesting methods derived from sources such as wind, solar and tidal power have long since been employed in low power applications, however with technological progress there has been seen an increased application of RF energy harvesting in numerous medical and small-scale applications [104]– [107].

In this research work, effort has been made to incorporate the concept of RF energy harvesting in a biomedical application using the integration of a commercial textile antenna and RF-DC rectifier. This research has found a practical application from industrial entities which interested in RF energy harvesting integration with their biomedical sensing products like Toyobo Co., Ltd. in Japan. Toyobo Co., Ltd. developed a film-like functional material for cloths capable of measuring biological information by using its own conductive material. The material, "COCOMI[®]," is used for electrodes and electric wires of sensors that measure the biological information of the wearer and realize both natural comfort and high-accuracy measurement [108].

In this communication, the sensing node with RF energy harvesting system is investigated and the experimental results shows a typical agreement between the measured and simulated results. The proposed rectifier configuration is discussed in sec. II. The textile antenna characterization is illustrated in sec. III. The rectenna integration with the measurement results is introduced in sec. IV. Finally, sec. V draws the main conclusions.

7.5 Rectifier Circuit Topology

The rectifier circuit topology is constituted by a series LC network followed by a voltage doubler configuration, one of the common RF energy harvesting architecture [109]. The rectifier block diagram is shown in Fig.7.7. The voltage doubler rectifier use a series pair of SMS7630-005LF Schottky diode from SKYWORKS. To facilitate the interfacing between the RF source and the rectifier input, a matching circuit is introduced for reflection losses minimization. The matching circuit is simply constructed by a series LC reactive elements from Murata

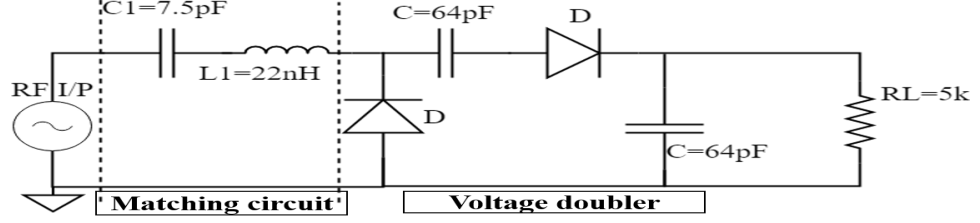


Figure 7.7: Block diagram of the rectifier circuit

Electronics.

A prototype circuit has been realized on FR4 substrate with dielectric constant $\epsilon_r = 4.4$ and thickness $h = 0.8\text{mm}$ and was fabricated using a milling machine. The total size of the rectifier circuit is $19.5 \times 9.7\text{mm}^2$.

As to characterize the RF behavior of the rectifier, the measurement of S_{11} is carried out with a network analyzer from 0.5 to 1.5 GHz, and the measured and simulated results are as plotted in Fig. 7.8. Both results have low peak values of approximately -10 dB around 1.05 and 1.25 GHz, respectively which indicates low reflections at the operating frequency. The resonance frequency is little shifted to lower side due to the inaccurate characterization of the substrate dielectric constant which may have fluctuation due to the fabrication process.

The measurement of efficiency versus input power (shown in Fig. 7.8(b)) was done with a signal generator as the power source is set at a fixed frequency 1.05 GHz and the input power is changed from -30 to 22 dBm. It is noted that, the measured efficiency is 26% at -20 dBm, 40% at -10 dBm, 52% at 0 dBm, of input power, and has a peak value of 63% at 5 dBm. The efficiency starts decaying above 7 dBm due to the breakdown of the diode. The measured and simulated efficiency match very well with a slight shift of the maximum peak efficiency. The previous measurement and simulation results were done with a fixed terminal load $R_L = 5\text{k}\Omega$.

Moreover, the variation of efficiency versus frequency is shown in Fig. 7.8(c) with different RF input power values ($P_{in} = 5\text{dBm}$, $P_{in} = 0\text{dBm}$, $P_{in} = -5\text{dBm}$, $P_{in} = -10\text{dBm}$) and fixed $R_L = 5\text{k}\Omega$. The data illustrate the rectifier efficiency performance has little shift with the peak efficiency response from 1.26 GHz simulation frequency to 1.05 GHz measured frequency as expected by the return loss response. As mentioned, this shift may be attributed due to the

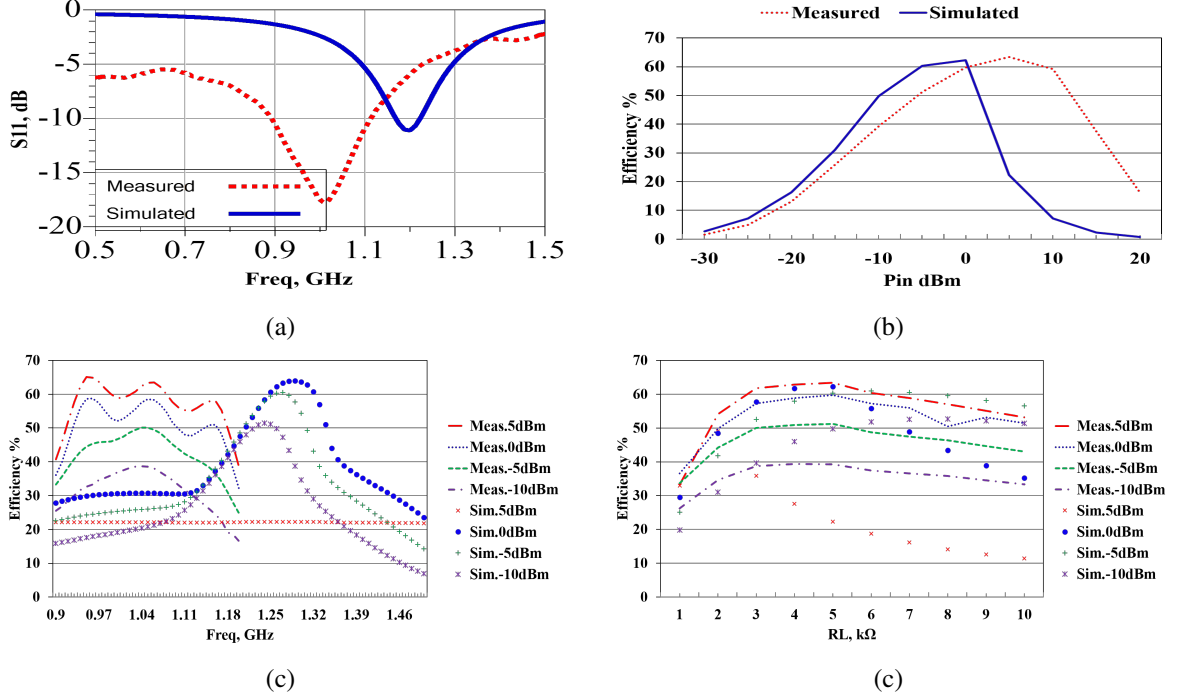


Figure 7.8: The measured and simulated rectifier performance comparison (a) Return loss S_{11} (b) Efficiency changes with the input power at a constant frequency ($1.05GHz$) and $R_L = 5k\Omega$ (c) Efficiency changes with the frequency at different RF input power ($P_{in} = 5dBm, 0dBm, -5dBm, -10dBm$), and at $R_L = 5k\Omega$ (d) Efficiency changes with the load terminal at different RF input power ($P_{in} = 5dBm, 0dBm, -5dBm, -10dBm$), and at frequency $1.05GHz$.

parasitics and the inaccurate modeling of the diode and surface mount components.

Likewise, the changing of efficiency versus the terminal load is given in Fig. 7.8(c) with different RF input power values ($P_{in} = 5dBm, P_{in} = 0dBm, P_{in} = -5dBm, P_{in} = -10dBm$) and fixed frequency $1.05GHz$. While the maximum measured efficiency is achieved at $P_{in} = 5dBm$, the the simulated peak value is obtained at $P_{in} = 0dBm$.

7.6 Textile Antenna

Toyobo Co., Ltd. developed a flexible and film like conductive material on clothes that is suitable for the electrodes of the body area network or for measuring the biological information. This conducting material is called COCOMI[®] [108] which has highly stretches and joint less

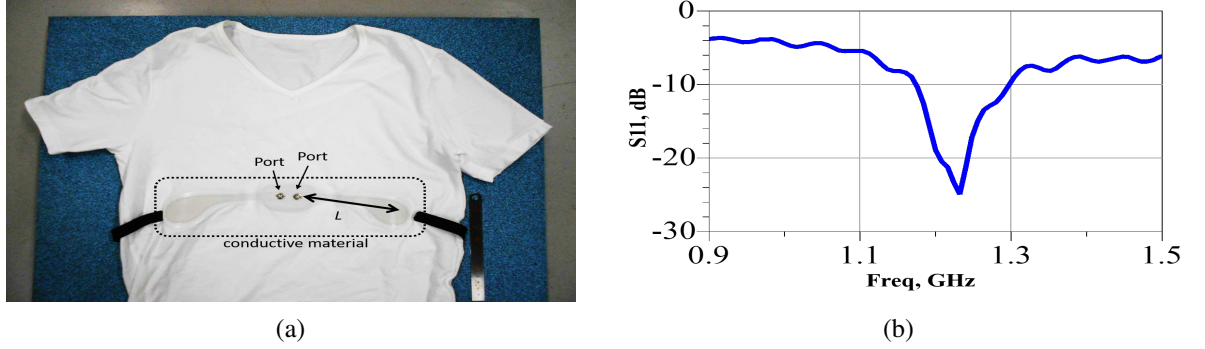


Figure 7.9: Textile antenna characterization (a) Antenna photograph (b) Antenna return loss S_{11} .

smooth surface. The conducting sheet is sandwiched by the insulating sheet and the total thickness is approximately $0.3mm$. The sheet resistance is less than 1Ω . In this study, COCOMI® on clothes is utilized as the energy harvested antenna. Fig. 7.9(a) shows the photograph of the COCOMI® on T-shirts. There are two port network and the length between the edge and one of the port is $l = 141mm$. Therefore, this conducting material is considered about the half wave-length dipole antenna, and the estimated center frequency is $1.06GHz$. The RF properties were measured by using vector network analyzer (VNA, 8722C, HP). Fig.7.9(b) show the input reflection coefficient (S_{11}). The center frequency is estimated as $1.232GHz$ and input impedance is $44.8 + j1.4\Omega$ respectively.

The antenna gain was measured by using the signal generator (E4428C, Agilent) and spectrum analyzer (N9010A, Agilent). RF signal is injected through the horn antenna at a fixed power and frequency. From the Friis transmission [110] equation the antenna gain is 3.8 dBi.

7.7 Rectenna Integration

The rectenna measurement setup is shown in Fig. 7.10(b). The transmitted RF input power is radiated by the horn antenna with gain $3.8dB$ at $1.05GHz$. The textile antenna mounted on a white T-shirt receive part of the propagated electromagnetic wave with a received gain $3.8dB$. The textile antenna is connected with the rectifier circuit through an BNC connector. The rectified DC voltage across the terminal load is measured with a multimeter. The data is

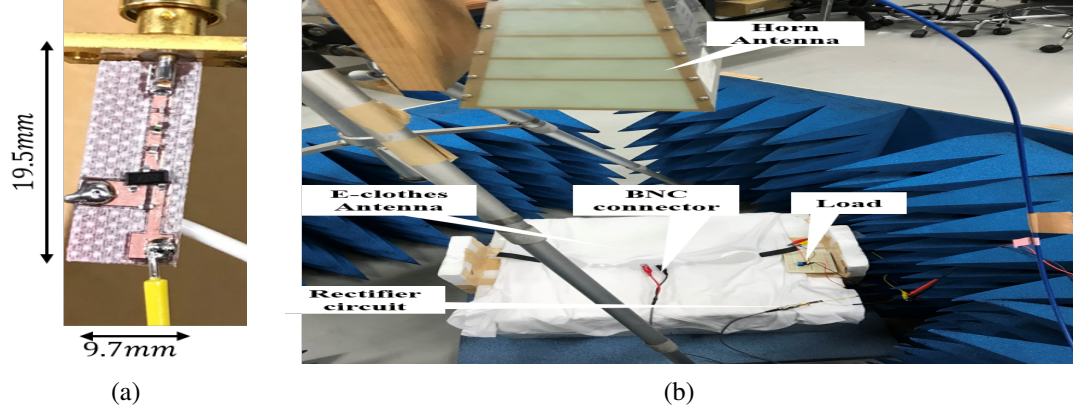


Figure 7.10: The rectifier prototype and rectenna measurement setup (a) Fabricated rectifier prototype (b) Measurement setup.

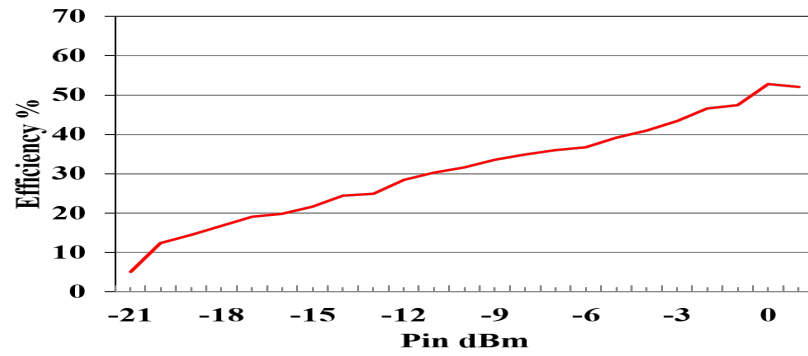


Figure 7.11: Measurement of the rectenna performance.

saved for several input power levels. The received power levels is computed using Friis equation which accounts for the line-of-sight propagation mode only and suppress for any reflections due to the surrounding objects in the environment. Thus the measurement setup has been performed inside an anechoic chamber. The overall rectenna performance is explained in Fig. 7.11. As can be noticed, the rectenna efficiency behaves well similar to the rectifier circuit. Thus, there are no any mismatch between the rectifier circuit and the antenna input port which shows the validation of the design.

7.8 Conclusion

In this chapter, an experimental demonstration of the RF energy harvesting systems was investigated in conjunction with both a BLE and WBSN units. An BLE unit attached with an array of sensors was used as the end-application for the proposed energy harvesting system. The architecture proved the proposed design and introduced a sufficient DC voltage for BLE unit supply. The system was tested in continuous operation for 20 hours. During this period, the measured output DC voltage at BLE terminal is almost constant.

The advance of wearable technology and the great miniaturization of the electronic devices are fostering the development of smart garments, able to provide information about the state of human's health and environment. Currently, clothes, shoes and accessories are able to communicate and interact wirelessly without the necessity of integrating expensive and huge equipment. Textile antenna that is fabricated in smart clothes can be integrated with a rectifier circuit for powering wearable devices, such as low-power sensor nodes and wireless body sensor network. In this study, the performance of the textile rectenna is improved and specifically at low input power around $0dBm$. The proposed topology was very simple and has the operating frequency design flexibility to realize across any wireless-band applications. Moreover, the rectifier could be integrated with the antenna on the same substrate to realize a compact rectenna that can be mounted directly on clothes without any limitations.

Chapter 8

Conclusions and Future Work

8.1 Introduction

Advances in energy harvesting: More efficient, lower consumption, higher capacity storage

The next generation of radio technology will enable up to ten times longer radio ranges for wireless transmissions of more than three kilometers for outdoor applications with high range requirements. The increased energy demands for such long distances will need to be met through progression of energy harvesting technology and the associated building blocks.

Lowering device energy consumption is an important adjustment for improved performance, especially for critical functions such as the sleep and receiver current of sensor nodes. Tests have already shown that a $10x$ reduction in timer currents is technically achievable for the next generation of sensor modules.

Advances are also being made that will improve the efficiency of motion, light temperature-based, and RF energy harvesting technology in the coming years, with research revealing the efficiency of new designs and innovative deployment models.

Current wireless energy harvesting architectures and emerging technologies are enabling new applications in almost every field of industry based on communications powered by the surrounding environment. The specific benefits of energy harvesting are currently contributing to the improvement of existing systems and the development of new IoT use cases in applications

that include structural health monitoring, environmental monitoring, healthcare applications, and automated logistic processes, though the potential applications are almost as unlimited as the available energy sources themselves.

To make energy harvesting work, the amount of available energy must be higher than what is required to perform the desired task. There are numerous examples of battery-free and forever battery life devices. Inductive wireless energy transfer allows battery-free NFC and RFID tags to operate battery free within a short range. Wireless charging pads are increasingly replacing power cords for improved convenience. The holy grail of energy harvesting today is to sever the power cord and allow our devices to harvest ambient energy at a convenient distance. Two of the most promising sources of ambient energy harvesting for IoT applications are light and RF.

The edge of the IoT is where the action is. It includes a wide array of sensors, actuators, and devices - those system end-points that interact with and communicate real-time data from smart products and services [1]. Thus, edge devices include end-user equipment and appliances that can be connected to networks and interact with the network and/or with other devices. These interactions can include issuing commands, activating actuators, or transmitting sensor data. For example a light and humidity sensor can activate a water pump to irrigate a field if the soil humidity became too low in a period of sunny rainless days. The connection to the network is either established with a cable connection or with a wireless radio-frequency protocol to a smartphone, gateway or a router. The type of wireless connection can vary from Wi-Fi, Bluetooth mobile internet to many others. Some devices can also include multiple forms of wireless connection.

Many IoT edge devices are battery powered, particularly actuators and sensors which are generally placed in decentralized locations. The corresponding energy use and physical waste related to batteries are considerable. One rough estimate yields a figure of more than 23 billion battery powered IoT devices in 2025. The elimination of batteries as an inefficient energy source is important and there are several measures which address this. Additionally, it is known that the materials needed for battery production are becoming scarcer, and the challenges associated

with the waste management at the end of life of batteries are also well documented. Energy Harvesting Technologies represent a key solution to this problem.

8.2 Proposed Future Work

Some of the proposed techniques to improve the EH system performance is listed below:-

- **Distributed Energy Beam forming** Distributed energy beam forming enables a cluster of distributed energy sources to cooperatively emulate an antenna array by transmitting RF energy simultaneously in the same direction to an intended energy harvester for better diversity gains.
- **Interface Management** Existing interference management techniques , e.g., Interference alignment and interference cancellation, attempt to avoid or mitigate interference through spectrum scheduling.
- **Antenna Array** Several distributed arrays of antennas, which are designed by scaling in array size, power, DC load, frequency, and gain level, are presented to increase harvested power and efficiency.
- **Diversity Combining** The use of diversity combining in RFEH systems is proposed to increase the amount of harvested energy. In current wireless communication systems, diversity combining is considered as an important tool to enhance wireless link performance by alleviating the effects of radio channels fading process. Diversity combining techniques are based on redundancy of transmitted information. Destinations combine multiple copies of the same information signal received over different points of a domain such as time, frequency, and space.
- **Smart System** Microcontroller-based power management system is proposed to obtain more energy than direct connection.

References

- [1] V. Raghunathan, S. Ganeriwal, and M. Srivastava, "Emerging Techniques for Long-Lived Wireless Sensor Networks," *IEEE Commun. Mag.*, vol. 44, Apr. 2006, pp. 10814.
- [2] Franciscatto, Bruno Roberto, "Design and development of a new low-power DSRC transponder" (Published Doctoral thesis). University of Grenoble, France, 2014.
- [3] C. Knight, J. Davidson, and S. Behrens, "Energy Options for Wireless Sensor Nodes," *Sensors*, vol. 8, pp. 8037-8066, 2008.
- [4] W. Wu, Y. Chen, B. Lee, J. He, Y. Peng. "Tunable resonant frequency power harvesting devices". *Proc SPIE*, 2006.
- [5] C. B. Williams and R. B. Yates, "Analysis of a micro-electric generator for microsystems," *Stockholm, Sweden*, pp. 369-372, 1995.
- [6] Radiom S, Vandenbosch G, Gielen G (2008) Impact of antenna type and scaling on scavenged voltage in passive RFID tags. In: *International workshop on antenna technology: small antennas and novel metamaterials*, 2008. *iWAT 2008*, pp 442–445.
- [7] Gosset G, Flandre D, "Fully-automated and portable design methodology for optimal sizing of energy-efficient CMOS voltage rectifiers", *IEEE J Emerg Sel Top Circuits Syst*, 1, 2011, 141149.

- [8] Tran, Le-Giang, and Cha, Hyouk-Kyu and Park, Woo-Tae, "RF power harvesting: a review on designing methodologies and applications", *Micro and Nano Systems Letters*, 2017, vol. 5, No. 1, pages, 14
- [9] A. Facen and A. Boni, "CMOS power retriever for UHF RFID tags," in *Electronics Letters*, vol. 43, no. 25, pp. 1424-1425, 6 Dec. 2007.
- [10] Kotani K, Sasaki A, Ito T, "High-efficiency differential-drive CMOS rectifier for UHF RFIDs", *IEEE J Solid-State Circuits*, 44, 2009, 3011–3018.
- [11] Chouhan SS, Nurmi M, Halonen K, "Efficiency enhanced voltage multiplier circuit for RF energy harvesting", *Microelectron J*, 2016, 48, 95–102
- [12] Wang W, Xiangjie C, Wong, "Analysis and design of CMOS full wave rectifying charge pump for RF energy harvesting applications" 2015 IEEE Region 10 conference TENCON 2015, pp 1–4.
- [13] Rodriguez AN, Cruz FRG, Ramos RZ, "Design of 900 Mhz AC to DC converter using native Cmos device of TSMC 0.18 micron technology for RF energy harvest application", *Univers J Electr Electron Eng* 3–7, 2015.
- [14] Hwang YS, Lei CC, Yang YW, Chen JJ, Yu CC "A 13.56-MHz low voltage and low-control-loss RF-DC rectifier utilizing a reducing reverse loss technique," *IEEE Trans Power Electron*, 29, 2014, 6544–6554.
- [15] H. W. Bode, *Network Analysis and Feedback Amplifier Design*, pp. 360-371 (D. Van Nostrand Co. New York, N.Y., 1945).
- [16] R. M. Fano, "Theoretical Limitations on the Broadband Matching of Arbitrary Impedances," *Journal of the Franklin Institute*, Vol. 249, pp. 57-84 and 139-154 (January-February 1950).
- [17] G. L. Matthai, L. Young, E. M. T. Jones "Microwave Filters, Impedance Matching Networks, and Coupling Structures," Artech House, 1985.

- [18] Shen S, Murch RD (2016) Impedance matching for compact multiple antenna systems in random RF fields. *IEEE Trans Antennas Propag* 64:820–825
- [19] Etor D, Dodd LE, Wood D, Balocco C (2015) Impedance matching at THz frequencies: optimizing power transfer in rectennas. In: 2015 40th international conference on infrared, millimeter, and terahertz waves (IRMMW-THz), pp 1–2
- [20] Hoarau C, Corrao N, Arnould JD, Ferrari P, Xavier P (2008) Complete design and measurement methodology for a tunable RF impedance-matching network. *IEEE Trans Microw Theory Tech* 56:2620–2627
- [21] Marrocco G (2008) The art of UHF RFID antenna design: impedance-matching and size-reduction techniques. *IEEE Antennas Propag Mag* 50:66–79
- [22] Mingo JD, Valdovinos A, Crespo A, Navarro D, Garcia P (2004) An RF electronically controlled impedance tuning network design and its application to an antenna input impedance automatic matching system. *IEEE Trans Microw Theory Tech* 52:489–497
- [23] C. H. P. Lorenz, S. Hemour and K. Wu, "Physical Mechanism and Theoretical Foundation of Ambient RF Power Harvesting Using Zero-Bias Diodes," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 7, pp. 2146–2158, July 2016.
- [24] G. Papotto, F. Carrara and G. Palmisano, "A 90–nm CMOS Threshold-Compensated RF Energy Harvester," in *IEEE Journal of Solid-State Circuits*, vol. 46, no. 9, pp. 1985–1997, Sept. 2011.
- [25] P. Lu, X. Yang, J. Li, and B. Wang, A Compact Frequency Reconfigurable Rectenna for 5.2- and 5.8-GHz Wireless Power Transmission, *IEEE Trans. Power Electronics*, Nov. 2015, Vol. 30, pp. 6006-6010.
- [26] P. Lu, X. Yang, J. Li, and B. Wang, Polarization Reconfigurable Broadband Rectenna With Tunable Matching Network for Microwave Power Transmission, *IEEE Trans. Antennas Propag.*, Mar. 2016, vol. 64, no. 3, pp. 1136-1141.

- [27] M. Piuela, P. D. Mitcheson, and S. Lucyszyn, Ambient RF Energy Harvesting in Urban and Semi-Urban Environments, *IEEE MTT*, Jul. 2013, vol. 61, no. 7, pp. 2715-2726.
- [28] Z. Zhou, W. Liao, Q. Zhang, F. Han, and Y. Chen, A Multi-band Fractal Antenna for RF Energy Harvesting, *IEEE AP-S*, 2016.
- [29] J. Chou, D. Lin, K. Weng, and H. Li, All Polarization Receiving Rectenna With Harmonic Rejection Property for Wireless Power Transmission, *IEEE Trans. Antennas Propag.*, Oct. 2014, vol. 62, no. 10, pp. 5242-5249.
- [30] H. Sun, Y. Guo, M. He, and Z. Sa, Design of a High-Efficiency 2.45-GHz Rectenna for Low-Input-Power Energy Harvesting, *IEEE Antennas And Wireless Propagation Letters*, 2012, vol. 11, pp. 929-932.
- [31] M. Nie, X. Yang, G. Tan, and B. Han, A Compact 2.45-GHz Broadband Rectenna Using Grounded Coplanar Waveguide , *IEEE Antennas And Wireless Propagation Letters*, vol. 14, pp. 986-989, 2015.
- [32] S. Y. Jung, M. Park, M. Lee, J. Yang and J. Kim, Time slot optimization algorithm for multisource energy harvesting systems, *ESSCIRC Conference 2016: 42nd European Solid-State Circuits Conference*, Lausanne, 2016, pp. 499-502.
- [33] J. Wang, Y. Jiang, J. Dijkhuis, G. Dolmans, H. Gao and P. Baltus, A 900 MHz RF energy harvesting system in 40 nm CMOS technology with efficiency peaking at 47% and higher than 30% over a 22dB wide input power range, *ESSCIRC 2017 - 43rd IEEE European Solid State Circuits Conference*, Leuven, 2017, pp. 299-302.
- [34] S. Kim, J. Bito, S. Jeong, A. Georgiadis and M. M. Tentzeris, A flexible hybrid printed RF energy harvester utilizing catalyst-based copper printing technologies for far-field RF energy harvesting applications, *2015 IEEE MTT-S International Microwave Symposium*, Phoenix, AZ, 2015, pp. 1-4.
- [35] O. Elsayed, M. Abouzied and E. Snchez-Sinencio, A 540 μ W RF wireless receiver assisted by RF blocker energy harvesting for IoT applications with +18 dBm OB-IIP3, *2016 IEEE*

- Radio Frequency Integrated Circuits Symposium (RFIC), San Francisco, CA, 2016, pp. 230-233.
- [36] Lin, T.-H.; Via-free broadband microstrip to CPW transition, *Electronics Letters*, Jul. 2001, vol.37, pp. 960 - 961.
- [37] C. C Chou, K. H, Lin, and H. L. Su, Broadband circularly polarized crosspatch-loaded square slot antenna, *Electron. Lett.*, Apr. 2007, vol. 43, no.9, pp. 485-486.
- [38] Y. Shinki, K. Shibata, M. Mansour, H. Kanaya, Impedance Matching Antenna-Integrated High-Efficiency Energy Harvesting Circuit , *Sensors*, 17(8), 1763; Aug. 2017.
- [39] J. Coonrod, The Effect of Radiation Losses on High Frequency PCB Performance, Rogers Corporation, Advanced Circuit Materials Division, IPC APEX EXPO Conference Proceedings.
- [40] F. J. Huang, T. C. Yo, C. M. Lee, and C. H. Luo, Design of circular polarization antenna with harmonic suppression for rectenna application,” *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 592-595, 2012.
- [41] V. Palazzi et al., ”Design of a ultra-compact low-power rectenna in paper substrate for energy harvesting in the Wi-Fi band,” 2016 IEEE Wireless Power Transfer Conference (WPTC), Aveiro, 2016, pp. 1-4.
- [42] J. H. Chou, D. B. Lin, K. L. Weng and H. J. Li, ”All Polarization Receiving Rectenna With Harmonic Rejection Property for Wireless Power Transmission,” in *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 10, pp. 5242-5249, Oct. 2014.
- [43] S. Hemour et al., ”Towards Low-Power High-Efficiency RF and Microwave Energy Harvesting,” in *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 4, pp. 965-976, April 2014.
- [44] SKYWORKS [Online]. Available: <http://www.skyworksinc.com/Product/512/SMS7630-061>.

-
- [45] M. He, H. Sun, Z. Zhong, Y. X. Guo and M. Xia, "Technology-independent table-based diode model for rectenna design in RF energy harvesting," Proceedings of the 2012 IEEE International Symposium on Antennas and Propagation, Chicago, IL, 2012, pp. 1-2.
- [46] R. Garg, I. Bahl, M. Bozzi "Microstrip Lines and Slotlines", Artech House, 3rd edition, 2013.
- [47] User Equipment (UE) Radio Transmission and Reception (FDD), Standard 25.101, Jun. 2015. [Online]. Available: <http://www.3gpp.org/DynaReport/25101.htm>
- [48] A. Sample and I. Smith, "Experimental results with two wireless power transfer systems," in Radio and Wireless Symposium, 2009. RWS '09. IEEE, pp. 16-18, 2009.
- [49] V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, "Ambient backscatter: wireless communication out of thin air," in Proceedings of the ACM SIGCOMM 2013 conference on SIGCOMM, pp. 39-50, ACM, 2013.
- [50] H. Kanaya, S. Tsukamoto, T. Hirabaru, D. Kanemoto, R. K. Pokharel, K. Yoshida, "Energy harvesting circuit on a one-sided directional flexible antenna," IEEE Microwave and Wireless Components Letters, vol. 23, no. 3, pp. 164-166, 2013.
- [51] S. Keyrouz, H. Visser, and A. Tjhuis, "Multi-band simultaneous radio frequency energy harvesting," in Antennas and Propagation (EuCAP), 2013 7th European Conference on, pp. 3058-3061, 2013.
- [52] C. Hsu, S. Lin, Z. Tsai, "Quadband Rectifier Using Resonant Matching Networks for Enhanced Harvesting Capability," IEEE MWCL, vol. 27, no. 7, pp. 669-671, Jul. 2017.
- [53] A. Collado, S. Daskalakis, K. Niotaki, R. Martinez, F. Bolos, A. Georgiadis. G. Harrison, "Rectifier Design Challenges for RF Wireless Power Transfer and Energy Harvesting Systems," in Radioengineering, vol. 26, no. 2, pp. 411-417, Jun. 2017
- [54] R. G. Harrison, "Full nonlinear analysis of detector circuits using RitzGalerkin theory," in IEEE MTT-S Int. Microw. Symp. Dig., buquerque, NM, USA, pp. 267-270, Jun. 1992.

- [55] T.-W. Yoo and K. Chang, "Theoretical and experimental development of 10 and 35 GHz rectennas," *IEEE Trans. Microw. Theory Techn.*, vol. 40, no. 6, pp. 1259–1266, Jun. 1992.
- [56] G. De Vita and G. Iannaccone, "Design criteria for the RF section of UHF and microwave passive RFID transponders," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 9, pp. 2978–2990, Sep. 2005.
- [57] S. D. Assimonis, S.-N. Daskalakis, and A. Bletsas, "Sensitive and efficient RF harvesting supply for batteryless backscatter sensor networks," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 4, pp. 1327–1338, Apr. 2016.
- [58] F. Bolos, D. Belo, A. Georgiadis, "A UHF rectifier with one octave bandwidth based on a non-uniform transmission line," in *IEEE MTT-S IMS*, pp. 15–64, May 2016.
- [59] J. Kimionis, A. Collado, M. M. Tentzeris, A. Georgiadis, "Octave and Decade Printed UWB Rectifiers Based on Nonuniform Transmission Lines for Energy Harvesting," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 4, pp. 1-9, Apr. 2016.
- [60] S. Abbasian and T. Johnson, "High efficiency GaN HEMT synchronous rectifier with an octave bandwidth for wireless power applications," in *IEEE MTT-S Int. Microw. Symp. Dig.*, pp. 1–4, May 2016.
- [61] Z. Popovi, S. Korhummel, S. Dunbar, Robert Scheeler, A. Dolgov, R. Zane, E. Falkenstein, and J. Hagerty, "A High-Efficiency Broadband Rectenna for Ambient Wireless Energy Harvesting," *IEEE Trans. Antennas and Propagation*, vol. 63, no. 8, pp. 3486-3495, Aug. 2015.
- [62] J. R. Smith, "M. H. Ouda, M. Arsalan, L. Marnat, A. Shamim, and K. N. Salama, "5.2-GHz RF power harvesting module in 0.18 m CMOS for biomedical implantable sensors," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 5, pp. 1–8, May 2013.
- [63] K. Kotani, A. Sasaki, and T. Ito, "High-efficiency differential-drive CMOS rectifier for UHF RFIDs," *IEEE J.Solid-State Circuits*, vol. 44, no. 11, pp. 3011–3018, Nov. 2009.

-
- [64] T. Le, K. Mayaram, and T. Fiez, "Efficient far-field radio frequency energy harvesting for passively powered sensor networks," *IEEE J. Solid-State Circuits*, vol. 43, no. 5, pp. 1287–1302, May 2008.
- [65] K. Huang, C. Zhong and G. Zhu, "Some new research trends in wirelessly powered communications," in *IEEE Wireless Communications*, vol. 23, no. 2, pp. 19-27, April 2016.
- [66] A. Costanzo and D. Masotti, "Smart Solutions in Smart Spaces: Getting the Most from Far-Field Wireless Power Transfer," in *IEEE Microwave Magazine*, vol. 17, no. 5, pp. 30-45, May 2016.
- [67] A. Boaventura, D. Belo, R. Fernandes, A. Collado, A. Georgiadis and N. B. Carvalho, "Boosting the Efficiency: Unconventional Waveform Design for Efficient Wireless Power Transfer," in *IEEE Microwave Magazine*, vol. 16, no. 3, pp. 87-96, April 2015.
- [68] A. Costanzo and D. Masotti, "Energizing 5G: Near- and Far-Field Wireless Energy and Data Transfer as an Enabling Technology for the 5G IoT," in *IEEE Microwave Magazine*, vol. 18, no. 3, pp. 125-136, May 2017.
- [69] S. Scorcioni, L. Larcher and A. Bertacchini, "A Reconfigurable Differential CMOS RF Energy Scavenger With 60% Peak Efficiency and -21 dBm Sensitivity," in *IEEE Microwave and Wireless Components Letters*, vol. 23, no. 3, pp. 155-157, March 2013.
- [70] Q. W. Lin and X. Y. Zhang, "Differential Rectifier Using Resistance Compression Network for Improving Efficiency Over Extended Input Power Range," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 9, pp. 2943-2954, Sept. 2016.
- [71] H. Kanaya, S. Tsukamoto, T. Hirabaru, D. Kanemoto, R. K. Pokharel, K. Yoshida, "Energy harvesting circuit on a one-sided directional flexible antenna," *IEEE Microwave and Wireless Components Letters*, vol. 23, no. 3, pp. 164-166, 2013.
- [72] P. Wei et al., "High-Efficiency Differential RF Front-End for a Gen2 RFID Tag," in *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 58, no. 4, pp. 189-194, April 2011.

- [73] S. S. Sarma, S. Chandravanshi and M. J. Akhtar, "Triple band differential rectifier for RF energy harvesting applications," 2016 Asia-Pacific Microwave Conference (APMC), New Delhi, 2016, pp. 1-4.
- [74] M. Fantuzzi, M. Del Prete, D. Masotti and A. Costanzo, "Quasi-isotropic RF energy harvester for autonomous long distance IoT operations," 2017 IEEE MTT-S International Microwave Symposium (IMS), Honolulu, HI, 2017, pp. 1345-1348.
- [75] X. Le Polozec, M.M. Mansour, "Performance of a Balanced-Detector Calculated by the Ritz-Galerkin Method", DOI10.13140/RG.2.2.28328.47363/2, Dec. 2017.
- [76] Z. Miaowang, L. Zihong, A. Andrey, L. Xianluo and T. Hong-Zhou, "Differential voltage octuple rectifiers for wireless energy harvesting", Microwave and Optical Technology Letters, vol. 59, no. 7, pp. 1574-1578, 2017.
- [77] [Online]. Available: <https://www.johansontechnology.com/wideband-ceramic-baluns>
- [78] D. E. Bockelman and W. R. Eisenstadt, "Combined differential and common-mode scattering parameters: theory and simulation," in IEEE Transactions on Microwave Theory and Techniques, vol. 43, no. 7, pp. 1530-1539, Jul 1995.
- [79] Popovietal, Z. Scalable RF Energy Harvesting. IEEE Trans. Microw. Theory Techn. 2014, 62, 1046–1056.
- [80] Kimionis, J.; Collado, A.; Tentzeris, M.M.; Georgiadis, A. Octave and Decade Printed UWB Rectifiers Based on Nonuniform Transmission Lines for Energy Harvesting. IEEE Trans. Microw. Theory Techn. 2017, 65, 4326–4334.
- [81] Erkmen, F.; Almoneef, T.S.; Ramahi, O.M. Scalable Electromagnetic Energy Harvesting Using Frequency-Selective Surfaces. IEEE Trans. Microw. Theory Techn. 2018, 66, 2433–2441.

- [82] Stutzman, W.L.; Thiele, G.A. *Antenna Theory and Design*, 3rd ed.; John Wiley & Sons, Inc.: New York, NY, USA, 2013.
- [83] Vinayagamooth, A. *Design and Implementation of Wideband BALUN for Archimedean Spiral Antenna*. Masters Thesis, Apr. 2011, Access Date: Apr. 5th, 2018.
- [84] Hinostroza, I. *Design of Wideband Arrays of Spiral Antennas*. Ph.D. Thesis, Jun. 2013, Access Date: Mar. 18th, 2018.
- [85] Wang, B.; Chen, A. Design of an Archimedean spiral antenna. In *Proceedings of the 2008 8th International Symposium on Antennas, Propagation and EM Theory*, Kunming, China, 2–5 November 2008; pp. 348–351.
- [86] C. R. Valenta and G. D. Durgin, "Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems," *IEEE Microw. Mag.*, vol. 15, no. 4, pp. 108-120, Jun. 2014.
- [87] B. Li, X. Shao, N. Shahshahan, N. Goldsman, T. Salter, and G. M. Metze, "An antenna co-design dual band RF energy harvester," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 60, no. 12, pp. 3256-3266, Dec. 2013.
- [88] H. Nakamoto et al., "A passive UHF RF identification CMOS tag IC using ferroelectric RAM in 0.35-um technology," *IEEE J. Solid-State Circuits*, vol. 42, no. 1, pp. 101-110, Jan. 2007.
- [89] C. Tsai, I. -. Liao, C. Pakasiri, H. Pan and Y. Wang, "A Wideband 20 mW UHF Rectifier in CMOS," in *IEEE Microwave and Wireless Components Letters*, vol. 25, no. 6, pp. 388-390, June 2015.
- [90] J. F. Dickson, "On-chip high-voltage generation in MNOS integrated circuits using an improved voltage multiplier technique," *IEEE J. SolidState Circuits*, vol. SSC-11, no. 3, pp. 374-378, Jun. 1976.

-
- [91] K. Kotani, A. Sasaki, and T. Ito, "High-efficiency differential-drive CMOS rectifier for UHF RFIDs," *IEEE J. Solid-State Circuits*, vol. 44, no. 11, pp. 3011–3018, Nov. 2009.
- [92] <https://www.markimicrowave.com/Assets/datasheets/BAL-0006.pdf>
- [93] F. Kocer and M. P. Flynn, "A New Transponder Architecture with On-Chip ADC for Long-Range Telemetry Applications," *IEEE Journal of Solid-State Circuits*, vol. 41, no. 5, pp. 1142–1148, May 2006.
- [94] L. Roselli et al., "Review of the present technologies concurrently contributing to the implementation of the Internet of Things (IoT) paradigm: RFID, green electronics, WPT and energy harvesting," in *Proc. IEEE Topical Conf. Wireless Sensors Sensor Netw. (WiSNet)*, Jan. 2015, pp. 1–3.
- [95] R. Bergs, L. Fadel, L. Oyhenart, V. Vigneras, and T. Taris, "A dual band 915 MHz/2.44 GHz RF energy harvester," in *Proc. Eur. Microw. Conf. (EuMC)*, Sep. 2015, pp. 307–310.
- [96] F. Bolos, D. Belo, and A. Georgiadis, "A UHF rectifier with one octave bandwidth based on a non-uniform transmission line," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2016, pp. 1–3.
- [97] M. M. Mansour and H. Kanaya, "Compact and Broadband RF Rectifier with 1.5 Octave Bandwidth Based on a Simple Pair of L-Section Matching Network", accepted for publication at IEEE MWCL letter.
- [98] H. Nakano, K. Kikkawa, Y. Iitsuka, and J. Yamauchi, "Equiangular spiral antenna backed by a shallow cavity with absorbing strips," *IEEE Trans. Antennas Propag.*, vol. 56, no. 8, pp. 2742–2747, Aug. 2008.
- [99] J. J. H. Wang and V. K. Tripp, "Design of multioctave spiral-mode microstrip antennas," *IEEE Trans. Antennas Propag.*, vol. 39, no. 3, pp. 332–335, Mar. 1991.
- [100] W. Fu, E. R. Lopez, W. S. T. Rowe, and K. Ghorbani, "A planar dual-arm equiangular spiral antenna," *IEEE Trans. Antennas Propag.*, vol. 58, no. 5, pp. 1775–1779, May 2010.

- [101] A. Sangwan¹, and P. Pratim, "Wireless Body Sensor Networks: A Review," *Inter. Jour. of Hybrid Information Technology*, vol.8, no.9, pp.105-120, 2015.
- [102] S. Kim et al., "Ambient RF energy-harvesting technologies for self-sustainable standalone wireless sensor platforms," *Proc. IEEE*, vol. 102, no. 11, pp. 1649–1666, Nov. 2014.
- [103] A. Shameli, A. Safarian, A. Rofougaran, M. Rofougaran, and F. D. Flaviis, "Power harvester design for passive UHF RFID tag using a voltage boosting technique," *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 6, pp. 1089–1097, Jun. 2007.
- [104] E. Y. Chow, A. L. Chlebowski, S. Chakraborty, W. J. Chappell and P. P. Irazoqui, "Fully Wireless Implantable Cardiovascular Pressure Monitor Integrated with a Medical Stent," in *IEEE Transactions on Biomedical Engineering*, vol. 57, no. 6, pp. 1487-1496, June 2010.
- [105] Eric Y. Chow, A. L. Chlebowski and P. P. Irazoqui, "A Miniature-Implantable RF-Wireless Active Glaucoma Intraocular Pressure Monitor," *IEEE trans. Biomedical Circuits and Systems*, vol. 4, no. 6, Dec 2010.
- [106] H. Le, N. Fong, H. C. Luong, "RF Energy Harvesting Circuit with On-chip Antenna for Biomedical Applications", *Communications and Electronics (ICCE)*, 2010
- [107] L. Marnat, M. H. Ouda, M. Arsalan, K. Salama, and A. Shamim, "On-Chip Implantable Antennas for Wireless Power and Data Transfer in a Glaucoma-Monitoring SoC," *IEEE Antennas And Wireless Propag. Lett.*, vol. 11, 2012.
- [108] [Online]. Available: <http://www.stc.toyobo.co.jp/wp2/cocomi02/>, TOYOBO STC Co., Ltd
- [109] H. J. Visser and R. J. M. Vullers, "RF Energy Harvesting and Transport for Wireless Sensor Network Applications: Principles and Requirements," in *Proceedings of the IEEE*, vol. 101, no. 6, pp. 1410-1423, June 2013.

REFERENCES

- [110] Constantine A. Balanis, "Antenna Theory Analysis and Design," 3rd edition, John & Wiley Sons, 2005.
-

List of Publications

Publications/ Journals

- Y, Shinki, K. Shibata, **M. M. Mansour**, H. Kanaya Impedance Matching Antenna-Integrated High-Efficiency Energy Harvesting Circuit, sensors, Aug. 2017, 17, 1763.
- **M. M. Mansour** and H. Kanaya, "Compact and Broadband RF Rectifier With 1.5 Octave Bandwidth Based on a Simple Pair of L-Section Matching Network," in IEEE Microwave and Wireless Components Letters, vol. 28, no. 4, pp. 335-337, April 2018.
- **M. M. Mansour** and H. Kanaya, "Efficiency - Enhancement of 2.45 - GHz Energy Harvesting Circuit Using Integrated CPW - MS Structure at Low RF Input Power," IEICE Transaction of Electronics, vol. E102-C, no. 5, pp.-, May. 2019
- **M. M. Mansour**; Le Polozec, X.; Kanaya, H. Enhanced Broadband RF Differential Rectifier Integrated with Archimedean Spiral Antenna for Wireless Energy Harvesting Applications. Sensors 2019, 19, 655.
- **M. M. Mansour** and H. Kanaya, "High-Efficient Broadband CPW RF Rectifier for Wireless Energy Harvesting," in IEEE Microwave and Wireless Components Letters, vol. 29, no. 4, pp. 288-290, April 2019.

Publications/ Conference

- Y, Shinki, K. Shibata, **M. M. Mansour**, H. Kanaya High Efficiency Energy Harvesting Circuit with Impedance Matched Antenna, Proc. of the 2016 IEEE 18th Electronics Packaging Technology Conference, pp.532-535, 2016.
- **M. M. Mansour**, and H. Kanaya, Compact RF Rectifier Circuit for Ambient Energy Harvesting, Proc. of the 2017 IEEE RFIT Conference, Aug. 2017, South Korea.
- **M. M. Mansour**, and H. Kanaya, Experimental Investigation of Wireless Energy Harvesting with a Bluetooth Low Energy Sensing Unit, ICEP, Nagoya, Apr. 2018.
- **M. M. Mansour**, X. Polozec, and H. Kanaya, Compact and Wide-band Efficiency Improved RF Differential Rectifier for Wireless Energy Harvesting, IEEE MTT-S IMS2018, USA, Jun. 2018.
- **M. M. Mansour**, and H. Kanaya, High-Efficient RF Energy Harvesting Textile Rectenna for Wireless Body Sensor Network Applications, accepted for publication in ICEP 2019, Niigata, Japan, Apr. 2019.
- **M. M. Mansour**, and H. Kanaya, Wide-band and Improved-Efficient 0.18um CMOS RF Differential Rectifier for Wireless Energy Harvesting, submitted to APMC19.
- **M. M. Mansour**, and H. Kanaya, Design of a Compact High-Gain Slotted Trapezoidal Antenna at 2.45 GHz For Energy Harvesting, APS-URSI2019, ATL, US.
- **M. M. Mansour**, and H. Kanaya, Implementation of a High-Efficient and Simple CPW Rectenna at the 2.45 GHz ISM Radio Band, accepted for publication in WPTC19, London, UK.

Declaration

I declare that the information reported in the current dissertation is the result of my own work, except where due to reference is made. The thesis has not been accepted for any degree and is not concurrently submitted to any candidature for any other degree or diploma.

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August, 2019