



Investigation of Ambient Radio-Frequency Energy Harvesting Circuits on Recyclable, Low-Cost and Eco-Friendly Substrates

Linge Pangsui Usifu

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**Investigation of Ambient Radio-Frequency
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Low-Cost and Eco-Friendly Substrates**

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DEDICATION

To My Father Linge Tatah Sule and My Little Daughter Pangsui Bashira

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ABSTRACT

The number of connected Internet of Thing (IoT) devices is increasing tremendously daily. IoT devices are involved in a wide spectrum of applications in sectors such as telecommunications, educational, healthcare, agricultural, financial, and industrial. Maximizing the use of IoT devices entails powering them autonomously. Among environmental sources (solar, mechanical, wind, Microbial fuel cells, etc) available for powering IoT devices, Radio Frequency Energy Harvesting (RFEH) is a practical if not convenient candidate, especially as the connections amongst IoT devices are mainly wireless. Besides the ecological issues are more and more pressing. The context of this work is to study the possibilities of designing RFEH systems on low-cost, eco-friendly, and recyclable substrates. These substrates include polymers and papers, usually not used in designing conventional RFEH circuits. The chosen materials for designing RFEH circuits are Polylactic acid polymer (PLA) and Cardboard paper. These substrates are environmentally friendly and cheap, and they are recyclable. This thesis has three main parts. The first part of this thesis is to study and characterize the selected substrates. Using fuse deposition modelling (FDM) as an additive manufacturing approach, PLA polymer is printed layer by layer. Using the Two Transmission Line (TTL) approach, the relative permittivity and loss tangents of the PLA and Cardboard substrates are determined. Cardboard paper substrates are selected from packaging wastes. The RF properties are fundamental in designing antennas and RF-DC rectifiers. Utilizing copper tapes to create conductive traces for transmission lines, antenna designs, and RF-DC rectifiers has further reduced costs and manufacturing burden. The second part of this work is to use the extracted RF properties to design antennas for capturing RF signals from the surrounding environment. The first antenna design is a Linearly Polarized (LP) microstrip patch antenna at 2.45 GHz. The second concept focuses on a Circularly Polarized (CP) patch to address the problems caused by polarization mismatch. The design of the RF-DC rectifiers is the third section of this thesis. This part discusses the techniques of matching a rectifier to an antenna with a $50\ \Omega$ impedance. Additionally, discussed is the method for determining the rectifiers' ideal load to adapt them to a power management unit (PMU). This part also discusses the concept of optimal input impedance of rectifiers, and rectifiers are designed with input impedance value different from $50\ \Omega$. The results are quite comparable to rectifiers designed on standard RF substrates on the one hand and polymers as in literature in another hand.

Keywords: Antennas, Cardboard, Low-cost, Eco-friendly, Fuse Deposition Molding, Maximum Power Point, Polylactic Acid, Radio Frequency Energy Harvesting, Recyclable.

RESUME

Le nombre d'appareils connectés à l'Internet des objets (IoT) augmente considérablement chaque jour. Les applications des appareils IoT sont présentes dans des secteurs tels que les télécommunications, l'éducation, la santé, l'agriculture, la finance et l'industrie. Maximiser l'utilisation des appareils IoT implique de les alimenter de manière autonome. Parmi les sources environnementales (solaires, mécaniques, éoliennes, piles à combustible microbiennes, etc.) disponibles pour alimenter les appareils IoT, la récupération d'énergie par radiofréquence (RFEH) est la meilleure candidate pour ce travail. Le cadre de ce travail est la recherche et l'étude des possibilités de conception de systèmes RFEH sur des substrats peu coûteux, écologiques et recyclables. Ces substrats comprennent des polymères et des papiers, pour la plupart non utilisés dans la conception de circuits RFEH. Le polymère d'acide polylactique (PLA) et le papier cartonné sont choisis pour la conception des circuits RFEH. Ces substrats sont respectueux de l'environnement, bon marché et leur recyclabilité a été prouvée. Cette thèse comporte trois phases principales. Ces phases sont décrites ci-dessous. La première partie de cette thèse consiste à étudier et caractériser les substrats choisis. La modélisation par dépôt de fusible (FDM) est utilisée pour imprimer le polymère PLA couche par couche. Les tangentes de perte et la permittivité relative des substrats PLA et carton sont extraites à l'aide de la méthode à deux lignes de transmission (TTL). Ces propriétés sont fondamentales dans la conception d'antennes et de redresseurs RD-DC. Une minimisation supplémentaire des coûts a été réalisée en utilisant des bandes de cuivre pour créer les traces conductrices pour les lignes de transmission, la conception des antennes et des redresseurs RF-DC. La deuxième partie de ce travail consiste à utiliser les propriétés RF extraites dans la première phase pour concevoir les antennes permettant de capturer les signaux RF de l'environnement. La première conception d'antenne est une antenne patch micro ruban à polarisation linéaire (LP) à 2,45 GHz. Pour surmonter les défis liés à l'inadéquation de la polarisation, la deuxième conception se concentre sur le patch à polarisation circulaire (CP). L'optimisation de la bande passante se fait en concevant des antennes multiples et à large bande. La conception des redresseurs RF-DC constitue la troisième section de cette thèse. Cette phase aborde les techniques d'adaptation d'un redresseur à une antenne avec une impédance de 50 Ω . De plus, la méthode permettant de déterminer la charge idéale des redresseurs afin de les adapter à une Power Management Unit (PMU) est discutée. Cette phase aborde également le concept d'impédance d'entrée optimale des redresseurs, et les redresseurs sont conçus avec une impédance d'entrée différente de 50 Ω . Les résultats sont comparables à ceux des redresseurs conçus sur des substrats RF et des polymères standards de la littérature.

Mots clés : Antennes, carton, économique, écologique, dépôt de fil fondu, point de puissance maximale, acide polylactique, récupération d'énergie radiofréquence, recyclable.

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LIST OF ABBREVIATIONS

Advanced Designed Software	ADS
Axial Ratio	AR
Circular Polarization	CP
Control Unit	CU
Direct Current	DC
Defected Ground Structure	DGS
Electroless Deposition	ELD
Electromagnetics	EM
Electromagnetic Energy Harvesting	EME
Electromagnetic Field	EMF
Energy Harvesting	EH
European Union	EU
Fused Deposition Modelling	FDM
Frequency Modulation	FM
Full Wave Rectifier	FWR
Global System for Mobile Communication	GSM
Harmonic Balance	HB
Half Power Beam width	HBPBW
High Temp	HH
Half Wave Rectifier	HWR
Integrated Circuit	IC
Internet of Things	IoT
Liquid Crystal Polymer	LCP
Large Signal Scattering Parameter	LSSB
Linear Polarization	LP
Microbial Fuel Cell	MF
Micromagnetic Field	MF
Magnetic Tunnel Junction	MJC
Magnetic Tunnel Junction	MJC

Maximum Power Point Tracking	MMPP
Maximum Power Point	MPP
Magnetic Tunnel Junction	MTJ
Nicholson Ross Weir	NRS
Power Conversion Efficiency	PCE
Printed Circuit Board	PCB
Printed Electronics	PE
Polylactic Acid	PLA
Power Management Unit	PMU
Polyethylene Terephthalate	PET
Radio Frequency	RF
Radio Frequency Energy Harvesting	RFEH
StereoLithography Apparatus	SLA
Surface Mounted Device	SMD
Two Transmission Line	TTL
Vector Network Analyzer	VNA
Voltage Standing Wave Ration	VSWR
Zero Bias Resistance	ZBR

CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

Improving communications among devices entails getting them all connected to the internet. This is a typical scenario of the Internet of Things (IoTs). In 2018 and 2023, there were approximately 23.14 billion and 51.11 billion, of connected IoT devices respectively. These figures are expected to rise to 80 billion and 500 billion by 2025 and 2030 respectively [1], [2]. Powering these billion of rising IoT devices has become one of the main challenges in recent years. According to the report provided by the European Union, about 78 million batteries will be dispatched per day, by 2025 if nothing is done to extend their lifespan [3]. Using batteries to power these devices is no longer the best solution because of the following reasons;

- Continuous deposition of batteries to the environment causes a lot of environmental pollution.
- Battery replacement requires constant human interaction with IoT devices and this can be tedious, especially in hard-to-reach areas.
- In the case of biomedical devices, additional surgeries are done to replace batteries. It places patients at higher risk of being infected and makes it an economic burden on healthcare institutions [4].

A considered solution to this problem or at least to reduce the number of discarded batteries is to develop self-autonomous devices by integrating energy harvesting circuits into IoT devices. Natural energies available in the environment are wind, thermal, mechanical vibrations, solar, friction, RF waves, or organic wastes [4][5][8] [9][10]. Among them, Radio Frequency Energy Harvesting circuit becomes a good candidate when there is no sun, wind, or heat or when objects are motionless. Radio Frequency Energy Harvesting seems to be an ideal solution in powering these rising IoT devices, since the connection between them are mainly wireless. Adjusting IoT devices to automatically get their source of power from the environment will enable them to be somehow self-autonomous, as there will be less interaction with the user in the process of battery replacement.

1.2 RF Energy Harvesting System

The RF energy harvesting system consists of an antenna, a matching network, an optional power management circuit, and the load. Figure 1.1 shows a functional block diagram of each subsystem of the RF energy harvesting circuit.

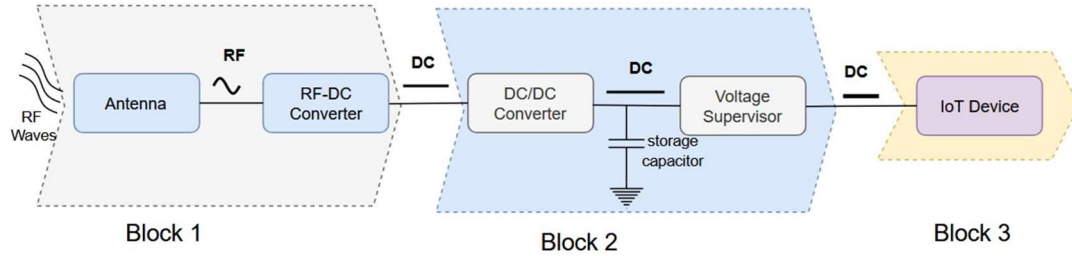


Figure1.1: Functional diagram of RF energy harvesting system

In Figure 1.1, the rectenna block (block #1) consists of both the antenna and the rectifier. This block helps to capture the RF waves from the environment and convert them into DC currents and voltages. In this block, the wave capturer is the antenna and the RF-DC converter (rectifier) processes the captured waves and convert them to DC currents and voltages. The power management unit (block #2) is an optional block, which is a DC-DC converter. It helps to boost and regulate the rectified voltage only when the DC voltage is not large enough to power the consumption load. The power management unit is usually an integrated or discrete circuit. The third block is the consumption load. It can be a microcontroller, a low-power consumption LED, or any IoT sensor device.

In this work, block one will be our main focus because it deals with the antenna and rectifier that will be implemented on the chosen low-tech substrates. The substrate is one of the most important components in designing RFEH circuits. Conventional substrates are often used for this purpose. However, these are high-tech materials that are not yet recyclable and nonfriendly to the environment. It is important that this gap should be bridged by studying the possibilities of implementing RFEH circuits on low-tech materials that are eco-friendly and recyclable. Since block 1 is the most important block in this work, our grasp of several issues about RF and electronics at low power levels needs to be improved to address the challenges involved in constructing RFEH circuits on conventional substrates. Therefore, it is interesting to classify the difficulties in terms of scientific questions as follows:

1.3 Scientific Questions

- RF properties of PLA polymer and Cardboard paper over a wide range of frequencies.
- Concept of Antenna and Rectifier on low-tech, recyclable and eco-friendly materials.
- Conductor properties (roughness, conductivity) on polymers and papers.
- The methodology of simulating antennas and rectifiers on low-tech and recyclable materials.
- Types and forms of antenna on low tech, recyclable and eco-friendly materials.
- Electrical interconnection of components and their functions on polymers and papers substrates.

To show that these scientific questions are well structured to answer the shortcomings using non-recyclable and high-tech materials from literature, we have some key demonstrators given in section 1.4.

1.4 Context and Motivation of the study

In RFEH, conventional substrates (FR4 and Rogers) are typically used to fabricate RF energy harvesting circuits, because of their superior RF properties. Their primary disadvantages are their lack of environmental friendliness, relative high cost of manufacturing (mass-production is necessary), and inability to recycle and dispose of. Besides, these substrates cannot be used easily to create complicated 3D structures.

To bypass these limitations, we have the following demonstrators;

- 1) The use of PolyLactic Acid Polymer (PLA¹) as a demonstrator in RF energy harvesting. PLA is compatible with a cheap printing technology (Fuse Deposition Modelling) and it is eco-friendly.
- 2) Demonstrators based on Cardboard paper as a substrate in RF energy harvesting. Cardboard paper material is more eco-friendly, cheaper, and easily recyclable than PLA polymer. In this thesis, recycled cardboard materials were chosen from dustbin. The demonstrators have been fabricated using second-hand paper materials.

¹ For material point of view, there are a lot of PLA flavors. We will not enter these considerations here. We only consider that PLA under certain circumstances is compostable. It was demonstrated recently that PLA could be turned into monomer again: it is a proposal of recycling for circular economy, [Goument, C., Gerges, T., Lombard, P. et al. In-Mold Electronics on Poly(Lactic Acid): towards a more sustainable mass production of plasmonic devices. *Int J Adv Manuf Technol* 125, 2643–2660 (2023). <https://doi.org/10.1007/s00170-023-10878-4>]

- 3) The flexibilities of PLA and Cardboard materials will be demonstrated by curving or bending them to create more interesting shapes and forms and designing RF circuits on them.
- 4) This thesis employs a short-time scheme of making conductive tracks on cardboard or PLA material by using copper tapes. Using copper tapes does not require any additional resources unlike elaborate techniques (electroless deposition, electrodeposition, and inkjet printing) frequently employed in the state of the art.

In summary, the demonstration of low-tech materials for rectenna design is the fundamental motivation of this work. Low-tech materials here mean simple constructed materials, using local and preferably natural materials or easily available wastes. Using local materials reduces the overall cost of fabricating RFEH circuits.

1.5 Objectives of the study

The main objective of this work is to investigate the design of RF circuits (antennas and rectifiers) on low-tech materials that can be recyclable and are eco-friendly to the environment. The following tasks will be accomplished to meet up with the main objective;

- Selecting two low-tech, eco-friendly and recyclable materials (PLA and Cardboard).
- Characterization of the printed PLA and Cardboard paper substrates using the Two Transmission-Line method (TTL).
- Designing RF energy harvesting circuits on the characterized substrates.

1.6 Organization of thesis

This work has seven chapters. Chapter two reviews the state of the art on RF energy harvesting. A measurement of power densities from some cities is also presented. The Two Transmission Lines method, which is used to extract the RF properties of the selected substrates is covered in Chapter 3. The extracted dielectric constant and loss tangent values are the focus in this chapter. In Chapter Four, the construction of antennas on Polylactic acid polymer and cardboard is addressed. In this chapter both linearly and circularly polarized antennas are designed. The design and implementation of different bands of antenna is presented in this chapter. Thereafter, the results of the radiation pattern measurement in an anechoic chamber are presented. In chapter five, the implementation of the rectifiers on both materials is addressed. The main electrical properties that will be addressed are the DC voltage and DC power. A detailed description of the design and

fabrication process is provided. Results from characterization are equally presented. The optimal input impedance of the rectifier is discussed in chapter six. Simulation and experimental results at different input impedances are given. The chapter also gives methods for characterizing a rectifier at a non50 Ω input impedance. Finally, in chapter seven, the conclusion and perspectives are given.

CHAPTER 2

STATE OF THE ART ON RF ENERGY HARVESTING

2.1 Introduction

Many types of energy harvesters exist, some of which include solar energy harvester [4], [5], piezoelectric energy harvester [9], thermal energy harvester [8], mechanical energy harvester [7], [8], microbial fuel energy harvester [17] [18] and radio frequency energy harvester. Energy can also be harvested from a combination of more than one harvester [14], [15]. High power density is provided by thermal energy harvester, yet its main flaw is its intermittency [4], [5]. There are numerous sources for mechanical energy harvesters, but their implementation calls for a sizable space [8]. This is a significant obstacle, particularly when downsizing is required. Energy can be extracted from a wide range of sources using microbial fuel cells, but their implementation requires considerable surface area. Since the connections amongst IoT devices are mainly wireless, harvesting energy wirelessly from RF sources seems a good solution for powering these increasing number of IoT devices. At very high frequency (as in the case of 5G for the mm Wave band), it will be very easy to integrate the energy harvester into IoT devices because of the very small size of the energy harvesting circuit.

RF waves are becoming more widely available due to the advancement of communication

Table 2.1. Classification of energy harvesters, power densities, advantages and disadvantages

EH	Power Density	Advantages	Disadvantages
Solar	10 $\mu\text{W}/\text{cm}^2$ - 100 $\mu\text{W}/\text{cm}^2$ [16] [17] (Indoor) 15 mW/cm^2 - 100 mW/cm^2 [17] [16] (outdoor) 10 - 200 $\mu\text{W}/\text{mm}^2$ [18]	High power density, and highest Output power	Intermittent Orientation issues
Thermal	60 $\mu\text{W}/\text{cm}^2$ [16], [19] 10 mW/cm^2 [16] 1 - 10 mW/cm^2 [18] 35 $\mu\text{W}/\text{cm}^2$ [17]	Can be oriented in any direction.	large area. Intermittent
Mechanical	4 $\mu\text{W}/\text{cm}^2$ [17] 0.4 - 30 $\mu\text{W}/\text{mm}^2$ [18]	Has a vast number of sources	Large size
Microbial fuel cells	1.1 $\mu\text{W}/\text{cm}^2$ [20] 6 - 8 W/m^2 [21]	High efficiency and Variety of sources	High cost

Radio	0.1 $\mu\text{W}/\text{cm}^2$ (GSM)[17], 0.01 $\mu\text{W}/\text{cm}^2$ (WiFi) [17]	Always available Easy Implementation	Lowest power density
Frequency	0.01 $\mu\text{W}/\text{cm}^2$ [16],1 $\mu\text{W}/\text{cm}^2$ [22]	High efficiency	

EH: Energy Harvester

technologies. The low power densities of RF signals are a primary drawback, as they might be insufficient for present-day IoT devices. Also, RF sources in the environment are notoriously fluctuating. As a result, it becomes challenging to design a rectifier to operate at a particular input power. It poses a significant challenge to the efficient design of matching circuits. Despite these challenges, it remains an intriguing option for cleaner and greener energy harvesting technology. Table 2.1 provides an overview of the energy harvesters' power densities, benefits, and drawbacks.

2.2 Sources and Power Densities of Ambient RF Energy Harvesting

Wireless communication devices are increasing tremendously, especially in urban areas. Base stations, mobile telephones, radio stations, television stations, and other RF transceivers are everywhere to maintain communications. Some of these sources are summarized in Table 2.2. *Table 2.2: Frequencies Available for RFEH*

Band	Uplink frequency, (MHz) UE Transmit	Frequency Range	Downlink frequency (MHz) UE receive
GSM 900/LTE	880-915 MHz	---	925 – 960 MHz
GSM 1800/LTE Band 3	1710 – 1785 MHz	---	1805 – 1880 MHz
UMTS Band 1	1920 – 1980 MHz		2110 – 2170 MHz
ISM WiFi 2.4 GHz		2400 – 2495 MHz	
FM	---	88 – 108 MHz	---
GSM 1900 MHz	1850-1910 MHz	---	1930-1990 MHz
WiFi 5 GHz	---	5150 – 5850 MHz	---

The first thing to keep in mind before harvesting RF energy from the surrounding environment is the available power density. Each of the sources in Table 2.1 has a different power density. These densities vary with respect the frequency and the distance from the source. Literature reports different power levels at various locations. Khalid et al [24] performed RF power density measurements in a semi-urban region (Figure 2.1). The measurements are for indoors and outdoors using a portable spectrum analyzer and a set of broadband omnidirectional whip antennas. At GSM900 band, the measurements for indoor and outdoor readings were -35 dBm and -15 dBm, respectively.

Other indoor measurements were -38 dBm, -50 dBm, and -48 dBm for FM, GSM 1800 MHz, and WiFi 2.45 GHz, respectively. Other measurements were conducted by authors in [25] at

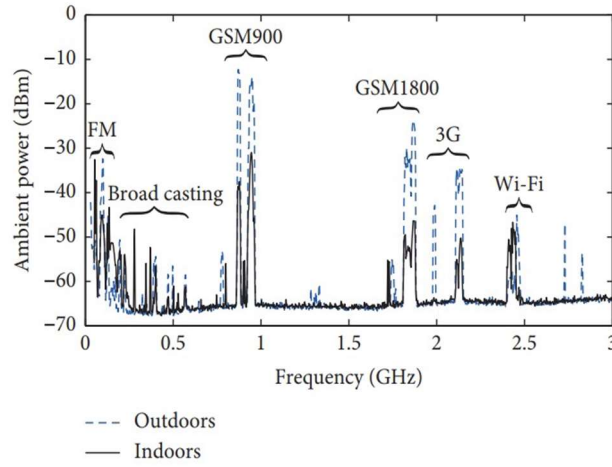


Figure 2.1: Khalid et al Peak ambient versus frequency in an urban environment [24]

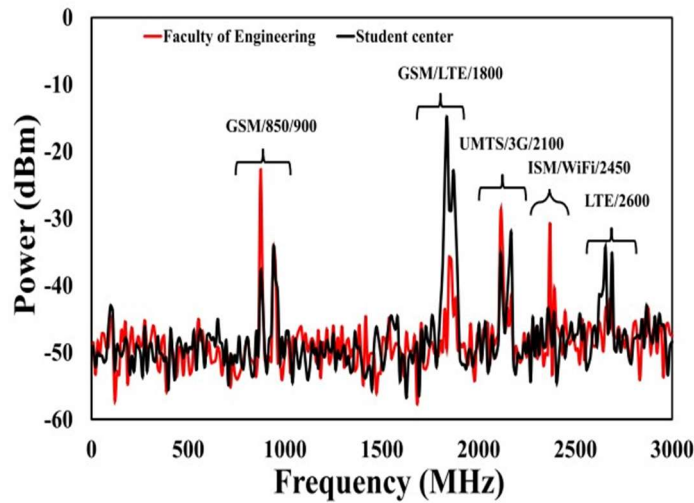
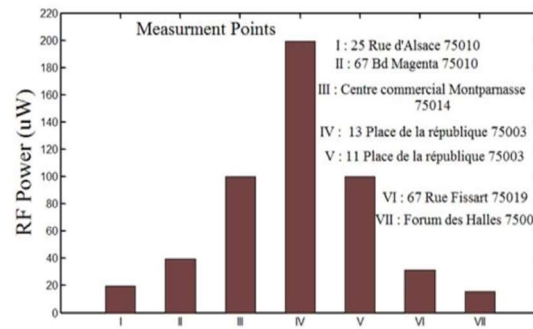


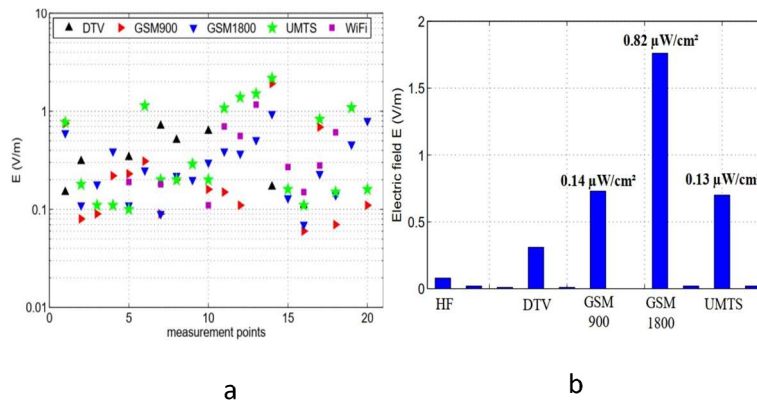
Figure 2.2: Measured ambient RF power density at Multimedia University, Cyberjaya Campus in Malaysia [25]

Two distinct places at Multimedia University, Cyberjaya Campus in Malaysia (Figure 2.2). The results obtained were -25 dBm, -40 dBm, -30 dBm, -37 dBm, and -45 dBm for GSM/850/900, GSM/LTE/1800, UMTS/3G/2100, ISM/WiFi/2450, and LTE/2600, respectively at the faculty of engineering laboratory. Further field measurement surveys were conducted by Khemar and collaborators in Paris [26] (Figure 2.3). The measurements set up consisted of a portable EM field meter (CORNET ED85EX) operating in the frequency band of 1MHz to 8 GHz with a dynamic ranging from -55 dBm to 0 dBm. The result varies from 0.1 to 100 μ W depending on the measurement site. The

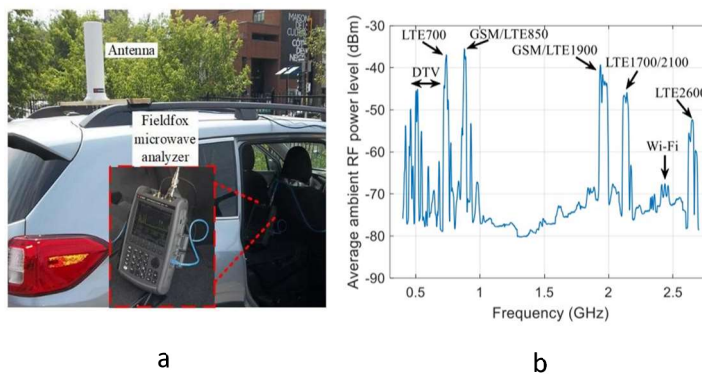
highest average measured outdoor power was predicted in the GSM 1800, UMTS band 1, and LTE 2600 bands. The authors in [27] presented measurements of estimated ambient electric field strength performed by the National French Agency for Frequencies Management (ANFR) in Paris. Figure 2.4a displays the electric field strength values for 20 places near a base station. Figure 2.4b shows the histogram when the measurement was performed 190 meters away from an RF transmitter.



Figur23:Measured ambient RF power levels at different lφ26tions in



Figur24:Examples of measurements conducted by the ANFR in Paris and surroundings(A), measurements of electromagnetic field, at 190 m from a radio transmitter, conducted by the ANFR Paris region (B)



Figur25: a) Ambient RF power measurement in Montreal. (b) Average RF power levels in DT Montreal

Narda SRM 300 spectrum analyser with an isotropic probe was used by [28] to measure the electromagnetic field (EMF) strength close to a base station in urban areas of

Cheltenham, Gloucestershire. Authors in [29] measured the outdoor dynamic ambient RF power density in the core area of downtown (DT) Montreal City, Canada (Figure 2.5). The measurement covers

a frequency range from 400 MHz to 2700 MHz. The optimum bands for RF energy harvesting, according to the research, are GSM/LTE850 and LTE700 for cellular communication.

Keysight's Fieldfox microwave analyzer N9951A and wideband omnidirectional antenna N6850A were employed. Aline Eid et al [30] used a support vector machine to predict the time and location of maximum WiFi coverage for RFEH. The power values were collected at five different locations over three months at the University of Cyprus. Figure 2.6 displays a representation of the data that was gathered at a specific place over three weeks. The power value on average was -40 dBm.

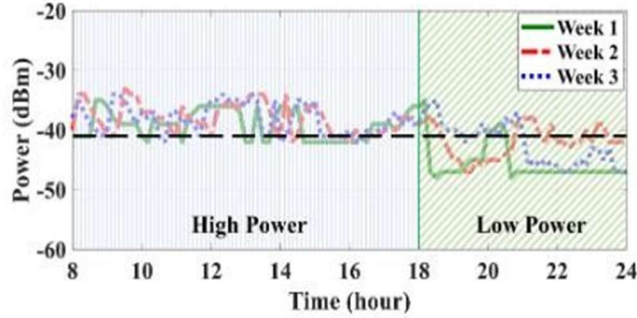


Figure 2.6: WiFi data collected over a period of three weeks at a particular location

2.3 Partial Conclusion

An overview of the state-of-the-art on ambient RF power density for WiFi and GSM900 frequencies is provided in Table 2.3. From the literature, the measured ambient power for GSM 900 is greater than that for WiFi. The values for GSM ranges approximately from -25 dBm to -89 dBm. For WiFi it ranges from -45 dBm to -120 dBm. From the literature, it is still impossible for GSM900 and WiFi sources to power low-power sensors such as HTS221(capacitive digital sensor for relative humidity and temperature) and STTS22H, which is a low-voltage, ultralow-power temperature sensor. The HTS221 sensor uses a supply voltage between 1.7 and 3.6V as well as a current of 2 μ A at 1 Hz [31]. STTS22H requires 1.75 μ A under 1.5V to 3.6V[32]. Another ultra-low-power IoT device is the STM32L052 microcontroller. It requires a minimum supply voltage of 1.65 V and a supply current of 88 μ A/MHz [33]. In the medical domain, we have biomedical devices and their power consumption mentioned in [34] and summarized in Table 2.4.

In this thesis, we have chosen an input RF power of -20 dBm/10 μ W and -10 dBm/100 μ W for rectifiers designed on PLA and Cardboard substrates, respectively. The selected values will be able to power microcontrollers and many of the biomedical sensors listed in Table 2.4. So far, the demonstration is not close to surrounding environment RF power (less than 40 dBm) but neither close to illuminated conditions (generally accepted above 0 dBm).

Table 2.3:RF power densities measurements from state of art

Frequency Band	Power density	Location	Tools Used	Ref
2.45 GHz	-93.23dBm	automobile manufacturing plant in the UK	long periodic antenna (EM-6947), R&S ESPI-7 spectrum analyser	[35]
2.45 GHz	-46 dBm	Semi urban area (indoor)	portable spectrum analyser and a set of broadband omnidirectional whip antenna	[24]
2.45 GHz	-48 dBm	Semi urban area (outdoor)	portable spectrum analyser and a set of broadband omnidirectional whip antenna	[24]
2.45 GHz	-40 dBm	Multimedia University Cyberjaya Campus, Malaysia (faculty of Engineering)	Aim TTI PSA6005 6 GHz RF spectrum analyzer.	[25]
2.45 GHz	-45 dBm	Multimedia University Cyberjaya Campus, Malaysia (student centre)	Aim TTI PSA6005 6 GHz RF spectrum analyzer.	[25]
2.45 GHz	-70 dBm	Down Town (DT) Montreal city, Canada	wideband omnidirectional antenna N6850A, handheld Fieldfox micro-wave analyser N9951A from Keysight	[29]
900 MHz	-40 dBm	Down Town (DT) Montreal city, Canada	wideband omnidirectional antenna N6850A, handheld Fieldfox micro-wave analyser N9951A from Keysight	[35]
900 MHz	-35 dBm	Semi Urban area (Outdoors)	portable spectrum analyser and a set of broadband omnidirectional whip antenna	[24]

Table 2.4: Average power requirements and specifications of various biomedical devices

Biomedical Device	Power Consumption	Application	Ref
Pulse oximeter	294 mW	Measures the oxygen saturation level	[36]
Hearing aid	1.82 mW	Amplifiers sound for patience with hearing loss	[36]
Cochlear implant	100-2000 μ W	Stimulates the cochlear nerve electrically	[37]
Pacemaker IC	0.28 mW	Monitors heart rate	[36]
Drug pump for Ophthalmic use	400 μ W	Controls drug delivery	[38]
Neutral activity monitoring recorder	1 – 10 mW	Records brain activities	[39]
Combo insulin pump	15 mW	Deliver insulin, monitors blood glucose levels	[36]
Wireless intraocular pressure monitor	3.65 nW	Frequent measurement of intraocular pressure	[40]
Health monitoring sensor on wristband	0.83 mW	Monitors chronic respiratory disease	[41]
Electrocardiogram amplifier	2.76 μ W	Transfers weak electrical signals from the heart into signals that can be transmitted to a monitoring system	[42]
Spirometer	0.01 mW	Measures FEV1, PEF, FVC	[41]
Retinal prostheses	250 mV	Stimulates the retinal	[43]
Cardiac activity Sensing	0.3 μ W	Monitors vital signs	[44]

2.3.1 Rectifiers

In RFEH, the rectifier converts the captured electromagnetic waves from the antenna to DC currents. Researchers focus on constructing rectifiers on conventional substrate for RFEH applications. Besides, most of these substrates cannot be used to create advanced 3D structures. Many studies are nonetheless being conducted on using polymers and paper substrates for RF energy harvesting solutions because of their many benefits. The

drawback of such technologies is the high surface roughness and low melting points of some polymers, making the brazing of SMA components challenging. Besides, great effort has been made in selecting polymer substrates that meet the goals of this thesis. Using copper foils makes brazing relatively easier as compared to electroless and electrodepositions, which are often used to create conductive traces on polymers. Because of the increased RF losses caused by this significant surface roughness, the overall performance of the circuit decreases. However, we have developed a method to make the surface smoother after printing. In this section, we will discuss the state of the art of rectifiers based on the type of topology. Before proceeding, we must lay the foundation by looking at some key concepts of rectifiers.

2.4 Some Key Concepts on Rectifiers

2.4.1 Rectifier Efficiency

Designing a rectifier with satisfying efficiency is indeed challenging. This is because of the non-linear behaviour of the diode (Schottky) used in rectification and the very low fluctuating RF power densities available in the environment. The performance of the circuit is determined by the non-linearity of Schottky diode barriers and series resistance losses. The non-linear nature of the diode is due to its junction capacitor C_d and junction resistor R_j [45] (Figure 2.7).

The behaviour of the diode changes due to a variation in input power, input impedance, matching network, operating frequency, and load impedance. Typically, the PCE (Equation 2.1) is used to express efficiency.

$$\eta_{RF-DC} = \frac{P_{dc}}{P_{RF}} = \frac{V_{dc}^2}{P_{RF} * R_L} \quad (2.1)$$

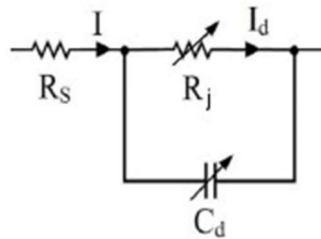


Figure 2.7: Equivalent model of Schottky diode without parasitic elements [45]

Transistors or diodes are used in the design of rectifier circuits [46]. Therefore, the type of diode plays a vital role in the performance of the rectifying circuit. The frequently used diodes for this purpose are Schottky HSMS-28xx, MA4E-1317 [47], and SMS-76xx

diodes [48]. HSMS-28xx has a low threshold voltage of 0.2 V and low junction capacitance (lower than PN diodes [49]) and is widely used for most RF-DC applications. The low junction capacitor increases the maximum frequency at which the diode can operate. HSMS-285x is a family of zero bias Schottky detector diodes designed and optimized for use in small-signal for input power less than -20 dBm and applications with frequencies below 1.5 GHz. For detecting applications with input power levels greater than -20 dBm, the HSMS-282x series at frequencies below 4.0 GHz is preferable. HSMS-286x series are suitable for frequencies above 4.0 GHz, while HSMS-285x series is not recommended for high power level applications (above 0 dBm). SMS7630 diode is preferable for low RF input power levels. One of the drawbacks of the SMS7630 diode is to know the exact values of the packaging elements. It poses an impedance mismatch problem after fabrication. The summarized characteristics and parameters of Schottky diode models are given in [50]. The diode with low junction parasitic capacitor (C_d) and low zero-bias resistance (R_d) are good candidates for RF-DC conversion [51]. This is because it increases the PCE of the rectifying circuit [45]. The authors in [52] compared several types of diodes in terms of detectable input radio frequency energy. Figure 2.8 displays plots of the system efficiency against the input RF power. The study showed that HSMS-2850 and SMS-7630 are the most suitable devices for low RF input power (less than -20 dBm), while HSMS-2860, HSMS-2820 and HSMS 2810 are suitable for high input RF signal. The authors in [51] postulated that Schottky diodes, CMOS devices, and MA4E-1317 diodes exhibited limited low-power rectification capabilities. Due to this limitation, a novel type of non-linear device called Magnetic Tunnel Junctions (MTJs), or simple spin diodes, was proposed. The main advantage of this device is zero-bias response and zero-bias resistance (ZBR). This device is based on the field of spintronics, which investigates the diode's spin effect in addition to its electronic charge. Another added advantage of this device over Schottky diodes is its lower ZBR and its ability to perform rectification at nanowatts of input power [53]. Unfortunately, this diode could not be used because it was not available during the designs of our circuits. In this work, SMS-7630 -079LF from Skyworks and HSMS-2850 from Avago technology will be adopted in designing the rectifying circuits. This is because of their low turn-on voltages and also because these diodes were readily available during our studies.

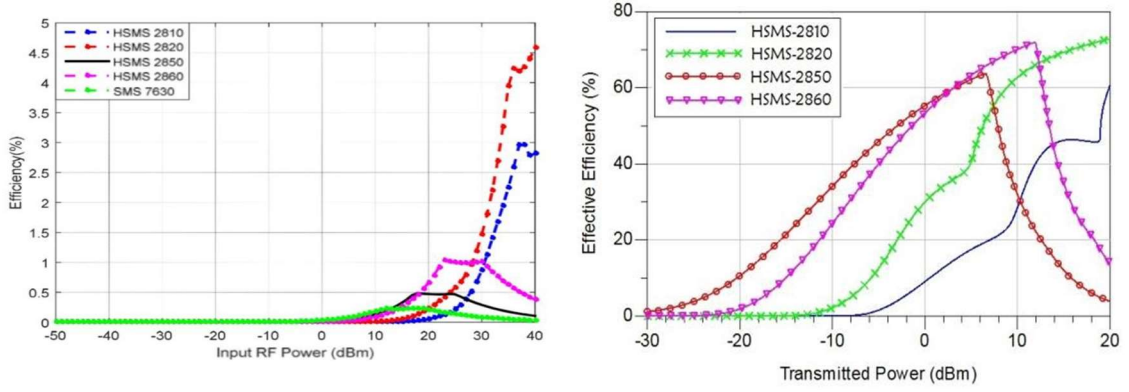


Figure 2.8: Comparing different diodes detection threshold [52]

2.4.2 Factors Affecting Rectifiers' Efficiencies (PCE)

Achieving high PCE at low input power is the target of RFEH circuits. We have deduced from the literature that, in most cases, the minimum power density ranges for GSM900 and WiFi signals are between -25 dBm to -89 dBm and -30 dBm to -120 dBm, respectively. Rectifiers from literature are usually designed at input powers higher than these values. This is partly to facilitate characterization in the Lab. These low input power contribute to the low values obtained for power conversion efficiency. Below are some additional explanations why the PCE values for RFEH circuits are usually low.

2.4.2.1 Threshold and reverse breakdown voltage

The threshold voltage limits efficiency at low input powers. The capacitor cannot be charged unless sufficient power is incident at the input of the energy harvester. The capacitor begins to charge up when the incident energy surpasses the threshold voltage of the diode. Diode breakdown voltage also limits PCE. The effect of the breakdown voltage occurs at higher power levels. The high power shuts down the diode when the diode DC bias voltage is equal to half the breakdown voltage [54]. Above this point, the efficiency decreases, but the DC power remains constant.

2.4.2.2 Impedance mismatch

A portion of the antenna's input power will be released back into the environment if the energy harvesting circuit and the antenna cannot match each other 100%. This reduces the amount of power being absorbed by the circuit for rectification, and consequently, PCE reduces.

2.4.2.3 Device parasitics

The diode junction resistor R_S and package parasitics decrease the rectifier efficiency. This is due to the dissipation of power by the resistor when current flows through the semiconductor junction [55]. Performance degradations of junction capacitor C_J and package inductance occur at higher frequencies. The junction capacitance limits the maximum frequency at which the diode can operate [54].

2.4.2.4 The presence of harmonics

Diode nonlinearity is another source of loss when converting from RF to DC [54]. The diode generates frequency harmonics from the input power. These harmonics reduce the amount of energy that can be converted to DC power. These harmonics increase as the incident power increases.

After discussing the main factors that lead to low PCE, let us discuss in detail the state of the art on RFEH applications while paying great attention on the substrate use and the PCE obtained from the various researches presented. The main aim of this chapter is to show that literature mainly uses high-tech materials that are not yet recyclable and non-eco-friendly in the construction of antennas and rectifiers for RF energy harvesting circuits. There are two types of rectifiers, half wave and full wave rectifiers.

2.4.2.5 Half-Wave Rectifiers (HWR)

In an HWR circuit, only a half cycle of the input wave is rectified. HWR can either be a series or a shunt configuration. In the series configuration, a single diode is connected in series and only the positive wave cycle is considered for rectification. In the shunt configuration, the diode is connected in parallel to the filter, and only the negative cycle of the wave is considered for rectification. Since this type of rectifier has just one diode, losses are minimized compared to full-wave circuits. This makes it suitable for low RF input power environment. The drawback of such a topology is the low output rectified voltage. Figure 2.9 shows the types of HWR circuits.

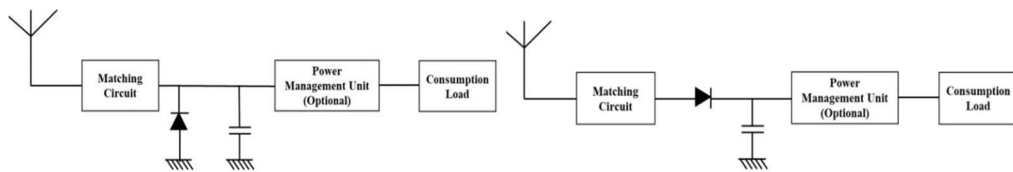


Figure 2.9: Half-wave rectifier (a) with shunt configuration (b) with series configuration

HWR has been used by majorities of researchers in literature. As a proof, High Temperature (HT) Resin V1 is used by the authors in [56] in a half-wave rectifier using an SMS-7630 diode at -24 dBm input power. At 2.45 GHz, a DC voltage of 72 mV and PCE of 13% were obtained, respectively (Figure 2.)

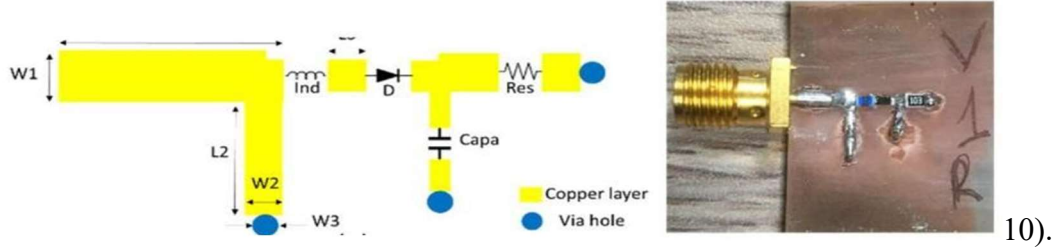


Figure 2.10: HWR rectifier with series configuration [56]

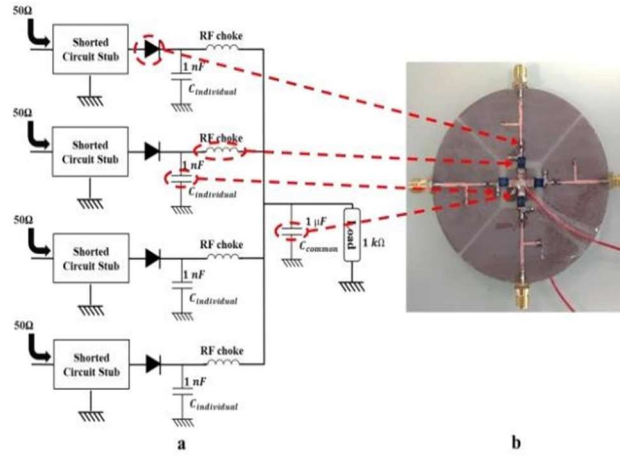


Figure 2.11: a) Schematic of the 4-port rectifier; b) Rectifier circuit fabricated using Plantronics [7].

HT Resin V1 was printed using a StereoLithography Apparatus (SLA), a method of 3D printing based on resin and not filaments. Another work carried out by the same authors using the same substrate is presented in [57]. The conductive tracks were copper ink deposited by an additive manufacturing process of electroless deposition (Figure 2.11). At an input power of -13 dBm, a global efficiency of 14% was obtained.

Liquid Crystal Polymer (LCP) has been used in [58] for fabricating flexible rectifiers at 2.45 GHz (Figure 2.12). SMS-7630 diode is used in the rectifying circuit. The PCE maintains a flat curve for a wide range of load values (between $0.1\text{k}\Omega$ and $7\text{k}\Omega$). A maximum PCE of 50% was achieved with a single series topology when the input power was 0 dBm.

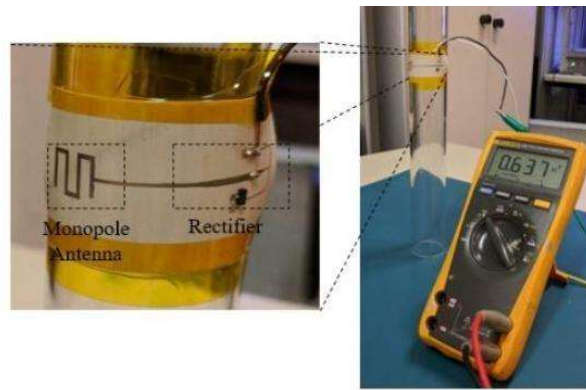


Figure 2.12: Flexible rectenna fabrication and measurement on LCP [58]

LCP is a high-temperature thermoplastic polymer. Brazing on it is not an issue. It has a low loss tangent (0.0022), making it suitable for RF energy harvesting circuits. LCP printing is unfortunately complex and expensive. A flexible folded dipole rectenna on Kapton substrate has been designed by authors in [59]. With an input power of -9 dBm at 3.5 GHz and a load value of 3 k Ω , a PCE of 53% was obtained. The rectifying diode is SMS7630-079LF in a single series half-wave topology (Figure 2.13).

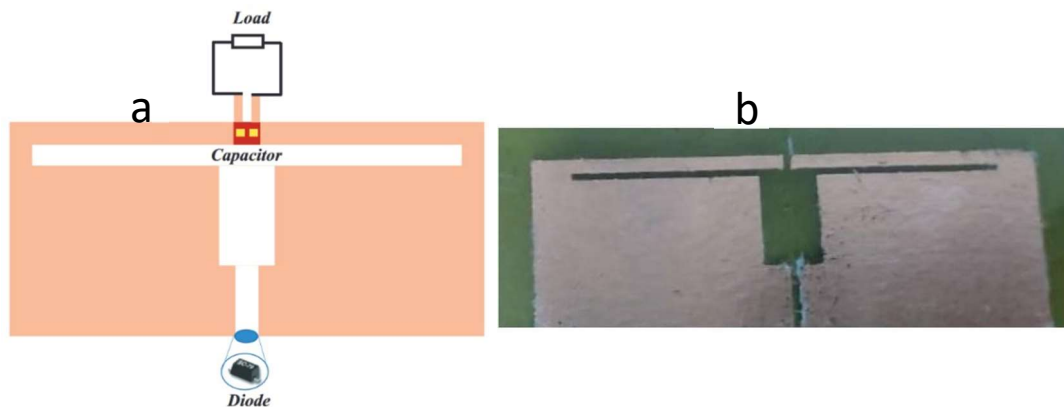


Figure 2.13: Kapton based rectenna for RFEH at 3.5 GHz (a) design (b) picture of fabricated rectenna [59]

Another flexible rectenna based on paper substrate is seen in the work of Palazzi et al [60]. The obtained efficiency was 40% at an input power of -10 dBm at 2.45 GHz. The rectifying diode is HSMS 2850, used in a single series topology. The load consisted of a 2.7 k Ω resistor. The fabricated rectenna is shown in Figure 2.14.

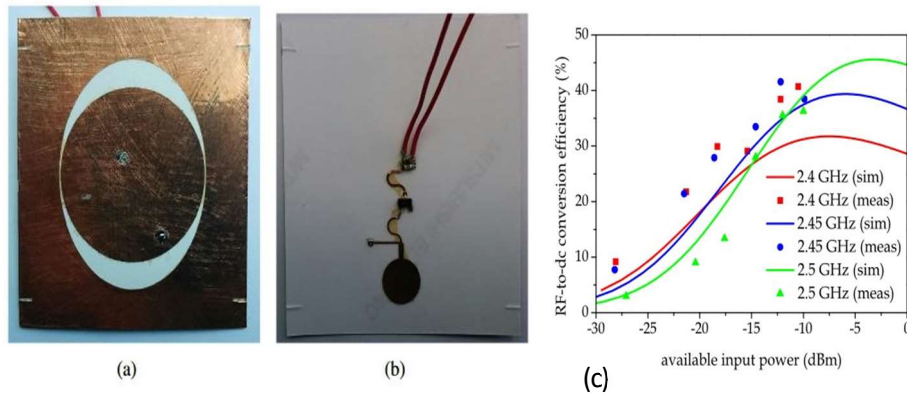


Figure 2.14: Rectenna on paper for FWR. (a) Top view, and (b) bottom view. Area: $4.9 \times 5.4 \text{ cm}^2$
(c) PCE vs. input power

More review of rectifiers and rectennas designed on flexible substrates is found in [61].

2.4.2.6 Full-Wave Rectifiers (FWR)

In a Full wave rectifier (FWR), there is a complete conversion of RF signal to DC voltage. Both the negative and positive cycles of the RF signal are rectified. FWR can either be a fullwave bridge rectifier, a voltage doubler rectifier, or the Greinacher rectifier. Figure 2.15 shows a voltage doubler FWR circuit. In the negative cycle, D2 conducts, D1 is blocked, and capacitor C2 charges up. In the positive cycle, D1 conducts, D2 is blocked, and C1 charges up. At the same time, C2 discharges its content to C1. Thus, the total output voltage across C1 and the load is almost twice the amplitude of the input RF voltage. A flexible rectifier based on full wave topology has been designed on a paper substrate [62] (Figure 2.16). The design works well in the frequency ranges of 0.79-0.96 GHz, 1.71-2.17 GHz, and 2.5-2.69 GHz.

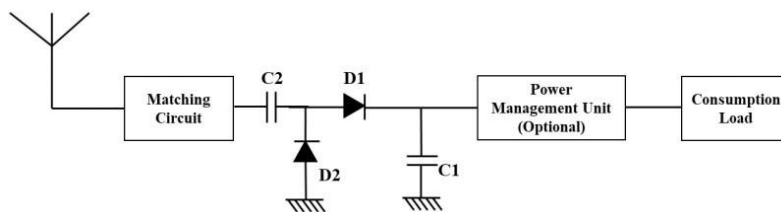


Figure 2.15: Voltage Doubler rectifier circuit configuration.

At -20 dBm, PCEs of 5-16% were obtained for a load value of 3 k Ω . The design consists of four series HSMS2850 Schottky diode rectifiers connected in parallel.

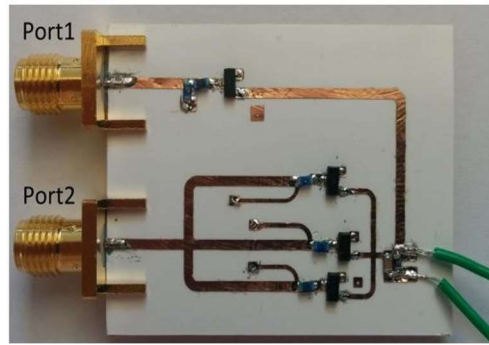


Figure 2.16: Fabricated full wave rectifier on paper substrate [62]

Paper substrate is low-cost, easy to manufacture, and available everywhere [63]. It is easy to fold paper into various shapes and forms. Copper conducting ink is deposited on the paper substrate using 3D inkjet printing. Paper is porous, just like the Cardboard material used in this work. Also, the life span of circuits on them is not long. The authors in [54] used hybrid printing electronics to print RF energy harvesting circuits on a low-cost, flexible polymer in the frequency band of 868 MHz to 915 MHz. On an open circuit, a PCE of 20% was achieved with an input power of -7 dBm. A dual-band textile-based rectenna fabricated on a 3.2 mm felt substrate with a loss tangent of 0.02 for Simultaneous Wireless Information and Power Transfer (SWIPT) using the voltage doubler topology has been investigated in [64] (Figure 2.17).

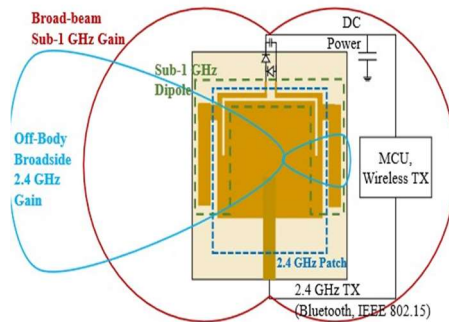


Figure 2.17: SWIPT antenna architecture for antenna communication and rectifier based on voltage doubler topology [64]

At an input power of $0.8 \mu\text{W}/\text{cm}^2$, the rectifier's conversion efficiency is 62% at 2.4 GHz.

Other rectifiers based on the voltage doubler topology can be seen in the works of [61]–[66].

2.4.2.7 RF Filter and impedance matching network

RF filter blocks the harmonics created by the diode in the rectifying circuit, providing matching between the antenna and rectifier. It prevents the harmonics from being radiated

by the antenna. Harmonics usually come because it is not easy to achieve 100% matching and the non-linearity of the diode. In the ideal case of a perfect matching network, no waves are reflected to the antenna. Below is a discussion of some matching methods and approaches.

2.4.2.8 Conjugated impedance matching

Conjugating the antenna's output complex impedance to the rectifier's input complex impedance is typically how it is accomplished (calculation of conjugate pair). This technique has been described in detail by authors in [72]. The demonstration of matching by conjugating impedances is shown in [64] (Figure 2.17). The antenna-rectifier co-design has been used to eliminate the matching network. The advantage of this technique is limited losses as a result of matching networks not using additional elements. Further examples of conjugate impedance matching are found in the research works of the authors in [66], and [67].

In designing matching networks, literature mostly focus at $50\ \Omega$ impedance, as it facilitates characterization in the Lab. Matching networks are constructed using lumped components, which can be capacitors or inductors. Microstrip lines (stubs) can also be used. Matching can also be done by using a mixture of both lump components and microstrip stubs.

2.4.2.9 Matching with Lumped Components

Inductors and capacitors are examples of lumped components used in matching networks construction. These passive devices are used because they do not dissipate power, hence they do not add noise to the circuit. They are preferable in the case of miniaturization as they do not take up much space. However, they incur more losses than microstrip lines. Besides, lumped components have limited frequencies of operation. The work in [75] provides a conceptual approach to dynamic impedance matching (Figure 2.18).

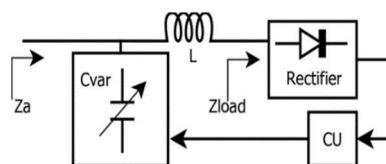


Figure 2.18 Conceptual approach for dynamic impedance matching [75]

Using an algorithm, the control unit (CU) determines the circuit's input power and selects the capacitance in the impedance-matching network that has the best value. The authors

in [76] achieved matching using two lumped components in an L-matching network structure (Figure 2.19).

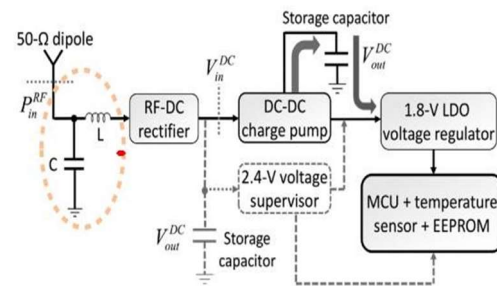


Figure 2.19: Lumped components used in matching of Rectifier design [76]

2.4.2.10 Matching with Microstrip Lines

Another way of implementing matching is using microstrip transmission lines. The main configurations are radial stub, short circuit stub, open circuit stub, quarter wavelength impedance transformer, and tapered line. The advantages of using stubs are their limited losses and the accuracy in designing the dimensions of the lines. However, the size of the lines becomes quite cumbersome when working at low frequency. Thus, this technique is preferred when working with a circuit at high frequency. Assogba et al [77] used microstrip lines in designing the matching network of triple bands rectifier. The rectenna was designed at 900 MHz, 1.8 GHz, and 2.1 GHz frequencies using a single series HSMS-285B diode topology. The matching is designed at -5 dBm with a varying load (Figure 2.20). FR4 substrate is used for the design.

The authors in [78] fabricated a rectifier using microstrip lines in a Π -matching network topology (Figure 2.21). The rectifier was designed to work at GSM-1800 and UMTS-2100 frequencies. A 5 k Ω load yields a PCE of 40%.

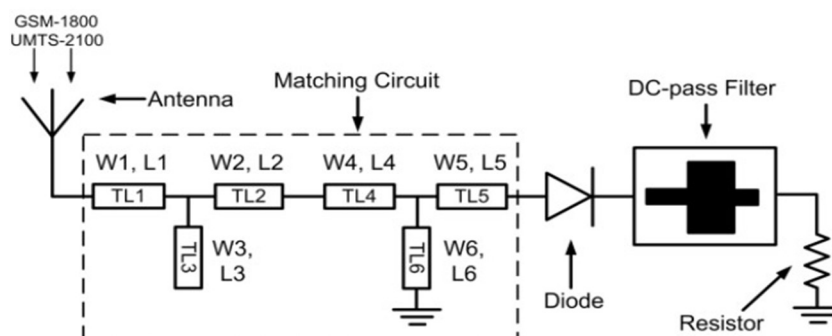


Figure 2.20: Topology of the dual-band rectifier with a microstrip matching circuit [78]

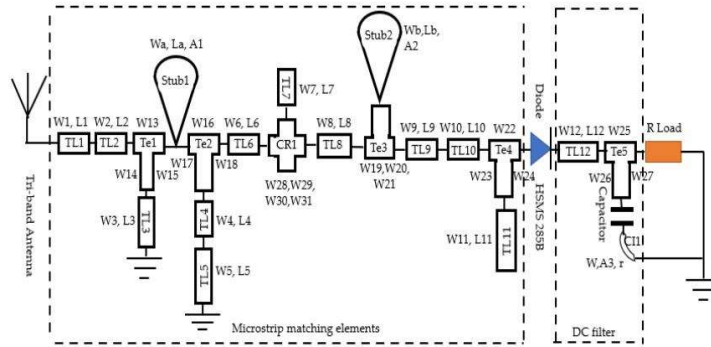


Figure 2.21: Topology of the tri-band rectifier with a microstrip matching circuit [77]

2.4.2.11 Matching with mixed elements

It is also possible to design matching using a mixture of both lumped components and microstrip transmission lines. As proof, Shen et al [79] designed a triple-band rectifier using mixed components (Figure 2.22).

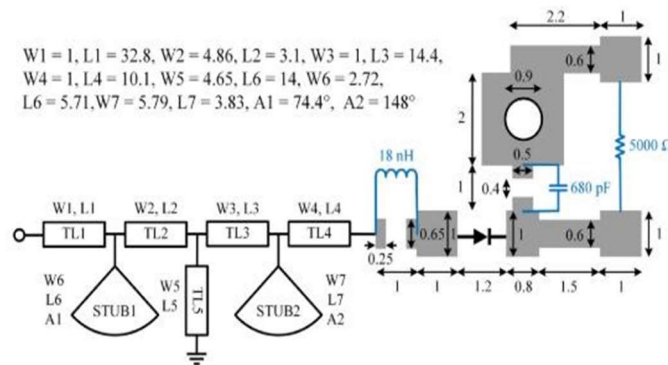


Figure 2.22: Topology of the triple-band rectifier with a microstrip matching circuit [79]

The rectifier was designed using SMS7630-079L diode on Duroid 5880 substrate. The rectifier resonates at GSM-900, GSM-1800, and UMTS-2100 frequencies. Measurement results showed that the prototyped dual-port triple-band rectenna can receive RF power from nearly all directions with an efficiency greater than 40% and an output voltage of more than 600 mV when the power density is greater than 500 $\mu\text{W}/\text{m}^2$. Another rectifier design using mixed components matching is seen in [80].

2.5 Antennas

The antenna picks up RF signals from the surrounding environment. The antenna is one of the most important parts of wireless communication systems. An effective antenna design can reduce system needs and boost overall system efficiency. Designing a good antenna is of utmost importance as the PCE of the rectenna depends on the efficiency of

the antenna. A good antenna structure is desired to have a high gain, omnidirectional radiational pattern, wide operating frequency, compact dimension, low profile [50], and high efficiency. In this thesis, we have chosen Microstrip patch and monopole antennas due to their light weight and low profile [81], [82], [83]. Patch antennas are easy to fabricate on many kinds of substrates, even on non-planar substrates such as the skin of an existing polymer object [56]. However, it has some limitations owing to its low gain, small bandwidth, surface wave excitation, and lower power handling capabilities [84], [85].

This section reviews the state of the art on antennas, and the types of bands of antennas (single, broad, and multiple bands antennas). The antennas designed on polymer and paper substrates will be the primary focus of the state of the art. Similar to the rectifier, depending on the design, an antenna can either be single band, multiple bands, or broadband.

2.5.1 Single band antennas

The antenna resonates at a single frequency. This type of antenna is often called resonant antennas. It is easy to obtain impedance matching for such antennas. The single-band antenna has the smallest bandwidth. Literature has addressed the design of resonance patch antennas on polymer substrates. As evidence, authors in [86] designed a resonant antenna on Cardboard using Inkjet 3D printing. The antenna design and return loss plots are shown in Figure 2.23a and b, respectively.

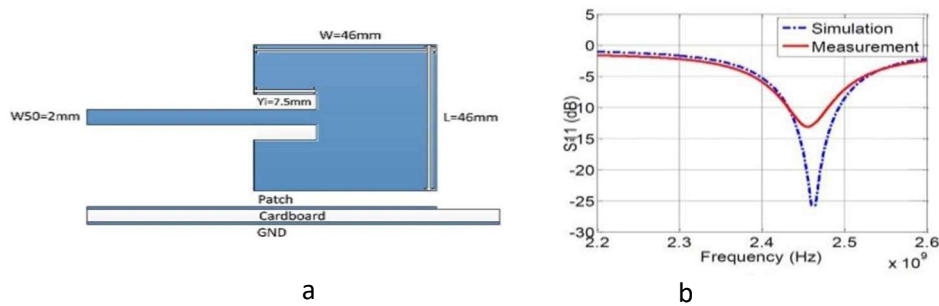


Figure 2.23: Design of Resonant antenna on Cardboard polymer substrate and return loss results [86]

A suitable material for creating patch antennas is high-temperature resin created by SLA [56]. The fabricated piece on 1.5 mm thick resin V1 and the return loss results are shown in Figure 2.24. The relative permittivity and loss tangent are 3 and 0.22, respectively. The antenna has a simulated and measured gain of 2.6 dB and 2.5 dB respectively.

SLA is quite an expensive 3D printing technology. Besides, liquid resin is also a high-cost material. These limitations made us shy away from using resin polymer in this work. Liquid Crystal Polymer (LCP) has good RF properties. Its dielectric constant is 2.9, and its loss tangent is 0.002. These properties are stable over a wide range of frequencies, making them suitable for antenna design [87]. A flexible patch antenna at 10 GHz has been designed on a 100 μm thick LCP substrate using copper as the conducting material. The major drawback of using LCP in designing RF energy circuits is the expensive 3D printing technology involved. In addition, LCP is not recyclable.

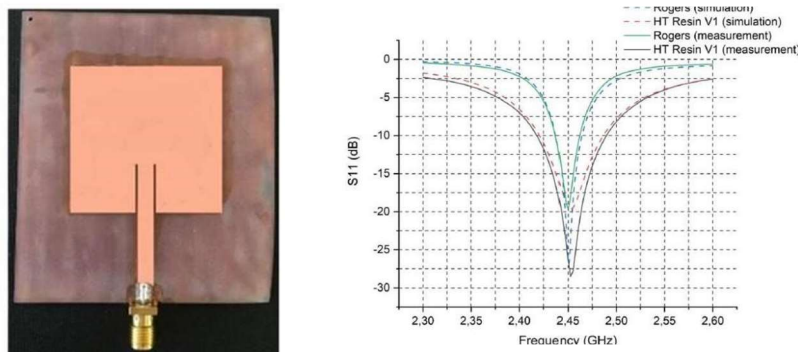


Figure 2.24: Stereolithography based patch antenna on high temperature resin

Antenna design also uses paper substrate. As proof, a flexible single-band wearable patch antenna at 2.45 GHz is designed on a 2.7 mm tattoo paper substrate by the authors in [88]. The antenna was attached to a supporting PDMS substrate with loss tangent and relative permittivity of 0.002 and 2.5 respectively. The conducting lines are created by coating the substrate with silver epoxy and liquid metal. Figure 2.25b displays the antenna's measured and



Figure 2.25: Flexible tattoo polymer antenna on PDMS support integrated with rectifier [88]

simulated return loss. The antenna has simulated and measured gains of -1.13 dB and -2.33 dB, respectively. In [89], a compact single-band advanced antenna for 5G

communication has been designed on a flexible and biocompatible polyethylene naphtholate (PEN) substrate,

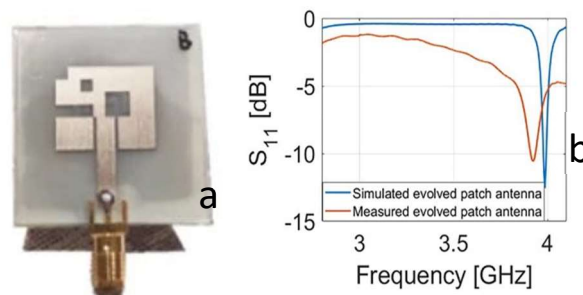


Figure 2.26 Flexible and biocompatible polyethylene naphtholate base patch antenna for 5G applications (a) picture (b) simulated and measured return loss

printed with 3D inkjet printing. The thickness of the substrate is 125 μm with a loss tangent of 0.005 and a dielectric constant of 2.9. The simulated and measured gains of the antenna at 4 GHz are -0.8 dBi and -1.5 dBi, respectively. Figure 2.26 a and b displays the created patch along with the return loss.

2.5.2 Enhancing parameters of single band antennas

Stacking antennas together in an array arrangement increases the gain of the antennas. The gain and directivity of an antenna were increased respectively from 5.49 dB to 8 dB and 7.48 dBi to 9.88 dBi by putting the antennas in an array configuration [90] (Figure 2.27). Increasing bandwidth by staging has been proven in [167] and [176]. Selecting the ideal height for the substrate will increase the microstrip patch antenna's bandwidth. As proof, Mishra et al showed that the optimal bandwidth is obtained when the antenna is designed with a substrate height of 1.6 mm and 1.5 mm at design frequencies of 6 GHz and 7 GHz, respectively [101] (Figure 2.28). The bandwidths begin to drop above the optimal heights due to the introduction of surface waves [102]. Surface waves are not desirable because they extract power from the total power to be radiated. They travel within the substrate and are scattered at bends and cavities and degrade the antenna pattern and polarization characteristics [103], [104]. The same result was obtained in [105].

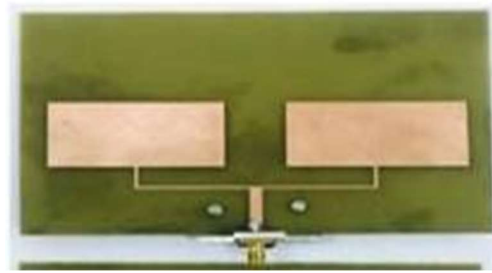


Figure 2.27: Enhancing parameters of antenna by staging them in an array configuration [90]

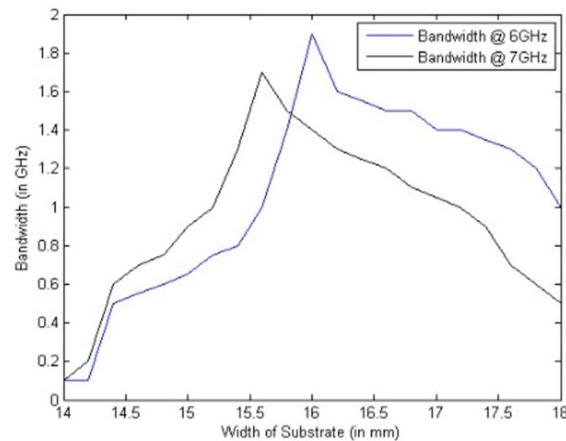


Figure 2.28: Variation of Bandwidth with the height of the substrate [101]

2.5.3 Multi Band Antenna

It is easy to convert Microstrip patch antennas from single band to broadband or multi bands

[106], [107] by adding slots on the patch to make the antenna resonate at multiple frequencies [50], [108], [109]. The dimensions of the patch are reduced by some percentages [110], making it more compact and suitable for portable wireless applications. Compared to singleband patch antennas, achieving an appropriate impedance matching between the antenna and

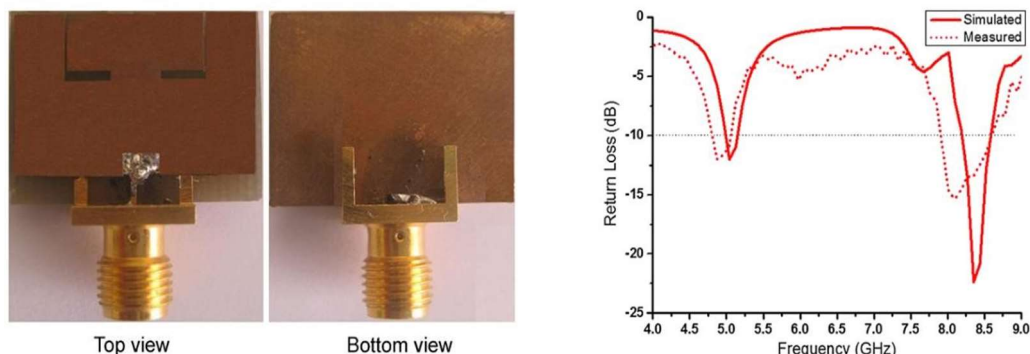


Figure 2.29: planar double L-shape slotted patch antenna on resin 1.6mm polymer substrate [111] the

rectifier circuit is laborious. The literature presents a limited number of multi-band antennas. Very limited multi-band antennas on polymer substrates are given in the literature. A planar double L-shape slotted patch antenna has been designed on polymer resin (1.6mm thick) (Figure 2.29) [111]. The antenna has gains of 7.6 dBi and 4.1 dBi at 4.87 GHz and 8.10 GHz, respectively.

In the most recent work, Deepal et al have used FDM on PLA to fabricate a 2x1 dual-band circular monopole antenna (CMA) array [112]. The gain is increased by 42% by using a 16x16 Frequency Selective Surface placed below the CMA (Figure 2.30). The author in [113] used a dipole antenna at 1800 MHz and 5 GHz for RF energy harvesting designed on Rogers RO4003 substrate. A third resonant frequency at 2.45 GHz was obtained by placing a parasite element near the first conductor to create coupling between them. (Figure 2.31).

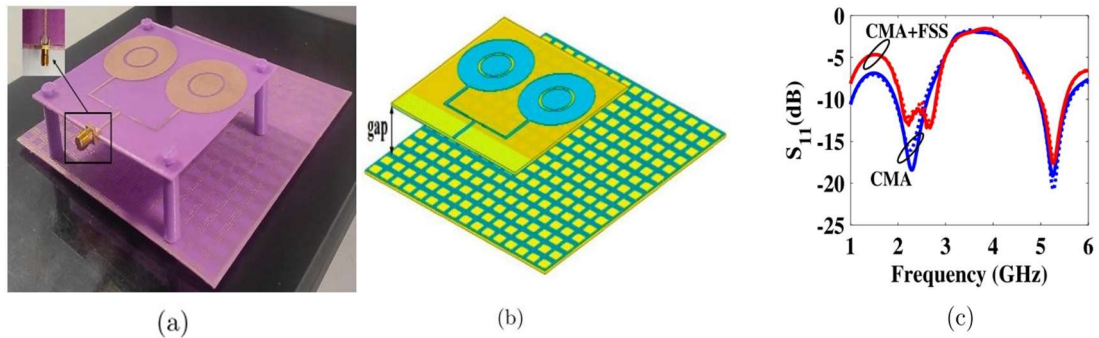


Figure 2.30: (a) fabricated of 2x1 CMA (b) schematic of FSS integrated CMA array (c) return loss result [112]

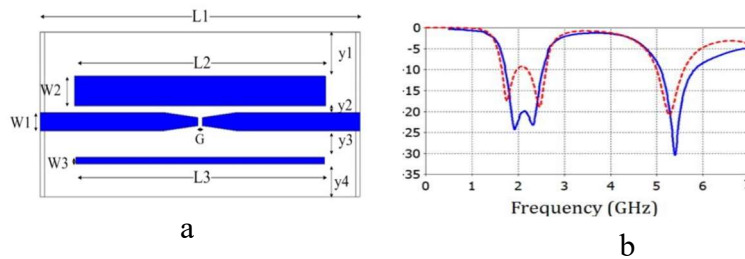


Figure 2.31: Structure of proposed dipole Antenna (a) design (b) return loss [113]

Multi bands antenna can also be obtained by making the feed line unequal. As evident, authors in [114] obtained multiple bands by shifting the feed line, making the lower widths separated by the feed line unequal. With these changes, we have triple bands at 0.9 GHz, 2.4 GHz, and 5.2 GHz frequencies. The design was done on conventional substrate.

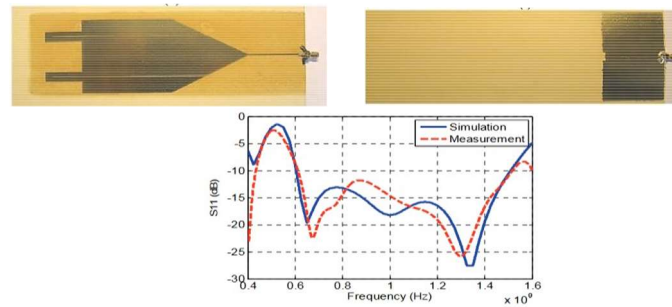


Figure 2.33: Front view, Back view and Return loss results of fabricated rectangular planar monopole antenna on cardboard [20]

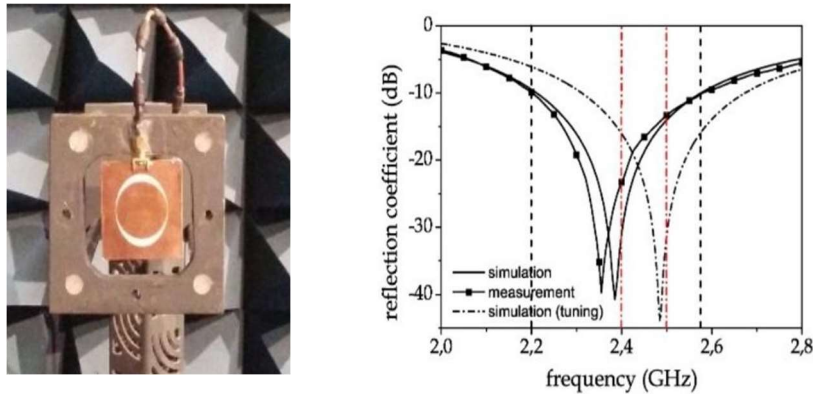


Figure 2.34: Broadband antenna fabrication on paper substrate [122]

Wideband wearable monopole antenna can be fabricated on cotton fabric polymer. As proof, the authors in [122] designed a broadband monopole antenna on 0.9 mm single-layer cotton fabric with a relative permittivity of 1.7. Figure 2.35 displays the constructed antenna together with the return loss measurement. The simulated and measured gains are 2dBi and 1.9 dBi, respectively.

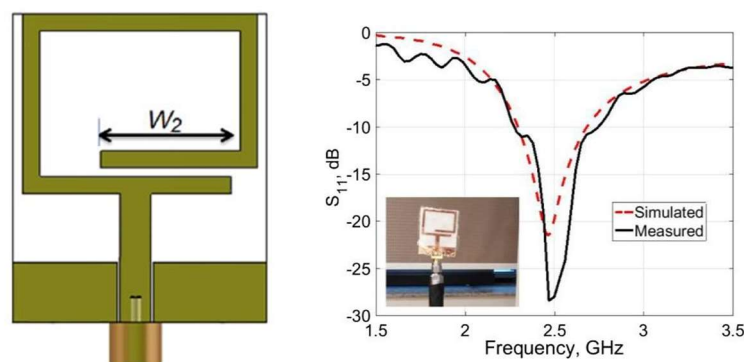


Figure 2.35: Wideband cotton fabric polymer monopole wearable antenna with CPW feeding [122]

The following references contain further broadband and multi-band antenna designs on conventional substrates: [204][206][207][209][210][211].

2.6 Take-away

This chapter has presented a literature review on antennas and rectifiers for RF energy harvesting. Results have equally been presented on RF power density measurements from the state of the art. From the results reviewed, the average power density for Wi-Fi is less than 35 dBm. In fact, in a low-power environment (< -20 dBm), the single diode topology rectifier is preferred. Shunt and voltage doubler topologies perform better at higher input power. Various matching strategies have been thoroughly examined. Microstrip stubs are the recommended solution for matching network design at high frequencies. Blocking harmonics from reaching the load has been seen as one of the methods to increase PCE. Radial stubs and choke inductors are used quite often for this purpose. In summary, it is worth noting that the literature has the following shortcomings in constructing RFEH circuits;

- The construction of RFEH circuits uses high-tech and environmentally hazardous materials.
- The construction of RFEH circuits using non-optimal input impedance value.
- A large proportion of rectifiers in literature does not consider the Maximum Power Point (MPP) condition.
- Creating conductive traces on polymers or paper substrates using expensive printing technology (electroless and electrodeposition).
- The inability to create complex 3D substrates for RFEH circuits.

These are the issues that will be addressed in chapters four, five and six of this work. To wrap it up, Table 2.5 summarizes recent state of the art on RF energy harvesting. From the table irrespective of whether the substrate use is conventional or polymers, the key challenge stills stand. These materials are high-tech materials, not yet recyclable and non-eco-friendly. Figure 2.36 shows the plot of Table 2.5. The maximum power conversion efficiency is plotted as a function of the RF input power. Most results consider an arbitrary DC load at the output of the rectifier. Hence, it is not possible to evaluate if the maximum PCE is obtained under Maximum PowerPoint conditions. The main focus is on the type of substrate. Rectifiers produced mainly with conventional substrates (FR4 and Rogers, represented by squares and triangles) are the majority of those seen in the literature. The graph in Figure 2.36 hides the size of the rectennas at hand. Generally, the smaller the size, the lower the PCE as the antenna gain decreases. However, with extremely low RF

input power (< -20 dBm), acceptable PCE values are reported nonetheless. One diode topology, SMS-7630, and HSMS-2850 diodes are mostly preferred when working at input power less than -20 dBm. Low RF input power characterizes ambient RF energy harvesting as opposed to Wireless Power Transfer, where RF energy is voluntarily emitted in far-field conditions to the system-to-be-powered. RF input power is higher than -10 dBm. Polyethylene Terephthalate (PET) offers a significant result [9], but PET is not eco-friendly so-far. Few rectennas constructed on polymer substrates are reported. Paper substrate rectennas have been reported as well [6]. PLA, and to some extent, cardboard materials are not reported to the best of the author's knowledge. This is one of the reasons why I was asked to investigate RFEH circuits on them. Cardboard and PLA are chosen because they are low-cost, eco-friendly, and recyclable.

After extracting the fundamental RF properties of the selected substrates in chapter three, we will proceed in chapters four and five to demonstrate the possibilities of building rectennas on these ecological materials.

Table 2.5: State of the art on Radio Frequency Energy Harvesting Circuits

Ref	Frequency (GHz)	Topology	Substrate	Diode Type	Load / k Ω	Input Power(dBm)	Maximum PCE (%)	Year
[134]	2.45	Voltage doubler	RT-Duroid 5880	HSMS286C	10	-5	18.5	2024
[135]	2.4	Voltage doubler	FR4	HSMS2860	NM	NM	NM	2024
[136]	2.45	Series	FR4	HSMS2850	1.6	-5	52	2024
[137]	0.9	CMOS	NM	MOSFET	100	-23	50	2024
[138]	2.45	Voltage doubler	FR4	HSMS28XX	14.5	-2	38.7	2024
[59]	3.5	Series	Flexible Kapton	SMS7630-079LF	3	-9	53	2023
[112]	2.4	Voltage doubler	PLA	SMS7630	8.2	0	34	2023
[139]	2.4	Rectifier topology	FR4	HSMS2850	NM	-20	44.2	2023
[140]	2.1	Series	RT-Duroid 5880	SMS7630-079	10	-20	30	2023
[88]	2.45	Voltage doubler	NM	BAT15-03W	20	-22	59	2023
[141]	2.45	Voltage doubler	FR4	HSMS2852	1	5	33.8	2023
[56]	2.45	Series	HT Resin	SMS7630	10	-24	13	2022
[57]	2.45	Series	HT Resin	SMS7630	1	-13	14.7	2022
[142]	1-2.6	Shunt	NM	1PS70SB82	0.2	10	71	2022
[55]	35	Voltage doubler	RT-Duroid 5880	MA4E1317	1.5	10	80	2022
[143]	5.75	Voltage doubler	NPC-H220A	SMS7621	1000	34.7	75.3	2022
[70]	0.095	Voltage doubler	RO4003C	HSMS2850	14	-5	69	2022
[144]	0.92	Bridge	NM	SMS7630	4	-10	34	2022
[67]	2.423	Voltage doubler	NM	HSMS285C	13	0	81	2021

Table 2.6: Sate of the art on Radio Frequency Energy Harvesting Circuits

[145]	0.9-1.7	Series	TLC-32	NM	0.75	0	50	2021
[25]	0.9/1.8	Series	FR-4	HSMS2850	4.5	-30	12.9	2021
[146]	2.2	Series	RT-Duroid 5880	SMS7621	0.2	0	50	2020
[147]	0.9	Series	FR-4	HSMS2852	3.8	0	52	2020
[147]	2.45	Series	FR-4	HSMS2852	3.8	0	46.5	2020
[147]	1.8	Series	FR-4	HSMS2852	3.8	0	50	2020
[148]	2.4	Voltage Doubler	RO4003C	SMS7630	2	5.5	69.3	2020
[148]	5.2	Series	FR-4	HSMS2860	0.14	13	65.4	2020
[149]	2.4	Series	FR-4	HSMS2860	0.14	13	63.38	2020
[150]	5.8	Shunt	R04350B	HSMS286F	0.45	15	81	2020
[151]	0.9	Series	Rogers	HSMS2850	9.1	-20	41	2020
[58]	2.4	Shunt	Rogers	SMS7630	7	0	58	2020
[24]	0.9	Series	RO4350B	SMS7630	10	-6	41.7	2020
[24]	2.4	Series	RO4350B	SMS7630	10	-6	27.7	2020
[152]	5.8	Shunt	F4B	HSMS2860	0.12	20	66	2019
[153]	1.4	Voltage Doubler	FR-4	SMS7630	1	10	74.8	2019
[154]	2.4	Series	FR-4	HSMS2860	0.6	12.3	63	2019
[155]	0.9	Series	RT-Duroid 5880	HSMS2850	7	-5	57.5	2019
[155]	1.8	Series	RT-Duroid 5880	HSMS2850	7	-5	52.6	2019
[156]	2.45	Greinacher	Textile	HSMS2822	10	0	17	2018
[157]	1.1	Voltage Doubler	FR-4	SMS7630	2	10	63	2018
[65]	2.45	Cockcroft-Walton	FR-4	HSMS2850	5	5	68	2018

Table 2.11: Sate of the art on Radio Frequency Energy Harvesting Circuits

[158]	2.5	Voltage Doubler	Rogers RO3003	HSMS2850	1	3.5	69	2018
[159]	2.45	Shunt	Rogers RO350B	HSMS2850	0.68	10	27	2018
[160]	1.8	Greinacher	CMOS	NM	70	-11.8	22.59	2018
[161]	0.93	Dickson	CMOS	NM	500	-15.4	12.6	2017
[162]	2.45	Voltage Doubler	RO5880	SMS7630	5	0	57.1	2017
[163]	2.45	Shunt	RO3203	SMS7630	2.47	0	57	2017
[164]	2.45	Voltage Doubler	FR-4	SMS7630	2.4	0	37	2017
[165]	1.85	Voltage Doubler	Duroid 5880	SMS7630	14.7	-24	23	2015
[165]	2.15	Voltage Doubler	Duroid 5880	SMS7630	14.7	-24	15	2015
[166]	0.9	Series	3D printing	SMS7630	11	-24	12	2018
[166]	1.8	Series	3D printing	SMS7630	11	-24	12	2018
[166]	2.1	Series	3D printing	SMS7630	11	-24	3	2018
[80]	2.45	Voltage doubler	FR-4	HSMS2850	5	-20	19	2018

NM: Not Mention in the article

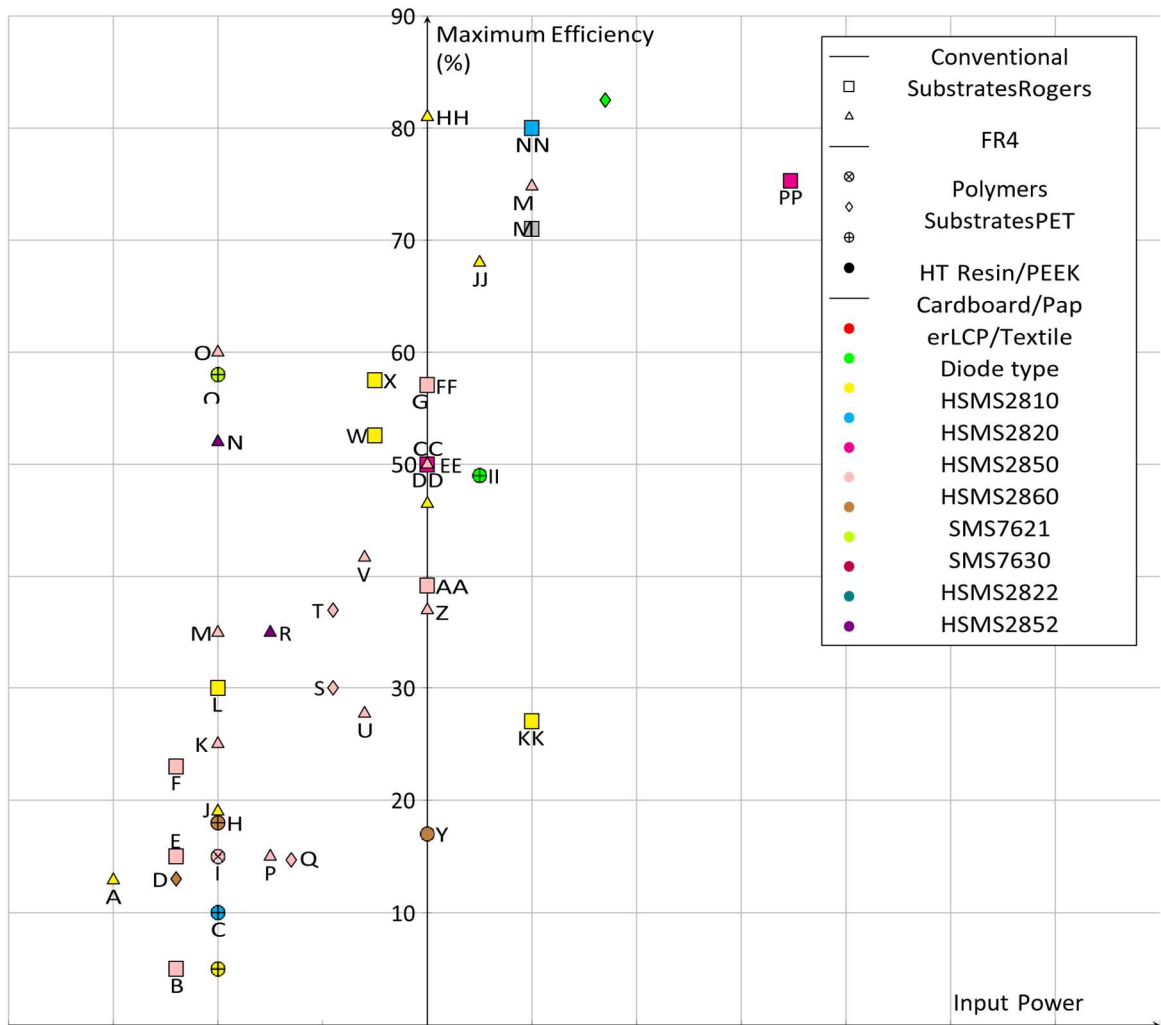


Figure 2.36: Recent state of the art on RFEHs: Maximum PCE vs RF input power based on the type of substrate and diode type. A-[25], B-[165], C-[166], D-[56], E-[165], F-[165], G-[80], H-[80], J-[80], K-[169], L-[78], M-[169], N-[170], O-[169], Oo-[171], P-[78], Q-[57], R-[170], S-[48], T-[48], U-[24], V-[24], W-[78], X-[78], Y-[55], Z-[164], AA-[55], BB-[147], CC-[147], DD-[146], EE-[163], FF-[58], GG-[55], HH-[67], II-[172], JJ-[80], KK-[159], LL-[142], MM-[164], NN-[55], OO-[169], PP-[143].

CHAPTER 3

CHARACTERIZATION OF SUBSTRATES

The substrate is a crucial part of RF Energy Harvesting Circuits. This chapter describes how to derive the relative permittivity and loss tangent of PLA polymer and cardboard paper using the Two Transmission Line (TTL) approach.

3.1 Introduction

The Two Transmission Lines (TTL) have been used for extracting the loss tangent and relative permittivity of materials [173], [174]. The TTL method is also known as multilayer calibration [174]. Other techniques used in characterizing RF substrates are the Near-Field technology [175], Coplanar Waveguide (CPW) [171], I-V method [176], [177], [178], Nicholson-Ross-Weir (NRW) method [177], [179], [180], [181], the resonator method [182], the resonant cavity method [207][209] or the THz-time domain spectroscopy method [186], [187]. Each of these methods has its pros and cons. Near-field technology involves a complex measurement architecture for a wide range of frequencies. The Resonator and Resonant Cavity methods give accurate results only at the frequency of resonance of the circuit. It is not possible to use them for circuits with broadband. For frequencies up to THz, the THz-time domain spectroscopy method is employed; however, it entails a complex algorithm and measurement procedure. The I-V and NRW methods are reliable for a broad spectrum of frequencies, providing precise results. The NRW methods also involve complex algorithms and complicated methods in deployment.

The TTL method is chosen here due to its simplicity and can be used for broadband transmission lines (from 1 MHz to 10 GHz) [178]. Low-complexity in measurement method is also very important for promoting low-tech devices. The range of measurement with TTL varies depending on the length and thickness of the substrate and the lines. Different thickness of the substrate gives slightly different results. To address this discrepancy, we maintained a consistent thickness during the fabrication of our circuits.

The attenuation coefficient (α) and phase constant (β) are the primary parameters that will be derived utilizing the TTL. These parameters are extracted from the measured S-parameters of the transmission lines. After extracting these two parameters, the substrate's relative permittivity and loss tangent can be evaluated. The real component of the propagation constant is the attenuation coefficient. It accounts for all the losses in the

transmission line as the EMW propagates across it. As the signal travels down the transmission line, it causes the signal amplitudes to fall. It is measured in Nepers per meter or decibels per meter. The imaginary component of the propagation constant is called the phase constant. It establishes the signal's sinusoidal phase and amplitude along a transmission line at a fixed time [188]. Its unit is radian/meter. The TTL method involves calculating the ABCD matrix of a transmission line. The ABCD matrix is formed from the S-parameters of the line [189]. The TTL is deployed with two sets of microstrip transmission lines of different lengths with the same width. These lines are attached to the substrate under investigation. Figure 3.1 shows a two-transmission lines model where the lengths L_1 and L_2 ($L_1 > L_2$) have the same width. The ports 1 and 2 represent SMA connectors. The mathematical formulation of the TTL can be seen in the Annex section of this work. This method has been validated on Rogers RO4003C substrate (see annex section of this manuscript).

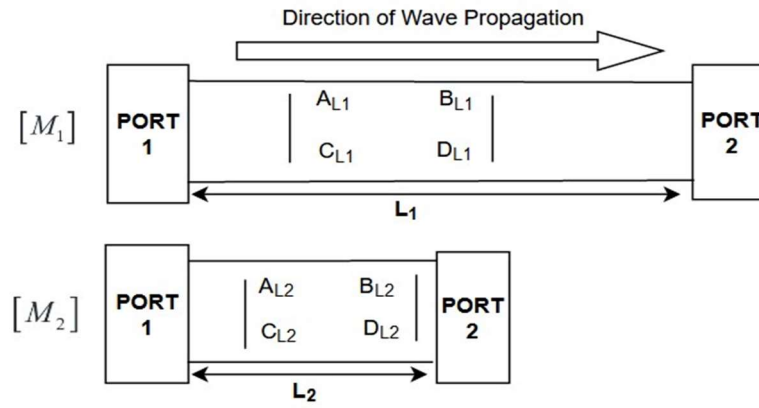


Figure 3.1: Two Transmission Line Model

3.2 Polylactic Acid Polymer Substrate

3.2.1 Fuse Deposition Modelling

Injection molding, thermoforming compression molding, hand layup, pultrusion, and automated fibre placement are 3D Plastronics approaches often used in mass production of 3D substrates [190][191][192][193]. These production methods necessitate the use of very expensive dies, molds, or lithographic masks [194]. It therefore becomes necessary to seek cheaper and alternative techniques. For 3D printing of Plastronics polymers, the main three printing methods are [182];

- Stereolithography Apparatus(SLA) – which is curing a liquid photopolymer layer by layer by the use of light [195].

- Laser Sintering – which is sintering a thermoplastic powder layer by layer, by using an infrared laser [196].
- Fused Deposition Modelling (FDM) – which is forming 3D object with a thermoplastic wire passing through a heated nozzle [197].

Laser Sintering and SLA require expensive printers due to high printing temperatures. In addition, buying a liter of liquid resin can be quite costly. However, the finished surfaces of objects printed using SLA and Laser Sintering are smoother and less porous than those of FDM.

In this thesis, FDM is selected as the 3D printing method for the PLA object using the Ultimaker printer (Figure 3.2). FDM uses cheap printers and filaments. The main drawbacks of FDM when using PLA are the surface roughness of finished structures and challenges in mounting surface-mounted devices (SMDs) due to its low melting point of 65°C. Methods were created to enhance the smoothness of the surface and soldering of SMD devices.



Figure 3.2: Ultimaker 3D printers use in printing PLA substrate

In FDM, parts are formed by depositing fused materials in layers. One way to think of it is like putting one card on the other to build a pack of cards [198]. FDM works by melting filament and extruding it onto a printing bed through a nozzle to form layers. The printing process begins by feeding the plastic wire through rollers and pushing the thread through the heated nozzle, where the wire is heated, melted, and ejected from the nozzle to build a crosssection of the CAD model. Layers are added one at a time after the constructing platform is lowered [199]. To put it another way, this is additive manufacturing, where objects are built layer by layer using the melting, extrusion, and depositing of filament onto a print bed. Supporting structures are added if need be. FDM is made up of three

sub-systems that characterize the processes during printing (Figure 3.3)[112]. These sub-systems are;

- a) **Pinch Roller Mechanism:** This mechanism pushes the wire into the chamber protected from the surroundings. This is done by heating the wire and turning it into liquid. The temperature of liquifying is around 65°C . This is a very low temperature to manage, making FDM an affordable 3D printing technology.
- b) **Molten State Transfer Mechanism:** This mechanism converts the melted wire into a molten state. The molten state of the wire is pushed into a narrow slot. It is then deposited on the substrate after its extrusion from the nozzle.
- c) **Relative Motion Mechanism:** This is the sub-system that involves relative movement between the substrate and the deposition from the nozzle to create the finished structure.

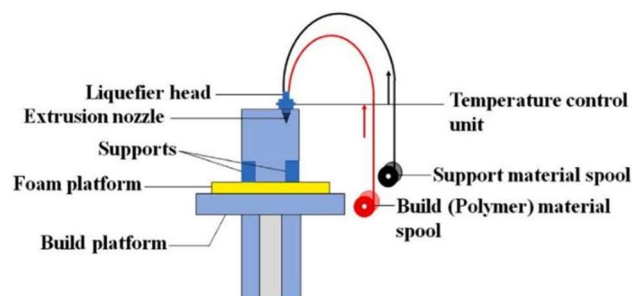


Figure 3.3: Sub-systems of FDM manufacturing process [134]

3.2.2 Application of TTL Method

Creating at least two lines in pairs with varying lengths and the same width is how the TTL approach is applied. Lengths of 40 mm and 70 mm and width of 4.1 mm are selected on a 1.5 mm PLA substrate. The substrate thickness shouldn't be altered after that. The configuration of the FDM printer is unchanged throughout the study. This is to ensure the best accuracy of the results when the substrate is used in designing RF circuits using the extracted loss tangent and relative permittivity parameters. The evaluation is to be repeated for any thickness of the substrate if this is to be a design parameter in the system. For the sake of simplicity, the work only evaluates one value of substrate thickness. PLA material is quite fragile, so 1.5 mm is the minimum thickness considered in this work. Whatever the case, the thickness shouldn't be too little because that will impact the patch antenna's gain. Two further pairs of lines with lengths of (20 mm, 40 mm) and (50 mm, 70 mm) are made and examined to guarantee the accuracy of the outcome (Figure 3.4). The conductive material is a $35\text{ }\mu\text{m}$ thick copper tape with a conductivity value of 5.8×10^7

S/m. It is simple and accurate to cut copper tape into any twodimensional shape. It is possible to use PLA filament in the same FDM printer with conductive charges. Copper tape is a trade-off between conductivity, availability and ecology. The thesis is demonstrating that the copper tape can be removed easily from the PLA substrate to be transferred to another substrate or reshaped. This capability is not possible with conductivecharge PLA filaments. Figure 3.5 depicts the laboratory setup used to measure the lines' Sparameters. The Short, Open, Load, and Through (SOLT) calibration technique is used to calibrate the R&S ZNL3 Vector Network Analyzer (VNA) (see appendix). To verify good matching, the input impedance of the lines is measured (Figure 3.6). To find the substrate's relative permittivity and loss tangent, the four S-parameters are measured and a script is



Figure 3.4:3D FDM printed substrat&transmission lines with copper tapes as conducting material

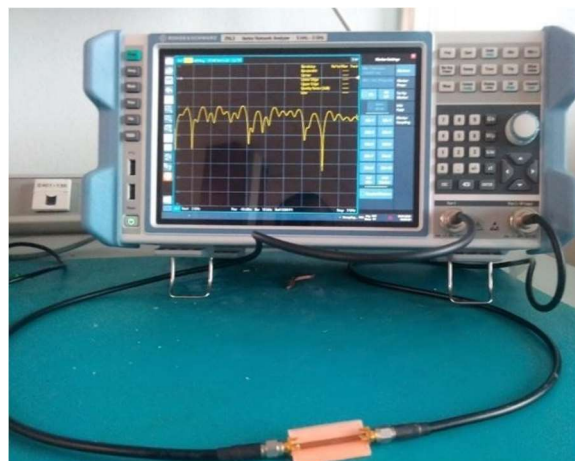


Figure 3.5:Deployment of the TTL for measuring the-parameters

constructed. A third polynomial fitting function is employed to interpolate the findings (see annex). Similar results were obtained using the other pairs of lines. Figure 3.7 shows the plots for the two RF properties.

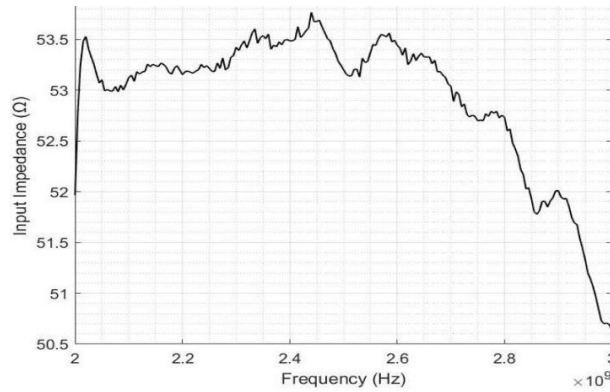


Figure 3.6. Measured Input Impedance of lines fabricated on PLA

The variation in the results has the same tendency as the results presented by authors in [200]

[201]. The results' dispersion related over a range of frequency is due to;

- The printed PLA is relatively non-homogeneity in height over a sizable surface.
- Furthermore, PLA is a porous material whose RF properties is affected by environmental factors. Authors in [202] stipulated that the electrical properties of plastic polymers are affected by environmental conditions.
- The high surface roughness of the printed PLA.
- Substrate minor melting during brazing.

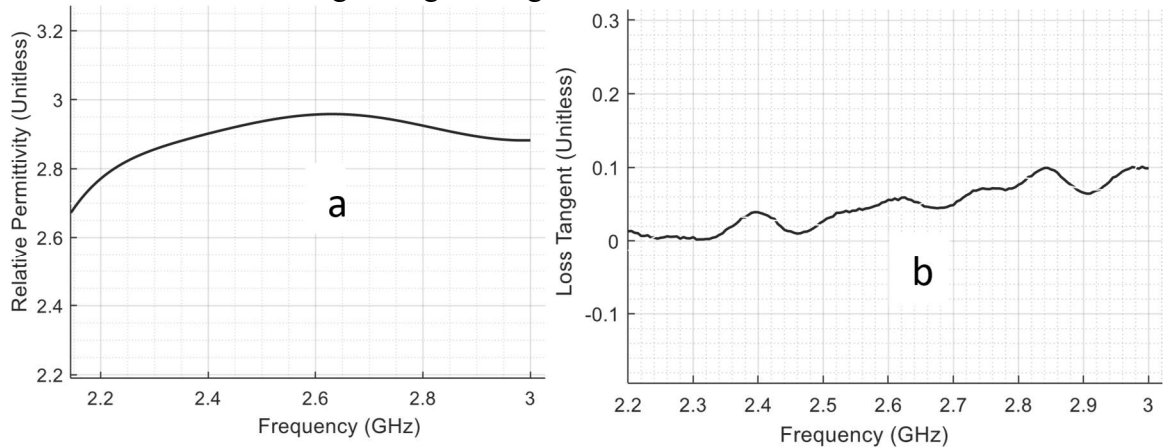


Figure 3.7: Measure RF properties of PLA Substrate (a) relative permittivity (b)loss tangent PLA

The Hypothesis is that there might be other properties of the PLA substrate or environmental conditions that affect the electrical properties of the material that require further investigations to properly account for these variations.

At 2.45 GHz, the average loss tangent is 0.013, and the relative permittivity is 2.923. The results show slight changes between 2.2 and 3 GHz. PLA's mechanical characteristics are not as strong as those of resin. This explains why PLA has a low melting temperature. While compared to the state-of-the-art results (Table 3.1), the results are acceptable to consider while building RFEH circuits.

3.3 Cardboard Paper

There are numerous varieties of cardboard materials, each with a varied thickness and level of surface roughness. For characterization, four distinct cardboard materials are chosen, each having a different thickness, air gap, and surface roughness. The thickness of the cardboard in samples #1, #2, #3, and #4 is 2.2 mm, 2.15 mm, 3.6 mm, and 1.7 mm, respectively. Figure 3.8 displays the raw samples. The samples were observed through a Stemi 305 microscope to quantify the level of air gap density.

The images are shown in Figure 3.9. It was found that samples #1 and #4 presented higher mass density compared to other materials and, thus, will be selected for the final tests.

Table 3.1: Dielectric permittivity and loss tangent evaluated for PLA substrate in Figure 4.4 and compared

Freq (GHz)	$\tan \delta$	R	$L_1 / L_2(\text{mm})$	Method	Ref
0.02 – 3	0.0004-0.04	2 – 4	80/100	TTL	[174]
0.5 -5	0.015-0.024	2.52 - 2.91	10/20	TTL	[203]
2.4 – 5.4	0.02 – 0.04	2.8 – 3.2	19/30	TTL	[204]
2.4 – 5.4	0.003 – 0.04	2.05 – 3.15	19/24	Not given	[205]
0.5 – 3	Not given	1.8 – 2.7	10/20	TTL	[203]
2.2 – 3	0.001 – 0.09	2.7 – 2.95	40/70	TTL	This work

Moreover, Figure 3.8a shows that sample #1 presents a thin colour coating on one side, which gives a surface of less roughness than the other, and both surfaces will be evaluated.



Figure 3.8: Different cardboard materials (a) sample #1 (2.2 mm) (b) sample #2 (2.15 mm) (c) sample #3 (d) sample #4

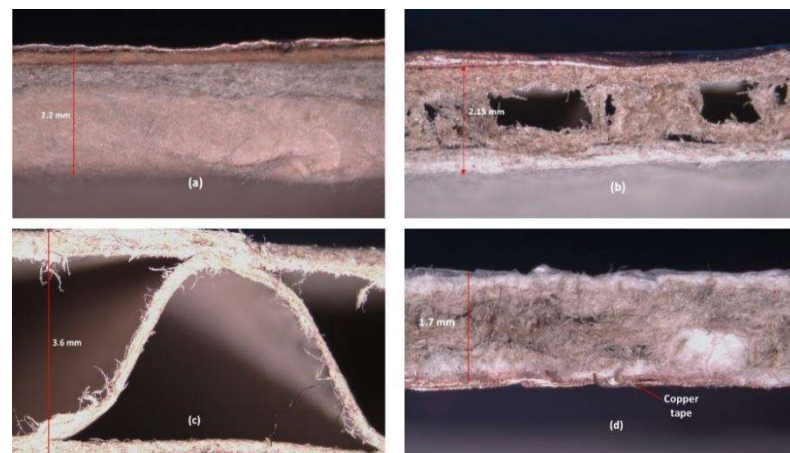


Figure 3.9: Different Cardboard Samples were observed under microscope: (a) sample #1 (b) sample #2 (c) sample #3 (d) sample #4.

3.3.1 Physical Properties

The mass densities of the cardboard samples #1, #2, #3, and #4 are 696 kg/m^3 , 182 kg/m^3 , 139 kg/m^3 , and 434 kg/m^3 , respectively. The cardboard samples #2 and #3 have more air gaps than samples #1 and #4. The cardboard sample #1 is affected by the fewest air gaps. The roughness of the used conductor (copper tape) on each cardboard sample was measured using a nanopoint-scanner (NPS) with a zooming scale of $600 \text{ }\mu\text{m}$. Figure 3.10 presents the surface roughness of each sample observed under the Hirox microscope with a zooming scale of $600 \text{ }\mu\text{m}$. The average roughness was calculated after conducting three roughness measurements on each sample. Cardboard materials are soft, so three measurements in different areas of the sample were considered to provide significant information. The results are listed in Table 3.2 and Figure 3.11 shows the minimum, maximum, and average roughness values for each cardboard sample.

Table 3.2 shows that the cardboard samples #2 and #3 have the highest surface roughness while the sample #4 has the lowest value. This is due to a smooth plastic coating of thickness 0.1 mm on sample #4. The roughness of cardboard sample #1 is slightly higher than that of sample #4. However, the cardboard sample #1 has the most limited quantity of air gaps. There is a trade-off between the roughness and the air gaps. The air gaps make the substrate more fragile and decrease its relative permittivity. Moisture may also be a contaminant that affects permittivity. As a result, the energy related to the electric field in the substrate material is reduced. In addition, the air gaps also introduce geometric imperfections in the substrate, leading to variations in the loss tangent and dielectric constant of the substrates. Cardboard sample #1 is most suitable for this work. Table 3.2 also shows that the roughness values for the two surfaces (front and ground plane) on the same sample differ. This difference is due to the presence of the coating on only one side of the cardboard substrates. In conclusion, the average roughness values when considering both surfaces of the cardboard samples #1, #2, #3, and #4 are 2.415 μm , 3.15 μm , 4.735 μm , and 1.91 μm , respectively.

3.3.2 Relative Permittivity and Loss Tangent of Cardboard Material Substrates

The loss tangent and the relative permittivity of the various cardboard samples are the primary RF parameters to be retrieved using the TTL method. Figure 3.12 shows the several cardboard samples that were created using the TTL approach. Figure 3.13 depicts the lab setup used to measure the various S-parameters. The effect of the SMA connectors on the two lines was investigated by interchanging the ports during measurements (Figure 3.13). In all cases, S_{12} was always equal to S_{21} . There was a slight discrepancy seen in the situations of S_{11} and S_{22} .



Figure 3.10 The surface roughness of different cardboard samples observed under the microscope
(a) sample #1, (b) sample #2, (c) sample #3 (d) sample #4

Table 3.2: Roughness Measurement of the different Cardboard Samples and Copper Tape.

Sample name	Measurement 1(μm)	Measurement 2(μm)	Measurement 3(μm)	Average 1(μm)
copper tape	0.52	0.52	0.52	0.52
sample #1	1.34	1.45	1.38	1.39
sample #1 ground	3.14	3.53	3.85	3.50
copper tape on sample #1	0.82	0.63	0.74	0.73
sample #2	1.79	1.76	1.67	1.74
sample #2 ground	4.56	4.68	4.9	4.71
copper tape on sample #2	0.59	0.61	0.6	0.6
sample #3	5	4.73	4.89	4.87
sample #3 ground	4.8	5.2	4.9	4.97
sample #4	0.69	0.82	0.78	0.76
sample #4 ground	2.7	3.2	3.27	3.06

Given that the Rogers RO4003C substrate does not exhibit this effect, the cause may be geometric defects in the samples. However, it is worth noting that the effect of SMA connectors and junctions have not been de-embedded in the calculations of the TTL method because all calculations were based on transmission line length difference ($|L2 - L1|$) thereby cancelling out these parasitic effects [206] [207].

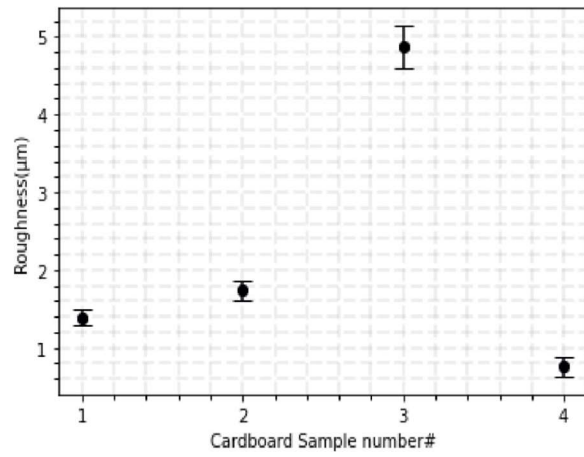


Figure 3.11: Plot depicting the range of roughness values for each cardboard sample

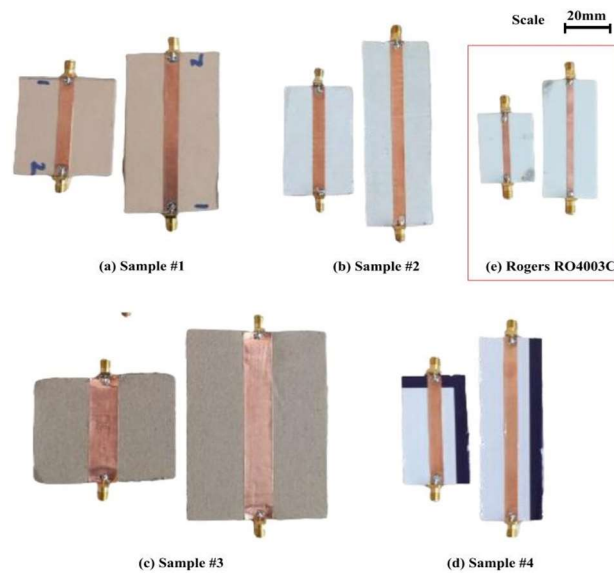


Figure 3.12: Devices for the TRL on the substrate (a) sample #1, (b) sample #2, (c) sample #3, (d) sample #4, (e) Rogers RO4003C as reference sample

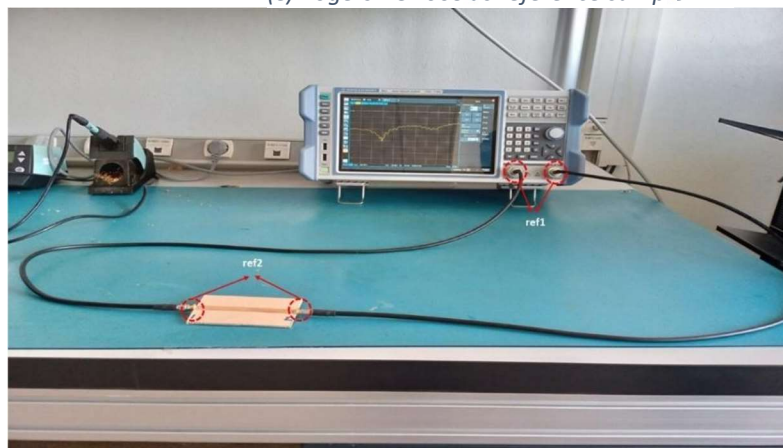


Figure 3.13: Laboratory set-up for measuring S-parameters of Cardboard substrates.

Figures 3.14, 3.15, and 3.16 display the measured S-parameters for the cardboard samples. The Figures show the results with the ports of the SMA in both forward and reversed directions. Theoretically, S_{11} in the forward direction should be equal to S_{22} when the direction of the SMA connectors is reversed. It is observed that S_{12} is always equal to S_{21} with slight variations between S_{11} and S_{22} . It was confirmed that the lines' input impedance was consistently close to $50\ \Omega$ to get precise and satisfying results. The graphs of the input impedance for the various samples are shown in Figure 3.17.

Figure 3.14 shows the results with the ports of the SMA in both forward and reversed directions. Figure 3.17 (a) and (d) have an abnormal point for samples #1 and #4, respectively. These abnormalities can be due to slight errors from the measurement setup or geometric inaccuracies of the samples. Figures 3.17 (b) and (c) display some deviations in the input impedance measurements. Given the increased surface roughness values of the two samples under consideration, it is plausible that this is the cause. In general, at 2.45 GHz, all four samples show good matching around $50\ \Omega$.

The relative permittivity and loss tangent for the four cardboard samples are shown in Figure 3.18 and Figure 3.19, respectively. Figures 3.18 and 3.19 demonstrate how the amount of air space in the cardboard materials directly affects their RF properties. Relative permittivity falls with increasing air gap and approaches that of air. This explains the greater values for the loss tangent and lower values for relative permittivity in cardboard samples #2 and #3.

Cardboard sample #1 gets the highest value for relative permittivity because of its narrow air gaps. Although the loss tangent is lower because of a coating on both surfaces, the coatings are rougher than the plastic coating on cardboard sample #4. Comparing cardboard sample #4 to sample #1, the value of the loss tangent is somewhat lower. The reason for this is that cardboard sample #4's upper surface has a smooth plastic coating. Table 3.3 shows a comparison of the dielectric constant and loss values with comparable values from the literature.

3.4 Conclusion

In this chapter, we have provided a detailed description of the characterization of PLA and cardboard substrates. The process of using FDM for printing PLA has been explained. FDM is a cheap printing technology. Mounting SMDs on the printed PLA substrate is quite challenging owing to the low melting temperature of PLA. The TTL method has been described and used in characterizing the substrates. The TTL is preferred over alternative techniques due to its ease of usage and broad frequency range deployment. The conducting substance on both substrates is copper tape. The results of relative permittivity and loss tangent of the two substrates have also been presented. In chapters four and five, fabricating antennas and rectifiers with the measured values of loss tangent and relative permittivity will be addressed.

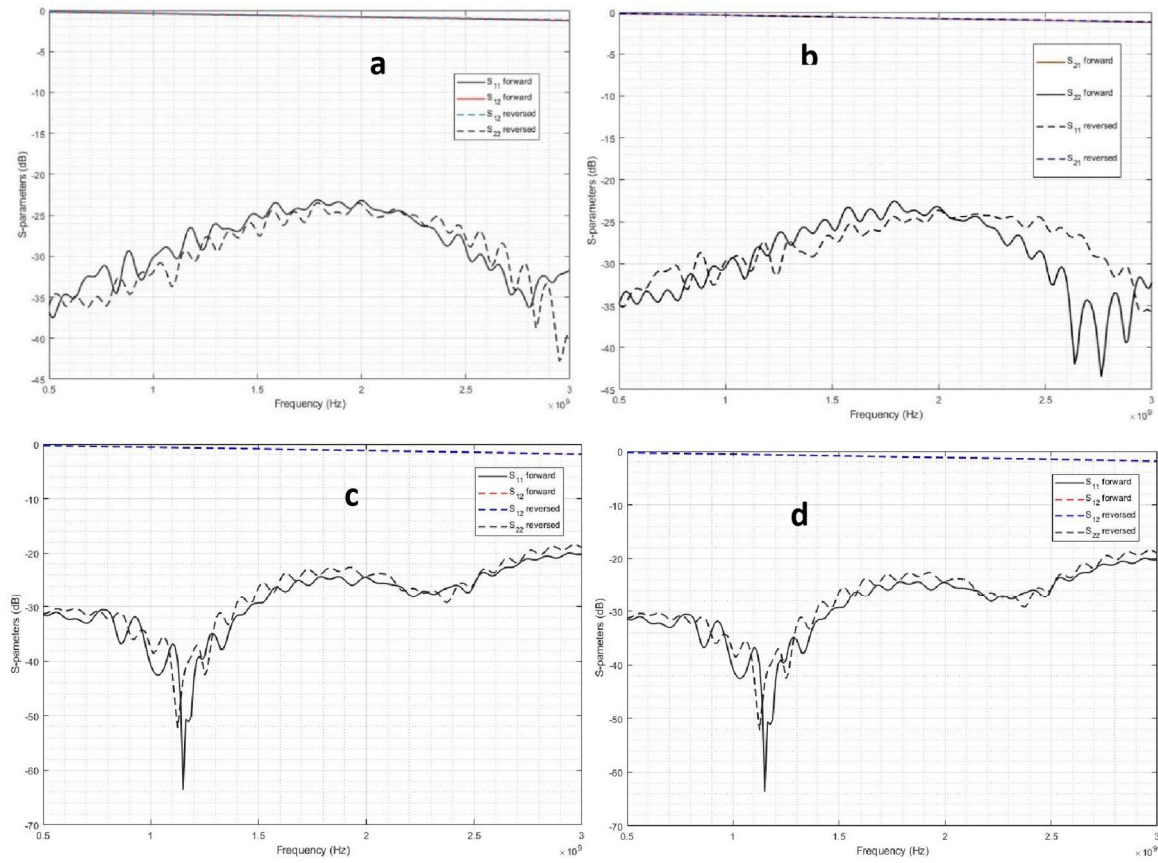


Figure 3.14: S-parameters of cardboard sample #1 with SMA ports in the forward and reversed for (a and b) the short line, (c and d) the long line

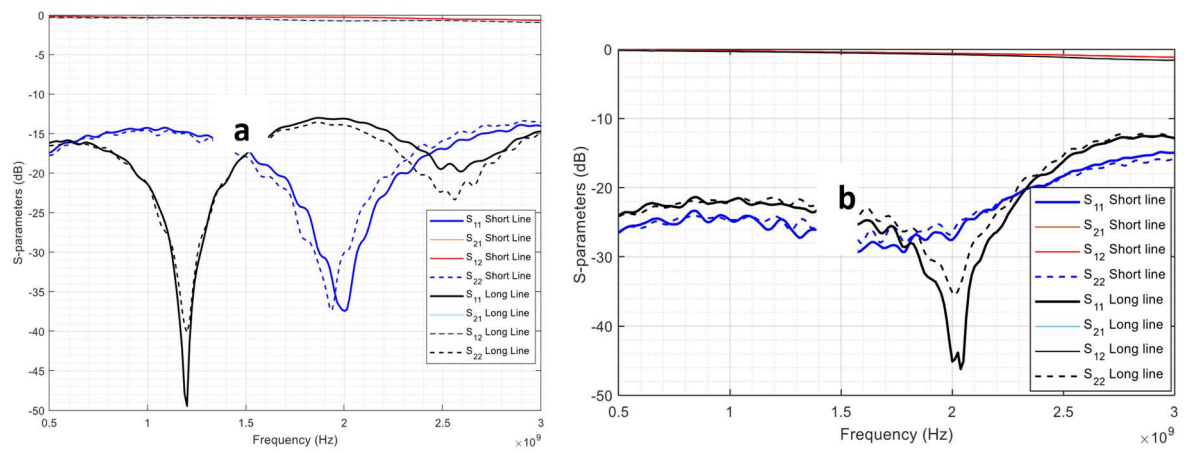


Figure 3.15: S-parameters of packaging cardboard material: (a) sample #2, (b) sample #3.

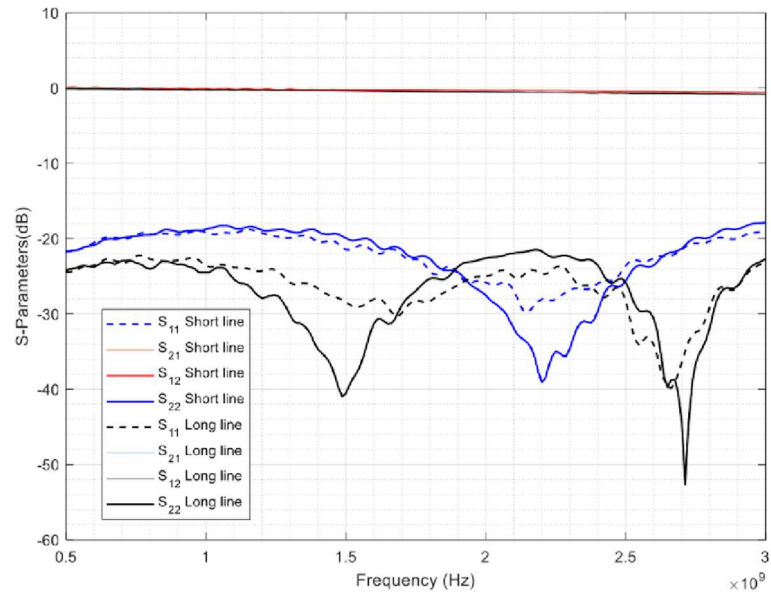


Figure 3.16:S-parameters of sample #4

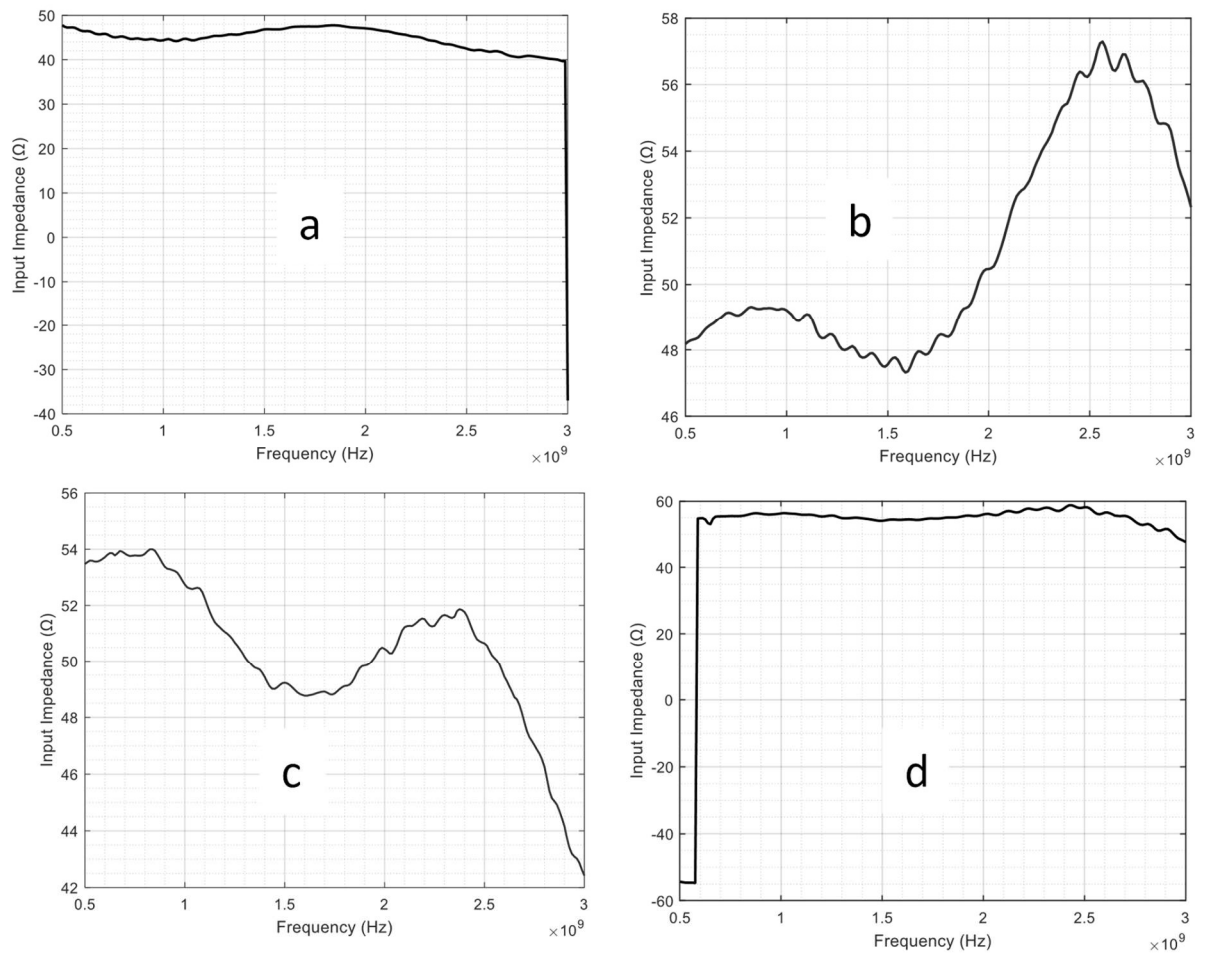


Figure 3.17:Input Impedance of (a) sample #1, (b) sample #2, (c) sample #3, (d) sample #4.

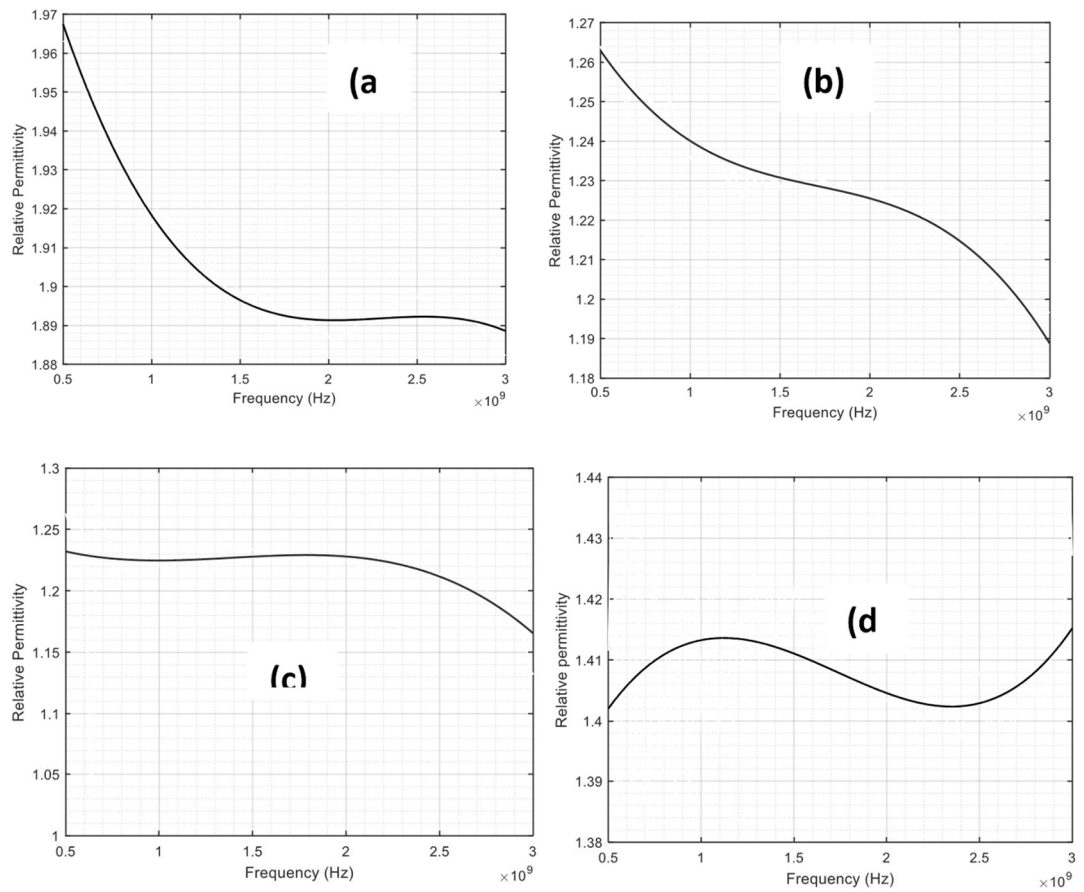


Figure 3.18: Relative Permittivity of (a) sample #1 (b) sample #2 (c) sample #3 (d) sample #4.

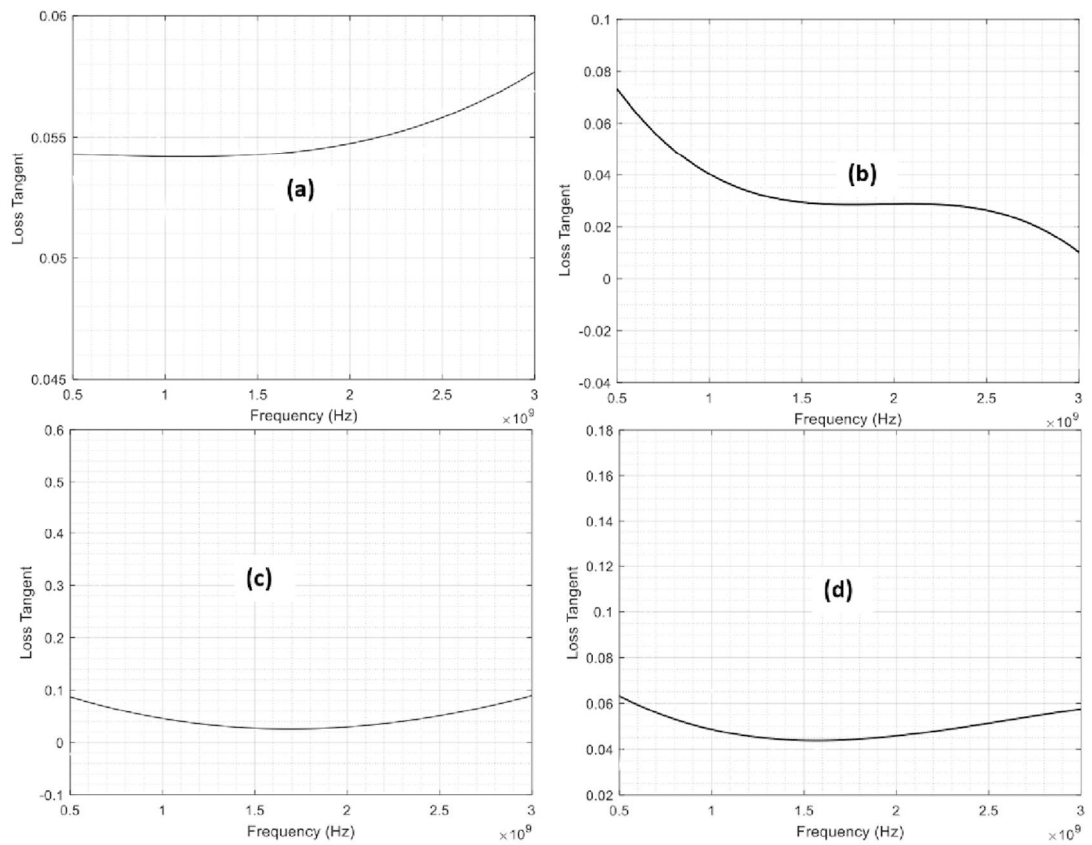


Figure 3.19: Loss Tangent of (a) sample #1 (b) sample #2 (c) sample #3 (d) sample #4.

Table 3.3: Dielectric permittivity and loss tangents of Cardboard papers as compared with literature

Freq (GHz)	L₁/L₂(m m)	h (mm)	Loss tangent	Relative Permittivity	Method	Conducting Material	Ref
0.5-3	30/100	2.9	0.4 - 0.08	1.4 - 2.6	CPW	Copper tape	[171]
0.5-3	50/100	0.56	0.015 - 0.028	1.78 - 1.82	TTL	Copper tape	[86]
0.5-3	55.5/91	2.2	0.054 - 0.057	1.889 - 1.968	TTL	Copper tape	Sample#1
0.5-3	60/100	2.15	0.01 - 0.07	1.189 - 1.264	TTL	Copper tape	Sample#2
0.5-3	65/108	1.7	0.045 - 0.065	1.401 - 1.415	TTL	Copper tape	Sample#3
0.5-3	67/108	3.6	0.042 - 0.061	1.17 - 1.24	TTL	Copper tape	Sample#4

CHAPTER 4

ANTENNA IMPLEMENTATION

Antennas play a key role in capturing RF signals and directing them towards the rectifier through a matching network. A good antenna design is desired to have an S_{11} less than -10 dB. This verifies that the matching network is well-designed. A good antenna design should be able to receive all of the signals directed towards it and be able to radiate all the received signal in the desired direction. To know if an antenna can radiate, the gain should be positive. In this chapter, single band, double bands and multi bands antennas will be implemented on PLA and Cardboard substrates. The first section in this chapter focuses on designing antennas on PLA, and the second part focuses on designing the antennas on cardboard paper. Both LP and CP antennas are envisaged. The designs are done using CST Microwave Studio version 2018. Fabrication and characterization in an anechoic chamber are considered later.

The goal of this chapter is not to propose a particular antenna geometry but to investigate the performance of the simple microstrip patch antenna with respect to the substrate and with regards to rapid prototyping.

4.1 Antenna implementation on PLA

Both linearly polarized and circularly polarized patch will be implemented on PLA.

4.1.1 Design of 2D Linearly Polarized Patch Antenna on PLA

The design equations for the length, L and width, W of the antenna are given by Equations.

(4.1) and (4.2) respectively [82], [85], [133].

$$L = \frac{\lambda_0}{2} - 2\Delta L \quad (4.1)$$

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (4.2)$$

Where $\Delta L = 0.412h \left(\epsilon_{eff} + 0.3 \right) \left(W_h + 0.264 \right) / \left(\epsilon_{eff} - 0.258 \right) \left(W_h + 0.8 \right)$ (4.3)

$$\text{And } \epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[\frac{1}{1 + 12h/W} \right]^{-1} \quad (4.4)$$

ΔL and ϵ_{eff} are the length extension and the effective dielectric constant of the antenna due to fringing effect. λ_0 , r , h , and f_0 are the wavelength, the dielectric constant of the substrate, the thickness of the substrate, and the operating frequency respectively. The antenna is simulated using CST Microwave software with the measured $\tan \delta$ and r obtained from

Chapter 3. Two physical notches are created in an insert feed manner which recessed a distance

L_f using the microstrip feedline to match the antenna to a 50Ω input impedance (Figure 4.1).

The dimensions of the antenna are summarized in Table 4.1.

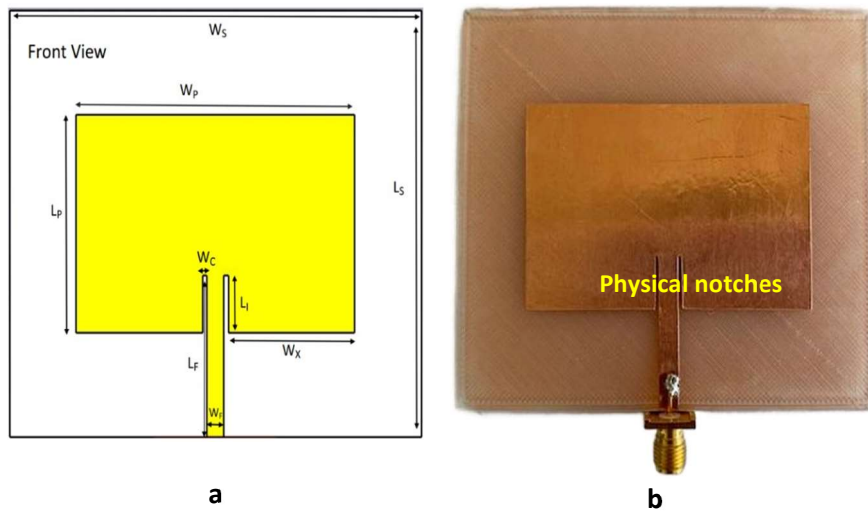


Figure 4.1: Patch antenna printed on PLA and using copper tape as conductive material. (a) Geometry (with parameters in Table 2), (b) fabricated patch.

Table 4.1: Dimensions related to the antenna geometry (in mm) in Figure 4.1

W_P	L_P	W_F	L_F	W_X	W_C	W_S	L_S	L_I
54	35.9	3.4	26.5	24.5	0.8	80	70	9.5

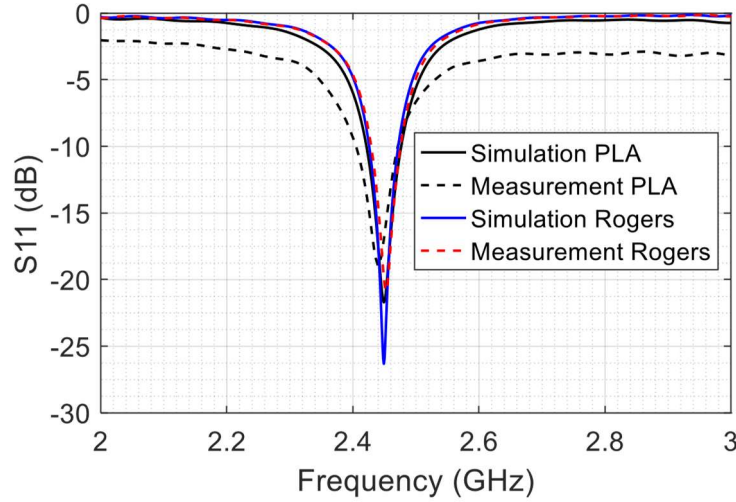


Figure 4.2: Comparison of simulated and measured S_{11} for Rogers and PLA

To study the effects of the relative permittivity and the loss tangent on the radiation properties of the antenna, a similar antenna is designed on a standard RF substrate (Rogers 4003C). The simulation and measurement of return losses of both antennas are shown in Figure 4.2. The radiation parameters for both antennas are shown in Table 4.1.

Both antennas have good return losses, as shown in Table 4.2, with Rogers 4003C achieving higher performance. In comparison to Rogers, PLA's rougher surface resulted in more losses.

Table 4.2: Main properties of the patch antenna in (Figure 4.1) compared with standard design on Rogers R04003C

Material	Gain(dB)	Bandwidth (MHz)	Resonance Frequency (GHz)	S_{11} (dB)	Size(mm ³)
PLA Simulation	8	58	2.453	-24.48	70x80x1.5
PLA Measurement	7.94	60	2.446	-18.45	70x80x1.5
Rogers Simulation	8.4	46.4	2.45	-25.16	58x70x1.5
Rogers Measurement	8.02	46.2	2.452	-21.15	58x70x1.5

It can be concluded that the average retrieved values of $\tan \delta$ and ϵ_r are suitable to depict the RF behavior of PLA based on the close match between simulation and measurement. The bandwidth of the antenna on PLA is higher than the one on Rogers' substrate. This is because the relative permittivity of PLA is lower than the one of Rogers. It is demonstrated in [208] that when the substrate's effective relative permittivity rises, bandwidth falls. The variation in PLA's relative permittivity and loss tangent may be the cause of the shift in resonance frequency observed in PLA measurements. Once more, substrate losses are the cause of the reduced gain observed in the patch antenna

experiment on PLA. The simulated and measured E-plane radiation pattern of the antenna in an anechoic chamber using a reference horn antenna of gain 9.8 dB at 2.45 GHz are shown in Figure 4.3 and summarized in Table 4.2. The antenna has a linear polarisation parallel to the feedline.

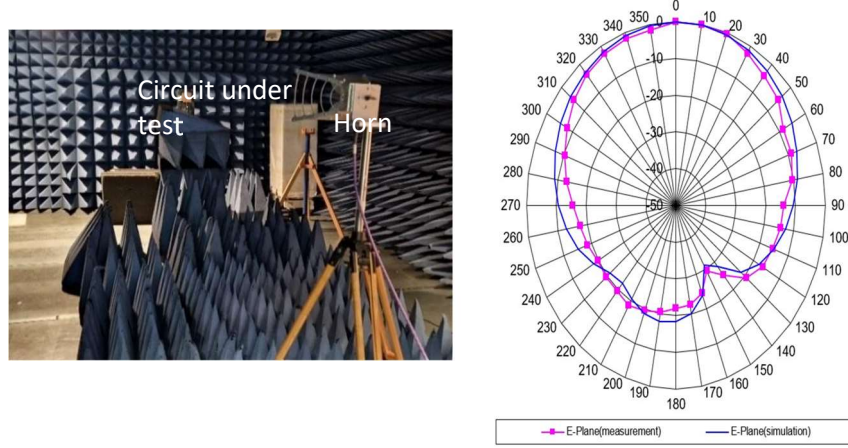


Figure 4.3. E-plane radiation pattern. (a) anechoic chamber (b) simulated and measured results

4.1.2 Circularly Polarised 2D patch Antenna

The primary design in section 4.1.1 has some shortcomings. The design has LP and a directional radiation pattern. The consequence is that the antenna will not be able to capture any arbitrary polarization at any incidence angle. To overcome this challenge, we design a CP antenna. Circularly Polarized antennas can receive the waves in both horizontal and vertical planes. An assembly of many CP antennas can produce an almost omnidirectional radiation pattern. The length and width of the antenna must be equal. The design equation of such an antenna is given by Equation 4.5.

$$W = L = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (4.5)$$

No external circuitry for the patch antenna is needed to generate CP [209]. CP antenna can be designed either using the Single-feed technique or the Multi-feed technique [210].

4.1.2.1 Single-feed technique

With this method, CP is obtained when two orthogonal but otherwise identical modes are excited when they have a phase difference of 90° . To generate CP by this method, a feed is put at the diagonal plane of the patch, and two orthogonal modes are excited simultaneously. One mode resonates in the x-direction and the other mode resonates in the y-direction. This satisfies one of the requirements of CP. To satisfy the second

requirement (to achieve a 90° shift between the two modes), one resonant dimension is made slightly longer than the other (Figure 4.4) [210].

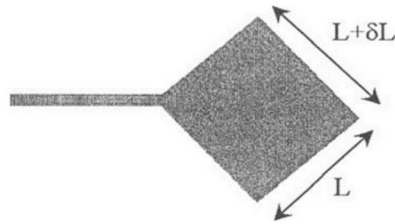


Figure 4.4: Circular Polarization by putting feed at diagonal plane patch [210].

Another way to generate CP could be to put a slot within the patch or truncating diagonal ends of the patch [85], [210] (Figure 4.5).

4.1.2.2 The multi-feed technique

Multi-feed technique can also be used to design a CP antenna [209]. CP has been produced by feeding a square patch with orthogonal microstrip feedlines (Figure 4.6). The two microstrip feed lines excite the patch antenna in two modes (TM_{01} and TM_{10}). This causes the antenna to radiate both a horizontally and vertically polarized waves simultaneously.

In this work, a CP antenna is designed using the single feed technique. CP is obtained by truncating any two diagonal edges of the square patch. $\lambda/4$ transformer is used to match it to a 50Ω SMA connector for ease of characterization.

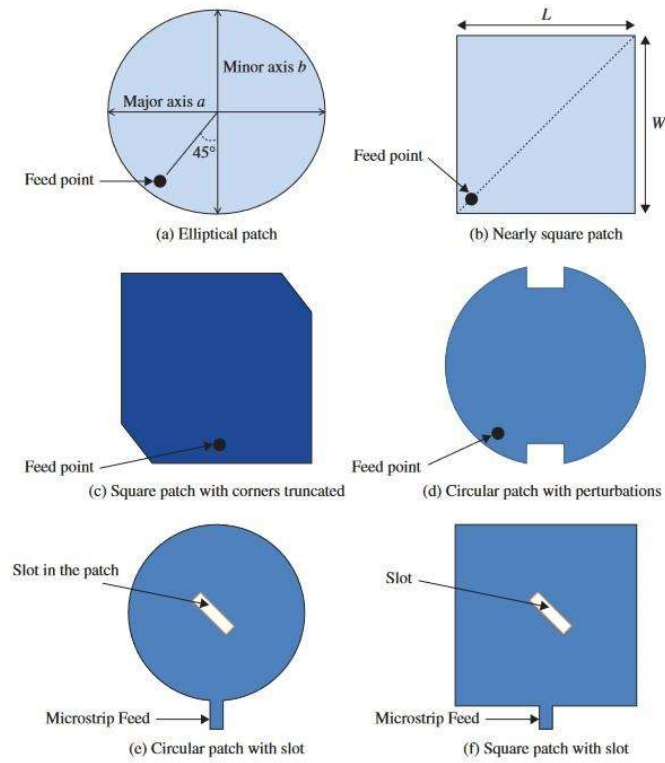


Figure 4.5: Generating CP by Single Feed technique (adding slots on patch or by truncating diagonal edges) [210]

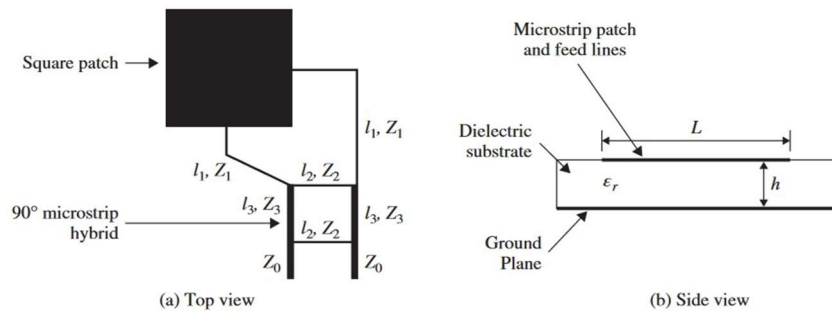


Figure 4.6: Generation CP by dual feed technique [207]

Steps in Designing the Circularly Polarized patch

- Firstly, the length and width of the square patch are calculated using Equation 4.5. The calculated length and width are used in CST Microwave Studio software to design the patch.
- Secondly, $\lambda/4$ transformer is designed to match it to 50Ω transmission line (Figure 4.11).
- The edges are truncated and optimized to have the antenna resonate at two frequencies, with 2.45 GHz being the centre frequency (Figure 4.11). After, the dimensions of the truncated edges were varied to obtain the best value for the return

loss parameter. The best result was obtained when the dimension was 3.6 mm (Figure 4.7).

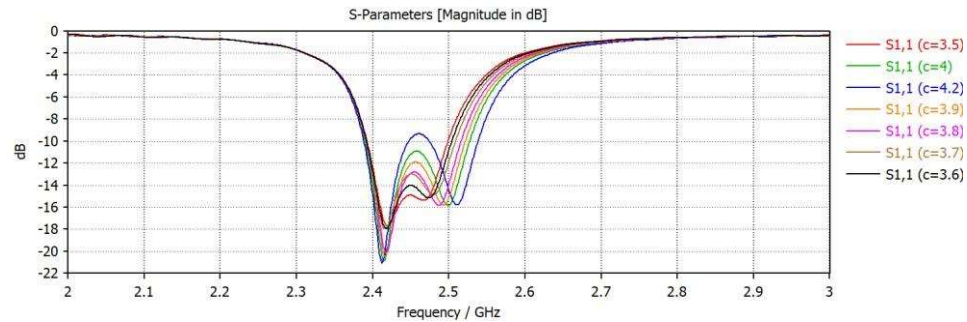


Figure 4.7: Simulated reflection coefficient of the antenna with respect to dimension of truncated part

- Although the antenna can resonate at two frequencies, it still does not meet all the requirements for CP. This is because the AR is greater than 5. To reduce this value close to 1 (0 dB), the width of the feedline is varied. The best result for return loss is gotten when the width is 2 mm (Figure 4.8). This adjustment gave a simulated AR of 2.39 (Figure 4.9). ➤ To get a good polarisation of the antenna in both vertical and horizontal planes with better values for AR and return loss, the width of $\lambda/4$ transformer is varied. The best results were obtained when the width was 1.4 mm with a simulated AR of 0.18 dB (Figure 4.10).

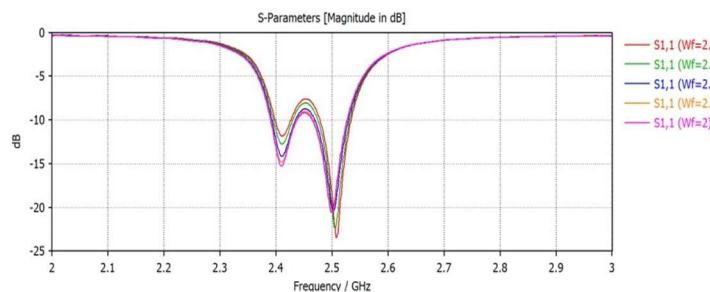


Figure 4.8: Simulated reflection coefficient of the antenna with respect to width of feedline

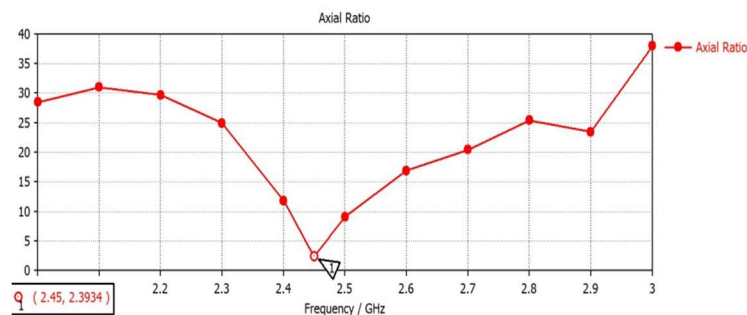


Figure 4.9: Simulated Axial Ratio of the antenna with respect to width of feedline

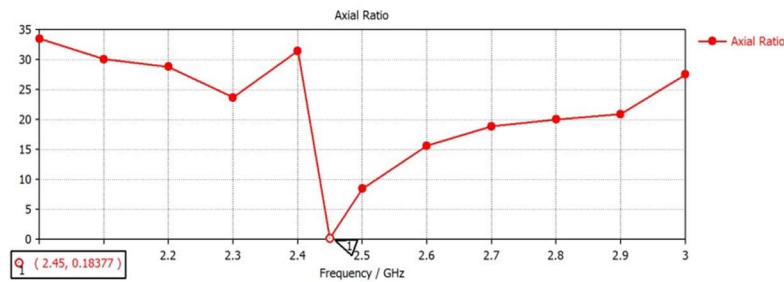


Figure 4.10: Simulated Axial Ratio of the antenna with variation of width of $\lambda/4$ transformer.

To study the effects of the relative permittivity and the loss tangent on the radiation properties of the antenna, a similar antenna is designed on Rogers RO4003C (Figure 4.11c). The return loss measurements and simulations for both patches are shown in Figure 4.12b. The radiation parameters are given in Table 4.3.

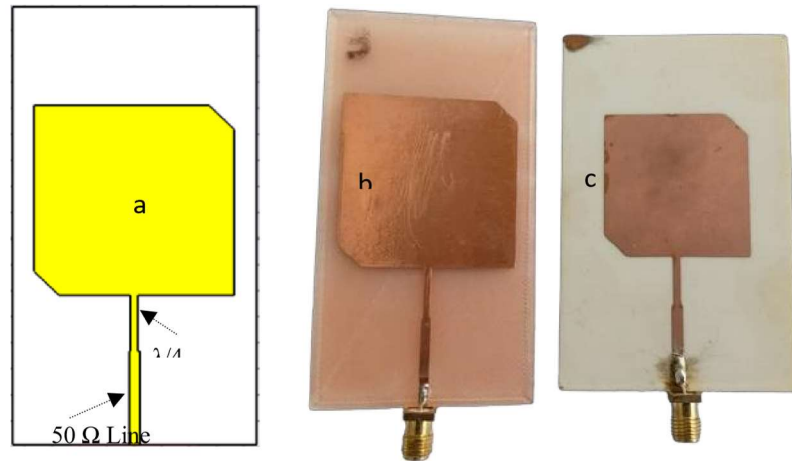


Figure 4.11: CP Patch antenna geometries (a) CST design (b) fabricated patch on PLA (c) fabricated patch on Rogers 4003C

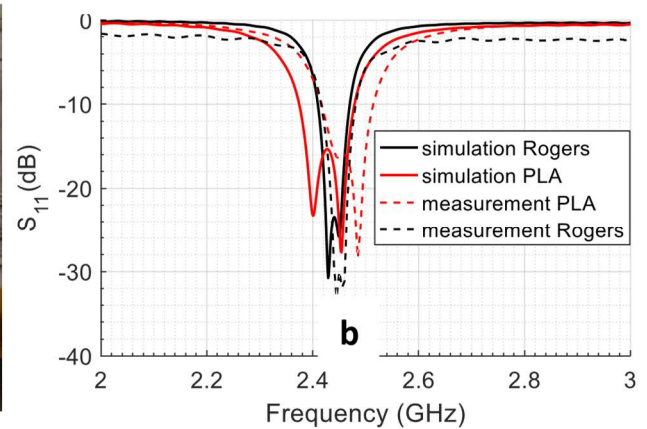
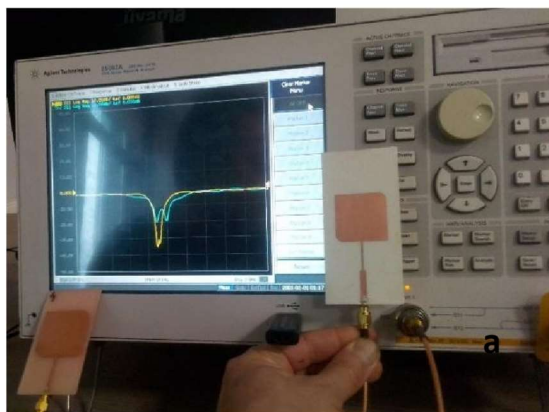


Figure 4.12: Measurement of return loss for PLA circularly polarised antennas (a) Lab set up (b) return loss results

Table 4.3:: Radiation parameters of CP antennas on Rogers and PLA

Material	Gain (dBi)	Bandwidth (MHz)
PLA Simulation	4.09	105.6
PLA Measurement	3.7	107.4
Rogers 4003C Simulation	5.56	63.3
Rogers 4003C Measurement	5.43	69.5

Both antennas are well matched at 50 Ω . Rogers shows better results (Table 4.3). This is because the surface of PLA is rougher than that of Rogers 4003C. The S_{11} values have two peaks, with 2.45 GHz being the centre frequency. With this, we can conclude the antennas have multiple polarizations. The bandwidth of the antenna on PLA is higher than that on Rogers (Figure 4.12). This is because the relative permittivity of PLA is lower than that of Rogers RO4003C. The shift in resonance frequency for measurement on PLA can be due to the fluctuation in the loss tangent and relative permittivity of PLA. The radiation pattern is measured in an anechoic chamber with a reference horn antenna of gain of 9.8 dBi at 2.45 GHz (Figure 4.13). Figure 4.13 shows the results in both horizontal and vertical planes. The difference in the measured power received from the antenna in both planes is less than 1 dB. This concludes that the antenna offers multi-polarization.

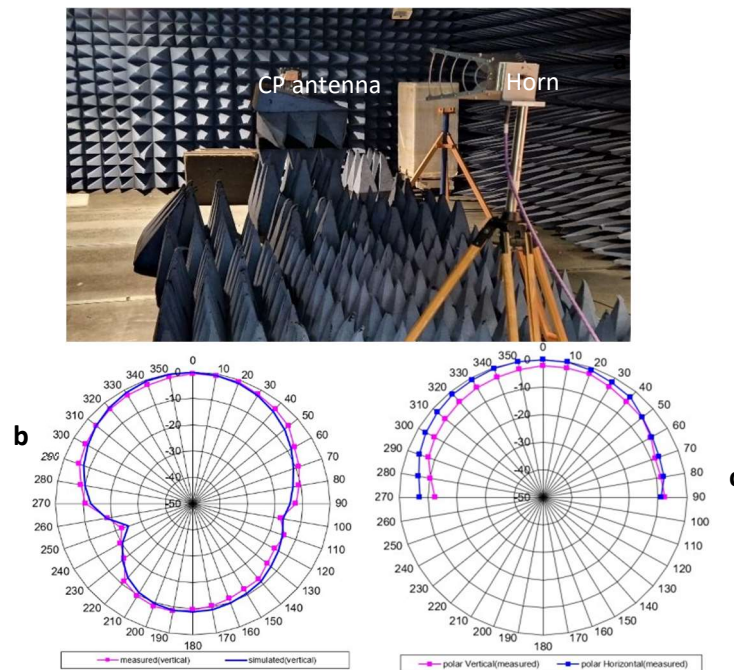


Figure 4.13: Radiation pattern measurement (a) anechoic chamber (b) E-plane simulation and measurement (c) Vertical and horizontal planes measurement

4.1.2.3 Effects of Bending

To overcome the limitation in the directional radiation pattern of patch antennas and to increase the Half Power Beam Width (HPBW), we create a 3D structure by bending the patch (Figure 4.14). A bending radius of 0.25λ has been proposed by authors in [211] to give a broader radiation pattern than other curved radii. The measured HPBW increases from 86° to 91.5° in the vertical plane and from 74.4° to 89.7° in the horizontal plane (Table 4.4). The negative effect of bending is the degradation of the gain of the antenna. The gain reduces because the back lobe of the curve patch is stronger than the back lobe of the planar patch. Besides, the resonance frequencies shift to the right while still maintaining a good match at 2.45 GHz (Figure 4.14b). The measured radiation pattern in both planes is shown in Figure 4.15. The bending causes the difference in received power in both planes to increase, but still less than 3 dB. We can also conclude that the antenna maintains its multiple polarization.

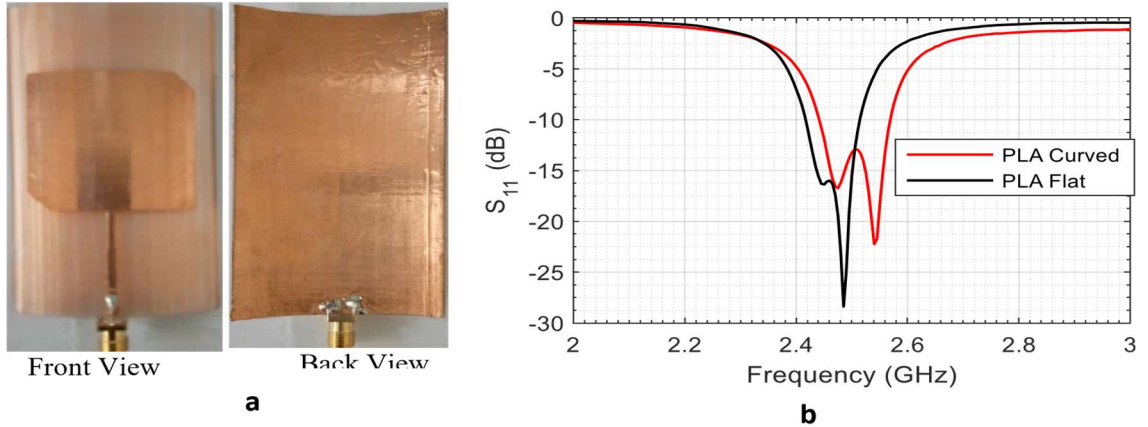


Figure 4.14: Effect of bending on CP patch (a) picture (b) return loss

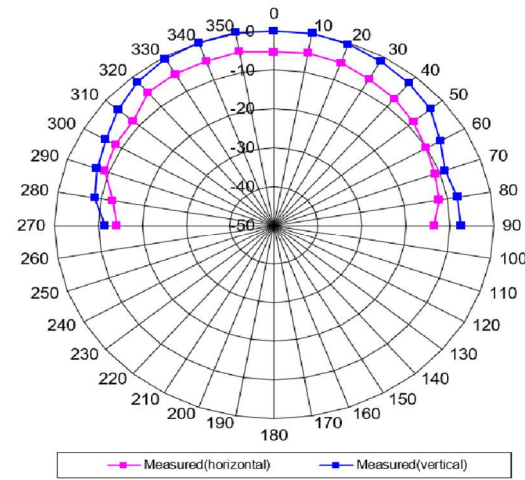


Figure 4.15: Measured radiation pattern in the horizontal and vertical planes

Table 4.4: Comparison of HPBW of the curved and planar CP patches at 2.45 GHz

	Planar Patch	Curved Patch
Simulation (Vertical plane)	87.1 ⁰	93.4 ⁰
Measurement (Vertical plane)	86 ⁰	91.5 ⁰
Simulation (Horizontal plane)	75.5 ⁰	90.3 ⁰
Measurement (Horizontal plane)	74.5 ⁰	89.7 ⁰
Simulation (Gain)	4.09 dB	3.5 dB
Measurement (Gain)	3.7 dB	3.2 dB

4.2 Antenna design on Cardboard Paper

Cardboard is an eco-friendly and recyclable material that is available quite easily. In addition, it is easily foldable to create flexible radio frequency circuits. The inkjet printing technique is often used in literature to generate conductive traces on cardboard and other paper substrates. Inkjet printing for creating conductive tracks is quite expensive and time consuming for the objective of this work, so for rapid and cheap prototyping, conducting traces are created using copper tape of thickness 35 μm . In contrary to ink that melts inside paper fibers, the conductive tape can be removed and let the cardboard material be more conveniently recycled.

Three types of antennas will be designed (single band, broadband, and dual bands). Before proceeding with the design, we must look at the effects of dielectric and loss tangents on the geometry of the antenna. We will be examining how the antenna geometry is affected by the substrate's height. This is because the thickness of the Cardboard material is not uniform throughout the substrate owing to different air and fibres densities at different points of the material. It is even more important when the cardboard material comes from waste packages.

4.2.1 Effect of Losses and Dielectric Constant on Antenna Parameters

Due to the asymmetrical dimension of the substrate, it is important to study the influence of the losses and the relative permittivity on the radiation parameters of the antenna. Some areas of the substrate have more air gaps than others, causing fluctuations in the values of the loss tangent and the relative permittivity along the substrate. In addition,

the cardboard material can absorb humidity from the environment, thereby altering its physical and RF parameter values. Figures 4.16 and 4.17 show simulation evaluations of how variations in the loss tangent and dielectric constant affect the antenna's electrical impedance. Tables 4.5 and 4.6 summarize the alteration of the antenna global gain in response to the variation in dielectric constant and losses of the substrate, respectively.

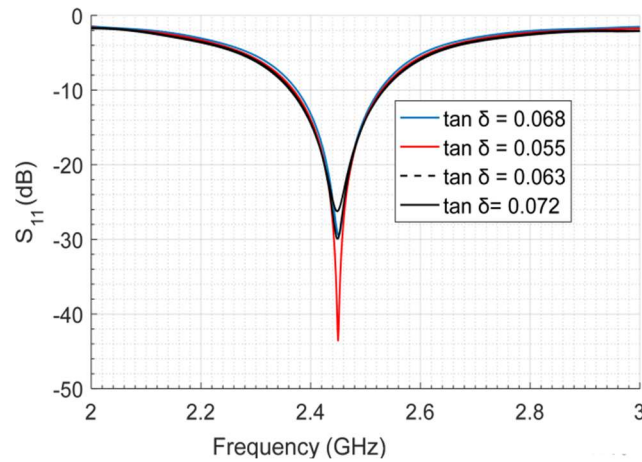


Figure 4.16: CST simulations S_{11} variation according to the losses of the cardboard substrate

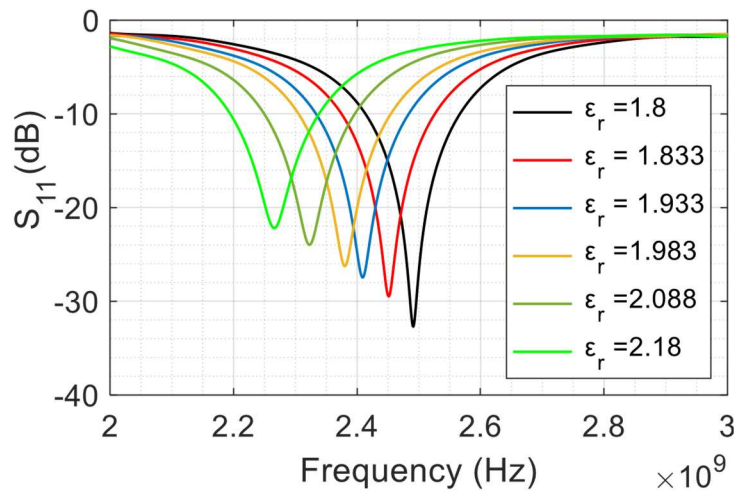


Figure 4.17: CST simulations. S_{11} variation according to the relative permittivity of the cardboard substrate

Table 4.5: Effect of Loss Tangent on Cardboard Antenna Radiation Parameters.

Loss tangent ($\tan\delta$)	Recessed Distance (mm)	Dielectric Constant (ϵ_r)	S_{11} (dB)	Gain (dB)	Bandwidth (MHz)	Efficiency (%)
0.055	2.7	1.833	-43.5	2.46	146.5	33.9
0.063	1.5	1.833	-30	2.03	154	31
0.068	0.8	1.833	29.85	1.78	158.2	29.35
0.072	0.6	1.833	-26.34	1.58	160.4	28.14

Table 4.5 shows that the S_{11} improves with decreasing loss tangent. The values of S_{11} in Figure 4.16 shifts to the left as the relative permittivity decreases. This is because the electrical length of the patch increases as the dielectric constant decreases.

Table 4.6: Effect of Dielectric Constant on Cardboard Antenna Radiation Parameters

Loss tangent ($\tan\delta$)	Length of patch (mm)	Dielectric Constant (ϵ_r)	S_{11} (dB)	Gain (dB)	Bandwidth (MHz)	Efficiency (%)
0.055	43.40	1.8	-33.45	2.46	147.9	34
0.055	42.8	1.933	-28.85	2.54	146.6	33.7
0.055	42.05	1.963	-27.25	2.29	142.8	33.4
0.055	41.70	2.088	-26.10	1.88	142	33.1
0.055	39.5	2.14	-24.13	0.319	138.1	32.8

This latter increase in electrical length causes the minimum value of the S_{11} parameter to shift to a lower frequency. The cardboard material is not very homogeneous and the RF properties may vary across the area. The impact of varying dielectric constant values and loss tangent values impact the geometry of the antenna. Considering worst-case and best-case values, the latter impact is shown in Figure 4.18 and Figure 4.19, respectively. As the dielectric constant increases, the desired resonant frequency changes. To resonate the antenna at the desired frequency, the length of the patch should be reduced. The variation in the dielectric constant affects only the length of the patch antenna, while all other dimensions remain constant. A comparable pattern is noticed with variations in the losses of the substrate. As the loss tangent increases, the desired resonant frequency remains unchanged, but the matching becomes destabilized with an upward shift in the return loss. To improve the return loss value, the recessed distance (W_C) should be reduced (Figure 4.19). From Table 4.6, as the dielectric constant increases, radiation parameters decrease. This is because an increase in dielectric constant leads to a reduction in fringing effect, thereby reducing the ability of the antenna to radiate. As the losses increase, the gain, S_{11} , and efficiency of the patch decrease (Table 4.5).

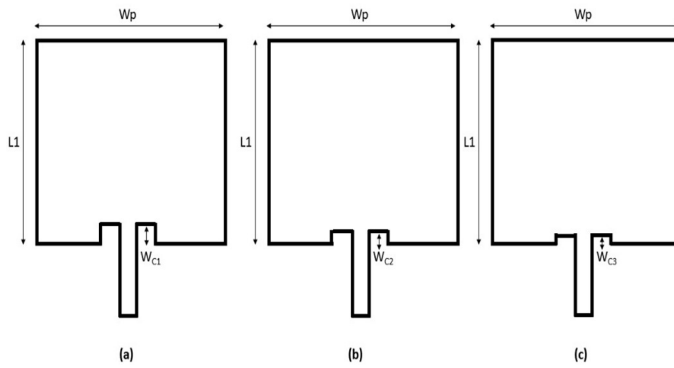


Figure 4.18 Impact on antenna geometry by varying loss tangent. $W_p = 2.7$ mm, $L_1 = 1.5$ mm, and $W_{c1} = 0.8$ mm are the lengths of the inset with loss tangent 0.055, 0.063, and 0.068 respectively

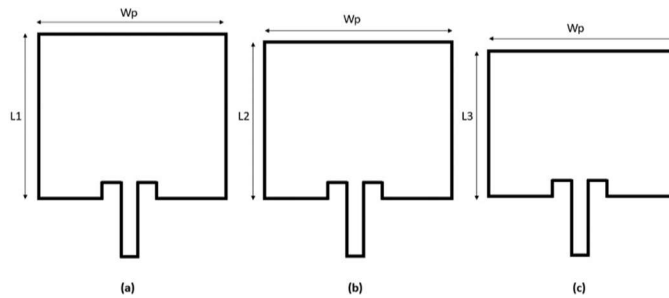


Figure 4.19 Impact on antenna geometry by varying dielectric constant. $L_1 = 43.40$ mm, $L_2 = 41.70$ mm, and $L_3 = 39.5$ mm are the lengths of the patch with DK 1.833, 1.983, and 2.2 respectively).

4.2.2 Effect of Substrate Thickness on Antenna Parameters

respectively).

In Chapter Three, we have established that there are various categories of cardboard with different thicknesses. The effects of antenna thickness on radiation parameters warrant further investigation. The simulation of the antenna's radiation pattern variations with substrate thickness are summarized in Table 4.7.

As the thickness of the substrate increases, the gain, efficiency, and bandwidth also increase.

Table 4.7: Effect of Cardboard substrate height on Antenna Radiation Parameters.

Height (mm)	$\tan \delta$	ϵ_r	Lp (mm)	Wp (mm)	S ₁₁ (dB)	Gain (dB)	Bandwidth (MHz)	Efficiency (%)
2.15	0.055	1.87	43.2	54	-34.4	1.84	140.4	32.12
1.7	0.055	1.86	43.2	54	-48.7	2.47	146	33.88
2.2	0.055	1.85	43.2	54	-27.3	2.9	157	39.55
3.6	0.055	1.81	43.2	54	-16.8	3.6	166.2	52.14

This is consistent with the findings shown in [85]. Above a certain limit of the thickness value, the radiation parameters begin to decrease. This occurs due to surface waves entering the system and lowering the antenna radiation characteristics [85]. The antenna efficiency can be increased by as much as 90% and its bandwidth by 35% in the absence of surface waves[85]. But as height increases, surface waves are created, and these are often undesirable since they take away from the total amount of power that may be used for direct radiation. As surface waves propagate through the substrate and disperse at bends and surface discontinuities such as the ground plane and dielectric truncation, they impair the antenna pattern and polarization properties.

4.2.3 Single Band Antenna

A single-band antenna at 2.45 GHz is simulated using CST Microwave software with the identified values of $\tan\delta$ and ϵ_r . A microstrip feed line is considered for the ease of matching to $50\ \Omega$ by tuning the insertion position. To match the antenna to a $50\ \Omega$ input impedance, a recessed distance H from one edge is calculated using Equation (4.6) and later optimized with CST Microwave Studio (Figure 4.20).

$$H = \frac{0.822 * L}{2} \quad (4.6)$$

Where L is the length of the patch antenna. The geometry of the designed antenna and the fabricated patches on cardboard sample #4, cardboard sample #1a, and sample #1b are shown in Figure 4.20 a, b, c, and d, respectively. Two identical patches were made on sample #1 to guarantee the accuracy of the measured RF properties in chapter three (Figure 4.20c and d). The laboratory setup for measuring the S_{11} parameters of both samples #1 and #4 is shown in Figure 4.21a and b, respectively. Another patch was made on the rougher side of cardboard sample #1 to confirm the impact of losses on the cardboard sample. The patch's geometry is identical to the patches in Figures 4.21c and d. Figure 4.22 displays the lab setup and the manufactured patch. Figures 4.23 and 4.24 present the measured and simulated return loss results for cardboard samples #1 and #4, respectively. Measurement findings for cardboard sample #1's smooth and rough surface are presented in Figure 4.24. The Figure shows results for the two patches in Figure 4.20 c and d (measured sample 1 and measured sample 2). It also shows the result for the patch fabricated on the rough surface of cardboard sample #1(measured sample 3). There is a slight variation between the two fabricated patches of the same geometry. This comes

from slight inaccuracy when sticking the copper tapes on the cardboard substrates. It can also be due to minor differences in cutting the substrates (since cutting was done manually).

Equations 4.7 and 4.8 show the relationship between the length and width of the substrate as a function of the resonant frequency. Figure 4.24 further shows that the antenna on cardboard sample #1 fabricated on the rough surface has more losses than the same patch antenna made on the smooth surface. Whatever the case, both samples still have a good match at intended frequency of interest, which is close to the simulated result. The radiation characteristics of the antennas, both simulated and measured, are compiled in Table 4.9.

$$L_s = 6h + \frac{C_0}{2f_r \sqrt{\epsilon_{\text{reff}}}} - 2\Delta L \quad (4.7)$$

$$W_s = 6h + \frac{C}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (4.8)$$

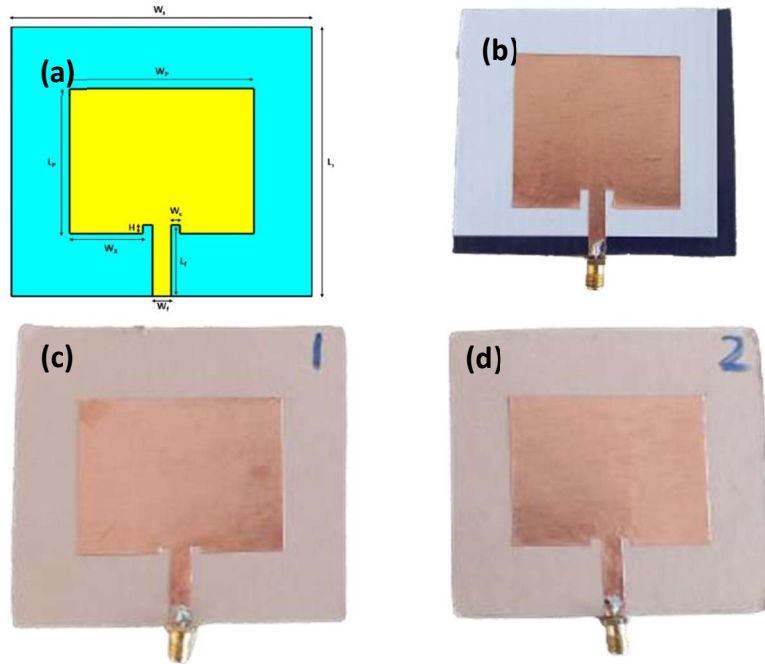


Figure 4.20: Patch antenna manufacturing on cardboard and using copper tape as the conductive material.
 (a) Geometry (with parameters in Table 4.8), (b) fabricated patch on cardboard sample #4, (c) fabricated patch on cardboard sample #1a, (d) fabricated patch on cardboard sample #1b

Table 4.8: Dimensions related to the antenna geometry (in mm) in Figure 5.5

Sample name	W_P	L_P	W_F	L_F	W_X	W_C	W_S	L_S	H
Sample #1	54	41.5	5.4	21	21.6	2.7	88	80	1.9
Sample #4	54	41.5	5.4	21	21.6	2.7	88	80	5.9

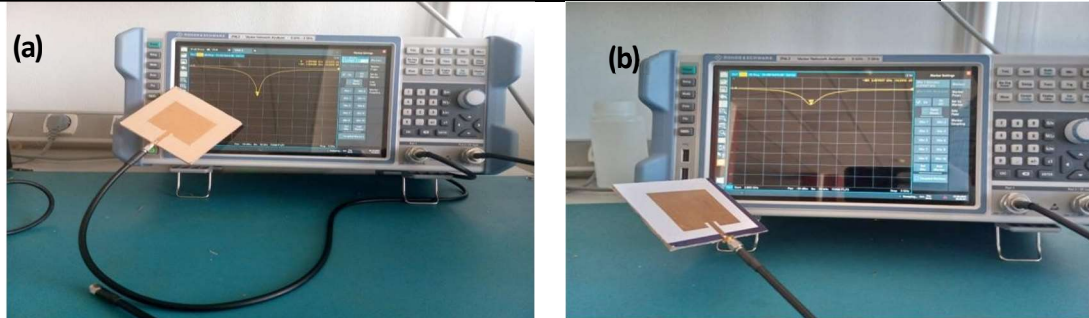


Figure 4.21: Lab setup for measuring return loss parameters of (a) Cardboard sample #1, (b) Cardboard #4

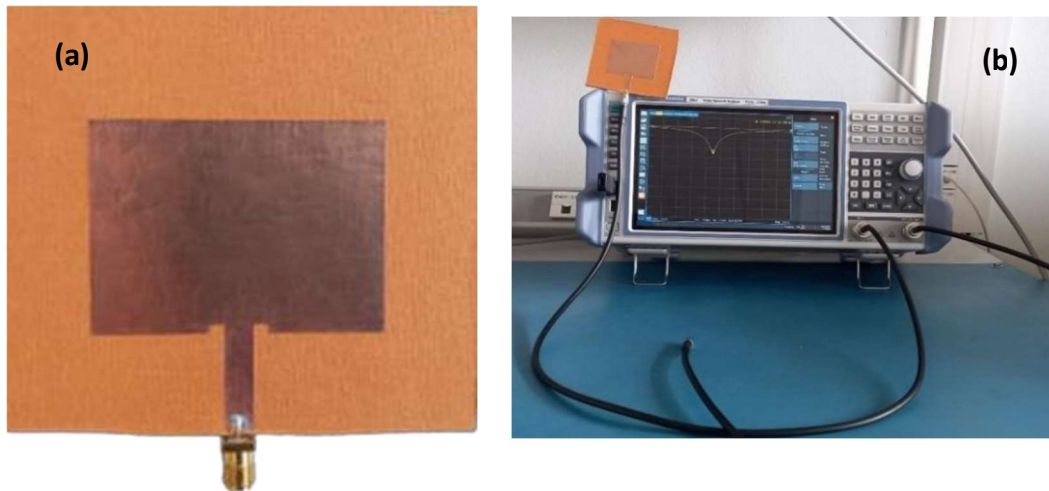


Figure 4.22(a) Patch antenna printed on rougher surface(b) measurement setup for S_{11} for cardboard

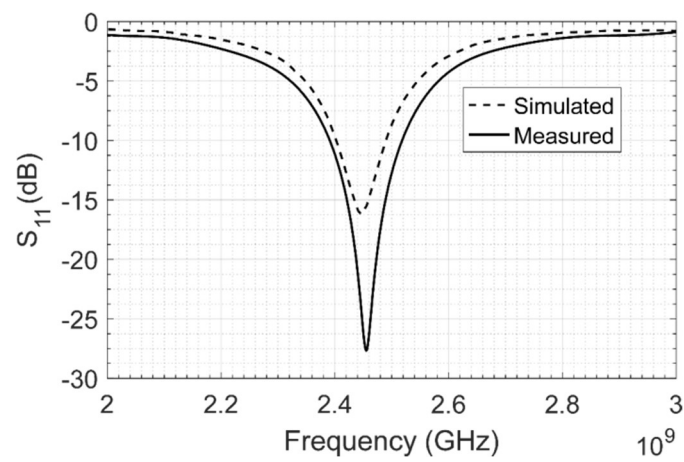


Figure 4.23: Simulated and Measured S_{11} of antenna on cardboard sample #4 (Figure 4.20b).

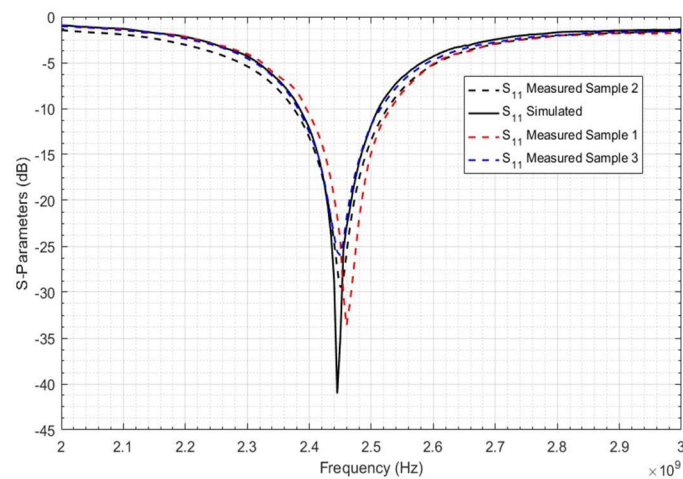


Figure 4.24: Simulated and Measured S_{11} of antenna on cardboard sample #1 (Figure 4.20c and d).

Table 4.9: Main properties of patch antenna printed on cardboard paper substrate.

Sample numb	Gain (dB)	Bandwidth (MHz)	Resonance frequency (GHz)	Return loss (dB)	Size (mm ³)
#1 Simulation	2.98	169.9	2.4513	-39.76	80x88x2.2
#1a Measurement	2.53	160.4	2.46	-33.653	80x88x2.2
#1b Measurement	2.51	168.7	2.45	-25.98	80x88x2.2
#4 Simulation	3.12	136.8	2.4523	-37.098	80x88x1.7
#4 Measurement	3.01	109	2.446	-16.204	80x88x1.7
#1Sim GSM900	0.21	20	0.90	-11.387	190x186x2.2
#1Mea GSM900	0.45	25	0.898	-14.15	190x186x2.2
#1Mea GSM1800	0.369	107.2	1.816	-12.847	190x186x2.2
#1Mea GSM1800	0.54	120	1.862	-21.15	190x186x2.2

1a sample #1 printed on smooth(front) surface (Figure 5.5 c & d), 1b sample #1 printed on rough(back) surface (Figure 5.7)

4.2.4 Dual Band Antenna

An antenna resonating at GSM 900 and 1800 are simulated on the smooth face of cardboard sample #1a. Since this antenna can capture the RF signals at two different frequencies, it can lead to a higher PCE of the rectenna circuit. The geometry and fabricated patch are shown in Figure 4.25. The dual-band capability is achieved by shifting the feed line to the left, resulting in unequal widths W_{X1} and W_{X2} . The radiation parameters of the antenna at both frequencies are shown in Table 4.9.

Table 4.10: Geometry (in mm) of patch in figure 4.25

Sample name	W_P	L_P	W_F	L_F	W_{X1}	W_{X2}	W_C	W_S	L_S	H
Sample #1	152	108.1	7.6	47	64.2	63.7	8	186	190	2.2

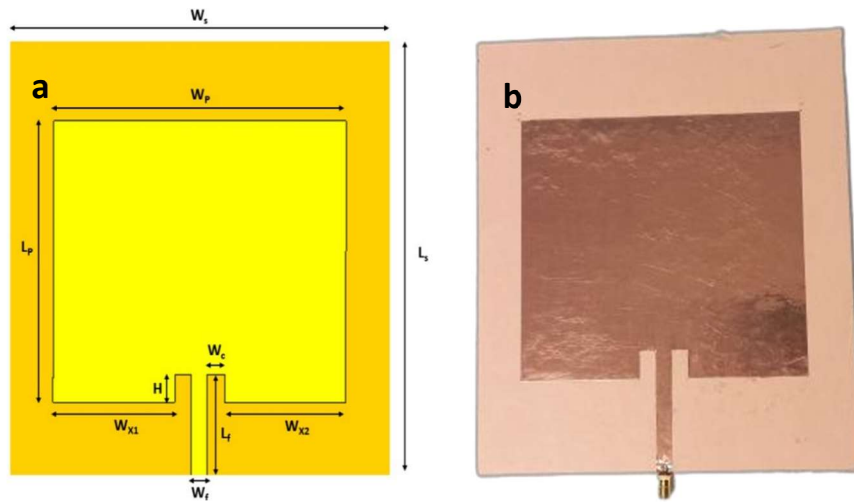


Figure 4.25 Dual band patch antenna fabricated on Cardboard #1a (smoother surface) using copper tape as conductive material. (a) Geometry (with parameters in Table 8), (b) fabricated patch on cardboard sample 1

The laboratory setup for measuring the return loss of the fabricated multi-band patch cardboard antenna is shown in Figure 4.26.

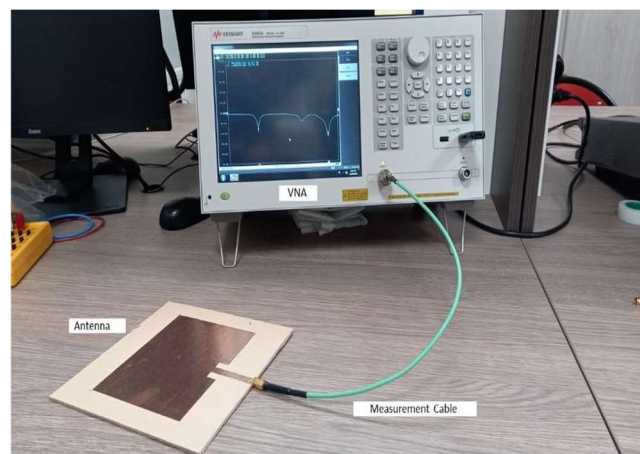


Figure 4.26 Laboratory setup for measuring return loss of dual band microstrip patch antenna fabricated on cardboard sample #4

Figure 4.27 displays the measured and simulated S_{11} . At 900 MHz, simulation and measurement concur, with simulation slightly outperforming measurement. There is a discrepancy between simulation and measurement at 1800 MHz. At the frequency of interest, both results still have a close match. The fact that the measured and simulated results at both frequencies agree further establishes the validity of using the extracted relative permittivity and loss tangent when building radio frequency circuits on cardboard.

4.2.5 Broadband Antenna

An advantage of broadband antennas is their ability to function across a broad frequency range. This allows them to receive most of the signal at various frequencies. The PCE of the rectenna circuit rises in proportion to the intensified captured signal. Since it is hard to create a broadband matching network for a rectifier, matching broadband antennas to the rectifier is the primary challenge. Slots have been made on the patch and ground planes in this work to generate a broadband antenna.

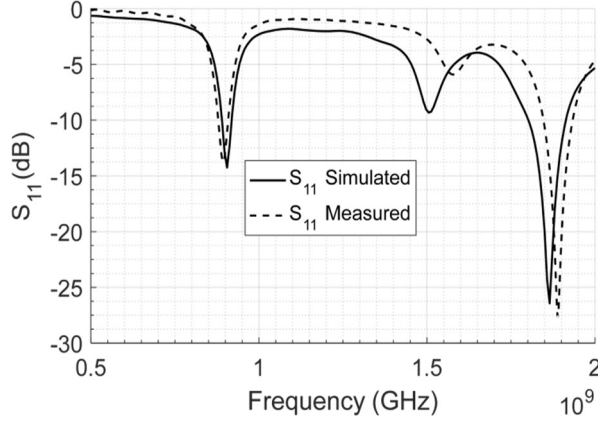


Figure 4.27: Simulated and measured return loss of dual band patch antenna on cardboard sample #1

The antenna has been modelled in CST design software and fabricated on the smooth surface of cardboard sample #1. Figure 4.28 displays the constructed monopole and its geometry. Two antennas are made exactly alike. This will facilitate the gain measurement later using the 'Two identical antenna method' which is based on the Friis free space equation. The length and width of the monopole is calculated using Equation 5.4.

$$L = W = \lambda/4 \quad (5.4)$$

The laboratory set-up for measuring the return loss is shown in Figure 4.29. The simulated and measured return loss for the antenna is shown in Figure 4.30. The radiation parameters of the antenna are summarized in Table 4.12. There are some differences between the simulated and measured findings, as shown in Figure 4.30. The measured result indicates a leftward shift. The modelling and experimental return loss values at 2.45 GHz are -16.519 dB and -22.23 dB, respectively. Both results demonstrate a strong correlation across a broad range of frequencies. The discrepancy between the results is due to the variation of the relative permittivity of the Cardboard substrate over a wide

range of frequencies. It might also be due to slight errors in the measurement setup. The measured bandwidth of the antenna is 2132 MHz (1287 MHz – 3419 MHz).

4.3 Conclusion

This section gives a brief explanation of antennas' radiation parameters. The return loss, bandwidth, polarization and the gain are the four most important parameters to consider when designing an antenna. For an acceptable design, the return loss should be less than -10 dB and the gain greater than 0 dB. Both LP and CP antennas have been designed and characterized. The LP patch has a higher gain than the CP patch, while the CP patch has the advantage of capturing the wave at a wider angle. Increasing the capturing angle was done by curving the patch. Although it decreases the gain, an increase in HPBW was recorded. In conclusion, the acceptable values in antenna parameters of both designs suggest that the extracted loss tangent and the relative permittivity of the substrates can further be used to design RFEH circuits.

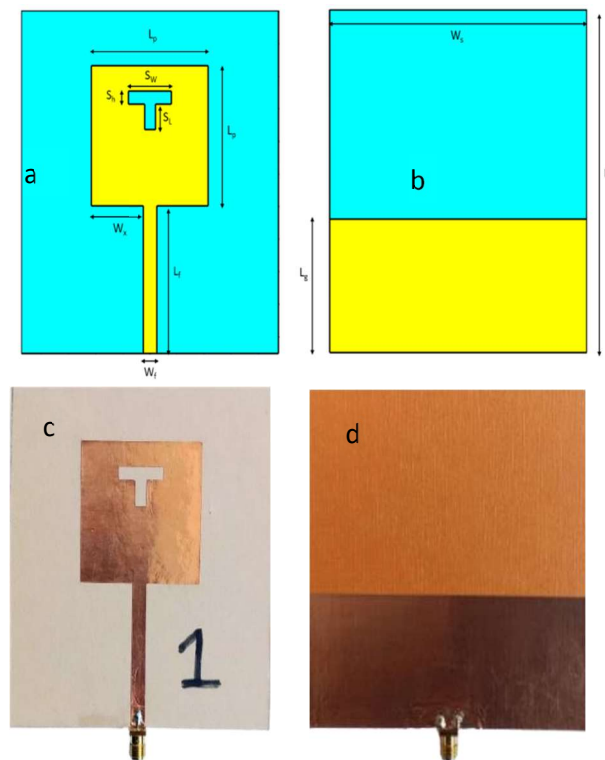


Figure 4.28 Monopole antenna fabricated on Cardboard sample #1 using copper tape as the conductive material. (a) Geometry of front view (with parameters L_p , W_p , L_r , W_s , W_t , L_s , and S), (b) Back view (ground plane), (c) Fabricated monopole (front view), (d) Fabricated monopole (ground plane)

Table 4.11: Geometry (in mm) of antenna in Figure 4.28

Sample name	L _P	L _S	L _G	W _S	W _X	L _F	S _H	S _W	S _L	W _F
Sample #1	43	105	41	95	19	45.1	4	16	6	5

Table 4.12: Main properties of monopole antenna printed on cardboard paper substrate sample #1.

Sample number	Gain@2.45(dB)	Bandwidth (MHz)	S ₁₁ @2.45(dB)	Size(mm ³)
#1 Simulation	2.51	2010.2	-16.519	105x95x2.2
#2 Measurement	2.2	2132	-22.23	105x95x2.2



Figure 4.29: Lab setup for measuring return loss parameter of

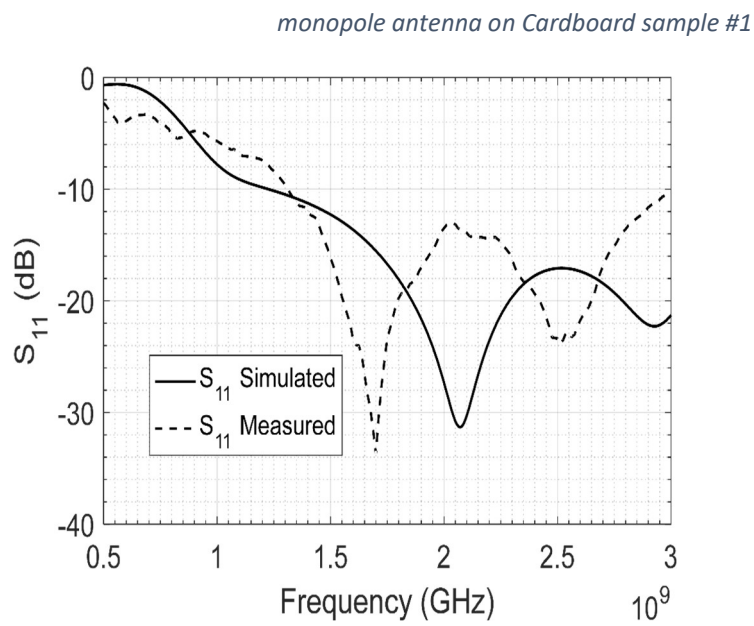


Figure 4.30 Simulated and measured return loss of broadband monopole antenna on cardboard sample #1 (smooth face)

CHAPTER 5

RECTIFIER IMPLEMENTATION

To have DC power from RF sources, there has to be a processing circuit. The processing circuit is the RF-DC rectifier. The rectifying circuit is made up of Schottky diodes with very low DC turn-on voltage. The conversion efficiency of the rectifier depends on the Zero-bias junction capacitor, C_{j0} , the breakdown voltage, V_{br} and the series Resistor, R_s [212]. To maximize the rectifier conversion efficiency, the diode is desired to have a low junction capacitor, low series resistor, and high breakdown voltage. In addition, the diode should have a low threshold voltage, V_{TH} and high reverse saturation current, I_s [50]. Table 5.1 summarises these important parameters of the most commonly used Schottky diodes.

Table 5.1: Characteristics parameters of most commonly used Schottky diodes models from manufacturers

Diodes	I_s (μA)	C_j (pF)	$R_s(\Omega)$	V_{TH} (V)	V_{br} (V)
HSMS2820	0.022	0.7	6.0	0.15	15.0
SMS7630-079LF	5.00	0.14	20.0	0.09	2.0
HSMS2850	3.00	0.08	25.0	0.15	3.8
HSMS2852	3.00	0.08	25.0	0.15	3.8
HSMS2860	0.05	0.18	6.0	0.25	7.0
MA4E1317	0.10	0.02	4.0	0.7	7.0
HSMS286B	0.06	0.18	6.0	0.69	7.0

Among the diodes presented, SMS7630-079LF and HSMS2850 have the highest reverse saturation currents, with SMS7630 having a higher value. The Zero-bias junction capacitor is the lowest for both diodes. However, the value for HSMS2850 is the lowest. Again, SMS7630 has the lowest threshold voltage, which is slightly lower than that of HSMS2850. Both diodes have the lowest breakdown voltages, with HSMS2850 having a higher value. HSMS2820 model has the highest value, with a very low saturation current and high junction capacitance, making it inappropriate for our design. HSMS2850 and SMS7630 are selected for this work due to the advantages enumerated. Another additional advantage for HSMS2850 is that the diode has a more accurate vendor model in the ADS simulation software. Diode models will be discussed in the next section.

Diode Models

There are two diode models in ADS; the spice generic model (the user in charge of parameter values) and the vendor model.

To carry out a comparison of the two models, we consider the single series configuration HWR in Figure 5.1 The model of Figure 5.1 is the vendor model. It has all the packaging elements. Thus, this can directly be used for simulation as it should reflect the practical implementation. In Figure 5.2, we have the circuit diagram with the generic spice model. This Figure does not consider the packaging elements (C_P and L_P). Figure 5.3 shows the spice model with packaging and parasitics taken into consideration.

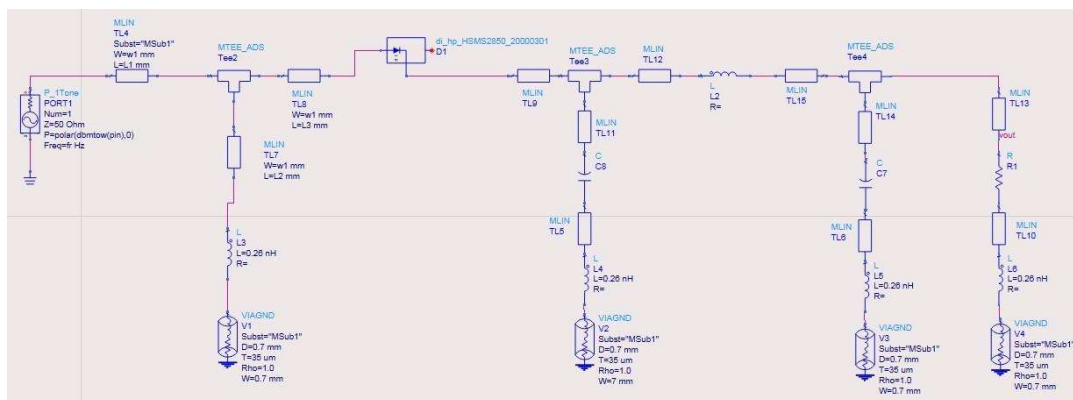


Figure 5.1: Vendor Model simulation set up

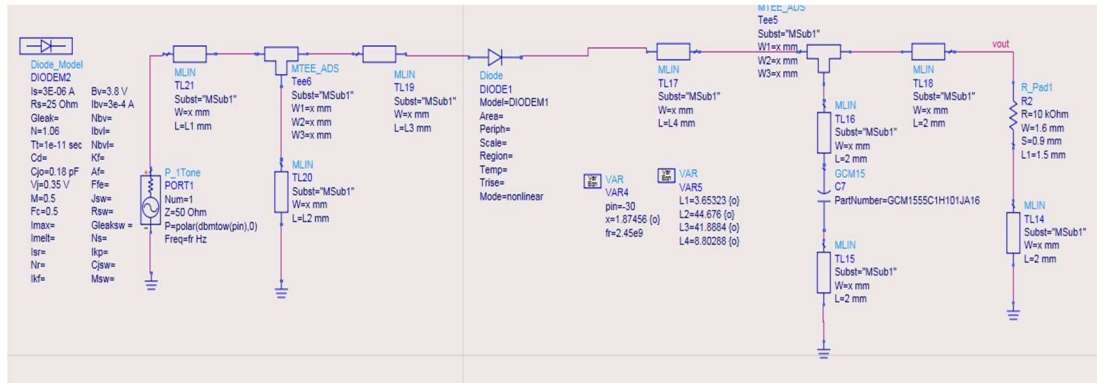


Figure 5.2: The generic spice model without packaging or parasitics simulation set up

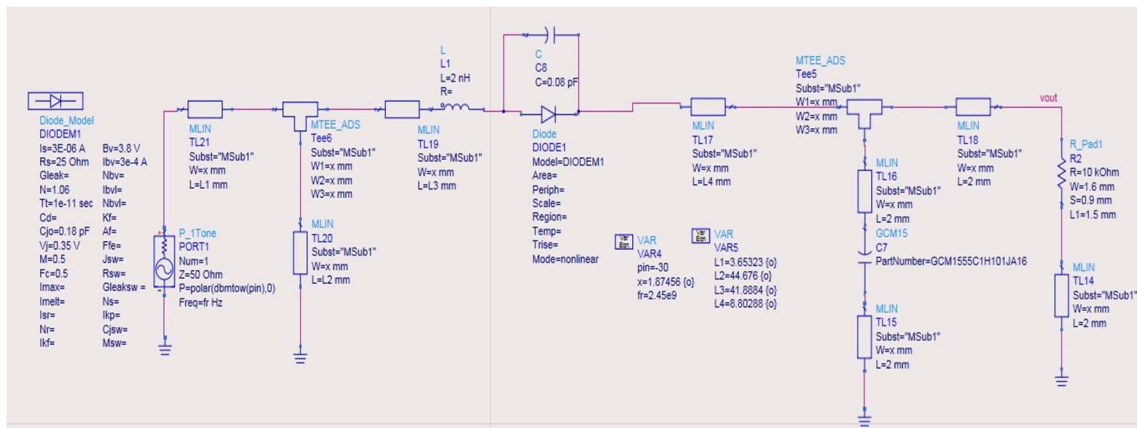


Figure 5.3: The Generic spice model with parasitic simulation set up

We have performed the comparison in terms of the S_{11} and efficiency. Figures 5.4a and b show the return loss and efficiency results considering the vendor model, and the generic spice model with and without parasitics. The generic spice model without parasitics is far from the vendor model. There is a kind of agreement between the generic spice model with parasitics and the vendor model. Thus, any of the two models can be used in the simulation of our circuits.

For the rest of this work, we will keep the vendor model. The vendor model is similar to measurement in real-life cases (except for losses from board parasitics, and SMA connectors), as will be seen from the results of the prototype fabrication later.

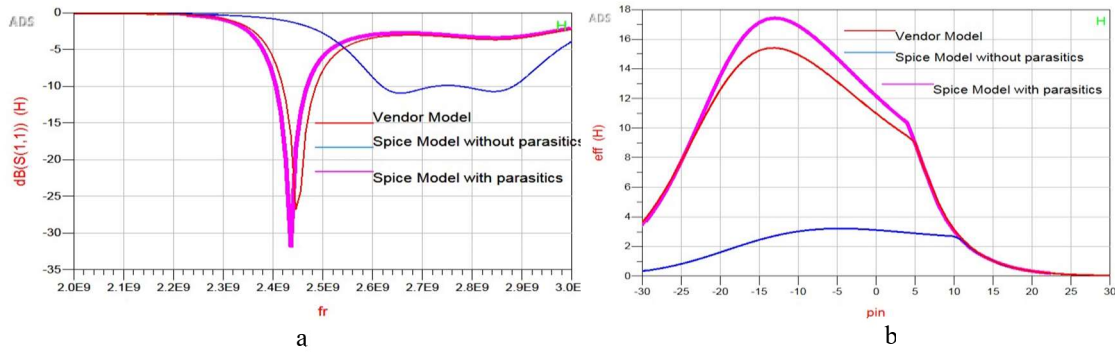


Figure 5.4: (a) S_{11} comparison in HWR configuration and using three diode models and (b) Efficiency of HWR configuration using three diode models (vendor, spice without parasitics and spice model with parasitics)

Thus, in this chapter we will use vendor model to implement our rectifiers on cardboard and PLA substrates.

5.1 Rectifier Implementation on Cardboard Paper

The rectifier operates at a frequency of 2.45 GHz and is designed to handle an input power of -10 dBm. According to literature, this frequency band is widely recognized. Besides, it is not attenuated strongly in free space, even under some weather conditions [45]. The rectifier is validated by Momentum co-simulation in ADS 2022. Large Signal Scattering Parameter (LSSP), Harmonic Balance Simulation (HBS), and multiple Parameters Sweeps are used in the simulation. HBS analysis is considered for optimizing the design concerning DC output voltage, i.e. tuning an output filtering action. HBS is a frequency domain analysis technique for simulating distortion in non-linear circuits and systems. LSSP is performed on non-linear circuits, and thus it takes into consideration non-linear effects such as gain compression and variation in power levels.

The voltage doubler topology is used in the design because theoretically it doubles the output voltage. We will use three distinct diode models, HSMS-2860, HSMS-2580, and SMS7630079LF—to develop three designs in this part. The aim is to have the optimal diode model on a cardboard substrate. Thereafter, the impact of substrate material on RFEH is concerned with comparing rectifiers fabricated on three different substrates (PLA, Cardboard, and Rogers RO4003C). The schematic of the rectifier is shown in Figure 5.5 with a complete path for DC current. The choke inductor is used to block unrectified signals from the diode.

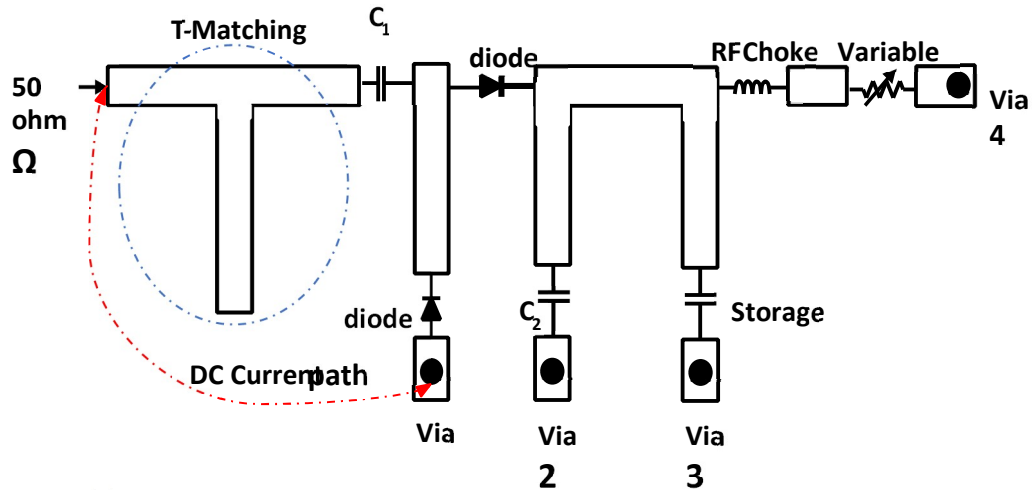


Figure 5.5: Rectifier schematics based on the voltage doubler topology with complete DC path.

The rectifier was designed following the steps outlined below.

- 1) The first step was to design the rectifier in ADS schematics using the calculated lengths of the microstrip stubs (Figure 5.1). LSSP, HBS, and multiple parameter sweeps are used for simulations. This is contrary to S-parameter simulations that are performed on linear circuits [45]. The LSSP simulation employs harmonic balance techniques as it is grounded on harmonic balance simulation.
- 2) The simulation layout is generated from the schematic design software. Pins' effects are added as lump components at the various gaps between ground and input power supply (Figure 5.6).
- 3) The RF properties from the characterization in chapter 3 are applied to the substrate model. The frequency range is set between 2 GHz to 3 GHz in the momentum co-simulation, and the symbol for momentum simulation is generated.
- 4) The lumped components, ground, power supply, ViaGround, and via inductors are connected to the various gaps in the generated symbol.

The fabricated rectifier on cardboard sample #1 is shown in figure 5.7.

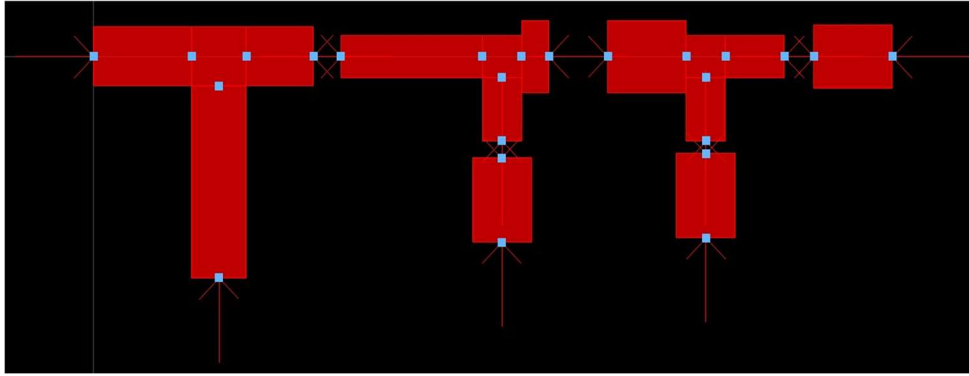


Figure 5.6: Layout setup for simulation

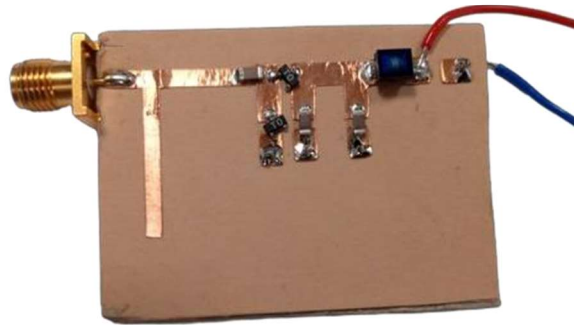


Figure 5.7: Fabricated rectifier on cardboard sample #1 using MS-2860 diode model at 2.45 GHz

5.1.1 Results and Discussion

5.1.1.1 Return Loss

To verify if the matching network is well designed, we measure the S_{11} parameter (Figure 5.8). Figure 5.9 displays the rectifier's simulated and measured return loss at -10 dBm and -5 dBm. The measured results show some discrepancies with the simulation results. Our Hypothesis is that the difference can be due to fluctuations of the cardboard's RF properties due to moisture absorption, solder paste use in soldering the surface mounted components, imperfect sticking of the copper tape on the substrate, diode packaging or it can be due to the variations of the thickness of the airgap inside the substrate or other environmental factors that affect the electrical properties of cardboard paper that needs further investigation. The measurements for the three input powers show a good match at 2.45 GHz.

5.1.1.2 Maximum Power Point and Optimal Load Value

In this work, the maximum power point (MPP) is the point where maximum power is obtained. The optimal load value is the value of the load at which maximum power is obtained. To determine the optimal load, a study is performed in terms of load variation.

The test uses circulators to guarantee that the rectifier receives the desired input power (-10 dBm, -5 dBm, or 0 dBm).

Using an RF generator, the incidence power, P_i , is calculated; however, there are losses, P_l ,

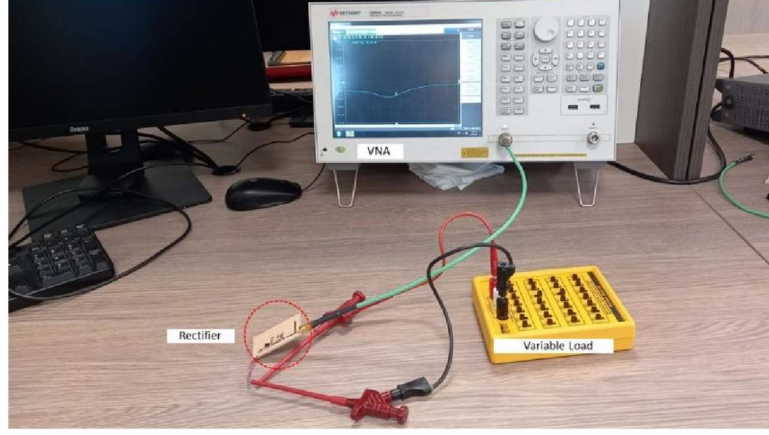


Figure 5.8: Lab set-up for measuring S_{11} of rectifier.

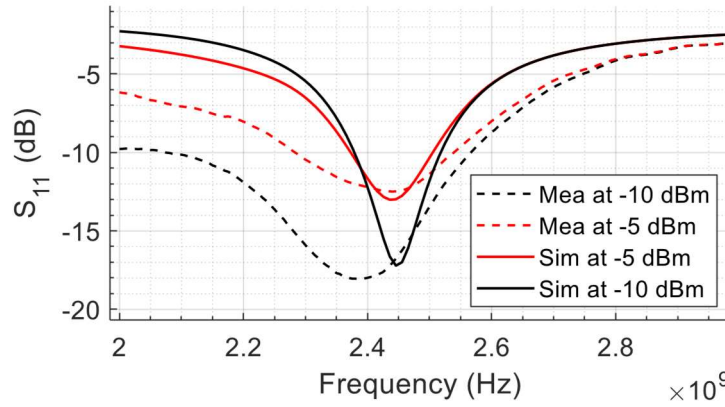


Figure 5.9: Simulated and measured S_{11} of rectifier fabricated on Cardboard sample #1 under different

due to the connecting equipment. Before the experiment, the losses from the coupler, measuring cables, and connectors are measured to produce accurate and compelling data. Equation 5.1 is used to determine the power transmitted to the rectifier (P_t) from the reflected power (P_r), the input power (P_i), and the losses. For each load value, we measure (P_r) using coupler number 2 and adjust P_i until P_t equates to the desired value for characterization. That is if the rectifier is designed and optimized at -10 dBm, the incident power is adjusted until the transmitted power gives -10 dBm. In this manner, we guarantee the rectifier receives a -10 dBm supply. A high internal impedance voltmeter is employed to measure the rectified DC voltage across the DC load. After measuring the DC voltage across the load, equations 5.2 and 5.3 are used to compute the DC power and PCE, respectively. This procedure is repeated for a range of load values (0.5 – 40 k Ω)

and a plot is made of DC power on the y-axis and load on the x-axis. From the plot, the optimal load value is determined. This will facilitate in adapting the rectifier to a PMU.

$$P_t = P_i - P_r - P_l \quad (5.1)$$

$$P_{DC} = V_{RDC}^2 / R_L \quad (5.2)$$

$$\eta_{DC} = P_{DC} / P_{in} \quad (5.3)$$

Figures 5.10 illustrates the laboratory set up for measuring rectified DC voltage.

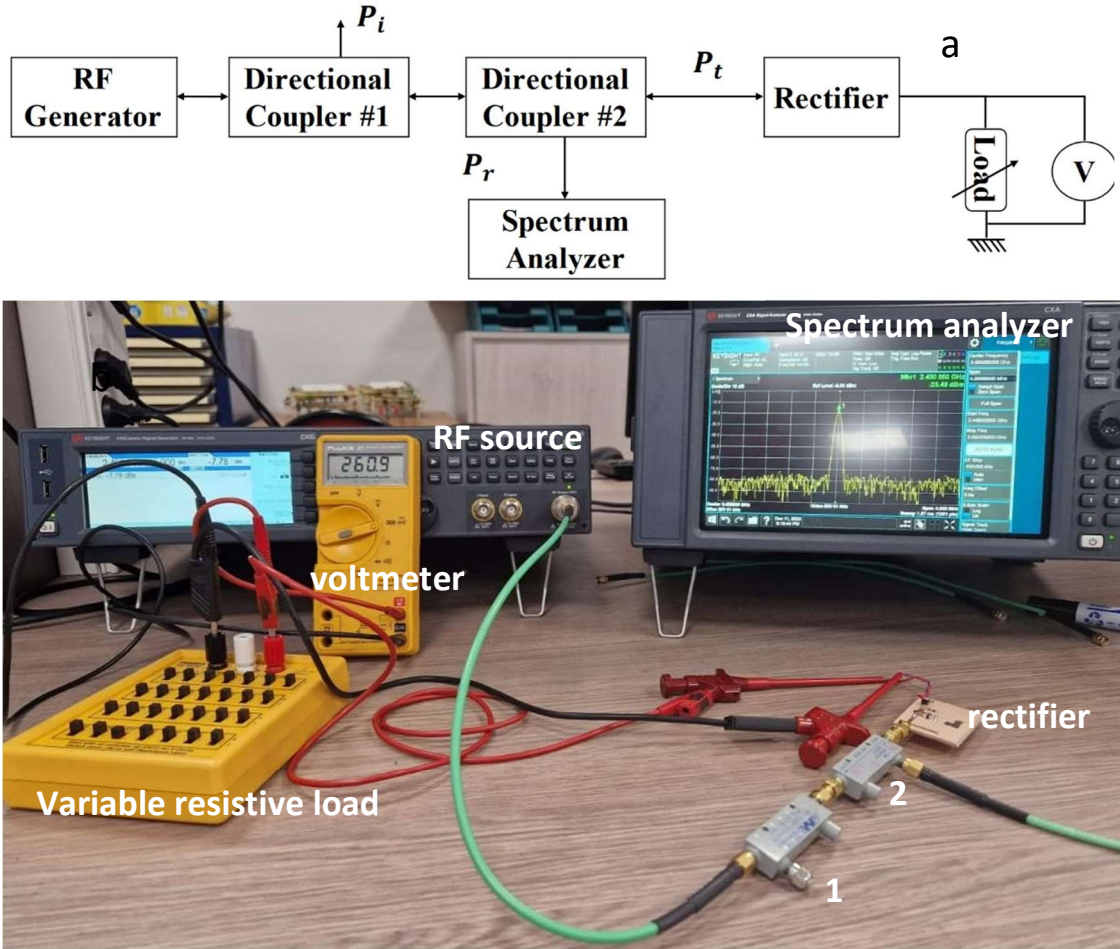


Figure 5.10: a) Measurement schematic; b) Measurement setup (1 – circulator #1 used to measure the incident power; 2 – circulator #2 used to measure the reflected loss).

Figure 5.11 displays the output DC power, both measured and simulated. The measurement exhibits the same tendency as the simulation, with little changes between them, as seen in Figure 5.11. According to both results, the optimal load for simulation and measurement are 8.03 kΩ and 8 kΩ, respectively, at which point the MPP condition

is reached. For simulation and measurement, this translates to an output DC power of $1.78 \mu\text{W}$ and $1.73 \mu\text{W}$, respectively.

5.1.2 Impact of different diode models

Three identical rectifiers were fabricated utilizing the diode models SMS7630-079LF, HSMS2850, and HSMS-2860 to validate the best diode model on a cardboard substrate. Figure 5.12 displays the constructed circuits using the three diode models

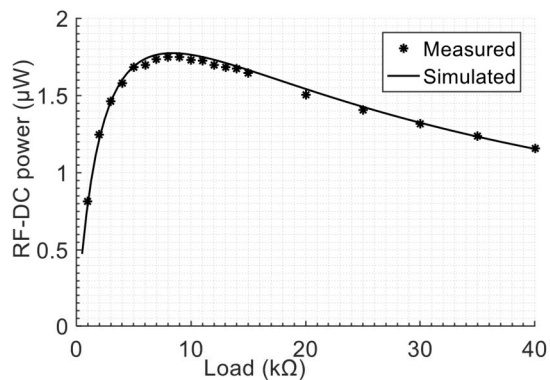


Figure 5.11: Simulated and Measured DC output power of cardboard sample #1 rectifier under -10 dBm input RF power at 2.45 GHz

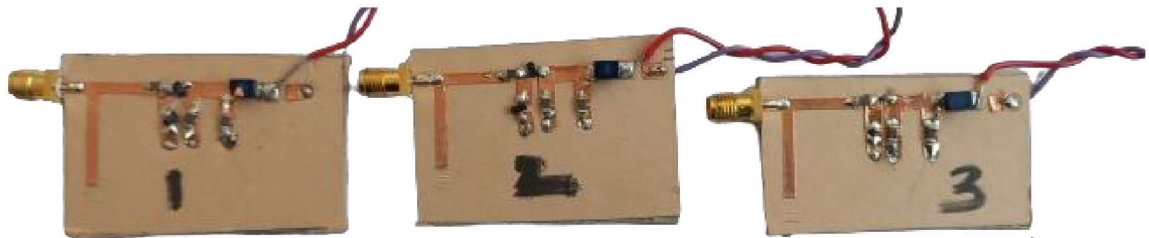


Figure 5.12: Rectifiers with three diode models under -10 dBm of input power (1) HSMS 2860, (2) HSMS 2850 (3) SMS7630-079LF 7630

Before proceeding with the analysis, we have to ensure that all circuits with difference diode models are well matched. The S_{11} parameters of the three circuits are shown in Figure 5.13.

The Figure shows good matching for all circuits at 2.45 GHz.

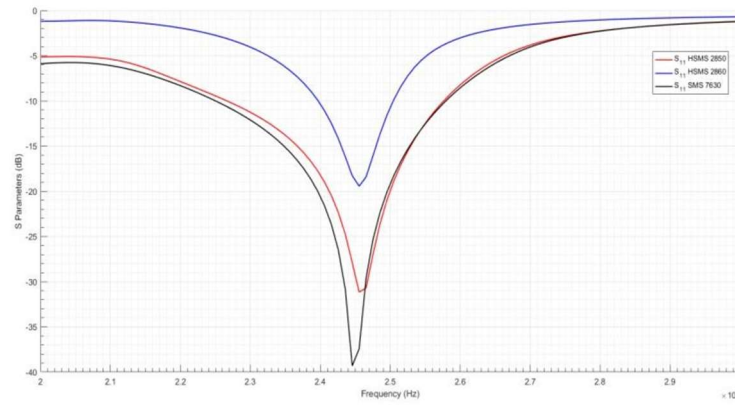


Figure 5.13 S_{11} parameters of rectifiers with SMS7630-079LF, HSMS2850 and HSMS2860 diode models under 10 dBm input RF power at 2.45 GHz

The plot in Figures 5.14 shows the measured output power versus the load resistance for all three diode models under -10 dBm of input power. Other measurements were done at input powers of 0 dBm and -5 dBm (Figures 5.15a and 5.15b respectively).

Simulations and experiments demonstrate that the SMS7630-079LF diode model yields the highest output DC power regardless of the input power. This is followed by the HSMS-2850

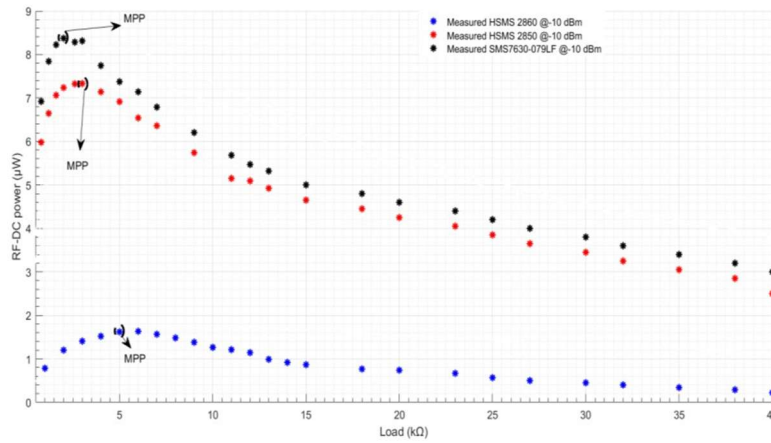


Figure 5.14: Output power versus load for cardboard rectifiers with three diode models under -10 dBm

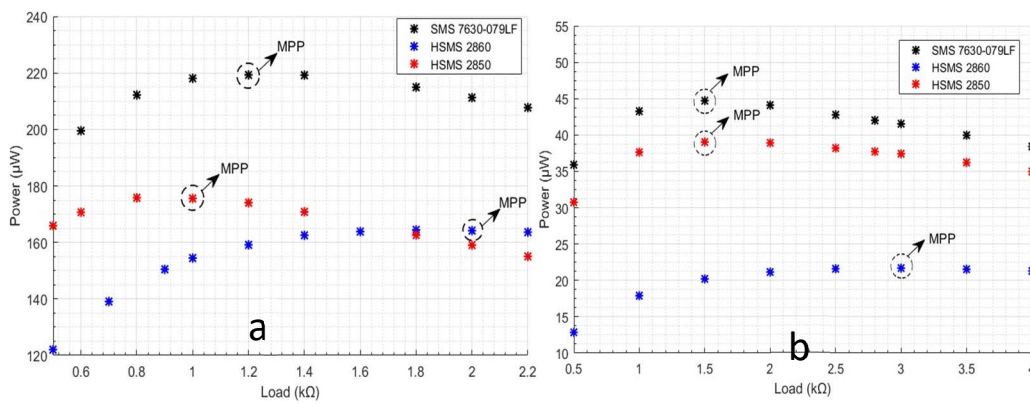


Figure 5.15: Measured rf-dc power at varying load under (a) 0 dBm of power input and (b) -5 dBm of input

model and least by the HSMS-2860 model. The diode model SMS7630-079LF yields the highest results since it has the lowest threshold voltage (V_{th}) and the highest saturation current (I_s). HSMS-2860 has the highest threshold voltage and lowest saturation current. For all three diode variants, the ideal load falls with increasing input power (Table 5.2). This is because a higher RF input power causes a higher current, which in turn causes a stronger polarization of the diode and a reduction in some losses.

Table 5.2: Optimal loads for rectifiers constructed with HSMS 2850, HSMS 2860 and SMS7630-079LF diode models under different input power conditions

Power (dBm)	MPP Load (k Ω) SMS7306-079L	MPP Load (k Ω) HSMS-2850	MPP Load (k Ω) HSMS-2860
0	1.1	1	2
-5	1.5	1.5	3
-10	2	2.6	8

5.2 Rectifier Implementation on PLA

The second rectifier implementation is done on PLA. For this design a single series diode topology was adopted since we desired our circuit to work as low input RF power. Single series diode topology has limited components and less losses. The design on a 1.5 mm thick PLA substrate using the rectangular microstrip line in a T-matching network is shown in Figure 5.18. The Momentum co-simulation setup is shown in Figure 5.17. To enable a close loop for the flow of direct current, a short circuit stub is used in the matching network. Figure

5.16 shows the schematic with the closed DC loop for the current.

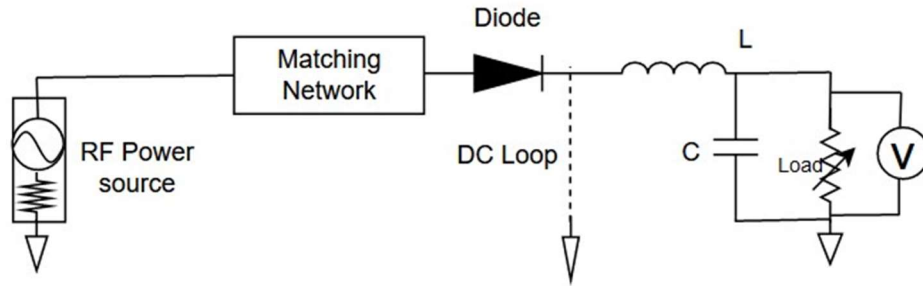


Figure 5.16: Rectifier Schematic showing complete path for DC current

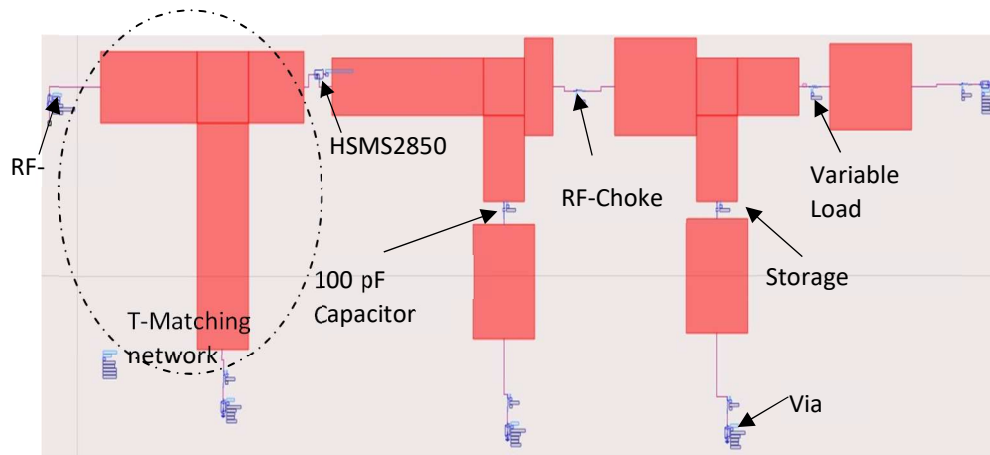


Figure 5.17: Momentum Setup for rectifier simulation



Figure 5.18: Picture of single series PLA base fabricated rectifier

5.2.1.1 Return Loss simulations and measurements

The laboratory setup, simulated, and measured S_{11} of the rectifier at -30 dBm, -20 dBm, and 10 dBm are shown in Figures 5.19 and 5.20, respectively. The load is a variable resistor. The measurement results have shifts in resonance frequency but with a good match at 2.45 GHz though lower than the simulation values. The simulated and measured S_{11} at 2.45 GHz are -32 dB and -29 dB respectively at -30 dBm. This disparity could result from PLA's varying RF characteristics and minor melting during brazing. The high

level of substrate roughness could potentially be the cause or the variation of the electrical properties of PLA with environment factors [202] [213].

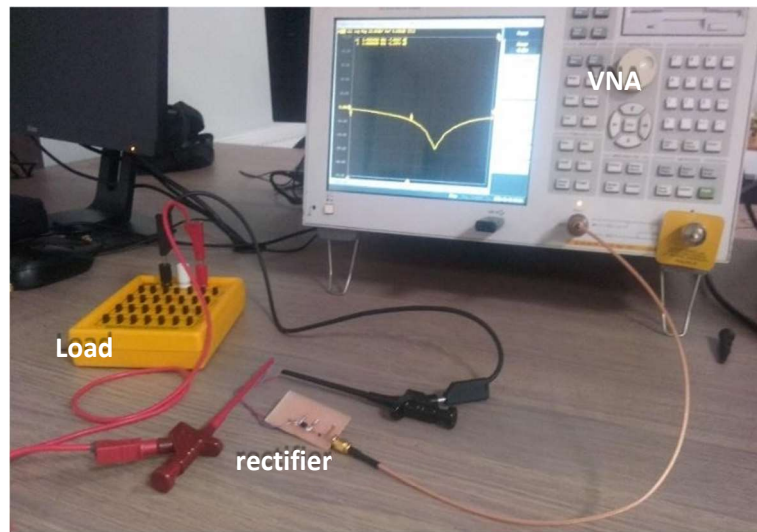


Figure 5.19: Laboratory-scale setup for measuring S_{11}

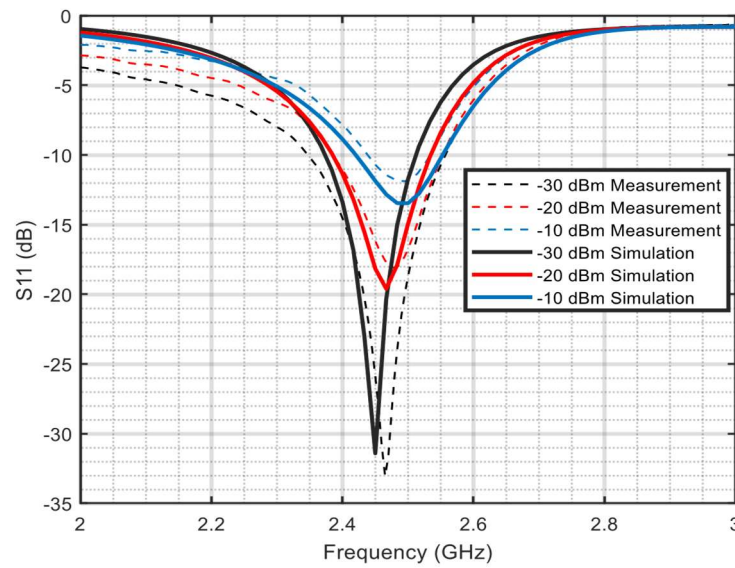


Figure 5.20: Measurement and Simulation results of S_{11}

5.2.1.2 Measurement and Maximum Power Point

The same methodology as in the case of cardboard was used to obtain the optimal load. The measured and simulated results for the DC power are shown in Figure 5.21. The input power was set to -20 dBm at 2.45 GHz.

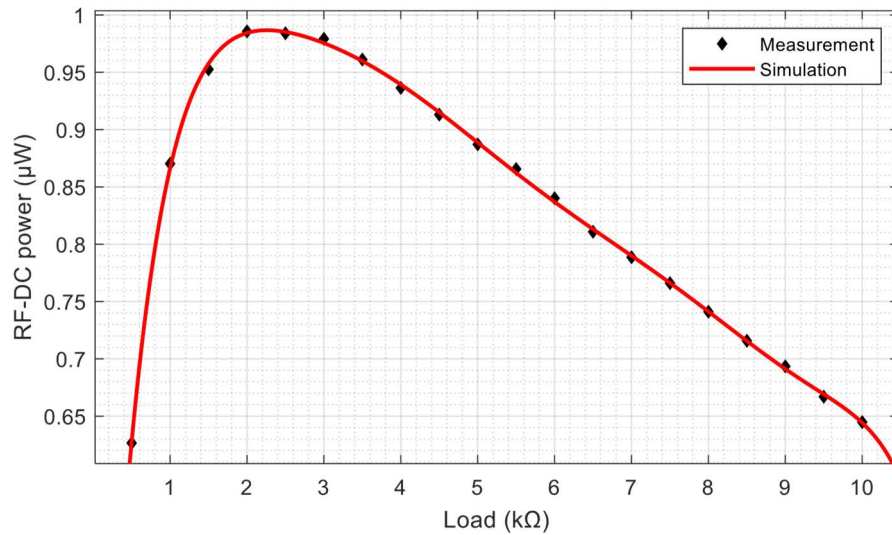


Figure 5.21: Simulated and Measured DC output power under -20 dBm input RF power at 2.45 GHz

As seen in Figure 5.21, the measurement has the same tendency as in the simulation, with a close match between the two. With an input RF strength of -20 dBm, Figure 5.21 shows a maximum available power of 0.98 μW . The Figure shows the value of the so-called ideal DC load, which is 2.2 $\text{k}\Omega$. A simple model of the rectifier output may be an ideal voltage source (open-circuit DC voltage) in series with a resistive impedance of the optimal load value. This is only representing the MPP condition. More Results of MPP are presented in Figures 5.22,

5.23, and 5.24 under input RF power of -25 dBm, -15 dBm, and -10 dBm, respectively.

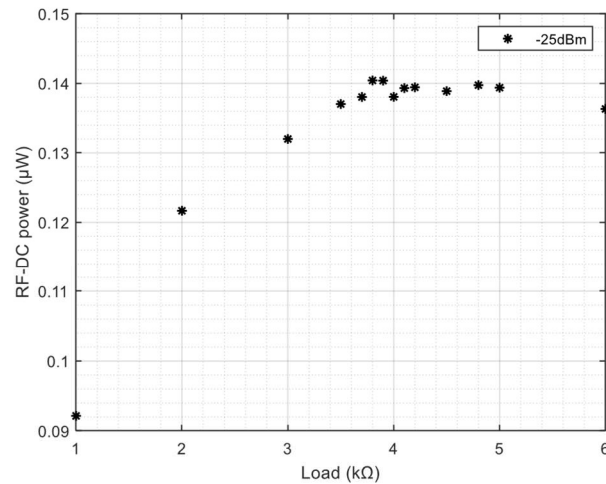


Figure 5.22: Measured DC output power under RF input power conditions at 2.4 GHz of -25 dBm

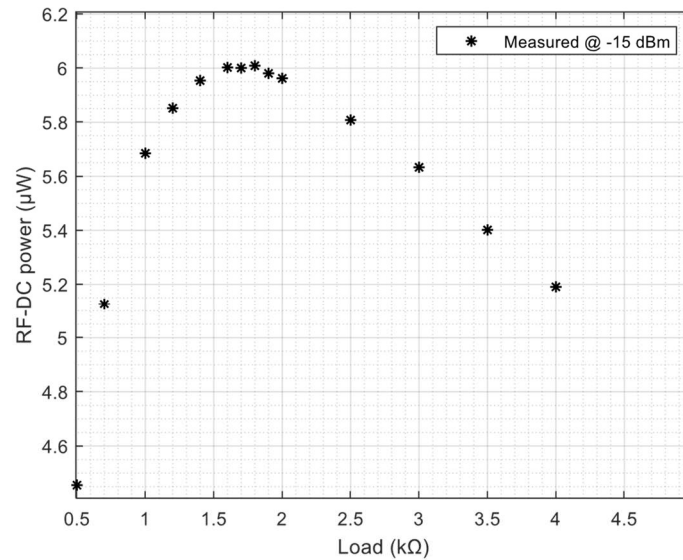


Figure 5.23: Measured DC output power under RF input power conditions at 2.4 GHz of -15 dBm

5.2.1.3 Voltage Doubler rectifier

To increase the rectified DC voltage of the primary design, a voltage doubler topology is used. The rectifier is fabricated at 2.45 GHz frequency and optimized at an input RF power of -15 dBm using the HSMS 2860 diode model. The fabricated rectifier is shown in Figure 5.25. A variable resistor box is used at the load as this will facilitate the determination of MPP condition. The laboratory set up for measuring the return loss is shown in Figures 5.26. The simulated and measured return loss is shown in Figure 5.27. The simulated and measured dc power at -14dBm is shown in Figure 5.28.

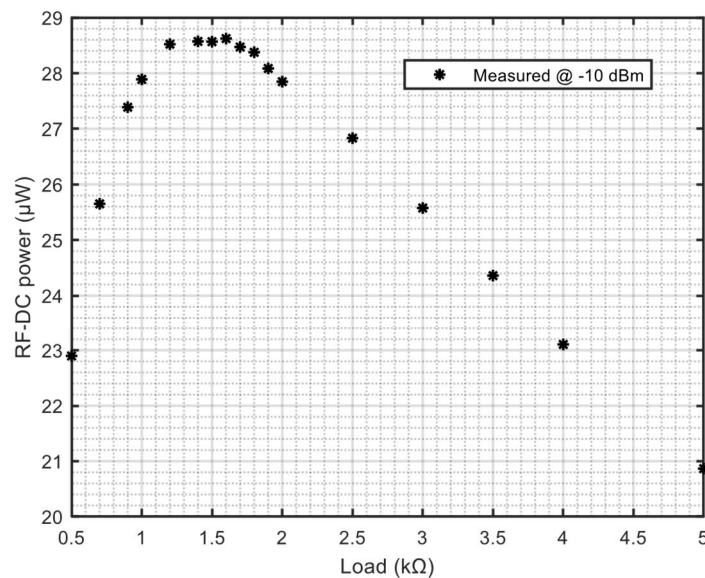


Figure 5.24: Measured DC output power under RF input power conditions at 2.4 GHz of -10 dBm



Figure 5.25: Picture of fabricated rectifier base on the voltage doubler topology

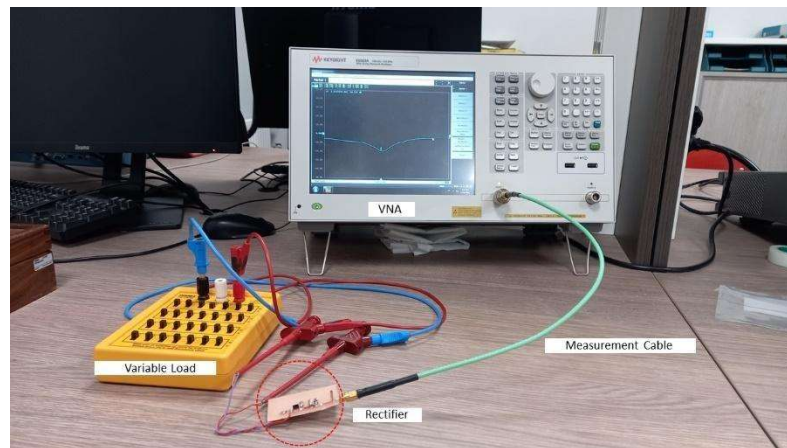


Figure 5.26: Lab set up for measuring return loss of PLA rectifier at 2.45 GHz at -14 dBm

The simulated and measured dc power at MPP condition is $12.4 \mu\text{W}$ and $11.2 \mu\text{W}$ for the simulation and the measurement respectively. Both cases have an optimal load of $8 \text{ k}\Omega$.

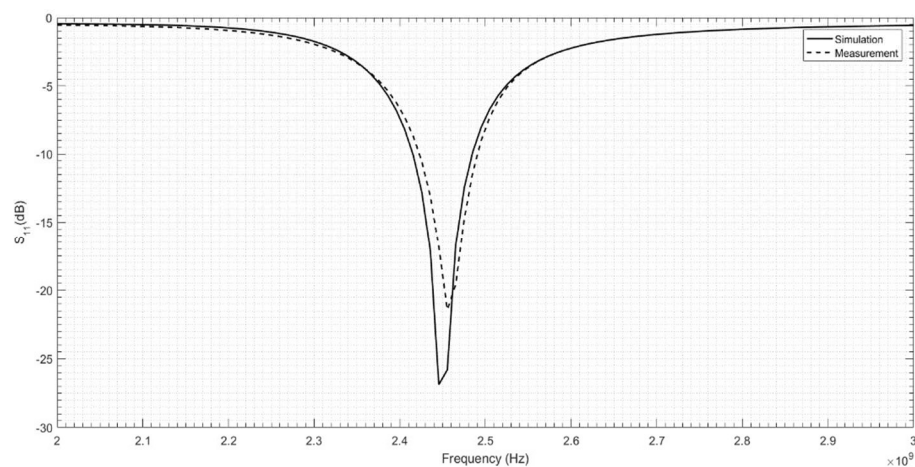


Figure 5.27: Measured and Simulated return loss at 2.45 GHz under 14 dBm input power

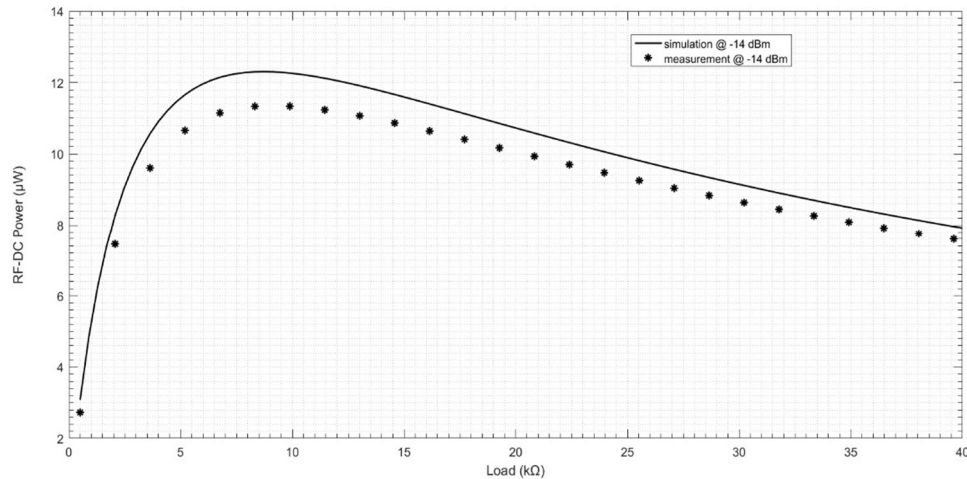


Figure 5.28: Simulated and Measured rf_{dc} power at 2.45 GHz under an input RF power of -14 dB

5.3 Impact of the substrate on RF rectifier

Research has also been done on how the substrate affects rectifier design. Three identical rectifiers were fabricated on Rogers RO4003C, PLA, and Cardboard substrates (Figure 5.29).



Figure 5.29: Identical rectifiers with three different (1) Rogers RO4003C, (2) PLA (3) Cardboard sample #1

Since we are interested in the losses of each substrate, the circulators are not used in the measurement setup. Figures 5.30a, b, and c display the measured values for power against load under 0 dBm, -5 dBm, and -10 dBm, respectively.

As anticipated, the rectifier fabricated on Rogers yields the best results, followed by the one on PLA, while the one on cardboard yields the lowest. This is because Roger's substrate has the lowest loss tangent (0.0027), which is around four times lower than PLA's (0.01) and almost six times lower than cardboard's (0.055). Table 5.3 shows that although the cardboard rectifier has the lowest DC power value, it is still within an acceptable power range for RF energy-collecting methods. This demonstrates that it is possible to manufacture RF energy harvesting circuits even with affordable, recyclable, and eco-friendly substrates. PLA and cardboard are cheap, eco-friendly, and recyclable, thus permitting the implementation of high tech at low cost.

5.4 Comparison with state of art and conclusion

The measurement results show no gain in performance but the advantage of using bio-source materials, ready for recycling, which is not the case with numerous other materials. The obtained power conversion efficiencies are in line with other literature results, somewhat lower but not much. In the case of PLA at -25 dBm and -20 dBm RF input power, the maximum available DC power is 0.14 μ W and 0.96 μ W, respectively, for single series topology at 2.45 GHz. The doubler topology gives an output power of 11.2 μ W at -14 dBm of input power. In the case of cardboard, at low RF input power, -10 dBm, the maximum available DC power is 1.73 μ W, 7.5 μ W, and 8.5 μ W at 2.45 GHz for HSMS-2860, HSMS2850, and SMS7630 diode models, respectively.

The impact of the substrates' RF properties has also been investigated with the best results obtained for rectifiers on Rogers and the least for rectifiers on cardboard substrates. The final remarks of this chapter confirm that the rectenna made on a cardboard substrate is a feasible option.

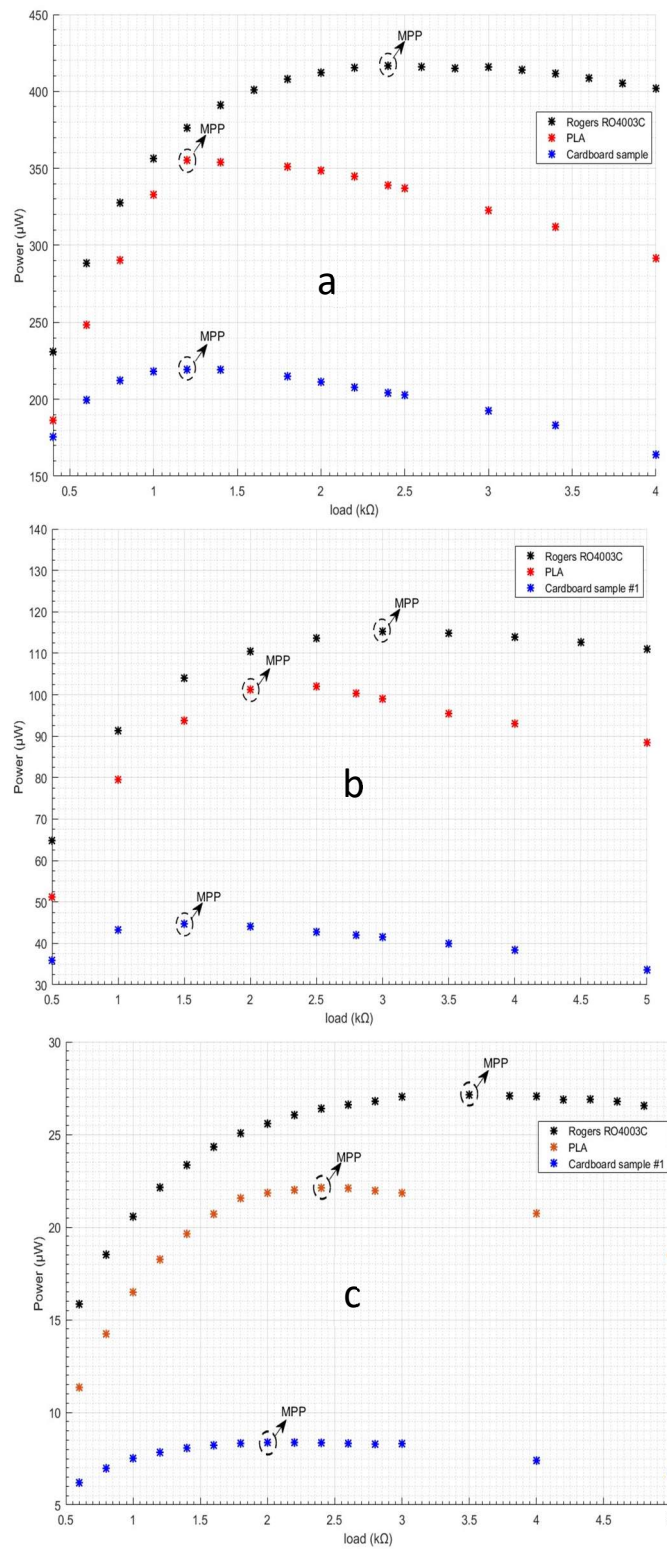


Figure 5.30 Measured dc power at varying load for identical rectifiers on Rogers, PLA and Cardboard substrates under different input power (a) 0 dBm, (b) 5 dBm, (c) 10 dBm

Table 5.3: Comparison with the state of the art

Freq (GHz)	Pin(dBm) @ Load (k Ω)	PCE @ RF-DC power	Substrate/Printing Technology	Size (mm ³)	Ref
2.45	0 @ 5	39.2% @ 392 μ W	Rogers RT/Duroid 5880/PCB	60 x 40 x 1.57	[55]
2.45	-24 @ 10	13% @ 0.52 μ W	Resin/Stereolithography 3D printing polymer	60 x 83 x 1.5	[56]
2.45	0 @ 7	50% @ 500 μ W	LCP/Not mention	15.1 x 8.15 x 0.18	[58]
2.3	-24 @ 14.7	5% @ 0.2 μ W	FR4/printed circuit board	70 x 70 x 13.2	[165]
2.4	-20 @ 6.81	13% @ 1.3 μ W	FR4/printed circuit board	32.07 x 35.75 x 1.6	[170]
2.1	-24 @ 11	3% @ 0.12 μ W	3D printing substrate/Screen printing (conductive silver paste from DuPont)	50x50x50	[166]
2.45	-10 @ 1.5 -15 @ 1.7 -20 @ 2 -25 @ 3.9	29% @ 28.75 μ W 19% @ 6 μ W 9.6% @ 0.96 μ W 4.43% @ 0.14 μ W	PLA/Fuse Deposition Modelling 3D printing polymer	42 x 14 x 1.5	This work
2.45	0 @ 2.4 -5 @ 3 -10 @ 3.5	41.5% @ 415 μ W 36.4% @ 115 μ W 27.5% @ 27.5 μ W	Rogers RO4003C/PCB	35x17x1.5	This work
2.45	0 @ 1.1 -5 @ 1.5 -10 @ 2	22% @ 220 μ W 14.2% @ 45 μ W 8.5% @ 8.5 μ W	Cardboard/copper tape	50 x 20 x 2.2	This work

CHAPTER 6

OPTIMAL VALUE OF THE RECTIFIER INPUT IMPEDANCE

Literature seldom questions the optimal value of the rectifier input impedance for maximum

PCE. Designing rectifiers at $50\ \Omega$ is the main focus of research efforts. Authors in [214] demonstrated that rectifiers should be designed at input impedance lower than $50\ \Omega$. $50\ \Omega$ is not optimal in all cases. Different diode models and rectifier topologies give different values for the optimal input impedance. It has been established that rectifiers design with HSMS-

28xx diode model gives values higher than $50\ \Omega$, while SMS7630-xx model gives values lower than $50\ \Omega$. The designs make use of the single series topology. The single-state voltage doubler topology with HSMS 2850 diode model gives an optimal value around $50\ \Omega$.

The work objectives in this chapter are multi-fold with details on analytical modelling, analysis, and verifying the results through simulation using ADS software, fabrications, and laboratory measurements.

6.1 Simulations with different topologies and diodes models

Using the Rogers RO4003C substrate's RF characteristics, the input RF power versus the power conversion efficiency of the rectifier's is simulated. Simulations are performed for the single series and single state voltage doubler topologies. The circuits incorporate a matching network with either HSMS-2850, HSMS-2860, or SMS7630079LF diode models. The ADS schematic of the circuit used in performing the simulations is shown in Figure 6.1. The RF input power is varied from -25 dBm to 0 dBm. The simulation is performed for input RF power versus PCE. The simulated results for the series topology have an optimal input impedance higher than $50\ \Omega$ for the HSMS-2850 diode model ($140\ \Omega$). Figure 6.2 displays the simulated results for the single series topology with a $3\ \text{k}\Omega$ load value. For each input impedance value, the matching network was adjusted to have a satisfactory value for return loss ($S_{11} < -20\ \text{dB}$). Optimal input impedance of $50\ \Omega$ was noted for the voltage doubler topology using the HSMS2850 diode model (Figure 6.3). The PCE value obtained for the doubler topology is lower. This is because the doubler topology functions well at higher input power. With the matching network modified, the simulation was run again using the HSMS-2860 diode model, yielding identical

outcomes to those shown with HSMS-2850 (Figure 6.4). The single series topology was used. The main differences are a higher peak value of PCE and a shift in the PCE to the right (optimal input impedance is $290\ \Omega$). In contrast, the SMS7630-079LF diode model yields a different outcome (Figure 6.5). In Figure 6.5, the maximum PCE value is achieved when the input impedance is less than $50\ \Omega$ ($10\ \Omega$).

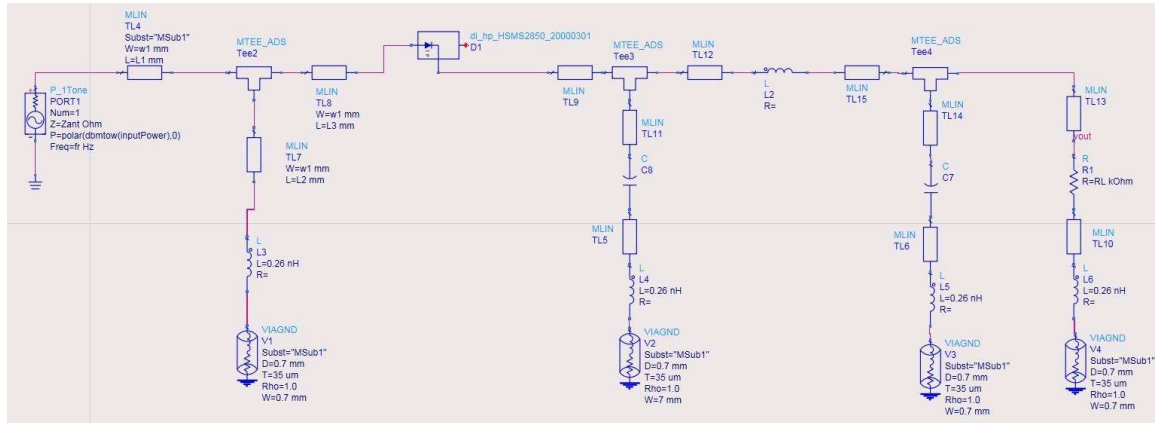


Figure 6.1: Schematics of single series diode circuit used in simulation

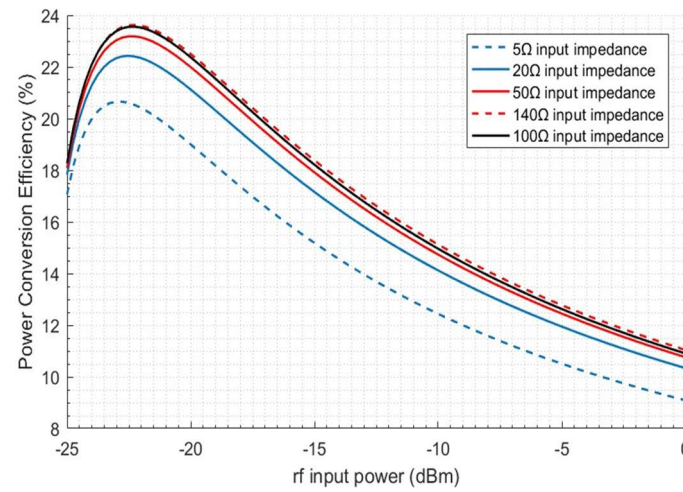


Figure 6.2: RF input power versus efficiency simulation of single series topology with varying input impedance for SMS2850 diode

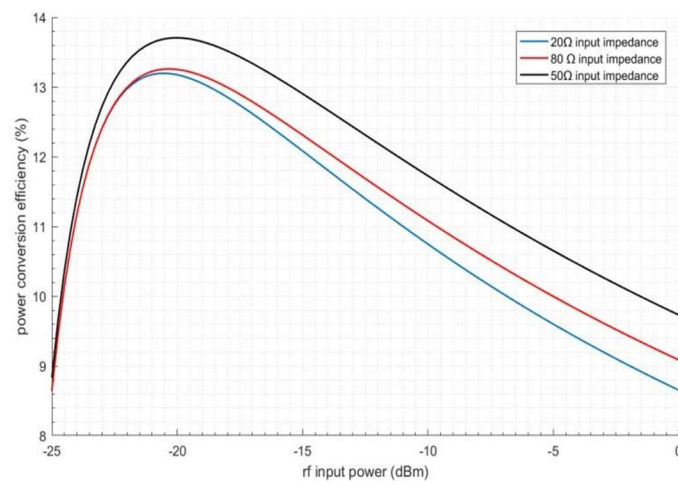


Figure 6.3: RF input power versus efficiency simulation of single stage voltage doubler topology with varying input impedance for H-2850 diode model at 2.45 GHz

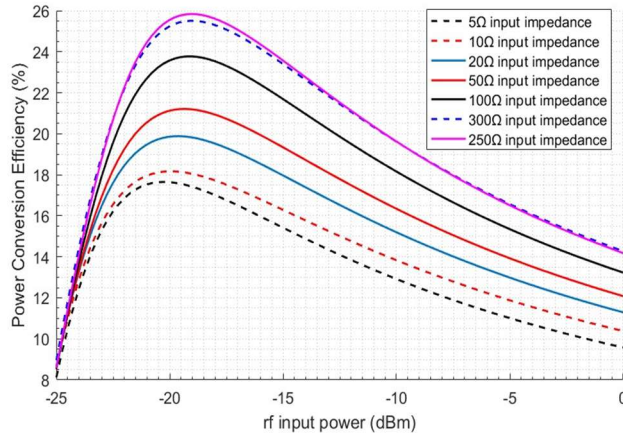


Figure 6.4: RF input power versus efficiency of single series topology with varying input impedance for HSMS2850 diode

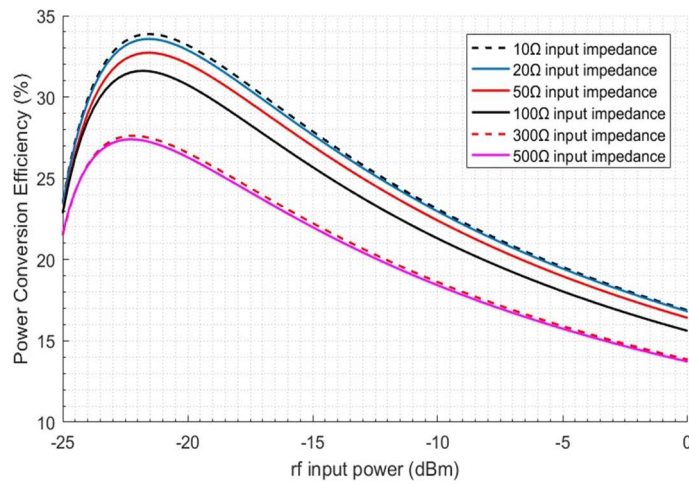


Figure 6.5: RF input power versus efficiency of single series topology with varying input impedance for SMS7630-079LF diode model at 2.45 GHz

Figure 6.6, Figure 6.7 and Figure 6.8 illustrate the value for the optimal input impedance by examining the fluctuation of PCE with the rectifier's input impedance. The Figures are simulation plots of input impedance versus PCE for the HSMS2850, HSMS2860, and SMS7630 -079LF diode models, respectively. The results are consistent with Figures 6.2, 6.4 and 6.5, respectively. The optimal impedances are 140 Ω , 290 Ω , and 10 Ω , respectively, for HSMS 2850, HSMS2860, and SMS7630 diode models. For the voltage doubler topology, the optimal input impedance is 50 Ω (Figure 6.9).

The lowest optimal impedance value of the SMS7630 diode model can be due to its highest saturation current, causing the diode to polarise strongly. Its lowest threshold voltage also contributes to its lowest optical input impedance value. With the highest saturation current, the barrier junction becomes easily polarized, hence lower impedance to current flow across the barrier junction.

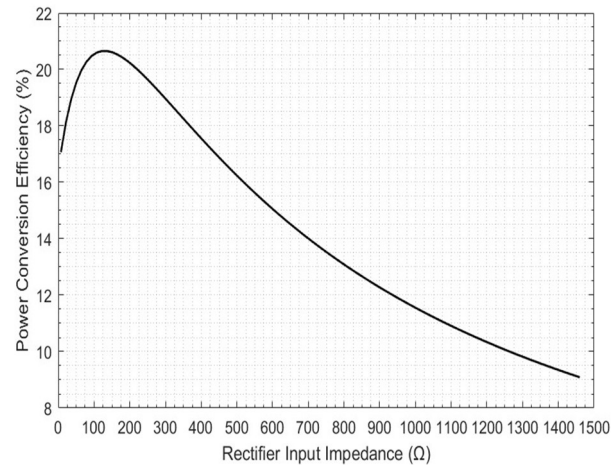


Figure 6.6: Simulation of input impedance versus efficiency of single diode series topology for HSMS2850 diode at 2.45 GHz under 20dBm

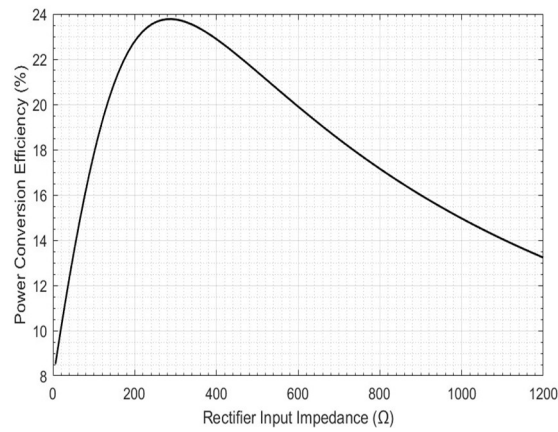


Figure 6.7: Rectifier input impedance versus efficiency simulation of single series topology for HSMS2850 diode model at 2.45 GHz.

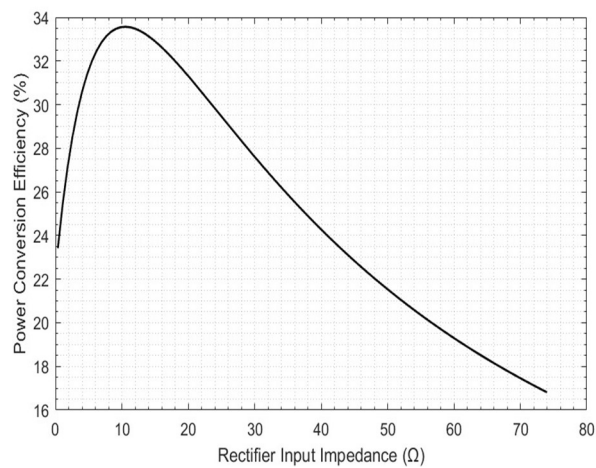


Figure 6.8: Rectifier input impedance versus efficiency simulation of single series topology for SMS7630F diode model at 2.45 GHz.

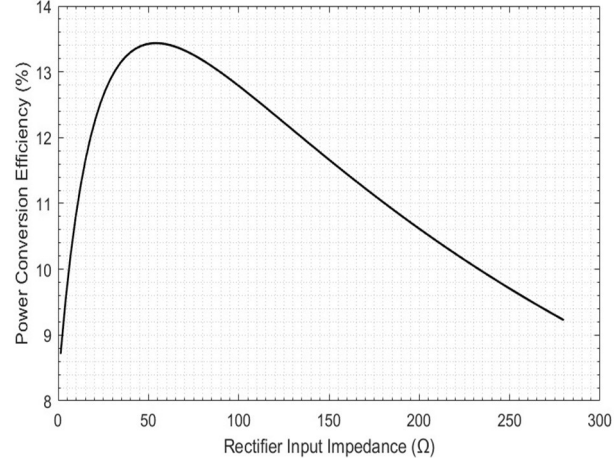


Figure 6.9: Rectifier input impedance versus efficiency simulation of voltage doubler topology with SMS2850 diode model at 2.45 GHz.

Simulations in ADS using the SMS7630 diode model demonstrate that the saturation current (I_s) and threshold voltage (V_J) of the diode have an impact on the rectifier input impedance and the PCE (Figure 6.10). As seen in the Figure 6.10, as the saturation current decreases, the optimal input impedance increases or shift to the right. This explains why the HSMS2860 diode with the lowest saturation current has the highest optimal input impedance.

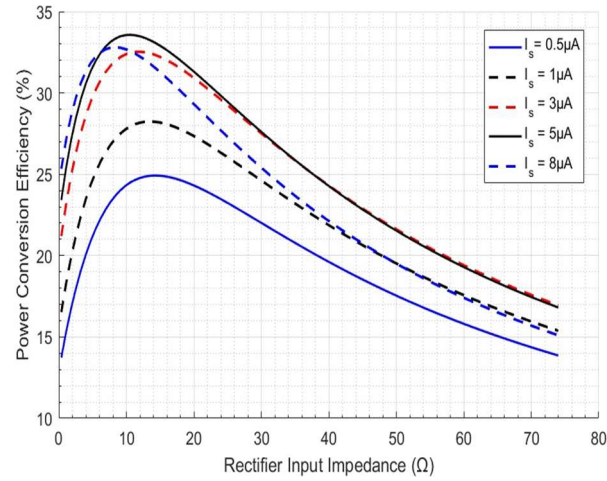


Figure 6.10 Simulation of the diode model saturation current on the optimal input impedance at 2.45 GHz 20dBm (case of SMS7620 diode)

6.2 Method of Characterization

The simulation suggested that 50 Ω is not always an adequate rectifier input impedance. Characterization is the major obstacle in the design of rectifiers with input impedances other than 50 Ω. The majority of RF apparatus is calibrated at 50 Ω. Two approaches to the characterization of non-50 Ω rectifiers are discussed.

6.2.1 Impedance Transformer

The idea behind this technique is to connect the rectifier and the 50 Ω RF generator via a 50-to-higher value impedance transformer (Figure 6.11). Such an impedance transformer is designed for simulation using ADS software (Figure 6.12).

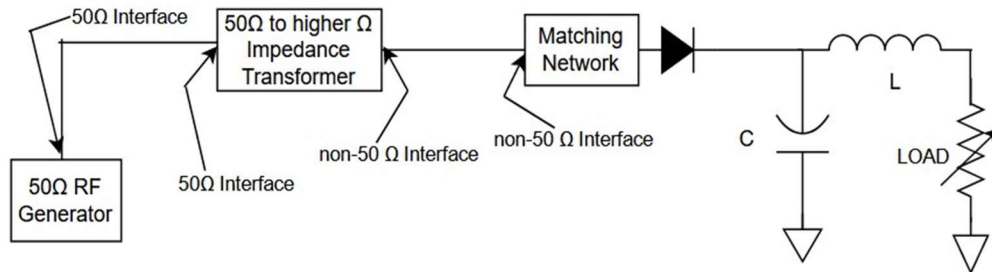


Figure 6.11: Principle of an Impedance Transformer for characterizing a 50 Ω input impedance rectifier

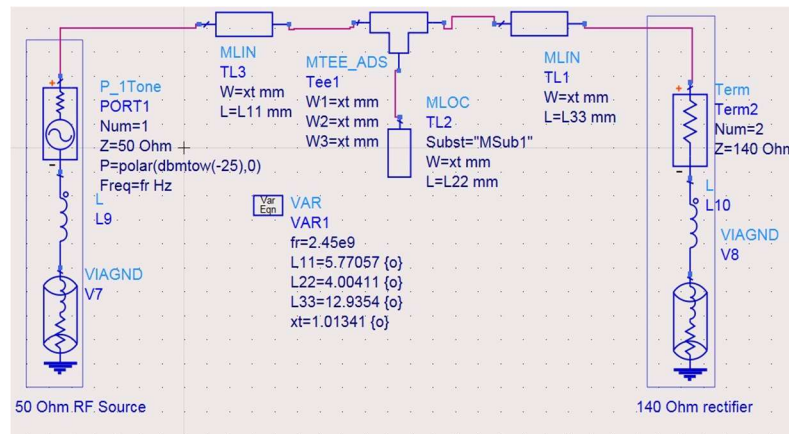


Figure 6.12: ADS schematic for an impedance transformer

Figure 6.13 displays the simulation results for an impedance transformer of 50-to-140 Ω . As anticipated, a solid match is obtained between 2 and 3 GHz. Losses in the transformer are limited. Figure 6.14 shows a combination of the impedance transformer and a non-50 Ω rectifier. A short circuit stub is utilized to create the rectifier's matching network. The return loss seen from the 50 Ω input source is simulated and shown in Figure 6.15. However, characterization using this scheme offers a limited practicality. When changing the RF input power, the diode changes its behaviour, hence introducing a slight change in the rectifier input impedance. The impedance transformer will not take this change into account. The impedance transformer should thus be tuned for each possible operating input RF power. One possible solution to this is that for each input power or load value, a separate matching network should be constructed, which is simply constructing a separate circuit. This is quite very complicated.

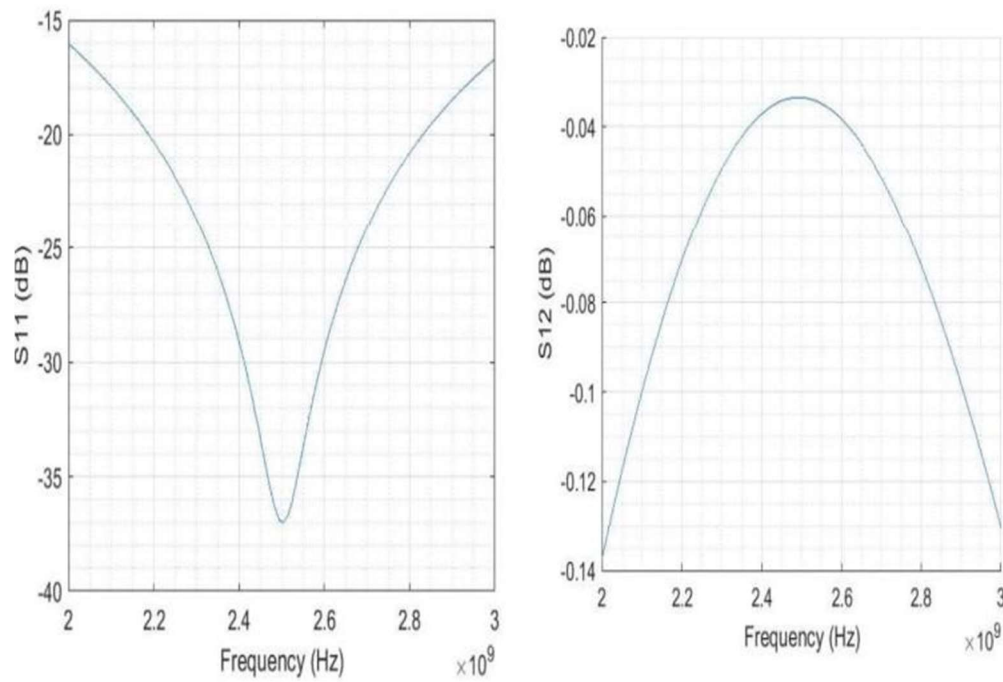


Figure 6.13: S_{11} , and S_{12} simulation results for the 50-to-higher Ω impedance transformer

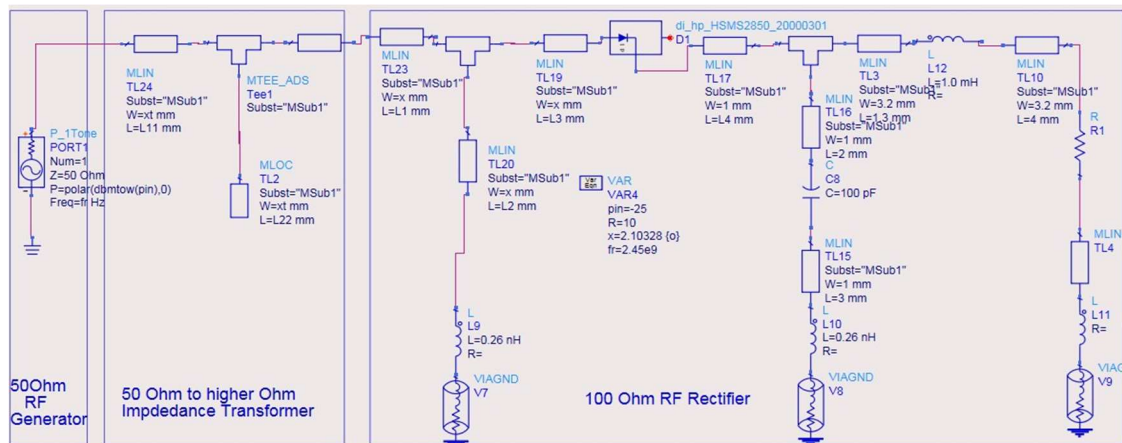


Figure 6.14 ADS Schematic of impedance transformer connected between 50 RF Generator and a higher rectifier.

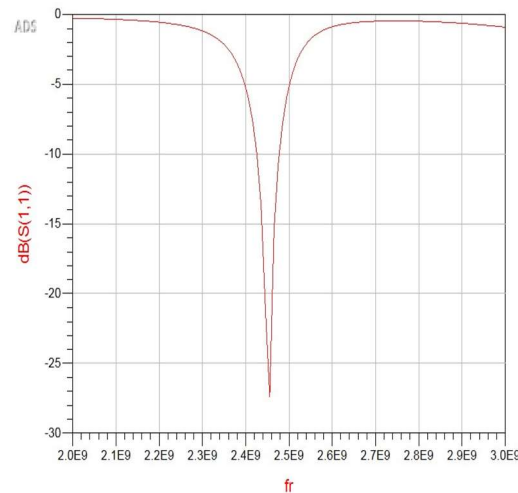


Figure 6.15 Simulation result of rectifier with impedance transformer circuit.

6.2.2 The Circulator

A circulator is a signal-processing device. It is usually a four-port device used to sample a small amount of input power for measurement purposes. Port 1 is the input port, port 2 is the output port, port 3 is the coupled port, and port 4 is the isolated/terminated port. As the input signal travels from port 1 to port 2, a part of the signal is coupled to port 3. The portion of the power coupled to port 3 depends on the coupling value of the coupler being used. For example, if we use a 3-dB coupler, the power split between port 2 and port 3 would be 50%, however, if we use a 10-dB coupler, then this power split would be 9:1. The coupling is one of the key parameters based on which a circulator is selected. The same set up used in measuring the optimal load of the PLA and Cardboard rectifiers was used to determine the optimal input impedance. The only different is that the reflected power from the non 50 Ω will be very high. This means the input power has to be increased until the desired transmitted power is obtained ($P_t = P_i - P_r$). Figure 6.16 shows the images of the fabricated rectifiers while Figure 6.17 illustrates the algorithm use in performing the measurement.

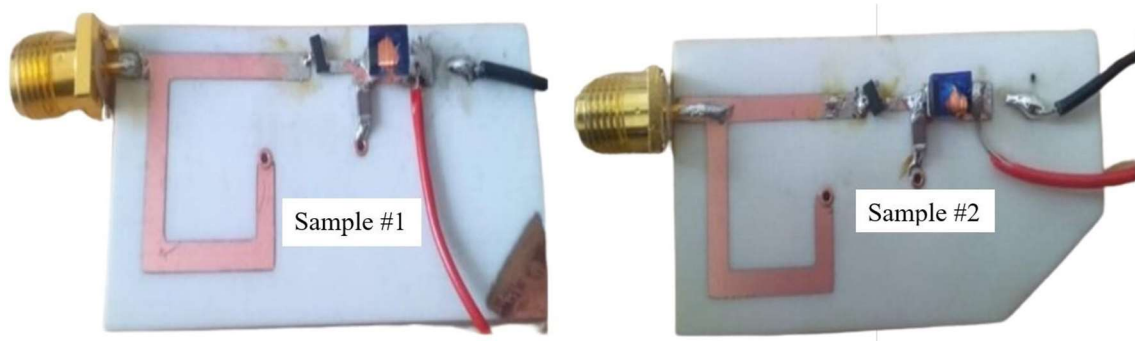


Figure 6.16: Pictures of fabricated rectifiers

Two series, one-diode rectifiers have been fabricated on Rogers RO4003C substrate using HSMS 2850 diode. Circuit sample #1 is designed for a higher RF input impedance (around $140\ \Omega$) and circuit sample #2 for $50\ \Omega$ (Figure 6.16). Figure 6.18a depicts the S_{11} measurement setup in the lab. In Figure 6.18b, the measured and simulated S_{11} are displayed. Circuit sample #1 presents a slight disagreement between simulation and measurement, with the resonance frequency shifted to the right for the measurement result. The rectifier sample #1 is not well matched at 2.45 GHz, with S_{11} being -8 dB. The rectifier is designed with an input impedance close to $140\ \Omega$, and the measurement setup towards a $50\ \Omega$ Vector Network Analyzer (VNA) is imperfect. The simulation does not suffer from the practical limitation. There are also disagreements between the simulated and measured results for circuit sample #2. The measured result matched at 2.45 GHz. The correct matching is because the circuit is designed at $50\ \Omega$, and measurement is done using a $50\ \Omega$ VNA. There is a mismatch in the simulated result. This is normal since the simulation is done when the input impedance of the rectifier is not $50\ \Omega$.

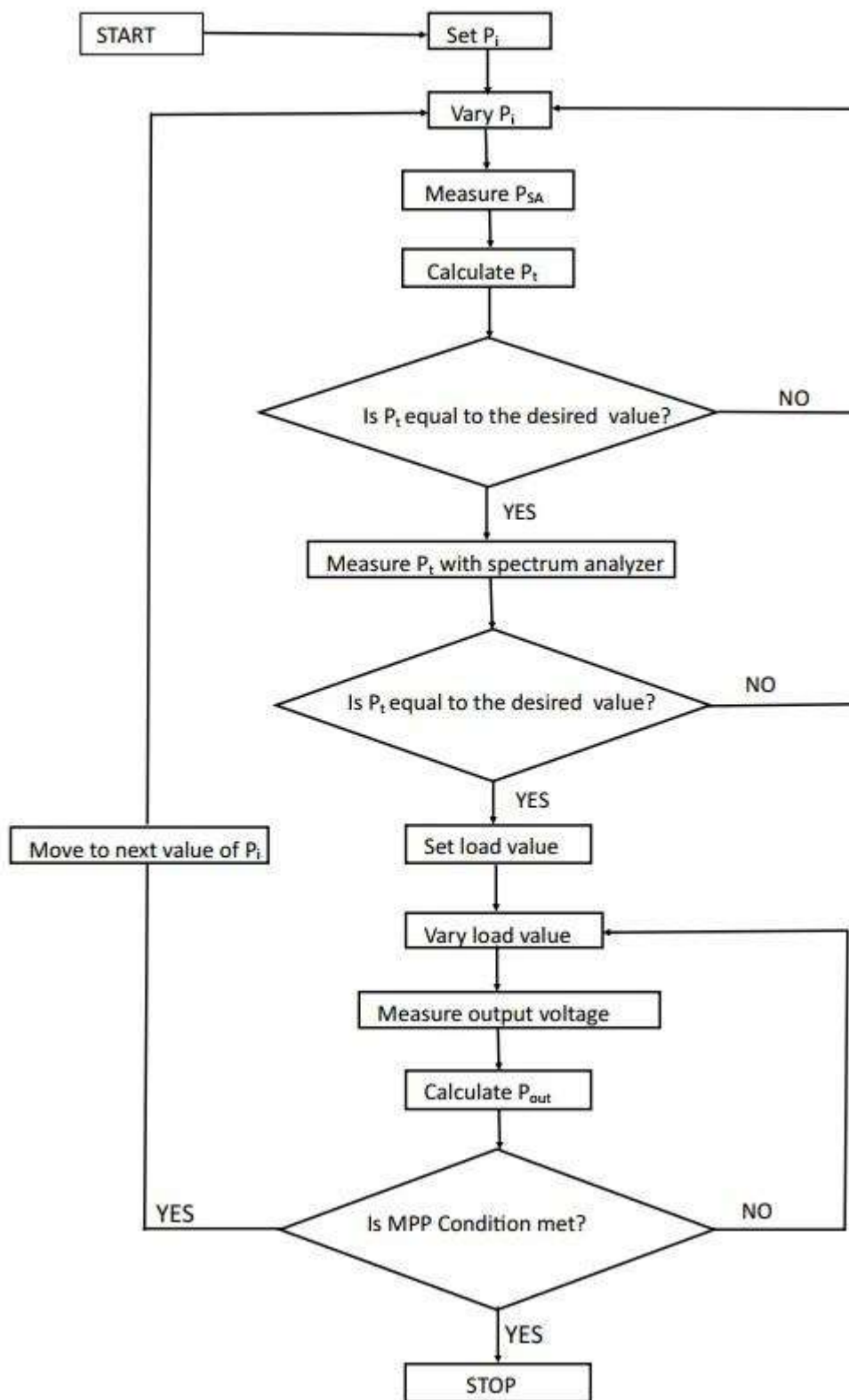


Figure 6.17: Algorithm of flow chart use in characterising rectifiers.

6.3 Maximum Power Point

The same methodology used in determining the MPP condition of the Cardboard rectifier is used here. The results are plotted in Figure 6.19 and summarized in Table 6.1. Table 6.1 also gives the DC open circuit voltage for both samples. The rectifier input impedance depends on the diode model and the rectifier topology use. The graphs in Figure 6.19 define an abacus of MPP conditions for circuit sample #1 (about 140 Ω) and circuit sample #2 (50 Ω). Clearly for single series diode topology using HSMS2850 diode, higher input impedance gives better results. Unfortunately, the gain in DC open-circuit voltage in the case of the high value of input impedance is not large enough to let us think that the cold start issue could be solved in a more straightforward manner. A specific cold-start circuit is required in the case of the two rectifiers tested here.

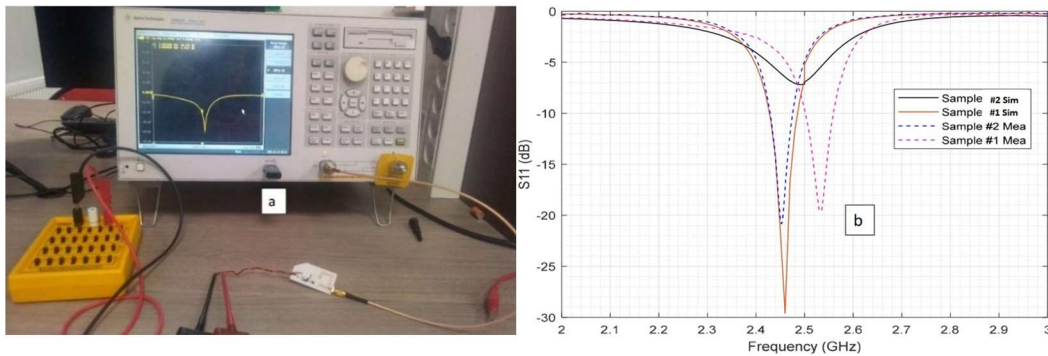


Figure 6.18: Return loss simulation and measurement results for circuits #1 and #2. (a) Laboratory setup (b) Return loss simulation and measurement.

Table 6.1: Measured DC load and open-voltage for MPP conditions at 2.45 GHz.

Power (dBm)	MPP load (k Ω) Sample #1	MPP load (k Ω) Sample #2	DC open circuit Voltage (mV) Sample #1	DC open circuit Voltage (mV) Sample #2
0	1	1	1436	1438
-5	1.4	1.6	818	816
-10	1.5	1.7	426	425
-15	1.7	1.8	215.6	214
-20	3	2.3	102.4	100
-25	4.5	2.6	44.3	36.8
-30	7.2	4.5	16.7	15.6

6.4 Conclusion

From the latter results, it is clear that an optimal value of the rectifier input impedance exists, but depends on the RF input power, the rectifier topology, the diode type, and the input matching network. The topologies were tested in the Lab using the HSMS-2850 diode in a single-series diode topology. Table 6.2 lists the appropriate RF input impedance values and comparison with the state of the art. Literature mainly presents RFEH Circuits with $50\ \Omega$ input impedance. As demonstrated before, this is not an optimal value of input impedance depending on certain conditions. Determining the optimal value of the RF input impedance has not been fully covered in the literature. ADS software simulations show that the rectifier should be designed at input impedance higher than $50\ \Omega$ when considering a single-series diode topology with HSMS-28XX diode models. For the SMS7630 diode model, a lower impedance value yields better PCE. The price to pay is the issue of characterization. Verifying matching with the S_{11} parameter is not straightforward. Using a Circulator with a proper methodology makes it easier to characterize the rectifier. The circulator eliminates the requirement for a matching with $50\ \Omega$ equipment. Measurement is probably time-consuming, hence the choice of $50\ \Omega$ impedance. There is then a reasonable question if selecting a non- $50\ \Omega$ -input-impedance is worth the trouble concerning measurement to balance the real but limited gain in DC performances of the rectenna. Future research will focus on creating and characterizing rectennas with different input impedances to provide a more conclusive and persuasive conclusion regarding the value of RF input impedance to consider for some scenarios in RF energy harvesting. PCE is a suitable performance metric in MPP conditions.

In conclusion, choosing a value of a rectifier input impedance different from $50\ \Omega$ depends on numerous parameters (the type of matching network, diode model, topology, and RF input power).

Table 6.2: Comparison with state of art

Topology	Matching Network	Optimal Impedance	Reference
Not mentioned	Not mentioned	10 Ω	[214]
Mono-diode series	T-Matching	152 Ω	[215]
Mono-diode series	L-Matching	11 Ω	[215]
Mono-diode series	Pi-Matching	56 Ω	[215]
Voltage Doubler	T-Matching	240 Ω	[215]
Mono-diode Series (HSMS2850)	T-Matching	140 Ω	This work
Mono-diode Series (HSMS2860)	T-Matching	500 Ω	This work
Mono-diode Series (SMS7630)	T-Matching	10 Ω	This work
Voltage Doubler	T-Matching	50 Ω	This work

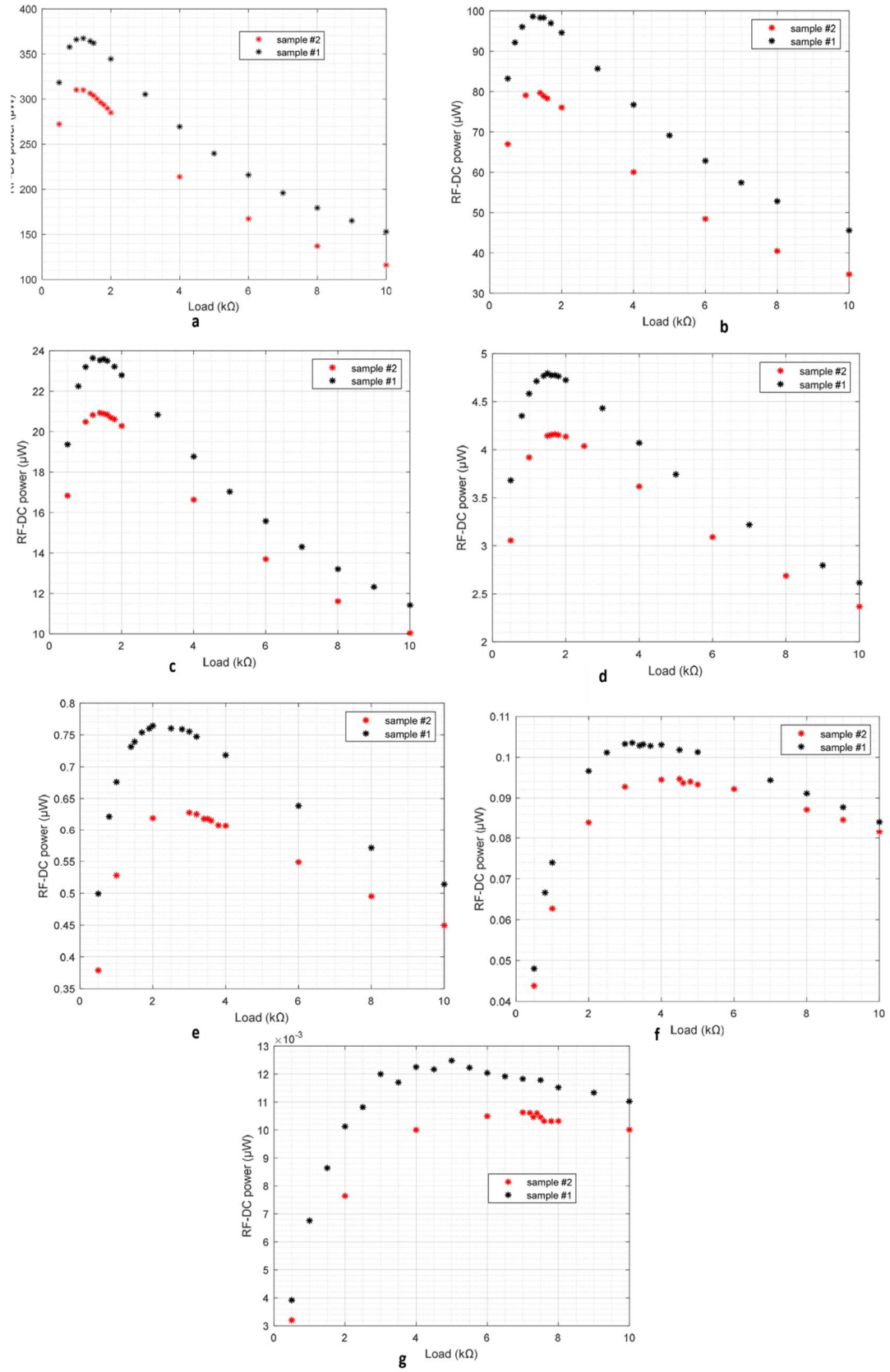


Figure 6.19: Experimental measurement of the rectifier output DC power under different RF input power dBm (a) @000 μW , (b) @316 μW , (c) @100 μW , (d) @32 μW , (e) @10 μW , (f) @3 μW , (g) @1 μW

CHAPTER 7

PERSPECTIVES AND CONCLUSION

7.1 Conclusion

This work focuses on designing Radio Frequency Energy Harvesting circuits on eco-friendly, cheap, and recyclable substrates. The main contributions of this work are:

- The demonstration of RFEH circuits implementation on low cost and eco-friendly polymer.
- The demonstration of RFEH circuits implementation on eco-friendly, zero cost and recyclable cardboard paper.
- This work has demonstrated which input impedance value to consider when designing
- RFEH circuits for maximum PCE.
- An easy and efficient method for determining optimal load (MPP condition) of RFEH circuits

The first key part of this work was to extract the loss tangent and relative permittivity of our selected substrates. The relative permittivity and loss tangents of the PLA polymer and Cardboard paper were extracted using the TTL method. It was ensured that the TTL were functioning properly by testing them on standard RF substrates before moving forward. The substrates were characterized from 0.5 GHz to 3 GHz. The extracted relative permittivity and loss tangent for Polylactic acid polymer are in the ranges of 2.771-2.959 and 0.014-0.099, respectively, on a 1.5 mm thick Polylactic acid material. The thickness of the copper tape is 35 μm . Four types of cardboard materials have been chosen for characterization. The selections are based on different thicknesses and roughness. The measured relative permittivity is in the ranges of 1.889 -1.968, 1.189 – 1.264, 1.401 – 1.415, and 1.17 – 1.24 for Cardboard with thicknesses of 2.2 mm, 2.15 mm, 1.7 mm and 3.6 mm, respectively. Their respective loss tangents are in the ranges of 0.054 – 0.057, 0.01 – 0.07, 0.045 – 0.065, and 0.025 – 0.08.

The second part of this is antenna implementation. In an RFEH system, the antenna captures waves and directs them through a matching circuit to the rectifier. In the first

demonstrator on PLA polymer, linear and circular polarized microstrip patch antennas are designed and fabricated. The linear polarized antenna suffers from polarization mismatch, which is not the case with circularly polarised antenna. The gains for the linear and circular polarized antennas at 2.45 GHz are 7.94 dB and 3.7 dB, respectively. The patch is bent to increase the HPBW for the circularly polarized antenna. The negative effect is the degradation in gain. In the second demonstrator, a microstrip patch antenna and monopole are fabricated on Cardboard paper. Microstrip patch antennas have a narrow bandwidth with high directivity in a particular direction. The bandwidth is increased by using a monopole. Thus, on the Cardboard paper, single band, dual bands, and broadband antennas have been fabricated. At 2.45 GHz, the gain of the microstrip patch antenna and the monopole antenna are 2.98 dB and 2.2 dB, respectively.

The third part of this work is the rectifier design. In RFEH systems, the rectifier converts RF signals from the antenna to DC currents and voltages. HSMS-2850, HSMS-2860, and SMS7630-079LF are the main diode models used in the rectifying circuits. Both half and fullwave rectifiers have been designed. For the first demonstrator on PLA, a half-wave rectifier is designed at 2.45 GHz using the HSMS-2850 diode model. At MPP, optimal load values are

1.5 k Ω , 1.7 k Ω , 2 k Ω , and 3.9 k Ω for input powers of -10 dBm, -15 dBm, -20 dBm, and -25 dBm, respectively. Their respective MPP values are 28.75 μ W, 6 μ W, 0.96 μ W and 0.14 μ W. For the second demonstrator on Cardboard, a voltage doubler rectifier is designed at 2.45 GHz.

The MPP load values are 1.1 k Ω , 1.5 k Ω , and 2 k Ω at input RF powers of 0 dBm, -5 dBm, and -10 dBm, respectively. The MPP values are -220 μ W, -45 μ W, and 8.5 μ W at input powers of 0 dBm, -5 dBm, and -10 dBm, respectively.

In the last part of this work, optimal input impedance between antenna and rectifier is studied for maximum PCE. The majority of RFEH circuits with 50 Ω input impedance are presented in literature. This value is not optimal in all situations. The rectifier should be constructed at a higher input impedance (140 Ω) value when considering a single-series architecture using HSMS-28XX diode types. Better PCE is obtained with a lower impedance (10 Ω) value for the SMS7630xx diode model.

7.2 Perspectives

In RFEH, the primary goal is to generate sufficient output power to meet the intended consumption load. The current circuits performances are insufficient to power most IoT devices. Pending works will focus on:

Treating the surface of the printed PLA and Cardboard materials with a waterproof material can prevent them from absorbing moisture from the environment. It helps to prevent variations in the RF properties over time. The lifespan of the circuits constructed on the treated substrates will be increased.

The antennas will be curved in two or multiple directions to receive RF waves from all directions. Curving will be further enhanced by adding other antennas to form an array of antennas. Capturing more waves will result in an increased PCE of the rectifier. To make the antenna more compact and suitable for RFEH, probe feeding will be used as opposed to microstrip line feeding.

To match the output impedance of the antenna to the input impedance of the rectifier, both impedances must be complex conjugate of each other, and additional components are not required. The drawback of this technique is that it is difficult to obtain proper matching by conjugating impedances.

To increase the PCE, it would be beneficial to switch from Schottky diodes to spin diodes while combining multiple rectifiers connected to a common load. Figure 7.1 shows this anticipated topology. The number of rectifiers (n) will be chosen based on the power required by the selected load.

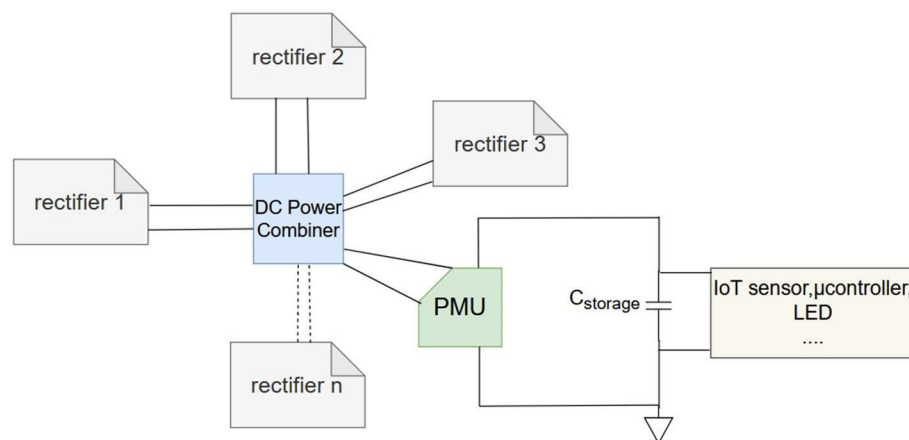


Figure 7.1: Increasing PCE by combination of many rectifiers

Further future work will also be focused on incorporating an adequate PMU into the system (figure 7.1) as this will boost and regulate the voltage to the level require by the load. Finally, since the coming of 5G offers a unique opportunity to RFEH, other future work will be on designing antennas and rectifiers for 5G applications.

List of Journals Publications

- **Linge, P.U.**; Gerges, T.; Bevilacqua, P.; Duchamp, J.-M.; Benech, P.; Verdier, J.; Lombard, P.; Cabrera, M.; Tsafack, P.; Mieyeville, F.; et al. Evaluation of Polylactic Acid Polymer as a Substrate in Rectenna for Ambient Radiofrequency Energy Harvesting. *J. Low Power Electron. Appl.* 2023, 13, 34. <https://doi.org/10.3390/jlpea13020034>.
- **Linge, P.U.**; Pandey, A.; Gerges, T.; Duchamp, J.-M.; Benech, P.; Verdier, J.; Lombard, P.; Mieyeville, F.; Cabrera, M.; Tsafack, P.; Allard, B. Evaluation of Recycled Cardboard Paper as an Eco-Friendly Substrate for Rectenna and Ambient Radio Frequency Energy Harvesting Application. *Electronics* 2023, 13, 2499. <https://doi.org/10.3390/electronics13132499>
- **Linge, P.U.**; Bevilacqua, P.; Duchamp, J.-M.; Benech, P.; Verdier, J.; Lombard, P.; Cabrera, M.; Tsafack, P.; Mieyeville, F.; et al. Optimal Value of Rectifier Input Impedance in a Rectenna for Radio-Frequency Energy Harvesting. *Microwave and Optical Technology Letters*.(submitted)
- Nguyen, X.V.L.; Gerges, T.; Bevilacqua, P.; Duchamp, J.-M.; Benech, P.; Verdier, J.; Lombard, P.; **Linge, P.U.**; Mieyeville, F.; Cabrera, M.; et al. Radio-Frequency Energy Harvesting Using Rapid 3D Plastronics Protoyping Approach: A Case Study. *J. Low Power Electron. Appl.* 2023, 13, 19. <https://doi.org/10.3390/jlpea13010019>.

RESUME ETENDU EN FRANCAIS

(Circuits De Récupération D'énergie Ambiante RF Sur Substrats Recyclables, Low-Tech Et Bas Coût)

1) Introduction

Améliorer les communications entre les appareils implique de les connecter tous à l'Internet : ceci est le principe de l'Internet des objets (IoT). En 2018 et 2023, environ 23,14 milliards et 51,11 milliards d'appareils IoT connectés ont été recensés de manière respective. Cette statistique connaîtra une hausse à 80 milliards et 500 milliards d'ici 2025 et 2030, respectivement [1], [2]. Un problème se pose donc au niveau de l'alimentation de ces milliards d'appareils IoT connectés. En effet, environ 78 millions de batteries seront inutilisables par jour d'ici 2025 si rien n'est fait pour prolonger leur durée de vie [3]. Il est donc indéniable que l'utilisation de batteries pour alimenter ces appareils n'est plus une solution efficace pour les raisons suivantes :

- L'abandon continu de batteries dans l'environnement provoque une pollution environnementale importante.
- Le remplacement des batteries nécessite une intervention humaine régulière et cela peut s'avérer fastidieux ; en particulier dans les zones difficiles d'accès.
- Les batteries représentent un frein à la réduction de la taille des appareils IoT, en particulier à l'ère où la miniaturisation est d'une importance primordiale.
- Dans le cas des appareils biomédicaux, des interventions chirurgicales supplémentaires sont effectuées pour remplacer les batteries. Cela expose les patients à un risque plus élevé d'infection et constitue un fardeau économique pour les établissements de santé [4].

La solution à ce problème ou du moins pour réduire le nombre de batteries jetées est de développer des appareils autonomes ; d'où la récupération d'énergie. Les énergies naturelles disponibles dans l'environnement sont le vent, la chaleur, les vibrations mécaniques, le soleil, la friction, les ondes RF ou les déchets organiques. Parmi ceux-ci, le circuit de récupération d'énergie par radiofréquence devient un bon candidat lorsqu'il n'y a pas de soleil, de vent ou de chaleur ou lorsque les objets sont immobiles.

Étant donné que la connexion entre les appareils IoT est principalement sans fil, l'utilisation de la récupération d'énergie par radiofréquence pour les alimenter semble être

une solution idéale, d'autant plus que les signaux RF sont toujours disponibles dans notre environnement. Le réglage des appareils IoT pour obtenir automatiquement leur source d'énergie à partir de l'environnement leur permettra d'être en quelque sorte autonomes, car il y aura moins d'interaction avec l'utilisateur lors du processus de remplacement de la batterie.

1.1 System de récupération d'énergie RF : Le système de récupération d'énergie RF est constitué d'une antenne, d'un réseau d'adaptation, d'un circuit de gestion de l'alimentation (optionnel) et d'une charge. La figure 1.1 illustre un schéma fonctionnel de chaque sousystème de la solution de récupération d'énergie RF. Les points clés abordés dans ce travail sont l'antenne, les circuits d'adaptation et le redresseur. Dans la figure 1.1, le bloc rectenna (bloc n°1) se compose à la fois de l'antenne et du redresseur. Ce bloc permet de capturer les ondes RF de l'environnement et de les convertir en courants et tensions CC. Pour analyser les performances électriques de ce bloc, nous nous concentrons sur la tension CC et la puissance. L'unité de gestion de l'alimentation (bloc n°2) est un bloc optionnel, qui est un convertisseur CC-CC. Il permet d'élever et de réguler la tension redressée uniquement lorsque la tension CC n'est pas suffisamment élevée pour alimenter la charge de consommation. Le troisième bloc est la charge de consommation ; il peut s'agir d'un microcontrôleur, d'une LED à faible consommation d'énergie ou de tout dispositif de capteur IoT.

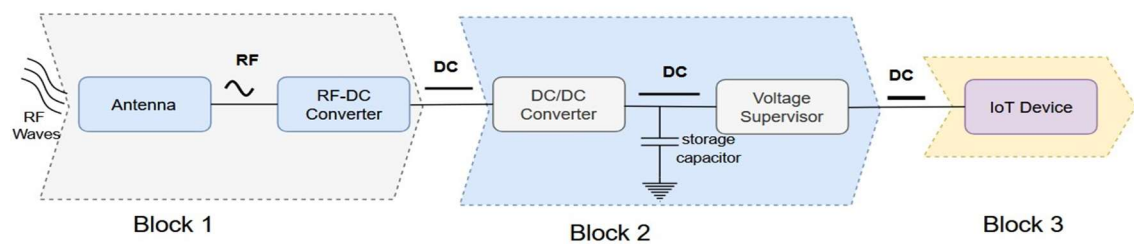


Figure 7.2: Schéma fonctionnel du système de récupération d'énergie RF

Le composant le plus important de la construction de circuits RFEH est le substrat. Jusqu'ici, des substrats conventionnels coûteux, non recyclables et non respectueux de l'environnement ont souvent été utilisés à cette fin. Le bloc 1 étant le bloc le plus important de ce travail, notre compréhension et maîtrise des différents aspects concernant la RF et l'électronique à faible puissance doivent être amélioré pour relever les défis liés à la construction de circuits RFEH sur des substrats conventionnels. Il est donc intéressant de classer les difficultés en termes de questions scientifiques comme suit :

1.2 Questions scientifiques

- Propriétés RF du polymère PLA et du papier carton sur une large gamme de fréquences.
- Concept d'antenne et de redresseur RF-DC sur matériaux recyclables et/ou écologiques.
- Propriétés du conducteur (rugosité, conductivité) sur polymères et papiers.
- Impédance d'entrée du rectenna pour un PCE optimal.
- La méthodologie de simulation d'antennes et de redresseurs sur matériaux recyclables et écologiques (polymère PLA et papier carton).
- Types et formes d'antenne sur PLA et carton.
- Interconnexion électrique des composants et leurs comportements sur substrats polymères et papiers.

Afin de démontrer que ces questions scientifiques sont bien structurées pour combler aux lacunes de l'utilisation des matériaux non recyclables et coûteux de la revue de littérature, nous avons quelques démonstrateurs clés donnés dans la section 1.4.

1.3 Contexte et motivation de l'étude

En RFEH, les substrats conventionnels (FR4 et Rogers) sont généralement utilisés pour fabriquer des circuits de récupération d'énergie RF, en raison de leurs caractéristiques RF supérieures. Leurs principaux inconvénients sont leur dégradation de l'environnement, leur coût de fabrication relativement élevé (une production de masse est nécessaire) et leur incapacité à les recycler et à les éliminer. De plus, ces substrats ne peuvent pas être utilisés facilement pour créer des structures 3D complexes.

Pour contourner ces limitations, nous avons les démonstrateurs suivants :

- L'utilisation du polymère d'acide polylactique (PLA) comme démonstrateur dans la récupération d'énergie RF. Le PLA est compatible avec une technologie d'impression bon marché (Fuse Deposition Modelling). De plus, il est respectueux de l'environnement.
- Démonstrateurs basés sur du papier cartonné comme substrat dans la récupération d'énergie RF. Le papier cartonné est encore plus écologique, moins cher et facilement recyclable que le polymère PLA. Les démonstrateurs ont été fabriqués à partir de papier d'occasion.

- Les flexibilités des matériaux PLA et carton seront révélées en les courbant ou en les pliant pour créer des formes plus intéressantes et en concevant des circuits RF sur eux.
- Cette thèse utilise un schéma à faible coût de fabrication de pistes conductrices sur du carton ou du PLA. Contrairement aux techniques élaborées (dépôt autocatalytique, électrodéposition et impression à jet d'encre) fréquemment utilisées selon la revue de littérature, la démonstration sera réalisée en utilisant des bandes de cuivre.

En résumé, la démonstration de matériaux low-tech pour la conception de rectenna est la motivation fondamentale de ce travail. Les matériaux low-tech signifient ici des matériaux simples construits, utilisant des matériaux locaux et de préférence naturels ou des déchets facilement disponibles. L'utilisation de matériaux locaux réduit le coût global de fabrication des circuits RF.

1.4 Objectifs de l'étude : L'objectif principal de ce travail est d'étudier la conception de Circuits RF (antennes et redresseurs) sur des matériaux recyclables, peu coûteux et éco-responsable. Les tâches suivantes seront accomplies pour atteindre l'objectif principal :

- Sélection de deux matériaux peu coûteux, écologiques et recyclables (PLA et carton).
- Caractérisation des substrats imprimés en papier PLA et carton à l'aide de la méthode à deux lignes de transmission (TTL).
- Conception de circuits de récupération d'énergie RF sur les substrats caractérisés
- Démonstration de l'impédance d'entrée optimale pour les circuits de récupération d'énergie RF.

1.5 Organisation de la thèse : Ce travail comporte sept chapitres.

Le chapitre deux passe en revue l'état de l'art sur la récupération d'énergie RF. Une mesure des densités de puissance de certaines villes est également présentée. La méthode des deux lignes de transmission, qui est utilisée pour extraire les propriétés RF des substrats sélectionnés, est abordée au chapitre trois. Les valeurs extraites de la constante diélectrique et de la tangente de perte sont au centre de ce chapitre. Le chapitre quatre traite la construction d'antennes sur polymère d'acide polylactique et carton. Dans ce chapitre, des antennes à polarisation linéaire et circulaire sont conçues. Le chapitre se concentre également sur la conception d'antennes à bande unique, à double bande et à

bandes multiples. Ensuite, les résultats de la mesure du diagramme de rayonnement dans une chambre anéchoïque sont présentés. Le chapitre cinq est consacré à la mise en œuvre des redresseurs sur les deux matériaux. Les principales propriétés électriques qui seront abordées sont la tension continue et la puissance continue. Une description détaillée du processus de conception et de fabrication est fournie. Les résultats de la caractérisation sont également présentés. L'impédance d'entrée optimale du redresseur est discutée au chapitre six. Des résultats de simulation et expérimentaux à différentes impédances d'entrée sont donnés. Le chapitre donne également des méthodes pour caractériser un redresseur à une impédance d'entrée supérieure à 50Ω . Au chapitre sept, la conclusion et les perspectives sont données.

2. Etat de l'art sur la récupération d'énergie ambiante : De nombreux chercheurs se concentrent sur la construction de redresseurs RF, sur des substrats coûteux, non-recyclables ou non respectueux de l'environnement. De plus, la plupart de ces substrats ne peuvent pas être utilisés pour créer des structures 3D avancées. Dans ce chapitre, nous avons étudié l'état de l'art des récupérateurs d'énergie radiofréquence construits sur des substrats conventionnels et polymères. L'objectif principal de ce chapitre est de montrer que ;

- Selon la littérature, l'on utilise principalement des substrats coûteux, non écologiques et coûteux dans la construction de circuits de récupération d'énergie RF.
- Presque tous les redresseurs présentés lors de la revue de la littérature sont construits à une valeur d'impédance d'entrée non optimale (50Ω).
- D'après ce chapitre, il est clair qu'aucun redresseur n'a été fabriqué sur des substrats PLA ou carton de la littérature.

En résumé, le graphique de la figure 2.1 montre une distribution du rendement de conversion de la puissance maximale sur l'axe des y et de la puissance d'entrée RF sur l'axe des x. D'après le graphe de la figure 2.1, la majorité des travaux de la littérature utilisent des substrats FR4 et Rogers, comme indiqué par les rectangles et les triangles. Les diodes Schottky sont principalement utilisées dans le circuit de redressement et les principaux modèles utilisés sont les modèles HSMS28XX et SMS76xx. Le graphique montre clairement qu'aucun travail n'a été effectué en utilisant un substrat PLA ou carton. Le système RFEH est composé d'une antenne, d'un circuit d'adaptation, d'un redresseur et d'un PMU. Le réseau d'adaptation est destiné au transfert maximal de puissance de

l'antenne au redresseur. Il s'agit généralement d'un filtre passe-bande, qui assure la non-réémission dans l'environnement des harmoniques générées par l'élément redresseur. Le redresseur convertit l'énergie RF capturée par l'antenne en tensions et courants continus. Dans ce chapitre, des résultats des chercheurs ont également été présentés sur des mesures de densité de puissance RF. D'après les résultats examinés, la densité de puissance moyenne pour le Wi-Fi est inférieure à -35 dBm. En effet, dans un environnement de faible puissance (< -20 dBm), La topologie à diode unique du redresseur est préférée. Les topologies de shunt et doubleur de tension fonctionnent mieux à une puissance d'entrée plus élevée. Diverses stratégies d'adaptation ont été examinées en profondeur. Les stubs microstrip sont la solution recommandée pour adapter la conception du réseau aux hautes fréquences. Empêcher les harmoniques d'atteindre la charge a été considéré comme l'une des méthodes permettant d'augmenter le PCE. Les stubs radiaux et les inductances d'arrêt sont assez souvent utilisés à cette fin. En résumé, il convient de noter que la littérature présente les lacunes suivantes dans la construction de circuits RFEH :

- La construction de circuits RFEH utilisant des matériaux coûteux et dangereux pour l'environnement.
- La construction de circuits RFEH utilisant une valeur d'impédance d'entrée non optimale.
- Une grande partie des redresseurs dans la littérature ne prend pas en compte la condition du point de puissance maximale (MPP).
- Création de traces conductrices sur des polymères ou des substrats en papier à l'aide d'une technologie d'impression coûteuse (électrolyse et électrodéposition).
- L'incapacité à créer des substrats 3D complexes pour les circuits RFEH.

Ce sont donc les problèmes qui seront abordés dans les chapitres quatre, cinq et six de cet ouvrage.

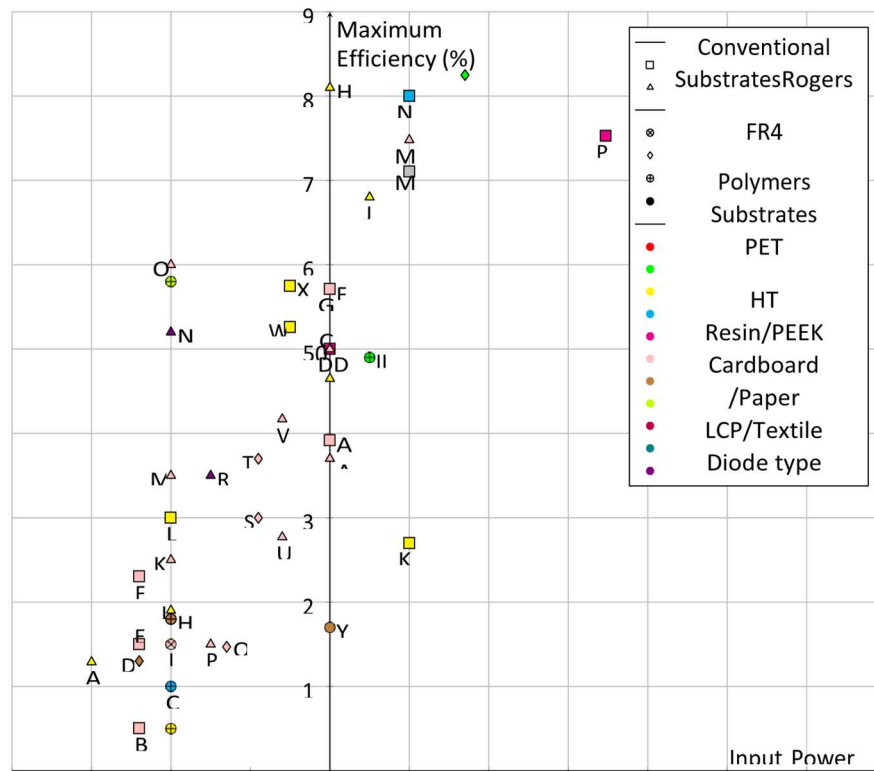


Figure 2.1: État de l'art récent sur les RFEH: PCE maximum vs puissance d'entrée RF en fonction du type de substrat et du type de diode

3. Caractérisation des matériaux : Dans ce chapitre, nous avons fourni une description détaillée de la caractérisation des substrats PLA et carton. Le processus d'utilisation de FDM pour l'impression de PLA a été expliqué. FDM est une technologie d'impression bon marché. Le montage de CMS sur le substrat PLA imprimé est assez difficile en raison de la faible température de fusion du PLA. La méthode TTL a été décrite et utilisée pour caractériser les substrats (voir annexe). Le principe de TTL est d'obtenir la tangente de perte et la permittivité relative des substrats à partir des valeurs mesurées du paramètre S. Le TTL est préféré aux techniques alternatives en raison de sa facilité d'utilisation et de son déploiement sur une large gamme de fréquences. La substance conductrice sur les deux substrats est une bande de cuivre d'une épaisseur de 35 μm . Les substrats ont été caractérisés dans une gamme de fréquences de 0,5 GHz à 3 GHz. L'épaisseur de 1,51 mm a été maintenue tout au long de la conception du substrat PLA. La permittivité relative et la tangente de perte mesurées pour le PLA sont respectivement comprises dans les intervalles [2,7 - 2,95] et [0,001 - 0,09]. Le deuxième substrat caractérisé est le carton. Pour la caractérisation, quatre matériaux de carton distincts sont choisis, chacun ayant une épaisseur, un espace d'air et une rugosité de surface différents. Quatre échantillons différents de carton (échantillons n° 1, n° 2, n° 3 et n° 4) d'épaisseur respective de 2,2 mm, 2,15 mm, 3,6 mm et 1,7 mm ont été

sélectionnés pour la caractérisation. Les masses volumiques des échantillons de carton n° 1, n° 2, n° 3 et n° 4 sont respectivement de 696 kg/m³, 182 kg/m³, 139 kg/m³ et 434 kg/m³. Les échantillons de carton n° 2 et n° 3 ont plus d'espaces d'air que les échantillons n° 1 et n° 4. L'échantillon de carton n° 1 est affecté par le moins d'espaces d'air. En conclusion, les valeurs moyennes de rugosité des deux surfaces des échantillons de carton n° 1, n° 2, n° 3 et n° 4 sont respectivement de 2,415 µm, 3,15 µm, 4,735 µm et 1,91 µm. Les résultats extraits sont présentés dans le tableau 3.1.

4. Antennes : L'antenne est destinée à capter les signaux radiofréquences de l'environnement du voisinage. L'antenne est l'un des éléments les plus importants des systèmes de communication sans fil. La conception d'une bonne antenne est de la plus haute importance car le PCE de la rectenna dépend de l'efficacité de l'antenne. Une bonne conception d'antenne doit être capable de recevoir la majorité des incidents d'ondes et de les rayonner dans la direction appropriée. L'antenne doit avoir:

- Un gain élevé (supérieur à 0 dB)
- Une valeur S₁₁ inférieure à -10 dB
- Un diagramme de rayonnement omnidirectionnel
- Une large fréquence de fonctionnement

Une antenne Patch est sélectionnée dans ce travail en raison de sa simplicité et de son processus de fabrication facile. Le patch rectangulaire a été conçu pour fonctionner à une fréquence de 2,45 GHz. Nous concevrons à la fois des patches LP et CP.

Antennes à bande unique : L'antenne résonne à une fréquence unique. Ce type d'antenne est

Table 3.1: Résultats de la caractérisation des différents échantillons de papier carton

Freq (GHz)	L ₁ /L ₂ (m m)	h (mm)	Loss tangent	Relative Permittivity	Method	Conducting Material	Ref
0.5-3	55.5/91	2.2	0.054 - 0.057	1.889 - 1.968	TTL	Copper tape	Sample#1
0.5-3	60/100	2.15	0.01 - 0.07	1.189 - 1.264	TTL	Copper tape	Sample#2
0.5-3	65/108	1.7	0.045 - 0.065	1.401 - 1.415	TTL	Copper tape	Sample#3
0.5-3	67/108	3.6	0.042 - 0.061	1.17 - 1.24	TTL	Copper tape	Sample#4

souvent appelé antenne résonnante. Il est facile d'obtenir une adaptation d'impédance pour de telle antenne. L'antenne à bande unique a la plus petite bande passante. Dans ce chapitre, des antennes monobandes ont été conçues sur des substrats PLA et carton. Un exemple de conception sur PLA est présenté dans la figure 4.1.

Antenne multibande : Il est facile de convertir des antennes patch Microstrip d'une bande unique à une large bande ou à plusieurs bandes en ajoutant des fentes sur le patch pour faire résonner l'antenne à plusieurs fréquences.

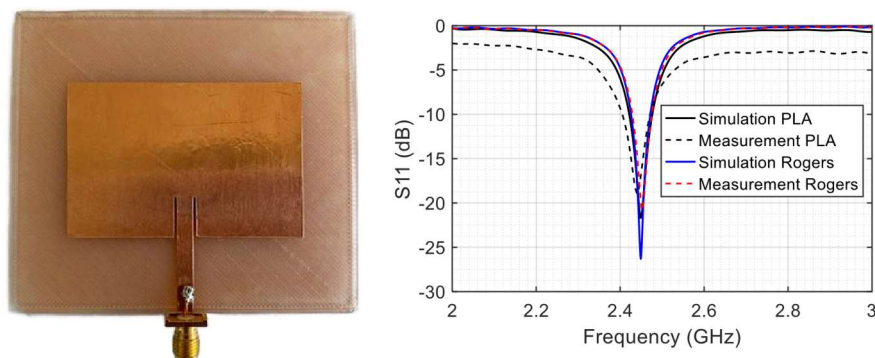


Figure 4.1 Antenne à bande unique et résultat de perte de retour sur PLA

Une antenne double bande à 900 MHz et 1800 MHz a été réalisée sur du carton dans ce chapitre (figure 4.2).

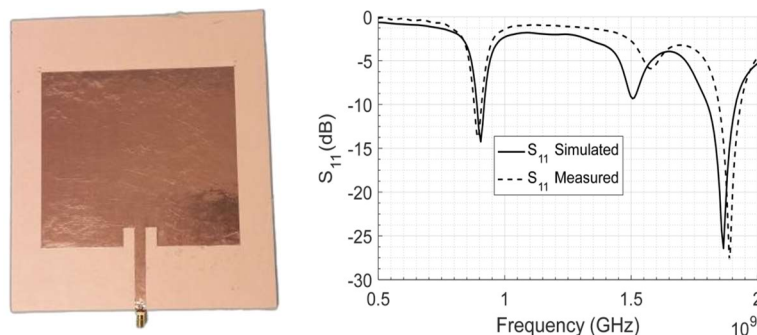


Figure 4.2 Résultat d'antenne multi bande et de perte de retour sur l'échantillon de carton n°1

Antennes microruban à large bande : Ces antennes fonctionnent sur une large gamme de fréquences. Elles peuvent donc collecter de l'énergie provenant de plusieurs sources simultanément. Comme elles fonctionnent sur une large gamme de fréquences, il n'est pas facile d'obtenir une adaptation d'impédance appropriée entre l'antenne et le circuit redresseur. Une antenne à large bande a été conçue sur l'échantillon de carton n°1 de ce chapitre (figure 4.3).

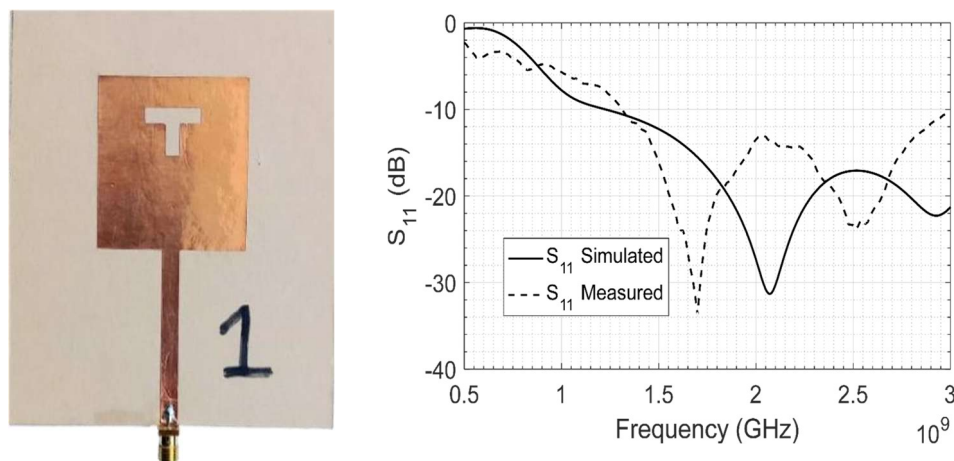


Figure 4.3 Résultat d'antenne multi band et de perte de retour sur l'échantillon de carton n°1

Antenne patch polarisée linéairement 2D : Les antennes patch polarisées linéairement sont conçues sur PLA et sur l'échantillon de carton n°1. Pour étudier les effets de la permittivité relative et de la tangente de perte sur les propriétés de rayonnement de l'antenne, une antenne similaire est conçue sur un substrat RF standard (Rogers 4003C). Les résultats simulés et mesurés sont présentés dans le tableau 4.1.

Patch Polarisé Circulaire sur PLA : Une antenne CP est conçue selon la technique d'alimentation unique. La CP est obtenue en tronquant deux bords diagonaux quelconques du patch carré. Un transformateur $\lambda/4$ est utilisé pour l'adapter à un connecteur SMA de 50Ω (figure 4.4). Les gains simulés et mesurés de l'antenne sont respectivement de 4,09 et 3,7.

Table 4.1 : Résultats de la caractérisation des antennes

Material	Gain(dB)	Bandwidth (MHz)	Resonance Frequency (GHz)	S ₁₁ (dB)	Size(mm ³)
PLA Simulation	8	58	2.453	-24.48	70x80x1.5
PLA Measurement	7.94	60	2.446	-18.45	70x80x1.5
Rogers Measurement	8.02	46.2	2.452	-21.15	58x70x1.5
Cardboard sample #1 Sim	2.98	169.9	2.4513	-39.76	80x88x2.2
Cardboard sample #1 Mea	2.53	160.4	2.46	-33.65	80x88x2.2

La différence de puissance mesurée reçue de l'antenne dans les plans horizontal et vertical est inférieure à 1 dB. Cela permet de conclure que l'antenne offre une multipolarisation.

5. Redresseurs : Le redresseur est responsable de la conversion des signaux RF en puissance CC. Le circuit de redressement est composé de diodes Schottky avec une

tension de mise en marche CC très faible. L'efficacité de conversion du redresseur dépend du condensateur de jonction à polarisation nulle, C_{jo} , de la tension de claquage, V_{br} , et de la résistance série, $R_{s,}$.

Pour maximiser l'efficacité de conversion du redresseur, il est souhaitable que la diode ait un condensateur de jonction faible, une faible résistance série et une tension de claquage élevée. De plus, la diode doit avoir une faible tension de seuil, V_{TH} , et un courant de saturation inverse élevé, $I_{s,}$. Les modèles HSMS2850 et SMS7630 répondent à la plupart de ces exigences, c'est pourquoi ils sont adoptés pour ce travail. Le redresseur fonctionne à une fréquence de 2,45 GHz et est conçu pour gérer une puissance d'entrée de -20 dBm et -10 dBm pour le PLA et le carton, respectivement. Le redresseur est validé par co-simulation Momentum dans ADS 2022. Le paramètre de diffusion de grands signaux (LSSP), la simulation d'équilibre harmonique (HBS) et les balayages de paramètres multiples sont utilisés dans la simulation. Deux redresseurs principaux fabriqués sur des substrats PLA et carton sont présentés dans la figure 5.1. La condition MPP a également été étudiée. À -20 dBm et -10 dBm, la puissance maximale des redresseurs à base de PLA et de carton est respectivement de 0,98 μ W et 1,73

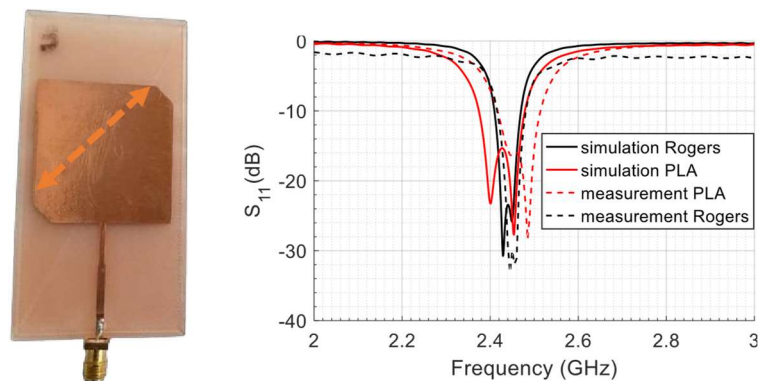


Figure 4.4 Antenne patch CP sur PLA et perte de retour

μ W (Figure 5.2). Les valeurs de charge optimales pour les redresseurs sur PLA et carton sont **results** respectivement de 2,2 k Ω et 2 k Ω .

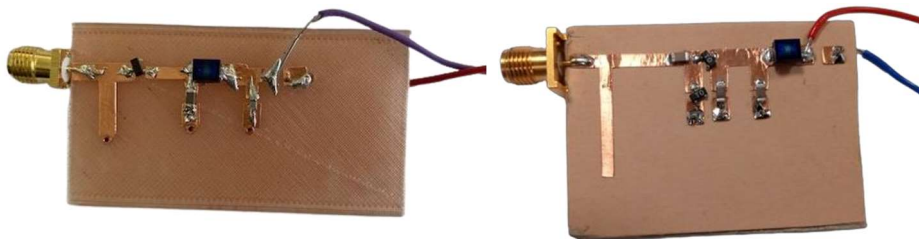


Figure 5.1 Exemples de redresseurs fabriqués sur PLA et carton

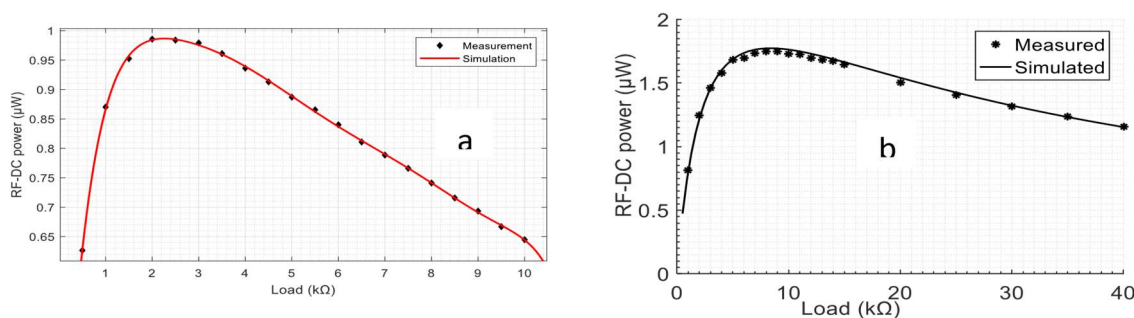


Figure 5.2 Charge optimale des redresseurs (a) PLA et (b) carton

6. Impédance d'entrée optimale : La littérature remet rarement en question la valeur optimale de l'impédance d'entrée du redresseur pour un PCE maximal. La conception de redresseurs à $50\ \Omega$ est l'objectif principal des efforts de recherche. $50\ \Omega$ n'est pas optimal dans tous les cas. Différents modèles de diodes et topologies de redresseurs donnent différentes valeurs pour l'impédance d'entrée optimale. Il a été établi que les redresseurs conçus avec le modèle de diode HSMS-2850 donnent des valeurs supérieures à $50\ \Omega$, tandis que le modèle SMS7630-079LF donne des valeurs inférieures à $50\ \Omega$. Ces conceptions utilisent la topologie en série simple. La topologie du doubleur de tension à une étage a donné $50\ \Omega$ comme valeur optimale avec le modèle de diode HSMS2850.

Simulations avec différentes topologies et modèles de diodes : En utilisant les caractéristiques RF du substrat Rogers RO4003C, la puissance RF d'entrée par rapport au rendement de conversion de puissance du redresseur est simulée. Les circuits intègrent un réseau d'adaptation avec les modèles de diodes HSMS-2850, HSMS-2860 ou SMS7630079LF. La puissance d'entrée RF varie de $-25\ \text{dBm}$ à $0\ \text{dBm}$. Les résultats simulés pour la topologie série ont une impédance d'entrée optimale supérieure à $50\ \Omega$ pour le modèle de diode HSMS-2850 ($140\ \Omega$). Pour chaque valeur d'impédance d'entrée, le réseau d'adaptation a été ajusté pour avoir une valeur satisfaisante pour la perte de retour ($S_{11} < -20\ \text{dB}$). Une impédance d'entrée optimale de $50\ \Omega$ a été notée pour la topologie du doubleur de tension utilisant le modèle de diode HSMS2850. En revanche, le modèle de diode SMS7630079LF donne un résultat différent. La valeur optimale est de $10\ \Omega$. L'impédance optimale obtenue est résumée dans le tableau 6.1.

Table 6.1: Impédance d'entrée optimale de différents modèles de diodes et topologies de redresseurs

Topology	Matching Network	Optimal Impedance
Mono-diode Series (HSMS2850)	T-Matching	140 Ω
Mono-diode Series (HSMS2860)	T-Matching	280 Ω
Mono-diode Series (SMS7630)	T-Matching	10 Ω
Voltage Doubler	T-Matching	50 Ω

7. Perspectives et conclusion

7.1 Conclusion : Ce travail se concentre sur la conception de circuits de récupération d'énergie radiofréquence sur des substrats écologiques, bon marché et recyclables. Les principales contributions de ce travail s'appuient sur:

- Utilisation d'un polymère d'acide polylactique comme démonstrateur de matériau recyclable et à faible coût. La possibilité d'utiliser le moulage par dépôt par fusion a été démontrée et utilisée dans l'impression du substrat d'acide polylactique. Le moulage par dépôt de fusibles est une technologie d'impression 3D simple et bon marché. Ainsi, elle est choisie par rapport à d'autres technologies d'impression 3D comme la stéréolithographie et la structuration directe au laser. Des traces conductrices sont créées à l'aide de rubans de cuivre.
- Utiliser le Carton comme deuxième démonstrateur dans un contexte de coût extrêmement bas et de respect de l'environnement. Les matériaux en carton sont facilement disponibles et ont démontré une entière recyclabilité. Habituellement, la métallisation est réalisée sur des substrats en papier et en carton par impression jet d'encre. Pour éliminer le coût de l'encre et de la technologie d'impression complexe, nous avons utilisé des rubans de cuivre pour créer des pistes conductrices pour un prototypage rapide et bon marché.
- Prouver que 50 Ω n'est pas une impédance d'entrée optimale dans la conception de redresseurs RF.

La permittivité relative et les tangentes de perte du polymère PLA et du papier carton ont été extraites à l'aide de la méthode TTL. Nous nous sommes réassurés que les TTL fonctionnaient correctement en les testant sur des substrats RF standard avant de continuer. Les substrats ont été caractérisés de 0,5 GHz à 3 GHz. La permittivité relative

extraite et la tangente de perte pour le polymère d'acide polylactique se situent respectivement dans les plages de 2,7 à 2,9 et de 0,001 à 0,09 sur un matériau d'acide polylactique de 1,5 mm d'épaisseur. L'épaisseur du ruban de cuivre est de 35 μm . Quatre types de matériaux cartonnés ont été choisis pour la caractérisation. Les sélections sont basées sur différentes épaisseurs et rugosités. La permittivité relative mesurée se situe dans les plages de 1,889 à 1,968, 1,189 à 1,264, 1,401 à 1,415 et 1,17 à 1,24 pour le carton d'épaisseurs de 2,2 mm, 2,15 mm, 1,7 mm et 3,6 mm, respectivement. Leurs tangentes de perte respectives sont comprises entre 0,054 – 0,057, 0,01 – 0,07, 0,045 – 0,065 et 0,025 – 0,08. Dans un système RFEH, l'antenne capte les ondes et les dirige via un circuit d'adaptation vers le redresseur. Dans le premier démonstrateur sur polymère PLA, des antennes patch microruban à polarisation linéaire et circulaire ~~sont~~ ont été conçues et fabriquées. L'antenne à polarisation linéaire souffre des lors d'une désadaptation de polarisation, ce qui n'est pas le cas d'une antenne à polarisation circulaire. Les gains pour les antennes à polarisation linéaire et circulaire à 2,45 GHz sont respectivement de 7,94 dB et 3,7 dB. Le patch est plié pour augmenter le HPBW de l'antenne à polarisation circulaire. L'effet négatif est la dégradation du gain. Dans le deuxième démonstrateur, une antenne patch microruban et un monopôle sont fabriqués sur du papier cartonné. Les antennes patch microruban ont une bande passante étroite avec une directivité élevée dans une direction particulière. La bande passante est augmentée en utilisant un monopôle. Ainsi, sur le papier cartonné, des antennes monobande, bibande et large bande ont été fabriquées. À 2,45 GHz, le gain de l'antenne patch microruban et de l'antenne monopôle est respectivement de 2,98 dB et 2,2 dB. Dans les systèmes RFEH, le redresseur convertit les signaux RF de l'antenne en courants et tensions CC. HSMS-2850, HSMS-2860 et SMS7630-079LF sont les principaux modèles de diodes utilisés dans les circuits redresseurs. Des redresseurs demi-onde et pleine onde ont été conçus. Pour le premier démonstrateur sur PLA, un redresseur demi-onde est conçu à 2,45 GHz en utilisant le modèle de diode HSMS-2850. Au MPP, les valeurs de charge optimales sont de 1,5 k Ω , 1,7 k Ω , 2 k Ω et 3,9 k Ω pour des puissances d'entrée de -10 dBm, 15 dBm, -20 dBm et -25 dBm, respectivement. Leurs valeurs MPP respectives sont de 28,75 μW , 6 μW , 0,96 μW et 0,14 μW . Pour le deuxième démonstrateur sur carton, un redresseur doubleur de tension est conçu à 2,45 GHz. Les valeurs de charge MPP sont de 1,1 k Ω , 1,5 k Ω et 2 k Ω à des puissances RF d'entrée de 0 dBm, -5 dBm et -10 dBm, respectivement. Les valeurs MPP sont de -220 μW , -45 μW et 8,5 μW à des puissances d'entrée de 0 dBm, -5 dBm et -10 dBm, respectivement.

La majorité des circuits RFEH avec une impédance d'entrée de $50\ \Omega$ sont présentés dans la littérature. Cette valeur n'est pas optimale dans toutes les situations. Le redresseur doit être construit à une valeur d'impédance d'entrée plus élevée lorsque l'on envisage une architecture en série unique et un doubleur de tension utilisant des types de diodes HSMS-28XX. Un meilleur PCE est obtenu avec une valeur d'impédance inférieure pour le modèle de diode SMS7630.

7.2 Perspectives : Dans RFEH, l'objectif principal est de générer une puissance de sortie suffisante pour répondre à la charge de consommation prévue. Les résultats actuels sont insuffisants pour alimenter la plupart des appareils IoT. Les travaux en cours porteront sur:

- Traiter la surface des matériaux PLA et carton : imprimer avec un matériau imperméable peut les empêcher d'absorber l'humidité de l'environnement. Cela aide à éviter de légères variations dans les propriétés RF. La durée de vie du circuit construit sur les substrats traités pourrait être augmentée. Les traces conductrices pourraient être renforcées par dépôt chimique et électrolytique. Cela permettrait aux pistes conductrices de mieux adhérer au substrat par rapport aux rubans de cuivre. L'inconvénient des dépôts autocatalytiques et électrolytiques est le coût élevé et la durée plus longue de fabrication des circuits. La recyclabilité serait également compromise.

- Les antennes seront courbées dans deux ou plusieurs directions pour recevoir des ondes RF de toutes les directions. La courbure sera encore améliorée en ajoutant d'autres antennes pour former un réseau d'antennes. Capturer plus d'ondes entraînera une augmentation du PCE du redresseur. Pour rendre l'antenne plus compacte et adaptée au RFEH, l'alimentation par sonde sera utilisée par opposition à l'alimentation par ligne microruban.

- La réduction des pertes dues aux composants supplémentaires se fera en supprimant le réseau d'adaptation entre l'antenne et le redresseur. Pour faire correspondre l'impédance de sortie de l'antenne à l'impédance d'entrée du redresseur, les deux impédances doivent être conjuguées de manière complexe et aucun composant supplémentaire n'est requis. L'inconvénient de cette technique est qu'il est difficile d'obtenir une bonne adaptation en conjuguant les impédances. Pour mieux comprendre le comportement des diodes utilisées dans le redresseur, la modélisation de son comportement sera intéressante. Pour

augmenter le PCE, il serait avantageux de combiner plusieurs redresseurs connectés à une charge commune. La figure 7.1 montre cette topologie anticipée. Le nombre de redresseurs (n) sera choisi en fonction de la puissance requise par la charge sélectionnée. La conception des redresseurs sur des structures complexes sera également intéressante. D'autres travaux futurs seront également axés sur l'intégration d'une PMU adéquate dans le système (figure 7.1). Le PMU est un convertisseur

DC-DC qui augmente et régule la tension de sortie. Cela n'est nécessaire que lorsque la puissance de sortie n'est pas suffisante pour alimenter la charge. La refonte de la rectenne à 900 MHz présente un grand intérêt puisque la revue de littérature a révélé que les densités de puissance RF environnementales sont plus élevées aux basses fréquences. Il est normal qu'à des fréquences plus basses, la perte de rayonnement diminue. Cela peut être un facteur important à prendre en compte pour augmenter le PCE. Le défi posé lorsque les circuits RF sont conçus à des fréquences plus basses réside dans la structure encombrante des circuits.

REFERENCES

- [1] D. Newell, ‘Optimised Energy Management for Energy Harvesting Powered Wireless Sensors’, 2018.
- [2] FIRENOLLY TV, *IoT Crash Course | IoT Course | Internet Of Things | Internet Of Things Full Course | Simplilearn*, (Nov. 17, 2021). Accessed: Jan. 03, 2024. [Online Video]. Available: <https://www.youtube.com/watch?v=7FfeYocueH4>
- [3] European Comission, ‘Up to 78 million batteries will be discarded daily by 2025, researchers warn’, 2021.
- [4] N. Sezer and M. Koç, ‘A comprehensive review on the state-of-the-art of piezoelectric energy harvesting’, *Nano Energy*, vol. 80, no. November 2020, p. 105567, 2021, doi: 10.1016/j.nanoen.2020.105567.
- [5] D. Hao *et al.*, ‘Solar energy harvesting technologies for PV self-powered applications: A comprehensive review’, 2022, *Elsevier Ltd.* doi: <https://doi.org/10.1016/j.renene.2022.02.066>.
- [6] K. Hammoud, S. Pollin, D. Esat-wavecore, D. Schreurs, and D. Esat-wavecore, ‘Efficient Indoor Solar Panel Energy Harvesting Exploiting the Crest Factor’, pp. 653–657, 2022.
- [7] A. Kumar, S. S. Balpande, and S. C. Anjankar, ‘Electromagnetic Energy Harvester for Low Frequency Vibrations Using MEMS’, *Procedia Computer Science*, vol. 79, pp. 785–792, 2016, doi: 10.1016/j.procs.2016.03.104.
- [8] D. Wang and K. Chang, ‘Electromagnetic energy harvesting from flow induced vibration’, *Microelectronics Journal*, vol. 41, no. 6, pp. 356–364, 2010, doi: 10.1016/j.mejo.2010.04.005.
- [9] C. Fleischer, ‘How Piezoelectricity Works | EAGLE | Blog’, 2019.
- [10] A. Cuadras, M. Gasulla, and V. Ferrari, ‘Thermal energy harvesting through pyroelectricity’, *Sensors and Actuators, A: Physical*, vol. 158, no. 1, pp. 132–139, 2010, doi: 10.1016/j.sna.2009.12.018.

- [11] H. Wang, J. Do Park, and Z. J. Ren, 'Practical energy harvesting for microbial fuel cells: A review', *Environmental Science and Technology*, vol. 49, no. 6, pp. 3267–3277, 2015, doi: 10.1021/es5047765.
- [12] F. Ma, C. Fu, X. Rong, and H. Wang, 'Advanced energy harvesting in microbial fuel cells for environmental monitoring', *Proceedings - 2017 Chinese Automation Congress, CAC 2017*, vol. 2017-Janua, pp. 7357–7361, 2017, doi: 10.1109/CAC.2017.8244107.
- [13] T. Yamashita, T. Hayashi, H. Iwasaki, M. Awatsu, and H. Yokoyama, 'Ultra-low-power energy harvester for microbial fuel cells and its application to environmental sensing and long-range wireless data transmission', *Journal of Power Sources*, vol. 430, no. May, pp. 1–11, 2019, doi: 10.1016/j.jpowsour.2019.04.120.
- [14] A. Georgiadis, A. Collado, S. Via, and C. Meneses, 'Flexible hybrid solar/EM energy harvester for autonomous sensors', *IEEE MTT-S International Microwave Symposium Digest*, pp. 6–9, 2011, doi: 10.1109/MWSYM.2011.5972963.
- [15] L. Guo, X. Gu, P. Chu, S. Hemour, and K. Wu, 'Collaboratively Harvesting Ambient Radiofrequency and Thermal Energy', *IEEE Transactions on Industrial Electronics*, vol. 67, no. 5, pp. 3736–3746, May 2020, doi: 10.1109/TIE.2019.2914627.
- [16] P. De Mil *et al.*, 'Design and implementation of a generic energy-harvesting framework applied to the evaluation of a large-scale electronic shelf-labeling wireless sensor network', *Eurasip Journal on Wireless Communications and Networking*, vol. 2010, no. May, 2010, doi: 10.1155/2010/343690.
- [17] M. Shirvanimoghaddam *et al.*, 'Towards a Green and Self-Powered Internet of Things Using Piezoelectric Energy Harvesting', *IEEE Access*, vol. 7, pp. 94533–94556, 2019, doi: 10.1109/ACCESS.2019.2928523.
- [18] J. Zhao *et al.*, 'Self-Powered Implantable Medical Devices: Photovoltaic Energy Harvesting Review', *Advanced Healthcare Materials*, vol. 9, no. 17, pp. 1–22, 2020, doi: 10.1002/adhm.202000779.

- [19] R. Edwards and C. Gould, 'Review on micro-energy harvesting technologies', *Proceedings - 2016 51st International Universities Power Engineering Conference, UPEC 2016*, vol. 2017Janua, pp. 1–5, 2016, doi: 10.1109/UPEC.2016.8114023.
- [20] A. Capitaine, T. Chailloux, G. Pillonnet, and B. Allard, 'Electrical characterization and modeling of benthic microbial fuel cells for energy harvesting', *5e Journées Nationales sur la Récupération et le Stockage d'Energie pour l'alimentation de microsystemes autonomes (JNRSE'2015)*, no. Sge, pp. 4–5, 2015.
- [21] J. E. Mink, R. M. Qaisi, B. E. Logan, and M. M. Hussain, 'Energy harvesting from organic liquids in micro-sized microbial fuel cells', *NPG Asia Materials*, vol. 6, no. 3, pp. 1–5, 2014, doi: 10.1038/am.2014.1.
- [22] L. Mateu and F. Moll, '<title>Review of energy harvesting techniques and applications for microelectronics (Keynote Address)</title>', *VLSI Circuits and Systems II*, vol. 5837, pp. 359– 373, 2005, doi: 10.1117/12.613046.
- [23] F. Orfei, 'Disadvantages and Advantages of Energy Harvesting - Technical Articles', 2019.
- [24] F. Khalid, W. Saeed, N. Shoaib, M. U. Khan, and H. M. Cheema, 'Quad-Band 3D Rectenna Array for Ambient RF Energy Harvesting', vol. 2020, 2020.
- [25] S. Muhammad, J. J. Tiang, S. K. Wong, A. Smida, R. Ghayoula, and A. Iqbal, 'A Dual-Band Ambient Energy Harvesting Rectenna Design for Wireless Power Communications', *IEEE Access*, vol. 9, no. July, pp. 99944–99953, 2021, doi: 10.1109/ACCESS.2021.3096834.
- [26] A. Khemar, A. Kacha, H. Takhedmit, and G. Abib, 'Design and experiments of a dual-band rectenna for ambient RF energy harvesting in urban environments', pp. 49–55, 2017, doi: 10.1049/iet-map.2016.1040.
- [27] H. Takhedmit, 'Ambient RF Power Harvesting Application to Remote Supply of a Batteryless Temperature Sensor', no. January, 2017.

- [28] D. Briggs, L. Beale, J. Bennett, M. B. Toledano, and K. De Hoogh, 'Science of the Total Environment A geographical model of radio-frequency power density around mobile phone masts', *Science of the Total Environment, The*, vol. 426, pp. 233–243, 2012, doi: 10.1016/j.scitotenv.2012.03.066.
- [29] X. Gu, L. Grauwin, D. Dousset, and S. Hemour, 'Dynamic Ambient RF Energy Density Measurements of Montreal for Battery-Free IoT Sensor Network Planning', vol. 4662, no. c, pp. 1–13, 2021, doi: 10.1109/JIOT.2021.3065683.
- [30] A. Eid, S. Mghabghab, J. Costantine, M. Awad, and Y. Tawk, 'Support Vector Machines for Scheduled Harvesting of Wi-Fi Signals', *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 11, pp. 2277–2281, Nov. 2019, doi: 10.1109/LAWP.2019.2943250.
- [31] D. Features, 'Capacitive digital sensor for relative humidity and temperature', no. August, pp. 1–33, 2016. S. Hvac and R. Air, 'Stts22H Stts22H', no. November, 2021.
- [32] U. M. C. U. A. Cortex-m, K. B. Sram, and K. B. Eeprom, 'STM32L052x6 STM32L052x8', no. February, pp. 1–50, 2014.
- [33] A. Review, 'Self-Sustainable Biomedical Devices Powered by RF Energy : A Review', pp. 1–33, 2022.
- [34] E. I. Adegoke, R. M. Edwards, W. Whittow, and A. Bindel, 'RF Power Density Measurements for RF Energy Harvesting in Automobile Factories', 2015.
- [35] N. U. Khan and F. U. Khan, 'RF Energy Harvesting for Portable Biomedical Devices', 2019, *22nd International Multitopic Conference (INMIC)*.
- [36] R. Sarpeshkar *et al.*, 'An ultra-low-power programmable analog bionic ear processor', *IEEE Transactions on Biomedical Engineering*, vol. 52, no. 4, pp. 711–727, 2005, doi: 10.1109/TBME.2005.844043.
- [37] S. Saati, R. Lo, P. Y. Li, E. Meng, R. Varma, and M. S. Humayun, 'Mini drug pump for ophthalmic use', *Current Eye Research*, vol. 35, no. 3, pp. 192–201, 2010, doi:

10.3109/02713680903521936.

- [38] K. D. Wise, D. J. Anderson, J. F. Hetke, D. R. Kipke, and K. Najafi, ‘Wireless implantable microsystems: High-density electronic interfaces to the nervous system’, *Proceedings of the IEEE*, vol. 92, no. 1, pp. 76–97, 2004, doi: 10.1109/JPROC.2003.820544.
- [39] G. Chen *et al.*, ‘A cubic-millimeter energy-autonomous wireless intraocular pressure monitor’, *Digest of Technical Papers - IEEE International Solid-State Circuits Conference*, pp. 310–311, 2011, doi: 10.1109/ISSCC.2011.5746332.
- [40] J. Dieffenderfer *et al.*, ‘Low-Power Wearable Systems for Continuous Monitoring of Environment and Health for Chronic Respiratory Disease’, *IEEE Journal of Biomedical and Health Informatics*, vol. 20, no. 5, pp. 1251–1264, 2016, doi: 10.1109/JBHI.2016.2573286.
- [41] L. Turicchia *et al.*, ‘Ultralow-power electronics for cardiac monitoring’, *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 57, no. 9, pp. 2279–2290, 2010, doi: 10.1109/TCSI.2010.2071610.
- [42] J. D. Weiland, W. Liu, and M. S. Humayun, ‘Retinal prosthesis’, *Annual Review of Biomedical Engineering*, vol. 7, pp. 361–401, 2005, doi: 10.1146/annurev.bioeng.7.060804.100435.
- [43] F. Silveira and D. Flandre, ‘Low power analog CMOS for cardiac pacemakers: design and optimization in bulk and SOI technologies’, 2004, *Springer-Verlag New York Inc, New York*.
- [44] Y. Zhou, ‘Contribution to electromagnetic energy harvesting for wireless autonomous devices Thèse de Doctorat Yuwei ZHOU’, 2015.
- [45] S. Kim *et al.*, ‘Ambient RF energy-harvesting technologies for self-sustainable standalone wireless sensor platforms’, *Proceedings of the IEEE*, vol. 102, no. 11, pp. 1649–1666, 2014, doi: 10.1109/JPROC.2014.2357031.
- [46] S. Gao, W. Hu, and H. Zhang, ‘Millimeter-Wave Rectifiers Using Proprietary Schottky Diodes : Diode Modeling and Rectifier Analysis’, pp. 180–184, 2022.

- [47] I. Kyriaki Niotaki, , Student Member, IEEE, Sangkil Kim , Student Member, IEEE, Seongheon Jeong, Member, A. Ana Collado, Senior Member, IEEE, Apostolos Georgiadis, Senior Member, IEEE, and I. Manos M. Tentzeris, Fellow, ‘A Compact Dual-Band Rectenna Using Slot-Loaded Dual Band Folded Dipole AntennaKyriaki’, 2013, *IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS*, VOL. 12,.
- [48] K. Finkenzeller, ‘RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification’, 2003, *2nd Edition, John Wiley & Sons Ltd., Munich*.
- [49] D. Surender, T. Khan, F. A. Talukdar, A. De, Y. M. M. Antar, and A. P. Freundorfer, ‘Key Components of Rectenna System: A Comprehensive Survey’, *IETE Journal of Research*, vol. 0, no. 0, pp. 1–28, 2020, doi: 10.1080/03772063.2020.1761268.
- [50] S. Hemour *et al.*, ‘Towards low-power high-efficiency RF and microwave energy harvesting’, *IEEE Transactions on Microwave Theory and Techniques*, vol. 62, no. 4, pp. 965–976, 2014, doi: 10.1109/TMTT.2014.2305134.
- [51] G. V. K. Alex Mouapi Nadir Hakem, ‘A Selective Rectifier for RF Energy Harvesting under nonstationary Propagation Conditions’, 2018, *IEEE, Palermo*. doi: 10.1109/EEEIC.2018.8494509.
- [52] P. N. Skirdkov and K. A. Zvezdin, ‘Spin-Torque Diodes: From Fundamental Research to Applications’, *Annalen der Physik*, vol. 532, no. 6, p. 1900460, 2020, doi: 10.1002/andp.201900460.
- [53] C. R. Valenta and G. D. Durgin, ‘Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems’, *IEEE Microwave Magazine*, vol. 15, no. 4, pp. 108–120, 2014, doi: 10.1109/MMM.2014.2309499.
- [54] M. U. Hoque, D. Kumar, Y. Audet, and Y. Savaria, ‘Design and Analysis of a 35 GHz Rectenna System for Wireless Power Transfer to an Unmanned Air Vehicle’, *Energies*, vol. 15, no. 1, 2022, doi: 10.3390/en15010320.

- [55] X. V. Linh Nguyen *et al.*, ‘Stereolithography-Based Rectenna for Wireless Energy Harvesting’, in *2021 IEEE 34th International System-on-Chip Conference (SOCC)*, Sep. 2021, pp. 34–39. doi: 10.1109/SOCC52499.2021.9739329.
- [56] X. V. L. Nguyen *et al.*, ‘3D Plastronics Radio Frequency Energy Harvester on Stereolithography Parts’, in *2022 Wireless Power Week (WPW)*, Jul. 2022, pp. 156–161. doi: 10.1109/WPW54272.2022.9854010.
- [57] A. Eid, J. G. D. Hester, J. Costantine, Y. Tawk, A. H. Ramadan, and M. M. Tentzeris, ‘A Compact Source-Load Agnostic Flexible Rectenna Topology for IoT Devices’, *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 4, pp. 2621–2629, 2020, doi: 10.1109/TAP.2019.2955211.
- [58] M. Bajtaoui, M. A. Ennasar, M. Aznabet, A. Tachrifat, and O. El Mrabet, ‘A Folded Rectenna on a Flexible Substrate for 5G Energy Harvesting Applications’, *Progress In Electromagnetics Research C*, vol. 135, pp. 69–81, Jan. 2023, doi: 10.2528/PIERC23051505.
- [59] V. Palazzi *et al.*, ‘Performance analysis of a ultra-compact low-power rectenna in paper substrate for RF energy harvesting’, in *2017 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet)*, Jan. 2017, pp. 65–68. doi: 10.1109/WISNET.2017.7878757.
- [60] K. Niotaki *et al.*, ‘RF Energy Harvesting and Wireless Power Transfer for Energy Autonomous Wireless Devices and RFIDs’, *IEEE Journal of Microwaves*, vol. 3, no. 2, pp. 763–782, Apr. 2023, doi: 10.1109/JMW.2023.3255581.
- [61] V. Palazzi *et al.*, ‘A Novel Ultra-Lightweight Multiband Rectenna on Paper for RF Energy Harvesting in the Next Generation LTE Bands’, *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 1, pp. 366–379, Jan. 2018, doi: 10.1109/TMTT.2017.2721399.
- [62] J. M. Romo-Herrera *et al.*, ‘Paper-based plasmonic substrates as surface-enhanced Raman scattering spectroscopy platforms for cell culture applications’, *Materials Today Bio*, vol. 11, p. 100125, Jun. 2021, doi: 10.1016/j.mtbio.2021.100125.

- [63] M. Wagih, G. Hilton, A. Weddell, and S. Beeby, 'Dual-Band Dual-Mode Textile Antenna/Rectenna for Simultaneous Wireless Information and Power Transfer (SWIPT)', *IEEE Transactions on Antennas and Propagation*, vol. 69, Mar. 2021, doi: 10.1109/TAP.2021.3070230.
- [64] Q. Awais, Y. Jin, H. T. Chattha, M. Jamil, H. Qiang, and B. A. Khawaja, 'A compact rectenna system with high conversion efficiency for wireless energy harvesting', *IEEE Access*, vol. 6, pp. 35857–35866, 2018, doi: 10.1109/ACCESS.2018.2848907.
- [65] K. K. A. Devi, N. Md. Din, and C. K. Chakrabarty, 'Optimization of the Voltage Doubler Stages in an RF-DC Converter Module for Energy Harvesting', *Circuits and Systems*, vol. 03, no. 03, pp. 216–222, 2012, doi: 10.4236/cs.2012.33030.
- [66] M. S. Papadopoulou, A. D. Boursianis, C. K. Volos, I. N. Stouboulos, S. Nikolaidis, and S. K. Goudos, 'High-Efficiency Triple-Band RF-to-DC Rectifier Primary Design for RF EnergyHarvesting Systems', *Telecom*, vol. 2, no. 3, pp. 271–284, 2021, doi: 10.3390/telecom2030018.
- [67] K. Kawai, N. Takabayashi, and T. Toyonaga, 'Development of Rectenna for Estimating Received Power Level Using Second Harmonic Wave', pp. 175–179, 2022.
- [68] C. Song, Y. Huang, J. Zhou, J. Zhang, S. Yuan, and P. Carter, 'A high-efficiency broadband rectenna for ambient wireless energy harvesting', *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 8, pp. 3486–3495, 2015, doi: 10.1109/TAP.2015.2431719.
- [69] N. Nikkhah and J. Lipman, 'Efficient Dual-Band Single-Port Rectifier for RF Energy Harvesting at FM and GSM Bands', pp. 141–145, 2022.
- [70] N. Akter, B. Hossain, H. Kabir, A. H. Bhuiyan, M. Yeasmin, and S. Sultana, 'Design and Performance Analysis of 10-Stage Voltage Doublers RF Energy Harvesting Circuit for Wireless Sensor Network', *Journal of Communications Engineering and Networks*, vol. 2, pp. 84–91, 2014, doi: 10.18005/jcen0202004.

- [71] D. Hanh and N. Bui, 'Do Hanh Ngan Bui To cite this version : HAL Id: tel-01721461 Antennes souples imprimables pour la récupération d ' énergie de champs électromagnétiques ambiants', 2018.
- [72] Z. Hameed and K. Moez, 'Design of impedance matching circuits for RF energy harvesting systems', *Microelectronics Journal*, vol. 62, no. April 2016, pp. 49–56, 2017, doi: 10.1016/j.mejo.2017.02.004.
- [73] H. Takhedmit, L. Cirio, F. Costa, and O. Picon, 'Transparent rectenna and rectenna array for RF energy harvesting at 2.45 GHz', *8th European Conference on Antennas and Propagation, EuCAP 2014*, no. EuCAP, pp. 2970–2972, 2014, doi: 10.1109/EuCAP.2014.6902451.
- [74] C. Felini, M. Merenda, and F. G. D. Corte, 'Dynamic impedance matching network for RF energy harvesting systems', *2014 IEEE RFID Technology and Applications Conference, RFIDTA 2014*, no. September, pp. 86–90, 2014, doi: 10.1109/RFID-TA.2014.6934206.
- [75] D. De Donno, L. Catarinucci, and L. Tarricone, 'An UHF RFID energy-harvesting system enhanced by a DC-DC charge pump in silicon-on-insulator technology', *IEEE Microwave and Wireless Components Letters*, vol. 23, no. 6, pp. 315–317, 2013, doi: 10.1109/LMWC.2013.2258002.
- [76] O. Assogba, A. K. Mbodji, A. Bréard, A. K. Diallo, and Y. Duroc, 'Tri-Band Rectenna Dedicated to UHF RFID, GSM-1800 and UMTS-2100 Frequency Bands', *Sensors*, vol. 22, no. 9, 2022, doi: 10.3390/s22093565.
- [77] H. Sun, Y. X. Guo, M. He, and Z. Zhong, 'A dual-band rectenna using broadband yagi antenna array for ambient rf power harvesting', *IEEE Antennas and Wireless Propagation Letters*, vol. 12, no. c, pp. 918–921, 2013, doi: 10.1109/LAWP.2013.2272873.
- [78] S. Shen, C. Y. Chiu, and R. D. Murch, 'A dual-port triple-band L-probe microstrip patch rectenna for ambient RF energy harvesting', *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 3071–3074, 2017, doi: 10.1109/LAWP.2017.2761397.

- [79] J. K. Huang, W. T. Hung, T. H. Cheng, and S. Y. Chen, 'A 2.45-GHz high-efficiency loop-shaped PIFA rectenna for portable devices and wireless sensors', *IEEE Antennas and Propagation Society, AP-S International Symposium (Digest)*, vol. 2015-Octob, pp. 1284–1285, 2015, doi: 10.1109/APS.2015.7305031.
- [80] A. Kumar and A. P. S. gh, 'Enhancement of the Performance Parameters of Microstrip Slotted Patch Antenna using Defected Ground Structure', *International Journal of Engineering Trends and Technology*, vol. 60, no. 2, pp. 122–127, 2018, doi: 10.14445/22315381/ijett-v60p217.
- [81] A. Majumder, 'Rectangular Microstrip Patch Antenna Using Coaxial Probe Feeding Technique to Operate in S-Band', *International Journal of Engineering Trends and Technology*, vol. 4, no. 4, pp. 1206–1210, 2013.
- [82] and H. U. I. Ebrahim Sailan Aabidi, M.R. Kamarudin, T.A. Rahman, 'antenna1.pdf', *Piers Proceedings, Stokholm, Sweden*. doi: August 2013.
- [83] Dr. S. Bhunia, 'Microstrip Patch Antenna's Limitation and Some Remedies', 2013, *International Journal of Electronics and Communication Technology, West Bengal, India*.
- [84] B. C. A., 'Antenna theory; analysis and design', *Proceedings of the IEEE*, vol. 72, no. 7, pp. 989–990, 2008, doi: 10.1109/proc.1984.12959.
- [85] H. Saghlatoon, L. Sydänheimo, L. Ukkonen, and M. Tentzeris, 'Optimization of Inkjet Printing of Patch Antennas on Low-Cost Fibrous Substrates', *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 915–918, 2014, doi: 10.1109/LAWP.2014.2322572.
- [86] D. Feili, N. Pagel, V. L. Ngo, P. Schwarz, and H. Seidel, 'Cu based patch antenna on polymer substrate for flexible wireless sensor systems applications', *Procedia Engineering*, vol. 5, pp. 890–893, Jan. 2010, doi: 10.1016/j.proeng.2010.09.252.
- [87] X. L. Chang, P. S. Chee, and E. H. Lim, 'Compact conformal tattoo-polymer antenna for onbody wireless power transfer', *Sci Rep*, vol. 13, no. 1, Art. no. 1, Jun. 2023, doi: 10.1038/s41598-023-36335-6.

- [88] I. Marasco *et al.*, ‘A compact evolved antenna for 5G communications’, *Sci Rep*, vol. 12, no. 1, Art. no. 1, Jun. 2022, doi: 10.1038/s41598-022-14447-9.
- [89] N. J. Shimu and A. Ahmed, ‘Design and performance analysis of rectangular microstrip patch antenna at 2.45 GHz’, in *2016 5th International Conference on Informatics, Electronics and Vision (ICIEV)*, May 2016, pp. 1062–1066. doi: 10.1109/ICIEV.2016.7760161.
- [90] N. Montgomery, ‘Triple-frequency stacked microstrip element’, in *1984 Antennas and Propagation Society International Symposium*, Jun. 1984, pp. 255–258. doi: 10.1109/APS.1984.1149253.
- [91] W. Richards, S. Davidson, and S. Long, ‘Dual-band reactively loaded microstrip antenna’, *IEEE Transactions on Antennas and Propagation*, vol. 33, no. 5, pp. 556–561, May 1985, doi: 10.1109/TAP.1985.1143617.
- [92] S. Long and M. Walton, ‘A dual-frequency stacked circular-disc antenna’, *IEEE Transactions on Antennas and Propagation*, vol. 27, no. 2, pp. 270–273, Mar. 1979, doi: 10.1109/TAP.979.1142078.
- [93] A. Henderson, J. R. James, and C. M. Hall, *Bandwidth extension techniques in printed conformal antennas*. 1986, pp. 329–334. Accessed: Sep. 08, 2023. [Online]. Available: <https://ui.adsabs.harvard.edu/abs/1986mimi.proc..329H>
- [94] H. F. Pues and A. R. Van de Capelle, ‘An impedance-matching technique for increasing the bandwidth of microstrip antennas’, *IEEE Transactions on Antennas and Propagation*, vol. 37, no. 11, pp. 1345–1354, Nov. 1989, doi: 10.1109/8.43553.
- [95] J. J. Schuss, J. D. Hanfling, and R. L. Bauer, ‘Design of wideband patch radiator phased arrays’, in *Digest on Antennas and Propagation Society International Symposium*, Jun. 1989, pp. 1220–1223 vol.3. doi: 10.1109/APS.1989.134929.
- [96] C. H. Tsao, Y. M. Hwang, F. Kilburg, and F. Dietrich, ‘Aperture-coupled patch antennas with wide-bandwidth and dual-polarization capabilities’, in *International Symposium, Antennas and Propagation 1988 IEEE AP-S*, Jun. 1988, pp. 936–939 vol.3. doi: 10.1109/APS.1988.94241.

- [97] A. Ittipiboon, B. Clarke, and M. Cuhaci, 'Slot-coupled stacked microstrip antennas', in *International Symposium on Antennas and Propagation Society, Merging Technologies for the 90's*, May 1990, pp. 1108–1111 vol.3. doi: 10.1109/APS.1990.115305.
- [98] A. Sabban, 'A new broadband stacked two-layer microstrip antenna', in *1983 Antennas and Propagation Society International Symposium*, May 1983, pp. 63–66. doi: 10.1109/APS.1983.1149074.
- [99] C. Chen, A. Tulintseff, and R. Sorbello, 'Broadband two-layer microstrip antenna', in *1984 Antennas and Propagation Society International Symposium*, Jun. 1984, pp. 251–254. doi: 10.1109/APS.1984.1149257.
- [100] R. Mishra, P. Kuchhal, and A. Kumar, 'Effect of Height of the Substrate and Width of the Patch on the Performance Characteristics of Microstrip Antenna', *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 5, pp. 1441–1445, Dec. 2015, doi: 10.11591/ijece.v5i6.pp1441-1445.
- [101] M. Kara, 'Effects of Substrate Thickness on the Properties of Rectangular Microstrip Antenna Elements', in *AMPC Asia-Pacific Microwave Conference*, Aug. 1992, pp. 203–206. doi: 10.1109/APMC.1992.672012.
- [102] J. T. Aberle and F. Zavosh, 'Analysis of Probe-fed Circular Microstrip Patches Backed by Circular Cavities', *Electromagnetics*, vol. 14, no. 2, pp. 239–258, Apr. 1994, doi: 10.1080/02726349408908382.
- [103] R. Mailloux, 'On the use of metallized cavities in printed slot arrays with dielectric substrates', *IEEE Transactions on Antennas and Propagation*, vol. 35, no. 5, pp. 477–487, May 1987, doi: 10.1109/TAP.1987.1144146.
- [104] L. C. Paul, M. S. Hosain, S. Sarker, M. H. Prio, M. Morshed, and A. K. Sarkar, 'The effect of changing substrate material and thickness on the performance of inset feed microstrip patch antenna', *American Journal of Networks and Communications*, vol. 4, no. 3, pp. 54–58, 2015.
- [105] J. S. Kulkarni, S. Habbu, G. Ghule, A. Ratnaparakhi, P. Deshpande, and C. Y. D. Sim, 'Defected ground planar antenna for GSM 1800/1900, LTE 46/47 and Wi-Fi

- 5 wireless applications', *2021 2nd International Conference for Emerging Technology, INCET 2021*, pp. 21–24, 2021, doi: 10.1109/INCET51464.2021.9456445.
- [106] H. Elftouh, N. A. Touhami, M. Aghoutane, S. El Amrani, A. Tazon, and M. Boussouis, 'Miniaturized microstrip patch antenna with defected ground structure', *Progress In Electromagnetics Research C*, vol. 55, no. February 2015, pp. 25–33, 2014, doi: 10.2528/PIERC14092302.
- [107] F. N. Pierre Moukala Mpele, Franck Moukanda Mbango, Dominic B.O Konditi, 'A novel quadband ultra miniaturized planar antenna with metallic vias and defected ground structure for portable devices', 2021, *CellPress*. doi: doi.org/10.1016/j.heliyon.2021.e06373.
- [108] S. Divakaran, D. D. Krishna, Nasimuddin, and J. Antony, 'Dual-band multi-port rectenna for rf energy harvesting', *Progress In Electromagnetics Research C*, vol. 107, no. November 2020, pp. 17–31, 2020, doi: 10.2528/PIERC20100802.
- [109] P. K. S. Ankita Ambh, 'SIZE REDUCTION OF RECTANGLAR MICROSTRIP PATCH ANTENNA FOR GSM APPLICATION', *International Research Journal of Engineering and Technology(IRJET)*, vol. 03, pp. 1–4, 2016.
- [110] M. H. Ullah, M. T. Islam, J. S. Mandeep, and N. Misran, 'A new double L-shaped multiband patch antenna on a polymer resin material substrate', *Appl. Phys. A*, vol. 110, no. 1, pp. 199– 205, Jan. 2013, doi: 10.1007/s00339-012-7114-0.
- [111] D. D. Patil, K. S. Subramanian, N. C. Pradhan, E. K. Varadharaj, S. K., and M. M., '3D-printed dual-band energy harvester for WSNs in green IoT applications', *AEU - International Journal of Electronics and Communications*, vol. 164, p. 154641, May 2023, doi: 10.1016/j.aeue.2023.154641.
- [112] D. Hanh *et al.*, 'Antennes souples imprimables pour la récupération de champs électromagnétiques ambiants', pp. 65–67, 2015.
- [113] D. N. A. Yanik, 'A Multi-Band Rectangular Patch Antenna for Wireless Communications'. doi: Spring 2004.

- [114] C. M. L. Yong-Ping Zhang, Hao-Yu Jin, 'A Compact Dual-Wideband Monopole Antenna With Parasitic Patch For 2G/3G/LTE/WLAN/WiMAX Applications', 2017, *Conference: 2017 IEEE 5th International Symposium on Electromagnetic Compatibility (EMC-Beijing), Beijing*. doi: DOI: 10.1109/EMC-B.2017.8260438.
- [115] A. Keerthanai Priya, K. U. Uma Magesh, V. Kokila, and Dr. B. Bhuvaneswari, 'Investigation of Placing Defective Ground Structures for Bandwidth Enhancement in Microstrip Patch Antennas', *International Journal of Engineering Research and*, vol. V6, no. 02, 2018, doi: 10.17577/ijertcon045.
- [116] G. Singh, R. Rajni, and R. Singh Momi, 'Microstrip Patch Antenna with Defected Ground Structure for Bandwidth Enhancement', *International Journal of Computer Applications*, vol. 73, no. 9, pp. 14–17, 2013, doi: 10.5120/12769-9759.
- [117] B. K. K. and S. K. Mukesh Kumar Khandelwal, 'Defected Ground Structure: Fundamentals, Analysis, and Applications in Modern Wireless Trends', 2016, *International Journal of Antennas and Propagation*.
- [118] M. 1Micro andNano Electronics Research Group, Faculty ofElectronics andComputer Engineering, Technical University ofMalaysia Melaka, Durian Tunggal, M. 2Faculty ofManufacturing Engineering, Technical University ofMalaysia Melaka, Durian Tunggal, and Abstract, 'Miniature High Gain Slot-fed Rectangular Dielectric Resonator Antenna for IoT RF Energy Harvesting Alphonsos', *International Journal of Electronics and Communications*, 1384, doi: <https://doi.org/10.1016/j.aeue.2017.12.023>.
- [119] H. Saghlatoon, T. Björninen, L. Sydänheimo, M. M. Tentzeris, and L. Ukkonen, 'Inkjet-Printed Wideband Planar Monopole Antenna on Cardboard for RF Energy-Harvesting Applications', *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 325–328, 2015, doi: 10.1109/LAWP.2014.2363085.

- [120] V. Palazzi *et al.*, ‘Design of a ultra-compact low-power rectenna in paper substrate for energy harvesting in the Wi-Fi band’, in *2016 IEEE Wireless Power Transfer Conference (WPTC)*, May 2016, pp. 1–4. doi: 10.1109/WPT.2016.7498823.
- [121] A. Ayd R. Saad, W. M. Hassan, and A. A. Ibrahim, ‘A monopole antenna with cotton fabric material for wearable applications’, *Sci Rep*, vol. 13, no. 1, Art. no. 1, May 2023, doi: 10.1038/s41598-023-34394-3.
- [122] M. Arrawatia, M. S. Baghini, and G. Kumar, ‘Broadband Bent Triangular Omnidirectional Antenna for RF Energy Harvesting’, *IEEE Antennas and Wireless Propagation Letters*, vol. 15, no. c, pp. 36–39, 2016, doi: 10.1109/LAWP.2015.2427232.
- [123] R. M. Yaseen, D. K. Naji, and A. M. Shakir, ‘Optimization Design Methodology of Broadband or Multiband Antenna for RF Energy Harvesting Applications’, vol. x, no. July, 2021. [125] W. P. Letters, ‘A Wideband , Quasi-Isotropic , Ambient RF Energy’, 2021.
- [126] C. Song *et al.*, ‘A Novel Six-Band Dual CP Rectenna Using Improved Impedance Matching Technique for Ambient RF Energy Harvesting’, *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 7, pp. 3160–3171, 2016, doi: 10.1109/TAP.2016.2565697.
- [127] A. K. Arya, A. Patnaik, and M. V. Kartikeyan, ‘Microstrip patch antenna with skew-F shaped DGS for dual band operation’, *Progress In Electromagnetics Research M*, vol. 19, no. November 2014, pp. 147–160, 2011, doi: 10.2528/PIERM11052305.
- [128] L. Y. and M. W. Yanyan Shi, Yue Fan, Yan Li, ‘An Efficient Broadband Slotted Rectenna for Wireless Power Transfer at LTE Band’, 2018, *IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION*. doi: 10.1109/TAP.2018.2882632.
- [129] D. P. D. Ngo Hoai Nguyen, Kieu Trung Liem, Nguyen Dinh Uyen, ‘A Small Patch Antenna for GSM Applications’, 2014, *Conference: 2014 IEEE Fifth International Conference on Communications and Electronics (ICCE), Vietnam*. doi: 10.1109/CCE.2014.6916736.

- [130] B. K. S. Saswati Ghosh, 'Design of microstrip crossed monopole antenna for ultra wideband communication Microstrip crossed monopole for ultra wideband communication', 2012, *Annual IEEE India Conference (INDICON), Kharagpur, India*. doi: 10.1109/INDCON.2012.6420669.
- [131] D. K. Ho, V. D. Ngo, I. Kharrat, T. P. Vuong, Q. C. Nguyen, and M. T. Le, 'A novel dual-band rectenna for ambient rf energy harvesting at GSM 900 MHz and 1800 MHz', *Advances in Science, Technology and Engineering Systems*, vol. 2, no. 3, pp. 612–616, 2017, doi: 10.25046/aj020378.
- [132] S. B. Tapas Tewarya, Smarajit Maitya, Surajit Mukherjeeb, Avisankar Royb, Partha Pratim Sarkarc, 'Design of high gain broadband microstrip patch antenna for UWB/X/Ku band applications', 2021, *AEU - International Journal of Electronics and Communications*. doi: <https://doi.org/10.1016/j.aeue.2021.153905>.
- [133] N. M. Din, C. K. Chakrabarty, A. Bin Ismail, K. K. A. Devi, and W. Y. Chen, 'Design of RF energy harvesting system for energizing low power devices', *Progress in Electromagnetics Research*, vol. 132, no. January, pp. 49–69, 2012, doi: 10.2528/pier12072002.
- [134] B. Tariq, M. Amjad, K. A. Al-Jaloud, F. A. Tahir, W. A. Malik, and R. Hussain, 'Design and Analysis of a Dual-Port Multiband RF-to-DC Converter for IoT Energy Harvesting Applications', Apr. 22, 2024. doi: 10.21203/rs.3.rs-4266282/v1.
- [135] N. F. Friska, N. Nasrul, and R. Vitria, 'Serial Rectifier Antenna (Rectenna) Microstrip Patch Circular 2.4 Ghz For Radio Frequency Energy Harvester', *International Journal of Wireless And Multimedia Communications*, vol. 1, no. 1, Art. no. 1, Jan. 2024, Accessed: Apr. 23, 2024. [Online]. Available: <https://jowim.org/index.php/jowim/article/view/9>
- [136] A. Reddafa *et al.*, 'Modeling of Schottky diode and optimal matching circuit design for low power RF energy harvesting', *Heliyon*, vol. 10, no. 6, Mar. 2024, doi: 10.1016/j.heliyon.2024.e27792.

- [137] Q. Lian and N. Mei, 'A High-Efficiency, Ultrawide-Dynamic-Range Radio Frequency Energy Harvester Using Adaptive Reconfigurable Technique', *Electronics*, vol. 13, no. 7, Art. no. 7, Jan. 2024, doi: 10.3390/electronics13071193.
- [138] J. Zhao, J. Song, D. Li, Y. Li, and J. Cheng, 'Dual-band RF energy harvesting for low-power IoT devices', *Wireless Netw*, Feb. 2024, doi: 10.1007/s11276-024-03685-6.
- [139] S. Nagaveni, S. S. Regulagadda, and A. Dutta, 'A Stage–Stage Dead-Band Compensated Multiband RF Energy Harvester for Sensor Nodes', *IEEE Sensors Journal*, vol. 23, no. 5, pp. 4940–4950, Mar. 2023, doi: 10.1109/JSEN.2023.3237544.
- [140] A. Bakytbekov, T. Q. Nguyen, G. Zhang, M. S. Strano, K. N. Salama, and A. Shamim, 'Synergistic multi-source ambient RF and thermal energy harvester for green IoT applications', *Energy Reports*, vol. 9, pp. 1875–1885, Dec. 2023, doi: 10.1016/j.egyr.2023.01.027.
- [141] X. Liu, M. Li, X. Chen, Y. Zhao, L. Xiao, and Y. Zhang, 'A Compact Stacked RF Energy Harvester with Multi-Condition Adaptive Energy Management Circuits', *Micromachines*, vol. 14, no. 10, Art. no. 10, Oct. 2023, doi: 10.3390/mi14101967.
- [142] S. Asakura, S. Yamanokuchi, S. Yoshida, and K. Nishikawa, 'Design and Prototyping of a Single-Shunt Rectifier with 71% Fractional Bandwidth Having Acceptable Matching on 10 dBm LSSP', in *2022 Wireless Power Week (WPW)*, Jul. 2022, pp. 383–387. doi: 10.1109/WPW54272.2022.9853949.
- [143] K. Kawai, N. Takabayashi, T. Toyonaga, K. Suzuki, and N. Shinohara, 'Development of Rectenna for Estimating Received Power Level Using Second Harmonic Wave', in *2022 Wireless Power Week (WPW)*, Jul. 2022, pp. 175–179. doi: 10.1109/WPW54272.2022.9854024.
- [144] Y. Muramoto, S. Naoki, and I. Kenyi, 'A 920 MHz band rectenna with the impedance transformed small loop antenna (IT-SLA)', pp. 400–403, 2022.

- [145] G. Le, N. Nguyen, N. D. Au, and C. Seo, 'A Broadband High-Efficiency Rectifier for Mid-field Wireless Power Transfer', *IEEE Microwave and Wireless Components Letters*, vol. 1309, no. c, pp. 10–13, 2021, doi: 10.1109/LMWC.2021.3077566.
- [146] T. S. Almoneef, 'Design of a Rectenna Array without a Matching Network', *IEEE Access*, vol. 8, pp. 109071–109079, 2020, doi: 10.1109/ACCESS.2020.3001903.
- [147] H. Tafekirt, J. Pelegri-Sebastia, A. Bouajaj, and B. M. Reda, 'A Sensitive Triple-Band Rectifier for Energy Harvesting Applications', *IEEE Access*, vol. 8, pp. 73659–73664, 2020, doi: 10.1109/ACCESS.2020.2986797.
- [148] F. Leplingard *et al.*, 'FWM-Assisted Raman Laser for Second-Order Raman Pumping', 2003.
- [149] J. Zhao, G. Subramanyam, and H. Yue, 'A Dual-Band Rectifying Antenna Design for RF Energy Harvesting', *Midwest Symposium on Circuits and Systems*, vol. 2020-Augus, pp. 415–418, 2020, doi: 10.1109/MWSCAS48704.2020.9184606.
- [150] S. C. Wang, M. J. Li, and M. S. Tong, 'A Miniaturized High-Efficiency Rectifier with Extended Input Power Range for Wireless Power Harvesting', *IEEE Microwave and Wireless Components Letters*, vol. 30, no. 6, pp. 617–620, 2020, doi: 10.1109/LMWC.2020.2990534.
- [151] X. Gu, L. Guo, S. Hemour, and K. Wu, 'Optimum Temperatures for Enhanced Power Conversion Efficiency (PCE) of Zero-Bias Diode-Based Rectifiers', *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 9, pp. 4040–4053, 2020, doi: 10.1109/TMTT.2020.2992024.
- [152] M. Wang, J. Chen, X. Cui, and L. Li, 'Design and Fabrication of 5.8GHz RF Energy Harvesting Rectifier', *2019 Cross Strait Quad-Regional Radio Science and Wireless Technology Conference, CSQRWC 2019 - Proceedings*, pp. 1–3, 2019, doi: 10.1109/CSQRWC.2019.8799201.
- [153] M. M. Mansour and H. Kanaya, 'High-Efficient Broadband CPW RF Rectifier for Wireless Energy Harvesting', *IEEE Microwave and Wireless Components Letters*, vol. 29, no. 4, pp. 288–290, 2019, doi: 10.1109/LMWC.2019.2902461.

- [154] K. Bhatt, S. Kumar, P. Kumar, and C. C. Tripathi, 'Highly Efficient 2.4 and 5.8 GHz Dual-Band Rectenna for Energy Harvesting Applications', *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 12, pp. 2637–2641, Dec. 2019, doi: 10.1109/LAWP.2019.2946911.
- [155] S. Shen, Y. Zhang, C.-Y. Chiu, and R. Murch, 'An Ambient RF Energy Harvesting System Where the Number of Antenna Ports is Dependent on Frequency', *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 9, pp. 3821–3832, 2019, doi: 10.1109/tmtt.2019.2906598.
- [156] C. H. Lin, C. W. Chiu, and J. Y. Gong, 'A Wearable Rectenna to Harvest Low-Power RF Energy for Wireless Healthcare Applications', *Proceedings - 2018 11th International Congress on Image and Signal Processing, BioMedical Engineering and Informatics, CISP-BMEI 2018*, no. 1, pp. 1–5, 2019, doi: 10.1109/CISP-BMEI.2018.8633222.
- [157] A. Fumtchum, P. Tsafack, F. Hutu, G. Villemaud, and E. Tanyi, 'A Survey of RF Energy Harvesting Circuits', *International Journal of Innovative Technology and Exploring Engineering*, vol. 10, no. 7, pp. 99–106, 2021, doi: 10.35940/ijitee.g8944.0510721.
- [158] M. Aboualalaa *et al.*, 'Dual-band Rectenna Using Voltage Doubler Rectifier and Four-Section Matching Network', *2018 IEEE Wireless Power Transfer Conference, WPTC 2018*, no. 1, pp. 1–4, 2019, doi: 10.1109/WPT.2018.8639451.
- [159] A. Mouapi, N. Hakem, N. Kandil, and G. V. Kamani, 'A Miniature Rectifier Design for Radio Frequency Energy Harvesting Applied at 2.45 GHz', *Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, IEEEIC/I and CPS Europe 2018*, pp. 1–5, 2018, doi: 10.1109/IEEEIC.2018.8493844.
- [160] A. Biswas, S. Babak Hamidi, C. Biswas, P. Roy, D. Mitra, and D. Dawn, 'A novel CMOS RF energy harvester for self-sustainable applications', *2018 IEEE 19th Wireless and Microwave Technology Conference, WAMICON 2018*, vol. 1, no. c, pp. 1–5, 2018, doi: 10.1109/WAMICON.2018.8363908.

- [161] C. H. Li, M. C. Yu, and H. J. Lin, 'A Compact 0.9-/2.6-GHz Dual-Band RF Energy Harvester Using SiP Technique', *IEEE Microwave and Wireless Components Letters*, vol. 27, no. 7, pp. 666–668, 2017, doi: 10.1109/LMWC.2017.2711506.
- [162] M. Ur Rehman, W. Ahmad, and W. T. Khan, 'Highly efficient dual band 2.45/5.85 GHz rectifier for RF energy harvesting applications in ISM band', *Asia-Pacific Microwave Conference Proceedings, APMC*, pp. 150–153, 2017, doi: 10.1109/APMC.2017.8251400.
- [163] A. Eid *et al.*, 'An efficient RF energy harvesting system', *2017 11th European Conference on Antennas and Propagation, EUCAP 2017*, pp. 896–899, 2017, doi: 10.23919/EuCAP.2017.7928573.
- [164] M. M. Mansour and H. Kanaya, 'Compact RF rectifier circuit for ambient energy harvesting', *2017 IEEE International Symposium on Radio-Frequency Integration Technology, RFIT 2017*, pp. 220–222, 2017, doi: 10.1109/RFIT.2017.8048256.
- [165] C. Song, Y. Huang, J. Zhou, J. Zhang, S. Yuan, and P. Carter, 'A high-efficiency broadband rectenna for ambient wireless energy harvesting', *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 8, pp. 3486–3495, 2015, doi: 10.1109/TAP.2015.2431719.
- [166] A. Bakytbekov, T. Q. Nguyen, C. Huynh, K. N. Salama, and A. Shamim, 'Fully printed 3D cubeshaped multiband fractal rectenna for ambient RF energy harvesting', *Nano Energy*, vol. 53, pp. 587–595, Nov. 2018, doi: 10.1016/j.nanoen.2018.09.022.
- [167] QASIM AWAIS, YANG JIN, HASSAN TARIQ CHATTHA, MOHSIN JAMIL, and BILAL A. KHAWAJA, 'A compact rectenna system with high conversion efficiency for wireless energy harvesting', *IEEE Access*, vol. 6, pp. 35857–35866, 2018, doi: 10.1109/ACCESS.2018.2848907.
- [168] Q. Awais, Y. Jin, H. T. Chattha, M. Jamil, H. Qiang, and B. A. Khawaja, 'A Compact Rectenna System With High Conversion Efficiency for Wireless Energy Harvesting', *IEEE Access*, vol. 6, pp. 35857–35866, 2018, doi: 10.1109/ACCESS.2018.2848907.

- [169] S. Roy, J. J. Tiang, M. B. Roslee, M. T. Ahmed, A. Z. Kouzani, and M. A. P. Mahmud, 'QuadBand Rectenna for Ambient Radio Frequency (RF) Energy Harvesting', *Sensors*, vol. 21, no. 23, Art. no. 23, Jan. 2021, doi: 10.3390/s21237838.
- [170] S. Roy, J.-J. Tiang, M. B. Roslee, M. T. Ahmed, A. Z. Kouzani, and M. A. P. Mahmud, 'Design of a Highly Efficient Wideband Multi-Frequency Ambient RF Energy Harvester', *Sensors*, vol. 22, no. 2, Art. no. 2, Jan. 2022, doi: 10.3390/s22020424.
- [171] 'Low-cost environment-friendly energy scavenging system - IOPscience'. Accessed: Jan. 01, 2024. [Online]. Available: <https://iopscience.iop.org/article/10.1088/26318695/acd224/meta>
- [172] Z. Khonsari, T. Björninen, M. M. Tentzeris, L. Sydänheimo, and L. Ukkonen, '2.4 GHz inkjetprinted RF energy harvester on bulk cardboard substrate', in *2015 IEEE Radio and Wireless Symposium (RWS)*, Jan. 2015, pp. 153–155. doi: 10.1109/RWS.2015.7129721.
- [173] P. Ferrari, B. Fleche, and G. Anghieux, 'Time Domain Characterization of Lossy Arbitrary Characteristic Impedance Transmission Lines'. *IEEE Microwave and Guided Wave Letters*, vol. 4, no. 6, pp. 177–179, Jan. 1994. [Online]. Available: doi: 10.1109/75.294284.
- [174] A. A. Takach, F. M. Moukanda, F. Ndagijimana, M. Al-Husseini, and J. Jomaah, 'TWO-LINE TECHNIQUE FOR DIELECTRIC MATERIAL CHARACTERIZATION WITH APPLICATION IN 3DPRINTING FILAMENT ELECTRICAL PARAMETERS EXTRACTION', *PIER M*, vol. 85, pp. 195–207, 2019, doi: 10.2528/PIERM19071702.
- [175] S.-M. Wu *et al.*, 'Dielectric constant and loss-tangent extraction using near-field technology and phase delay method', in *2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC)*, May 2018, pp. 683–686. doi: 10.1109/ISEMC.2018.8393868.

- [176] C. Orlob, D. Kornek, S. Preihs, and I. Rolfes, ‘Characterization of Electromagnetic Properties of Molded Interconnect Device Materials’, in *2009 German Microwave Conference*, Mar. 2009, pp. 1–4. doi: 10.1109/GEMIC.2009.4815856.
- [177] P. I. Deffenbaugh, R. C. Rumpf, and K. H. Church, ‘Broadband Microwave Frequency Characterization of 3-D Printed Materials’, *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 3, no. 12, pp. 2147–2155, Dec. 2013, doi: 10.1109/TCPMT.2013.2273306.
- [178] J. Baker-Jarvis, M. D. Janezic, and D. C. Degroot, ‘High-frequency dielectric measurements’, *IEEE Instrumentation & Measurement Magazine*, vol. 13, no. 2, pp. 24–31, Apr. 2010, doi: 10.1109/MIM.2010.5438334.
- [179] V. Palazzi, P. Mezzanotte, F. Alimenti, M. Tentzeris, and L. Roselli, ‘Microfluidics-based 3DPrinted 4×4 Butler Matrix in Coaxial Technology for Applications up to K Band’, in *2019 IEEE MTT-S International Microwave Symposium (IMS)*, Jun. 2019, pp. 1371–1374. doi: 10.1109/MWSYM.2019.8700773.
- [180] V. Palazzi *et al.*, ‘3-D-Printing-Based Selective-Ink-Deposition Technique Enabling Complex Antenna and RF Structures for 5G Applications up to 6 GHz’, *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 9, no. 7, pp. 1434–1447, Jul. 2019, doi: 10.1109/TCPMT.2019.2919187.
- [181] J. A. Byford, C. Oakley, and P. Chahal, ‘Additively Manufactured Frequency Selective Structures on Curved Surfaces’, in *2018 48th European Microwave Conference (EuMC)*, Sep. 2018, pp. 671–674. doi: 10.23919/EuMC.2018.8541568.
- [182] H. Bikas, P. Stavropoulos, and G. Chryssolouris, ‘Additive manufacturing methods and modelling approaches: a critical review’, *Int J Adv Manuf Technol*, vol. 83, no. 1, pp. 389–405, Mar. 2016, doi: 10.1007/s00170-015-7576-2.
- [183] D. Béchevet, ‘Contribution au développement de tag RFID UHF et Microondes sur matériaux plastiques’, phdthesis, Institut National Polytechnique de Grenoble - INPG, 2005. Accessed: Dec. 29, 2022. [Online]. Available: <https://theses.hal.science/tel-00119837>

- [184] C. Orlob, D. Kornek, S. Preihs, and I. Rolfes, ‘Characterization of Electromagnetic Properties of Molded Interconnect Device Materials’, in *2009 German Microwave Conference*, Mar. 2009, pp. 1–4. doi: 10.1109/GEMIC.2009.4815856.
- [185] F. M. Mbango, ‘Contribution A La Caractérisation des Matériaux Utilisés en Microélectronique RadioFréquence’, phdthesis, Université Joseph-Fourier - Grenoble I, 2008. Accessed: Dec. 29, 2022. [Online]. Available: <https://theses.hal.science/tel-00353177>
- [186] *Principles of Terahertz Time-Domain Spectroscopy*. Jenny Stanford Publishing, 2018. doi: 10.1201/b22478.
- [187] N. Duangrit, B. Hong, A. D. Burnett, P. Akkaraekthalin, I. D. Robertson, and N. Somjit, ‘Terahertz Dielectric Property Characterization of Photopolymers for Additive Manufacturing’, *IEEE Access*, vol. 7, pp. 12339–12347, 2019, doi: 10.1109/ACCESS.2019.2893196.
- [188] ‘Microwaves101 | Propagation Constant’. Accessed: Dec. 29, 2022. [Online]. Available: <https://www.microwaves101.com/encyclopedias/propagation-constant>
- [189] L. Cai, Z. H. Jiang, and W. Hong, ‘Broadband Measurement of Substrate Complex Permittivity Using Optimized ABCD Matrix’, *IEEE Access*, vol. 8, pp. 224513–224521, 2020, doi: 10.1109/ACCESS.2020.3044699.
- [190] C. Hu and Q.-H. Qin, ‘Advances in fused deposition modeling of discontinuous fiber/polymer composites’, *Current Opinion in Solid State and Materials Science*, vol. 24, no. 5, p. 100867, Oct. 2020, doi: 10.1016/j.cossms.2020.100867.
- [191] M. Boopalan, M. Niranjanaa, and M. J. Umapathy, ‘Study on the mechanical properties and thermal properties of jute and banana fiber reinforced epoxy hybrid composites’, *Composites Part B: Engineering*, vol. 51, pp. 54–57, Aug. 2013, doi: 10.1016/j.compositesb.2013.02.033.
- [192] C. Hu, X. Liao, Q.-H. Qin, and G. Wang, ‘The fabrication and characterization of high density polyethylene composites reinforced by carbon nanotube coated carbon fibers’, *Composites Part A: Applied Science and Manufacturing*, vol. 121, pp. 149–156, Jun. 2019, doi: 10.1016/j.compositesa.2019.03.027.

- [193] P. Parandoush and D. Lin, 'A review on additive manufacturing of polymer-fiber composites', *Composite Structures*, vol. 182, pp. 36–53, Dec. 2017, doi: 10.1016/j.compstruct.2017.08.088.
- [194] R. L. Truby and J. A. Lewis, 'Printing soft matter in three dimensions', *Nature*, vol. 540, no. 7633, Art. no. 7633, Dec. 2016, doi: 10.1038/nature21003.
- [195] M. Cabrera, J. Y. Jezequel, and J. C. Andre, 'Three-dimensional machining by laser photopolymerization', *Lasers in Polymer Science Technology*, pp. 73–95, 1989.
- [196] F. Lupone, E. Padovano, F. Casamento, and C. Badini, 'Process phenomena and material properties in selective laser sintering of polymers: a review', *Materials*, vol. 15, no. 1, p. 183, 2021.
- [197] V. Dhinakaran, K. M. Kumar, P. B. Ram, M. Ravichandran, and M. Vinayagamoorthy, 'A review on recent advancements in fused deposition modeling', *Materials today: proceedings*, vol. 27, pp. 752–756, 2020.
- [198] P. Chennakesava and Y. S. Narayan, 'Fused Deposition Modeling - Insights', 2014.
- [199] 'Fused Deposition Modeling, FDM'. Accessed: Jul. 14, 2023. [Online]. Available: <https://www.manufacturingguide.com/en/fused-deposition-modeling-fdm>
- [200] T. Picha, S. Papezova, and S. Picha, 'Evaluation of Relative Permittivity and Loss Factor of 3D Printing Materials for Use in RF Electronic Applications', *Processes*, vol. 10, no. 9, Art. no. 9, Sep. 2022, doi: 10.3390/pr10091881.
- [201] C. Dichtl, P. Sippel, and S. Krohns, 'Dielectric Properties of 3D Printed Polylactic Acid', *Advances in Materials Science and Engineering*, vol. 2017, no. 1, p. 6913835, 2017, doi: 10.1155/2017/6913835.
- [202] E. McGibney, J. Barton, L. Floyd, P. Tassie, and J. Barrett, 'The High Frequency Electrical Properties of Interconnects on a Flexible Polyimide Substrate Including the Effects of Humidity', *IEEE Transactions on Components, Packaging and*

- Manufacturing Technology*, vol. 1, no. 1, pp. 4–15, Jan. 2011, doi: 10.1109/TCPMT.2010.2100731.
- [203] G. Boussatour, P.-Y. Cresson, B. Genestie, N. Joly, and T. Lasri, ‘Characterization of biodegradable and biosourced polylactic acid (PLA) substrate in a wide frequency range (0,5– 26 GHz)’, in *2017 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP)*, Sep. 2017, pp. 1–3. doi: 10.1109/IMWS-AMP.2017.8247428.
- [204] K. Alhassoon, Y. Malallah, J. J. Alcantar-Peña, N. Kumar, and A. S. Daryoush, ‘Broadband RF Characterization and Extraction of Material Properties in 3-D Printed Composite Substrates for Magnetically Tuned Circuits’, *IEEE Transactions on Microwave Theory and Techniques*, vol. 69, no. 3, pp. 1703–1710, Mar. 2021, doi: 10.1109/TMTT.2020.2971979.
- [205] K. Alhassoon, Y. Malallah, A. Sarnaik, C. Kolwalkar, D. N. Kumar, and A. S. Daryoush, ‘Broadband and Accurate Material Characterization of 3D Manufactured RF Structures’, in *2018 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP)*, Jul. 2018, pp. 1–3. doi: 10.1109/IMWSAMP.2018.8457147.
- [206] ‘Determination of microwave dielectric constant by two microstrip line method combined with EM simulation - Chang - 2006 - Microwave and Optical Technology Letters - Wiley Online Library’. Accessed: Sep. 17, 2023. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/mop.21936?casa_token=sROV3Vx7nmsAAAAA:PG4O1EzHvw3tPlzc8Yr9dfo9yQJSwC5E05roHWBi cl9qMvVgi2dMIRBMhNMQEknxHzP70lbCul7Gw8
- [207] N. K. Das, S. M. Voda, and D. M. Pozar, ‘Two Methods for the Measurement of Substrate Dielectric Constant’, *IEEE Transactions on Microwave Theory and Techniques*, vol. 35, no. 7, pp. 636–642, Jul. 1987, doi: 10.1109/TMTT.1987.1133722.

- [208] A. Thakur, M. Chauhan, and M. Kumar, 'Effect of Substrate relative dielectric constant on Bandwidth characteristics of Line feed Rectangular Patch Antenna', 2015.
- [209] S. S. Gao, Q. Luo, and F. Zhu, *Circularly Polarized Antennas*. John Wiley & Sons, 2014.
- [210] S. Gao, Q. Luo, and F. Zhu, 'Introduction to Circularly Polarized Antennas', in *Circularly Polarized Antennas*, 2013, pp. 1–28. doi: 10.1002/9781118790526.ch1.
- [211] N. Burum and Z. Sipus, 'Radiation properties of spherical and cylindrical rectangular microstrip patch antennas', *Automatika*, Oct. 2002, Accessed: Mar. 09, 2023. [Online]. Available: <https://www.semanticscholar.org/paper/Radiation-properties-of-spherical-andcylindrical-Burum-Sipus/b0c42bdb44414631678745a64fb4b0576c6ff8c6>
- [212] 'Nonlinear Modeling and Harmonic Recycling of Millimeter-Wave Rectifier Circuit | IEEE Journals & Magazine | IEEE Xplore'. Accessed: Jul. 25, 2023. [Online]. Available: <https://ieeexplore.ieee.org/abstract/document/7029110>
- [213] G. P. Srivastava and Y. P. Varshni, 'Variation of dielectric constant with temperature', *Physica*, vol. 22, no. 6, pp. 584–586, Jan. 1956, doi: 10.1016/S0031-8914(56)90004-0.
- [214] M. Stoopman, S. Keyrouz, H. J. Visser, K. Philips, and W. A. Serdijn, 'Co-design of a CMOS rectifier and small loop antenna for highly sensitive RF energy harvesters', *IEEE Journal of Solid-State Circuits*, vol. 49, no. 3, pp. 622–634, 2014, doi: 10.1109/JSSC.2014.2302793.
- [215] V. Marian, 'Transmission d'énergie sans fil : Application au réveil à distance de récepteurs en veille zéro consommation', vol. Autre. Ecole Centrale de Lyon, 2012, [Online]. Available: https://drive.google.com/file/d/1ETOM5uJa8qoBn_BlEcWXym3q2tgmzzB/view?usp=sharing
- [216] '[PDF] Microstrip Filters for RF / Microwave Applications by Jia-Shen G. Hong | Perlego'.

Accessed: Dec. 29, 2022. [Online]. Available:
<https://www.perlego.com/book/2764187/microstrip-filters-for-rf-microwave-applicationspdf>

- [217] X. V. L. NGUYEN, ‘Investigation of Ambient Radio-Frequency Energy Harvesting using a Rapid Prototyping Plastronic Approach Investigation of Ambient Radio-Frequency Energy Harvesting using a Rapid Prototyping Plastronic Approach’, *PhD Manuscript, Accessed on 27, Sept 2022.*
- [218] G. Boussatour, ‘Caractérisation diélectrique et thermique de films biopolymères pour l’électronique flexible haute fréquence’, These de doctorat, Université de Lille (2018-2021), Accessed: Jul. 17, 2023. [Online]. Available:
<https://www.theses.fr/2019LILUI015>

ANNEX

Mathematical Formulation of the TTL

The complex propagation constant γ as a function of the angular velocity w is given by Equation 1.

$$\gamma(w) = \alpha(w) + j\beta(w) \quad (1)$$

The ABCD matrix is derived from the S-parameters measurement of the transmission lines. Two ports network characterization uses Equation 2 containing ABCD matrix [189].

$$[V_{I_1}] = [A \quad D] [V_{I_2}]$$

$$M = [M_2] \times [M_1]^{-1} = [A \quad D] \quad (2)$$

Where V_1 and V_2 are the voltages and currents at ports 1 and 2, respectively. M_1 and M_2 are the ABCD matrices of line 1 and line 2, respectively. Since the SMA connectors always have some effects on the S-parameters of the lines, the two matrices are written as;

$$M_2 = [M]_{SMA} [M]_{line2}, [M_1]^{-1} = [M]_{-SMA1} \times [M]_{-lin11}$$

Where $[M]_{SMA}$ is the ABCD matrix of the SMA connector, $[M]_{line1}$ and $[M]_{line2}$ are the ABCD matrices of the non-conducting parts of lines 1 and 2, respectively.

If the two lines have lengths l_1 and l_2 and characteristics impedance Z_c , the ABCD parameters is calculated using the system of Equations in Equation 3 [216].

$$\begin{aligned} A &= \cosh \gamma(l_2 - l_1) & B &= Z_c \sinh \gamma(l_2 - l_1) \\ C &= \frac{\sinh \gamma(l_2 - l_1)}{Z_c} & D &= \cosh \gamma(l_2 - l_1) \end{aligned} \quad (3)$$

The propagation constant is obtained by calculating the trace (Tr) of the matrix M [217].

$$Tr(M) = A + D = 2 \cosh \gamma(l_2 - l_1) \quad (4)$$

$$\gamma = \frac{\cosh^{-1}(0.5 Tr(M))}{l_2 - l_1}$$

$$(l_2 - l_1)$$

Recall that $\gamma(w) = \alpha(w) + j\beta(w)$, α is a sum of conduction loss $\alpha_c (Np/m)$, dielectric loss $\alpha_d(Np/m)$, and radiation loss $\alpha_r (Np/m)$ [189] (Equation 5).

$$\alpha(w) = \alpha_c(w) + \alpha_d(w) + \alpha_r(w) \quad (5)$$

The radiation loss of microstrip lines is difficult to determine. Since the lines are not too long, this loss is usually neglected compared to the conductive and dielectric losses [217]. Equation 5 is simplified and given by Equation 6.

$$\alpha(w) = \alpha_c(w) + \alpha_d(w) \quad (6)$$

The conduction loss is given by Equation 7

$$\alpha_c = \frac{R_s}{Z_c W} = \frac{\sqrt{\frac{\mu_0 W}{2\sigma}}}{Z_c W} \quad (7)$$

Where R_s is a linear resistance (Ω/m), σ is the conductivity of the conductor (S/m), μ_0 is the magnetic permeability constant ($4\pi \times 10^{-7}$) (H/m), Z_c is the reference impedance of the line in Ω (in this work, Z_c is set to 50 Ω) and W is the width of the line (m).

The relation between the propagation constant and the complex effective permittivity can be expressed as [218]

$$\gamma = j \frac{w}{c} \sqrt{\epsilon_{eff} \mu_{eff}} \quad (8)$$

γ , ϵ_{eff} and μ_{eff} are function of w . μ_{eff} is the effective permeability of the substrate. For a nonmagnetic material, this parameter is equal to 1, and c is the speed of light.

The complex permittivity of the substrate is given by [217] as

$$\epsilon_{complex}(\omega) = \left(2\epsilon_{eff}(\omega) + \frac{1}{\sqrt{\left(1 + \frac{12h}{W}\right)}} - 1 \right) \times \left(\frac{\sqrt{\left(1 + \frac{12h}{W}\right)}}{1 + \sqrt{\left(1 + \frac{12h}{W}\right)}} \right) \quad (9)$$

Where h is the thickness of the substrate (m) and W is the width of the microstrip line (m). The relative permittivity of the substrate (ϵ_r) is the real part of equation 9.

$$r(\omega) = Re(\text{complex}(\omega)) \quad (10)$$

The relationship between the ABCD parameters and the S-parameters is given by Equation 11 [216].

The S-parameters are obtained from the vector network analyser (VNA).

$$[CD] = \begin{bmatrix} \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}} & \frac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{2} \\ \frac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{2} & \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{2} \end{bmatrix} \begin{matrix} Z_c \\ S_{21} \end{matrix} \quad (11)$$

The loss tangent of the substrate ($\tan\delta$) is the ratio between the imaginary and the real part of $\text{complex}(\omega)$.

$$\tan \delta = \frac{Im(\text{complex}(\omega))}{Re(\text{complex}(\omega))} \quad (12)$$

It is worth noting that the effect of SMA connectors and junctions have not been de-embedded in our calculations because all calculations were based on transmission line length difference thereby cancelling out these parasitics effects[206], [207].

Validation of TTL

Before characterizing the substrates-under-test using the TTL method, it is necessary to validate this method on a standard RF substrate. Rogers RO4003C is used to validate this technique. Rogers RO4003C is a well-known and standard substrate for many RF applications. The manufacturer specifies a relative permittivity (DK) between 3.33 and 3.43 and a loss tangent of 0.0027 (Figure 1).

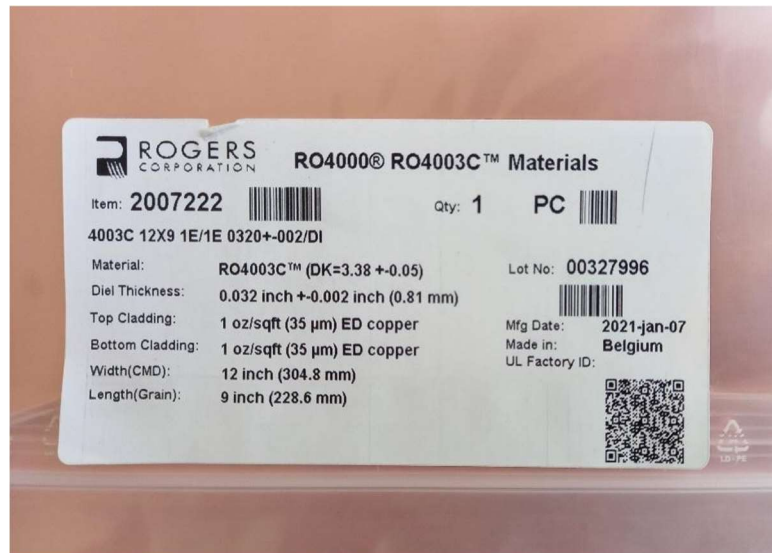


Figure 1: Manufacturer's specifications of Rogers RO4003C (Relative Permittivity between 3.33 and 3.43)

The two lines ($L_1 = 42$ mm and $L_2 = 72$ mm) fabricated on RO4003C substrate are shown in Figure 2. The Short, Open, Load, and Through (SOLT) calibration technique is used to calibrate the R&S ZNL3 Vector Network Analyzer (VNA) to minimize measurement errors and produce good results. The aim is to move the reference point of the VNA to the reference where the lines are connected, thereby eliminating the errors due to measuring cables. The measured S-parameters for both the long and short lines are shown in Figure 3. For both lines, $S_{12} = S_{21} = 0$ dB. This shows that all the power is transferred from ports 1 to 2 without any reflections. Measuring the input impedance is required to guarantee correct matching. The plot for the input impedance is shown in Figure 4.



Figure 2: Image of fabricated Lines on RO4003C

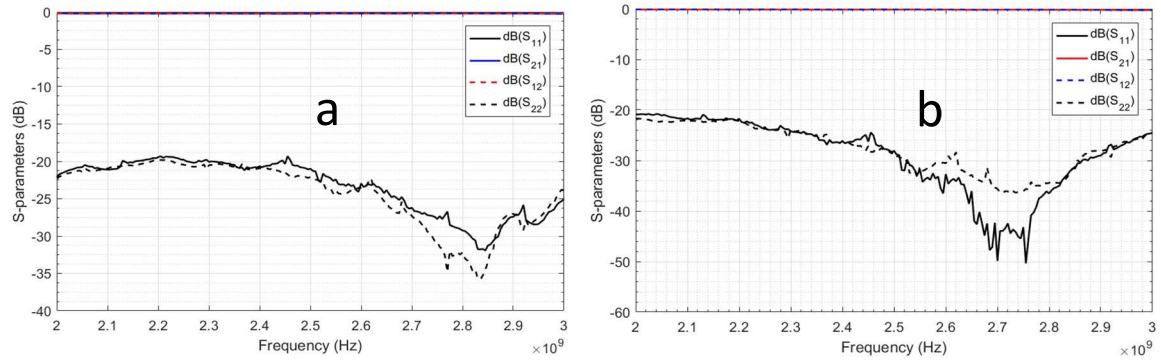


Figure 3: Measured S-parameters of Rogers RO4003C Substrate (a) Long line (b) Short line

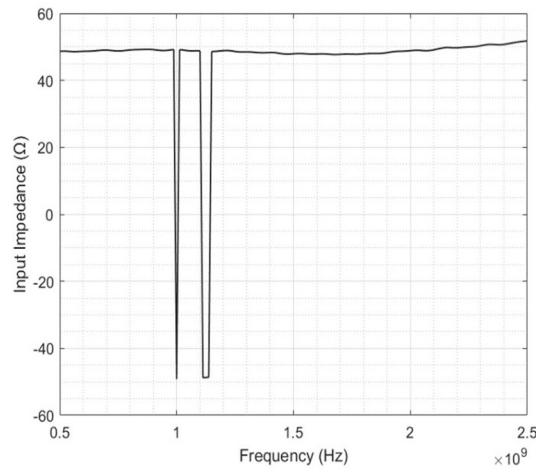


Figure 4: Input Impedance Obtained using TTL method applied to Rogers RO4003C substrate

Figure 4 shows an input impedance of 50 Ω . The matching is good with two abnormal points. The abnormal points might be due to measurement setup. A script (see end of annex) is written to determine the loss tangent and relative permittivity of the substrate. A third polynomial fitting function is used to interpolate the results (see end of annex). The measurement results for the relative permittivity and loss tangent are shown in Figure 5 a and b, respectively. The dielectric constant is between 3.42 and 3.45. This is close to the value given by the Rogers cooperation (Figure 1). The measured loss tangent is between 0.0026 and 0.0048. This is also close to the manufacturer's specification of 0.0027. The slight differences between the measured and the values provided by the manufacturer can again be due to slight imperfections from the measurement setup.

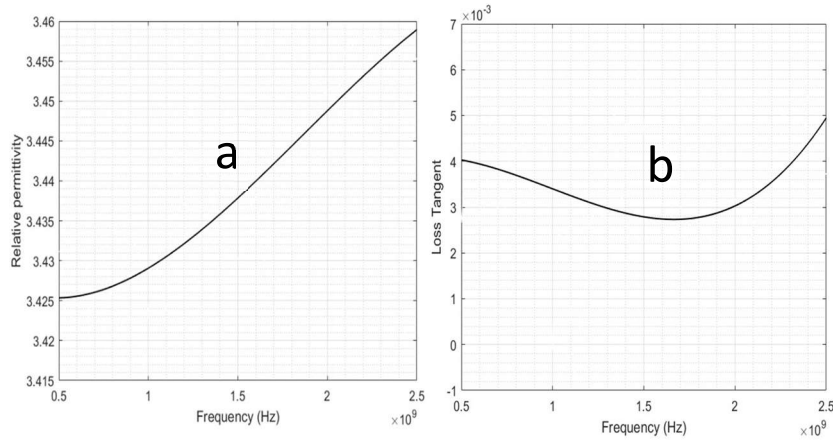


Figure 5: Measure RF properties of rogers RO4003C Substrate (a) relative permittivity (DK) (b)loss tangent

Fabrication using TTL method:

1. Precise measurement of the substrate's thickness using a Vernier calliper.
2. Utilization of the substrate's height for the computation of the effective dielectric constant, essential for determining the substrate's geometry.
3. Evaluation of the width of the conductive line to achieve a 50 Ohm match for optimal RF to DC conversion efficiency.
4. Calculation of the substrate's width, set at least five times the width of the conductive line to facilitate appropriate surface wave propagation (Equation 13).

$$W_{\text{substrate}} = 5 \times (W_{\text{line}}) \quad (13)$$

5. Assessment of the substrate's length within the necessary frequency range for the antenna's operation is calculated using equation 14 and 15.
6. Use of the maximum and minimum wavelengths for estimating the length of the two lines, while ensuring a constant width during fabrication (Equation 16 and 17).

$$\lambda_{\text{max}} = \frac{c}{f_{\text{max}} \sqrt{\epsilon_r}} \quad (14)$$

$$\lambda_{\text{min}} = \frac{c}{f_{\text{min}} \sqrt{\epsilon_r}} \quad (15)$$

$$\lambda_{\text{min}} \quad L2 \geq \text{---} \quad (16)$$

10

$$\lambda_{\text{max}} \quad |L1 - L2| \leq \text{---} \quad (17)$$

2

7. Prior to the measurement of S-parameters, the R&S ZNL3 Vector Network Analyzer (VNA) underwent calibration utilizing a 3.5 mm R&S ZN Z-135 calibration kit, employing the Short, Open, Load and Through (SOLT) calibration technique (Figure 6).



Figure 6. R&S ZN Z-135 calibration kit

8. Employment of a Virtual Network Analyzer (VNA) to acquire the S-parameters of the transmission lines.
9. The ensuing measurement procedure was carried out within an isolated environment void of any conductors.
10. Interchanging ports to minimize measurement errors and obtain values of S_{11} , S_{21} , S_{12} , and S_{22} .
11. Computation of the averages of S-parameter values after interchanging of ports is necessary to ensure minimal errors in mathematical analysis of the two-line parameters
12. Subsequent calculation of the substrate's dielectric constant and loss tangent.

RF Property Assessment of TTL method:

After obtaining the S-parameters file using a Vector Network Analyzer (VNA), it is processed through mathematical analysis using specialized software. The resultant data is acquired over a range of frequency for comprehensive analysis. However, the obtained outcomes might deviate from accuracy due to losses in an uncontrolled environmental setting or geometry inaccuracies of the substrate. To address these concerns, the raw data is subjected to curve fitting for refinement.

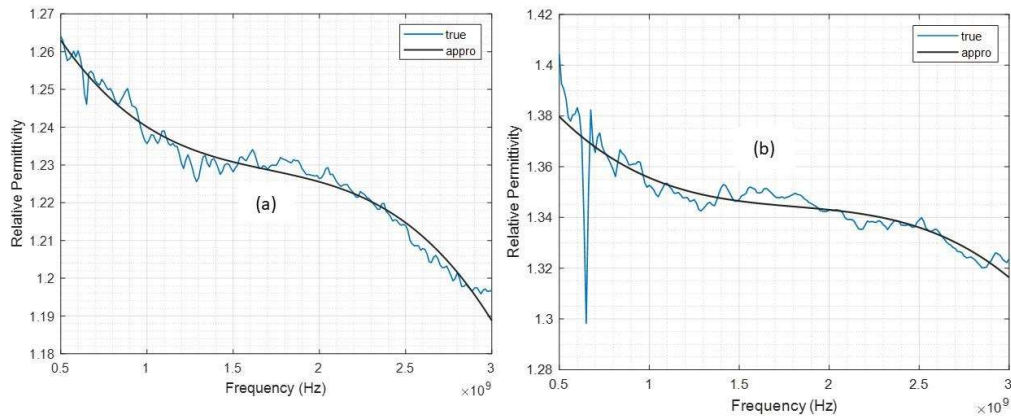


Figure 7. Approximation using curve fitting on Relative permittivity of cardboard sample (a) cardboard sample#2 (b) cardboard sample sample#4

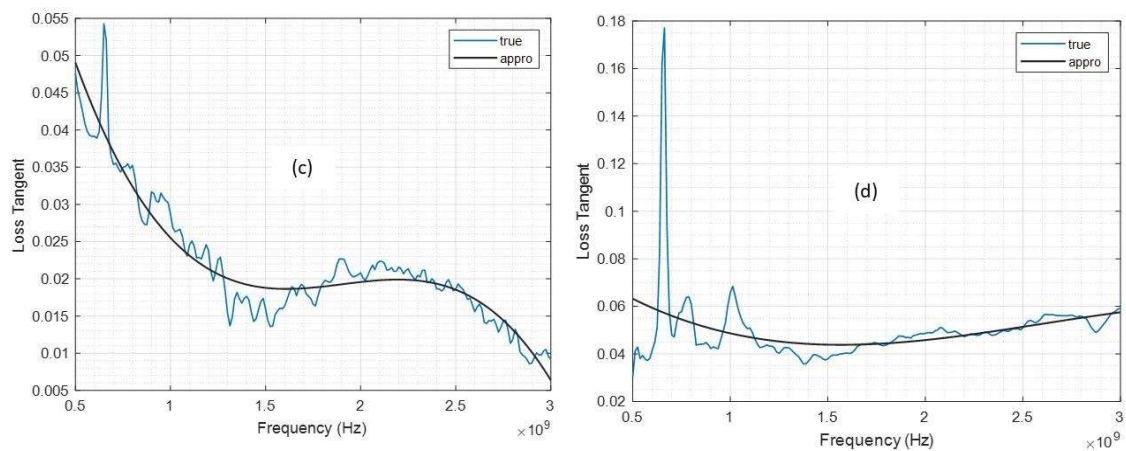


Figure 8. Approximation using curve fitting on loss tangent of cardboard sample (a) cardboard sample#2 (b) cardboard sample sample#4

Figure 7 and Figure 8 depict the application of a 3-degree curve fitting technique to mitigate nonuniformity arising from the measurement setup, thereby yielding results that contribute significantly to the understanding of the RF properties of the cardboard substrate. True results show the brute result, and the approximation is a third-degree polynomial curve fitting.

Script used for determining the RF properties of TTL:

```
len1 = 0.065;
len2 = 0.110; h
= 1.6; %
epaisseur du
substrat; w =
6.5; % largeur
de la ligne;
cond = 60*10^6;
```

```

L1_mat = xlsread('short1.6.xlsx');
L2_mat = xlsread('long1.6.xlsx'); freq
= L1_mat(:,1); % displaying freq
from min to max om = 2*pi*freq; Z0
= 50; for j = 1:201

    S11_L1(j) = (complex(L1_mat(j,2), L1_mat(j,3)) + complex(L1_mat(j,8), L1_mat(j,9)))/2;
    S21_L1(j) = (complex(L1_mat(j,4), L1_mat(j,5)));
    S12_L1(j) = (complex(L1_mat(j,6), L1_mat(j,7)));
    S22_L1(j) = (complex(L1_mat(j,8), L1_mat(j,9)) + complex(L1_mat(j,2),
L1_mat(j,3)))/2;
    S11_L2(j) = (complex(L2_mat(j,2), L2_mat(j,3)) +
complex(L2_mat(j,8), L2_mat(j,9)))/2;
    S21_L2(j) = (complex(L2_mat(j,4), L2_mat(j,5)));
    S12_L2(j) = (complex(L2_mat(j,6), L2_mat(j,7)));
    S22_L2(j) = (complex(L2_mat(j,8), L2_mat(j,9)) + complex(L2_mat(j,2),
L2_mat(j,3)))/2; end

for j = 1:201

    [A1(j) B1(j) C1(j) D1(j)] = S_to_ABCD(S11_L1(j), S12_L1(j), S21_L1(j), S22_L1(j), Z0); % ABCD de la
1ère ligne + con

    [A2(j) B2(j) C2(j) D2(j)] = S_to_ABCD(S11_L2(j), S12_L2(j), S21_L2(j), S22_L2(j), Z0); % ABCD de la
2ème ligne
+ con

    [M11(j), M12(j), M21(j), M22(j)] = twoS_to_M(A1(j), B1(j), C1(j), D1(j), A2(j), B2(j), C2(j),
D2(j)); % mutuelle, forming matrix M(L2-L1)
    gamma(j) = (1/(len2-
len1))*acosh((M11(j)+M22(j))/2); % propagation cnt from trace of matrix M(L2-L1)

    detK(j)=(A1(j)+cosh(gamma(j)*(len1)))*sinh(gamma(j)*(len2))-(A2(j)+
cosh(gamma(j)*(len2)))*sinh(gamma(j)*(len1));

    Zc(j) = (B2(j)*(cosh(gamma(j)*(len1)) + A1(j)) - B1(j)*(cosh(gamma(j)*(len2)) +
A2(j)))/detK(j); beta(j) = imag(gamma(j));

    % 2ème approche

    Rs(j) = sqrt(om(j)*4*pi*10^-7/(2*cond)); alpha_c_2(j) =
Rs(j)/(Z0*w); alpha_d_2(j) = real(gamma(j)) - alpha_c_2(j);
gamma_eff_2(j) = complex(alpha_d_2(j), beta(j)); e_eff_2(j) = -
((gamma_eff_2(j)*2.98*10^8)/(om(j)))^2; % gamma_eff e_r_2(j) =
(2*e_eff_2(j) + 1/sqrt(1+10*h/w) -
1)*sqrt(1+10*h/w)/(1+sqrt(1+10*h/w)); ta_2(j) = -

```

```

imag(e_r_2(j))/real(e_r_2(j));      e_r_export(j) = real(e_r_2(j))';
ta_export(j) = ta_2(j)';
End
e_r_exp
rt    =
e_r_exp
ort';
ta_expo
rt    =
ta_expo
rt';
%
f
o
r
j
=
1
:
2
0
1
%
e
n
d

n = 3; x = 1; e_r_coef = polyfit(freq(x:201),
e_r_export(x:201), n); e_r_poly =
polyval(e_r_coef, freq(x:201));
plot(freq(x:201), e_r_export(x:201),
freq(x:201), e_r_poly); legend('true',
'appro'); grid on; figure; ta_coef =
polyfit(freq(x:201), ta_export(x:201), n);
ta_poly = polyval(ta_coef, freq(x:201));

```

```

plot(freq(x:201),    ta_export(x:201),
freq(x:201),  ta_poly); legend('true',
'appro');    grid    on;    figure;
plot(freq(x:201),  Zc(x:201)); grid on;
function [A, B, C, D] = S_to_ABCD(S11,
S12, S21, S22, Z0)
A = ((1+S11)*(1-S22) + (S12*S21))/(2*S21);
B = Z0*((1+S11)*(1+S22) - S12*S21)/(2*S21);
C = ((1-S11)*(1-S22) - S12*S21)/(2*S21*Z0); D = ((1+S22)*(1-S11) + S12*S21)/(2*S21); end
function [t11, t12, t21, t22] = S_to_WCM(S11, S12, S21, S22) t11 = (S12*S21 - S11*S22)/S21; t12
= S11/S21; t21 = -S22/S21; t22 = 1/S21; end

```