EFFICIENT RECTENNA CIRCUITS FOR MICROWAVE WIRELESS POWER TRANSMISSION

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DEDICATION

This is a special dedication to Oluyemi, who brought upon me a new meaning to life. I love you boy.

To my Parents Mr. and Deaconess Teru, My brother Sola and sister Yemi. I love you all.

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Acknowledgements go out to all those who have supported me in my journey to the unknown, to have come so far. It was rough and tough sometimes with hopes failing and strength draining, but the support of family and friends, has seen me through**.**

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ABSTRACT

Miniaturisation has been the holy grail of mobile technology. The ability to move around with our gadgets, especially the ones for communication and entertainment, has been what semiconductor scientists have battled over the past decades. Miniaturisation brings about reduced consumption in power and ease of mobility. However, the main impediment to untethered mobility of our gadgets has been the lack of unlimited power supply. The battery had filled this gap for some time, but due to the increased functionalities of these mobile gadgets, increasing the battery capacity would increase the weight of the device considerably that it would eventually become too heavy to carry around. Moreover, the fact that these batteries need to be recharged means we are still not completely free of power cords.

The advent of low powered micro-controllers and sensors has created a huge industry for more powerful devices that consume a lot less power. These devices have encouraged hardware designers to reduce the power consumption of the gadgets. This has encouraged the idea of wireless power transmission on another level. With lots of radio frequency energy all around us, from our cordless phones to the numerous mobile cell sites there has not been a better time to delve more into research on WPT.

This study looks at the feasibilities of WPT in small device applications where very low power is consumed to carry out some important functionality. The work done here compared two rectifying circuits' efficiencies and ways to improve on the overall efficiencies. The results obtained show that the full wave rectifier would be the better option when designing a WPT system as more power can be drawn from the rectenna. The load also had a great role as this determined the amount of power drawn from the circuitry.

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WIRELESS POWER TRANSMISSION

1.1 INTRODUCTION

Wireless Power Transmission (WPT), can be defined as the process that takes place in any system whereby electrical energy is transmitted from a power source (or radiator) to an electrical load without interconnecting wires. Wireless power transmission is employed in cases where instantaneous or continuous energy transfer is needed, but interconnecting wires are inconvenient, hazardous, costly, or impossible.

However, the physics of WPT and wireless communication are related, but WPT is distinct from wireless transmission for transferring information (such as radio and mobile phones), where the percentage of the power that is received is only important if it becomes too low to successfully recover the signal. With wireless power transmission, the efficiency is a more critical parameter and this creates important differences in these technologies.

1.2 RATIONALE/MOTIVATION

The advent of low powered micro-controllers and sensors has created a huge industry for more powerful devices that consume a lot less power. This has encouraged the idea of wireless power transmission on another level. With lots of radio frequency energy all around us, from our cordless phones to the numerous mobile cell sites there has not been a better time to delve more into research on WPT. This has therefore motivated the design for more efficient rectenna circuits for use where low power sensors can be deployed.

The evolving needs for ubiquitous computing and sensorial spaces could provide a good platform for such types of wireless power transmission. Some important facts about WPT in the sensorial space are highlighted below:

- High frequency electronics are now very accessible, cheap, low power, small and more reliable. In the past, access to this kind of technology was restricted to military uses and high-end companies. Constantly, more electronic components that are capable of handling radio frequency signals and high frequencies are now more accessible because the packaged radio frequency (RF) front-ends are becoming more transparent to the end users that take advantage of them in the most diverse applications, from remote-controlled electronic doors up to advanced telecommunication systems.

- The use of low power electronics employing the latest Complementary Metal–Oxide–Semiconductor (CMOS) technology is in evidence almost everywhere. The trend now is to design new Integrated Circuits (ICs) that are extremely more energy efficient and, at the same time, powerful and capable of doing complex tasks. Power-saving issues arise almost everywhere and the new electronic systems that run on batteries tend to last longer due to the low power drain from these circuits.

- Modern computers with their very high processing capabilities are making it relatively easy to design high quality, high frequency electronics, and even more so, to custom-make antennas that can solve specific problems. In the past, such design problems were delegated to research environments and academic institutions, but now there are software that simplifies the design processes, on which complex electronic circuits such as filters and antennas can be designed with a high level of confidence and reliability.

The WPT technology is an extension of wireless communication. The only difference is in the power density of the used radio waves. The WPT uses three or four orders of magnitude higher power density. The energy-carrying microwave is in principle a monochromatic wave without modulation. As a means of transmitting energy from one point to another, beamed microwave power transmission has these features:

- No mass, either in the form of wires or ferrying vehicles, is required between the source of energy and the point of consumption.
- Energy can be transmitted at the velocity of light

- Direction of energy transfer can be changed rapidly

1.2.1 Wireless Power Transmission Systems

WPT systems can be divided into the following three subsystems:

(a) Direct Current (DC) to microwave conversion subsystem, which normally uses devices such as klystrons, magnetrons, TWTs (travelling wave tube) amplifier, or semiconductor FET (Field Effect Transistor) amplifier. Key points for better WPT systems in this subsystem are; (i) high conversion efficiency, (ii) low noise level.

(b) Microwave receiver subsystem; in this subsystem, any antenna such as dipole, microstrip, Yagi-Uda, parabolic antennae, can be used, depending on the applications.

(c) Microwave to (DC) conversion subsystem; most commonly used antenna is a rectenna. The rectenna is composed of receiving antenna and rectifiers with semiconductor diodes.

1.3 OBJECTIVES

The main objectives of the study are listed below:

1. To transmit microwave power to a fixed point using an antenna.
2. Collect microwave power using a device known as the rectenna, which is a combination of an antenna and rectifier(s).
3. Convert microwave power back into DC voltage.
4. Compare the conversion efficiencies of two (2) rectifying circuits.

1.4 METHODOLOGY

This dissertation has developed a system that gathers the RF power and converts it to DC voltage. So for starters, a rectenna system that gathers the RF energy from the transmitter and converts it to DC power was designed, constructed, and analysed. The metrics that were analysed are the amount of power delivered to a given load and the conversion efficiency (defined as the amount of RF power present at the receiver over DC power measured at the rectenna terminals).

1.5 OVERVIEW OF DISSERTATION

In chapter 2, the literature review delved into the history of RF and discussed the pioneering effort of the early scientists who showed and confirmed the presence of RF within the electromagnetic spectrum. The developments that have taken place and the improvements since the Second World War are also highlighted.

Chapter 3 explains the equipment and devices used to complete the experiments and are also analysed in detail. The full detail of the design-ruling physics (equations) used for the development of the wireless power transmission system, from the relations utilized in the use of the microwave generator to the transmission of power using an antenna to basic concepts of signal rectification using diodes.

Chapter 4 will present in the results of the experiment and conditions that were met from the implementation and realization of the rectenna system for small devices.

Chapter 5 gives the conclusions and future work proposal for the Wireless Transmission of Power concepts.

CHAPTER 2

REVIEW OF WIRELESS POWER TRANSMISSION

2.1 INTRODUCTION

Wireless power transmission has been demonstrated many times throughout the last century. The idea began with the experiments of Heinrich Hertz and Nikola Tesla around the 1890s and has continued until today. However, Tesla was confident in his hypothesis to transfer power wirelessly; nobody has been able to ratify it. In the modern world, wireless power transmission is largely exhibited through induction. Furthermore, functional, wireless power transmission through induction is constrained to very small distances; the transmission efficiencies get increasingly worse as the distance between transmitter and receiver increases. There have been several attempts to transmit power wirelessly over long distances through microwaves within the electromagnetic spectrum with varying degree of success. Two of the pioneering researchers, Hertz and Tesla are discussed in the next sections.

2.1.1 Heinrich Rudolf Hertz

Heinrich Rudolf Hertz (February 22, 1857 – January 1, 1894) was a German physicist who clarified and expanded the electromagnetic theory of light that had been put forth by Maxwell. He was the first to satisfactorily demonstrate the existence of electromagnetic waves by building an apparatus to produce and detect VHF or UHF radio waves. Hertz helped establish the photoelectric effect (which was later explained by Albert Einstein) when he noticed that a charged object loses its charge more readily when illuminated by ultraviolet light.

In 1887, he observed the photoelectric effect and of the production and reception of electromagnetic (EM) waves, published in the journal Annalender Physik. His receiver consisted of a coil with a spark gap, whereupon a spark would be seen upon detection of EM waves. He placed the apparatus in a darkened box to see the spark clearer. He observed that the maximum spark length was reduced when in the box.

Earlier in 1886, Hertz developed the Hertz antenna receiver. This set of terminals is not electrically grounded for its operation. He also developed a transmitting type of dipole antenna, which was a centre-fed driven element for transmitting UHF radio waves. These antennas are the simplest practical antennas from a theoretical point of view. In 1887, Hertz experimented with radio waves in his laboratory. Hertz altered the Maxwell's equations to take this view into account for electromagnetism. Hertz used a Ruhmkorff coil-driven spark gap and one-meter wire pair as a radiator. Capacity spheres were present at the ends for circuit resonance adjustments. His receiver, a precursor to the dipole antenna, was a simple half-wave dipole antenna for shortwaves.

His discoveries would later be further fully understood by others and be part of the new “wireless age”. In bulk, Hertz’ experiments explain reflection, refraction, polarization, interference, and velocity of electric waves [Wikipedia].

2.1.2 Nikola Tesla

Nikola Tesla (10 July 1856 – 7 January 1943) was an inventor and a mechanical and electrical engineer. He was one of the most important contributors to the birth of commercial electricity and is best known for his many revolutionary developments in the field of electromagnetism in the late 19th and early 20th centuries. Tesla's patents and theoretical work formed the basis of modern alternating current (AC) electric power systems, including the polyphase system of electrical distribution and the AC motor, with which he helped usher in the Second Industrial Revolution [Wikipedia].

Nicola Tesla first conceived the idea of wireless power transmission by radio waves more than a century ago. He attempted to distribute tens of thousands horsepower of electricity by radio waves. He said; “This energy will be collected all over the globe preferably in small amounts, ranging from a fraction of one to a few horsepower. One of its chief uses will be the illumination of isolated homes", [Brown, 1968]. He actually built a gigantic coil, which was connected to a 200-feet high mast with a ball 3 feet in diameter at its top. He fed 300 kW power to the Tesla coil, which resonated at 150 kHz. The RF potential at the top sphere reached 100 MV.

From the end of the 19th century to beginning of the 20th century and onwards, however, radio waves has been used mainly for transmitting intelligence and information, and very few attempts have been made to transmit electric power over radio following Tesla's work. The reason for lack of interest in wireless power transmission in the first half century was clear; the available radio frequency was too low to achieve small enough antenna for beamed power toward the customers' site. However, at the end of World War II, engineers and scientists started to re-examine the original Tesla idea of transmitting electric power via radio waves to a distant place, as high-power microwave technologies became available. However, the technology of the high-power microwave tube was not well developed yet for practical continuous transmission of electric power. Furthermore, no power device was available to convert microwave power back into DC power until the 1960s.

In "The Promises and Prospects of Worldwide Wireless Power Transfer: An Overview," Kurt Van Voorhies (1991), recognised Tesla's wireless power transfer efforts by saying, "the key challenge to feasible worldwide wireless power distribution is whether a means can be found for efficiently coupling power into and out of the cavity formed by the earth."

2.2 EXISTING MEDIA FOR WIRELESS POWER TRANSMISSION

There are three types of media for wireless power transmission that have been explored by pioneers in the past, but so far, the microwave option has seen the most significant growth. Others are; induction and lasers.

2.2.1 Microwave/Radio Frequency Wireless Power Transmission

Power transmission using microwaves goes back to the early work of Heinrich Hertz [Brown 1996]. Hertz experimented largely with power transfer through radio waves while Tesla's work was based on much longer wavelengths. For about fifty years after Hertz and Tesla, there were not many people who experimented with wireless power transfer because people realized that efficient point-to-point wireless transfer of energy depended upon concentrating electromagnetic energy into a narrow beam. The only practical way to do this was by using electromagnetic energy that was very short in wavelength and devices were not available to supply energy at these wavelengths. Although these devices were developed during World War II, it would be more than a decade later before serious interest in microwave power transmission would begin [Brown, 1996].

The post-war history of research on free-space power transmission is well documented by William C. Brown [Brown, 1969], who was a pioneer of practical microwave power transmission. Brown successfully carried out a demonstration experiment of microwave-powered helicopter in 1964, using the 2.45 GHz frequency. The frequency 2.45 GHz is within the frequency range of 2.4 – 2.5 GHz reserved for the ISM (Industrial, Scientific and Medical) applications of radio waves.

Brown also invented a new device called the "rectenna" to convert microwave power back to DC power [Brown, 1969] for the microwave-powered helicopter experiment. The highest record of 84% microwave-to-DC conversion efficiency was achieved in the demonstration experiment of microwave power transmission between two fixed points on the ground carried out in 1975 at the Jet Propulsion Laboratory (JPL) Goldstone Facility. Power was successfully transmitted from a transmitting large parabolic antenna dish to a receiving site equipped with rectenna over a distance of 1.6 km. The DC output was 30 kW [Dickinson and Brown, 1975].

In 1958, the funding of many sponsors, including Raytheon, the Air Force, and National Aeronautics and Space Administration (NASA), spurred research on the development of wireless power transmission in the solar-powered satellite area [Brown, 1996]. By 1980, most of the sponsors had dropped out and wireless power transmission research was largely limited to NASA [McSpadden and Mankins, 2002].

The advantage of using radio waves for wireless power transfer is that the technology is mature; as mentioned before, wireless power transmission through radio waves dates back to Heinrich Hertz in the 18th century. The key drawbacks are beam safety, frequency allocation, and affordability [Dickinson, 1996].

2.2.2 Inductive Power Transmission

Inductive power transmission systems are defined as systems where energy is transmitted from a primary winding to a secondary winding using an alternating magnetic field [Stielau et al, 2000]. The first developed inductive links were introduced in the 1960s, focusing mainly on artificial heart systems [Vandevoorde et al, 2001]. Today, there are many commercial products that use inductive power transfer; some of these include the Sonicare toothbrush [Dench, 1999], artificial cardiac pacemakers [Vandevoorde et al, 2001].

The structure of an inductive power transfer system is very simple. The basic structure consists of a primary AC source, a primary winding, a secondary winding, and the load output. Because the link between the primary and secondary winding is driven by electromagnetism, inductive power transfer can only be accomplished at short distances. In 2001, Vandevoorde celebrated an inductive link that transmitted 20 W of power over a distance of 1 centimetre (cm) with an overall efficiency of 80%.

The advantage of inductive wireless power transfer is that it is a low cost and highly efficient method of transferring power. The design of an induction link is straightforward and surprisingly efficient at small distances. The main drawbacks to inductive wireless power transfer include the following: (1) the amount of power transmitted is limited to the size of the coil geometries and (2) the distance between coils must be very small, such as distances lesser than 2 cm [Vandevoorde et al, 2001].

2.2.3 Laser Wireless Power Transmission

"Laser wireless power transmission systems for electric power transfer are newcomers", [Dickinson, 2003]. The International Space Information Service (ISIS) reported a breakthrough in laser power transfer in their "Highlights in Space Technology and Applications for 2000" paper. It was stated that, "power transmission by lasers was developed as a viable alternative to microwaves."

Laser transmission of power is performed by first converting DC power into electromagnetic waves using a laser. These waves are transmitted wirelessly by the laser and then are received and converted back to DC power [Dickinson, 2003]. Historically, the main problems with laser power transfer were low efficiencies (as low as 10% – 20% for the entire system) and safety concerns [ISIS, 2000]. Recently, solid-state lasers in the range of 1-1.4 microns have been developed. These lasers conform to the current regulatory limits on eye (retina) and skin exposure; they also seem to be better as far as efficiencies go (around 30%) [ISIS, 2000]. Once fully developed, these lasers may be a viable option to transfer power wirelessly. But lasers would still require a line of sight with no obstruction between the transmitter and receiver.

2.3 FREE SPACE TRANSMISSION

The components for transmitting power through free space using microwaves are the transmitting and receiving antenna apertures. The size and expense of these apertures have direct relationships to the wavelength, which is being used, the distance over which power is being transmitted, and the desired efficiency of transmission. Goubau and Schwering (1961) derived the following relationship between the aperture-to-aperture efficiency and a parameter, τ shown in Figure 2.1:

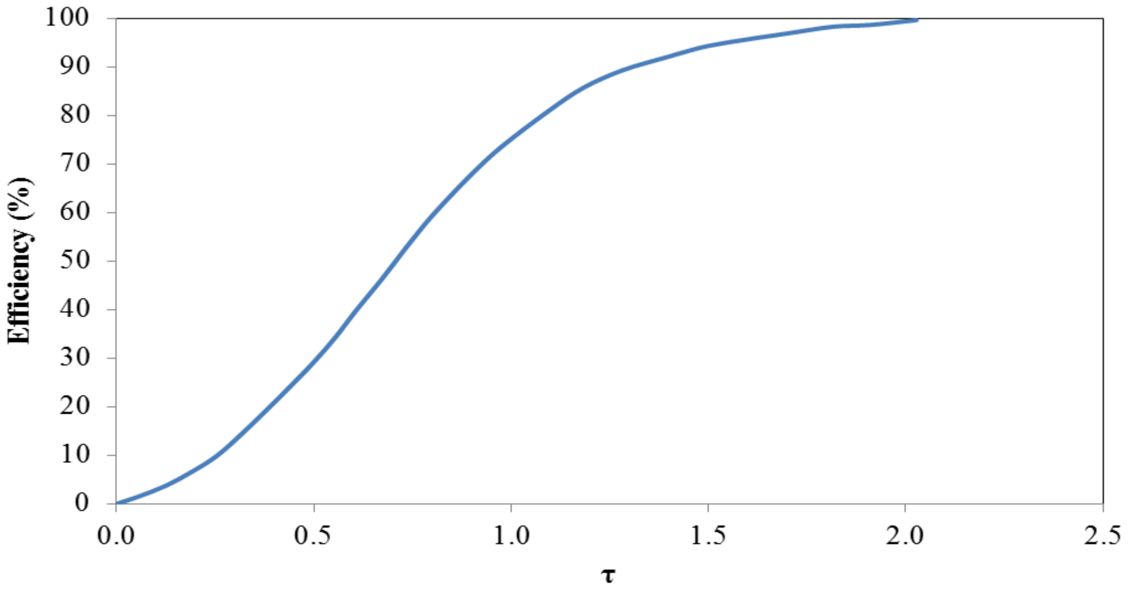

Figure 2. 1: Transmission efficiency as a function of the parameter, τ. [URSI, 2007]

This relation is expressed by the following equation:

$$\tau = \frac{\sqrt{A_t A_r}}{\lambda D} \qquad 2.\ 1$$

where

A_t is the transmitting aperture area

A_r is the receiving aperture area

λ is the wavelength of the microwave power being transmitted

D is the distance of separation between the two apertures

From equation 2.1, a simple expression for the transmitter and receiver aperture areas can be derived with the assumption that the aperture sizes are equal. Under these conditions:

$$A_t = A_r = \tau\lambda D \qquad 2.\,2$$

This is a revealing expression because it shows that the aperture area, rather than its diameter, varies with wavelength, and the advantages of going to higher frequencies are diminished if the aperture areas are approximately equal, as they tend to be for total overall economy.

However, there are applications where the reception area may be limited and where a particular intensity of the incident microwave illumination is desired. Under those circumstances, the following equation may be used:

$$P_d = \frac{A_t P_t}{\lambda^2 D^2} \qquad 2.\,3$$

where

P_d is the power density at the centre of the receiving antenna

P_t is the total radiated power from the transmitter

A_t is the total area of the transmitting antenna

Λ is the wavelength

D is the separation between the apertures

With this situation, it is seen that to achieve a desired value of P_d at the receiver end, while being constrained by a fixed transmitted power P_t, the transmitting aperture area varies as the inverse square of the wavelength of the radiation. For some applications, where the area available for a transmitter is limited, the short wavelengths are very attractive.

2.3.1 Frequency for Wireless Power Transmission

The choice of frequency for WPT is dependent on some criteria that must be considered carefully. If there were complete liberty to select the best frequency for wireless power transmission, the conditions that would have to be considered are:

1. The area of the aperture as given by expression (2.2).
2. The dependency of overall system efficiency, including the components at the two ends of the system, upon frequency
3. The heat radiation losses associated with the inefficiency of components
4. The losses due to blocking and fading elements in the air
5. The existing state of the art of available components, and
6. The impact of the use of the selected frequency upon other users of the electromagnetic spectrum.

2.3.2 Wireless Power Transmission and Radio Frequency Identification

The Wireless Power Transmission (WPT) proposed in the study can be compared to common Radio Frequency Identification (RFID) systems, but this is only used to power/charge small devices. It is thus worth establishing the similarities and differences.

WPT can be used to power existing active elements (sensors) due to its higher power densities in comparison to the classic RFID systems. The relay of information can be made in a different frequency band from where the RF power is located. RFID systems generally respond by modulating the reflection coefficient of their antenna. In comparison, WPT is positioned at the far-field transmission region, whereas RFID is classically located in the near field region. WPT system and an RFID system are similar because both systems collect energy from the surroundings. In addition, they can provide a base station with useful information (identification number) about the user. Finally, both systems use rectenna as the transducer element between RF energy and DC power.

2.3.3 Classes of Wireless Systems

In the comprehensive sense, a wireless system allows the communication of information between two points without the use of a wire link. This may be accomplished using infrared, optical, or radio frequency links. Infrared signals can provide moderate data rates, but the fact that infrared radiation is easily blocked by even minor obstructions limits its use to short-range indoor applications such as remote controllers and local area data links. Similarly, optical signals transmitting in an unhindered environment can provide moderate to high data rates, but require a line-of-sight path, and cannot be used where dust, foliage, or fog can hinder the signals. For these reasons, most modern wireless systems rely on RF and microwave signals, usually in the UHF (100 MHz) to millimetre wave (300 GHz) frequency range. Due to spectrum crowding and the need for higher bandwidth, the trend is to use higher frequencies so that the majority of wireless systems today operate at frequencies ranging from 800 MHz to a few GHz. RF and microwave signals offer wide bandwidths, and have the added advantage of being able to penetrate fog, dust, foliage, and even buildings and vehicles to some extent.

One way of classifying wireless systems is according to the nature and placement of the users. In a point-to-point radio system, a single transmitter communicates with a single receiver. Such systems generally use high-gain antennas in fixed positions to maximize received power and minimize interference with other radios that may be operating nearby within the same frequency range. Point-to-point radios are generally used for dedicated data communications by utility companies and for connection of cellular phone sites to a central switching office. Point-to-multipoint systems connect a central station to a large number of possible receivers. The most common examples are commercial AM and FM broadcasting radio and broadcast television. Multipoint-to-multipoint systems allow simultaneous communication amongst individual users, who may not be in fixed locations.

Wireless systems can be classified according to their operating frequency. Table 2.1 lists the operating frequencies of some of the most common wireless systems.

Table 2. 1: Wireless System Frequencies [Pozar, 2005]

Wireless Systems	Operating Frequency
Advanced Mobile Phone Service (AMPS)	T: 824 – 849 MHz R: 869 – 894 MHz
Global System for Mobile (European GSM)	T: 880 – 915 MHz R: 925 – 960 MHz
Personal Communication Services (PCS)	T: 1710 – 1985 MHz R: 1805 – 1880 MHz
US Paging	931 – 932 MHz
Global Position Satellite (GPS)	L1: 1575.42 MHz L2: 1227.60 MHz
Direct Broadcast Satellite (DBS)	11.7 – 12.5 GHz
Wireless Local Area Networks (WLANS) Industrial, Medical, and Scientific (ISM) bands	902 – 928 MHz 2.400 – 2.484 GHz 5.725 – 5.850 GHz
Local Multipoint Distribution Services (LMDS)	28 GHz

2.4 MICROWAVE WIRELESS POWER TRANSMISSION CONCERNS

There are three issues in transmitting power through electromagnetic waves: (1) beam safety, (2) frequency allocation or wavelength, (3) affordability. The evolution of wireless power transmission system engineering studies has revealed that these issues have staying power.

2.4.1 Beam Safety

Safety concerns are the most critical for users of wireless equipment, particularly in regard to possible hazards caused by radiated electromagnetic fields. However, microwaves are non-ionizing radiation, the fact that it is used in cooking in microwave ovens is a serious concern and this has restricted the rate of development of WPT. The body can absorb RF and microwave energy and convert it to heat; as in the case of a microwave oven, this heating occurs within the body, and may not be felt at low power levels. Such heating is most dangerous in the brain, eyes, genitals, and stomach organs. Excessive radiation can cause cataracts, cancer, or sterility. For this reason, it is important to define a safe radiation level standard, so that users of wireless equipment are not exposed to harmful power levels.

The good news is that you can transfer energy without wires. The sun does it every day. The bad news is that to commercially transport energy without wires in an economic fashion requires high-power flux densities. High-power flux densities can be hazardous to persons and equipment. Freedom of movement has been a hallmark of civilization. Although physical and environmental barriers and governmental impediments or restrictions do exist, it is nice to be able to move about the country or to take free flight paths except for restricted air space, for example. However, the public necessity and convenience of restricted right-of-way for methods of power transmission do constrain free movement. Coal trains, natural gas pipelines, electric utility transmission lines and hydroelectric streamflow channels all involve significant hazards to unrestricted transit of personnel and equipment. Easements, barriers, posted limits or other constructs are necessary to minimize loss of life or property while permitting commercial power delivery for benefit of the public. Alternate routes around, over or under such power transmission, routes are generally provided. Nevertheless, there is a major distinction of WPT from the above means of power transmission. In particular, for microwave and some laser beams, the wavelength is long enough that the human eye cannot see the beam. One cannot see the electric or magnetic fields around high voltage transmission lines either, but the open wire line conductors provide a visualization of the potentially dangerous region and utility education activities provide knowledge of the potential hazard (e.g. no kite flying with copper wires) [Dickinson, 2000].

In the RF microwave frequency range of 100 MHz to 300 GHz, exposure limits are set on the power density (in mW/cm^2) as a function of frequency. The recommended safe power density limit is as low as 0.2 mW/cm^2 at the lower end of this frequency range, because fields penetrate the body more easily at low frequencies. At frequencies above 1.5 GHz the power density limit rises to 10 mW/cm^2, since most of the power absorption at these frequencies occurs near the skin surface. By comparison, the sun radiates a power density as high as 100 mW/cm^2 on a clear day, but the effect of this radiation is much less severe than a corresponding level of microwave frequency radiation because the sun heats the outside of the body, with much of the generated heat being reabsorbed by the air, while microwave power heats the body inside out. At frequencies below 100 MHz, electric and magnetic fields interact with the body differently than at higher frequencies, hence separate limits are given for field components at these frequencies [IEEE Standards Board, 1992].

In addition to the above power density limits, the Federal Communications Commission (FCC) sets limits on the total radiated power of some specific wireless equipment [ICNIRP]. Vehicle-mounted cellular phones (using an external antenna) are limited to a maximum radiated power of 3 W. For handheld cellular phones, the FCC has set an exclusionary power level of 0.76 W, below which phones are exempt from the ANSI standard on radiated power density. Most cellular phones radiate a maximum of 0.6 W, and newer portable communication system (PCS) phones radiate even less power. Although cellular and PCS base stations are limited to a total effective radiated power of 500 W, depending on antenna height and location, most urban base stations radiate a maximum of 10 W.

Wireless products using the ISM bands are limited to a maximum radiated power of 1 W. While some countries have different standards for RF and microwave exposure limits, most experts feel that the above limits represent safe levels within a reasonable margin. Some researchers, however, are concerned that health hazards may occur due to non-thermal effects of long-time exposure to even low levels of microwave radiation [Eleanor, 2002].

In order to separate users from any risk of safety problems, a wireless power transmission system must remain below FCC regulations. In addition to abiding by the FCC regulations, a WPT system should allow the user to turn the system on or off manually. An alternative fail-safe approach that is commonly used is to use a beam intrusion detection system that shuts off the beam in the absence of the detection signal [Dickinson, 2003].

2.4.2 Frequency Allocation or Wavelength

The issue of frequency allocation or wavelength is always a problem for WPT systems. This is because of attenuation, due to scattering of radio waves by dust particles, raindrops, cloud droplets, ice crystals, sleet, hailstones, and snow, of the radio waves occurs. Because of this, frequencies below 3 GHz are necessary [Dickinson, 1996]. Beams of this frequency are much harder to focus than those of longer wavelengths. Therefore, a cost-performance trade-off is almost always made in designing wireless power transfer systems. This situation is further complicated by the many different RF signals that are already occupied by radio, broadcasting, and satellite [Dickinson, 1996]. An appropriate frequency allocation must be decided upon for each application.

2.4.3 Affordability

Dickinson (2003) stated, "in connection with the end-to-end beam power transfer efficiency, certified to be greater than 54%, these results should dispel doubts about the technical feasibility of wireless power transfer. Thus wireless power transmission is a proven technology. Its only current drawback is that it is expensive." Wireless power transmission involves many components that are sometimes expensive. One driver of the cost is that the wireless power transmission systems use different forms of power converters at the two ends of the system. It will not be commercially feasible to develop unless the system can be produced at an affordable price.

2.5 MICROWAVE TRANSMITTER FOR WIRELESS POWER TRANSMISSION

Microwave equipment consists of three major components, the power supply and microwave generator, the applicator, and the control circuitry. The power supply and microwave generator provide microwaves at the appropriate frequency. The power supply must be matched to the microwave source to ensure correct operation. The most common microwave sources are the magnetron and klystron, the former being robust, efficient, frequency stable and readily available while the latter is more expensive, available in higher powers, but with a somewhat longer operating life (80000 versus 10000 hours). Low power magnetrons for laboratory use typically come in the power range 1 - 6 *kW* and may be of fixed or variable power type, while higher power magnetron systems up 70 *kW* are available, usually at 915 MHz rather than the more common low power frequency of 2450 *MHz.* Power output from low power permanent magnet magnetrons can be achieved by thyristor control of the anode voltage, while high power systems usually use an electromagnet to vary the anode current [Bradshaw, 1998].

It is usual to insert a circulator between the magnetron and the load. This 3-port structure couples power clockwise between adjacent ports. As microwave power can be reflected, the circulator protects the magnetron from excessive reflected power by diverting reflected power to a water-cooled matched load, which is also equipped with a power meter. The circulator is particularly important in preliminary investigations where the dielectric properties of the load are not well known and where a general-purpose applicator is being used which may result in significant amounts of reflected power. To provide a good impedance match between the magnetron and the load a stub tuner is often provided. Even with the use of a circulator, it is sometimes found that significant power pulling (20% of nominal power) due to impedance mismatches can still occur. Both the stub tuner and the circulator are expensive and cope with powers of up to about 6 kW [Bradshaw, 1998].

Advantages of these microwave tubes are;

1. High conversion efficiency from DC to microwave (> 70%),
2. High output power (from several hundred watts to several hundred kilowatts).

Details and historical review of these microwave tubes are well documented [Granatstein, Parker and Armstrong, 1999]. The disadvantages of the microwave tubes compared with semiconductor microwave generators are;

1. Fragile and needs careful treatment,
2. Need high voltage DC power supply (several volts), and
3. They are noisy (especially magnetrons).

Amongst the microwave generators, magnetron is the most common and it is used for domestic microwave ovens and therefore very cheap compared to other microwave generators and semiconductor generators. Its DC-to-microwave conversion efficiency is as high as 80% if properly tuned. However, its disadvantage is its high level of cavity noise.

2.5.1 The Microwave Generator

The microwave power transmission was carried out in a controlled environment in the laboratory using a high power microwave generator. The power given off from this MW (microwave) generator can be varied from 1 *W* to 1.2 *kW*. This is to vary the power received and the distances between the transmitter and the receiver. The generator manufactured by Alter Power Systems, Italy, is a water-cooled microwave power generator. A microwave generator is shown in Figure 2.2.

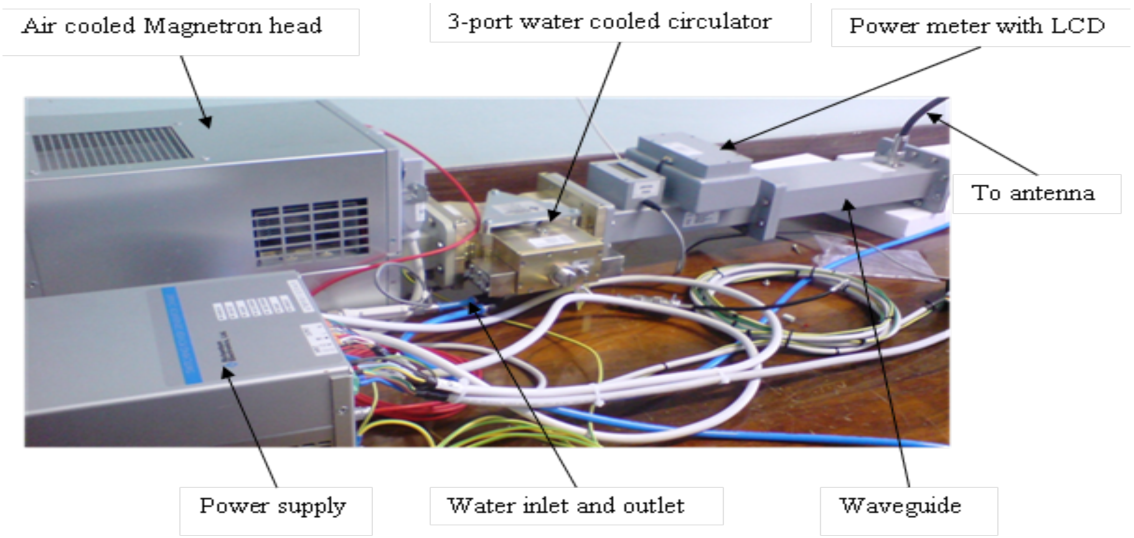

Figure 2. 2: Microwave Generator

The MW generator has different parts coupled together to deliver variable output. The various parts of the generator are listed below:

2.5.2 The Magnetron

A magnetron is a high power microwave oscillator in which the potential energy of an electron cloud near the cathode is converted into R.F. energy in a series of cavity resonators. As depicted by the low frequency analogue, the rear wall of the structure may be considered the inductive portion, and the vane tip region the capacitor portion of the equivalent resonant circuit. The resonant frequency of a microwave cavity is thereby determined by the physical dimension of the resonator together with the reactive effect of any perturbations to the inductive or capacitive portion of the equivalent circuit. In order to sustain oscillations in a resonant circuit, it is necessary to continuously input energy in the correct phase.

In a magnetron, the source of electrons is a heated cathode located on the axis of an anode structure containing a number of microwave resonators. Electrons leave the cathode and are accelerated toward the anode, due to the dc field established by the voltage source E. The presence of a strong magnetic field B in the region between cathode and anode produces a force on each electron which is mutually perpendicular to the dc field and the electron velocity vectors, thereby causing the electrons to spiral away from the cathode in paths of varying curvature, depending upon the initial electron velocity at the time it leaves the cathode [CPI, 2008].

As this cloud of electrons approaches the anode, it falls under the influence of the R.F. fields at the vane tips, and electrons will either be retarded in velocity, if they happen to face an opposing R.F. field, or accelerated if they are near an aiding R.F. field. Since the force on an electron due to the magnetic field B is proportional to the electron velocity through the field, the retarded velocity electrons will experience less “curling force” and will therefore drift toward the anode, while the accelerated velocity electrons will curl back away from the anode. The result is an automatic collection of electron “spokes” as the cloud nears the anode, with each spoke located at a resonator having an opposing R.F. field. On the next half cycle of R.F. oscillation, the R.F. field pattern will have reversed polarity and the spoke pattern will rotate to maintain its presence in an opposing field. The "automatic" synchronism between the electron spoke pattern and the R.F. field polarity in a crossed field device allows a magnetron to maintain relatively stable operation over a wide range of applied input parameters. For example, a magnetron designed for an output power of 200 kW peak will operate quite well at 100 *kW* peak output by simply reducing the modulator drive level [CPI, 2008].

2.5.3 Circulator and Isolator

Isolators and circulators are non-reciprocal devices. In many cases, they are made with ferrite materials. The nonreciprocal electrical properties cause that the transmission coefficients passing through the device are not the same for different directions of propagation. In an isolator, almost unattenuated transmission from port 1 to port 2 is allowed, but very high attenuation exists in the reverse direction from port 2 to port 1, as shown in Figure 2.3. The isolator is often used to couple a microwave signal source (oscillator) to the external load. It allows the available power to be delivered to the load but prevents the reflection from the load transmitted back to the source. Consequently, the source always sees a matched load, and the effects of the load on the source (such as frequency pulling or output power variation) are minimized. A practical isolator will introduce an insertion loss for the power transmitted from port 1 to port 2 and a big but finite isolation (rejection) for the power transmitted from port 2 to port 1. Cascading two isolators in series can increase isolation. However, the insertion loss is also increased.

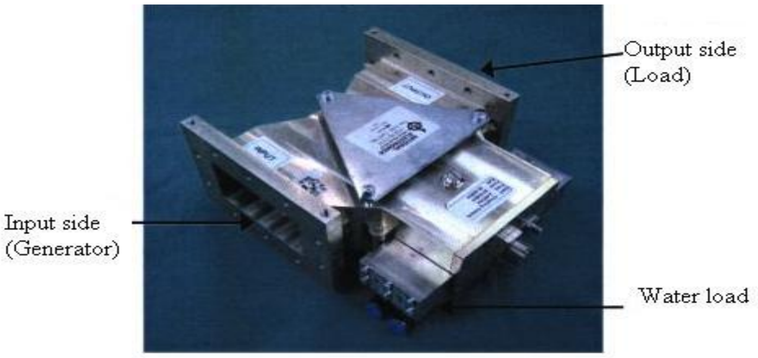

Figure 2. 3: The Circulator

2.5.4 Directional Coupler / Power Meter

A directional coupler is defined as a device used to couple power from the waveguide system (at a reduced value) to facilitate equipment interface for frequency, power, or other system measurements. Directional couplers are most commonly used to measure forward and/or reflected energy. Their output is an attenuated RF signal that can be measured in several different ways. The directional coupler/power meter is shown in Figure 2.4.

One such way to measure the sampled energy is to use a power meter and power sensor attached to the measuring port of the directional coupler. The power sensor, which is calibrated for a specific frequency range and attenuation leave, interprets the signal present at the couplers output and sends this information to the power meter for display. Another common measuring method is to use a detector diode attached to the measuring port of the coupler. The diode outputs a voltage proportional to the sampled energy with the output power determined from the diodes characteristic curve.

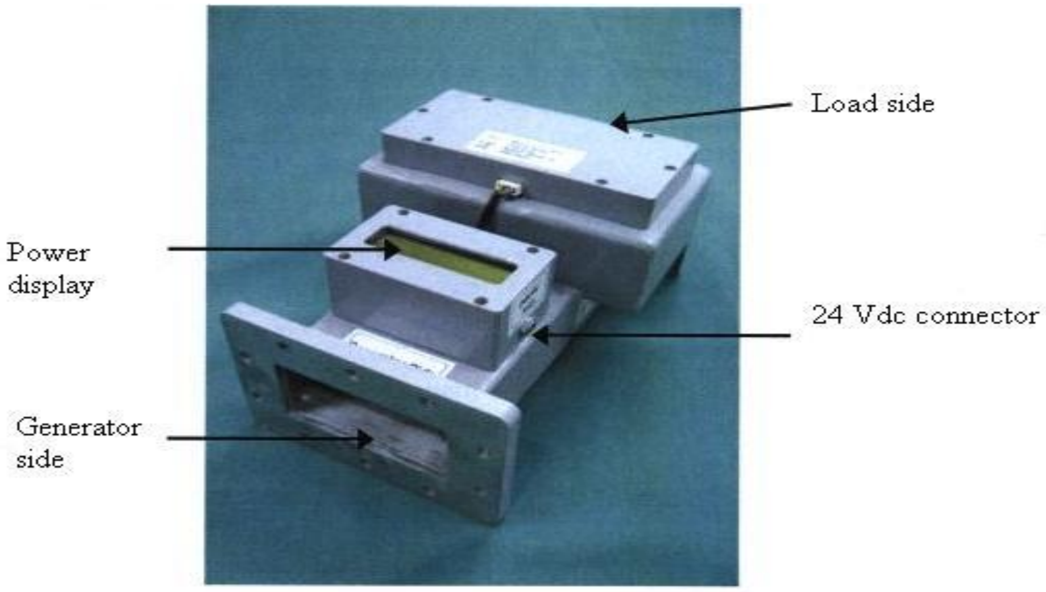

Figure 2. 4: Directional Coupler/Power Meter

2.5.5 The Waveguide

Waveguides are metallic transmission lines that are used at microwave frequencies, typically to interconnect transmitters and receivers (transceivers) with antennas. Though there are many types of waveguides, the rectangular waveguide was chosen because it was cheap and it easily interfaced with the microwave generator magnetron's head.

Waveguide has a number of advantages over coax, microstrip and stripline. It is completely shielded (excellent isolation between adjacent signals can be obtained), it can transmit extremely high peak powers and it has very low loss (often almost negligible) at microwave frequencies.

One disadvantage of waveguide is its high cost. Manufacturing volumes are low, and waveguide materials such as copper and silver are relatively expensive. Other disadvantages include unwieldy size and mass, particularly at lower frequencies. A final disadvantage of waveguide is that you cannot pass DC currents along with your RF signal. Nevertheless, the advantages of power handling often outweigh all of waveguide's perceived shortcomings.

To reach megawatt power levels, waveguides can be pressurized with special gasses that increase the peak power level before the waveguide short circuits with electrical arcing between the top and bottom walls. Silver plating used on the inside walls of the waveguide decreases the resistance loss, making the common aluminium or copper waveguides even more efficient [P-N Designs, 2008].

2.6 MICROWAVE RECEIVER FOR WIRELESS POWER TRANSMISSION

Different from a wireless communication, we do not need a demodulator but need a rectifier to obtain the DC output power. In most WPT experiments, diode-type rectenna have been adopted. Rectenna is most commonly used device in the back conversion device due to its simplest structure.

2.6.1 The Rectenna

The rectenna is a unique device that was conceived and developed for beamed microwave power reception [Raytheon, 1977]. It is spread out over the receiving aperture area and, as its nature suggests, combines the functions of an antenna and a rectifier. In its simple form, the rectenna consists of a collection of rectenna elements, each composed of a receiving element (usually a half wave dipole) that feeds a low pass filter circuit terminated in a rectifying diode. The rectenna has many desirable characteristics. They include:

- In its pure form, a relatively non-directional aperture analogous to that of a single dipole, regardless of the size of the aperture; in this form the aperture collection efficiency is independent of the illumination density distribution across the aperture.
- an overall efficiency from incident microwave power to DC power output that has been measured at over 85% [Brown, 1996].
- low specific mass of 1 to 2 kg per kilowatt of DC power output.
- relative insensitivity of the overall efficiency to changes in the level of power input or load impedance.
- Small amounts of the critical GaAs material required, less than 1/100 000 of that required for a solar photovoltaic array of the same area.

The term “rectenna” is now used universally for the receiving aperture of any beamed power transmission system that combines the function of capture and rectification, even though in some formats there has been a departure from the “one to one” relationship between dipoles and diodes in the original “pure” form of the device. This departure results in directional sensitivity of the rectenna, which may be tolerated for some applications.

W. C. Brown was the first to use the word “rectenna”. It means, “Rectifying Antenna”. In other words, the rectenna plays dual roles as a microwave receiver and as a converter of microwave to DC power [Brown, 1969]. Brown succeeded in demonstrating a microwave powered helicopter in 1964 using microwaves of 2.45 GHz and a rectenna composed of 28 half-dipoles terminated in abridge rectifier using point-contacted semiconductor diodes [Oida et al, 2007]. The rectenna is composed of the following components, namely antenna, diode capacitor and a load resistor, as shown in Figure 3.5 below:

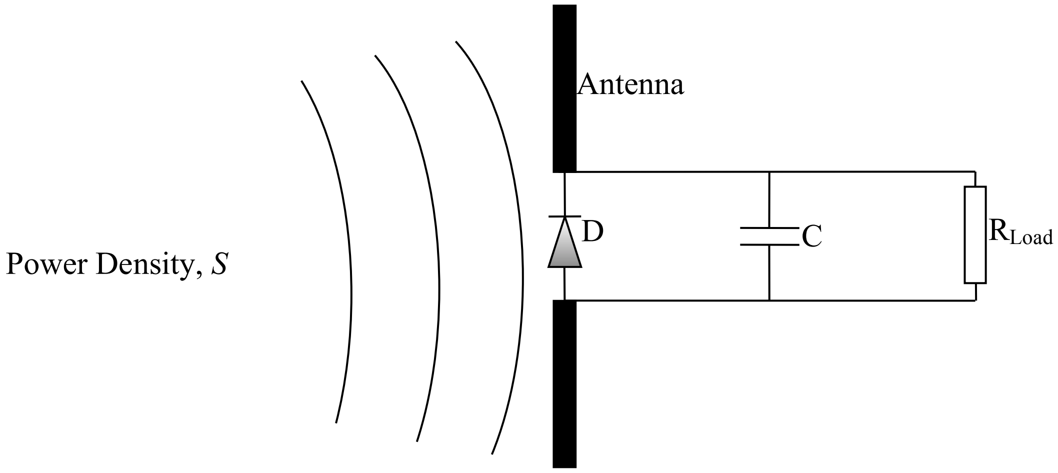

Figure 2. 5: Schematic of a rectenna [Curty, et al, 2007]

A unique characteristic of rectenna is the dependence of its RF-to-DC conversion efficiency on its RF input power and on its connected load. RF-to-DC conversion efficiency is defined as the ratio of DC output supplied to the load and its RF input power to the effective aperture area of the antenna. If an ideal diode is used, the RF-DC conversion efficiency does not depend on the RF input power. However, the RF-DC conversion efficiency does depend on RF input power in case of realistic diodes.

2.6.2 Rectifier Design

Detectors make use of the nonlinear characteristics of a solid-state device to bring about frequency conversion to an input signal. The more nonlinear the device's I-V characteristic curves are, the more efficient the detection process will be; that is, a higher percentage of the signal power at the input frequency will be converted to signal power at the output frequency. The three basic types of frequency conversion circuits are:

- Rectifier
- Detector
- Mixer

Each is described briefly as follows:

A rectifier is a circuit that converts the RF signal into a zero frequency signal (i.e. a DC signal) with time and frequency-domain signals as shown in Figure 2.6. The rectifier is used for automatic gain control (AGC) circuits or power monitor circuits, etc.

A detector (also called a demodulator) is a circuit that demodulates a modulated carrier wave by discarding the carrier wave and outputting the modulating signal as shown in Figure 2.7. Detectors are used in circuits such as AM demodulators.

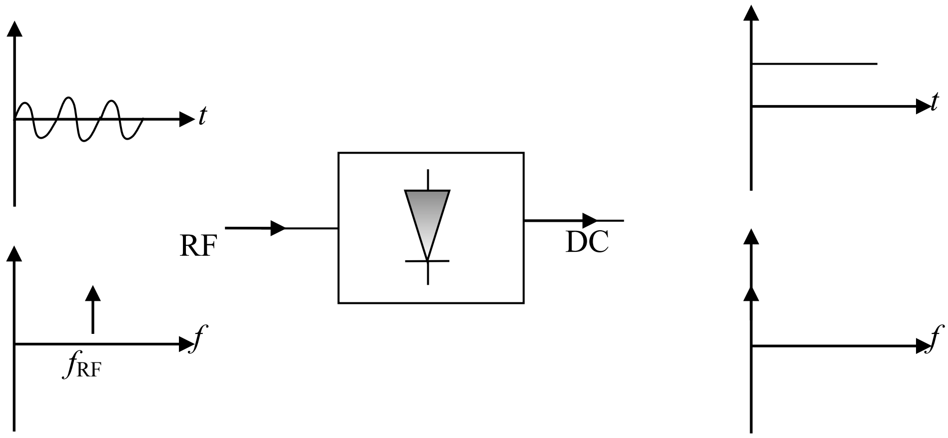

Figure 2. 6: Time and Frequency Domain Signals for a Rectifier

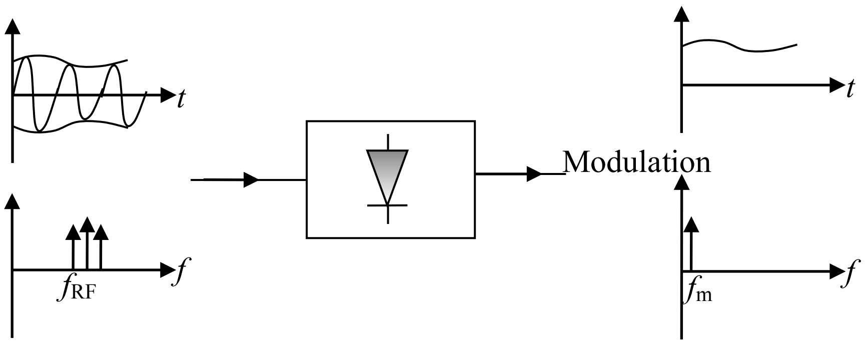

Figure 2. 7: Time and Frequency Domain Signals for a Detector

A mixer (also called a converter) is a circuit that converts an input signal to a higher-frequency signal (called an up-converter) or to a lower-frequency signal (called a down-converter) while ideally preserving all of the original signal characteristics (such as sidebands, wave shape, etc.). This frequency conversion can be readily obtained by mixing the input signal with another signal (called the Local Oscillator signal, or LO for short) as shown in Figure 2.8:

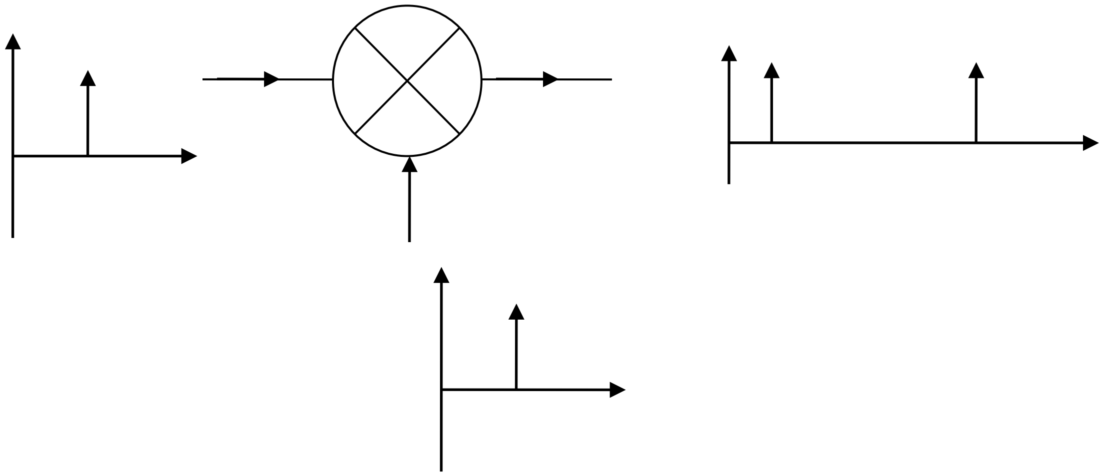

Figure 2. 8: Time and Frequency Domain Signals for a Mixer

2.6.3 *Small-Signal Analysis of A Diode*

A diode can be considered a nonlinear resistor with its I-V characteristic curve mathematically given by:

$$I(V) = I_s\left(e^{\alpha V} - 1\right) \qquad 2.4$$

where;

- $\alpha = q/nkT$, and q is the charge of an electron, k is Boltzmann's constant, T is temperature. $\alpha = q/nkT$ is approximately; 1 / (25 mV at T = 290 K)
- I_s = Diode saturation current
- n = Ideality factor ($1 \leq n \leq 2$) which depends on the material and physical structure of the diode itself, and can vary. For instance, for a point-contact diode n = 2 whereas for a Schottky barrier diode, n =1.2, etc.

Figure 2.9 shows a sketch of a diode I-V characteristic curve, as described in equation (2.4).

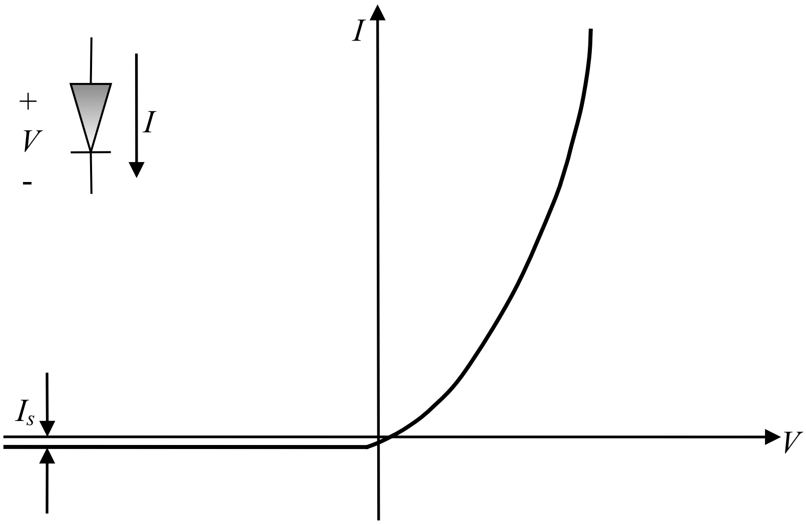

Figure 2. 9: I-V Characteristics of a Schottky diode [Pozar, 2005]

To perform a small signal analysis, it is assumed that the total voltage across the diode (*V*) is composed of a DC bias voltage (V_0) and a small-signal RF voltage (*v*), that is:

$$V = V_0 + v \tag{2. 5}$$

where V_0 is a DC bias voltage and v is a small AC signal voltage. Then (2.4) can be expanded in a Taylor series about V_0 as follows:

$$I(V) = I_0 + v\frac{dI}{dV}\Big|_{V_0} + \frac{1}{2}v^2\frac{d^2I}{dV^2}\Big|_{V_0} + \ldots, \tag{2. 6}$$

where $I_0 = I\,(V_0)$ is the DC bias current. The first derivative can be evaluated as:

$$\frac{dI}{dV}\Big|_{V_0} = \alpha I_s e^{\alpha V_0} = \alpha(I_0 + I_s) = G_d = \frac{1}{R_j} \tag{2. 7}$$

which defines R_j, the junction resistance of the diode, and $G_d = 1/R_j$, which is called the dynamic conductance of the diode. The second derivative is given by:

$$\frac{d^2I}{dV^2}\Big|_{V_0} = \frac{dG_d}{dV}\Big|_{V_0} = \alpha^2 I_s e^{\alpha V_0} = \alpha^2(I_0 + I_s) = \alpha G_d = G_d^{'} \tag{2. 8}$$

Equation (2.6) can now be written as a DC current (I_0) and an AC small signal current (*i*):

$$I(V) = I_0 + i = I_0 + vG_d + \frac{v^2}{2}G_d^{'} + \ldots \tag{2. 9}$$

The three-term approximation for the diode current, as given by equation (2.9) is known as the "small signal approximation". This means that for small signals (i.e.), higher order terms (above the second order) for *i* may be truncated without any loss of accuracy.

In practice, however, the diode's behaviour also involves reactive effects caused by junction and parasitic capacitances and lead inductances that are directly related to the packaging as well as the structure of the diode. A typical equivalent circuit for the diode is shown in Figure 2.10. In this Figure (C_p, L_p) are the parasitic elements due to packaging, R_s is the series resistance due to semiconductor neutral regions and the contact areas, and (R_j, C_j) are the junction resistance and capacitance, which are bias-dependent [Pozar, 2005].

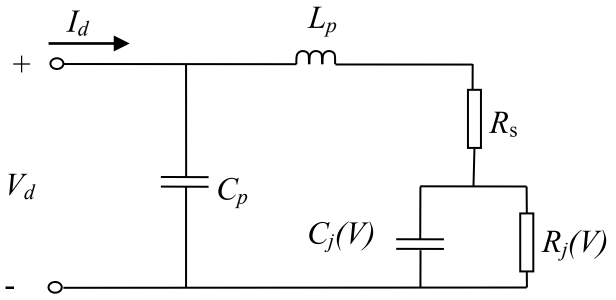

Figure 2. 10: Diode Equivalent Circuit Model

2.6.4 Diode Rectifiers and Detectors

In a rectifier application, a diode is used to convert a fraction of an RF input signal to DC power. Rectification is a very common function, and is used for power monitors, automatic gain control circuits, and signal strength indicators. If the diode voltage consists of a DC bias voltage and a small-signal RF voltage:

$$V = V_0 + v_0 \cos \omega_0 t \qquad 2.10$$

Then (2.9) shows that the diode current will be

$$I = I_0 + v_0 G_d \cos\omega_0 t + \frac{v_0^2}{2} G_d^{'} \cos^2 \omega_0 t$$

$$= I_0 + \frac{v_0^2}{4} G_d^{'} + v_0 G_d \cos\omega_0 t + \frac{v_0^2}{4} G_d^{'} \cos 2\omega_0 t \qquad 2.11$$

I_0 is the bias current and $v_0^2 G_d^{'} / 4$ is the DC rectified current. The output also contains AC signals of frequency ω_0, and $2\omega_0$ (and higher order harmonics), which are usually filtered out with a simple low-pass filter [Pozar, 2005].

2.6.5 Electrical Characteristics and Physics of Schottky Diode

Schottky diodes, based on silicon or gallium arsenide substrates, are used in many receiver and transmitter circuits for mixing and detecting at frequencies up to100 GHz. Today, advanced wafer and packaging processes allow the manufacture of low cost surface mount Schottky diodes in high volumes for commercial and consumer applications. Traditionally many of these diodes are used for mixing and power monitoring in RF applications such as mobile and cordless phones, satellite television receivers, RFID (radio frequency identification) systems and many others [Agilent Technologies, 1999].

The Schottky diode is a rectifying metal-semiconductor contact formed between a metal and an n-doped or p-doped semiconductor. When a metal-semiconductor junction is formed, free electrons flow across the junction from the semi-conductor and fill the free-energy states in the metal. This flow of electrons builds depletion potential across the junction. The difference in energy levels between semiconductor and metal is called a Schottky barrier.

P-doped Schottky barrier diodes excel at applications requiring ultra-low turn-on voltage (such as zero biased RF detectors), but their very low breakdown voltage and high series resistance make them unsuitable for the applications discussed in this note. As a result, we will focus entirely on n-doped Schottky diodes.

Under forward bias (metal connected to positive in an n-doped Schottky), there are many electrons with enough thermal energy to cross the barrier potential into the metal. Once the applied bias exceeds the built-in potential of the junction, the forward current I_f will increase rapidly with increase in V_f.

When the Schottky diode is reversed biased, the potential barrier for electrons becomes large: hence, there is a small probability that an electron will have sufficient thermal energy to cross the junction. The reverse leakage current will be in the nano-ampere range. In contrast to a conventional p-n junction, only majority carriers carry current in the Schottky diode. Because no minority carrier charge storage effects are present, Schottky diodes have carrier lifetimes of less than 100 *ps* and are extremely fast switching semiconductors. Another significant difference between Schottky and p-n diodes is the forward voltage drop. Schottky diodes have a threshold of typically 0.3 V compared to 0.6 V of p-n junction diodes. Through the careful manipulation of the diameter of the Schottky contact and the choice of metal deposited on the n-doped silicon, important characteristics of the diode (junction capacitance C_j, parasitic series resistance R_s, breakdown voltage V_{br} and forward voltage V_f) can be tailored to specific applications.

Schottky barrier diodes differ from junction diodes in that current flow involves only one type of carrier instead of both types. That is, in n-type Schottky barrier diodes the forward current consists of holes flowing from the n-type material into the metal. Diode action results from a contact potential set up between the metal and the semiconductor, similar to the voltage between the two metals in a thermocouple. When metal is brought into contact with an n-type semiconductor (during fabrication of the chip), electrons diffuse out of the semiconductor into the metal, leaving a region under the contact that has no free electrons (depletion layer). This region contains donor atoms that are positively charged (because each lost its excess electron), and this charge makes the semiconductor positive with respect to the metal. Diffusion continues until the semiconductor is so positive with respect to the metal that no more electrons can go into the metal. The internal voltage difference between the metal and the semiconductor is called the contact potential and is usually in the range of 0.3 – 0.8 volt for typical Schottky diodes. A cross section is shown in Figure 2.11 below.

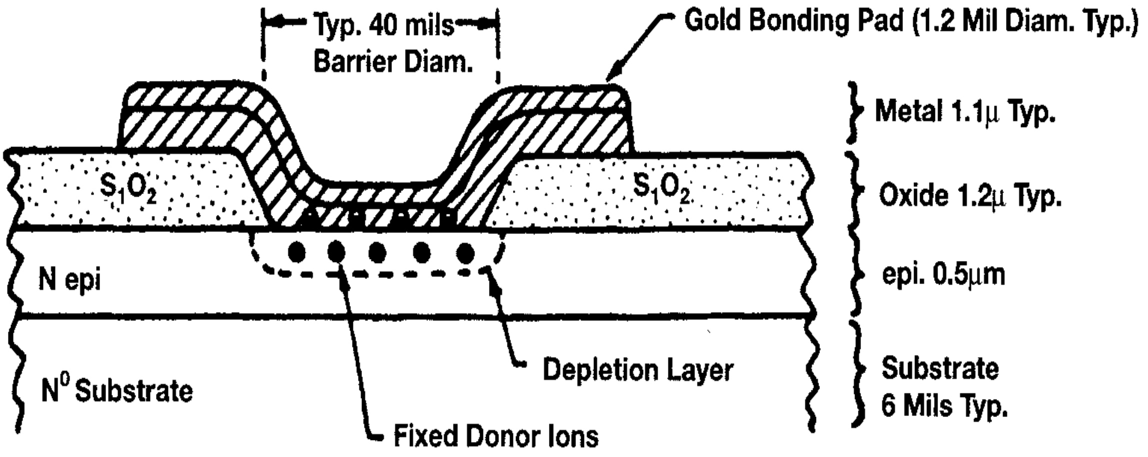

Figure 2. 11: Schottky diode chip cross section [Rohde, Newkirk, 2000]

When a positive voltage is applied to the metal, the internal voltage is reduced, and electrons can flow into the metal. The process is similar to thermionic emission of electrons from the hot cathode of a vacuum tube, except that the electrons are “escaping” into a metal instead of into a vacuum. Unlike the vacuum tube case, room temperature is “hot” enough for this to happen if enough voltage is applied. However, only those electrons whose thermal energy happens to be many times the average can escape, and these “hot electrons” account for all the forward current from the semiconductor into the metal.

One important thing to note is that there is no flow of minority carriers from the metal into the semiconductor and thus no neutral plasma of holes and electrons is formed. Therefore, if the forward voltage is removed, current stops “instantly,” and reverse voltage can be established in a few picoseconds. There is no delay effect to charge storage as in junction diodes. This accounts for the exclusive use of barrier diodes in microwave mixers, where the diode must switch conductance states at microwave oscillator rates.

The current–voltage relationship for a barrier diode is described by the Richardson equation (which also applies to thermionic emission from a cathode) [Rohde, Newkirk, 2000]. The equation is given as:

$$I = AA_{RC}T^2 \exp\left(-\frac{q\phi_B}{kT}\right)\left[\exp\left(\frac{qV_J}{kT}\right) - M\right] \tag{2. 12}$$

where;

A is area (cm2)

A_{RC} is modified Richardson constant (A/K^2.cm^2)

K is Boltzmann's constant

T is absolute temperature (K)

ϕ_B is barrier height in volts

V_J is external voltage across the depletion layer (positive for external voltage)

$= V - IR_S$

R_S is series resistance

M is avalanche multiplication factor

I is diode current in amperes (positive forward current)

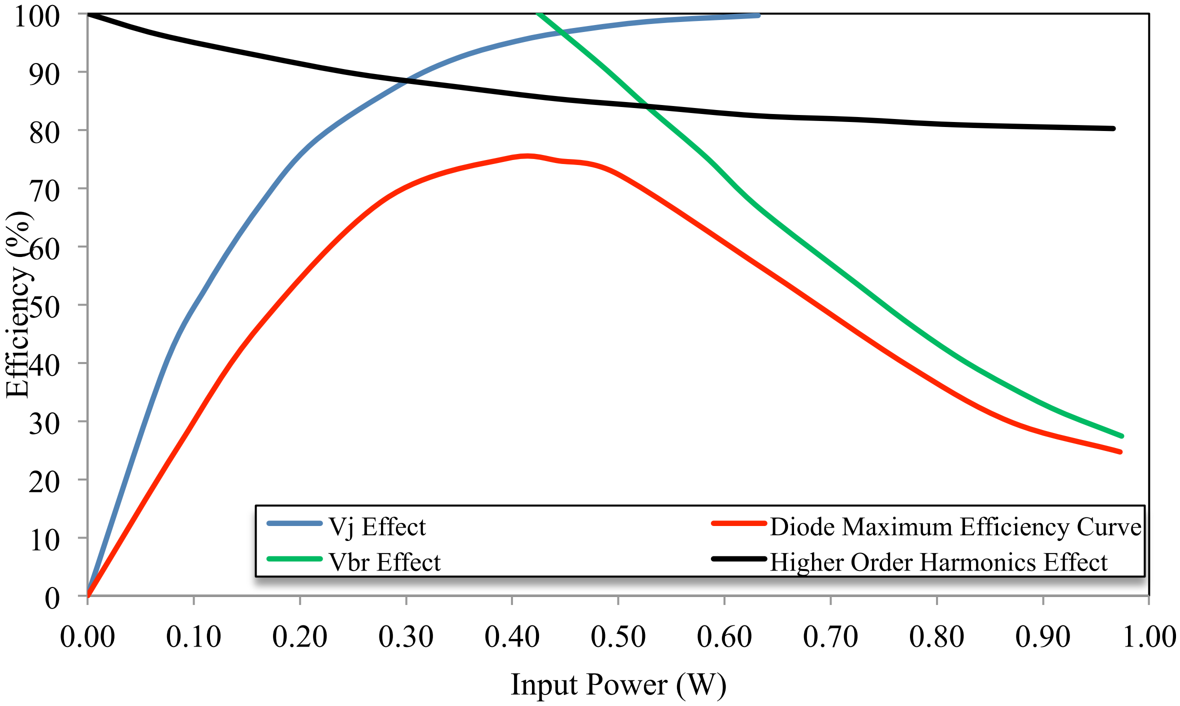

Figure 2. 12: General Relationship of RF-DC Power Conversion Efficiency [Matsumoto, 2002]

Figure 2.12 shows the general relationship between the microwave-to-DC power conversion efficiency and the input microwave power. The term "V_j effect", in the Figure means the junction voltage effect. The realistic diode cannot rectify the input AC current if the input microwave voltage is below the junction voltage. On the contrary, if the microwave power into the diode is too large, the rectifying diodes start to suffer from the breakdown. This is referred to as "V_{br} effect". These two effects appear not only in the rectenna but also in the general circuits with diodes. The higher order harmonic effect is another important characteristic of rectennas. The higher harmonic microwaves are generated due to the non-linear characteristics of diodes. These harmonic waves should not be radiated from the antenna part of the rectenna. To suppress the back travelling of these higher harmonics generated at the diodes, it should be choked in the part of the input filter.

These three effects give influence on the RF-to-DC conversion efficiency. Therefore, for realistic diodes used in rectennas, the maximum efficiency curve becomes as drawn in Figure 2.12. The GaAs Schottky barrier diode is mostly used for the rectifying circuit because of its low VJ, which is approximately 0.3 to 0.8 Volts. Similarly, the conversion efficiency depends on the connected load. Typical characteristic of the RF-DC conversion efficiency of the rectenna is as a function of the load.

The RF-DC conversion efficiency of the rectenna depends on the microwave power input intensity and the connected load. It has the optimum microwave power input intensity and the optimum load to achieve maximum efficiency. When the power or load is not optimum, the efficiency is nearly 0% (Figure 2.12). The conversion efficiency is determined by the diode characteristics. The diode has its own junction voltage and breakdown voltage. If the input voltage to the diode is lower than the junction voltage or higher than the breakdown voltage, the diode does not rectify the input microwave. As a result, the RF-DC conversion efficiency drops when the input is lower or higher than the optimum.

2.6.6 Rectenna Antenna

Many types of antennas can be classified as aperture antennas, meaning that the antenna has a well-defined aperture area from which radiation occurs. Examples include reflector antennas, horn antennas, lens antennas, and array antennas. The antenna cannot be considered a separate entity. This is due to the fact that the antenna affects the rectifier, and vice versa. In order to prevent impedance mismatch, the antenna and rectifier must be matched. The following need to be considered:

- size of each
- shape of each
- beam spread
- gain
- VSWR (Voltage Standing Wave Ratio)

It is necessary to minimize the VSWR so that power is transmitted from the antenna to the rectifier. Reflection causes a great deal of interference on the antenna. Several types of antenna have been considered which include dipole antennas, monopole antennas, microstrip antennas, printed dipole and parabolic antenna.

Factors deciding the total surface area of the rectenna require careful consideration of the following factors:

- the amount of microwave power that can be rectified
- the power density of the incoming microwave radiation
- antenna gain

In addition, the efficiency of the rectenna diminishes if the incoming power is too high or too low.

2.6.7 Rectifier Circuit

There are as many rectifier circuits as there are antennas for rectennas. Some of the more popular rectifiers include:

1. One diode plus quarter-wave circuit
2. Full-wave circuit with capacitor
3. Full-wave bridge rectifier

The diode is the key component of the rectifier circuit of the rectenna. The maximum RF-DC conversion efficiency is largely determined by;

1. Dependency on input microwave strength on the diode, and
2. Dependency on connected load at the output of the diode.

Though, efficiency varies with the type of configuration of the rectifier, the important characteristics are:

1. DC resistance
2. Stray capacitance
3. Turn on voltage, and
4. Breakdown voltage.

Rectennas generally use the silicon Schottky barrier diodes. This is because of its microwave characteristics and because of its transient build-up; voltage is around 0.1 to 0.3 V, which is a lot smaller than other diodes.

2.7 THE WIRELESS LINK

A general wireless link is shown in Figure 2.13, where the transmit power is P_t, the transmit antenna gain is G_t, the receive antenna gain is G_r, and the received power (delivered to a matched load) is P_r. Both transmit and receive antennas are separated by the distance R.

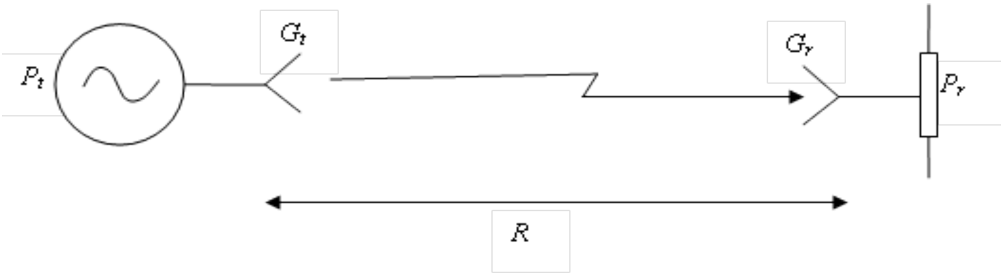

Figure 2. 13: A diagram for a general radio link [Pozar, 2005]

2.7.1 The Friis Equation

By conservation of energy, the power density S_{avg} radiated by an isotropic antenna ($D = 1 = 0\ dB$) at a distance, R is given by:

$$S_{avg} = \frac{P_t}{4\pi R^2}\ \text{W/m}^2 \qquad 2.\ 13$$

where P_t is the power radiated by the antenna. This result is deduced from the fact that we must be able to recover all of the radiated power by integrating over a sphere of radius R surrounding the antenna; since the power is distributed isotropically, and the area of a sphere is $4\pi R^2$, equation (2.13) follows. If the transmit antenna has a directivity greater than 0 *dB*, we can find the radiated power density by multiplying by the directivity, since directivity is defined as the ratio of the actual radiation intensity to the equivalent isotropic radiation intensity. Also, if the transmit antenna has losses, we can include the radiation efficiency factor, which has the effect of converting directivity to gain [Araiza, 2000]. Thus, the general expression for the power density radiated by an arbitrary transmit antenna is:

$$S_{avg} = \frac{G_t P_t}{4\pi R^2} \text{ W/m}^2 \qquad 2.14$$

2.7.2 *Effective Area*

For a receiving antenna, it is of interest to determine the received power for a given incident plane wave field. It is expected that the received power will be proportional to the power density, or Poynting vector, of the incident wave. Since the Poynting vector has dimension of W/m^2, and the received power P_r has dimension of Watts, W, the proportionality constant must have unit of area, m^2. Thus, we write:

$$P_r = A_e S_{avg} \qquad 2.15$$

where A_e is defined as the effective aperture area of the receive antenna. The effective aperture area has dimensions of m^2, and can be interpreted as the “capture area” of a receive antenna, intercepting part of the incident power density radiated toward the receive antenna. P_r in equation (2.15) is the power available at the terminal of the receive antenna, as delivered to a matched load [Araiza, 2000].

The maximum effective aperture area of an antenna is shown to be related to the directivity of the antenna by:

$$A_e = \frac{D\lambda^2}{4\pi} \qquad 2.16$$

where λ, is the operating wavelength of the antenna. For electrical aperture antennas, the effective aperture area is often close to the actual physical aperture area. However, for many other types of antennas, such as dipoles and loops, there is no simple relation between the physical cross-sectional area of the antenna and its effective aperture area. The maximum effective aperture area as defined above does not include the effect of losses in the antenna, which can be accounted for by replacing D in equation (2.16) with G, the gain of the antenna.

2.7.3 Received Power

If the power density obtained in equation (2.14) is incident on the receiver antenna, the concept of effective aperture area defined above can be used to obtain the following expression for the received power:

$$P_r = A_e S_{avg} = \frac{G_t P_t A_e}{4\pi R^2} \text{ W} \qquad 2.17$$

Here, equation (2.16) can be used to relate the effective area to the directivity of the receive antenna. Again, the possibility of losses in the receive antenna can be accounted for by using the gain rather than the directivity of the receive antenna. Therefore, the result for the received power is:

$$P_r = \frac{G_t G_r \lambda^2}{(4\pi R)^2} P_t \text{ W} \qquad 2.18$$

Equation (2.18) is also known as the Friis equation, which addresses the fundamental question of how much power is received by a radio antenna. In practice, the value given by equation (2.18) should be interpreted as the maximum possible received power, as there are a number of factors that can serve to reduce the received power in an actual radio system. These include impedance mismatch at either antenna, polarization mismatch between them, propagation effects leading to attenuation or depolarization, and multipath effects that may cause partial cancellation of the received field [Araiza, 2000].

It is observed in equation (2.18) that the received power decreases by $1/R^2$ as the separation between the transmitter and the receiver increases. As stated earlier, this dependence is a result of conservation of energy. While it may seem to be prohibitively large for large distances, in fact the space decay of $1/R^2$ is much better than the exponential decrease in power due to losses in a wired communications link. This is because the attenuation of power on a transmission line varies as $e^{-2\alpha z}$ (where α is the voltage attenuation constant of the line), and at large distances the exponential function always decreases faster than an algebraic dependence like $1/R^2$. Thus for long distance communications, radio links will perform better than wired links [Araiza, 2000].

As can be seen from the Friis formula, received power is proportional to the product P_tG_t. These two factors, the transmit power and the transmit antenna gain, characterize the transmitter, and in the main beam of the antenna the product P_tG_t can be interpreted equivalently as the power radiated by an isotropic antenna with input power P_tG_t. Thus, the product is defined as the effective isotropic radiated power (EIRP):

$$P_{EIRP} = P_t G_t \text{ W} \qquad 2.\ 19$$

For a given frequency, range, and receiver antenna gain, the received power is proportional to the EIRP of the transmitter, and can only be increased by increasing the EIRP. This can be done by increasing the transmit power, or the transmit antenna gain, or both [Pozar, 2005].

2.8 ANTENNA PROPERTIES

The antenna is one of the most important building blocks of the rectenna. Without it, there would be no transmission and reception of microwave. Its characteristics affect in many ways the overall efficiency of WPT systems. In general, an arbitrary antenna has complex input impedance (related to the feed point), which can be written in the form:

$$Z_{Ant} = R_A + j_{Xant} \qquad 2.\ 20$$

where

$$R_A = R_{loss} + R_s$$

R_s is the radiation resistance of the antenna, R_{loss} is the loss resistance of the antenna, X_{ant} is the imaginary part of the antenna input impedance, S corresponds to the effective aperture of the antenna and P_{AV} is the available power that the antenna can deliver to a matched load [Curty, et al.2007].

2.8.1 Loss resistance

The loss resistance R_{loss} is due to the actual resistance of the elements that form the antenna and the dielectric losses. Power dissipated in this manner is lost as heat. Although it may appear that, the "DC" resistance is low, at higher frequencies, the skin effect δ is in evidence and only the surface areas of the conductor are used. As a result, the effective resistance is higher than would be measured at DC for closed loop antennas. It is proportional to the circumference of the conductor and to the square root of the frequency.

The resistance can become particularly significant in high current sections of an antenna where the effective resistance is low. Accordingly, to reduce the effect of the loss resistance it is necessary to ensure the use of very low resistance conductors [Curty, et al., 2007]

2.8.2 Radiation resistance

The other resistive element is the "radiation resistance." This can be thought of as virtual resistor. It arises from the fact that power is "dissipated" when it is radiated. The aim, when designing an antenna, is to "dissipate" as much power in this way as possible. It varies from one type of antenna to another and from one design to another. It is dependent upon a variety of factors. A typical half wave folded dipole operating in free space has a radiation resistance of around 300 Ω. It should be noted that the radiation resistance is not a real resistor, but simply a convenient form for representing a loss of energy from the antenna. In a real resistance, the lost energy is converted to heat. With respect to radiation resistance, the energy is not converted to heat, but simply radiated as radio waves [Curty, et al., 2007].

The antennas, SL25-9 panel antenna, which was designed to operate between the ranges of the 2.4 – 2.5 GHz frequency band, are manufactured by Webb Industries. The electrical data is given in table 2.2 below:

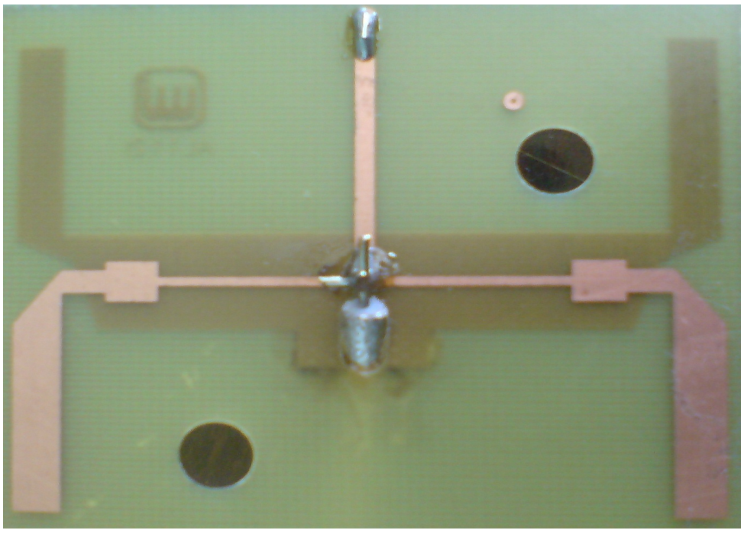

Figure 2. 14: The printed dipole array antenna

Table 2. 2: Electrical Data of SL25-9 Antenna

Electrical Data	SL25-9 Antenna
Frequency Range	2.4 – 2.5 GHz
Average Gain	9 -0.5 dBi
Front-to-back ratio	> 1:5
VSWR	<1.5:1
Polarisation	Vertical or horizontal
H Plane 3 dB beamwidth	60°
H Plane 3 dB beamwidth	60°
XPD	20 dB Typ.
Rated power	10 W
Impedance	50 Ω
Termination	N-Type female on rear of antenna

2.8.3 Beam Efficiency

Beam efficiency is another frequently used parameter to gauge the performance of an antenna. Beam efficiency is the ratio of the power received or transmitted within a cone angle to the power received or transmitted by the whole antenna. Thus, beam efficiency is a measure of the amount of power received or transmitted by minor lobes (beams) relative to the main beam [Chang, 2000].

2.8.4 Bandwidth

The bandwidth of an antenna is broadly defined as the range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard. In general, bandwidth is specified as the ratio of the upper frequency to the lower frequency or as a percentage of the centre frequency. Since antenna characteristics are affected in different ways as frequency changes, there is no unique definition of bandwidth. The two most commonly used definitions are pattern bandwidth and impedance bandwidth. The power entering the antenna depends on the input impedance locus of the antenna over the frequencies. Therefore, the impedance bandwidth (BW) is the range of frequencies over which the input impedance conforms to a specified standard.

This standard is commonly taken to be VSWR ≤ 2 (or $|\Gamma| \leq \frac{1}{3}$) and translates to a reflection of about 11% of input power. Some applications may require a more stringent specification, such as a VSWR of 1.5 or less. Furthermore, the operating bandwidth of an antenna could be smaller than the impedance bandwidth, since other parameters (gain, efficiency, patterns, etc.) are also functions of frequencies and may deteriorate over the impedance bandwidth [Chang, 2000].

2.8.5 Power Radiation Patterns

The power radiated (or received) by an antenna is a function of angular position and radial distance from the antenna. At electrically large distances, the power density drops off as $1\ /\ R^2$ in any direction. The variation of power density with angular position can be plotted by the radiation pattern. At electrically large distances (i.e., far-field or plane-wave regions), the patterns are independent of distance. The complete radiation properties of the antenna require that the electric or magnetic fields be plotted over a sphere surrounding the antenna. However, it is often enough to take principal pattern cuts [Chang, 2000].

2.8.6 Directivity, Gain, and Efficiency

The directivity D_{max} is defined as the value of the directive gain in the direction of its maximum value. The directive gain $D(\theta,\phi)$ is the ratio of the Poynting power density over $S(\theta,\phi)$ the power density radiated by an isotropic source. Therefore, one can write:

$$D(\theta,\phi) = \frac{S(\theta,\phi)}{P_t/4\pi R^2} \tag{2. 21}$$

$$D_{max} = \frac{maximum\ of\ S(\theta,\phi)}{P_t/4\pi R^2} \tag{2. 22}$$

where

$$\vec{S}(\theta,\phi) = \frac{1}{2}\,Re[\vec{E}\ \mathrm{x}\ \overrightarrow{H^*}].$$

The directivity of an isotropic antenna equals to 1 by definition, and that of other antennas will be greater than 1. Thus, the directivity serves as a figure of merit relating the directional properties of an antenna relative to those of an isotropic source [Chang, 2000].

The gain of an antenna is the directivity multiplied by the illumination or aperture efficiency of the antenna to radiate the energy presented to its terminal:

$$Gain = G = \eta D_{max} \tag{2. 23}$$

$$\eta = efficiency = \frac{P_{rad}}{P_{in}} = \frac{P_{rad}}{P_{rad} + P_{loss}} \tag{2. 24}$$

where P_{rad} is the actual power radiated, Pin is the power coupled into the antenna, and P_{loss} is the power lost in the antenna. The losses could include ohmic or conductor loss, dielectric loss, and so on. Generally, the narrower the beamwidth the higher the gain. The radiated power density in the direction of its maximum value is [Chang, 2000]:

$$P_{d,max} = G(P_t/4\pi R^2) \tag{2. 25}$$

2.8.7 Antenna Taper

The gain pattern of a reflector antenna depends on how the antenna is illuminated by the feed. The variation in electric field across the antenna diameter is called the antenna taper [Nelson, 2009]. The total antenna solid angle containing all of the radiated power, including side lobes, is:

$$W_A = h * (4p / G) = (1/h_a) (l^2 / A) \tag{2. 26}$$

where h_a is the aperture taper efficiency and h * is the radiation efficiency associated with losses. The beam efficiency is defined as

$$e = W_M / W_A \tag{2. 27}$$

where W_M is the solid angle for the main lobe. The values of h_a and e are calculated from the electric field distribution in the aperture plane and the antenna radiation pattern, respectively.

For a theoretically uniform illumination, the electric field is constant and the aperture taper efficiency is 1. If the feed is designed to cause the electric field to decrease with distance from the centre, then the aperture taper efficiency decreases but the proportion of power in the main lobe increases. In general, maximum aperture taper efficiency occurs for a uniform distribution, but maximum beam efficiency occurs for a highly tapered distribution.

For uniform illumination, the half power beamwidth is 58.4° l /*D* and the first side lobe is 17.6 dB below the peak intensity in the boresight direction. In this case, the main lobe contains about 84% of the total radiated power and the first side lobe contains about 7%.

If the electric field amplitude has a simple parabolic distribution, falling to zero at the reflector edge, then the aperture taper efficiency becomes 0.75 but the fraction of power in the main lobe increases to 98%. The half power beamwidth is now 72.8° l /*D* and the first side lobe is 24.6 dB below peak intensity. Thus, although the aperture taper efficiency is less, more power is contained in the main lobe, as indicated by the larger half power beamwidth and lower side lobe intensity.

If the electric field decreases to a fraction C of its maximum value, called the edge taper, the reflector will not intercept all the radiation from the feed. There will be energy spillover with a corresponding efficiency of approximately $1 - C^2$. However, as the spillover efficiency decreases, the aperture taper efficiency increases. The taper is chosen to maximize the illumination efficiency, defined as the product of aperture taper efficiency and spillover efficiency.

The illumination efficiency reaches a maximum value for an optimum combination of taper and spillover. For a typical antenna, the optimum edge taper C is about 0.316, or - 10 dB (20 log C). With this edge taper and a parabolic illumination, the aperture taper efficiency is 0.92, the spillover efficiency is 0.90, the half power beamwidth is 65.3° l /*D*, and the first side lobe is 22.3 dB below peak. Thus, the overall illumination efficiency is 0.83 instead of 0.75. The beam efficiency is about 95% [Nelson, 2009].

2.9 SUMMARY

In this chapter, the evolution of radio and microwaves has been discussed with the two major pioneers of the technologies. However, there is no frequency allocated to wireless power transmission, the 2.45 GHz has been chosen due to readily available components to take advantage of the existing technologies. These individual components have also been discussed and their properties analysed to show how these properties affect the WPT systems at different stages.

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CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

For a better Wireless Power Transmission (WPT) system, efficiency in each subsystem is an important factor. The DC-to-microwave and microwave-to-DC conversion efficiencies (η_t and η_r, respectively) depend on the adopted transmitter and rectifiers. The efficiency of wave reception of the transmitted microwave at the receiving antenna (η_{tr}) depends on the sizes of transmitting and receiving antennas, transmission distance, and wavelength of the microwave. A dimensionless quantity X is defined as follows and is used as a measure of the total efficiency of wireless power transmission.

$$X = \eta_{total} = 2\pi(\lambda D)^{-1} A_t A_r \qquad 3.\ 1$$

where A_t is the area of the transmitting antenna, A_r is area of the receiving antenna, λ is the wavelength, and D is the transmission distance.

The transmission efficiency η_{tr} depends on the amount of microwave power that can be collected by the receiving antenna, which depends on the wave collection efficiency. The wave collection efficiency increases as X increases; therefore, η_{tr} increases as X increases. A hundred per cent efficiency of η_{tr} is achieved when X reaches infinity [Matsumoto, 2002]. The total conversion efficiency (η_{total}) of DC-microwave-DC is expressed as follows:

$$\eta_{total} = \eta_t \times \eta_{tr} \times \eta_r \qquad 3.2$$

3.2 SPECIFICATIONS AND REQUIREMENTS

The system specifications and requirements considered for the study are listed in Tables 3.1 and 3.2. These are decisions made within the parameters of available components and conditions of operations.

Table 3. 1: Parameters considered for measurement

Symbol	Definition
A_r	Receiver antenna area
A_t	Transmitter antenna area
D	Distance between transmitter and receiver
D_0	Directivity of antenna
P_{RF}	Transmitted RF power
τ	Goubau's parameter
f	Frequency of operation
λ	Wavelength
G_t	Gain of transmitter
G_r	Gain of receiver

η_a	Antenna efficiency
η_t	Transmission efficiency
η_{rect}	Rectenna efficiency
S	Power density
η_{mag}	Magnetron efficiency

Table 3. 2: List of Specifications and Assumptions

Specifications			Assumptions	
D (m)	f (GHz)	λ (m)	η_a (%)	P_{mag} (W)
5	2.45	0.122	100	4

Using these known parameters, the areas of the antennas A_t and A_r, the power density S, the remaining system efficiencies as well as the transmitter and receiver configurations can be determined. The requirements are to calculate relatively small aperture sizes for minimum cost and fabrication complexity and optimum efficiencies in order to reduce losses and maximize the power transfer. The determination of the unknown parameters will require some trade-offs to fulfil the system requirements.

3.2.1 System configuration

A WPT system consists of three main functional blocks. A first block is needed to convert the electricity (DC or AC) into microwaves. After being radiated through an array of microwave radiators, the RF power is carried within a focused microwave beam that travels across free space towards a collector. This receiving block will convert the RF energy back into DC electricity. A simplified schematic in Figure 3.1 shows the block diagram of a WPT system.

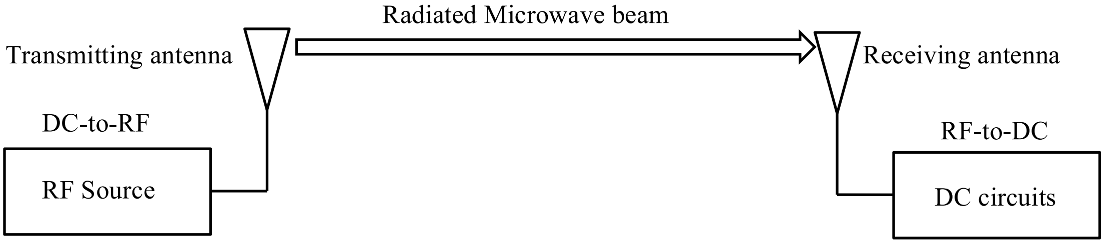

Figure 3. 1 Block diagram of wireless power transmission system

3.2.2 Beam characteristics

The radiation pattern obtained from the transmitting antenna is a function of the size as well as the illumination taper across the antenna aperture. The transmitter illumination taper also affects the collection efficiency. As shown by Brown, it can be seen from the curves that a taper close to uniform illumination can result in a very inefficient aperture-to-aperture transmission of power [Brown, 1974]. This low collection efficiency is due to a narrow main beam with high sidelobe levels produced by the uniform illumination.

To reach collection efficiency near 100%, the distribution should be a truncated Gaussian taper [Goubau and Schwering, 1968]. This optimal taper distribution will produce a more spread main beam with very low sidelobe levels over 20 dB below the main beam. For example, with a 10 dB Gaussian taper, the first sidelobe level is 23 dB below the main beam.

The degree of truncation or taper level is defined as the ratio of the centre over the edge power intensity. A larger taper will increase the collection efficiency and lower the sidelobes. However, by using a taper distribution instead of a uniform illumination, a higher power density will result at the transmitter aperture. In addition, the flattening and widening of the main beam with a taper distribution will require a larger receiver aperture. As can be seen, there exists a trade-off between low sidelobes levels and narrow beamwidth. Therefore, the choice of the taper will depend on the system constraints of collection efficiency, sidelobes levels, peak power density, and size of the apertures [Zepeda, 2003].

3.2.3 Frequency

The selection of the operating frequency has a significant impact on the configuration of the planned WPT system. The electromagnetic spectrum can be divided into three types of radiation, here given in order of increasing frequency: the radio waves, the optical rays and the high-energy waves. Microwaves are located between the radio and optics frequency bands. As the frequency is increased, the effect of the radiation grows progressively from heat production to ionizing effect (modification of the molecular structure). Waves produced in the microwave band are of low energy and have no ionizing effect on materials.

Spreading the microwave beam over a large cross sectional area can further lower the hazard level. The power density can be reasonably reduced to about 10 mW/cm^2, the US safety standard for microwave exposure, which is a considerably smaller amount compared to the sunlight energy radiating 100 mW/cm^2 [Pignolet, 1999]. Increasing the wavelength or the distance between the transmitter and the receiver can also spread the beam out.

In this study, the system operates at the ISM frequency of 2.45 *GHz*. This choice presents various advantages. Working at lower frequencies allows the transmitted microwave beam to travel through the atmosphere without suffering from excessive attenuation. Furthermore, WPT technology at 2.45 *GHz* has been proven efficient. Hence, it is a common practice to use the low-cost commercially available microwave oven magnetron tubes as sources for the transmitter at 2.45 *GHz*. Moreover, lower frequency technologies are more matured and the designs generally present higher efficiencies.

3.2.4 Microwave Source

Vacuum tubes such as the well-known magnetron (found in the domestic microwave oven), the traveling wave tube, and the klystron are all high power microwave sources that convert the DC (or AC) power into RF power. The magnetron based microwave generator was chosen for this study, as it is an inexpensive and efficient device. Typical DC(AC)-to-RF conversion efficiencies, η_{mag}, are in the range of 70% to 90%. Klystrons are not as efficient as magnetrons and more expensive. Although solid-state FET (field-effect transistor) sources are very simple, they still provide inferior efficiencies compared to high power microwave tubes.

The output power range of an oven magnetron, P_{mag}, varies from 1 W to about 1.2 *kW*. Higher power magnetrons used for industrial heating can provide up to 5 *kW* of output power. However, the microwave generator under study can output up to 1.2 *kW* RF power; it was limited to the FCC regulation of 4 *W* where human interaction is involved.

3.3 RECTIFIER DESIGN

The designs of the rectifier are in two forms. (1) Half-Wave, (2) Full wave bridge. These two rectifier designs were used to determine which was more efficient for the conversion of RF to DC voltage in this experiment and the applications.

3.3.1 Half-Wave Rectifier

A rectifier is a circuit, which converts Alternating Current (AC) into a Direct Current (DC) form, and the simplest of all the rectifier circuits is the Half-Wave Rectifier. A half-wave rectifier circuit uses just one half of each complete sine wave or cycle of the AC supply in order to convert it to a DC supply. Then this type of circuit is called a “half-wave” rectifier because it passes only half of the incoming AC power signal as shown below.

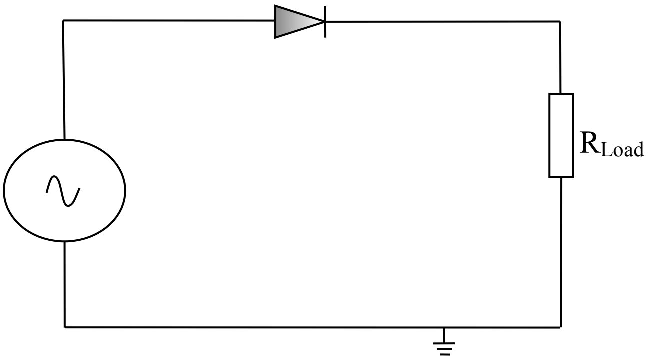

Figure 3. 2: Half-wave rectifier

During each positive half cycle of the AC sine wave, the diode is Forward Biased (Anode is positive with respect to the Cathode) and current flows through it. Since the DC load is resistive (resistor *R*), the current flowing in the load resistor is therefore proportional to the voltage (Ohm's Law), and the voltage across the load resistor is the same as the supply voltage, V_s (minus V_f), that is the DC voltage across the load is sinusoidal for the first half cycle only. Then $V_{out} = V_s$. [Storr, 2009a].

During each negative half cycle of the AC sine wave, the diode is Reverse Biased (Anode is negative with respect to the Cathode) and no current flows through it. Therefore, in the negative half cycle of the supply, no current flows in the load resistor as no voltage appears across it. Then $V_{out} = 0$.

The current on the DC side of the circuit flows in one direction only making the circuit unidirectional and the value of the DC voltage VDC across the load resistor is calculated as follows:

$$V_{DC} = \frac{V_{\max}}{\pi} = 0.138 V_{\max} = 0.45 V_s \qquad 3.3$$

where V_{max} is the maximum voltage value of the AC supply, and V_S is the root mean square (r.m.s.) value of the supply [Storr, 2009a].

3.3.2 Full-Wave Bridge Rectifier

This type of single-phase rectifier uses 4 individual rectifying diodes connected in a “bridged” configuration to produce the desired. The single secondary winding is connected to one side of the diode bridge network and the load to the other side as shown below [Storr, 2009].

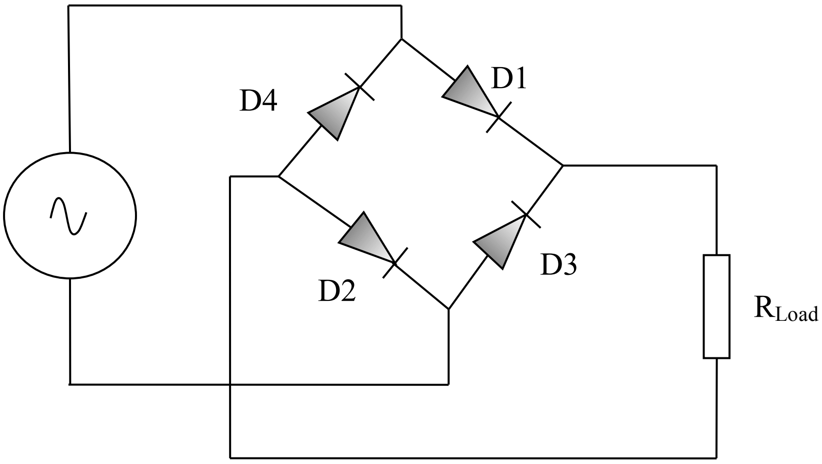

Figure 3. 3: Full-wave rectifier

The 4 diodes labelled D1 to D4 are arranged in “series pairs” with only two diodes conducting current during each half cycle.

3.3.2.1 The Positive Half-cycle

During the positive half cycle of the supply, diodes D1 and D2 conduct in series while diodes D3 and D4 are reverse biased and the current flows through the load as shown below.

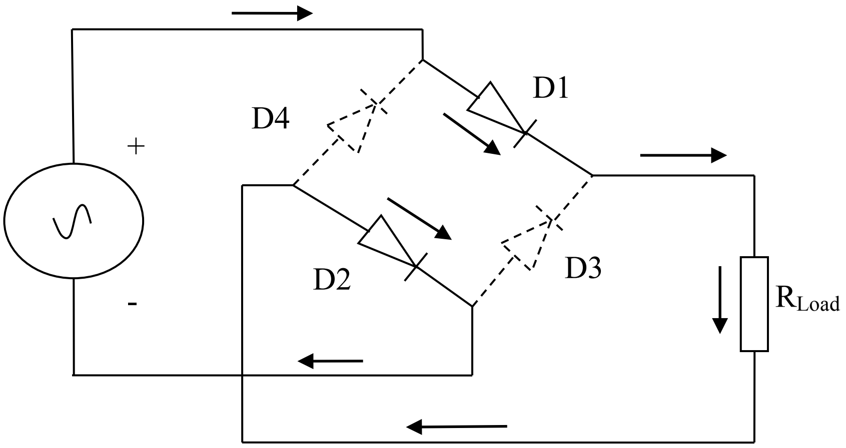

Figure 3. 4: Positive half cycle

3.3.2.2 The Negative Half-cycle

During the negative half cycle of the supply, diodes D3 and D4 conduct in series, but diodes D1 and D2 switch off as they are now reverse biased. The current flowing through the load is the same direction as before.

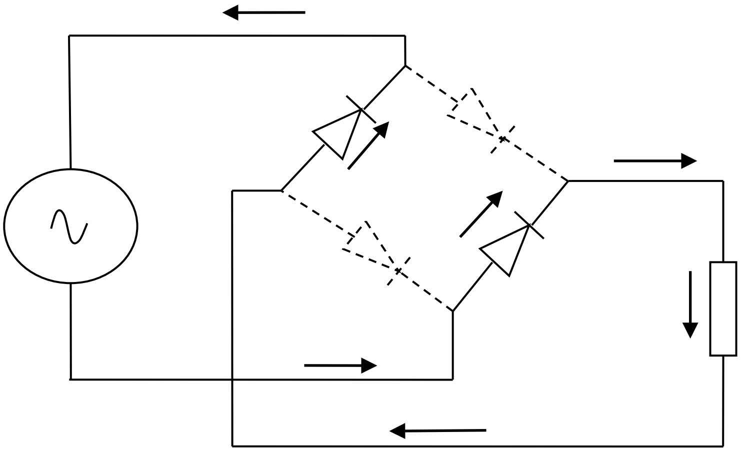

Figure 3. 5: Negative half cycle

As the current flowing through the load is unidirectional, so the voltage developed across the load is also unidirectional the same as for the previous two diode full-wave rectifier, therefore the average DC voltage across the load is 0.637Vmax and the ripple frequency is now twice the supply frequency (e.g. 100 Hz for a 50 Hz supply).

The main advantages of a full-wave bridge rectifier is that it has a smaller AC ripple value for a given load and a smaller reservoir or smoothing capacitor than an equivalent half-wave rectifier. Therefore, the fundamental frequency of the ripple voltage is twice that of the AC supply frequency (100 Hz) where for the half-wave rectifier it is exactly equal to the supply frequency (50 Hz). The amount of ripple voltage that is superimposed on top of the DC supply voltage by the diodes can be virtually eliminated by adding a much-improved π-filter (pi-filter) to the output terminals of the bridge rectifier. This type of low-pass filter consists of two smoothing capacitors, usually of the same value and a choke or inductance across them to introduce a high impedance path to the alternating ripple component [Storr, 2009b].

3.4 LINEAR EQUIVALENT CIRCUIT OF THE SCHOTTKY DIODE

The rectifiers are Schottky-barrier diodes, HSMS-8202, manufactured by Avago technologies; a branch of Agilent Technologies. These diodes are optimized for high-frequency operation (*f* > 1 *GHz*). A linear equivalent circuit, as shown in Figure 4.6, can represent the Schottky diode. In addition, the accurate values of the diode parameters I_s, n, and R_s are used. The manufacturer in the diode's data sheet generally provides these.

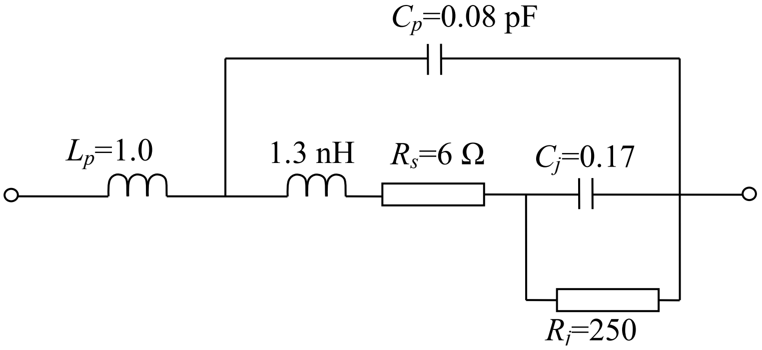

Figure 3. 6: Equivalent Circuit of a Schottky Diode.

C_j is the parasitic junction capacitance of the Schottky chip and R_S is parasitic series resistance of the chip. L_p and C_p are package parasitic. R_j is the junction resistance of the diode, where RF power is converted into DC out- put voltage. For maximum output, all the incoming RF voltage should ideally appear across R_j, with nothing lost in R_S. The equation for junction resistance is:

$$R_j = 0.026 / I_T \tag{3.4}$$

where

$I_T = I_s + I_b + I_0$, in amperes

I_s = the diode's saturation current, a function of Schottky barrier height

I_b = circulating current generated by the rectification of RF power

I_0= External bias current (if any)

This diode can be used to convert RF power to DC with a simple detector circuit. The behaviour of Schottky detector circuits has been well studied in an operating region defined by two conditions: low input power (square law operation) and high load resistance. These two conditions, however, are not consistent with the use of a Schottky diode to generate reasonable levels of DC voltage and current [Avago, 2007].

The input impedance Z_{in} and total impedance Z_{Tot} of the diode can be calculated from the values provided by the manufacturer in the data sheet. The linear equivalent circuit diagram needs to be redrawn to represent the complex conjugates of the circuit. This is expressed below:

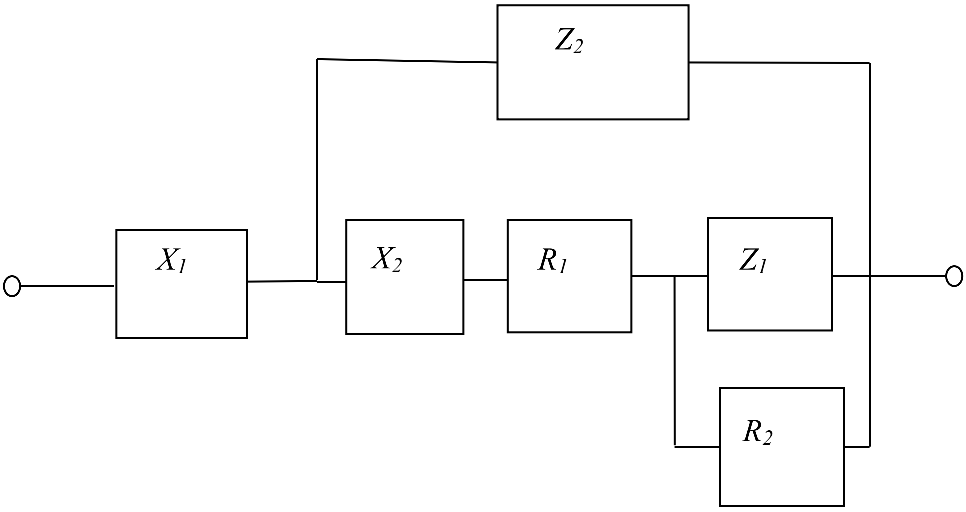

Figure 3. 7: Total impedance of Diode

From the values in the linear equivalent circuit, one could say,

$$X = j2\pi fL \tag{3. 5}$$

where f is the frequency, which is 2.45 GHz

Therefore,

$$X_1 = j2\pi\left(2.45\times10^9\right)\left(1.0\times10^{-9}\right)$$

$$= j15.39$$

$$X_2 = j2\pi\left(2.45\times10^9\right)\left(1.3\times10^{-9}\right)$$

$$= j20.01$$

$$Z = \frac{j}{2\pi fC} \tag{3. 6}$$

$$Z_1 = \frac{j}{2\pi fC} = \frac{j}{2\pi\left(2.45\times10^{9}\right)\left(0.17\times10^{-12}\right)}$$

$$= j382.13$$

$$Z_2 = \frac{j}{2\pi fC} = \frac{j}{\left(2.45\times10^{9}\right)\left(0.08\times10^{-12}\right)}$$

$$= j812.02$$

R1 = 6 Ω and R2 = 256 Ω, then;

$$A = Z_1 \,||\, R_2 \qquad 3.\,7$$

$$\frac{1}{A} = \frac{1}{Z_1} + \frac{1}{R_2} = \frac{1}{j382.13} + \frac{1}{256}$$

$$\therefore A = 176.697 + 118.374j$$

$$B = X_2 + R_1 + A \qquad 3.\,8$$

$$B = X_2 + R_1 + A = j20.01 + 6 + 176.697 + 118.374j$$

$$= 182.697 + 138.384j$$

$$C = Z_2 \,||\, B \qquad 3.\,9$$

$$\frac{1}{C} = \frac{1}{j812.015} + \frac{1}{182.697 + 138.384j}$$

$$\therefore C = 128.614 + 142.958j$$

From these results, input impedance Z_{in}, can be deduced from the expression;

$$Z_{in} = X_1 + C = 128.614 + 158.352j$$

$$\therefore |Z_{in}| = 204.00\Omega$$

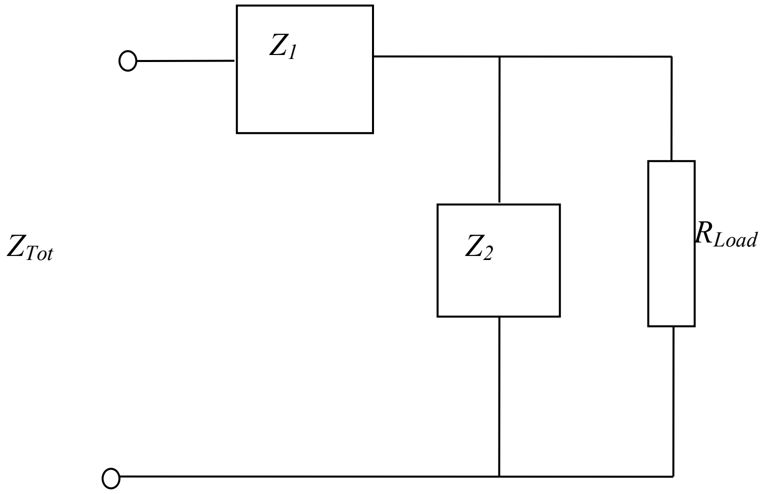

Figure 3. 8: Total impedance equivalent circuit

$$Z_{Tot} = Z_1 + Z_2 \,||\, R_{Load} \qquad 3.\ 10$$

Choosing $R_{Load} = 500\ \Omega$

$$Z_{Tot} = 257.245 + j316.62$$

$$|Z_{Tot}| = 407.95\Omega$$

AppCAD Software by Hewlett Packard (HP) was used to simulate the expected output voltages of the diodes in both the single and voltage doubler modes. The simulation was carried out from the SPICE parameters of the diode. These are summarised in Table 3.3 below:

Table 3. 3: SPICE parameters for the HSMS-8202 diodes

I_S	4.6 E-8 A
R_S	6 Ω
N	1.09
B_V	7.3 V
I_{BV}	10 E-5 A
E_G	0.69 *eV*
C_J	0.18 E-12 pF
$PB(V_j)$	0.5 V
M	0.5
FC	0.5
R_j	256 Ω at 1 mA

3.5 ANTENNA - RECTIFIER INTERFACE

With the aid of analytical models for the antenna and the rectifying circuit, single-layer, internally matched and filtered PCB rectennas may be designed for low input power [Visser, 2009].

The antenna is connected to the rectifying circuits that contain the Schottky diodes that are sensitive to voltages at their ports. In order for the diodes to transmit power, the voltage level must be sufficient. Furthermore, it is compulsory that the voltage applied to the diodes be larger than (or approaching) their threshold voltage. The physical condition for the rectifier to deliver a growing output voltage is satisfied when the charge due to the direct current exactly compensates the charge due to the inverse current of a rectifying diode. The voltage source amplitude v_s is thus proportional to the square root of the radiation resistance R_s.

$$v_s = 2\sqrt{2R_s P_{AV}} \qquad 3.\ 11$$

As the rectifier is modelled as a resistive load R_i, the input voltage v_{in} is equal to:

$$v_{in} = v_s \frac{R_i}{R_i+R_s} = 2\sqrt{2R_s P_{AV}} \frac{R_i}{R_i+R_s} \qquad 3.\ 12$$

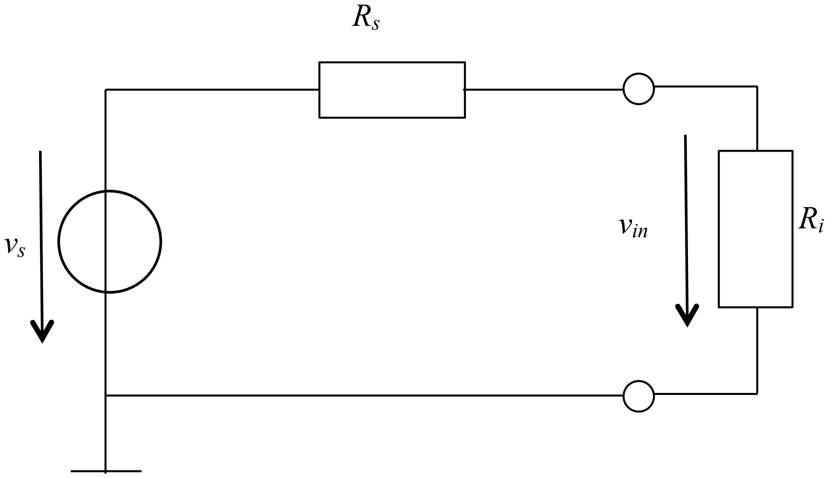

Figure 3. 9: First order model of the antenna connected to the rectifier

Equation (3.12) shows that to increase v_s, a high radiation resistance R_s is required. Furthermore, from (3.13), it is clear that the maximal transmitted power is obtained as antenna-rectifier matching is guaranteed, i.e. when the connected load impedance R_i is exactly equal to R_s. This result is very important to WPT because it says in essence that to design an optimal WPT system, it is necessary to have both power matching and a high radiation resistance at the receiving end of the system.

3.5.1 Numerical Analyses

The Friis formula that was derived in section 2.7.3, equation (2.18), was used to compute the amount of power that would be collected at the receive antenna. This equation has been used to calculate the expected radio link power levels at different distances between the transmitter and receiver. It should be noted that this formula does not consider phenomena such as reflection and absorption. It also assumes that the antennas are 100% efficient; that is, they radiate or absorb all the energy fed into them. The ideal conditions are almost never achieved in ordinary terrestrial radio transmission, due to obstructions, reflections from buildings, and most importantly reflections from the ground. It is of importance to note that the constraints given by the [ICNIRP, 2009] concerning the amount of power and power densities a transmitter in the ISM band can handle. According to regulations, the maximum EIRP from a transmitter in our chosen frequency is 4 W [ICNIRP, 2008].

The effective isotropically radiated power PEIRP, equal to $P_{RF}\ G_{PA}\ G_t$, is radiated in the direction of the rectenna situated at a distance D. The power density S at the device antenna is:

$$S = P_{EIRP}\frac{1}{4\pi D^2} \qquad 3.\ 13$$

The power P_r collected by the rectenna antenna and transmitted to the load is;

$$P_r = A_e S \qquad 3.\ 14$$

where:

A_e = effective aperture of the antenna.

Generally, the maximal effective aperture is related to the antenna gain G_r and the wavelength λ by;

$$A_e = \frac{\lambda^2}{4\pi} G_t \qquad 3.15$$

So that P_r is now written as;

$$P_r = S\frac{\lambda^2}{4\pi} G_r = P_{EIRP} G_r \frac{\lambda^2}{(4\pi D)^2} \qquad 3.16$$

Equation 3.17 is known as the Friis relation.

Using equation 3.14, the input voltage at the rectifier is;

$$v_{in} = 2\sqrt{2R_s P_{AV}} \frac{R_i}{R_i + R_s} \qquad 3.17$$

$$= 2\sqrt{2R_s} \frac{R_i}{R_i + R_s} \sqrt{P_{EIRP}} \frac{\lambda}{4\pi D} \sqrt{G_r} \qquad 3.18$$

3.6 EFFICIENCIES

The efficiency of a module is equivalent to its transfer function. The general definition of any efficiency used hereafter is the ratio of output power P_{out} over input power P_{in};

$$Efficiency, \eta = \frac{P_{out}}{P_{in}} \times 100 \tag{3. 19}$$

This efficiency is also expressed in terms of voltage; that is, the ratio of the output voltage, $v_{out,}$ to input voltage, $v_{in;}$

$$Efficiency, \eta = \frac{v_{out}}{v_{in}} \times 100 \tag{3. 20}$$

The overall efficiency of a WPT system, η_{total}, is the ratio of the DC output power at the receiver end over the DC (or AC) input power at the transmitter end. This end-to-end efficiency includes all the sub-efficiencies starting from the DC (or AC) supply feeding the RF source in the transmitter part to the DC-DC power interface at the receiver output. It encompasses of three distinct sub-efficiencies: the electric to microwave conversion efficiency (or transmitter efficiency), the collection of beam efficiency and the microwave to electric conversion efficiency (or receiver efficiency). In order for the overall efficiency to be sufficiently high, it has been shown that the transmitter illumination needs to be an optimal taper. One must also ensure excellent *DC(AC)-to-RF* conversion capabilities as well as efforts on the efficient output of the microwave generator up to the DC output of the rectenna.

3.6.1 Magnetron Efficiencies

The magnetron efficiency, η_{mag}, is a conversion efficiency that can be defined as the ratio of the RF output power over the DC (or AC) input power. η_{mag} can vary from 60 to 70% for microwave oven magnetrons. Off-the-shelf magnetrons used for industrial microwave heating as well as for laboratory models feature 85% efficiency and can go up to 90% at 3

GHz [Brown, 1974]. The microwave generator used for this study is assumed to have a relatively efficient magnetron $\eta_{mag} = 80\%$.

3.6.2 Power Density

The power density at any distance from an isotropic antenna is simply the transmitter power divided by the surface area of a sphere ($4\pi R^2$) at that distance. The surface area of the sphere increases by the square of the radius, therefore the power density, P_d, (W/m^2) decreases by the square of the radius [Naval Air Warfare Center, 1999]. The incident maximum power density can be derived as follows. Assuming a uniform taper at the transmitter and no conduction, matching or polarization match losses, an optimal directivity of:

$$D_0 = \frac{4\pi A_{met}}{\lambda^2} \qquad 3.21$$

is obtained which means that the power of the main beam is magnified by D_0 in a certain direction. A_{met} is the maximum effective transmitter antenna area. For an aperture type antenna with the assumptions given above, $A_{met} = A_t$. This magnification is reduced by the decay of the field strength with distance as expressed by the factor $1/(4\pi D^2)$. The distance D needs to be relatively large for the system to operate in the far field as will be seen later. Combining these two opposing effects into one expression, the peak power density at the center of the receive antenna is obtained

$$P_d = \frac{P_t A_{met}}{\lambda^2 D^2} \qquad 3.22$$

The power density function across the face of the receiver follows the Gaussian taper curve decaying from the center peak value towards the edges. The DC output power will feature the same radial decrease [Zepeda, 2003].

3.6.3 Antenna and Collection efficiencies

The antenna efficiency, η_a, is usually assumed to be close to 100%. It is defined as the ratio of the antenna gain G_t over the directivity D_0. For simplicity, $\eta_a = 100\%$ is assumed in this preliminary study. The antenna efficiency at the transmitter end, η_a, as illustrated in Figure 3.1, represents the ability of the antenna to efficiently radiate the distributed RF power fed from the RF source and launched into free-space. The matching between the antenna and the air characteristic impedance as well as the level of ohmic losses will mainly determine the antenna efficiency.

Another efficiency, which is very important since it is related to many other design parameters, is the collection efficiency, η_c. Once selected, the value of η_c along with some other assumptions will define the WPT system configuration. The collection efficiency is expressed as the received RF power over the transmitted RF power characterizing the receiver capability to efficiently collect the incident impinging energy. η_c is proportional to a design parameter, τ, which is expressed as Goubau's relation. The collection efficiency is also a function of the atmospheric attenuation, which depends on operating wavelength, weather and power density. For ground-based systems this attenuation is generally assumed negligible on a clear day for 2.45 GHz operating frequency. As can be seen from equation 3.20, Goubau's relation can be used to determine the size of the apertures involved. These calculations along with the optimization of the individual component efficiencies using the available specifications will be demonstrated. The design parameter τ is related to the aperture areas through the expression;

$$\tau = \frac{\sqrt{A_r A_t}}{\lambda R} \tag{3.23}$$

where A_t and A_r are the aperture areas of the transmitter and the receiver antenna, respectively, and R is the distance of separation of the two antenna. The advantage in using rectangular apertures is the simpler fabrication and system mounting. In order to optimize both the collection efficiency and the simplicity of fabrication, square apertures using absorber at the corners can be used in lieu of circular apertures [Zepeda, 2003].

The overall RF to DC efficiency is a combination of the collection efficiency, η_c, and the conversion efficiency, η_{rect}. The choice of the rectifier and the level of incident power at the receiver end mainly determine the latter.

3.7 SUMMARY

This chapter has described the equipment used for the study of WPT. The specifications and assumptions considered based on the available equipment were listed. The effects of the different parameters of the equipment on the rectenna are also discussed. Efficiencies at each stage of the system are discussed to show how these would affect the final output of the system.

3.8 REFERENCES

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CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

A microwave setup, consisting of 2.45 *GHz* 1.2 *kW* generator, a rectangular waveguide equipped with an isolator and forward and reflected power meter and a coupler to the transmit antenna was used as the source of radio frequency (RF) energy. However, due to the FCC regulations, the maximum Effective Isotropic Radiated Power (EIRP) was limited to 4 *W*. This is the exposure limits used by the FCC and are expressed in terms of SAR (Specific Absorption Rate), electric and magnetic field strength and power density for transmitters operating at frequencies from 300 *kHz* to 100 *GHz*.

4.2 POWER TRANSMISSION

As described in chapter 3, the Microwave generator used for the power transmission is capable of outputting RF power up to 1.2 *kW* of microwave energy. The RF power needs to be varied to produce the desired outputs, which are from 1 W through to 4 *W*. In doing so, the power meter was configured to do this and a coupler factor of –17 *dBm* at 2.45 *GHz* was applied which is equivalent to 2% of the transmitted power that is lost in the waveguide.

$$P(dBm) = 10\log_{10}\frac{P}{P_0} \tag{4. 1}$$

The equation 4.1, converts a power expressed in *dBm* to Watt and vice versa. Table 4.1 shows the quantities of power in *dBm* that must be transmitted through the microwave generator to get the desired output to the transmitting antenna. The reflected power is sent back to the circulator where it is absorbed by the dummy load (water). Thereby, allowing only the required power to pass through the waveguide to the antenna.

Table 4. 1: Power outputs to the antenna and with -17 dBm coupler factor

Power (*W*)	Power (*dBm*)	Total Power (*dBm*) with 17 *dBm* coupler
4	36.02	53.02
3	34.77	51.77
2	33.01	50.01
1	30.00	47.00

Using the SPICE (Simulation Program with Integrated Circuit Emphasis) parameters, the first analysis of rectification properties of an HSMS8202 diode in a single detector configuration was made using Agilent Technologies AppCAD design software. The resulting performance is shown in Figure 4.1.

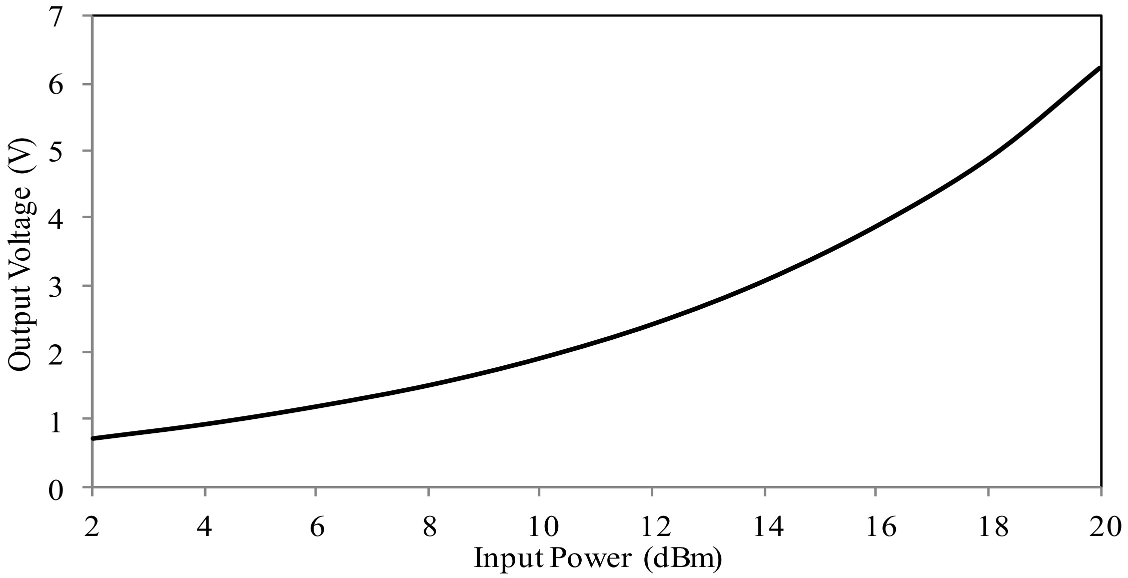

Figure 4. 1: Diode voltage Output

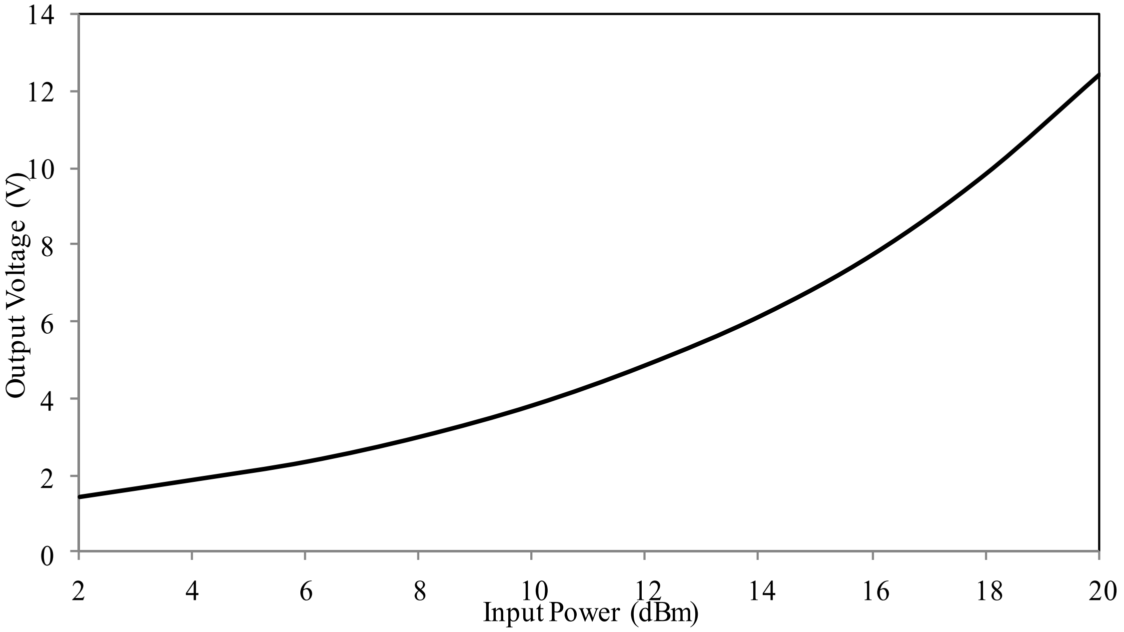

Figure 4. 2: Voltage-doubler Output for the rectifier

It should be observed that the presented voltage values correspond to a rectifier diode in a single configuration. Diode detectors may be combined in various ways to produce higher output voltages than would be produced by a single diode [Avago, 2008]. Thus, the expected performances are presented in Figure 4.3. Avago Technologies [Avago, 2007] considered for these experiments, but from the Technical Report Application Note 1088, the two (2) different diodes used; no significant difference could be seen between the two diodes. Therefore, the diode that was chosen is the HSMS8202 due to this and its availability.

Considering that the SPICE model assumes a perfect match between the antenna and the rectifier circuitry, the efficiency can be as high as 100% (ideal case) or, assuming a worst-case scenario with a poor match at the rectifier's input, the overall efficiency of the detector can be as low as 50% [Avago, 2008; Brown, 1984, 1991].

4.3 CHARACTERIZATION OF RECTENNA

Rectennas are used for converting wireless RF power into DC power. The challenge lies in maximizing the power conversion efficiency for low input power and at the same time minimizing the dimensions of the rectenna. By conjugate matching of a rectifying circuit directly to a microstrip antenna, a matching and filtering network between the antenna and rectifying circuit can be avoided.

To verify the rectenna design, the unloaded output voltage as a function of the input power was calculated and measured. Since the input power coupled into the rectifying circuit was not easily accessible, a relative measurement was performed.

A power-adjustable microwave generator used as the transmitter was connected to a dipole antenna. The rectenna, made from the same type of antenna as the transmitting antenna was placed at a fixed distance, and the output voltage was measured as a function of the transmitter power. For one transmitter power level, the input power to the rectifying circuit resulted in the observed unloaded output voltage that was measured. For all other transmitter power levels, the corresponding input power levels were scaled relative to this measured value (i.e. if the transmitter power level increases by 1 *W*, the input power to the rectifying circuit increases by the same quantity).

The results at 2.45 *GHz* measured in this way are shown in Figure 4.4 below. Also, shown in the figure is the percent difference in the rectified voltages from the two rectifying circuits. This is to show the efficiencies of the two rectennas.

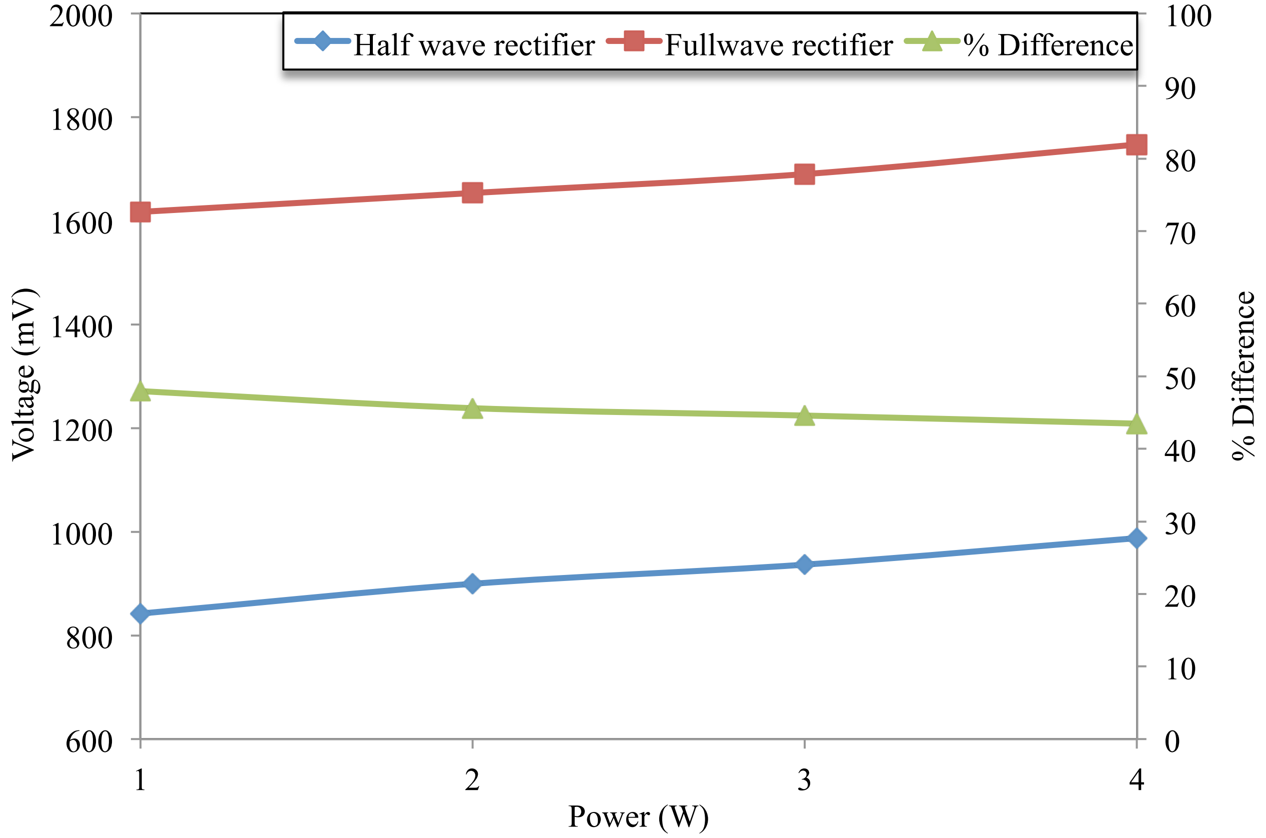

Figure 4. 3: The unloaded output voltages of the two rectifying circuits

Firstly, the excellent agreement between the measured and calculated output voltages, the differences are within a few percent, demonstrates the validity of the design. Furthermore, it shows that for a high-impedance load, relatively high voltages may be obtained for input powers at or below 4 *W*. To determine the efficiency of the rectenna, the distance between the transmitter and rectenna was first determined for 1 *W* of input power.

The graph also shows that the full wave rectifier generates a higher output than the half wave rectifier. This in itself shows that the full wave rectifier will perform better in our circuit than the half wave. In other words, the full wave rectifier is more efficient than the half wave rectifier.

4.3.1 Relationship between the Radiation resistance and Resistive load on the input voltage v_{in} and the effect on the Rectenna output

The output voltage from the rectenna depends on the radiation resistance and the resistive load connected to its output terminals.

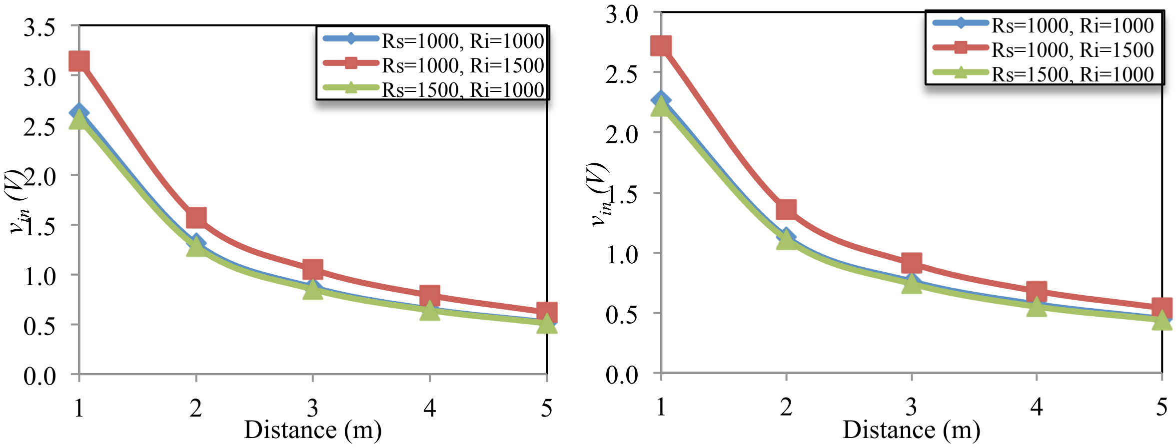

Figure 4.4 a: 4 W

Figure 4.4 b: 3 W

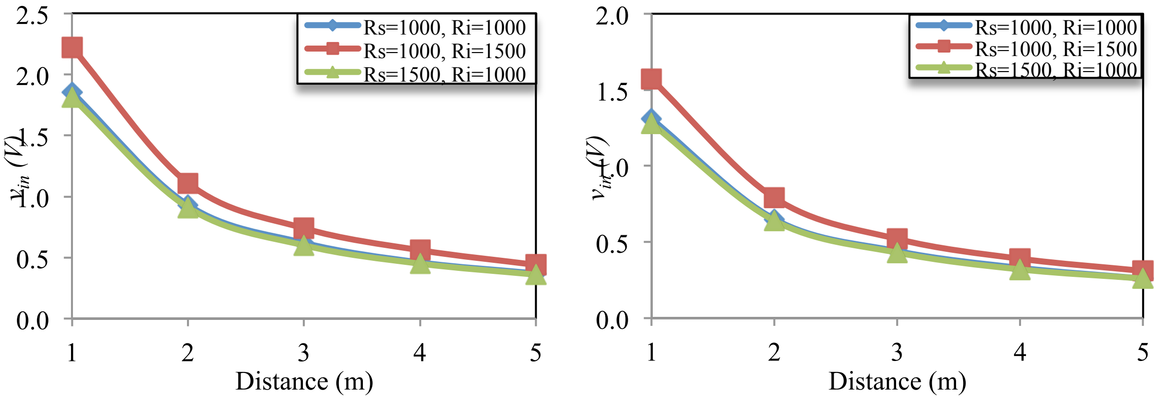

Figure 4.4 c: 2 W

Figure 4.4 d: 1 W

Figure 4. 4: Input voltage v_{in} for different values of R_s and R_i as a function of the distance D with power supplied varied from 4 W to 1 W.

Figures 4.5a – 4.5d show the output voltages from varied power supplied, when the radiation and reactive resistances are varied. The graphs are actually the input voltages, v_{in}, available at the receiver antenna to be converted by the rectenna. In order for the diodes to transmit power (by reducing the real part of their impedance), the voltage level has to be sufficient. Moreover, it is necessary that the voltage applied to the diodes be greater than (or approaching) their threshold voltage. The physical condition for the rectifier to deliver a growing output voltage is satisfied when the charge due to the direct current exactly compensates the charge due to the inverse current of a rectifying diode [Curty, et al, 2007]. The input voltages v_{in}, available at various distances are presented for different values of R_i as a function of R_s. In order to maximize the input voltage, v_{in}, it is necessary to have a high value for R_i. The impedance arrangement also has a noticeable impact. Subsequently, the consumption of the WPT device has to be minimized.

4.4 MEASURED RECTIFICATION

The measurements from the two rectifying circuits are presented below

Figure 4. 5: Half wave rectifier with the SMA connector

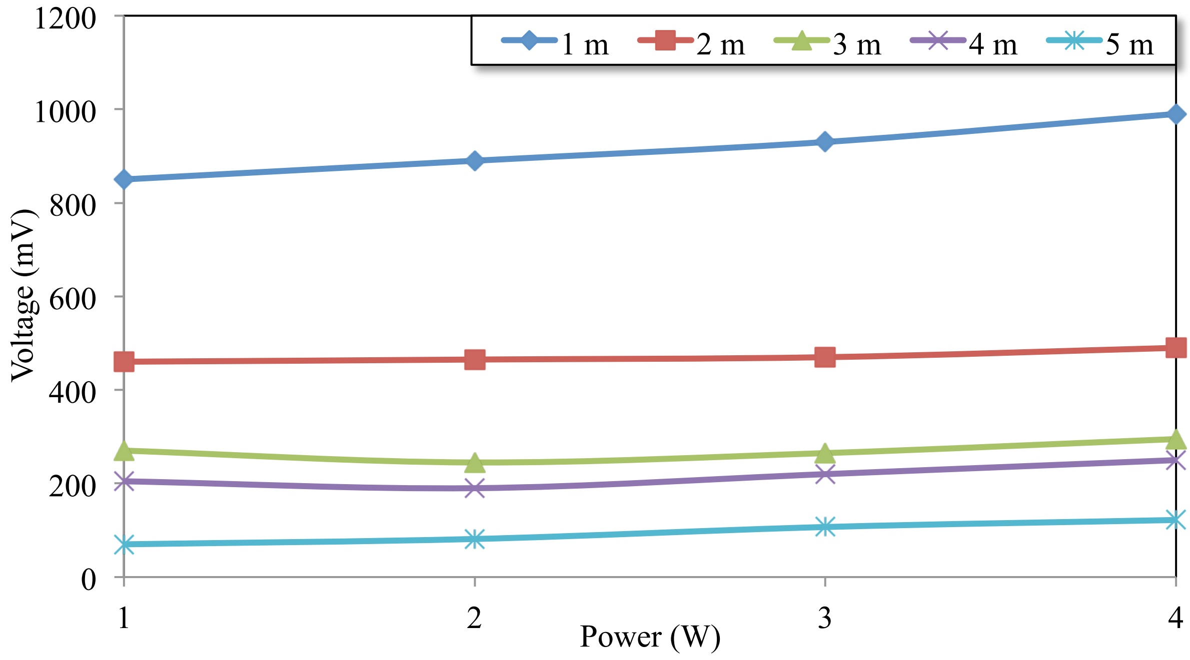

Figure 4. 6: Plot from the half wave rectifier measurement

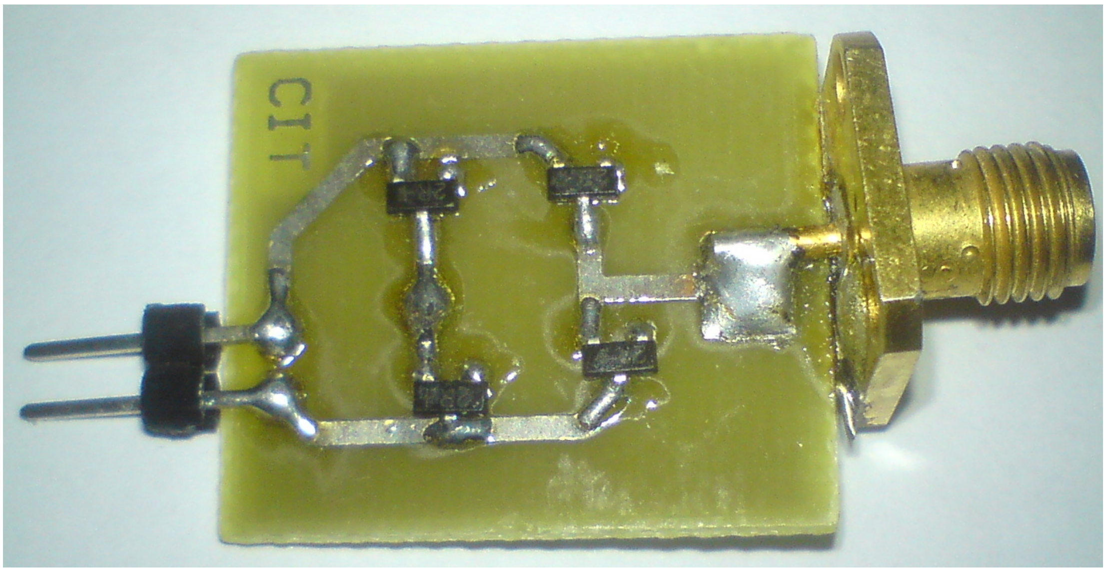

Figure 4. 7: Full wave rectifier circuit board with the SMA connector

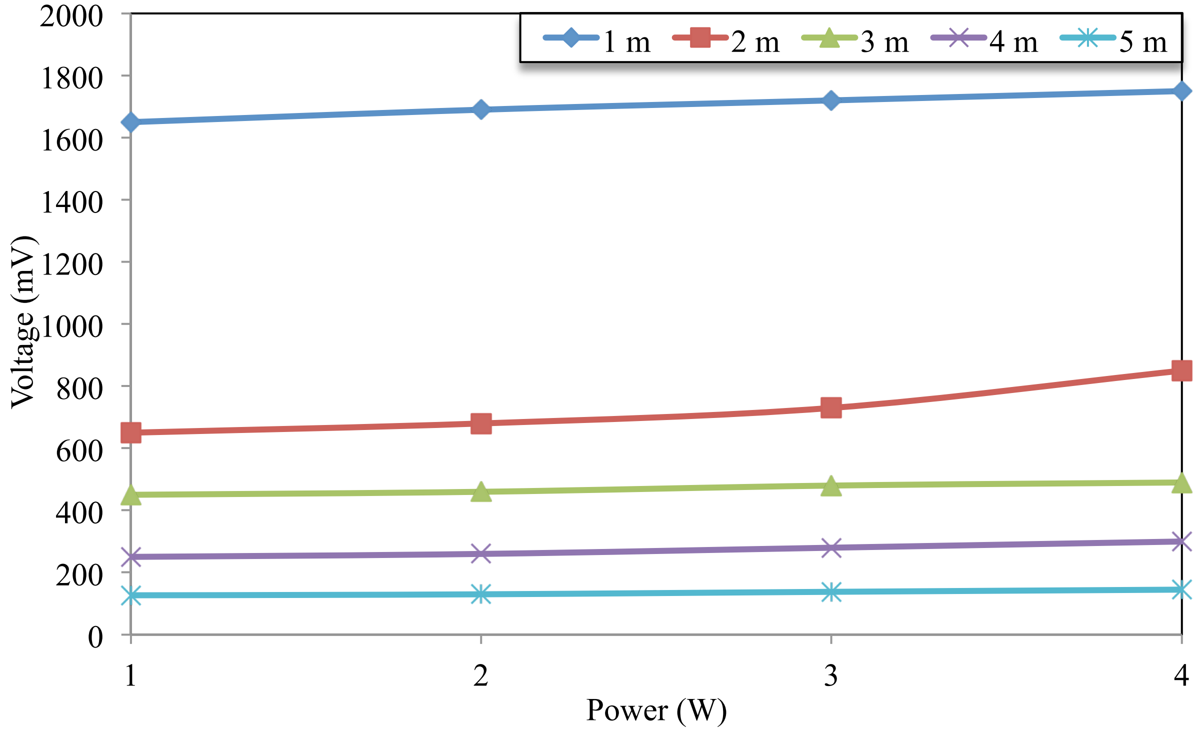

Figure 4. 8: Plot from the full wave rectifier

Figures 4.6 and 4.8 are the graphs for the output voltages of the half-wave and full-wave rectifiers respectively. It is clear that the full-wave rectifier was able to convert more of the RF power transmitted than the half-wave rectifier. The trend also shows that as the distance separating the transmitting and receiving antennas is increased, there is a decrease in the output. This agrees with the Friis transmission formula and shows that as the antennas move away from each other, the efficiency drops by a factor of $1/D^2$. However, it may make the whole system more expensive and in our application, low-power sensors, it may make them heavier. Nevertheless, those trade-offs may be worth the extra efficiency of the system as compared to the half-wave rectification. This is demonstrated in the calculation below which looks at the percent difference between the two rectifiers.

4.4.1 Percent Difference

Percent difference or relative percent difference (RPD) is the numerical interpretation of comparing two values with one another. It is often used as a quantitative indicator of quality assurance and quality control for repeated measurements where the outcome is expected to be the same [Wikipedia, 2010]. This is represented by the equation below:

$$\%Diff = \frac{|x_1 - x_2|}{((x_1 + x_2)/2)} \times 100 \qquad 4.2$$

Using the above equation, and inserting the values for both full wave and half wave rectifiers, the results for each value plotted in Figure 4.9, show clearly the percent difference between the two at all the distances.

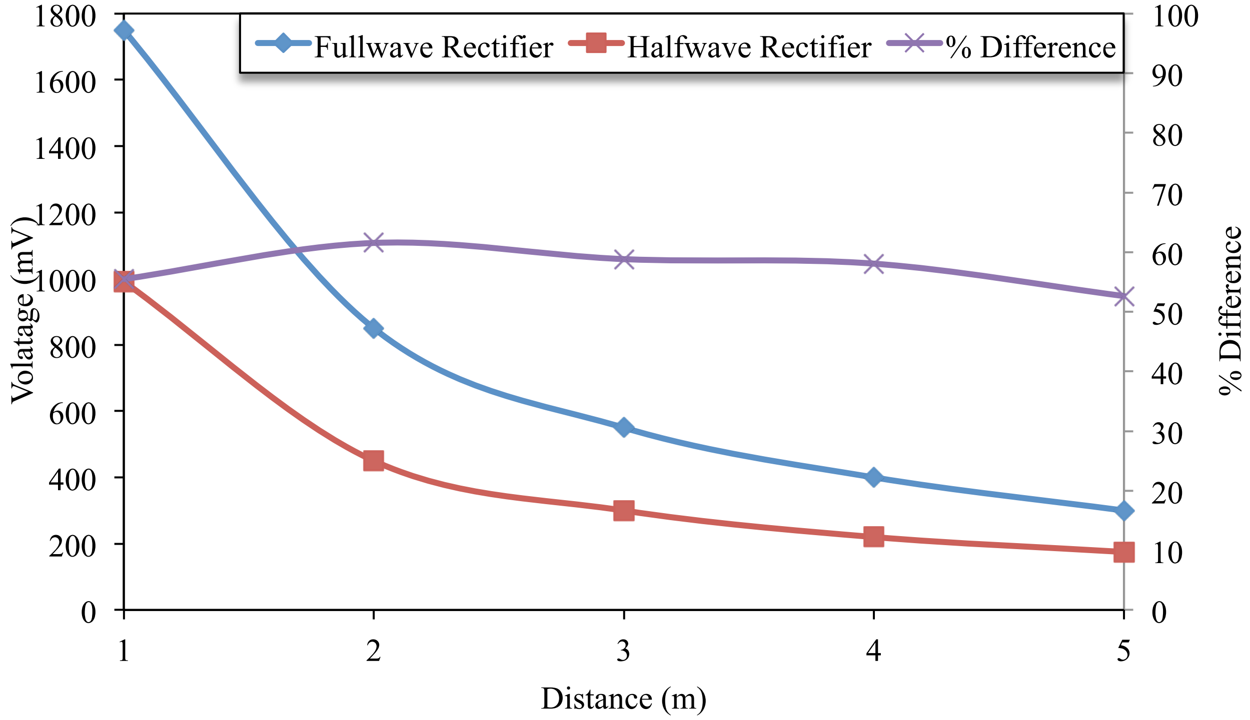

Figure 4. 9: Plot of Percent Difference of the Full wave and Half wave Rectifiers

Figure 4.9 shows the percent differences for the transmitted power and that the full wave rectifier at all the distances is over 50% more efficient at converting RF to DC than the half wave rectifier when used in the rectenna. The full wave rectifier would also be more adequate for the application when a voltage doubler circuit is applied to it in the case of larger distances.

4.5 EFFICIENCY

Efficiency as described in section 3.6 is defined as the ratio of the output power to the input power. The efficiency of the magnetron source is negligible here as the output power for the study is limited to a maximum of 4 *W*, which was easily supplied by the microwave generator. The most important efficiencies are the beam efficiency, transmission efficiency and the conversion efficiency. These efficiencies are deduced from the measurements and specifications of the system.

4.5.1 Power Density and Beam Efficiency

As described in section 3.6.2, power density at any distance from an isotropic antenna is simply the transmitter power divided by the surface area of a sphere ($4\pi R^2$) at that distance. However, the antenna used for the study is a directional antenna, which transmits most of its power in a particular direction. The beam efficiency is a measure of the power density of the RF power delivered to the receive antenna.

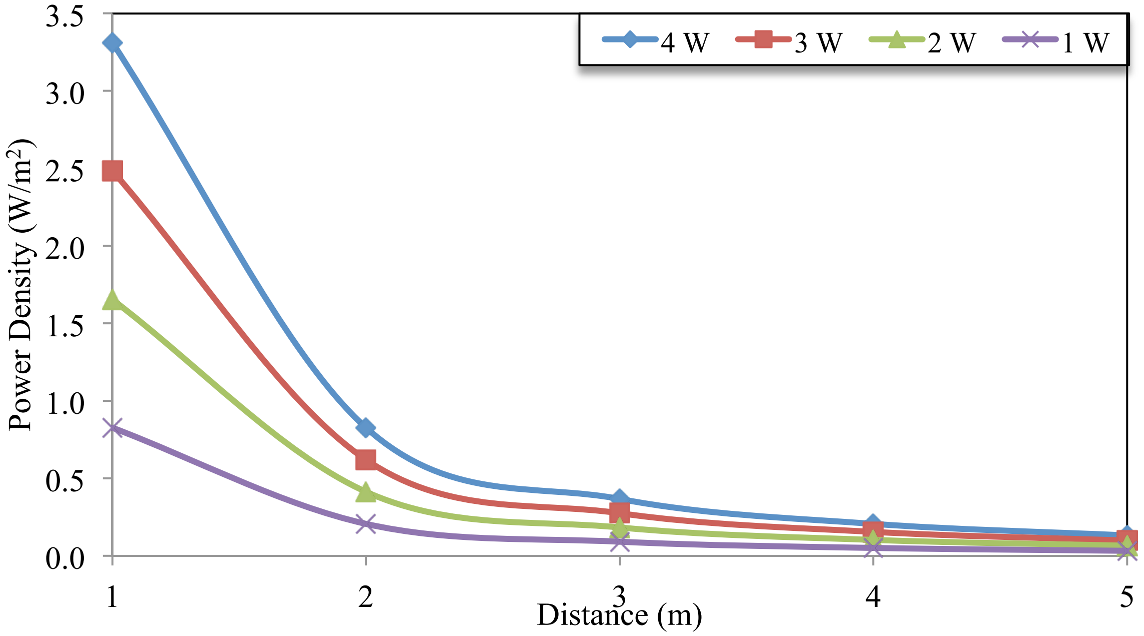

Figure 4. 10: Power Density as a function of Distance

The following is an approximation that used to calculate the beam efficiency of the antennas. The transmit and receive antennas are of the same technical configuration. Placing the transmit and receive antennas are in each other's far field, beam efficiency, η_{beam}, can be defined (from equation 3.20) as;

$$\eta_{beam} = \frac{P_T}{P_R} = \frac{A_t A_r}{\lambda^2 D^2} \tag{4. 3}$$

$A_t A_r$ have a combined area of 0.0124 m^2. At a distance of 1 m, the beam efficiency was calculated to be 82.6%. Moreover, at the furthest distance of 5 m, the beam efficiency was calculated to be 16.52%. This is comparable to the Friis transmission formula and shows that as the antennas move away from each other, the efficiency drops by a factor of $1/D^2$. This is because of the beamwidth of the antenna, which is 60° of the antennas and tends to spread outwards as the distance of separation increases.

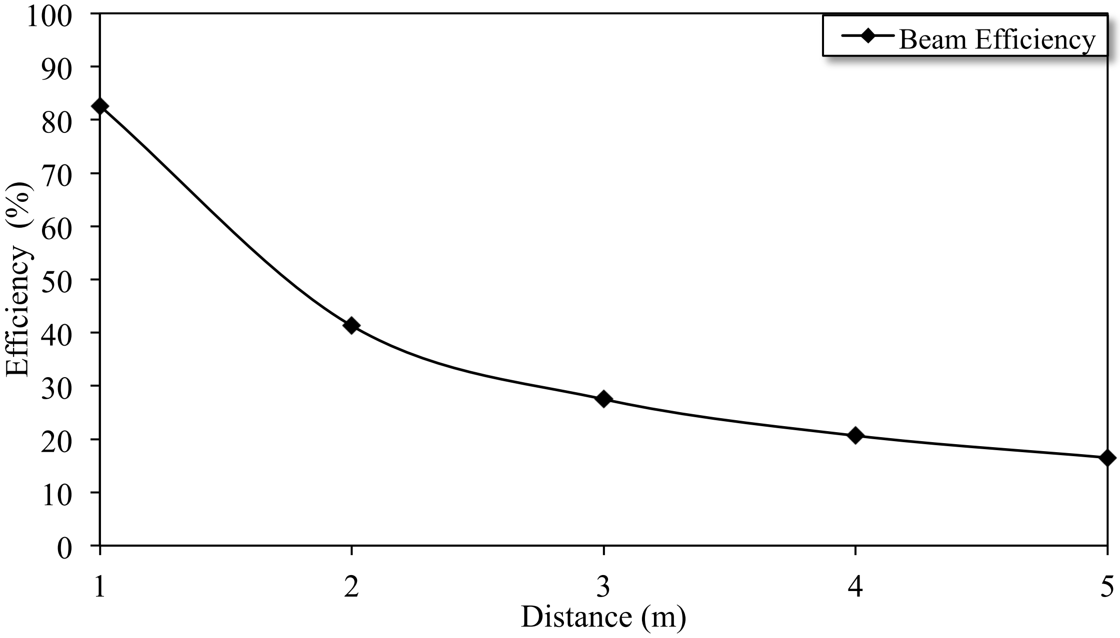

Figure 4. 11: Beam efficiency of the antenna

Figure 4.11 shows the antenna beam efficiency calculated for each of the distance that was proposed for the experiments. The distances are for five (5) values from 1 m to 5 m. The result plotted in the graph above. The graph shows that the beam efficiency reduces as the antennas moved further apart. This figure shows a huge degradation in efficiency, which can also be related to the Friis equation.

4.5.2 Conversion Efficiency

An important feature of the receiver is the capacity to efficiently convert the incident RF power density into DC power. This conversion efficiency is strongly dependent on the power density distribution across the receiver aperture. The conversion efficiency, η_{rect}, can be considered at the component level since it mainly represents the rectifying capabilities of the solid-state diode. This is the reason it is also commonly called the rectenna or rectifier efficiency. The conversion efficiency is also a function of losses in the dipole antenna and the entire rectifying circuit.

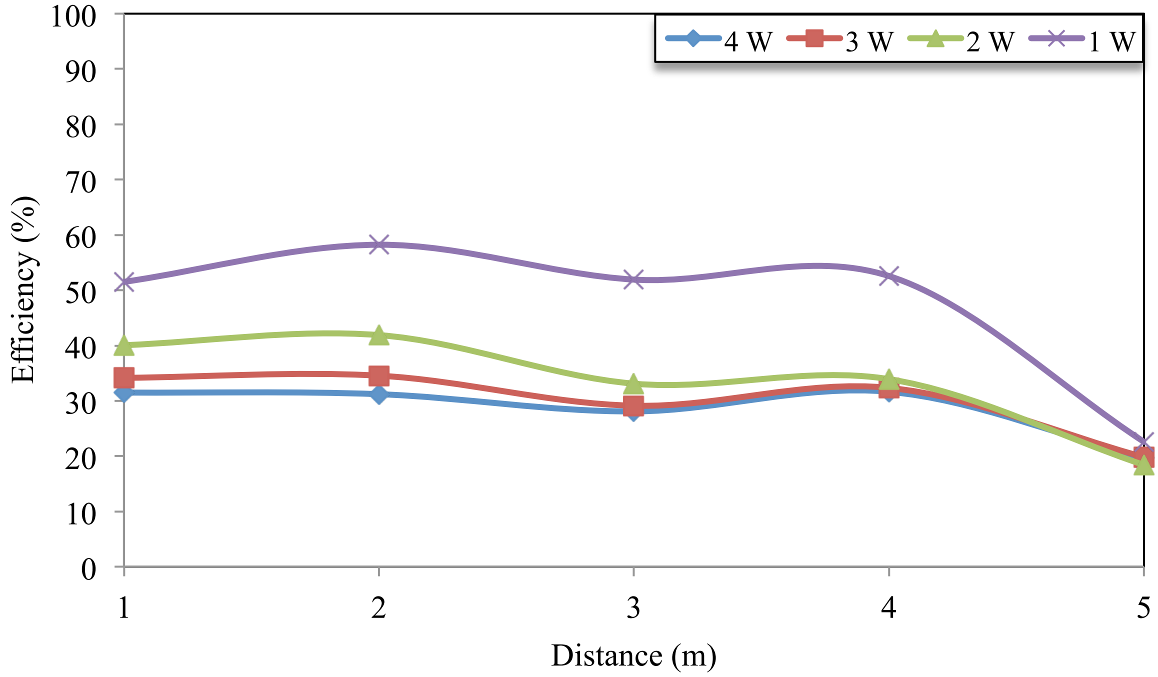

Figure 4. 12: Conversion Efficiency of the Half Wave Rectifier

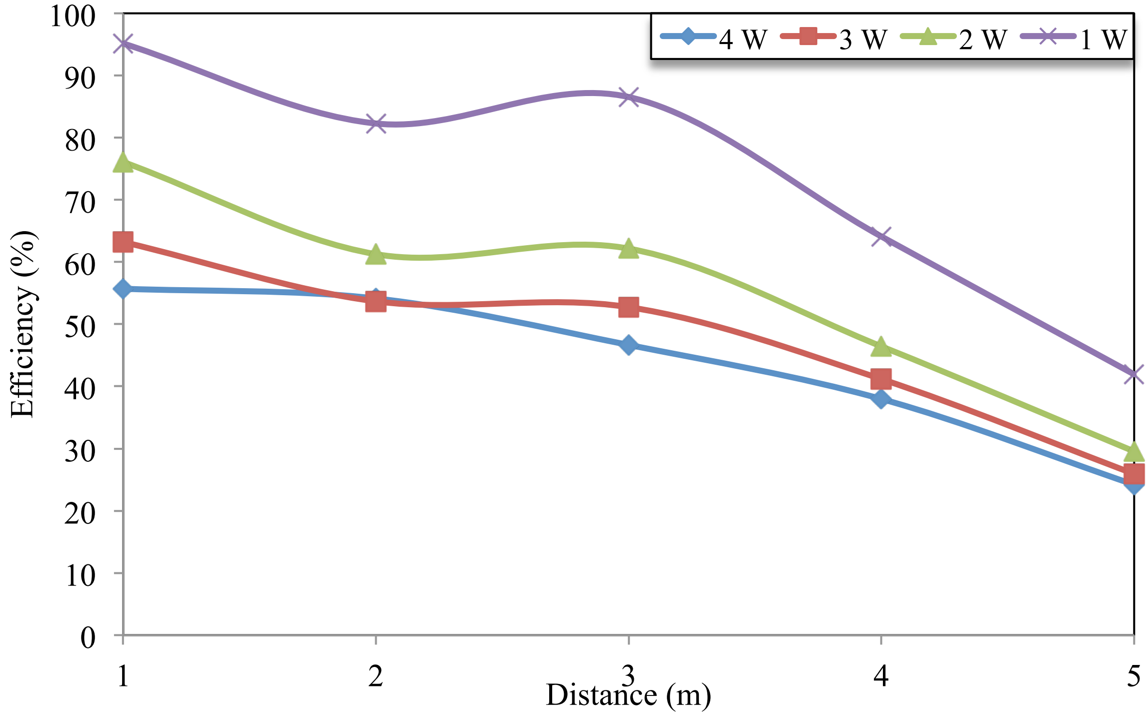

Figure 4. 13: Conversion Efficiency of the Full Wave Rectifier

Figures 4.12 and 4.13 show the conversion efficiencies of the two circuits used for the microwave conversion. From the two graphs, it is clear that the Full Wave rectifier converts more of the voltages that get to the input of the circuit. It is also clear from the two graphs that the conversion efficiencies are higher at lower power. This can be attributed to losses in the individual components of the rectifiers, which are released as heat at higher powers.

Though the output voltages measured from the 4 W transmissions was higher than those from 1 W to 3 W, the conversion efficiency was lower. This is because the bandwidth of the transmitting antenna is larger than the surface area of the receiving antenna, so a large percentage of the power density is outside its surface area. This can be solved by either using a larger receive antenna or using a transmit antenna with much narrower beamwidth.

4.6 SUMMARY

The experimental results for wireless power transmission have been presented and described. The possible circuit topologies that allow RF signal rectification have also been presented. The full wave rectifier showed significant improvement over the half wave rectifier as it almost doubled the output voltage from the same transmitted power. This structure constitutes a viable application for WPT devices. The antenna has also been identified to be a fundamental component of any WPT system. It was evident that a directive antenna with very narrow bandwidth would focus the RF power on to the receiving antenna, which will increase the collection efficiency of the rectenna.

The numerical analyses gave some understanding into the numbers involved, which showed clearly that a high input resistance performs better. Careful design and technology choices allow the overall input capacitance level presented to the antenna to be kept to a minimum.

4.7 REFERENCES

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CHAPTER 5

CONCLUSION

The study of a Wireless Power Transmission (WPT) system served as the preliminary design for a demonstration of a functional WPT system. Through calculations of key parameters, the feasibility of a ground-to-ground WPT link was studied. The main purpose was to calculate the system parameters that optimize the overall efficiency η, DC (AC) - DC of the power transmission. Each component of WPT system has been described and corresponding efficiencies were defined. The influences of some important system parameters on the efficiencies were also demonstrated. A possible configuration of the receiver fulfilling the efficient transfer of electric power requirement was presented. The selection of the operating frequency was also a significant factor on the planning of a WPT system.

Microwave experiments are diverse and are still very expensive to carry out on a regular basis. The use of simulation software greatly reduced the risks of errors and costs of tests and analyses of microwave equipment and experiments. In this study, mathematical models and simulations were used at different stages. From the conversion of DC voltage to microwave energy using the magnetrons and radiating the energy using an antenna through free space to the receiving antenna (rectenna), which converts the microwave energy into DC through series of other electronic components.

The complexities in simulating these stages of the systems require careful design. As 100% efficiency is assumed in the transmit antenna, the Friis transmission formula was sufficient to calculate the far field effect of the transmitted wave. This equation was used to derive how much power would be delivered to the receiving antenna in the absence of some physical phenomena.

The Radio link performance is comparable to what was derived from the theory obtained in section 4.6. These results had so many advantages at this stage. The main advantage is the lack of attenuation effects because the laboratory environment is somewhat free of humidity and particles (such as dust) that could affect radio waves. Although, this could have been improved as the radiation properties of the antennas used were not the expected ones, either these antennas have a lower gain than the expected 9-dBi values or the radiation efficiency for the FR4 material of the printed dipole array is very low. In addition, the radiation patterns of the antennas are broad, at 60°, and multipath effects could exist that create destructive interference of the signals arriving at the antenna at the receiver side.

The results show that the full wave rectifier would be the better option when designing a WPT system as more power can be drawn from the rectenna. The load also had a great role as this determined the amount of power drawn from the circuitry.

5.1 Future work

Based on the results of these experiments, the future is bright for WPT. As wireless devices get smaller and consume less power, the application of WPT to wireless devices can only improve. A strong argument has been made to design WPT in such a way that devices deployed in a WPT environment would seem to be generating power. This is by sending power in a fashion whereby all surrounding sensors would be able to receive the signals, and using a booster circuit to increase the power before delivering to the load. This would increase the total efficiency of the WPT system.

APENDIX A

- Oral Presentation at SAIP 2008, University of Limpopo, Turfloop Campus: “Power Transmission through Electromagnetic Waves”.
- Poster Presentation at SAIP 2009, University of KwaZulu-Natal (Westville Campus), Durban: “Wireless (Microwave) Power Transmission for Mobile Devices”.
- Poster Presentation at SAIP 2010, Centre for Scientific and Industrial Research (CSIR), Pretoria: “Wireless Power Transmission for Wireless Sensor Nodes”.