PLANAR RECTENNAS FOR WIRELESS POWER HARVESTING

Joseph J Trad

Bachelor of Engineering
Telecommunications Engineering

MACQUARIE
University
SYDNEY·AUSTRALIA

Department of Electronic Engineering
Macquarie University

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Supervisor: Prof. Karu Esselle
Co-Supervisor: Dr Basit Zeb

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STATEMENT OF CANDIDATE

I, Joseph J Trad, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Electronic Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment to any academic institution.

Student's Name: Joseph J Trad

Student's Signature: Joseph Trad

Date: 14/11/2016

ABSTRACT

Capturing and harvesting RF energy, using small antennas with an effective conversion of RF energy to DC energy with minimal losses, presents a significant research problem. The project addresses the opportunity to harvest RF energy from dedicated or ambient sources utilising a rectenna. The overall objective of this project is to successfully design, create and implement an effective rectenna system for low-cost low-power operation at the 2.45Ghz ISM band. The aim is to manufacture a prototype of an optimal rectenna design that is effective. The prototype is used to demonstrate the operating principal of the rectenna, its effectiveness and real world performance. This thesis presents two rectenna systems designed to harvest RF energy. Rectenna System 1 comprises of Subsystem 1, a single microstrip patch antenna whilst, Rectenna System 2 comprises of Subsystem 3, a microstrip patch antenna array. Both rectenna systems utilise Subsystem 2, the 2 stage Cockcroft Walton rectifier and multiplier circuit. The rectenna systems and their related subsystems achieved exceptional effectiveness and real world performance with the ability to harvest a significant amount of RF power at 2.45GHz. As a result, the operating principal of the rectenna systems, their effectiveness and real world performance are demonstrated, harvesting enough energy, to operate a selection of typical electronic devices such as a: 2.1v green LED, digital clock timer and digital humidity sensor; up to the range of 3.5 meters.

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Chapter 1

Introduction

Capturing and harvesting Radio-Frequency (RF) energy, using small antennas with an effective conversion of RF energy to Direct Current (DC) energy with minimal losses presents a significant research problem. In todays consumer driven, fast paced, continually changing and technically advanced environment there is a significant dependency on battery based wireless devices. Also, within this environment there are numerous other wireless devices such as Wi-Fi transmitters and RFID scanners, radiating significant amounts of excess RF energy which is wasted and unused.

This project looks to address and investigate the opportunity to harvest and capture RF energy from dedicated or ambient sources utilising a receiving rectifying antenna otherwise known as a 'rectenna'.

A rectenna system to harvest and capture RF energy from dedicated or ambient energy sources can be utilised for a wide variety of applications which also benefits the whole of society, both industry and consumers. Applications include; the wireless charging of battery based devices via trickle charging, wireless operation and powering of low power devices such as nodes in wireless sensor networks and the powering of battery less RFID Tags. The use of a rectenna system also provides for significant design advantages including: greater convenience of product use with the ability to charge devices without having to continuously replace battery units, leading to increased product reliability; also it eradicates the use of cables, connectors and in some cases the actual battery itself.

The overall objective of this project is to successfully design, create and implement an effective rectenna system for low-cost low-power operation at the Industrial-Scientific-Medical (ISM) frequency of 2.45 GHz.

The short-term goal and aim of the thesis project is to fabricate and manufacture using printed circuit board technology a prototype of an optimal rectenna design. This rectenna design is to be highly effective in converting RF energy at a frequency of 2.45 GHz into usable DC energy. Once manufactured this prototype would be used to demonstrate the operating principal of the rectenna, its effectiveness and real world performance.

The long-term goal and aim of the thesis project is to apply the advancements made in the design, creation and implementation of the prototype rectenna system at the frequency of 2.45 GHz, to other specific applications where higher power levels are required or where different frequency bands are in use.

1.1 Thesis Project Outline and Overview

This project has been supervised by both Professor Karu Esselle and Dr Basit Zeb from the Department of Engineering, Macquarie University. A weekly consultation meeting has been used: to discuss the progress of the project, to raise any significant issues and to discuss the purchase of suitable resources and materials for the project before gaining approval. The consultation meetings attendance form is displayed in Appendix A.1 of this progress report document.

The structure and organisation of this progress report document is as follow:

- Chapter 2 provides an in-depth, relevant and comprehensive literature review and background theory section specifically tailored for this project.
- Chapter 3 provides a detailed discussion which encompasses the design requirements, design considerations, procedures and methodology for the optimal design of the rectenna systems and key subsystems.
- Chapter 4 displays the results obtained from the simulations performed on the optimal design of the rectenna systems and the key subsystems. It also provides a detailed analysis and discussion of the results obtained.
- Chapter 5 discusses the manufacturing and fabrication processes used to create the prototypes of the key subsystems and hence the prototypes of the rectenna systems.
- Chapter 6 details the experimental procedures and setup undertaken for the physical testing of the prototypes of the key subsystems and the rectenna systems. This chapter also displays, analyses and discusses the results obtained from the physical testing of these key subsystems and systems.
- Chapter 7 concludes the thesis project and discusses what has been achieved. It also provides a discussion on the future work that can be undertaken using the advancements made from this research project.

Chapter 2

Background and Related Work

The main issue that faces this project, which is identified by the research question and introduction is based on; the need to successfully create and implement an optimal design for a rectenna that is highly effective in converting RF energy at the frequency of 2.45 GHz, into usable DC energy.

The optimal design of the rectenna can be split into two main categories or subsystems; the antenna design of the rectenna and the rectifying circuit design of the rectenna. By further researching, investigating and improving the efficiency and effectiveness of each of these subsystems or categories, it is possible to achieve the overall goal of an effective rectenna system. Hence, this chapter of the report provides an in-depth, relevant and comprehensive literature review and background theory section; where all research is split into the two above-mentioned subsystems or categories.

2.1 Antenna Theory and Design

2.1.1 Microstrip Patch Antennas

A microstrip patch antenna structure comprises of a thin layer of low-loss insulating material known as the dielectric substrate. On one side of the substrate it is entirely covered in a highly conductive metal, usually copper; this side is known as the ground plane. On the other side of the substrate it is partially covered by a radiating antenna patch made from the same highly conductive metal as the ground plane; this radiating antenna patch can take the form of any desired geometry or pattern [1–3]. Some typical microstrip patch antenna structures with popular geometries can be seen in Figures 2.1 and 2.2 [1].

The main advantages of microstrip patch antennas when compared to conventional antennas, include but are not limited to the following:

- They are lightweight, compact and are small in volume and profile;
- They have a low fabrication cost and can be easily mass manufactured and produced;

- They can be effortlessly integrated and combined with microwave integrated circuits(MIC);
- They allow linear and circular polarisation;
- Feedlines and matching circuits can be easily manufactured in conjunction with the antenna patch;
- They can easily allow for dual frequency operation [3], [4].

The main disadvantages of microstrip patch antennas when compared to conventional antennas, include but are not limited to the following:

- They have a narrow bandwidth;
- They have a lower gain and reduced efficiency;
- Low power handling capabilities;
- Extraneous radiation from feeds and junctions;
- Excitation of surface waves [3], [4].

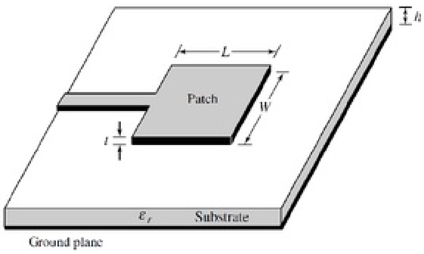


Figure 2.1: Rectangular Microstrip Patch Antenna Geometry

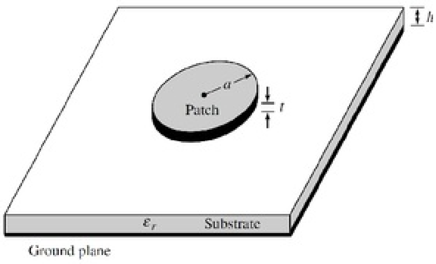


Figure 2.2: Circular Microstrip Patch Antenna Geometry

2.1.1.1 Dimensions and Geometrical Parameters of Microstrip Patch Antennas

The square, rectangular and circular geometry patches as shown beforehand in Figures 2.1 and 2.2, are the most commonly used antenna geometries for microstrip antennas. Although they seem basic they can be used for not only simple applications, but also demanding applications as well [3]. In this thesis and literature review, the rectangular antenna geometry will be focussed on greatly.

One of the most important design considerations to be considered when designing a square or rectangular microstrip patch antenna are the dimension parameters. The main dimension parameters which can be seen in Figure 2.1 of the diagram include; Length(L), Width(W) and Height(h). The Thickness (t) of the radiating antenna patch and the ground plane is not really critical in the design of a microstrip antenna; however, it should have a sufficient thickness, usually three times the skin depth or not smaller than 0.025 of the wavelength or the antenna efficiency will be degraded [2], [5].

The approximate length (L) of a resonant half-wavelength patch is given by equation (2.1), where λ is the free space wavelength and ϵ_r is the dielectric constant of the substrate. The length of the antenna patch is a highly important parameter as it controls the resonant frequency [3]. It must be noted that the length of a half-wave patch is to some extent smaller than half a wavelength in the dielectric substrate. Also this length is an approximate and hence empirical fine-tuning is needed in real life to get the correct resonant frequency [6].

(2.1)

$$L \approx 0.49 \times \frac{\lambda}{\sqrt{\epsilon_r}}$$

The width(W) for a square patch geometry is equal to the length as given in equation 2.1. However, for a rectangular patch geometry where the width varies from the length, a larger antenna patch width increases the power radiated and hence this results in decreased resonant resistance, increased bandwidth and increased radiation efficiency [3]. An approximate width of an antenna patch is given by equation 2.2; where c is the speed of light and f_0 is the frequency. Since this is an approximate, empirical fine-tuning is needed in real life to get the optimal width [4]. It also must be noted that the width of the patch also has a slight effect on the resonant frequency and the radiation pattern [3].

(2.2)

$$W \approx \frac{c}{2f_0\sqrt{\frac{\epsilon_r+1}{2}}}$$

The thickness or height (H) of the dielectric substrate material is another important parameter when designing a microstrip patch antenna. A thick substrate; provides an increase in radiated power, a reduction in conductor loss and an improvement in bandwidth. However, some negatives to an increase in the substrate include; an increase in weight, dielectric loss, surface wave loss, and extraneous radiations from the probe feed [3]. Also it must be pointed out that the choice of thickness is limited by what the manufacturer produces and it is best to consult data sheets to see what thicknesses are available.

2.1.1.2 Substrate Properties and Parameters

The dielectric substrate is a key component of a microstrip antenna, it plays an important role both electrically and mechanically. Electrically it is crucial for transmission lines, circuits and the antenna patch. The key electrical properties include the relative permittivity ϵ_r, and the dielectric loss factor $\tan \delta$ [2]. The thickness of the substrate is also a key property and has been discussed thoroughly in the previous section.

Generally, for microstrip antennas a substrate that has a low valued permittivity constant ϵ_r, increases and enhances fringing fields at the patch perimeter and hence increases the radiated power [3]. Also the value of permittivity determines the size of the microstrip patch antenna, with a higher permittivity resulting in a reduction in size [2]. However, it must be noted that for microwave circuits (such as a rectifying circuit section from a rectenna) attenuation occurs in the microstrip transmission lines. This attenuation is caused by; dielectric loss, conductor loss and radiation loss. Hence to reduce the attenuation, a substrate material that has a high permittivity constant should be selected as it reduces the radiation, the dielectric loss and also results in a reduction in size of the microwave circuit, which thus extends the performance of the substrate at higher frequencies [7].

The dielectric loss factor is another important parameter in relation to substrates. To achieve a highly efficient antenna, high circuit performance and overall efficiency; a substrate with a low dielectric loss factor should be used. Typically it should be smaller than $\tan \delta = 0.002$ [2].

The key mechanical properties of a substrate which may or may not be crucial depending on the application, include the: mechanical resistance, shape stability, expansion factor and temperature threshold [2].The main categories of dielectric substrate materials include: ceramic, semi-conductor, ferromagnetic, synthetic and composite [2].

2.1.1.3 Feeding Techniques for Microstrip Patch Antennas

The two main and most common feeding techniques by which microstrip patch antennas can be excited are; the coaxial probe feed technique and the microstrip transmission line feed technique.

For the coaxial probe feed technique, the coaxial line is set perpendicular to the ground plane, and the centre conductor is connected to the patch which then extends across the dielectric substrate [2]. A diagram of the coaxial probe feed can be seen in Figure 2.3 [4]. The main advantages of the coaxial probe feeding technique is that it can be easily located at any position on the patch so that it can be matched with the input impedance. The main disadvantage is that the substrate has to have a hole drilled through it, something that should be avoided, and hence since the connector will protrude outside the bottom of the ground plane, the structure would be no longer planar [4].

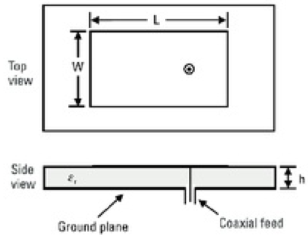


Figure 2.3: Microstrip Antenna Coaxial Probe Feed

The microstrip transmission line feeding technique is the simplest way to feed a microstrip patch antenna, for this technique the transmission line is directly connected to the edge of the antenna patch [2]. A diagram of the microstrip transmission line feed can be seen previously in Figure 2.1 [1].The main advantage of this is that the transmission line is etched on the same substrate as the patch and hence it remains planar. The disadvantage is the radiation from the transmission line can lead to an increase in the cross-polar level [4].

However, it must be noted that there are disadvantages for both these techniques when a thicker substrate is used. For the coaxial probe feed, an increased probe length due to substrate thickness causes the input impedance to be more inductive, which thus leads to matching problems. Whilst on the other hand for the microstrip transmission line feed an increase in substrate thickness would intern increase the width of the transmission line and thus leads to undesired feed radiation [4].

2.1.1.4 Bandwidth Issue and Improvement

As mentioned beforehand one of the issues and limiting factors of microstrip patch antennas is that they have a narrow bandwidth. To resolve this issue and improve the bandwidth of microstrip patch antennas there are a number of techniques that are practiced by antenna designers and engineers; these techniques and other factors that have an effect on bandwidth will be discussed below.

One of the most common techniques to enhance the bandwidth of square and rectangular antennas is to increase the width. As mentioned before, a larger antenna patch width increases the power radiated and hence this results in: decreased resonant resistance, increased bandwidth and increased radiation efficiency [3].

Another common technique to enhance bandwidth is to increase the thickness of the substrate as the bandwidth of the microstrip patch antenna is directly proportional to the substrate thickness [3], [4]. However, increasing the thickness of the substrate is counter-productive due to the occurrence of surface waves; but if a lower substrate permittivity is used in conjunction with the the thicker substrate it is possible to prevent surface waves and hence enhance the bandwidth [2].

Some other methods and techniques for improving the bandwidth of microstrip patch antennas include: increasing the inductance of the microstrip patch by cutting holes or slots; and by adding reactive components to reduce the Voltage Standing Wave Ratio (VSWR). It has also been suggested that using a high dielectric substrate to decrease the physical dimensions of the plate line would also enhance the bandwidth [8].

A factor which has an effect on bandwidth but not widely reported, is the dielectric loss factor tan δ. An increase in dielectric loss factor tan δ decreases the impedance variation and increases the loss in the patch, thus leading to an increase in bandwidth and a decrease in efficiency. The main reason for this increase of bandwidth is because of an increase in the dielectric losses in the substrate. Hence a higher dielectric loss factor tan δ substrate gives an enhancement in bandwidth but with a negative impact on efficiency and gain [4].

2.1.2 Microstrip Patch Antenna Arrays

For single element microstrip patch antennas, the radiation patterns of the elements are usually wide and the single element also produces low gain and directivity, which is a disadvantage in certain situations [1]. In certain applications such as wireless power harvesting using rectennas, an antenna with a high gain is typically preferred as according to the Friis transmission equation (see next section) a receive and/or transmit antenna with a high gain would thus lead to a higher received power that can be obtained. Hence, the higher the received power is, the more successful the rectenna is in harvesting a realistic usable amount of power that can be converted into usable DC power for many different applications. Typically to increase the gain of an antenna, the electrical size and dimensions must be increased. One way to do this is to place and group multiple antenna elements together in a certain geometrical and electrical configuration known as an array [1].

In addition to the main advantage of a microstrip patch antenna array which is, a higher gain and directivity, arrays also easily allow other functions to be performed which would be difficult when using individual elements. Also they can be easily printed and fabricated with their feed networks on a single layer of substrate using PCB fabrication techniques [1] [6]. Some of the key important design considerations and parameters to be considered when designing a microstrip patch antenna array include the: Feeding technique for the array, element spacing, substrate thickness and dielectric constant of the substrate [9].

2.1.2.1 Feeding Techniques

The two most common feeding techniques of a microstrip patch antenna array include the series feed configuration and the corporate feed configuration. The series feed configuration consists of multiple antenna patch elements which are organized linearly and are serially fed by a single microstrip transmission line. The series feed configuration can be categorized into two main categories known as the in-line feed and the out-of-line feed. In the case of the in-line feed, the microstrip transmission line is serially connected to the centre of each patch element, effectively meaning the transmission line is connected to two ports of some patch elements. Whereas in the case of the out-of-line feed, the transmission line is external to the patch elements and is connected to one port of each patch element [9]. Figure 2.4 shows the two main variations of the series feed configuration [9].

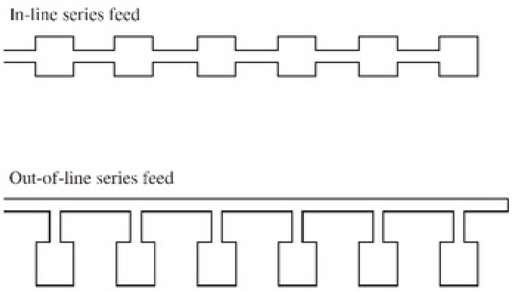


Figure 2.4: Series Feed Configuration for Microstrip Patch Antenna Arrays

The main disadvantage of the series feed configuration, is that it suffers from beam squint as the frequency shifts and deviates from a nominated centre frequency, hence this beam squint causes a degradation in the gain of the antenna. The main advantage is that it does not suffer from high levels insertion loss as in the case of the corporate feed configuration [9].

The corporate feed configuration is structured in a way, such that the microstrip transmission lines connects and feeds the antenna patch elements in parallel. Specifically, the microstrip transmission lines divide into two distinct branches and each branch then divides further until it reaches the antenna patch elements [9]. The parallel division microstrip transmission lines in the corporate feed configuration must be of equal length for the array to successfully be broadside radiating [9]. Figure 2.5 shows a typical variation of the corporate feed configuration.

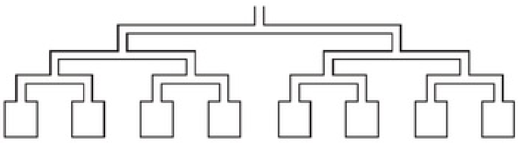


Figure 2.5: Corporate Feed Configuration for Microstrip Patch Antenna Arrays

The main disadvantage of the corporate feed configuration is that it suffers from high levels of insertion loss. However, the main advantages that the corporate feed has over the series feed are that it has greater wideband performance and does not suffer from beam squint [9].

2.1.2.2 Element Spacing

One of the most important design considerations to be considered when designing a microstrip patch antenna array is the element spacing. The spacing of each microstrip patch element is widely recommended to be less than one wavelength to avoid grating lobes and greater than or equal to a half wavelength to allow adequate space for the feedlines, to achieve a higher gain and to reduce any mutual coupling [6]. For a broadside beam design, element spacing is recommended to generally be less than one wavelength and for a wide angle beam design, element spacing is recommended to generally be less than 0.6 wavelength.

2.1.2.3 Thickness and the Dielectric Constant of the Substrate

Similarly, to a single element microstrip patch antenna the Substrate Thickness and the Dielectric Constant of the Substrate are key consideration to be considered when designing a microstrip patch antenna array. The substrate thickness affects bandwidth and the arrays power handling capabilities, where a thicker substrate can handle more power [9]. The dielectric constant of the substrate also has an effect on the bandwidth of an array; a higher dielectric constant would typically narrow the bandwidth of an array.

2.1.3 Antenna Theory - Friis Transmission Equation

The Friis Transmission Equation as shown in equation (2.3), is commonly used to calculate the power received from a transmit antenna (with gain G_T in dBi) with a transmit power of P_T in Watts, to a receive antenna (with gain G_R in dBi), separated by a distance R in meters, and at a wavelength λ which is calculated from the frequency and speed of light [8] [10].

(2.3)

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

2.1.4 Antenna Theory - Gain, Directivity and Radiation Efficiency

The directivity of an antenna is a measure of the directional properties when compared to an isotropic antenna. It is defined as the ratio of maximum power density in the main beam to the average radiated power density[2a]. The Gain G of an antenna is given by equation (2.4):

(2.4)

$$G = e_r D$$

Where D is the directivity and e_r is the radiation efficiency of an antenna. e_r lies in the range between 0 and 1, as gain is less than directivity [3].

Hence radiation efficiency of an antenna as a percentage can be given by equation (2.5):

(2.5)

$$e_r = \frac{G}{D} \times 100$$

2.1.5 Antenna Theory - Field in which Wireless Power Harvesting occurs and Antenna Aperture

There are two different concepts of fields or regions in which wireless power transfer occurs:

- The near field which is considered to be of a non-radiative type that occurs close to the antenna at a distance smaller than one wavelength [11].
- The far field which is considered to be of a radiative type that occurs from a distance equal to two wavelengths from the antenna up to infinity [11].

The antenna that is designed to facilitate wireless power transfer, must operate in the far field region, since the wavelength $\lambda = c/f = (3 \times 10^8)/(2.45 \times 10^9) = 0.1224m$ and because the design of the rectenna will need to operate in a distance of 2-3m.

In electromagnetics and antenna theory, antenna aperture or effective area is a measure of how effective an antenna is at receiving the power of radio waves. The aperture is defined as the area oriented perpendicular to the direction of an incoming radio wave, which would intercept the same amount of power from that wave as is produced by the antenna receiving it [12]. Antenna aperture is a key concept for this project and wireless power transfer in general, as the more effective an antenna is able to receive power, the more power there is to convert into DC energy.

2.1.6 Antenna Structures and Configurations used in Rectennas for Wireless Power Harvesting

A variation of the Fractal Antenna Structure was demonstrated in a rectenna test enviroment in 2010 by *Ugur Olgun et al* [13]. In this research paper, second iteration Koch fractal geometry was applied to a microstrip patch antenna to reduce its overall size [13]. The main advantages of these types of antennas when compared to more conventional antennas centre mainly on the miniature size of the antenna [13]. An image of the antenna is shown in Figure 2.6 [13].

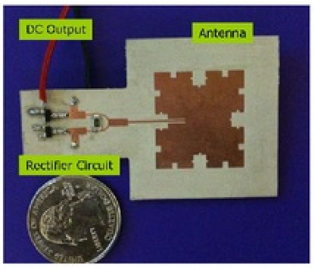


Figure 2.6: Fractal Antenna

In certain applications where size is a key issue, this antenna would be suitable. However, since size is not the key issue in this research project which mainly focuses on an optimal design of a rectenna that is effective, this antenna structure demonstrated with a small area would not be suitable, as it would have a reduced antenna aperture and hence not be effective and efficient in receiving power.

Nonetheless this Fractal antenna structure demonstrated by *Ugur Olgun et al.* still delivers a comparatively high realized gain (4 dBi) and an overall good RF to DC conversion efficiency (up to 70%) by employing a high dielectric substrate and a two-stage Dickson charge pump voltage-doubler [13], [14].

An improvement compared to using the previous fractal antenna design in the overall receiving antenna design, is to use multiple antennas/array configurations or different antenna structures that are larger in size. In most cases, a single antenna within a rectenna design does not harvest sufficient wireless/RF energy (dependent on the antenna size and structure). Instead, multiple antennas can be arranged to capture a greater percentage of RF energy and then channel it to a single rectifier or; each antenna can incorporate its own rectifier to harvest DC power and then the harvested DC power from all rectifiers can then be summed together. This then offers one of the most effective wireless power harvesting schemes [15].

Throughout the course of later studies in 2012 by *Ugur Olgun et al*, a 3×3 planar array of simple Koch-type patch antennas was designed with improved results compared to the studies undertaken in previous years [15]. The 3×3 planar array of simple Koch-type patch antennas designed and fabricated is shown in Figure 2.7 [15]. The 3×3 planar array of simple Koch-type patch antennas captured a greater percentage of RF energy more efficiently, hence allowing the rectenna system as a whole to generate battery like voltage to run a variety of low-power consumer electronics in the 1.5V - 3V range [15].

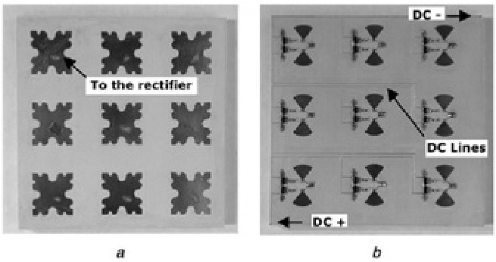


Figure 2.7: 3×3 planar array of Koch-type patch antennas

An alternative antenna structure and design known as a Cross Dipole Antenna for wireless power harvesting was demonstrated in a research paper undertaken in 2015 by *Chaoyun Song et al* [16]. The Cross Dipole Antenna designed and fabricated is shown in Figure 2.8 [16].

Since antennas used for wireless energy harvesting normally have special requirements because of the randomness of the ambient RF signal, a cross dipole antenna is selected due to its dual-polarization and broad beam-width which are suitable for incoming waves with arbitrary polarization and different incident angles [16], [17]

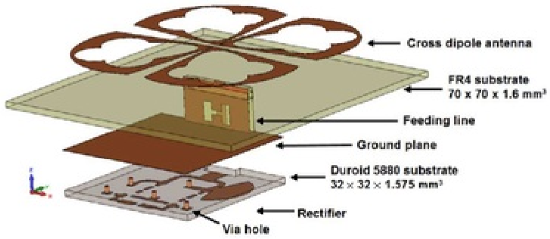


Figure 2.8: Cross dipole Antenna

The co-polarization and cross-polarization radiated fields of the antenna are high which means the antenna is able to receive RF waves with either vertical or horizontal polarisation. The radiation pattern of this antenna is bidirectional with a broad beam-width, thus the antenna can receive incident signals from many different angles. Hence this antenna is very suitable for wireless energy harvesting [16]. This antenna structure also demonstrates a larger area which would be suitable, as it would have a greater antenna aperture and hence be effective and efficient in receiving power.

2.2 Rectifying Circuit and Voltage Multiplier Theory and Designs

2.2.1 Rectifying Circuit and Voltage Multiplier Theory

A rectifying circuit allows for the rectification or conversion of alternating current (AC) to direct current (DC), it makes use of diodes which allow only a one-way flow of electrons. There are two common types of rectifier circuits: the half-wave rectifier and the full-wave rectifier [18], [19]. The half-wave rectifier only utilizes alternate half-cycles of the input sinusoid; it passes one half of each complete sine wave of the AC signal source in order to convert it into DC power. Whereas a full-wave rectifier utilizes both halves of the input sinusoid [18], [20].

The half-wave rectifier is typically used in low-power applications due to its major disadvantages which include: the output amplitude is usually less than the input amplitude; there is no output during the negative half cycle and hence half the input power capacity is unused; and the output has large amounts ripple voltage which can be difficult to filter out [19], [21].

On the other hand, full wave rectifiers have major advantages over half wave rectifiers, some of these include: the average DC output voltage is higher compared to a half wave rectifier and the DC output of the full wave rectifier has much less ripple [22]. The most common type of full wave rectifier circuit is known as the Full Wave Bridge Rectifier. Figure 2.9 shows a half wave rectifier and Figure 2.10 shows a full wave rectifier [20], [21].

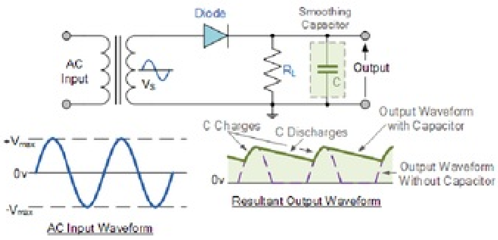


Figure 2.9: Half Wave Rectifier

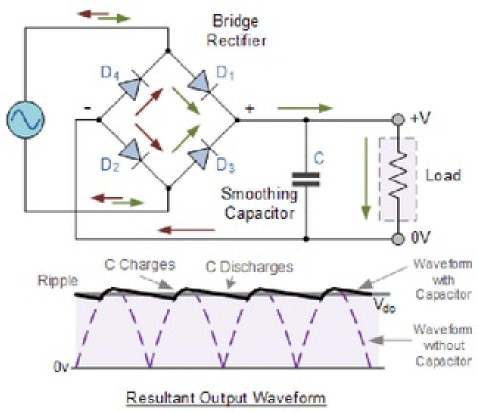


Figure 2.10: Full Wave Rectifier

Both types of rectifying circuits have ripple in the DC output, the ripple is voltage variations. Ripple needs to be minimised as most applications demand a steady and continuous DC supply. To minimise the ripple effect, a filter capacitor, better known as a smoothing capacitor is used [18], [21].

A variation of a rectifying circuit is known as a voltage multiplier circuit. This type of circuit has the potential to produce a DC output voltage greater than the peak value of the AC input voltage [22].

In the case of a usual half-wave or full-wave rectifier, the output DC voltage is limited by the maximum value of its AC input voltage. Whereas in a voltage multiplier circuit the effective use of a combination of diodes and capacitors can allow for the multiplication of the maximum input voltage, to produce a DC output equal to a multiple of the voltage value of the AC input voltage. Hence it is possible to produce an output DC voltage that is double, triple and even quadruple the input voltage. The use of large valued capacitors in voltage multiplier circuits have a positive impact on reducing the ripple voltage [23].

Connecting or cascading the output of one multiplying circuit onto the input of another can easily continue to increase the DC output voltage in integer steps. A typical type of circuit that uses this cascading topology is known as a Cockcroft Walton multiplier [23].

More specifically the Cockcroft Walton multiplier is formed with the use of cascaded half-wave doublers of arbitrary length, each cascaded doubler is known as a stage. Its main advantage is that it can produce high voltages at low current without the use of expensive transformers. The disadvantage of the Cockcroft-Walton multiplier is that there is a limit to the number of stages which can be used, as each additional stage adds less than the previous stage [23]. In theory with N stages and an input voltage of V_i the Cockcroft-Walton multiplier would produce an output voltage of $2 \times \mathrm{N} \times V_i$ volts.

One of the most important design parameters to be considered when designing a rectifying circuit or voltage multiplier circuit is the correct choice of diode. If the rectifier or voltage multiplier is to be used in an application at high frequency, a Schottky diode should be used as they have a short reverse recovery time and a low voltage drop [20]. Some other key parameters that should be considered when selecting the diode include; the current-handling capability required of the diode and the peak inverse voltage that the diode must be able to withstand without breakdown [18].More specifically for voltage multiplier circuits the diodes should have a minimum reverse breakdown voltage rating of at least twice the peak voltage across them, as multiplication circuits produce high voltages [23].

2.2.2 Rectifying and Voltage Multiplier Circuit Designs and Configurations used in Rectennas for Wireless Power Harvesting

2.2.2.1 Two cell Dickson Charge Pump Voltage Doubler Rectifier

A rectifying circuit known as a two cell Dickson charge pump voltage doubler rectifier (a variation of a voltage multiplier) was demonstrated within a rectenna system in 2010 by *Ugur Olgun et al* [13]. In this research paper the rectifying circuit was designed and fabricated on a 50 mil thick low-loss substrate material [13]. A circuit diagram of the rectifying circuit can be seen in Figure 2.11 [13].

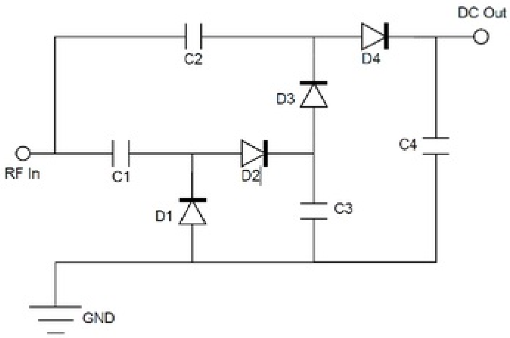


Figure 2.11: Two cell Dickson charge pump voltage doubler rectifier

In the circuit two zero-bias RF Schottky diode pairs, were used. These diodes do not require external biasing and they have a relatively low barrier height and high saturation current compared to externally biased detector diodes; this then results in higher output voltage at low power levels. However, a major drawback is their higher series resistance causing higher resistive losses. The capacitors C1 and C2 in the circuit prevent DC current from flowing between the input RF port and the diodes and the capacitors, C3 and C4 store the resulting charge to smooth the output voltage. This type of rectifying circuit can produce an output DC voltage which is four times the peak voltage of input RF signal and an RF to DC conversion efficiency from 60-70% [13].

2.2.2.2 Greinacher Rectifier

A rectifying circuit known as a wave Greinacher rectifier was demonstrated in a rectenna system in 2011 and 2012 by *Ugur Olgun et al* and in 2015 by Chaoyun Song et al [14–16]. The efficiency of rectifier design is critical for power harvesting, and hence a single-stage full-wave Greinacher rectifier fulfils this need, as it provides an efficient rectification scheme [14]. A circuit diagram of the rectifying circuit can be seen in Figure 2.12 [14].

In the circuit D1, D2, D3 and D4 are four zero-bias low-barrier Schottky diodes of the rectifier, implying higher output voltage even though the RF power is at low levels.

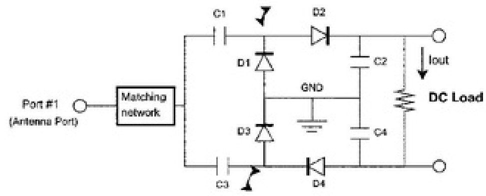


Figure 2.12: Greinacher Rectifier

These diodes do not require additional biasing, this is important as a few microamperes of bias current affect the conversion efficiency. The operation of the rectifier is as follows: First, the induced voltage at the output of the matching circuit passes through the DC blocking capacitors (C1 and C3). The rectified current output is then pumped to the storage capacitors (C2 and C4). The energy stored on these capacitors supply the DC power to the load, once the rectifier reaches its steady-state mode [15]. This rectifying circuit has further improved sensitivity and efficiency compared to other rectifying circuits discussed previously.

2.2.2.3 Cross Coupled Rectifier Based Charge Pump

Another variation of a rectifying circuit known as the Cross Coupled Rectifier Based Charge Pump was demonstrated in a research paper in 2013 by S. S. Chouhan and K. Halonen [24]. A circuit diagram of this type of rectifying circuit can be seen in Figure 2.13 [24].

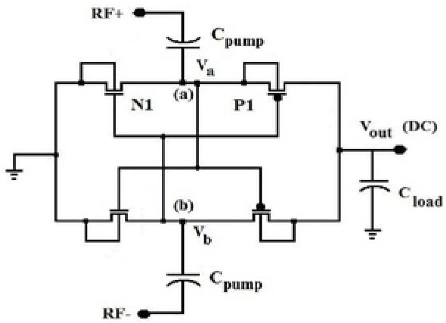


Figure 2.13: Cross Coupled Rectifier Based Charge Pump

The cross coupled rectifier is well known for its capability to achieve small ON resistance and small leakage current simultaneously. This rectifier is also capable of generating a higher output DC voltage over conventional designs [24].

Chapter 3

Design and Prototyping of the Rectenna System and Key Subsystems

This chapter of the report details the requirements that the key subsystems and the rectenna systems must meet, in order for the overall rectenna system to achieve its objectives. This section also encompasses the design considerations, procedures and methodology in obtaining suitable designs for all the key subsystems and the rectenna systems, which thus meets the stated requirements and achieves the overall objectives.

3.1 Microstrip Patch Antenna Design - Subsystem 1

The microstrip patch antenna is a key subsystem of the overall rectenna system (Rectenna System 1), as its primary function in the overall system is to collect and harvest RF energy at the 2.45 GHz ISM band frequency.

3.1.1 Requirements

The key requirements that the Microstrip Patch Antenna must meet include the following:

- The antenna is required to operate at the 2.45 GHz ISM band frequency,
- The antenna is required to have sufficient bandwidth to cover all the Wi-Fi channels,
- The antenna is required to have sufficient efficiency in collecting RF energy from a reasonable distance,
- The antenna is required to have sufficient gain in order for it to collect RF energy from a reasonable distance,
- The antenna should be small to moderately sized in order for it to be realistic for use in commercial and industrial applications.

3.1.2 Design Considerations, Procedure and Methodology

The first key step and consideration of the design process for the antenna was selecting a suitable dielectric substrate material in order to meet the requirements as set out previously. The choice of substrate material and the thickness of the substrate was limited by what substrates the university had in stock, please see Appendix B for a list of available substrates from the university. Once what was available was known, the decision of what substrate would be selected, was based on a combination of the three key properties, which included: the relative permittivity ϵ_r, the dielectric loss factor tan δ and the fixed thickness.

From the list available and based on the three key properties, ROGERS TMM4 was selected as the best substrate for this particular application. Firstly, with a thickness of 3.175 mm, it had the second largest thickness compared to the other substrates available. This large thickness would hence provide an increase in radiated power, a reduction in conductor loss, and a sufficient improvement in bandwidth [3].

Secondly, with a permittivity of 4.5, it was the perfect trade-off between a reduced size and an increase in radiated power. As a higher permittivity results in a reduction in size and a lower permittivity enhances fringing fields hence increasing the radiated power [2], [3]. Also this substrate with a moderately valued permittivity would be suitable for microwave circuitry, in this case the rectifying/voltage multiplier circuit [7].

Finally, in relation to the substrate it has a moderately low dielectric loss factor tan δ of 0.002. This moderately low loss factor would hence contribute to the antenna being highly efficient, with a sufficient amount of gain [2]. It must be noted that from the substrate list this loss factor tan δ was not the lowest which hence means other substrates provide better efficiency. However since it is fairly still low it still provides a reasonably good efficiency as a trade-off with bandwidth; as a higher dielectric loss factor tan δ substrate gives an enhancement in bandwidth but with a negative impact on efficiency and gain [2].

The next key step and consideration of the design process for the antenna was to calculate the length and width of the antenna patch using equation (2.1) and (2.2). The length of the antenna patch was calculated as 28.2842 mm. This length is a highly important parameter as it controls the resonant frequency of the antenna, hence in this case our antenna should have a resonant frequency of 2.45 GHz [3].

The width of the antenna patch was was calculated as 36.9197 mm. This width is a highly important parameter as a larger antenna patch width increases the power radiated and hence this results in: decreased resonant resistance, increased bandwidth and increased radiation efficiency [2a]. The width of the patch also has a slight effect on the resonant frequency and the radiation pattern [3].

Once the substrate was selected with the fixed thickness, and once the length and width was calculated, the final step was to proceed in making a 3-D model of the microstrip antenna design using computer aided design (CAD), via the CST microwave studio software package. The calculated length and width of the antenna patch is not optimal since it is an approximate. Hence empirical fine-tuning was needed to get the optimal length to achieve the correct resonant frequency; and to get the optimal width to achieve a sufficient enhancement of the bandwidth. The width for the microstrip transmission feed line was also fine-tuned empirically to gain the optimal feedline width. The majority of the empirical fine tuning was undertaken on CST using the parameter sweep, however a substantial amount of manual fine tuning was needed.

The resulting 3-D design of the microstrip patch antenna is shown in Figure 3.1.

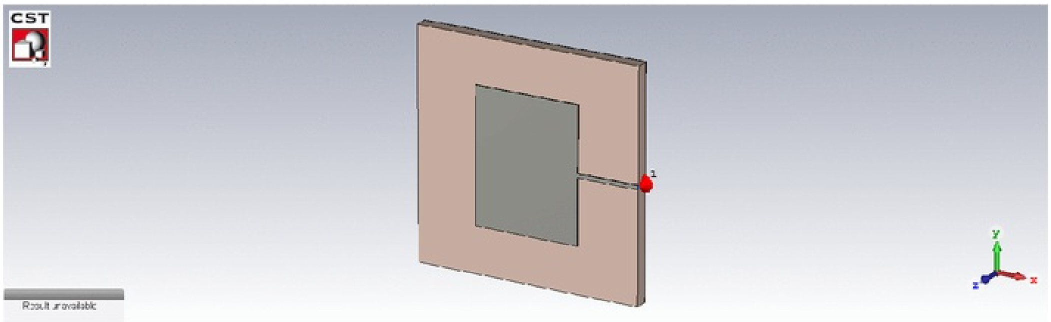


Figure 3.1: 3-D Design of the Microstrip Patch Antenna Prototype

This was the final prototype of the Microstrip Patch Antenna Design - Subsystem 1, as it was the optimal design compared to all the other preliminary prototypes that were created. Multiple preliminary prototypes were created with variances in substrate material, thickness, and the physical dimensions (Length and Width). Some of these preliminary prototypes can be seen in Appendix C. These preliminary prototypes met some of the requirements but failed to satisfy all of them. Hence after an investigation on why each of these preliminary prototypes failed to satisfy all the requirements, it was then possible to implement the improvements learnt from the past failed prototype into the design considerations and throughout the design procedures and methodology. This resulted in the creation and design of the final prototype of the Microstrip Patch Antenna Design - Subsystem 1, shown and analysed previously.

3.2 Rectifying and Voltage Multiplying Circuit Design - Subsystem 2

The Rectifying and Voltage Multiplying Circuit is another key subsystem of the overall rectenna system, as its primary function in the overall system is to convert the collected RF energy into usable DC energy.

3.2.1 Requirements

The key requirements that the Rectifying and Voltage Multiplying Circuit must meet include the following:

- The Rectifying and Voltage Multiplying Circuit is required to be effective with minimal losses in the conversion of RF energy to DC energy,
- The Rectifying and Voltage Multiplying Circuit is required to operate at a frequency of 2.45 GHz,
- The Rectifying and Voltage Multiplying Circuit is required to operate at low input power levels,
- The Rectifying and Voltage Multiplying Circuit is required to operate without external biasing,
- The Rectifying and Voltage Multiplying Circuit should be small to moderately sized in order for it to be realistic for use in commercial and industrial applications,
- The Rectifying and Voltage Multiplying Circuit should produce minimal ripple voltage in the output DC waveform.

3.2.2 Design Considerations, Procedure and Methodology

The first key step and consideration of the design process for the Rectifying and Voltage Multiplying Circuit was selecting a suitable circuit configuration in order to meet the requirements as set out previously. From the literature review and research, many different circuit configurations have been investigated. The choice of circuit configuration was the Cockcroft Walton multiplier in 2 stage or greater form. The reason for this is because the cascading of the output of one multiplying circuit onto the input of another would be a simple and effective way of increasing the DC output voltage in integer steps and because the Cockcroft Walton multiplier is effective in producing high voltages at low current.

The next key step and consideration of the design process for the Rectifying and Voltage Multiplying Circuit was to select a suitable diode. Diode selection is of critical importance since the circuit has to operate at a frequency of 2.45GHz and without any external biasing; as it would be extremely difficult to generate external DC bias current in this application and because it would add a whole range of complexities.

Since the rectifying circuit will be operating at 2.45 GHz a generally high frequency, Schottky diodes should be used as these types of diodes have a short reverse recovery time and a low voltage drop, which are ideal for this frequency [20]. The diodes that were selected for this application was the HSMS-2820 and HSMS-2850 Schottky diode produced by Broadcom/Avago technologies. The main reason that both these Schottky diodes were selected was because at the frequency of 2.45GHz they did not require any external biasing. The HSMS-2820 Schottky diode was selected as the Minimum Breakdown Voltage and Peak Inverse Voltage of 15Volts was sufficient enough to withstand breakdown in this voltage multiplier application. The HSMS-2850 Schottky diode was selected as it is optimised for use in small signal and low power applications. Also some other advantages to using both these diodes included their: high sensitivity, low turn on voltage, low failure in time rate and good thermal Conductivity for Higher Power Dissipation. Both the HSMS-2820 and HSMS-2850 Schottky diodes will be used in two different Rectifying and Voltage Multiplying Circuits for the Rectenna systems and hence the effectiveness of both the HSMS-2820 and HSMS-2850 Schottky diodes will be evaluated to determine which diode is more appropriate for the rectenna systems.

The permittivity of the substrate plays a critical role in determining the size of the circuit as; the Rectifying and Voltage Multiplying Circuit should be small to moderately sized in order for it to be realistic for use in commercial and industrial applications. This was considered in the previous section when designing the antenna and hence ROGERS TMM4 was selected with a permittivity of 4.5 which would give a small to moderately sized circuit. Also according to the data sheet of the substrate, it is a good option for microwave circuitry. An FR4 substrate with a similar permittivity of 4.3 may also be considered as an option for the prototype of the rectifying and voltage multiplying circuit in the manufacturing stage instead of ROGERS TMM4, as it is less costly and easier to fabricate.

Once a suitable circuit configuration and a suitable diode for the application was selected, the final step was to proceed in making a schematic model of the Rectifying and Voltage Multiplying circuit via the CST microwave studio software package, which included the circuit creator. A spice model of HSMS-2820 and HSMS-2850 Schottky diodes was used to enhance the accuracy of the schematic model. The optimal value of the capacitor was determined using empirical fine-tuning via the tune option on CST; a value of 100pF was obtained.

The resulting schematic of the Cockcroft Walton - Rectifying and Voltage Multiplying Circuit is shown in Figure 3.2.

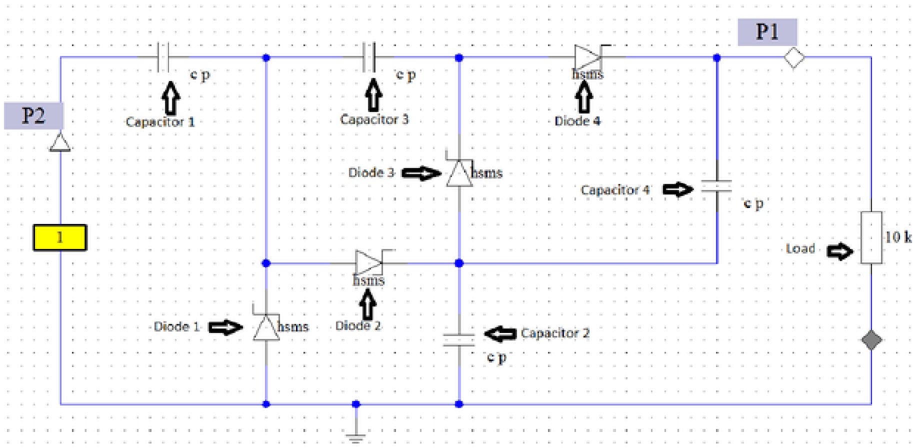


Figure 3.2: Schematic of the Cockcroft Walton - Rectifying and Voltage Multiplying Circuit

The designed Cockcroft Walton - Rectifying and Voltage Multiplying Circuit shown in Figure 3.2 consists of two stages. The first stage consists of diodes 1 and 2 and capacitors 1 and 2. Whereas the second stage consists of diodes 3 and 4 and capacitors 3 and 4. Whilst there is a negative half cycle for the input sinusoidal signal waveform, diode 1 becomes forward biased and conducts, thus charging up capacitor 1 to a value equal to the peak of the input voltage. Capacitor 1 remains fully charged and acts as a storage device in series with the input voltage source as theres no path for it to discharge. Simultaneously diode 2 conducts via diode 1 and therefore, charges up capacitor 2. Whilst there is a positive half cycle, diode 1 becomes reverse biased and thus blocks the discharge of capacitor 1; whilst diode 2 is forward biased and charges up capacitor 2. Since there is a voltage across capacitor 1 which has a value equal to the peak of the input voltage, capacitor 2 thus charges up to two times the peak value of the input voltage. Hence at the end of the first stage there is an output which is equal to double the input voltage and is rectified. It must be noted that this output of twice the input voltage is not instantaneous but settles to twice the peak input voltage eventually after each input cycle. Since the Cockcroft Walton - Rectifying and Voltage Multiplying Circuit is a half wave multiplier there is a substantial amount of ripple voltage that needs to be smoothed out; hence 100Pf capacitors are chosen to do this task. The second stage of the Cockcroft Walton - Rectifying and Voltage Multiplying Circuit is identical to the first and is connected to the output of the first, i.e it is cascaded. Therefore since the first stage doubles the peak input voltage, the second stage gives double the output of the first stage, effectively giving a rectified DC output with a value equal to quadruple the peak input voltage [22].

The abovementioned two stage Cockcroft Walton - Rectifying and Voltage Multiplying Circuit - Subsystem 2, was the final prototype for Subsystem 2 as it was the optimal design compared to all the other preliminary prototypes that were created. Multiple preliminary prototypes were created, these included; a standard full wave bridge rectifier and a single stage Cockcroft Walton voltage multiplier circuit (doubler). Some of these preliminary prototypes can be seen in the Appendix D. Once again these preliminary prototypes met some of the requirements but failed to satisfy all of them. Once the reason behind why each of these preliminary prototypes failed to satisfy all the requirements was sufficiently investigated, it was possible to implement the improvements learnt from the past failed prototypes into the design considerations and throughout the design process. This resulted in the creation and design of the final prototype of the two stage Cockcroft Walton - Rectifying and Voltage Multiplying Circuit - Subsystem 2, shown and analysed previously.

3.3 Rectenna Design - System 1

Once the designs and prototypes of the two key subsystems are complete; the microstrip patch antenna and the rectifying and voltage multiplying circuit can be combined to form the overall Rectenna System 1. Hence, now the function of the overall rectenna system is to effectively harvest and then convert electromagnetic/RF energy at the Industrial-Scientific-Medical (ISM) frequency of 2.45 GHz, into usable direct current (DC) energy.

3.3.1 Requirements

The key requirements that Rectenna System 1 must meet, encompass the requirements of each of the subsystems and hence as a summary, the general requirements include the following:

- The Rectenna System is required to operate at the 2.45 GHz ISM band frequency,
- The Rectenna System is required to be sufficiently effective in collecting and harvesting RF energy from a reasonable distance,
- The Rectenna System Circuit is required to effectively convert the collected RF energy into usable direct current (DC) energy with minimal losses,
- The Rectenna System should be small to moderately sized in order for it to be realistic for use in commercial and industrial applications.

3.3.2 Design Considerations, Procedure and Methodology

The overall Rectenna System 1 was designed on CST Microwave Studio. First a schematic of the Microstrip Antenna was combined with the schematic of the Cockcroft Walton - Rectifying and Voltage Multiplying Circuit. The resulting schematic of the overall rectenna system is shown in Figure 3.3.

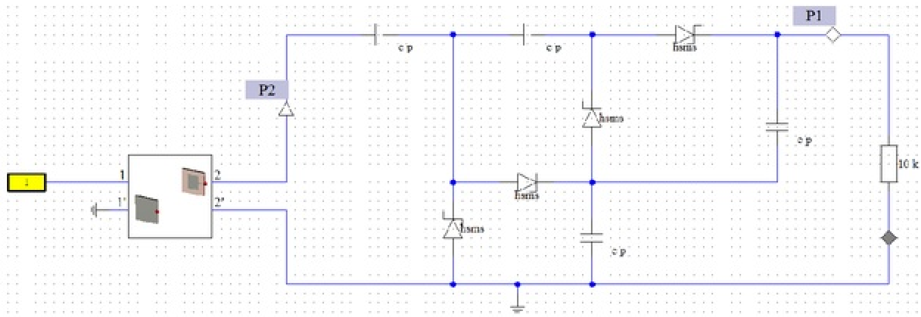


Figure 3.3: Schematic of Rectenna System 1

The next step of the design process was to use CST to create a 3-D model of the overall rectenna system. To do this, firstly a 3-D model of the circuit had to be created and then combined with the 3-D model of the Microstrip Antenna. This 3-D model would be extremely useful in the manufacturing stage as a visualisation of the entire rectenna system. The resulting 3-D Model of the overall Rectenna System 1, is shown in Figure 3.4. Since this 3-D model is only used as a visualisation, the coupling technique between the patch antenna and the Rectifying and Voltage Multiplying Circuit will not be finalised until the manufacturing stage. The two coupling techniques that will be considered include coupling via a microstrip line and coupling via SMA connectors.

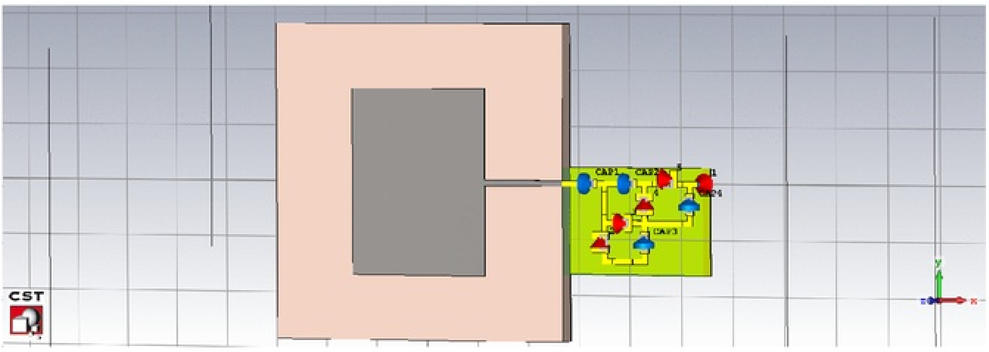


Figure 3.4: 3-D Design of Rectenna System 1

3.4 Microstrip Patch Antenna Array Design - Subsystem 3

The microstrip patch antenna array is a key subsystem of the overall rectenna system (Rectenna System 2), as its primary function in the overall system is to collect and harvest RF energy at the 2.45 GHz ISM band frequency. The main difference between this subsystem and Subsystem 1(the single microstrip patch antenna), is that this subsystem aims to achieve a greater gain which would hence allow it to collect and harvest a significantly greater amount of RF energy.

3.4.1 Requirements

The key requirements that the microstrip patch antenna array must meet, include the following:

- The antenna array is required to operate at the 2.45 GHz ISM band frequency,
- The antenna array is required to have sufficient bandwidth to cover all the Wi-Fi channels,
- The antenna array is required to have sufficient efficiency in collecting RF energy from a reasonable distance,
- The antenna array is required to have sufficient gain in order for it to collect RF energy from a reasonable distance,
- The antenna array is required to have a greater amount of gain in contrast to Subsystem 1 in order for it to collect and harvest a significantly greater amount of RF energy,
- The antenna array must use an appropriate feeding technique for a rectenna application,
- The antenna array should be small to moderately sized in order for it to be realistic for use in commercial and industrial applications.

3.4.2 Design Considerations, Procedure and Methodology

The first key step and consideration of the design process for the microstrip patch antenna array was, deciding whether to use the same dielectric substrate material and microstrip antenna patch as in Subsystem 1(the single microstrip antenna) or to use a different dielectric substrate material and hence create a new antenna patch with different geometric properties. From weighing up the choices available and the time restraints that existed with the project, it was decided that the same dielectric substrate material and microstrip antenna patch as in Subsystem 1 would be reused.

The main reason for reusing the same dielectric substrate material ROGERS TMM4 was that after weighing up and comparing the choices of substrate that were available, ROGERS TMM4 had the properties in terms of the: relative permittivity ϵ_r, the dielectric loss factor tan δ and the fixed thickness; to best meet the requirements as set out previously. With a permittivity of 4.5, it had the perfect trade-off between a reduced size and an increase in radiated power. Also, ROGERS TMM4 has a moderately low dielectric loss factor tan δ of 0.002; this moderately low loss factor would hence contribute to the antenna being highly efficient antenna, with a sufficient amount of gain [2]. ROGERS TMM4 also had a thickness of 3.175 mm, this relatively large thickness when compared to other substrates, would hence provide: an increase in radiated power, a reduction in conductor loss, and a sufficient improvement in bandwidth [3].

The next key step and consideration of the design process for the microstrip patch antenna array was to determine the size of the array in terms of the number of elements and the element spacing. The number of elements in an array is critical to the amount of gain the antenna array outputs. Approximately each time the number of elements is doubled there is an approximate 3dB theoretical increase in the gain of the antenna array. Hence the gain is proportional to the number of elements in the array. Since the same dielectric substrate material and microstrip antenna patch as in Subsystem 1 would be reused and thus knowing that the microstrip antenna patch had a realised gain of 6.1 dB(see simulations); a 4 element array was chosen as this would significantly increase the gain to a theoretical and approximate 12.1 dB without being extremely large. Hence it would still meet the requirements of being moderately sized with a greater amount of gain in contrast to Subsystem 1 in order for it to collect and harvest a significantly greater amount of RF energy.

The spacing between elements is another critical design consideration in the design process of the microstrip patch antenna array. The spacing of each microstrip patch element in the array has been set equal to half a wavelength ($\lambda = 3/49$)to avoid grating lobes, to: allow adequate space for the feedlines while still allowing the array to be moderately sized, to achieve a higher increase in the gain of the array and to reduce any mutual coupling [6].

Once the size of the array and the spacing of elements has been determined the next step in the design process for the microstrip patch antenna array is to determine the configuration of elements and the feeding technique for the antenna array. The corporate feed configuration technique has been selected for this application where the microstrip transmission lines connects and feeds the antenna patch elements in parallel. The main reason for selecting the corporate feed configuration over the series feed configuration is because, it has greater wideband performance and does not suffer from beam squint which leads to gain degradation. Since the corporate feed configuration has been selected the elements will be placed in a 4 by 1 configuration.

Once it was determined that the same substrate and patch elements would be reused; and the size of the array, element spacing, configuration of elements, and the feeding technique was selected; the next step was to proceed in making a 3-D model of the corporate feed network of microstrip transmission lines for the array using computer aided design(CAD), via the CST microwave studio software package.

The impedances of all the transmission lines which makes up the corporate feed network is an important constraint which was taken into account when creating the corporate feed network. The impedance of the transmission lines is reliant on the width of the transmission lines. Calculations of the width of the transmission lines in relation to the impedance, dielectric constant, substrate thickness and the frequency were undertaken using a macro tool calculator which exists in CST, or by using the online microstrip line calculator. When creating a corporate feed network and calculating required line widths and impedances, it is of common practice to work from the port where the antennas connect, all the way to the output which has a 50 Ohm impedance.

In the case of Subsystem 3 the impedance of the patch elements was measured as 196.9 Ohms and then it was required to use a quarter wave transformer to convert from 196.9 Ohms to 100 Ohms; the impedance of the quarter wave transformer is measured as $\sqrt{196.9 * 100}$ which equals 140.32 Ohms. It must be noted that for a quarter wave transformer both the length and width are critical; the online microstrip line calculator and CST calculator was once again used to determine both these values. After the quarter wave transformer, there was a 100 Ohm transmission line with the required width. At the end of the first branch there was a 50 Ohm transmission line, as two 100 Ohm transmission lines or resistors in parallel is equivalent to 50 Ohms, as can be seen and calculated by Equation 3.1. The next part of the corporate feed network after the branches was another quarter wave transformer which converted from 50 to 100 Ohms and hence had an impedance of 70.71 Ohms. After this there was once again a 100 Ohm transmission line and then after that at the end of the cooperate feed there was a final section of 50 Ohm transmission line, as once again two 100 Ohm transmission lines or resistors in parallel is equivalent to 50 Ohms. The corporate feed network with impedances displayed can be seen in Figure 3.5.

(3.1)

$$R_T = \frac{R1 \times R2}{R1 + R2}$$

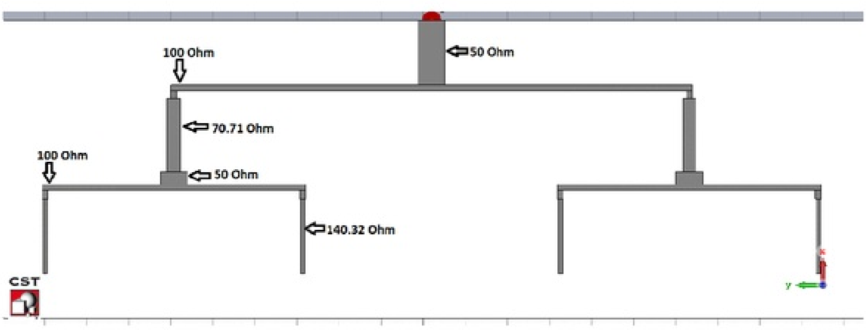


Figure 3.5: Corporate Feed Network with Impedances Displayed

After creating the corporate feed network, the microstrip antenna patch elements were then added to it to form the microstrip patch antenna array. However once the antenna patch elements were added, empirical fine-tuning was needed to get the optimal length and width for the 140.32 Ohm quarter wave transformer between the patch and the 100 Ohm transmission line. This empirical fine-tuning is needed to achieve the correct resonant frequency and to get the optimal performance for the antenna array. The resulting 3-D design of the microstrip patch antenna array is shown in Figure 3.6.

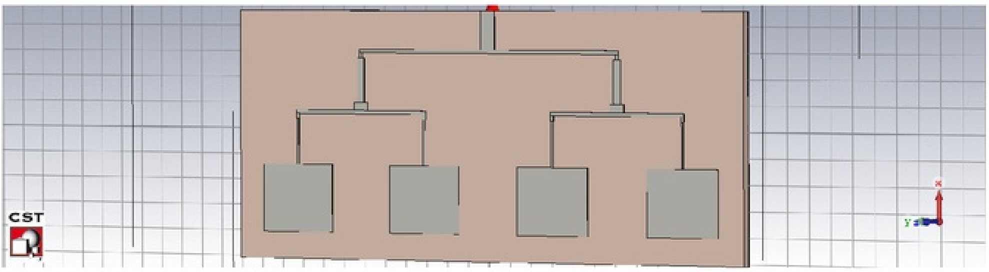


Figure 3.6: 3-D Design of of the Microstrip Patch Antenna Array

This was the final prototype of the Microstrip Patch Antenna Array Design - Subsystem 3, as it was the optimal design compared to all the other preliminary prototypes that were created. The various other preliminary prototypes that were created usually had variances in element spacing and variances in the dimensions of feed networks. Some of these preliminary prototypes can be seen in Appendix E. These preliminary prototypes met some of the requirements but failed to satisfy all of them. Hence after investigating why each of these preliminary porotypes failed to satisfy all the requirements, it was possible to implement the improvements learnt from the failed prototypes into the design considerations and throughout the design process. This resulted in the creation and design of the final prototype of the Microstrip Patch Antenna Array Design - Subsystem 3, shown and analysed previously.

3.5 Rectenna Design - System 2

Once the designs and prototypes of the two key subsystems (Subsystem 2 and 3) are complete; the rectifying and voltage multiplying circuit and the microstrip patch antenna array can be combined to form the overall Rectenna System 2. Hence, the function of the overall Rectenna System 2 when compared to Rectenna System 1; is to effectively harvest and then convert a significantly greater amount of RF energy at the frequency of 2.45 GHz, into usable DC energy.

3.5.1 Requirements

The key requirements that the overall Rectenna System 2 must meet encompass the requirements of each of the subsystems and hence as a summary, the general requirements include:

- The Rectenna System is required to operate at the 2.45 GHz ISM band frequency,
- The Rectenna System is required to be sufficiently effective in collecting and harvesting RF energy from a reasonable distance,
- The Rectenna System is required to have a greater amount of gain in contrast to Rectenna System 1, for it to collect and harvest a significantly greater amount of RF energy,
- The Rectenna System Circuit is required to effectively convert the collected RF energy into usable direct current (DC) energy with minimal losses,
- The Rectenna System should be small to moderately sized in order for it to be realistic for use in commercial and industrial applications.

3.5.2 Design Considerations, Procedure and Methodology

The overall Rectenna System 2 was designed on CST Microwave Studio. First a schematic of the microstrip antenna array was combined with the schematic of the Cockcroft Walton - Rectifying and Voltage Multiplying Circuit. The resulting schematic diagram of the overall rectenna system is shown in Figure 3.7.

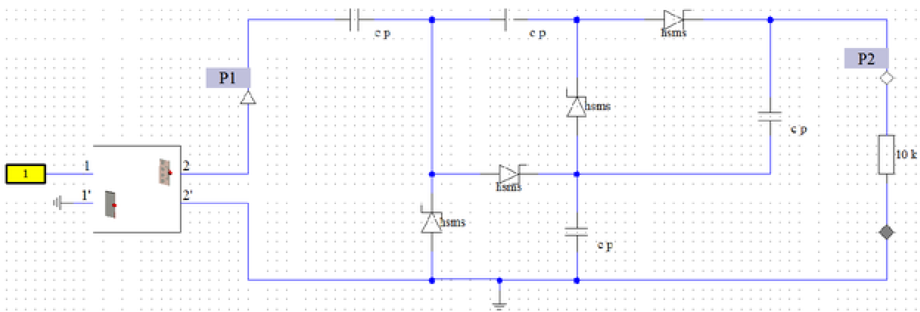


Figure 3.7: Schematic of Rectenna System 2

The next step of the design process was to use CST to create a 3-D model of the overall Rectenna System 2. To do this, firstly a 3-D model of the circuit had to be created and then combined with the 3-D model of the Microstrip Antenna array. The resulting 3-D Model of the overall rectenna system is seen in Figure 3.8. As stated before for Rectenna System 1; since this 3-D model is only used as a visualisation, the coupling technique between the antenna array and the Rectifying and Voltage Multiplying Circuit will not be finalised until the manufacturing stage. The two coupling techniques that will be considered include coupling via a microstrip line and coupling via SMA connectors.

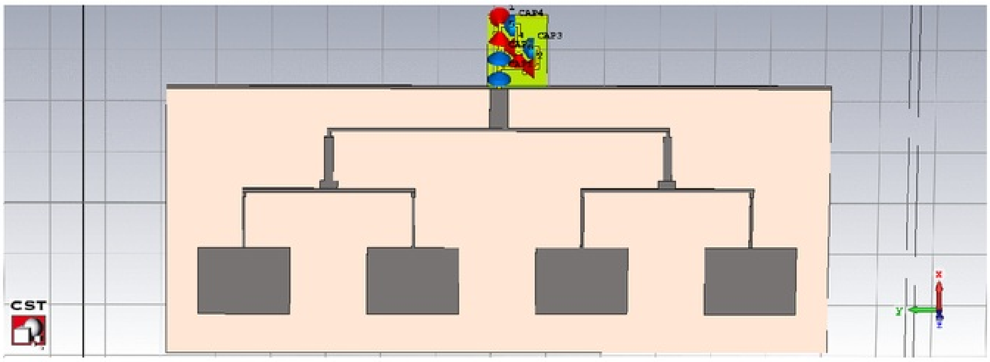


Figure 3.8: 3-D Design of Rectenna System 2

Chapter 4

Simulation & Results Obtained with Analysis for Prototypes of the Rectenna System & Key Subsystems

This chapter of the report displays, analyses and discusses the results obtained from the simulations of the key subsystems and the rectenna systems. The simulations were undertaken using CST Microwave Studio. For the antenna subsystems, the CST time domain transient solver was used which is based on the Finite Integration Technique and works on hexahedral grids. It calculates the development of fields through time at discrete locations and at discrete time samples. It also calculates the transmission of energy between various ports or other excitation sources and/or open space of the investigated structure. The time domain solver is remarkably efficient for most high frequency applications such as transmission lines and antennas and can obtain the entire broadband frequency behaviour of the simulated device from a single calculation run [25]. For the circuit subsystem a transient task circuit simulation is used to analyse the behaviour of a circuit for an arbitrary excitation in the time domain. External ports are used to define excitations and probes monitor voltages and currents inside the circuit during the simulation [26]. The rectenna systems when simulated use a combination of both these simulation techniques.

4.1 Microstrip Patch Antenna Simulation - Subsystem 1

After the prototype of the microstrip patch antenna was created, it was then simulated using CST microwave studio. The key results obtained from the simulation can be seen in Figures 4.1-4.4. In Figures 4.1 and 4.2, the return loss or the $S_{1,1}$ parameter obtained from the simulations is shown for the proposed prototype microstrip patch antenna. It can be seen that the antenna resonates at a frequency of 2.45 GHz, with the return loss equal to 40dB (-40dB $S_{1,1}$). This $S_{1,1}$ parameter of -40dB shows that the antenna is well matched; it also exceeds the typical industry benchmark of -10dB for the $S_{1,1}$ parameter.

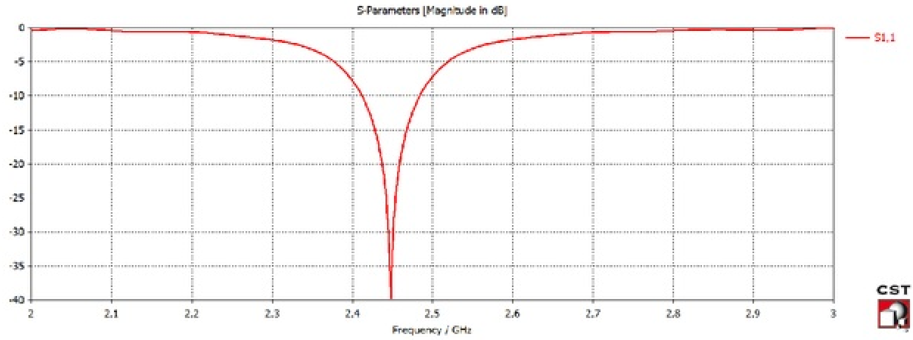


Figure 4.1: $S_{1,1}$ parameter obtained from the simulations

Figure 4.2 specifically shows the amount of bandwidth that the proposed prototype microstrip patch antenna has. At a $S_{1,1}$ parameter of -10dB the antenna has a bandwidth of 0.072145 GHz, which is equal to 72.145 MHz. This bandwidth is sufficient, as its range covers the centre frequency of all the different Wi-Fi channels.

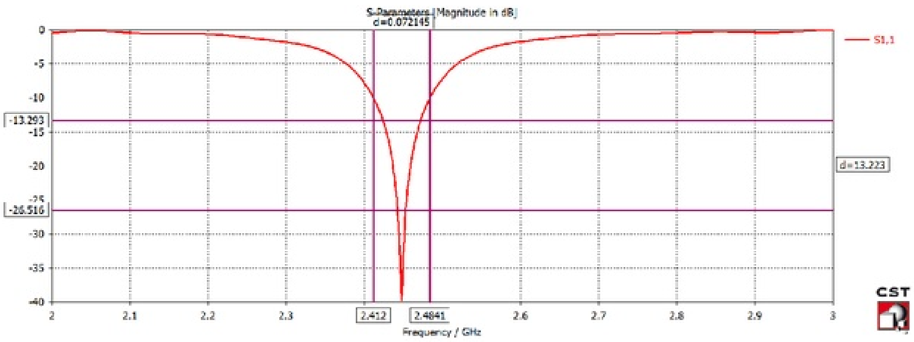


Figure 4.2: $S_{1,1}$ parameter with bandwidth measurement

In Figure 4.3 a realised gain of 6.1dB has been obtained which is relatively good considering the size of the antenna. From an estimation calculated using the Friis equation (equation 2.3), it can be said that this gain is more than sufficient, as the received power calculated for a rectenna system that utilises this antenna, should be enough to successfully facilitate wireless power harvesting. Also in Figure 4.4 a directivity of 6.43dBi has been obtained which is represented in 2-D polar form. With these two values obtained from the simulation, the radiation efficiency of the antenna can be calculated as:

$$e_r = \frac{6.1}{6.43} \times 100 = 94.86\%$$

Hence it can be said that this antenna with a radiation efficiency of 94.86% is highly efficient.

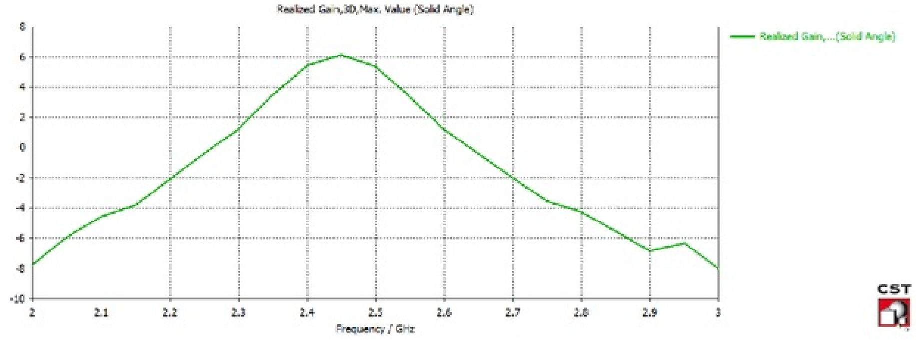


Figure 4.3: Realized Gain of Subsystem 1

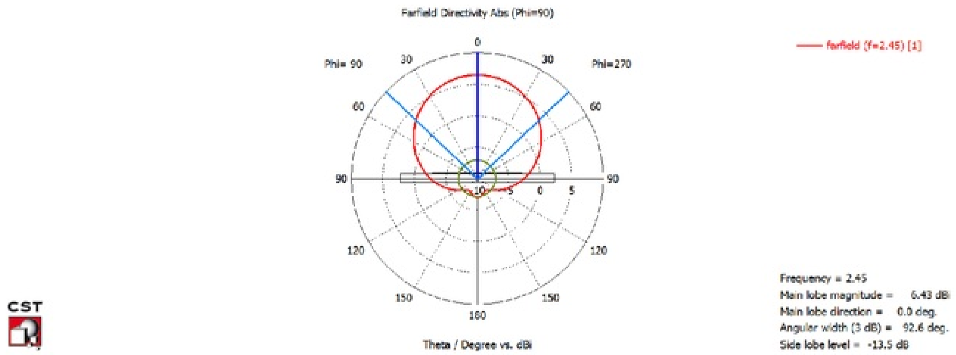


Figure 4.4: Directivity of Subsystem 1

4.2 Rectifying and Voltage Multiplier Circuit Simulation - Subsystem 2

After the prototype of the Cockcroft Walton - Rectifying and Voltage Multiplying Circuit was created, it was then simulated using the CST microwave studio circuit simulator.

To simulate the Cockcroft Walton 2 stage multiplier circuit implemented with the HSMS-2820 diode, an external port source was used to stimulate and provide to the circuit a continuous sinusoidal input signal with a frequency of 2.45GHz and an amplitude of 4v.

To obtain the output of the Cockcroft Walton 2 stage multiplier circuit implemented with the HSMS-2820 diode, differential ports were used across the 10kOhm load to determine the output voltage of the circuit. The output of the circuit can be seen in Figure 4.5.

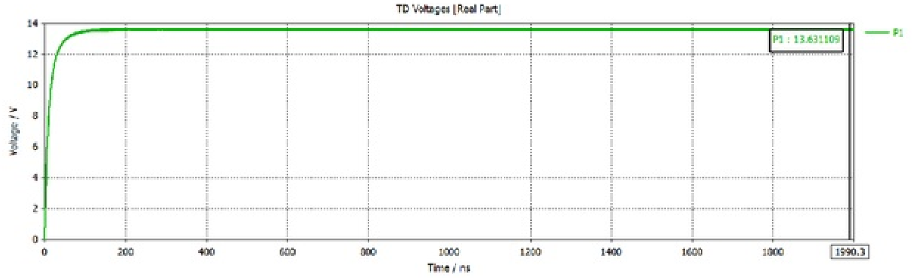


Figure 4.5: Output of the Cockcroft Walton 2-stage multiplier circuit - HSMS-2820

From the output, it can be seen that the input AC voltage signal is rectified and multiplied, hence a peak DC voltage of 13.63v is obtained. Theoretically since this is a 2 stage Cockcroft Walton multiplier circuit, 16 volts should be obtained as, 2*2 stages*4volts input = 16volts. However realistically this is hard to achieve once diode and capacitor losses are taken into account, and the fact that each additional stage Cockcroft Walton multiplier adds less than the previous stage. Hence it can be said that the Cockcroft Walton 2 stage multiplier circuit implemented with the HSMS-2820 diode gives good efficiency as it is obtaining close 4 times the input voltage.

Similarly, to simulate the Cockcroft Walton 2 stage multiplier circuit implemented with the HSMS-2850 diode, an external port source was used to stimulate and provide to the circuit a continuous sinusoidal input signal with a frequency of 2.45GHz and an amplitude of 0.8volts. To obtain the output of the Cockcroft Walton 2 stage multiplier circuit implemented with the HSMS-2850 diode, differential ports were used across the 15kOhm load to determine the output voltage of the circuit. The output of the circuit can be seen in Figure 4.6.

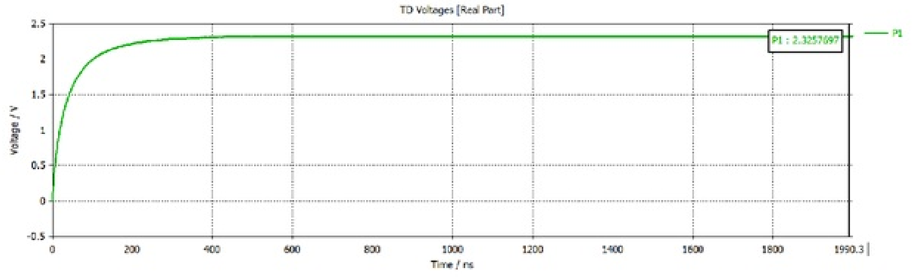


Figure 4.6: Output of the Cockcroft Walton 2-stage multiplier circuit - HSMS-2850

From the output it can be seen that the input AC voltage signal is rectified and multiplied, hence a peak DC voltage of 2.32 v is obtained. Theoretically since this is a 2 stage Cockcroft Walton multiplier circuit, 3.2 volts should be obtained as, 2*2 stages*0.8volts input = 3.2volts. However realistically this is hard to achieve as mentioned beforehand. Hence it can be said that the Cockcroft Walton 2 stage multiplier circuit implemented with the HSMS-2850 diode gives good efficiency as it is obtaining close 4 times the input voltage at small signal and low input power levels.

4.3 Rectenna Simulation - System 1

Once Rectenna System 1 was formed after combining the microstrip patch antenna and the Cockcroft Walton 2 stage multiplier circuit, it was then simulated using the CST microwave studio circuit simulator. The key results obtained from the simulation can be seen in Figures 4.7-4.9. For this simulation, the Cockcroft Walton 2 stage multiplier circuit implemented with the HSMS-2820 diode was used.

To simulate the overall rectenna system on CST, the system was excited by a secondary antenna at a moderate distance away, that generated a continuous sinusoidal waveform at 2.45 GHz with a peak amplitude of 8V. The distance between the secondary antenna and the rectenna system is enough for the rectenna system to considered to be in the far field. The overall system was then measured by placing probes at the output of the antenna (input to the circuit section) and then at the output of the rectenna system. Results at the probes were then collected after running the circuit simulator.

In Figure 4.7 the output of the antenna section of the system (input to the circuit section) can be seen. It shows an RF signal waveform with a peak amplitude of 1.77 V.

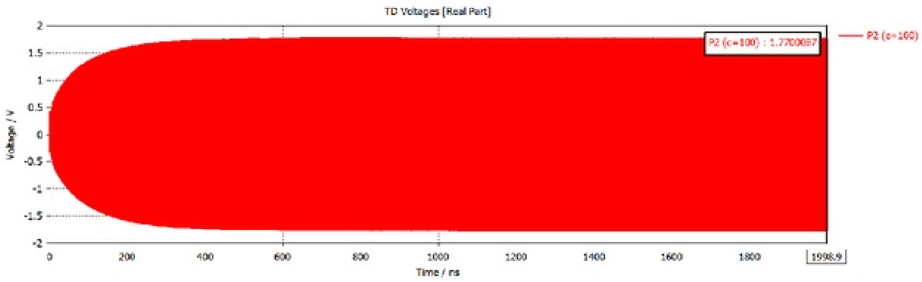


Figure 4.7: Output of the Antenna Section of the System

In Figure 4.8 the output of the rectenna system can be seen. From the output it can be seen that the input RF signal is rectified and multiplied, and hence a peak DC voltage of 5.5 V is obtained. Theoretically since this is a 2 stage Cockcroft Walton multiplier circuit, 7.08 volts should be obtained as, 2*2 stages*1.77 volts input = 7.08 volts; however realistically this is hard to achieve as mentioned beforehand in the previous section.

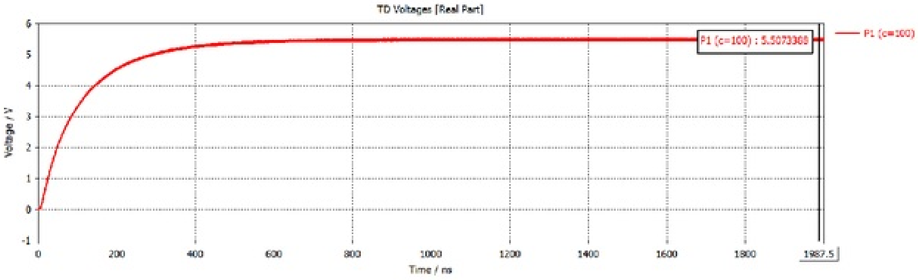


Figure 4.8: Output of the Rectenna System 1

Also the antenna component of the rectenna was simulated to see if there were any changes in terms of return loss or $S_{1,1}$ parameters and bandwidth. From Figure 4.9, it can be seen that there has not been any significant impact on the return loss or the $S_{1,1}$ parameter and bandwidth, when compared to previous simulations of just the microstrip patch antenna subsystem by itself.

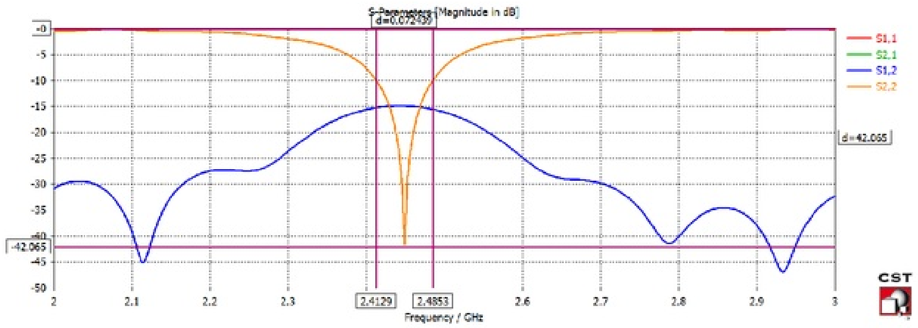


Figure 4.9: $S_{1,1}$ Parameters and Bandwidth of the Rectenna System 1

4.4 Microstrip Patch Antenna Array Simulation - Subsystem 3

After the prototype of the microstrip patch antenna array was designed, it was then simulated using CST microwave studio. The key results obtained from the simulation can be seen in Figures 4.10-4.11.In figures 4.10 and 4.11, the return loss or the $S_{1,1}$ parameter obtained from the simulations is shown for the proposed prototype microstrip patch antenna array. It can be seen that the antenna array resonates at a frequency of 2.45 Ghz, with the return loss equal to 20.54dB (20.54dB $S_{1,1}$). This $S_{1,1}$ parameter of -40dB shows that the antenna is well matched, it also exceeds the typical industry benchmark of -10dB for the $S_{1,1}$ parameter.

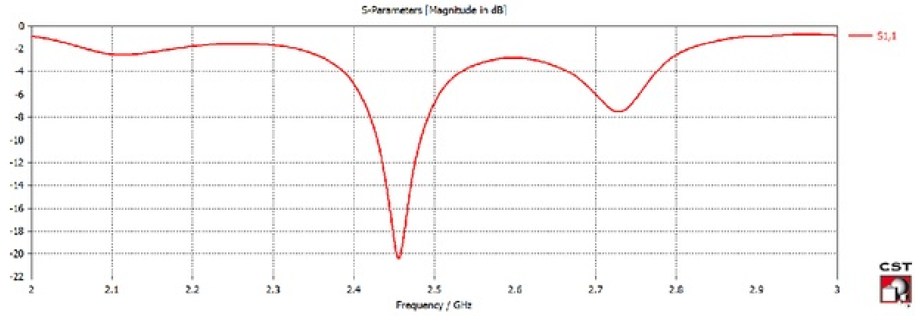


Figure 4.10: $S_{1,1}$ parameter obtained from the simulations

Figure 4.11 shows the amount of bandwidth that the proposed prototype microstrip patch antenna array has. At a $S_{1,1}$ parameter of -10dB the antenna has a bandwidth of 0.054093 GHz, which is equal to 54.093 MHz. This bandwidth is narrow, however it should be sufficient enough if the antenna is well matched at the frequency of 2.45 GHz when the prototype of the microstrip patch antenna array is fabricated and tested.

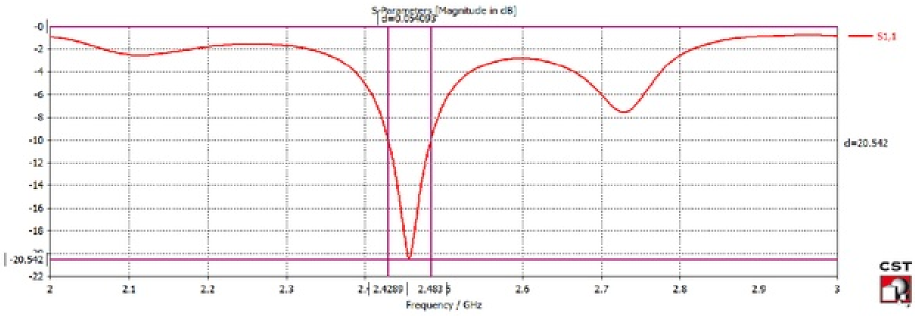


Figure 4.11: $S_{1,1}$ parameter with bandwidth measurement

In Figure 4.12 a realized gain of 10.85dB has been obtained which is relatively good considering the size of the antenna array and the feed technique used. This gain is a significant improvement over the single patch microstrip antenna and hence it can be said that this antenna array has successfully achieved its requirements relating to an increase in gain. From an estimation calculated using the Friis equation (equation 2.3), it can be said that this gain is more than sufficient, as the received power calculated for a rectenna system that utilises this antenna array, should be more than enough to successfully facilitate wireless power harvesting. Also in Figure 4.13 a directivity of 11.2dBi has been obtained for the antenna array which is represented in 2-D polar form. With these two values obtained from the simulation, the efficiency of the antenna can be calculated as:

$$e_r = \frac{10.85}{11.2} \times 100 = 96.875\%$$

Hence, this antenna with a radiation efficiency of 96.875% is highly efficient.

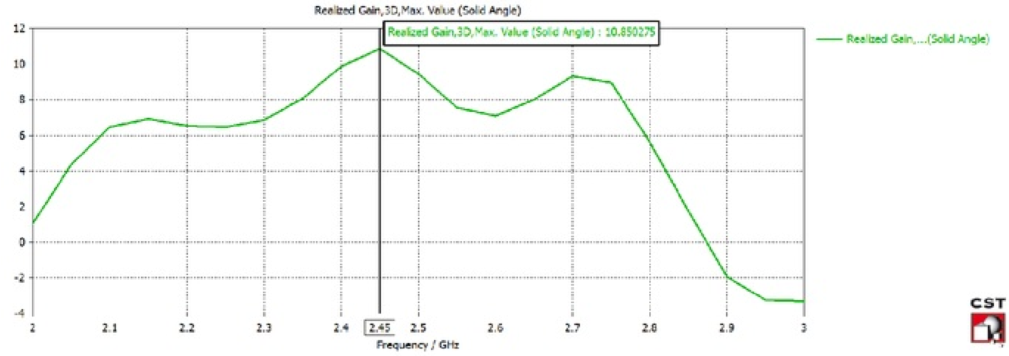


Figure 4.12: Realized Gain of Subsystem 3

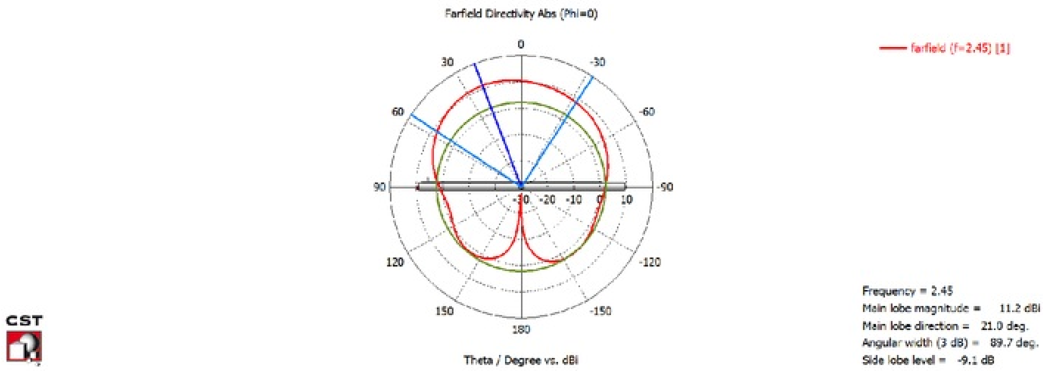


Figure 4.13: Directivity of Subsystem 3

4.5 Rectenna Simulation - System 2

Once Rectenna System 2 was formed, it was then simulated using the CST microwave studio circuit simulator. The key results obtained from the simulation can be seen in

Figures 4.14-4.17. For this simulation, the Cockcroft Walton 2 stage multiplier circuit implemented with the HSMS-2820 diode was used.

To simulate the overall rectenna system on CST, the system was excited by a secondary antenna that generated a continuous sinusoidal waveform at 2.45 GHz with a peak amplitude of 8V. The secondary antenna was placed a certain distance away from the rectenna system that is sufficient for the rectenna system to be considered to be in the far field. The overall system was then measured by placing probes at the output of the antenna (input to the circuit section) and then at the output of the rectenna system. Results at the probes were then collected after running the circuit simulator.

In Figure 4.14 the output of the antenna section of the system can be seen. It shows an RF signal waveform with a peak amplitude of 1.2 V.

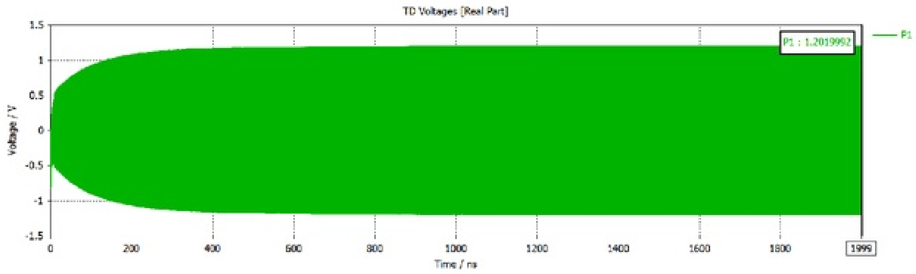


Figure 4.14: Output of the Antenna Section of the System

In Figure 4.15 the output of the rectenna system can be seen. From the output it can be seen that the input RF signal is rectified and multiplied, and hence a peak DC voltage of 3.52 V is obtained. Theoretically since this is a 2 stage Cockcroft Walton multiplier circuit, 4.8 volts should be obtained as, 2*2 stages*1.2 volts input = 4.8 volts. However realistically this is hard to achieve as mentioned beforehand in previous sections.

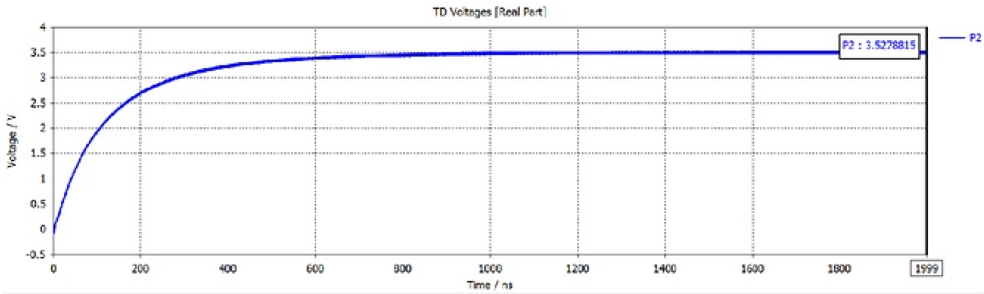


Figure 4.15: Output of the Rectenna System 2

Also the antenna component of the rectenna was simulated to see if there were any changes in terms of return loss or $S_{1,1}$ parameters and bandwidth. From Figure 4.16, it can be seen that there has not been any significant impact on the return loss or the $S_{1,1}$ parameter and bandwidth, when compared to previous simulations of just the microstrip patch antenna array subsystem by itself.

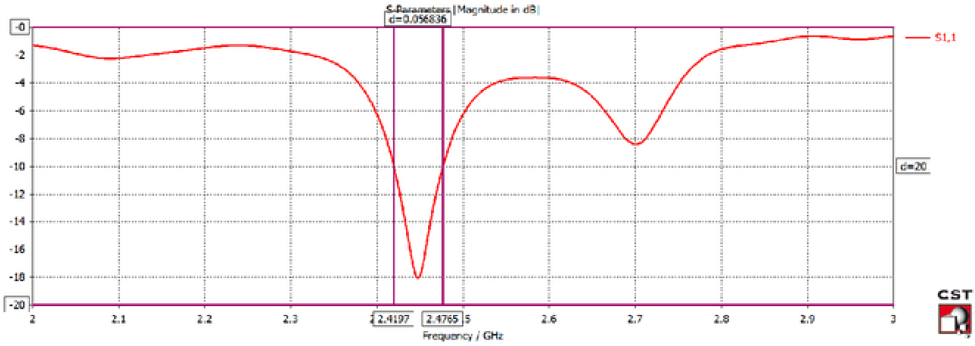


Figure 4.16: $S_{1,1}$ Parameters and Bandwidth of the Rectenna System 2

Chapter 5

Manufacture and Fabrication of Prototypes of the Rectenna System and Key Subsystems

This chapter of the report details the manufacturing and fabrication processes used to create the prototypes of the key subsystems and hence the prototypes of the rectenna systems. Before the subsystems were manufactured, they were simulated on CST microwave studio with a higher accuracy using a greater number of mesh cells to confirm results from regular simulations before the manufacturing process began. The manufacturing and fabrication of the project was contracted out to the Macquarie Engineering and Technical Services department (METS).

5.1 Microstrip Patch Antenna and Microstrip Patch Antenna Array; Manufacture and Fabrication - Subsystem 1 and 3

The Gerber files which contained the dimensions and 2-D schematics of both the single microstrip patch antenna and microstrip patch antenna array were obtained using CST microwave studio and were provided to METS. However due to some incompatibility with the Computer Aided Manufacturing (CAM) software that METS utilise, the Gerber files were incomplete and missed some critical dimensions. Hence hand drawn and detailed dimensions were provided to METS who then modified the Gerber files and added in the missing dimensions. Once the Gerber files were complete they were uploaded to the CAM software on a PC connected to a computer automated routing and milling machine known as the Quick Circuit. The Rogers TMM4 substrate with pre-existing copper cladding, was then mounted onto the Quick Circuit routing and milling machine. The routing and milling cutting and drill bits were changed to a more versatile cutting and drill bit that could cope with the extreme hardness of the TMM4 substrate without breaking.

Once the drill and cutting bits were changed and final adjustments were made to the Quick Circuit routing and milling machine, the fabricate option on the CAM software was initiated and hence the routing and milling machine became operational. The Quick Circuit routing and milling machine first cut through the top copper surface, tracing out and indenting the structure and geometry of: the single antenna patch, the array antenna patches and the microstrip transmission lines. After an outline of the geometries was created for both the single patch antenna and the patch antenna array, the routing and milling machine then proceeded to cut the single patch antenna and the antenna array out of the main substrate board with the correct amount of surrounding substrate. The Quick Circuit routing and milling machine with the remaining leftover substrate can be seen in Figure 5.1.

Figure 5.1: The Quick Circuit routing and milling machine with substrate

The recently cut single patch antenna and antenna array with outlines milled and indented in the first layer which can be seen in Figure 5.2 was then sprayed with a resin based acrylic conformal coating. The resin based acrylic conformal coating protects the patches, the microstrip transmission lines and the ground plane in the chemical etching stage of the manufacturing process. The unwanted surrounding copper layers were masked off prior to spraying with tape and hence did not get any protection from the coating. Once the resin based acrylic conformal coating dried, the surrounding tape masking the unwanted areas was then peeled carefully with a scalpel.

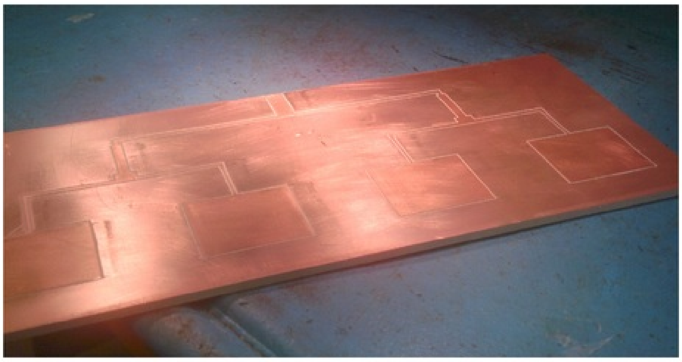


Figure 5.2: Cut Antenna Array with Outlines Milled

The next stage in the manufacturing process of the single microstrip patch antenna and microstrip patch antenna array was chemical etching. Once the conformal coating of both the antennas were complete, the antennas were placed in a tray of Ferric Chloride. Over time the corrosive Ferric Chloride has a chemical reaction with the copper and hence dissolves the surrounding unwanted copper with no protective acrylic conformal coating, whereas the copper with the protective conformal coating does not get affected and holds its shape and structure as seen in Figure 5.3. To speed up the chemical etching process the tray of Ferric Chloride was carefully swished around creating a wave motion. Once all the unwanted surround copper had dissolved both antennas were placed in a beaker of water to remove the corrosive Ferric Chloride and stop any chemical reactions from continuing to occur.

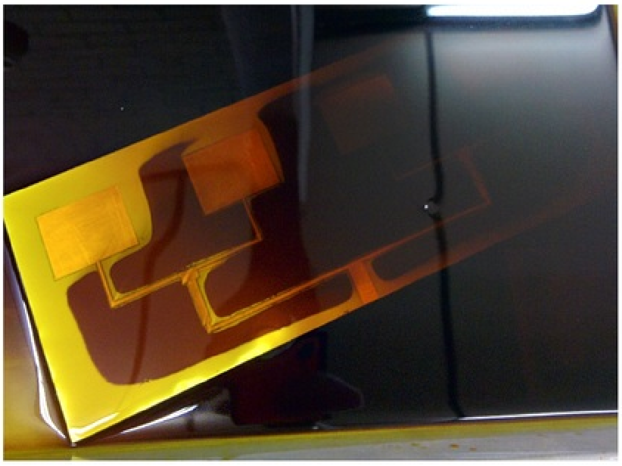


Figure 5.3: Chemical Etching of Antennas

After the chemical etching process was complete female SMA side feed connectors were soldered on to the edge of both antennas, where the microstrip transmission line met the edge of the substrate. The pin of the SMA connector was soldered on to microstrip transmission line and the frame of the SMA connector was soldered on to the ground plane. Once the SMA connectors were both soldered on to the single microstrip patch antenna and microstrip patch antenna array, a quick quality control test was performed using a network analyzer. This was performed to see if both antennas were resonating at the correct frequency as it is common for antennas after the manufacturing process to have a shift in frequency due to manufacturing errors, caused by the tolerances of the equipment used and variances in the actual value of the relative permittivity ϵ_r of the substrate when compared to what was stated in the manufactures data sheet. It was found there was a slight shift up in the resonant frequency, probably due to a variance in the relative permittivity ϵ_r when compared to the ideal value used in simulations. This shift in frequency was quickly tuned and fixed by adding 1.5mm in the length of the antenna patches using adhesive copper tape. Once this simple fix was performed and the both the single microstrip patch antenna and microstrip patch antenna array were resonating at the correct frequency the manufacturing process was complete; the end result of the manufacturing process can be seen in Figure 5.4 and Figure 5.5 respectively.

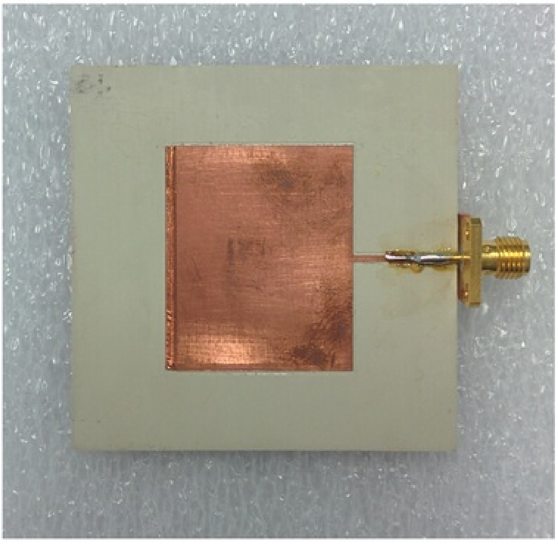


Figure 5.4: Manufactured Microstrip Patch Antenna - Subsystem 1

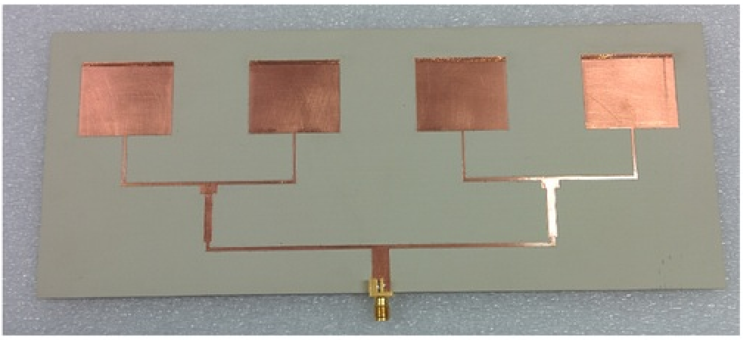


Figure 5.5: Manufactured Microstrip Patch Antenna Array- Subsystem 3

5.2 Rectifying and Voltage Multiplying Circuit; Manufacture and Fabrication - Subsystem 2

The data sheets for the circuit components and schematic diagrams, 3-D models of the two stage Cockcroft Walton Rectifying and Voltage Multiplying Circuit and the entire rectenna system were provided to METS. These were provided to METS with the instruction of placing the circuit elements as close as possible to each other, as the operating frequency of 2.45GHz is relatively high and hence all spacing between elements should be reduced to reduce any phase shift which may occur. METS was then able to create a Gerber 2-D schematic diagram and file of the PCB layout of the circuit, which can be seen in Figure 5.6. As two different Schottky diodes were used, the circuits for both these diodes had slightly different PCB layouts.

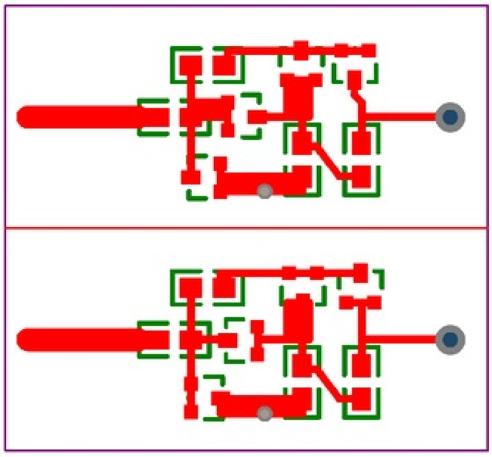


Figure 5.6: PCB layout of the circuit(TOP:HSMS-2820)(BOTTOM:HSMS-2850)

After the Gerber 2-D schematic for the two stage Cockcroft Walton Rectifying and Voltage Multiplying Circuit was complete, it was then uploaded to the CAM software on a PC connected to the Quick Circuit computer automated routing and milling machine. Once again the substrate was mounted onto the routing and milling machine; however, this time a different substrate known as FR4 was used, which had a similar permittivity of 4.3 when compared to TMM4s permittivity of 4.5. The main reason that the FR4 substrate was chosen for the circuit, was that it wasnt as hard when compared to TMM4 and hence would be easier and quicker to fabricate, as the circuit was small sized and trying to cut a small section out of the TMM4 substrate would be extremely difficult with a risk of cracking the substrate and the cutting bit. Once the substrate had been mounted on the quick circuit routing and milling machine, final adjustments were made and a suitable cutting and drilling bit was attached to the machine.

After final adjustments were made to the Quick Circuit routing and milling machine, the fabricate option on the CAM software was initiated and hence the routing and milling machine became operational. The automated Quick Circuit routing and milling machine used the Gerber file to trace out the tracks of the circuit and hence isolated the tracks of the circuit from the surrounding copper, it then drilled holes for the output of the circuit and the ground of the circuit as seen in Figure 5.7.

Figure 5.7: The Quick Circuit routing and milling machine Fabricating the circuit

Once the circuit had its tracks traced out and isolated with necessary holes drilled, the circuit for both the HSMS-2820 and HSMS-2850 Schottky diodes were cut out from the main board. The resulting incomplete circuits created using the Quick Circuit routing and milling machine are shown in Figure 5.8.

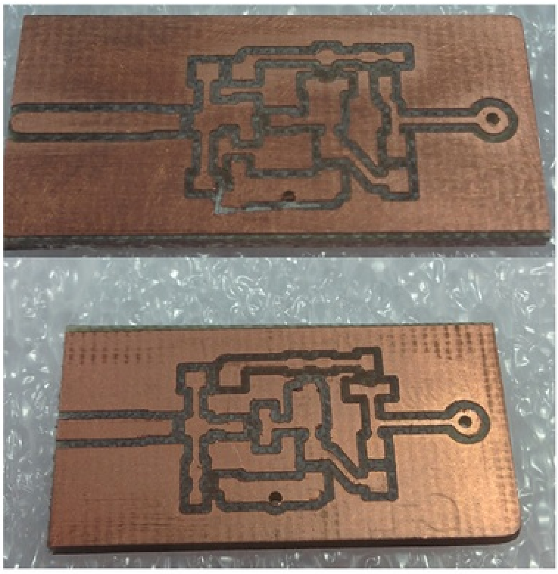


Figure 5.8: PCB with tracks Milled and Isolated(Top:HSMS-2820)(Bottom:HSMS-2850)

After the incomplete circuit was created: the female SMA input side feed connector and components were carefully hand soldered under a magnification lens, the circuit was connected to the bottom ground plane via a small pin and wires with alligator clips were soldered on to the circuit. The resulting complete circuit for both the HSMS-2820 and HSMS-2850 Schottky diodes are shown in Figure 5.9 and Figure 5.10.

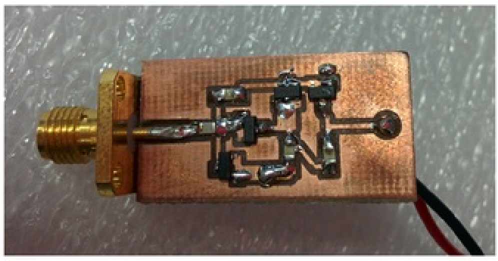


Figure 5.9: HSMS-2820 complete circuit - Subsystem 2

Figure 5.10: HSMS-2850 complete circuit - Subsystem 2

5.3 Rectenna; Manufacture and Fabrication - System 1 and 2

To reduce costs and to allow for flexibility in the manufacturing process, it was decided after consulting METS to use a SMA connector coupling to connect the key subsystems with each other to form the rectenna systems. This main advantage of using this type of coupling was that it allowed flexibility in terms of changing one subsystem without manufacturing a whole new rectenna system. Hence this flexibility reduced the cost of this project, as multiple rectenna systems were not needed to be manufactured.

Once Subsystems 1,2 and 3 were manufactured they were combined using a male SMA to SMA connector. Rectenna System 1 was formed by connecting and combining Subsystem 1 and 2 using a male SMA to SMA connector and can be seen in Figure 5.11.

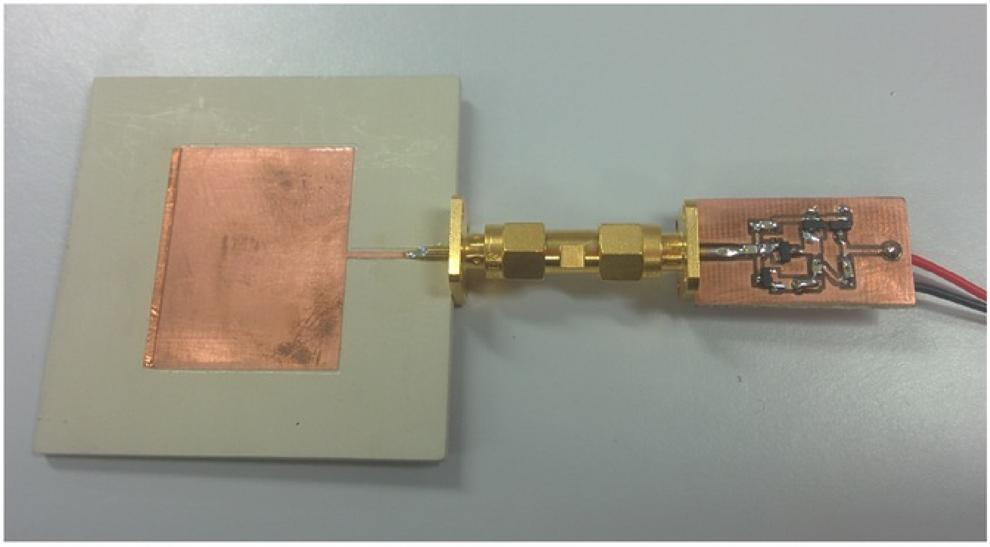


Figure 5.11: Manufactured Rectenna System 1

Rectenna System 2 was formed by connecting and combining Subsystem 2 and 3 using a male SMA to SMA connector and can be seen in Figure 5.12.

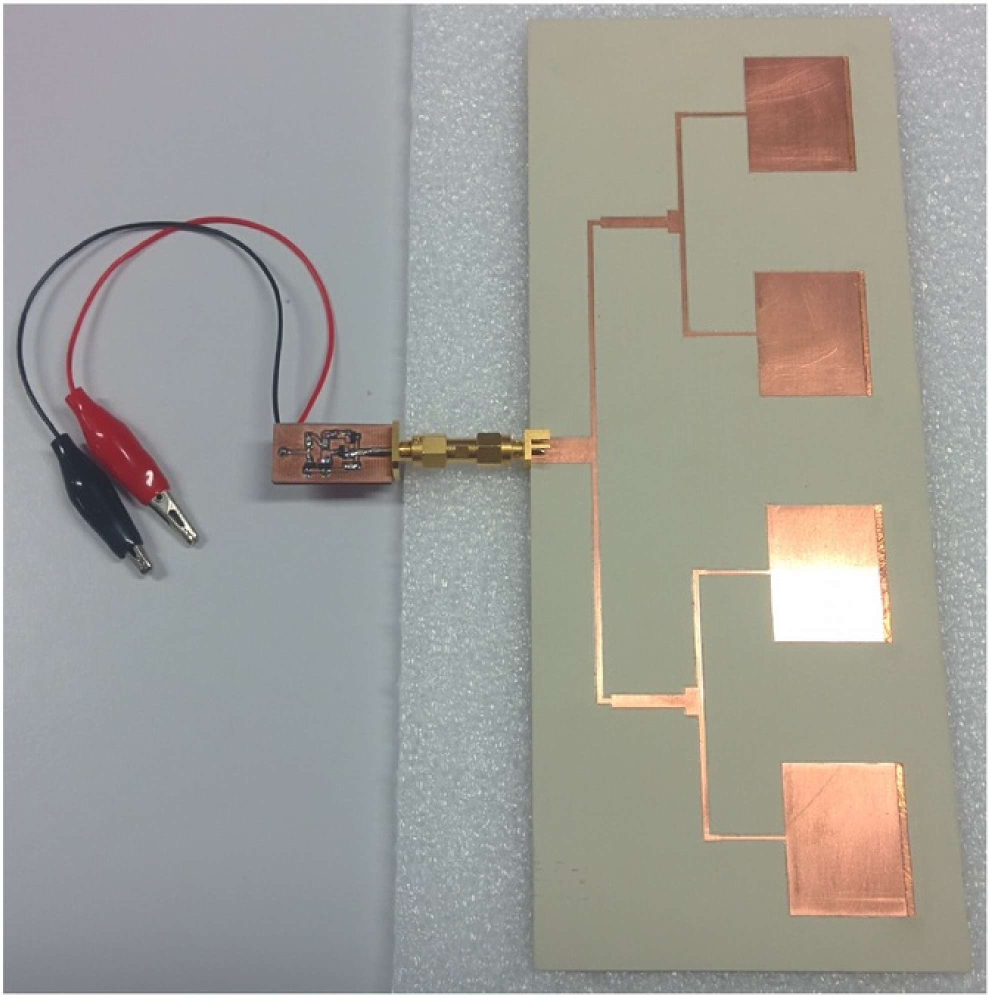


Figure 5.12: Manufactured Rectenna System 2

Chapter 6

Physical Testing and Results Obtained with Analysis for Prototypes of the Rectenna System and Key Subsystems

This chapter of the report details the experimental procedures and setup undertaken for the physical testing of the prototypes of the key subsystems and the rectenna systems. This chapter also displays, analyses and discusses the results obtained from the physical testing of these keys subsystems and systems. The physical testing was undertaken at the Macquarie University Research Laboratory and the CSIRO anechoic chamber. Various equipment was used during the physical testing of the subsystems and systems and will be detailed specifically in the upcoming subsections.

6.1 Microstrip Patch Antenna and Microstrip Patch Antenna Array; Physical Testing and Results Obtained with Analysis - Subsystem 1 and 3

6.1.1 Experimental Procedure and Setup

6.1.1.1 $S_{1,1}$ Reflection Coefficient Parameter Matching, Resonant Frequency and Bandwidth

The first key test to be performed was to obtain the $S_{1,1}$ reflection coefficient parameters to check: the matching, the resonant frequency, and the bandwidth, of both the single microstrip patch antenna and the microstrip patch antenna array (Subsystem 1 & 3). To perform these tests and measurements the Agilent Technologies N5242A PNA-X Network Analyser was used. Since the network analyser is sensitive to any static discharge, extreme caution was taken at all times whilst the network analyser was in use and all users were required to wear an anti-static wristband. Before using the network analyser to obtain measurements it had to be carefully calibrated to ensure that any results obtained were of high accuracy.

After calibrating the network analyser, the single microstrip patch antenna and then after that, the microstrip patch antenna array were then connected to the network analyser via a coax cable. Whilst connected the antennas were faced towards radiation absorbent foam pads as seen in Figure 6.1 and Figure 6.2 to stop any unwanted interference negatively affecting the measurements. The network analyser then ran a frequency sweep over the set range of 2-3 GHz for both antennas. The real time $S_{1,1}$ reflection coefficient parameters for both antennas were displayed on the screen of the network analyser, and the measurements as raw data were saved on a USB to be plotted with a suitable graphing software. More images of the experimental setup can be seen in Appendix F.

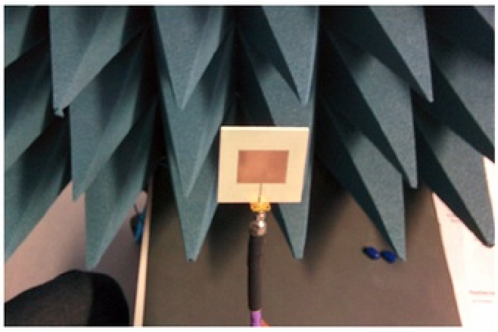


Figure 6.1: Experimental setup for the network analyser and single microstrip patch antenna

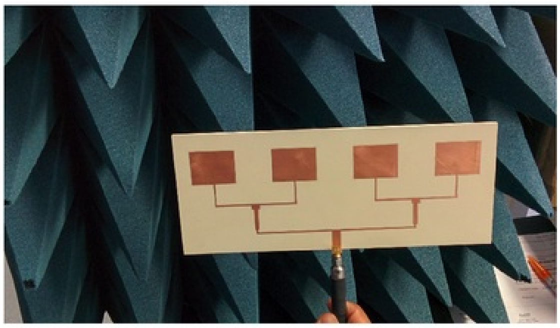


Figure 6.2: Experimental setup for the network analyser and microstrip patch antenna array

6.1.1.2 Directivity, Gain & Radiation Patterns

The next series of key tests to be performed was to obtain the directivity, gain and radiation patterns for antenna subsystems. However due to an accident whilst testing, Subsystem 3 the microstrip patch antenna array was not able to be tested due to a snapped off SMA connector and damaged ground plane which could not be repaired in time. These series of tests were performed at the CSIRO anechoic chamber in Marsfield. The CSIRO anechoic chamber was completely covered by radiation absorbent foam padding and is completely shielded from EM radiation. The measurements in the chamber were undertaken using Spherical Near Field Imaging. A test probe antenna that had the frequency of interest(2.45GHz) within its frequency range was selected and was placed a distance away directly opposite to the mounted prototype microstrip patch antenna. The antennas were connected to the network analyser and initially at the start of the measurements they were both facing each other. The experimental setup in the CSIRO anechoic chamber can be seen in Figures 6.3 and 6.4. The NSI Spherical Near Field Imaging system collected data by transmitting a signal from the probe antenna at a range of different frequencies to the mounted prototype microstrip patch antenna, that rotated at different orientations along the Theta and Phi planes. Similarly, the same set of procedures and measurements were undertaken for a standard gain horn to later calculate the gain of the antenna using the gain comparison method. The data obtained by the system was then converted into far field results using the NSI software on the PC which converted the data using a Fourier transform. The directivity of the antennas was recorded for the frequency points in the frequency range measured, so that it could be plotted with a suitable graphing software. Also, the radiation patterns of the Co-polar and Cross-polar measurements for the e-field and h-field were saved on USB.

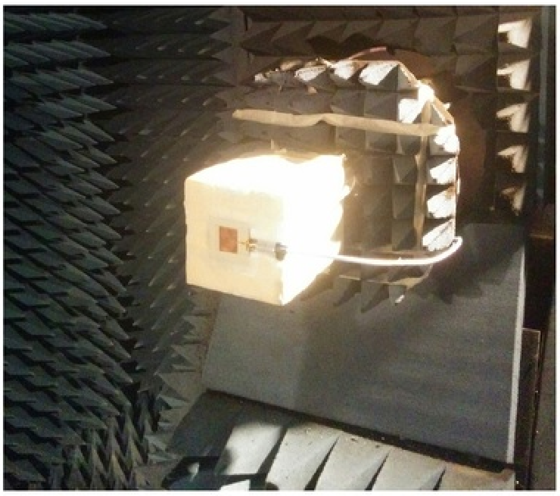


Figure 6.3: Experimental setup in anechoic chamber with microstrip patch antenna

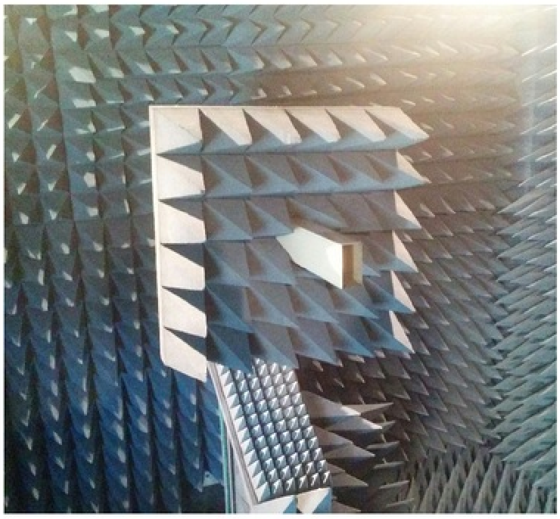


Figure 6.4: Experimental setup in anechoic chamber with test probe antenna

6.1.2 Results Obtained with Analysis and Further Discussion

6.1.2.1 Microstrip Patch Antenna - Subsystem 1

Once the test to obtain the $S_{1,1}$ reflection coefficient parameter was performed and the raw data was collected for the microstrip patch antenna; the raw data was then plotted using Microsoft excel. The resulting graph with the data plotted can be seen in Figure 6.5.

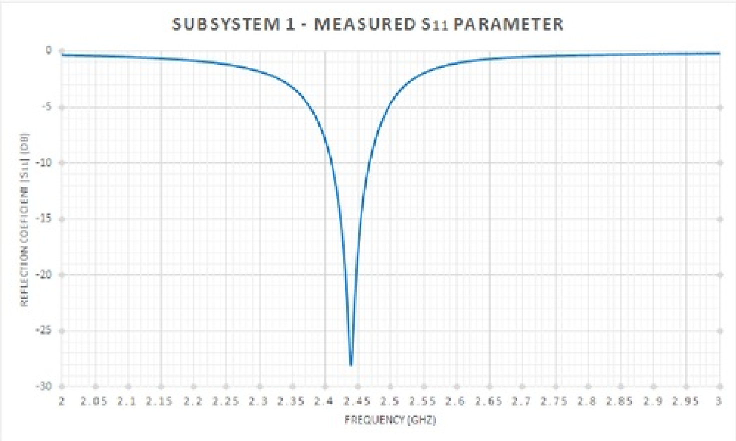


Figure 6.5: $S_{1,1}$ parameter obtained from the physical measurements

From Figure 6.5 it can be seen that the microstrip patch antenna resonates at a frequency of 2.439 GHz, with the return loss equal to 28dB (-28dB $S_{1,1}$). This $S_{1,1}$ reflection coefficient parameter of -28dB shows that the antenna is well matched and it also exceeds the typical industry benchmark of -10dB for the $S_{1,1}$ parameter. Figure 6.5 also shows the amount of bandwidth that the prototype microstrip patch antenna has. At a $S_{1,1}$ parameter of -10dB the antenna has a bandwidth of 0.057 GHz, which is equal to 57 MHz.

However, it must be noted that when the measured results for the single microstrip patch antenna are compared to the results obtained from simulations as shown in Figure 6.6, it can be seen that there is a slight shift in the resonant frequency and the bandwidth has dropped and become narrower. Even from the tuning undertaken whilst performing quality control in the manufacturing stage to fix the original shift in frequency, there still exists a shift in the resonant frequency of 14 MHz. As mentioned in the manufacturing section of the report, the most likely cause for this shift in the resonant frequency is due to a variance in the relative permittivity ϵ_r of the ROGERS TMM4 substrate compared to the ideal value of 4.5 used in simulations and stated in the manufactures data sheet. It could also be due other factors such as slight manufacturing errors caused by the tolerances of the equipment used. The narrower bandwidth displayed by the manufactured prototype of the single microstrip patch antenna when compared to simulated results can be also due to the variance in the relative permittivity ϵ_r compared to the ideal value of 4.5 and slight manufacturing errors caused by the tolerances of the equipment which may have affected the width of the patch and hence reduced the bandwidth.

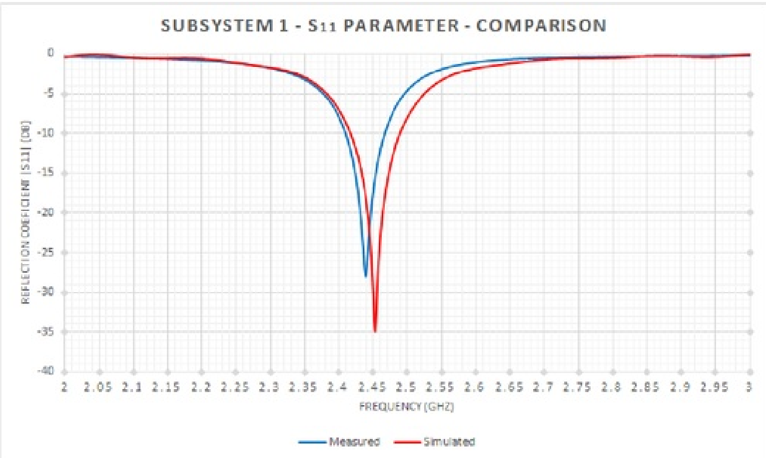


Figure 6.6: $S_{1,1}$ parameter comparison of measured vs. simulated

Once the measurements to obtain the directivity, gain and radiation patterns was performed and the raw data was collected for the microstrip patch antenna; the raw data was then plotted using Microsoft excel.

For the directivity of the microstrip patch antenna which can be seen plotted in Figure 6.7, the microstrip patch antenna has a directivity of 5.873 dBi at 2.45GHz. For the gain of the microstrip patch antenna, which was calculated using the gain comparison method from the measured results and can be seen plotted in Figure 6.8, the microstrip patch antenna has a gain of 4.686 dBi at 2.45GHz.

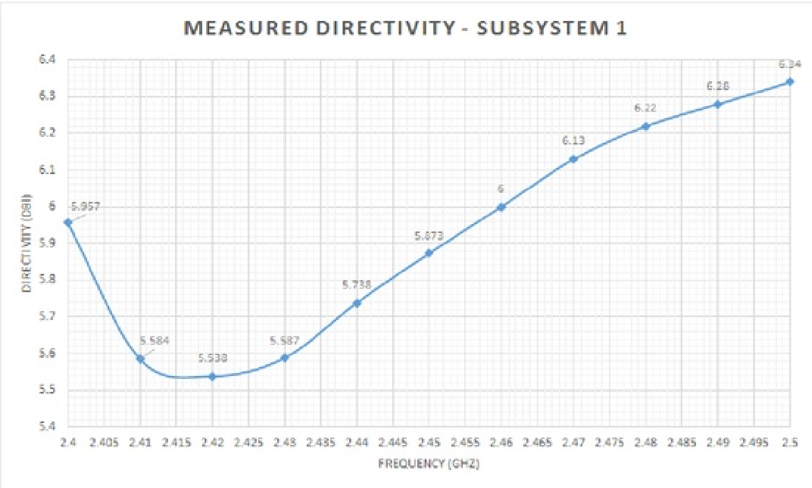


Figure 6.7: Measured Directivity of the the microstrip patch antenna

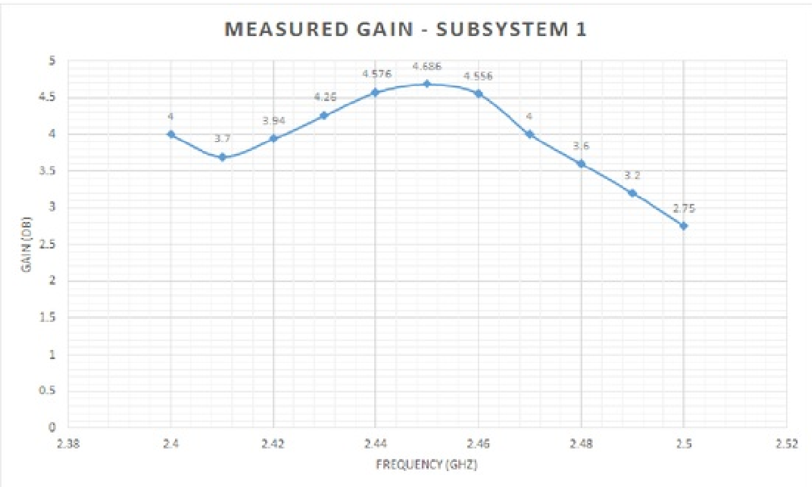


Figure 6.8: Measured Gain of the the microstrip patch antenna

The directivity obtained is much less than the directivity of 6.43 dBi obtained in simulations and the gain obtained is also less than the gain of 6.1 dB obtained in simulations. One reason for this drop in the directivity and gain when compared to the simulated results can once again be put down to the variance in the relative permittivity ϵ_r of the ROGERS TMM4 substrate compared to, the ideal value of 4.5 used in simulations and stated in the manufactures data sheet. Another reason for the drop in the directivity and gain, is that there could be a variance in the actual dielectric loss factor tan δ of the substrate compared to the ideal value of 0.002 which is stated in the manufactures data sheet. The actual value of the dielectric loss factor tan δ for the substrate is most likely to be higher than 0.002. This increase in the dielectric loss factor tan δ would increase the loss in the patch, thus leading to a decrease in efficiency and hence that is the reason why the gain and directivity is lower than expected when compared to simulation results.

The plots obtained for the radiation patterns of the Co-polar and Cross-polar measurements of the e-field and h-field for the microstrip patch antenna can be seen in Appendix G.

6.1.2.2 Microstrip Patch Antenna Array - Subsystem 3

Once again after the test to obtain the $S_{1,1}$ reflection coefficient parameter was performed and the raw data was collected for the microstrip patch antenna array, the raw data was then plotted using Microsoft excel. The resulting graph with the data plotted can be seen in Figure 6.9.

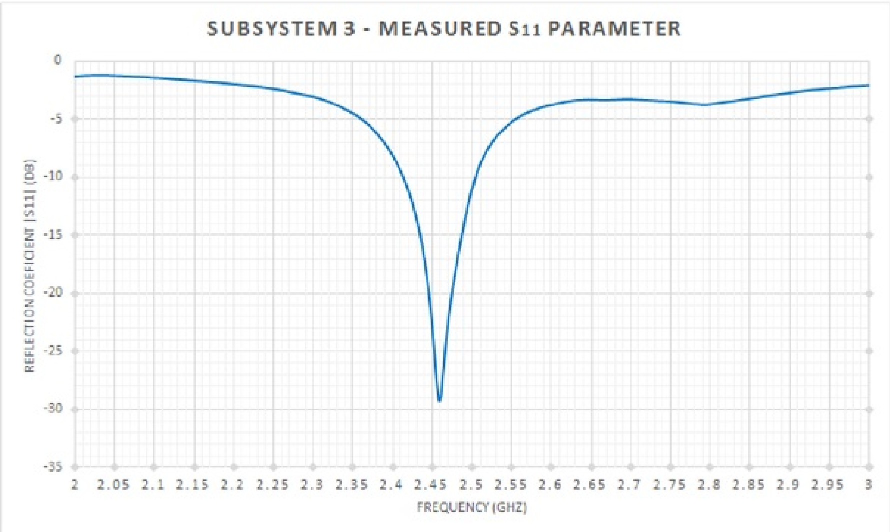


Figure 6.9: $S_{1,1}$ parameter obtained from the physical measurements

From Figure 6.9 it can be seen that the microstrip patch antenna array resonates at a frequency of 2.46 GHz, with the return loss equal to 29dB (-29dB $S_{1,1}$). This $S_{1,1}$ reflection coefficient parameter of -29dB shows that the antenna array is well matched and it also exceeds the typical industry benchmark of -10dB for the $S_{1,1}$ parameter. Figure 6.9 also shows the amount of bandwidth that the prototype microstrip patch antenna array has. At a $S_{1,1}$ parameter of -10dB the antenna array has a bandwidth of 0.09GHz, which is equal to 90 MHz.

Once again, it must be noted that when the measured results for the microstrip patch antenna array are compared to the results obtained from simulations as shown in Figure 6.10, it can be seen that there is a slight shift in the resonant frequency. However in this case the bandwidth has increased and has become broader. Even after the tuning undertaken whilst performing quality control in the manufacturing stage to fix the original shift in frequency, there still exists a slight shift in the resonant frequency of about 4 MHz. As mentioned beforehand, the most likely cause for this shift in the resonant frequency is due to a variance in the relative permittivity ϵ_r compared to the ideal value of 4.5 used in simulations and stated in the manufactures data sheet. It could also be due other factors such as slight manufacturing errors caused by the tolerances of the equipment used.

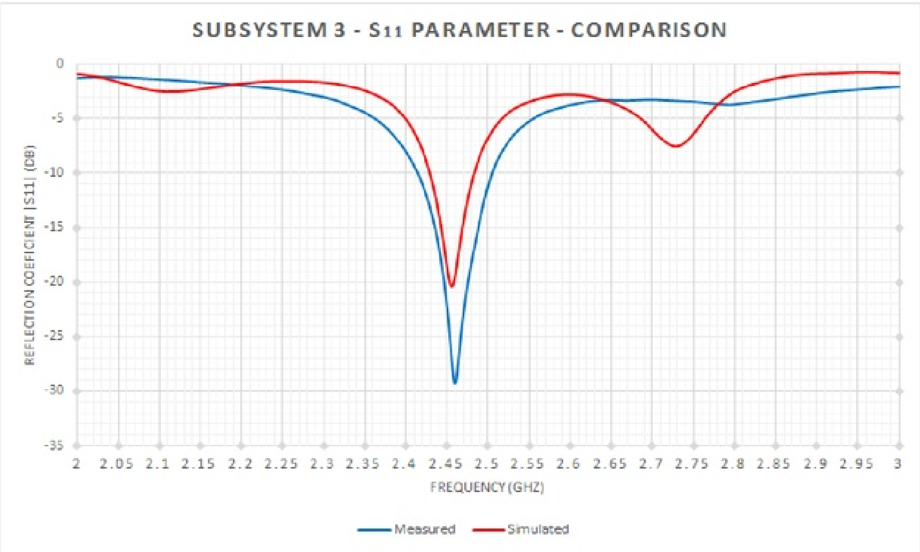


Figure 6.10: $S_{1,1}$ parameter comparison of measured vs. simulated

6.2 Rectenna System; Physical Testing and Results Obtained with Analysis - System 1 and 2

6.2.1 Experimental Procedure and Setup

To test and measure the performance and effectiveness of both the rectenna systems, a few different experimental procedures with variances in test conditions, were undertaken.

The first test was implemented to measure the performance of the rectenna systems and at the same time was used to determine and verify which diode that formed Subsystem 2 the rectifying and voltage multiplying circuit was most suitable for the rectenna systems. Both Rectenna Systems 1 & 2 were both tested with the two circuits of Subsystem 2 that each comprised of the different diodes, namely the HSMS-2820 & HSMS-2850 diodes.

In the first test a commercially available 19dBi dual polarity panel antenna was used with one of the polarisations blocked off with a 50 Ohm matched load. The antenna was placed at a height of 0.8 meters above the ground and was then connected to the Anritsu MG3696B Signal Generator via a coax cable. The signal generator produced a continuous wave at the frequency of 2.45Ghz, with a maximum transmit power of 29dBm, which is equal to approximately 0.79W. The rectenna systems were then placed at a certain distance away from the transmitting antenna and the distance was increased in 0.5 meter intervals up to a maximum distance of 3.5 meters, due to the limited size of the laboratory. The output rectenna system was then connected to a 10kOhm resistor acting as the load and the voltage across this load was then measured with the KEYSIGHT U1232A Multimeter at each distance interval. The experimental setup of the first test in the laboratory, is shown in Figure 6.11 and Figure 6.12.

Figure 6.11: Experimental setup for Rectenna System-1 testing in the laboratory

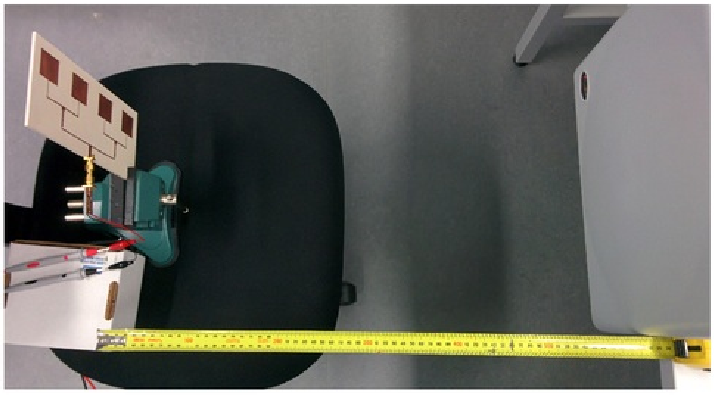


Figure 6.12: Experimental setup for Rectenna System-2 testing in the laboratory

The second test was implemented to measure the effectiveness and performance of both the rectenna systems at a lower power level compared to the previous test. The experimental setup and procedures were almost identical to the first test, however with the difference that only the optimal diode which was determined by the first test would be used and that the transmit power of the signal generator was now reduced to 27dBm, which is equal to 0.5W.

The third test was implemented to demonstrate the effectiveness and real world performance of both the rectenna systems. This test was application based and hence demonstrated and showcased the effectiveness and real world performance of both the rectenna systems by using the rectenna systems to power a selection of typical electronic devices. The devices that were selected included: a 2.1V green LED, a digital clock timer and a digital humidity sensor system. The experimental setup and procedures were almost identical to the first test and second test, where both a 27dBm(0.5w) and 29dBm(0.8w) transmitted signal was used. However instead of recording data at different distances the maximum operating distance of the electronic devices was recorded for both power levels.

6.2.2 Results Obtained with Analysis and Further Discussion

6.2.2.1 Rectenna - System 1

For the first test of Rectenna System 1, data was obtained for the rectenna system that was implemented with Subsystem 2 using the HSMS-2850 diodes. The data obtained was collected in the range of 0.5m to 3.5m with data recorded at 0.5m intervals. Similarly, data was obtained for the rectenna system that was implemented with Subsystem 2 using the HSMS-2820 diodes. The data that was recorded was then plotted using Microsoft Excel. The resulting graph of the data plotted can be seen in Figure 6.13.

It can be seen from Figure 6.13 that Rectenna System 1 implemented with Subsystem 2 using the HSMS-2850 diode had: a maximum voltage of 1.445v, a minimum voltage of 0.148v and an average voltage of 0.525 over the range of distances. Whereas Rectenna System 1 implemented with Subsystem 2 using the HSMS-2820 diode had: a maximum voltage of 6.304v, a minimum voltage of 0.608v and an average voltage of 2.421v over the range of distances. Therefore, from the results obtained it can be said Subsystem 2 the rectifying and voltage multiplying circuit implemented using the HSMS-2820 diode is the most suitable and optimal circuit/diode combination for Rectenna System 1. Also, it must be mentioned that Rectenna System 1 implemented with Subsystem 2 using the HSMS-2820 diode displayed good and consistent performance throughout the range of distances as it was effective in collecting the transmitted power in free space and converting into useable DC voltage.

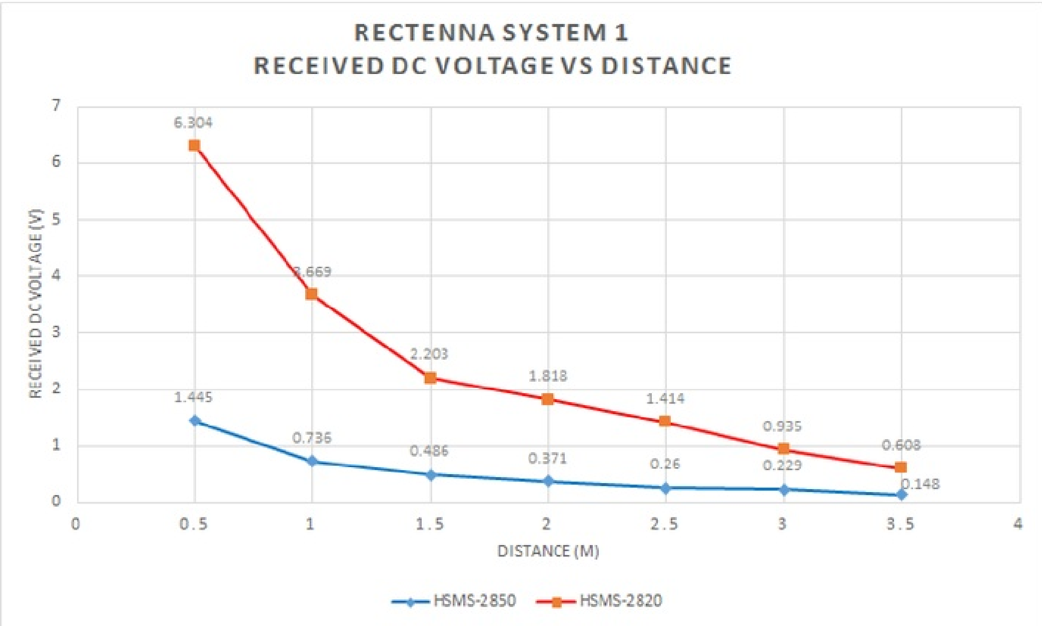


Figure 6.13: Rectenna System 1 - Received DC Voltage Vs Distance for both the HSMS-2820 and HSMS-2850 diodes

In the second test of Rectenna System 1, data was obtained for the rectenna system that was implemented with Subsystem 2 using the optimal HSMS-2820 diodes whilst the transmit power was reduced to 27dBm(0.5w). The data that was recorded was then plotted, the resulting graph of the data plotted can be seen in Figure 6.14. It can be seen, that even at a reduced transmit power the rectenna system displays good performance, as it is effective in collecting the transmitted power in free space and converting it into useable DC voltage.

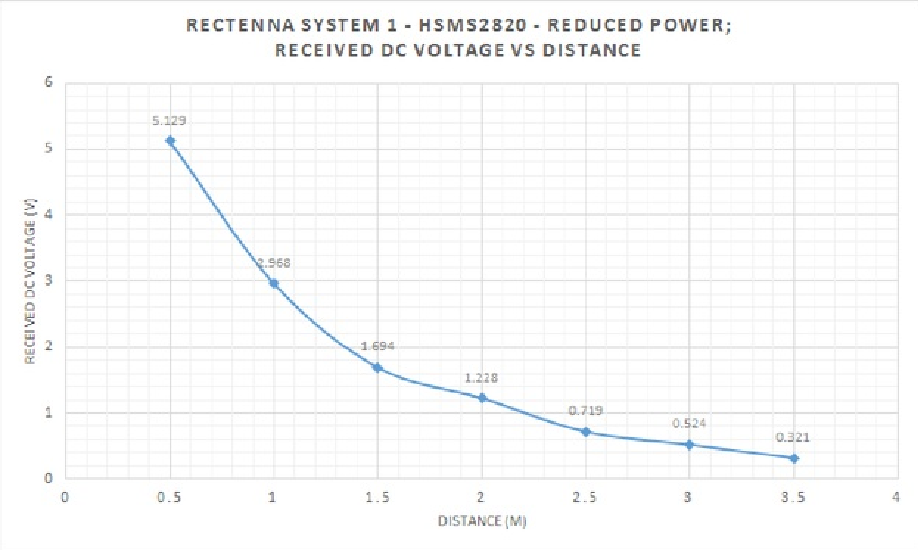


Figure 6.14: Rectenna System 1 at Reduced Power - Received DC Voltage Vs Distance

In the third test, the effectiveness and real world performance of Rectenna System 1 was demonstrated. The first stage of the third test consisted of Rectenna System 1 being connected to a 2.1v green LED. With the green LED connected to Rectenna System 1, the LED could turn on, within the range of 2-2.5m for both the two power levels. The green LED powered by Rectenna System 1 can be seen in Figure 6.15.

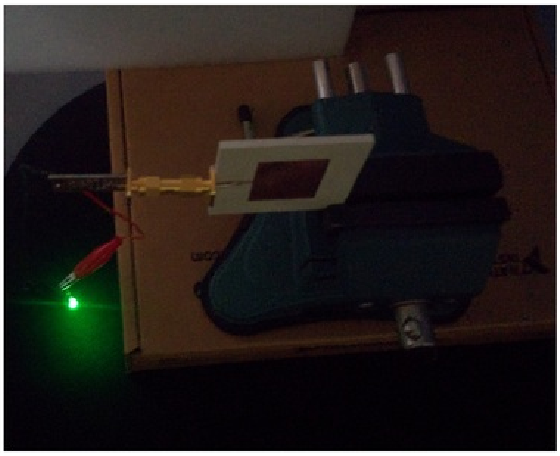


Figure 6.15: Rectenna System 1 Powering a 2.1v Green LED

The second stage of the third test consisted of Rectenna System 1 being connected to a digital clock timer. Whilst power was transmitted in free space by the transmitting antenna, the digital clock timer was able to turn on and operate within the range of 2.5-3m for both the two power levels. The digital clock timer powered by Rectenna System 1 can be seen in Figure 6.16.

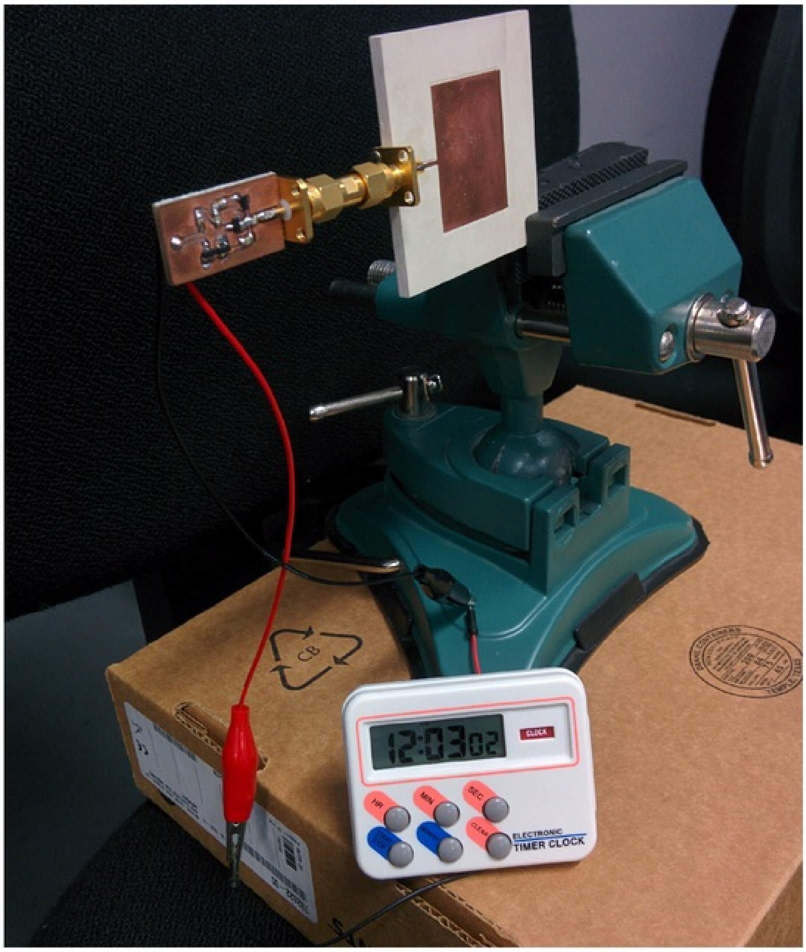


Figure 6.16: Rectenna System 1 Powering a digital clock timer

The final stage of the third test consisted of Rectenna System 1 being connected to a digital humidity sensor. Whilst power was transmitted in free space by the transmitting antenna, the digital humidity sensor was able to turn on and operate within the range of 2.5-3m for both the two power levels. The digital humidity sensor system powered by Rectenna System 1 can be seen in Figure 6.17.

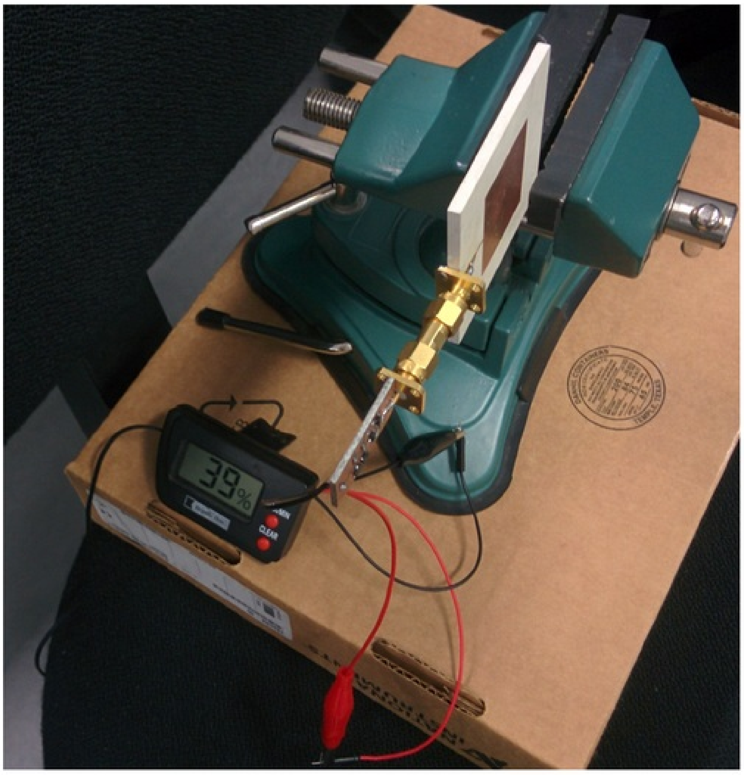


Figure 6.17: Rectenna System 1 Powering a digital humidity sensor

From all the three tests that were performed on Rectenna System 1, it can be said that the rectenna system displayed exceptional performance, as it effectively harvested RF power over the range of distances at different power levels. Particularly taking into consideration that Rectenna System 1 utilised only a small single patch. Also from these tests the real-world performance and effectiveness of the rectenna system was successfully demonstrated as the rectenna could effectively harvest RF power to power a range of typical electronic devices.

6.2.2.2 Rectenna - System 2

Similarly, for the first test of Rectenna System 2, data was obtained for the rectenna system that was implemented with Subsystem 2 using the HSMS-2850 diodes. The data obtained was collected in the range of 0.5m to 3.5m with data recorded at 0.5m intervals. Also, data was obtained for the rectenna system that was implemented with Subsystem 2 using the HSMS-2820 diodes. The data that was recorded was then plotted; the resulting graph of the data plotted can be seen in Figure 6.18.

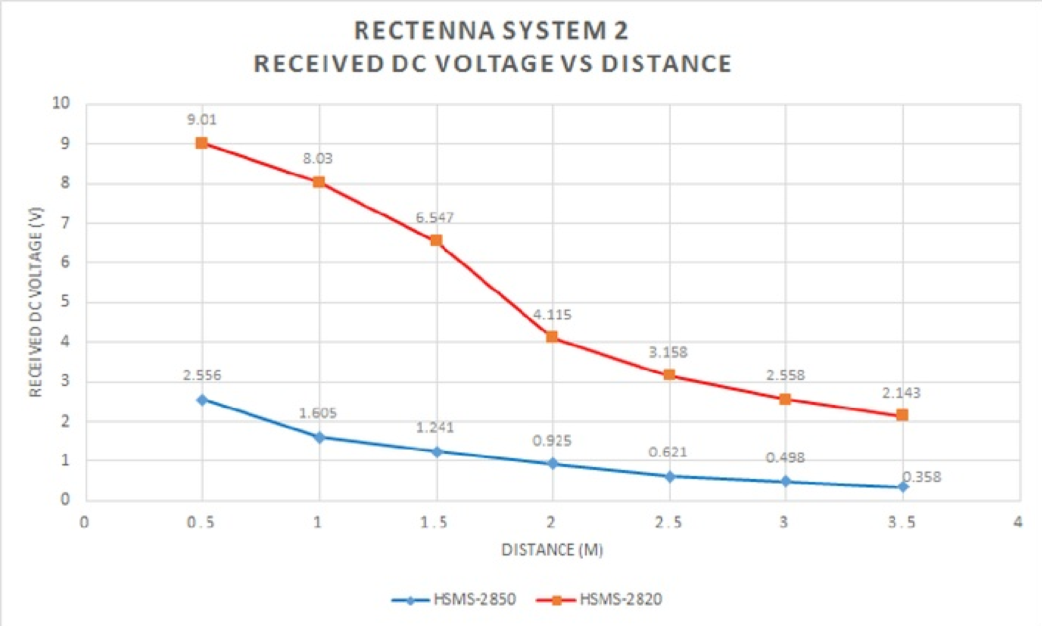


Figure 6.18: Rectenna System 2 - Received DC Voltage Vs Distance for both the HSMS-2820 and HSMS-2850 diodes

It can be seen from Figure 6.18 that Rectenna System 2 implemented with Subsystem 2 using the HSMS-2850 diode had: a maximum voltage of 2.556v, a minimum voltage of 0.358v and an average voltage of 1.114v over the range of distances. Whereas Rectenna System 2 implemented with Subsystem 2 using the HSMS-2820 diode had: a maximum voltage of 9.01v, a minimum voltage of 2.143v and an average voltage of 5.08v over the range of distances. From the results obtained it can be said Subsystem 2 the rectifying and voltage multiplying circuit implemented using the HSMS-2820 diode, is the most suitable and optimal circuit/diode combination for Rectenna System 2. Also, it must be mentioned that Rectenna System 2 implemented with Subsystem 2 using the HSMS-2820 diode displayed good and consistent performance throughout the range of distances as it was effective in collecting the transmitted power in free space and converting into useable DC voltage.

When Rectenna System 2 is compared with Rectenna System 1 as shown in Figure 6.19; it can be said that Rectenna System 2 has greater performance in harvesting RF energy and that it can operate more effectively at further distances. The reason for this greater performance is because Rectenna System 2 utilises Subsystem 3, a microstrip patch antenna array. Hence it has a greater amount of gain which allows it to collect and harvest a significantly greater amount of RF energy in contrast to Rectenna System 1.

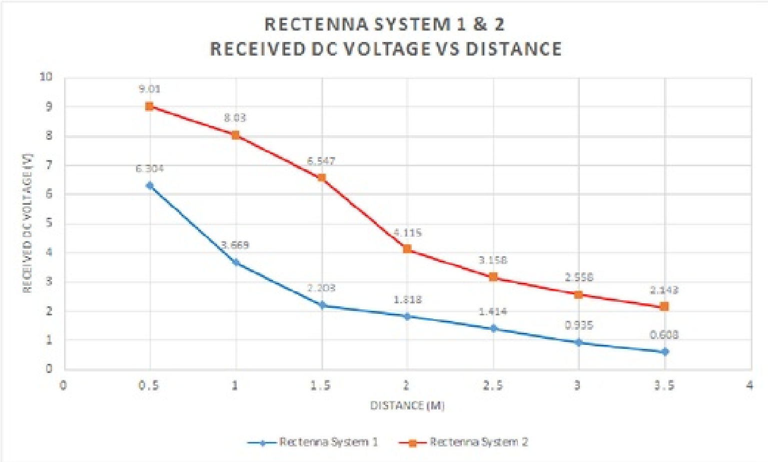


Figure 6.19: Rectenna System 1 and 2 comparison - HSMS-2820 diode

In the second test of Rectenna System 2, data was obtained for the rectenna system that was implemented with Subsystem 2 using the optimal HSMS-2820 diodes, whilst the transmit power was reduced to 27dBm(0.5w). The data that was recorded was then plotted, the resulting graph of the data plotted can be seen in Figure 6.20. It can be seen, that even at a reduced transmit power the rectenna system displays good performance, as it is effective in collecting the transmitted power in free space and converting it into useable DC voltage.

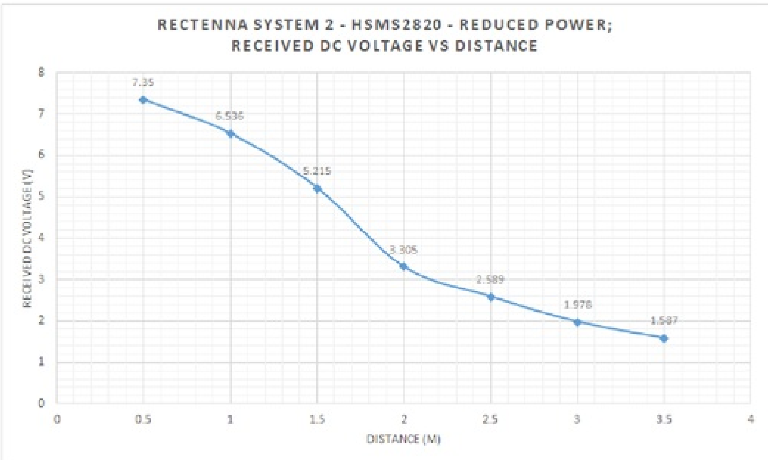


Figure 6.20: Rectenna System 2 at Reduced Power - Received DC Voltage Vs Distance

Once again when Rectenna System 2 is compared with Rectenna System 1 as shown in Figure 6.21; it can be said that Rectenna System 2 has greater performance in harvesting RF energy and is more effective, even with a reduced transmit power.

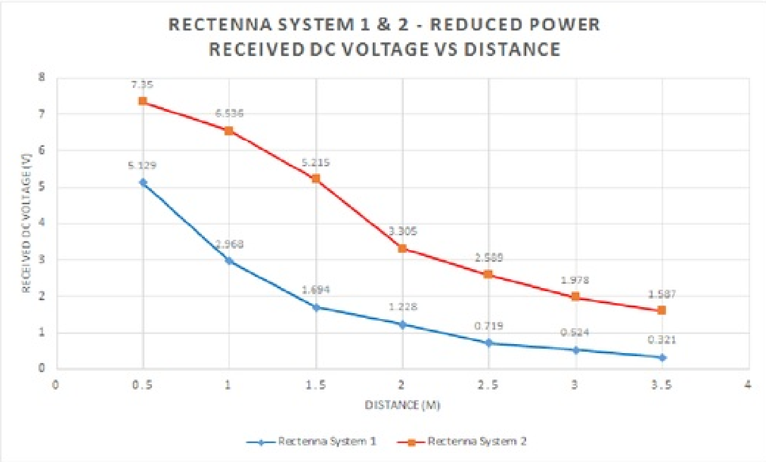


Figure 6.21: Rectenna System 1 and 2 comparison at Reduced Power

Similarly, for the third test, the effectiveness and real world performance of Rectenna System 2 1 was demonstrated. The first stage of the third test consisted of Rectenna System 2 being connected to a 2.1v green LED. With the green LED connected to Rectenna System 2, the LED could turn on within the range of 2.5-3m for both the two power levels. The green LED powered by Rectenna System 2 can be seen in Figure 6.22.

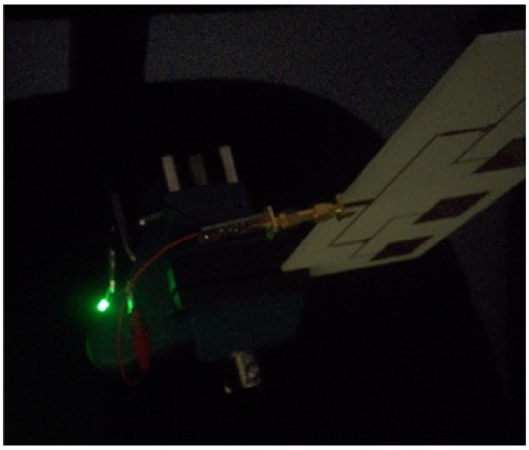


Figure 6.22: Rectenna System 2 Powering a 2.1v Green LED

The second stage of the third test consisted of Rectenna System 2 being connected to a digital clock timer. Whilst power was transmitted in free space by the transmitting antenna, the digital clock timer was able to turn on and operate, within the range of 3-3.5m for both the two power levels. The digital clock timer powered by Rectenna System 2 can be seen in Figure 6.23.

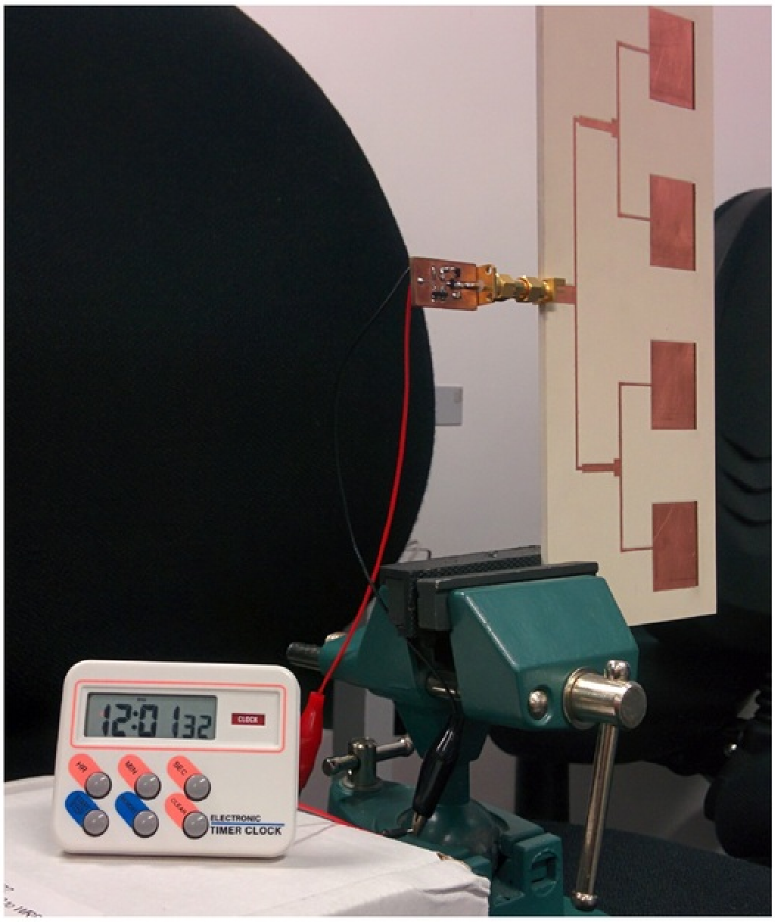


Figure 6.23: Rectenna System 2 Powering a digital clock timer

The final stage of the third test consisted of Rectenna System 2 being connected to a digital humidity sensor. Whilst power was transmitted in free space by the transmitting antenna, the digital humidity sensor system was able to turn on and operate, within the range of 3-3.5m for both the two power levels. The digital humidity sensor system powered by Rectenna System 2 can be seen in Figure 6.24.

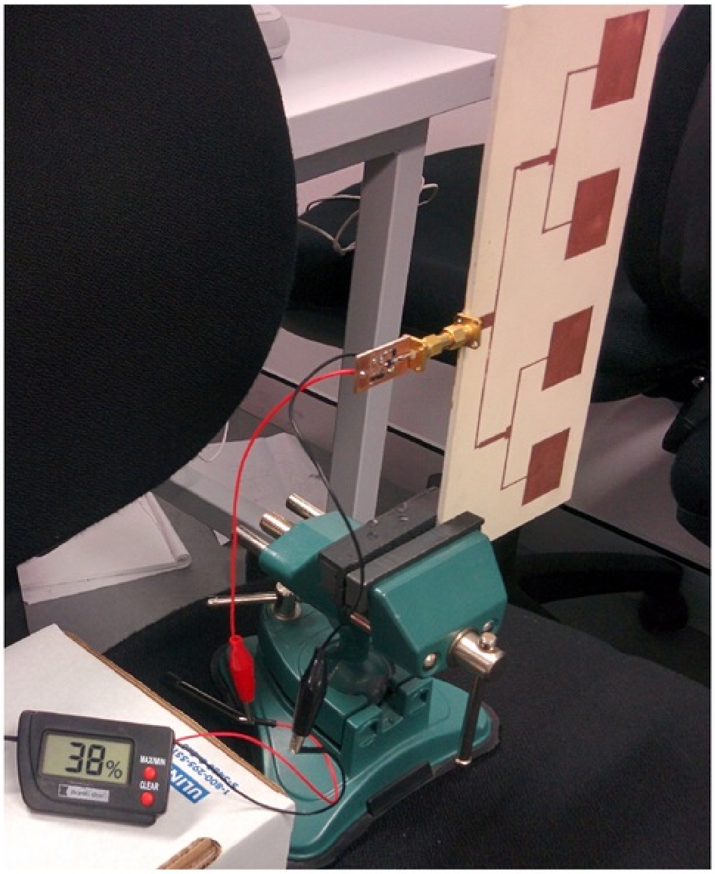


Figure 6.24: Rectenna System 2 Powering a digital humidity sensor

From all the three tests that were performed on Rectenna System 2, it can be said that the rectenna system displayed exceptional performance, as it effectively harvested RF power over the range of distances at different power levels. The performance that Rectenna System 2 displayed was greater than Rectenna 1 as it utilises Subsystem 3, a microstrip patch antenna array and hence has a greater amount of gain which allows it to collect and harvest a significantly greater amount of RF energy in contrast to Rectenna System 1. It can be said that Rectenna System 2 with this greater amount of gain would be more effective at further distances than Rectenna System 1. Hence Rectenna System 2 is much more effective than Rectenna System 1. Also from these tests the real-world performance and effectiveness of the Rectenna System 2 was successfully demonstrated, as the rectenna could effectively harvest RF energy to power a range of typical electronic devices.

Chapter 7

Conclusions and Future Work

This chapter of the report comprises of a general conclusion that accounts for the work that has been undertaken and the objectives that have been achieved through the undertaking of this thesis project. It also provides a discussion on the future work that can be undertaken using the advancements made from this research project.

7.1 Conclusion

This thesis project has explored and addressed the opportunities which presents a significant research problem in relation to, the capturing and harvesting of RF energy using small antennas with an effective conversion of RF energy to DC energy with minimal losses.

The overall objective of this thesis project was to, successfully design, create and implement an effective rectenna system for low-cost low-power operation at the frequency of 2.45 GHz. The short-term aim of the thesis project was to fabricate and manufacture using printed circuit board technology a prototype of this optimal rectenna design that was effective. Once manufactured, this prototype was used to demonstrate the operating principal of the rectenna, its effectiveness and real world performance.

The above aims and objectives of this thesis project have been fulfilled with the design, creation, implementation and testing of two different rectenna system at the 2.45Ghz ISM band. These rectenna systems were based on the different subsystems that were also designed, created, implemented and tested to meet the requirements of the overall rectenna systems.

The first of these rectenna system, Rectenna System 1 was designed with Subsystem 1, a single rectangular microstrip patch antenna and Subsystem 2 a two stage Cockcroft Walton rectifier and multiplier circuit. Whereas, the second rectenna system, Rectenna System 2 was designed comprising of Subsystem 3 a microstrip patch antenna array and Subsystem 2 a two stage Cockcroft Walton rectifier and multiplier circuit. These two rectenna systems and their related subsystems were then manufactured using printed circuit board technology comprising of computer automated milling and chemical etching.

The resulting two rectenna systems were then tested. Both displayed exceptional effectiveness and real world performance with the ability to harvest a significant amount of RF power at 2.45GHz, to operate a selection of typical electronic devices such as a: 2.1v green LED, digital clock timer and digital humidity sensor; up to the range of 3.5 meters. Rectenna System 2 displayed greater performance in comparison to Rectenna System 1, as during testing it obtained higher voltages at further distances and therefore Rectenna System 2 would be more effective in harvesting RF power at greater distances.

Hence after looking at the main results that have been achieved it can be said that this project has met its overall aims and objectives, as the outcome of this project was; the successful design, creation and implementation of two effective rectenna systems for low-cost low-power operation at the frequency of 2.45 GHz. Also, the operating principal of the rectenna systems, their effectiveness and real world performance have been successfully demonstrated. The next step would be to extend this project to further develop the rectenna systems in the future and apply the rectenna system to real world applications.

7.2 Future Work

In the near future, the advancement from this thesis project can be built upon by further developing and testing both rectenna systems that were created. This includes and is not limited to the following:

- Manufacturing and testing the rectenna systems with Subsystem 2 on the Rogers TMM4 substrate,
- Manufacturing and testing the rectenna systems on one whole substrate with the two subsystems coupled directly via a microstrip transmission line,
- Investigating and implementing different antenna array configurations and layouts,
- Investigating size reduction techniques, such as the use of a fractal geometry,
- Developing the rectenna systems specifically for certain applications, hence this requires impedance matching the rectenna systems to suit specific applications with their differing loads.

Future work in the long term relates to the long-term goal and aim of the thesis project. That being to apply the advancements made in the design, creation and implementation of the prototype rectenna system for low-cost low-power operation at the frequency of 2.45 GHz, to other specific applications where higher power levels are required or where different frequency bands are in use. Future work in the long term includes and is not limited to the following:

- Adapting the rectenna systems for applications that require higher power levels, by investigating higher levels of multiplication using the Cockcroft Walton rectifying and multiplying circuit,
- Adapting the rectenna systems for different frequency bands, by implementing different geometrical patch dimensions and investigating the use of different diodes for the circuit at different frequencies,
- Developing the rectenna systems as a commercial product.

Chapter 8

Abbreviations

AC	Alternating Current
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
dB	Decibels
DC	Direct Current
ISM	Industrial-Scientific-Medical
MIC	Macquarie Engineering and Technical Services department
MIC	Microwave Integrated Circuits
PCB	Printed Circuit Board
RF	Radio Frequency
VSWR	Voltage Standing Wave Ratio

Appendix A

Consultation Attendance Sheet

Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
1	1/08/16		Joseph Tad	[illegible]
1	5/08/16		Joseph Tad	[illegible]
2	9/8/16		Joseph Tad	[illegible]
2	9/8/16		Joseph Tad	[illegible]
3	16/8/16		Joseph Tad	[illegible]
5	29/8/16	To Make up for week 4 - was sick in week 4	Joseph Tad	[illegible]
5	30/8/16		Joseph Tad	[illegible]
6	6/9/16		Joseph Tad	[illegible]
7	13/9/16		Joseph Tad	[illegible]
8	4/10/16	Saw USMAN as both Supervisors were away	Joseph Tad	[illegible]
9	10/10/16		Joseph Tad	[illegible]
10	17/10/16		Joseph Tad	[illegible]
11	25/10/16		Joseph Tad	[illegible]
12	1/11/16		Joseph Tad	[illegible]

Appendix B

List of available Substrates stocked by the University

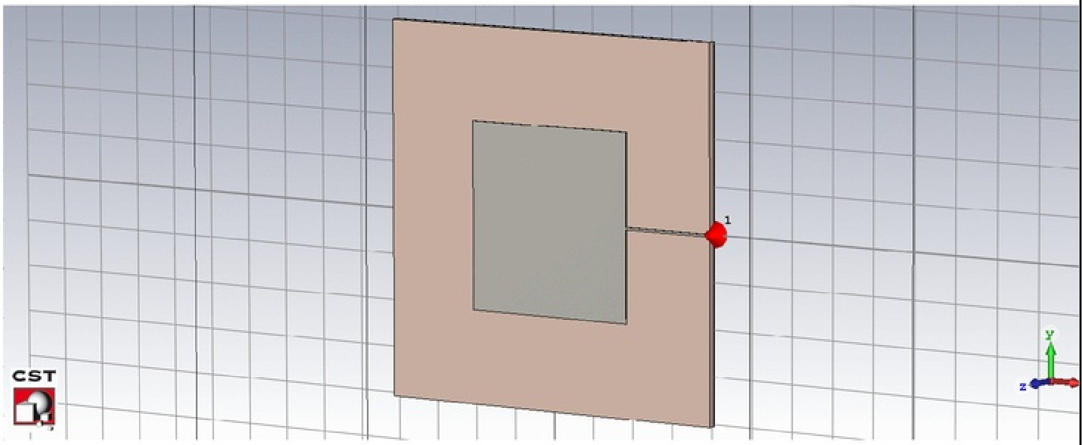
Substrates (Located at E6A 2nd floor, Storage Room near R.225)					
Name	Epsilon	Thickness		Panel Size	Quantity
		(inch)	(mm)	(inch)	
Sheets with copper cladding on both sides					
Arlon	2.33	0.06	1.52	24x12	1
Rogers RO3003	3	0.03	0.76	18x12 C	2.5
		0.06	1.52	12x9	1C
Rogers RO3203	3.02	0.01	0.254	18x12	2
Rogers RO4003	3.55	0.032	0.76	18x12	1
Rogers RO4003C	3.38	0.032	0.76	18x12	2
		0.06	1.52	18x12	2
Rogers RO6002	2.94	0.06	1.524	9x6 C	0.25
		0.06	1.524	6x6	2
Rogers RT/duroid 5870	2.33	0.005	0.127	18x12	2
		0.01	0.254	18x12	2
		0.031	0.76	18x12	2
Rogers RT/duroid 5880	2.2	0.005	0.127	18x12	2
		0.015	0.381	18x12	1
		0.06	1.524	18x12	0.25
Rogers RT/duroid 6002	2.94	0.06	1.524	6x6	2
Rogers RT/duroid 6006	6.15	0.025	0.635	10x10	0
		0.075	1.9	6x6	0
		0.1	2.54	6x6	0
Rogers RT/duroid 6010.2	10.2	0.025	0.635	6x6	1
		0.05	1.27	10x10	1
Rogers RT/duroid 6010.5	10.5	0.025	0.635	22x20	2.5
		0.05	1.27	22x20	1
		0.1	2.54	6x6	1
Rogers RT/duroid 6010.8	10.8	0.1	2.54	10x5	1
Rogers TMM3	3.27	0.125	3.175	18x12	2
				13x12	1
Rogers TMM4	4.5	0.125	3.175	18x12	1
Rogers TMM10	9.2	0.025	0.635	6x6	1
		0.05	1.27	6x6	1
		0.06	1.52	6x6	1
		0.125	3.175	18x12	2
		0.5	12.7	18x12 C	1
Rogers TMM10i	9.8	0.025	0.635	6x6	3
Rogers Ultralam 2000	2.4	0.01	0.254	18x12	1
		0.3	7.62	18x12	5
Rogers Ultralam 2000	2.5	0.062	1.57	18x12	1
Taconic TLC30	3	0.02	0.5	18x12	1
		0.06	1.52	18x12	0
Taconic TLY5	2.2	0.062	1.57	18x4	1
Taconic TLY-5A	2.17	0.093	2.36	18x12	0.75
Poligide	2.3	0.0124	0.315	12x11	1

Appendix C

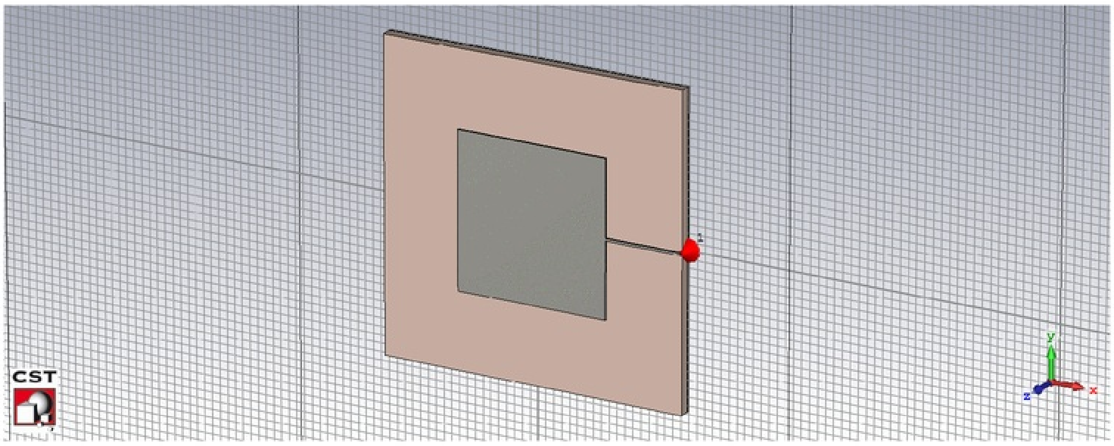
Microstrip Patch Antenna Preliminary Prototypes

This chapter of the appendix displays a selection of some of the preliminary prototypes that were designed and created before deciding on a final prototype for the Microstrip Patch Antenna - Subsystem 1. At first a simple substrate known as FR4 which is low in cost was used to design the first few prototypes, then more complex and advanced substrates were used in later prototypes.

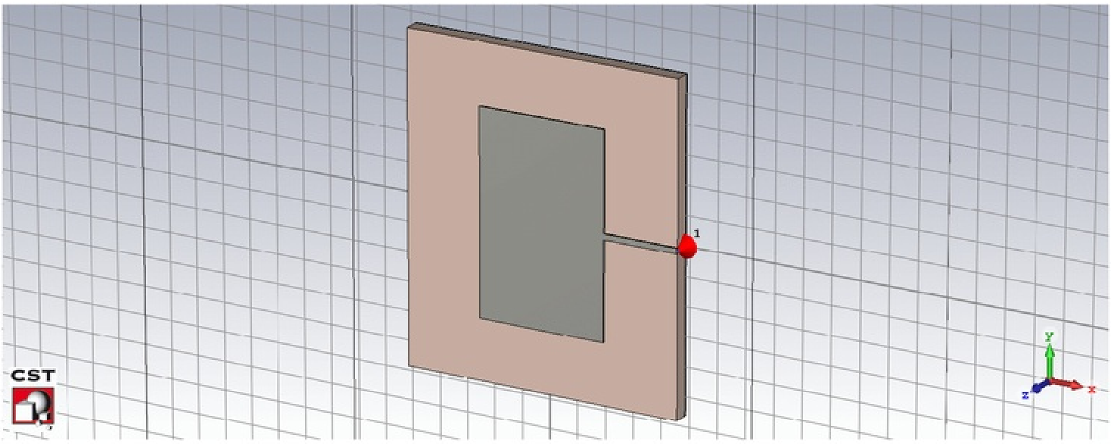
C.1 Rectangular Geometry Antenna on ROGERS RT 5880 Substrate



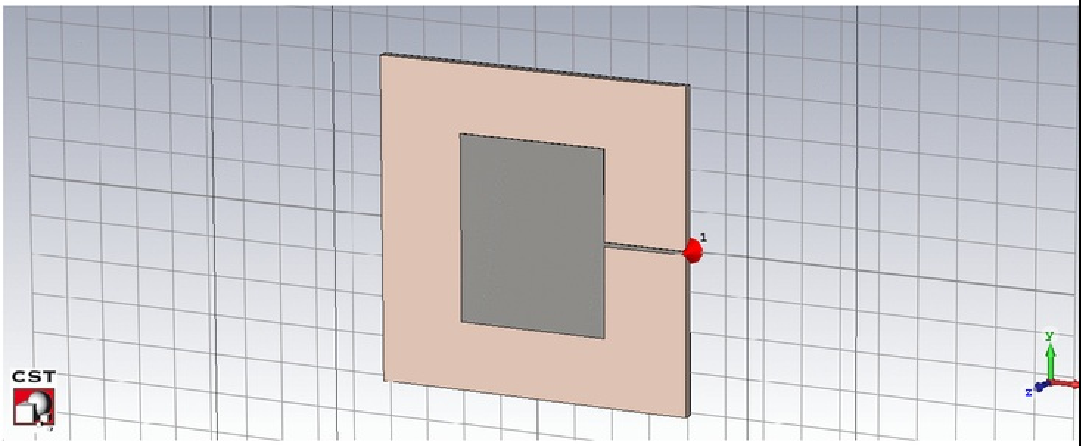
C.2 Rectangular Geometry Antenna on ROGERS RT 6010 Substrate



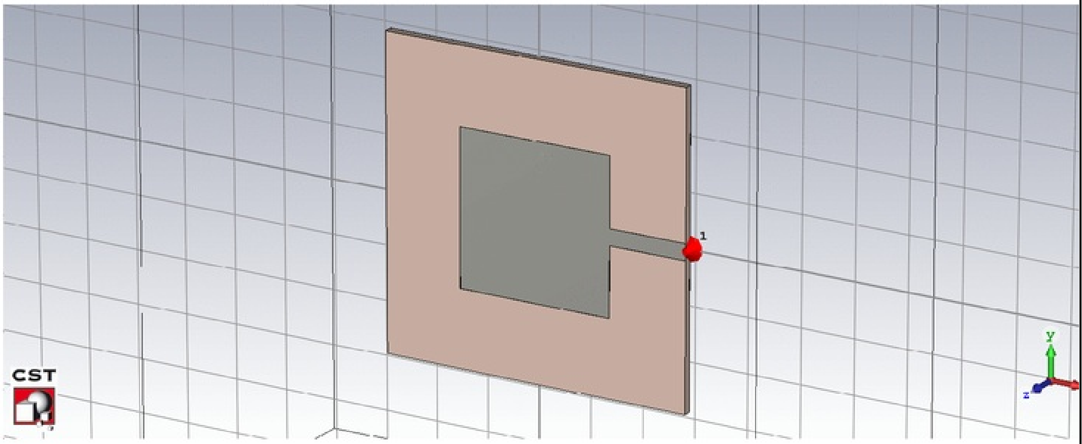
C.3 Rectangular Geometry Antenna on ROGERS RT 6006 Substrate



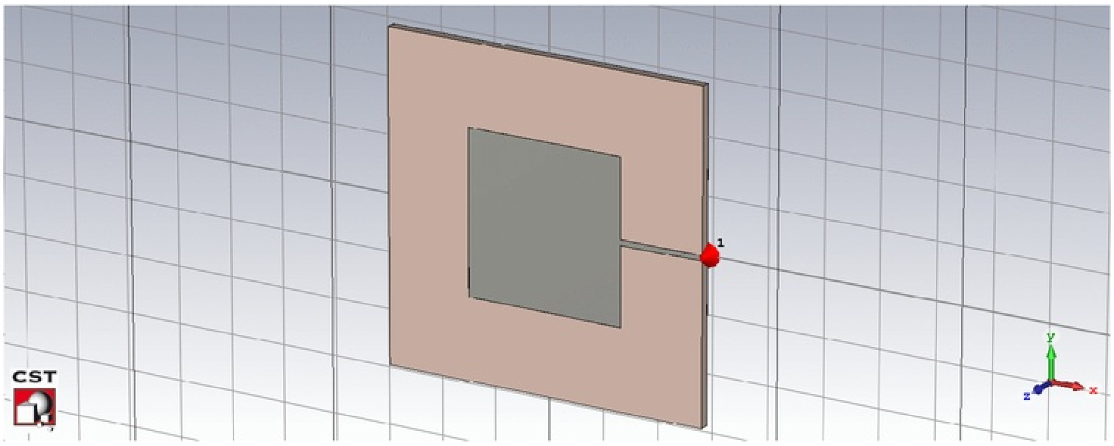
C.4 Rectangular Geometry Antenna on Taconic TLY-5A Substrate



C.5 Square Geometry Antenna on FR4 Substrate



C.6 Rectangular Geometry Antenna on FR4 Substrate



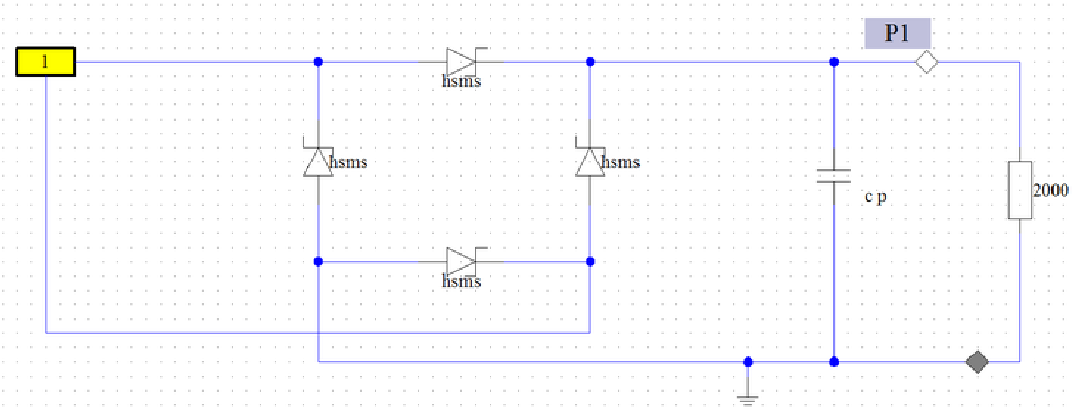
Appendix D

Rectifying and Voltage Multiplying Circuit Preliminary Prototypes

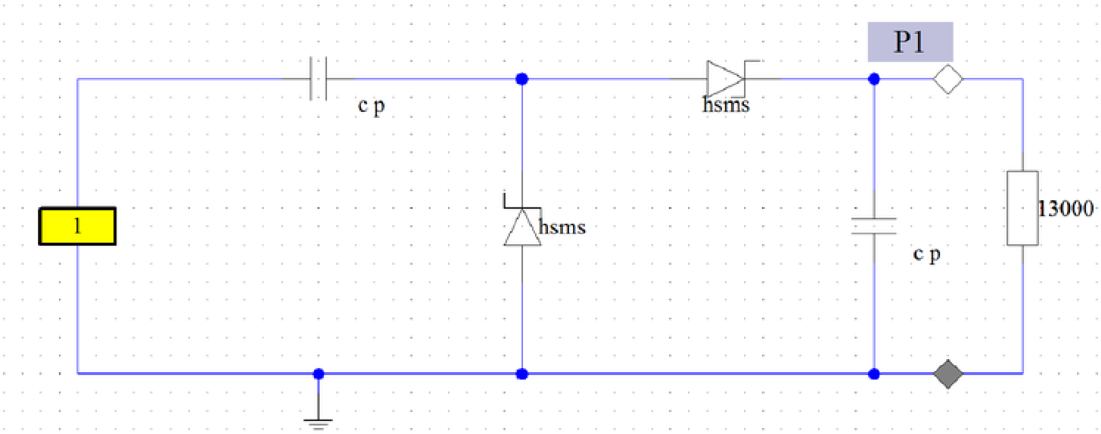
This chapter of the appendix displays a selection of some of the preliminary prototypes that were designed and created before deciding on a final prototype for the Rectifying and Voltage Multiplying Circuit - Subsystem 2.

At first simple rectifier circuits were designed before moving on to more advanced voltage multiplier circuits.

D.1 Full Wave Bridge Rectifier



D.2 Single Stage Cockcroft Walton multiplier circuit



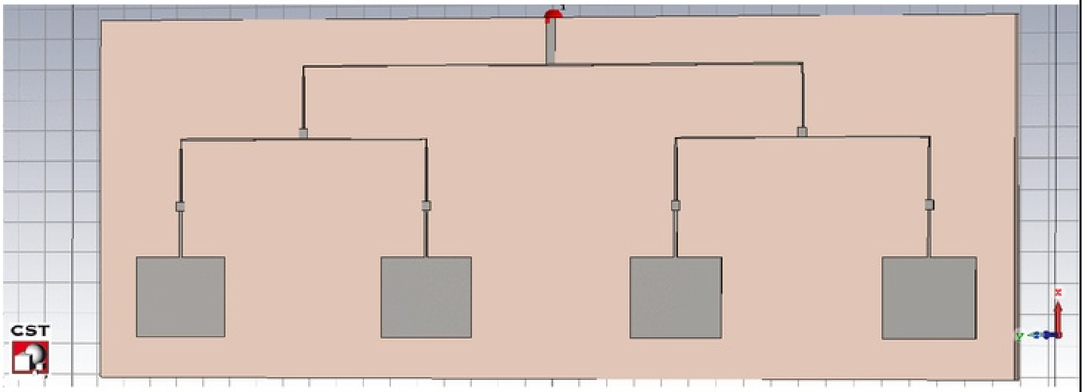
Appendix E

Microstrip Patch Antenna Array Preliminary Prototypes

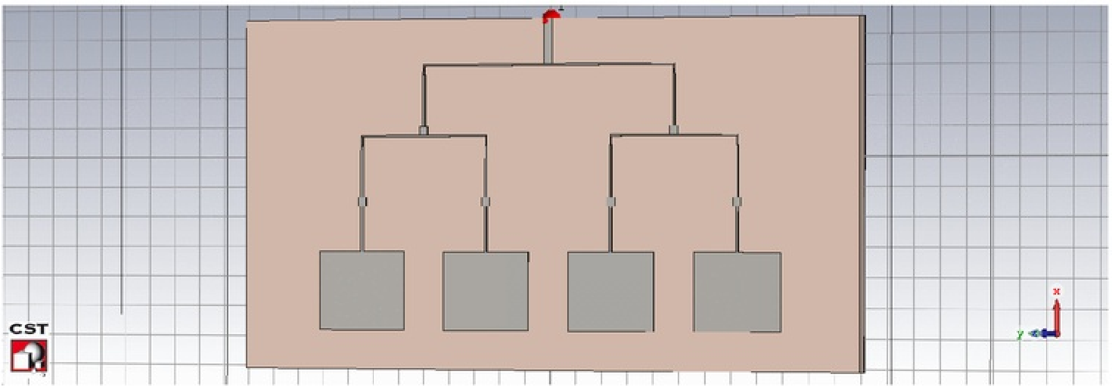
This chapter of the appendix displays a selection of some of the preliminary prototypes that were designed and created before deciding on a final prototype for the Microstrip Patch Antenna Array - Subsystem 3.

These preliminary Prototypes which had variations in the element spacing were not ideal for the subsystem.

E.1 Microstrip Patch Antenna Array with an Element Spacing of 0.75λ



E.2 Microstrip Patch Antenna Array with an Element Spacing of 0.4λ

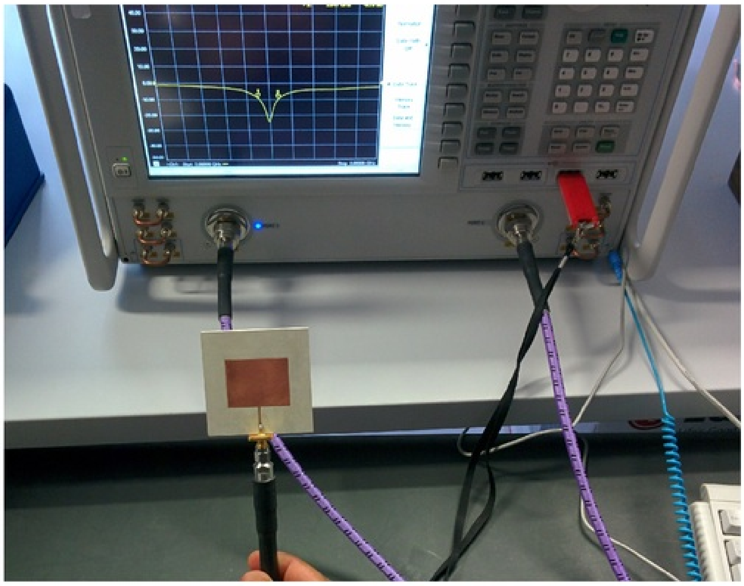


Appendix F

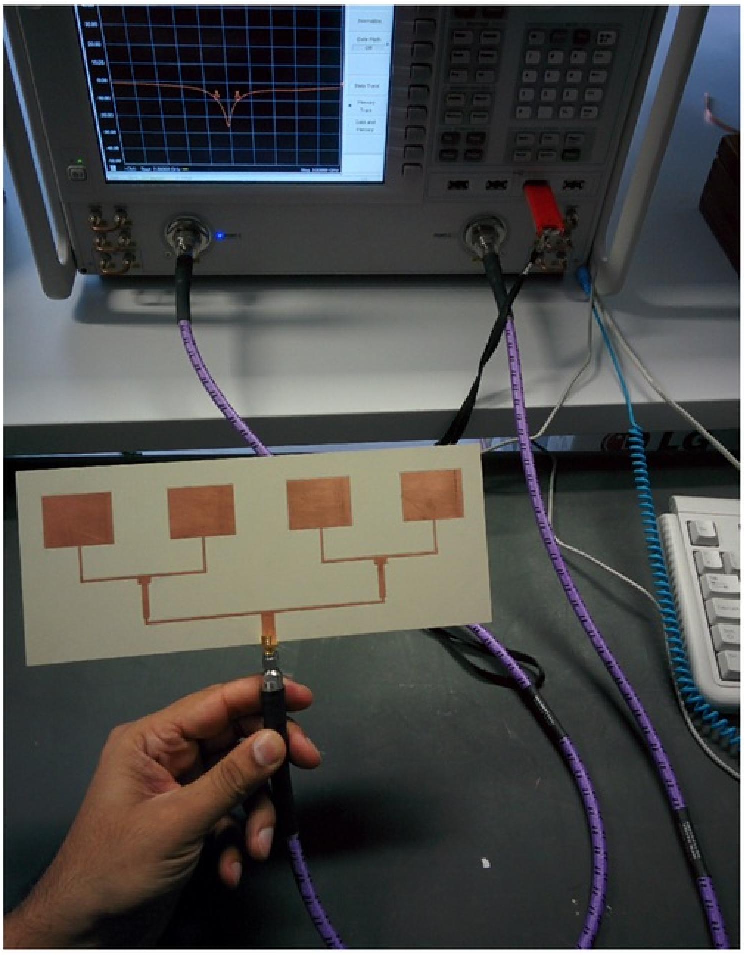
Further Images of the Experimental Setup

This chapter of the appendix displays some further images taken of the Experimental Setup for Subsystem 1 and 3.

F.1 Microstrip Patch Antenna Reflection Coefficient test using the Network Analyser



F.2 Microstrip Patch Antenna Array Reflection Coefficient test using the Network Analyser

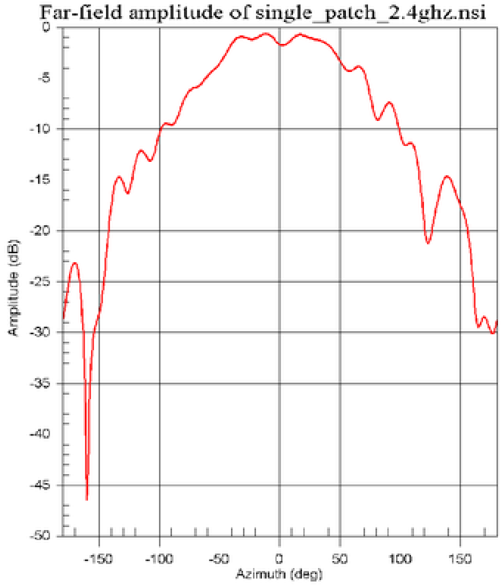


Appendix G

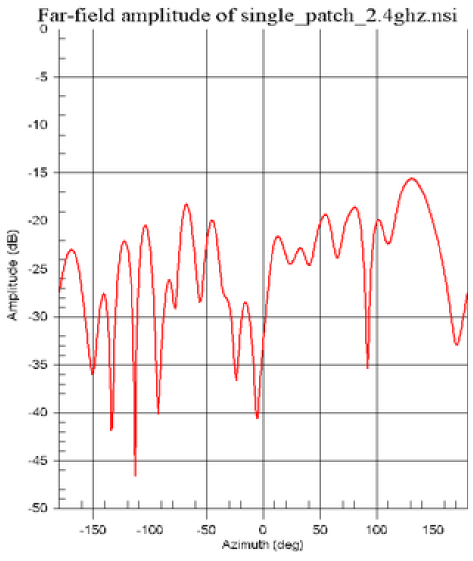
Radiation Patterns obtained for Subsystem 1

This chapter of the appendix displays the plots obtained for the radiation patterns of the Co-polar and Cross-polar measurements of the e-field and h-field for Subsystem 1.

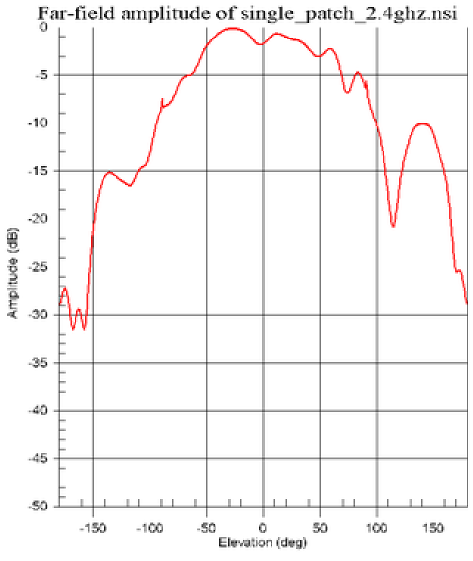
G.1 Radiation Pattern: E-Field Co-Polar



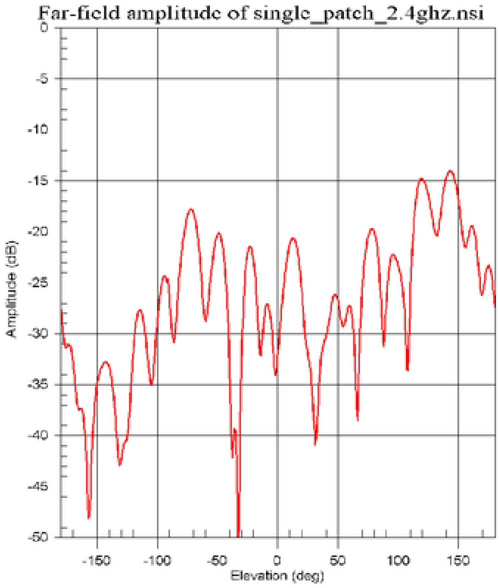
G.2 Radiation Pattern: E-Field Cross-Polar



G.3 Radiation Pattern: H-Field Co-Polar



G.4 Radiation Pattern: H-Field Cross-Polar



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