DESIGN RECTENNA FOR WIRELESS ENERGY HARVESTING

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CHAPTER 1

INTRODUCTION

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1.1 Introduction

Wireless communications have experienced a rapid development over the last two decades and have become an integral part of our daily lives. Cellular networks, wireless local networks (WLANs) and wireless personal area networks (WPANs) are just a few examples of the wireless technology that we are using every day. They enable us to be connected anywhere and anytime. These wireless systems also radiate a large amount of electromagnetic energy into the air but most of them are actually wasted.

Nowadays, the energy recycling has become a very significant issue all over the world. Thus, how to harvest and recycle the wasted ambient electromagnetic energy also has become an increasingly interested topic. In the past few decades, wireless power transmission (WPT) has become an interesting topic as one of the technologies for solving this problem [1].

There are many electronic devices or sensors that operate in conditions where it is costly, inconvenient or impossible to replace a battery, or deliver wired power. As a result there has been an increased demand for wireless power supplier for these devices. Let us take the low power sensor or device as an example; it normally works at a low duty cycle and in an environment with low-level of light or vibration. Thus RF wireless power suppliers offer a potential alternative for maintenance free operations [2].

One of the most important and main requirement of WPT system is the efficient transfer of the electrical power. The key component for the system consists of an antenna coupled to a rectifying unit. The combination of an antenna and a rectifier is commonly called a rectenna and it can convert electromagnetic energy to direct current (DC) energy [3].

1.2 Problem Statement

In 21st century's The world has witnessed an unprecedented increase in its energy requirements over the last few decades driven by the increasing size of the population, industrial development and the increasing level of activity of humans around the globe. Consequently, new paradigms are needed to produce clean and cheap energy of our daily life. Rectenna have a roused great interest in both theoretical research and engineering applications due to their live time, which is almost unlimited and it does not need replacement (unlike batteries). The rectenna project is interesting and challenging as it is intended to suppress the harmonic signal to avoid the rectenna efficiency reduction by converting the RF signal to DC voltage. However, the efficiency is a critical parameter, which needs a greater consideration to be given during the design of the project. Moreover, in this project is proposed to improve the efficiency of the rectenna design, which using matching circuit to model the nonlinear element HSMS2860 Schottky diode. In addition, the proposed design should be used for Wi-Fi application in wireless power system. Finally we achieve the expected Conversion efficiency in the simulation, which can be used for the proposed applications.

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1.3 Objectives

The objectives of this research are:

1. To develop and investigate rectenna with good matching impedance and rectifying circuit for wireless energy harvesting through ISM-band microwave at 2.45GHz.

2. To design Microstrip patch antenna integrated with rectifier as rectenna to improve the rectenna conversation efficiency for low power density.

1.4 Project Scopes

The scopes of this research is as follows:

1. Design a microstrip patch antenna that operated at 2.45GHz.
2. Design single diode rectifier circuit using HSMS2860 schottky diode.
3. Perform numerical solution using CST Microwave Studio and Advance Design System ADS
4. Fabricate of the microstrip patch antenna and the rectifier circuit on FR-4 material with dielectric constant ε_r is 4.3 and Substrate thickness, h is 1.6.
5. Measurement of the antenna properties using A Vector Network Analyzer and performance of the rectifier circuit using RF signal generator connect to the horn antenna.
6. Investigate the performance of the rectenna in term of conversion efficiency

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1.5 Thesis outline

As for Chapter 1, it covers on introduction of the project. A little bit of the explanation will be done due to the project. It also includes the objectives, motivation of work, scope and thesis outline.

Chapter 2 is a chapter which covers on literature review of the project. In this chapter is focusing into certain sub topic. The literature review begins with the introduction, followed by antennas formulations, transmission lines, rectifier equivalent circuit and rectenna applications.

Chapter 3 will be cover on project methodology where it is focusing on the method that used to completing the project accordingly. The methodology will be presenting in the flowchart. In addition, it is representing in details in the form of sentences. Besides, is also gives a detail on the fabrication processes and the flowed by measurement testing.

The expected result and analysis will be covered on chapter 4. This chapter will be elaborate on the expected result for the whole project as well as compering measured and simulated results.

The last chapter is the chapter 5, where it is on overall conclusion for the project. It is also includes the future works of the projects. The conclusion is related to the project. It is important in order to assure that our objective is achieved.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A wireless power transmission system shown in Figure. 2.1 consists of three main functional blocks. The first block is to convert the electricity into microwaves (DC to AC). After radiating through the transmitting antenna, the RF power is carried within a focused microwave beam that travels across free space towards a receiver. This receiving block will convert the RF energy back to the DC electricity [1].

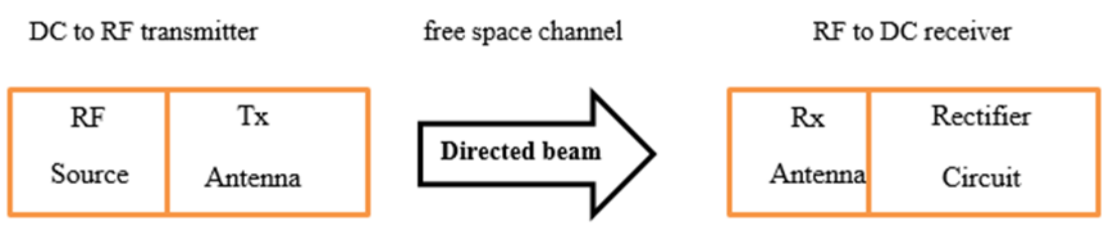

Figure 2.1: Overview project system diagram

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A 'traditional' rectenna system is shown in Figure 2.2. The wireless energy can be collected by the antenna attached to rectifying circuit through filters and a matching circuit. The rectifying circuit converts the received wireless energy into DC through a low-pass filter and a DC pass filter before and after the circuit. The low-pass filter can match the antenna with the rectifier and block the high order harmonics generated by the rectifying diode in order to achieve high RF to DC conversion efficiency. The rectifying diode is the core element of the rectifier circuit. A load resistor is placed at the output terminal to measure the DC output voltage [2 3].

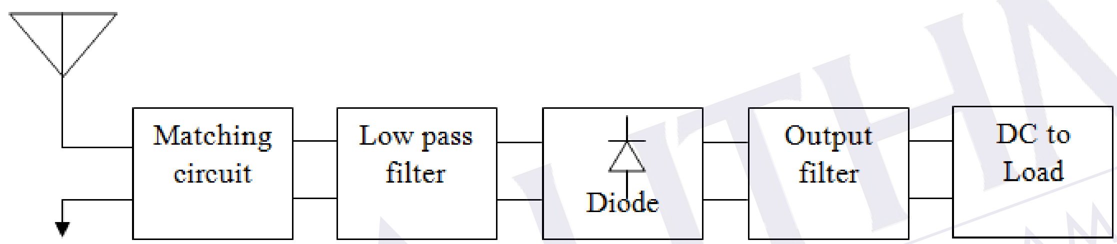

Figure 2.2: Rectenna black diagram

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2.2 Rectenna Conversion Efficiency

The RF to DC conversion efficiency of the rectenna is basically defined as the ratio of the output power Pout over the input power Pin, which means the conversion efficiency of the whole system is the DC power at the receiver end over the AC input power captured by the rectenna.

$$\eta_t = \frac{p_{out}}{p_{in}} = \left(\frac{V_{Dc}^2}{R_{load}}\right)\frac{1}{p_d A_{eff}} \qquad (2.1)$$

This conversion efficiency strongly depends on the power density (Pd) distribution across the receiver aperture. The effective area of the receiving antenna (Aeff) can be calculated by using the gain (Gr) and wavelength

$$A_{eff} = (\frac{\lambda_0^2}{4\pi})G_r \quad (2.2)$$

The maximum incident power density can be derived as follows. Assuming an antenna which has a gain of Gt at the transmitter, the directivity of

$$D_0 = \frac{4\pi A_t}{\lambda_0^2} \quad (2.3)$$

is obtained [4], which means the power of the main beam is magnified by D_0 in a certain direction. At is the effective area of transmitting antenna. In addition, the distance d which is the distance between transmitting antenna and the receiving antenna needs to be relatively large for the rectenna to operate in the far field. Therefore, the maximum power density at the center of an aperture is obtained

$$P_d = \frac{P_t G_t}{\lambda_0^2} \quad (2.4)$$

Form this equation, a higher P_d requires a larger G_t.

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Working frequency is also an important parameter to consider when designing a rectenna. It is often dictated by the desired application. At low frequencies (below 1 GHz), high gain antennas tend to be quite. Increasing the frequency thus allows the use of more compact antennas. On the other hand, the amount of available power at a certain distance from an emitter is given by Friis Equation

$$P_t = P_t G_t G_r (\frac{\lambda}{4\pi R})\hat{}2 \quad (2.5)$$

Where P_t is the power of the emitter, G_t and G_r are the emitter and receiver antenna gain, respectively, λ is the wavelength used and R is the distance separating the emitter and the receiver. This means that available power at a certain distance from the emitter decreases as the frequency increases. Frequencies in the 1 GHz to 3 GHz range are considered to provide a good compromise between free-space attenuation and antenna dimensions. We chose to design our circuits for a central frequency of 2.45 GHz.

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2.3 Early Stage Rectennas

At the early stage, In order to complete the wireless power transmission system rectennas were developed to receive and convert the electromagnetic wave into DC power.

The first rectenna was conceived at Raytheon Company in 1963 as shown in Figure 2.3; it was built and tested by R.H. George at Purdue University. It was composed of 28 half-wave dipoles, each terminated in a bridge rectifier made from four 1N82G point-contact, semiconductor diodes above a reflecting plane. In addition, a power output of 7 W was produced at an estimated 40% efficiency. To increase the power output suitable for helicopter experiment, a matching network was added into this structure and the measured output power was increased to 270 W [5].

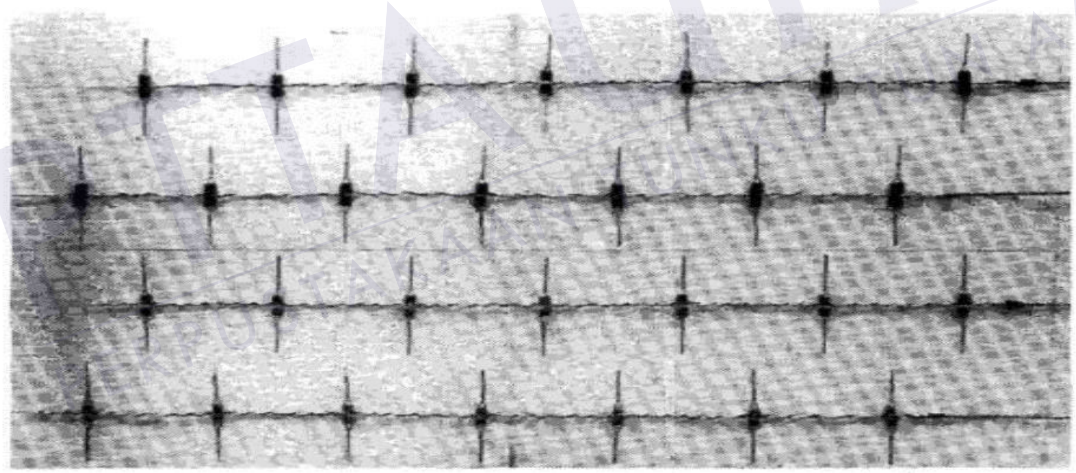

Figure 2.3: Views of the first rectenna made by Raytheon Co (1963) [5]

Recently, most of rectenna researches were still focused on the wireless power transmission. Due to the big challenge of designing wideband rectennas only a few of rectennas were designed for the RF energy harvesting.

2.4 Current Rectennas

Currently, other types of rectenna were proposed to sufficient various application requirements such as dipoles [6, 7], Yagi-Uda antennas [8], micro-strip patch antennas [9, 6-10], monopoles [11, 12], loops [13], spiral antennas [14, 15] and slot antennas [16-17]. The rectenna also take any type of rectifying circuit such as single shunt rectifier [18, 19, 20, 21, 22, 23], full-wave bridge rectifier [24] or other hybrid rectifiers [25]. In this project we use Microstrip patch antenna.

2.5 Single Microstrip Patch Antenna Design

The purpose of this part is to design a single microstrip patch antenna which consists of patch, quaterwave transformer and feedline. For the patch antenna design, a square patch antenna will be design. Since a 50 Ω surface mount adapter (SMA) connector is going to be used to connect the feedline to the coaxial cable, the feedline will be a 50 Ω feedline. The feedline will be feed to the patch through a matching network which is a quarter-wave transformer as shown in figure 2.4[26].

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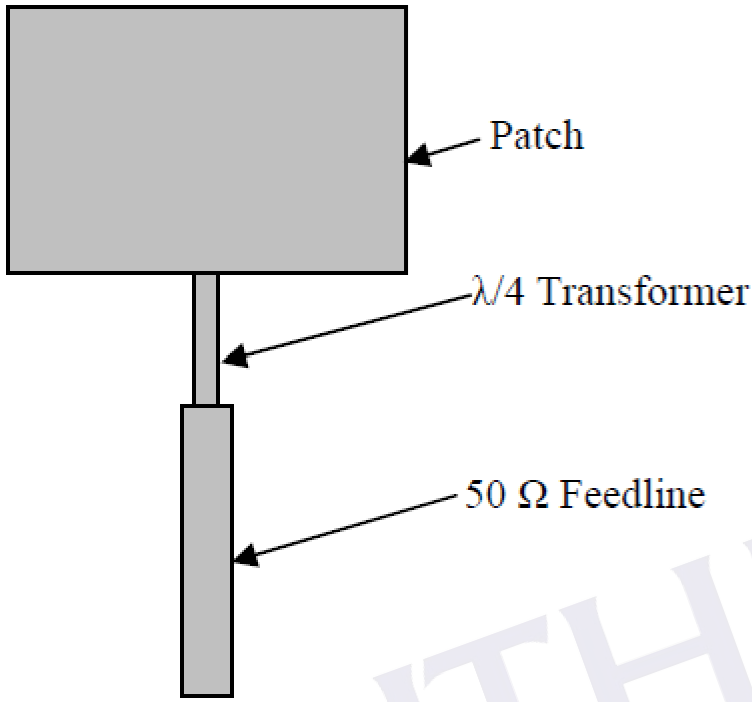

Figure 2.4: Patch Antenna with Quarter-Wave Transformer

There are numerous substrates that can be used for the design of the microstrip antennas, and their dielectric constants (ε_r are usually in the range of $2.2 \leq \varepsilon_r \geq 12$). The ones that most desirable for antenna performance are thick substrate whose dielectric constant is in the lower end of the range because they provide better efficiency, lager bandwidth, loosely bound fields for radiation into the space, but at the expense of larger element size[27].

The effective dielectric constant (ε_{reff}), of microstrip line is given approximately.

$$\varepsilon_{reff} = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\left[\frac{1}{\sqrt{1+12\left[\frac{h}{w}\right]}}\right] \quad (2.1)$$

The effective dielectric constant can be interpreted as dielectric constant of the homogeneous medium that replaces the air and dielectric regions of the microstrip given the dimensions of the microstrip line. The characteristic impedance (Zo) can be calculated as [28].

$$\mathrm{Zo} = \frac{60}{\sqrt{\varepsilon_{reff}}} \ln\left[\frac{8\mathrm{h}}{\mathrm{w}} + \frac{\mathrm{w}}{4\mathrm{h}}\right] \quad \text{For w/h} < 1 \tag{2.2}$$

$$\mathrm{Zo} = \frac{120\pi}{\left[\frac{\mathrm{w}}{\mathrm{h}} + 1.393 + 0.667 \ln\left(\frac{\mathrm{w}}{\mathrm{h}} + 1.444\right)\right]\sqrt{\varepsilon_{reff}}} \quad \text{For w/h} > 1 \tag{2.3}$$

Normalized extension of the length is

$$\Delta \mathrm{L} = 0.412\mathrm{h}\,\frac{(\varepsilon_{\mathrm{reff}}+0.3)\left(\mathrm{W}/\mathrm{h}+0.264\right)}{(\varepsilon_{\mathrm{reff}}-0.258)\left(\mathrm{W}/\mathrm{h}+0.8\right)} \tag{2.4}$$

For practical length of the square patch antenna is

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{2.5}$$

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A practical width that leads to good radiation efficiencies

$$W = \frac{c}{2f_r\sqrt{\frac{(\varepsilon_r+1)}{2}}}. \tag{2.6}$$

2.5.1 Quarter wave transformer feed

The type of the feeding technique that will be used is the quarter wave transformer technique. It is a simple and useful method for matching real load impedance to different source impedance and is frequently used in antenna. Calculation of the microstrip feed line width is shown by equation (2.6).

$$\frac{W1}{h} = \frac{8e^{A}}{e^{2A}-2} \quad \frac{W1}{h} < 2 \tag{2.7}$$

Where, A is $\frac{Z_o}{60}\sqrt{\frac{\varepsilon r+1}{2}} + \frac{\varepsilon r-1}{\varepsilon r+1}(0.23 + \frac{0.11}{\varepsilon r})$

$$\frac{2}{\pi}\left[B - 1 - \ln(2B-1) + \frac{\varepsilon r-1}{2\varepsilon r}\left\{\ln(B-1) + 0.39 - \frac{0.61}{\varepsilon r}\right\}\right] \quad for\,\frac{W}{h} > 2 \tag{2.8}$$

Where, B is $\frac{377\pi}{2Z_O\sqrt{\varepsilon r}}$

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The single section quarter-wave transformer has a length equal to the quarter wave in microstrip and its characteristic impedance should be given. The edge resistance at resonance Z_{in}can be calculated by using the equation

$$Z_{in} = \frac{1}{2G_e} \tag{2.9}$$

$$\text{Where} G_e = 0.00836 \frac{W}{\lambda_0} \tag{2.10}$$

G_e is represent of edge conductance.

Below is the calculation of the quarter-wave transformer impedance and the edge resistance at resonance.

$$Z_1 = \sqrt{R_{in} Z_0} \tag{2.11}$$

Where Z_o the characteristic impedance of the 50ohm is line and Z_{in} is the input impedance of the square ring patch.

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2.6 Rectifying Circuit

A rectifier is an electrical device that converts alternating current (AC) into direct current (DC). It makes sure current only flows in one direction. The process is can be said as rectification. Physically, rectifiers have several features, including vacuum tube diodes, mercury-arc valves, solid-state diodes, silicon-controlled rectifiers and other silicon-based semiconductor switches. The rectifier in a rectenna circuit is similar to any rectifier circuit, except that the circuit operates at microwave frequency and its components are mostly surface mount components. The conversion of RF to DC efficiency is altered by losses of diodes and impedance matching circuit. The significant loss comes from diodes. The overall efficiency of a rectenna depends on types of antenna, rectifier configuration and operating frequency. The rectifying circuit is optimized to increase the conversion efficiency [29].

The equivalent circuit of the circuit with the Schottky diode is shown in Figure 2.5. Cp is a parasitic capacitance, Lp is a parasitic inductance, and Cj (V) is a variable capacitor at zero bias potential and is called the integrated (built-in potential). The boundary conditions in the area of the Schottky diode given by the equivalent circuit are [30]

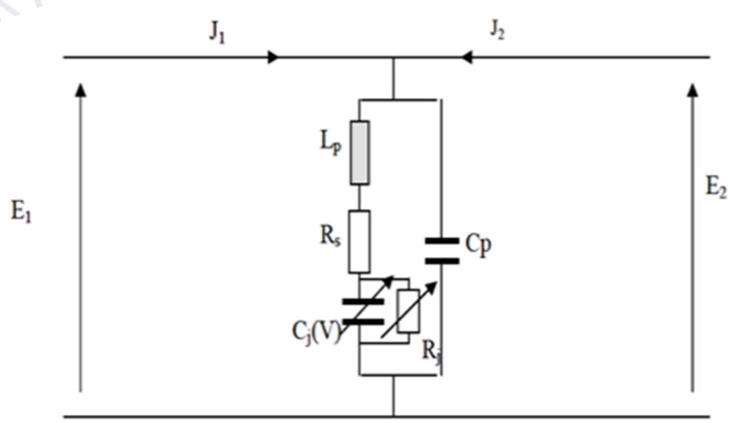

Figure 2.5: Equivalent circuit of planar circuit with Schottky diode

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Variable capacitor

$$\mathrm{Cj}\ (\mathrm{V}) = {C_{j(0)}}\Big/{\sqrt{1-\frac{V}{\varphi}}} \qquad (2.14)$$

Where Cj (0) = 1pF is junction capacitance at zero bias potential.

$$E_1 = \left[j\omega\ Lp + R_s + \frac{\frac{R_j}{\omega C_j}}{\left[\left[\frac{1}{\omega C_j}\right]^2 + R^2\right]^2} \right] J_1 \qquad (2.15)$$

$$E_2 = \frac{1}{j\omega C_p} j_2 \qquad (2.16)$$

$$E_1 = E_2 = Z_s(j_1 + j_2) \qquad (2.17)$$

Thus we can define the surface impedance ZS by:

$$Z_s = \frac{E}{J} = \frac{W_R}{L_R}\frac{V_L}{I_L} = \frac{W_R}{L_R} Z_L \qquad (2.18)$$

${W_R}/{L_R}$ is the form factor of the element located and ZL is the impedance of the equivalent circuit element, the electric field in the area of the element.

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2.7 Energy Harvesting System

Energy harvesting is commonly defined as the conversion of ambient energy into electrical energy. We define energy harvesting as “the collection and storage of ambient energy for on -demand, off-grid use”. Ambient energy is all around us, in many different forms – thermal, chemical, electrical, mechanical and more. To make use of energy harvesting one or more of these energy fields must be present in the environment of interest, and there must be a suitable transducer to convert the energy in this project we use rectifier antennas in order to covert the energy. Energy harvesting can exploit different sources of energy, such as solar power, wind, mechanical vibrations, temperature variations, magnetic fields, and so on. Continuously providing energy, and storing it for future use, energy harvesting subsystems enable WSN nodes to last potentially forever [31].

2.7.1 Energy From Radio Waves

RF energy harvesting converts radio waves into DC power. This is accomplished by receiving radio waves with an antenna, converting the signal, and conditioning the output power, as shown in Figure 2.6 [32].

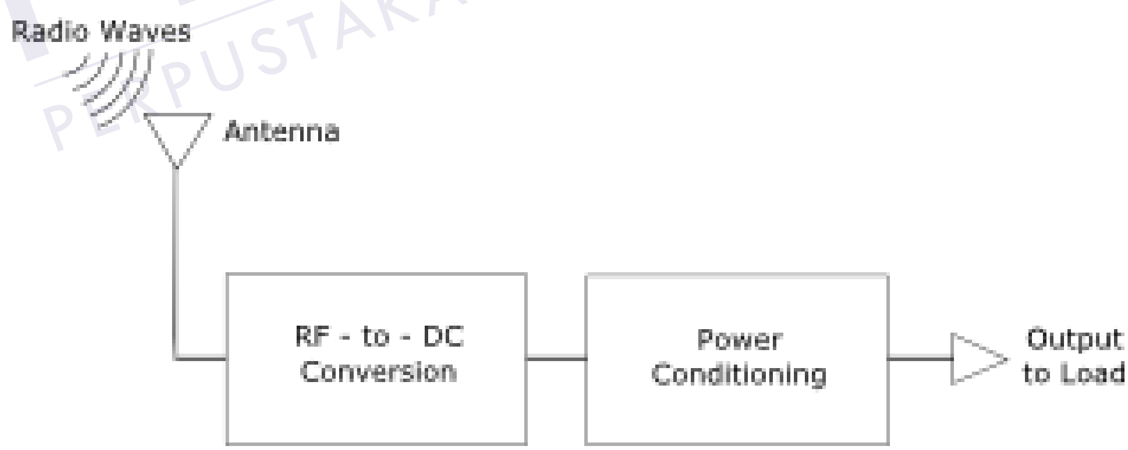

Figure 2.6: Overview of an RF energy harvesting system

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An energy harvesting system consists of two main subsystems. The first one is the receiving antenna, which functions to capture ambient RF energy to power up the integrated embedded system. The second subsystem is the rectification circuitry, which converts the input RF power into DC output power efficiently.

The antenna captures the RF signals, and subsequently the rectifier circuit extracts the power of those signals and converts them into DC voltage. Therefore, an antenna with high efficiency is needed to transfer wireless power effectively [33].

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2.8 Related Previous Papers

2.8.1 Efficient 2.45 GHz Rectenna Design with High Harmonic Rejection for Wireless Power Transmission

The output DC voltage across the resistor load has been measured by a voltmeter. The rectifying circuit has been optimised at 2.45 GHz for an input power of 10 dBm. The rectenna exhibits a measured efficiency of 74 % at 0.3 mW/cm² power density and an output DC voltage of 2.9 V.

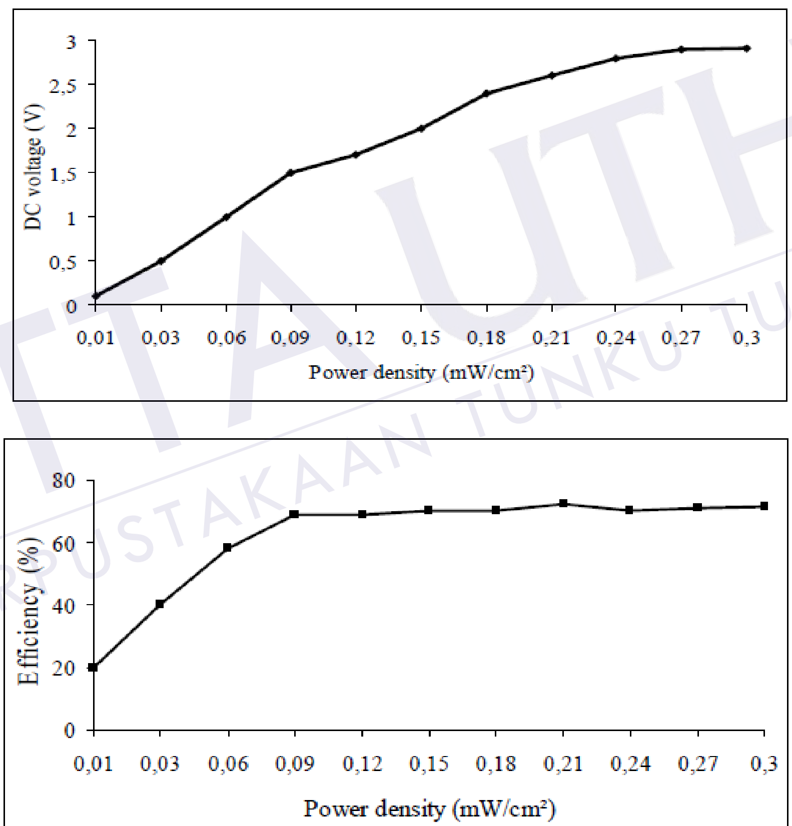

Figure 2.7: Measured DC voltages and rectenna efficiency against power density

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2.8.2 Rectenna Design, Development and Application

This paper describes the progressive development of rectenna in terms of its applications in various fields. The maximum efficiency as microwave power transmission was found to 91 % with 1.2 W of input power while in case of harmonic rejection, rectenna designed with circular sector antenna provides conversion efficiency of 77.8 % with 150 Ω load and very high return loss at 2nd and 3rd harmonics.The RF to dc conversion efficiency for circularily polarized is 78% at 16.5 mW/cm2 incident power density while in case of dual frequency the RF to dc conversion efficiency of 65% and 46% are achieved at 2.45 GHz and 5.8 GHz respectively when power density is 10mW/cm2.

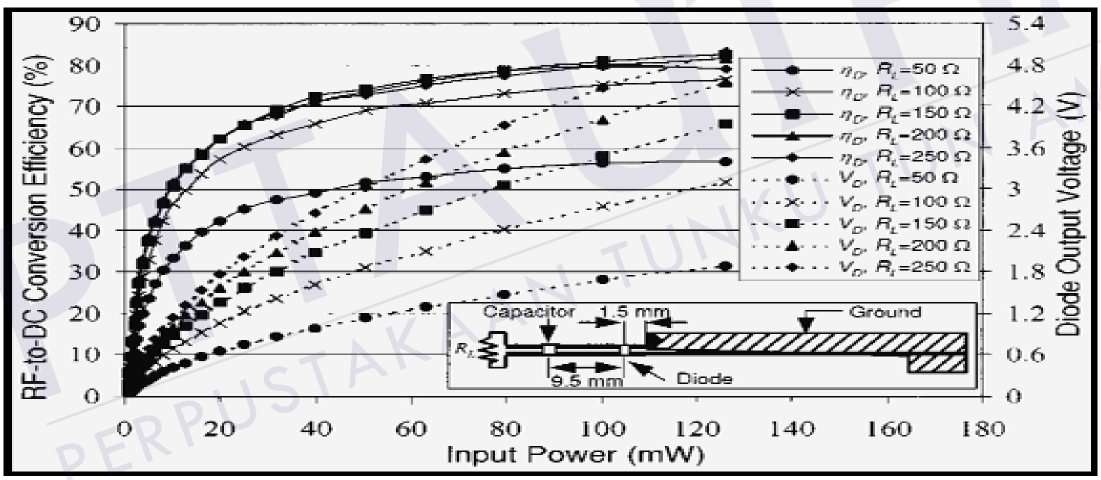

Figure 2.8: Directly measured diode conversion efficiency and output voltage versus power delivered to the diode for various load resistances

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2.8.3 Design of a 2.45 GHz Circularly Polarized Rectenaa for Electromagnetic Energy Harvesting

A 2.45 GHz circularly polarized rectenna has been simulated using Agilent ADS. It gives volt output DC voltage at 10dBm received input RF power. Harmonics levels at output are significantly reduced. Work is on progress to practically validate this design. The DC voltage is obtained by measuring the voltage difference between V1 and V2 across the 1500 Ω resistor load, without reference to the RF ground plane.

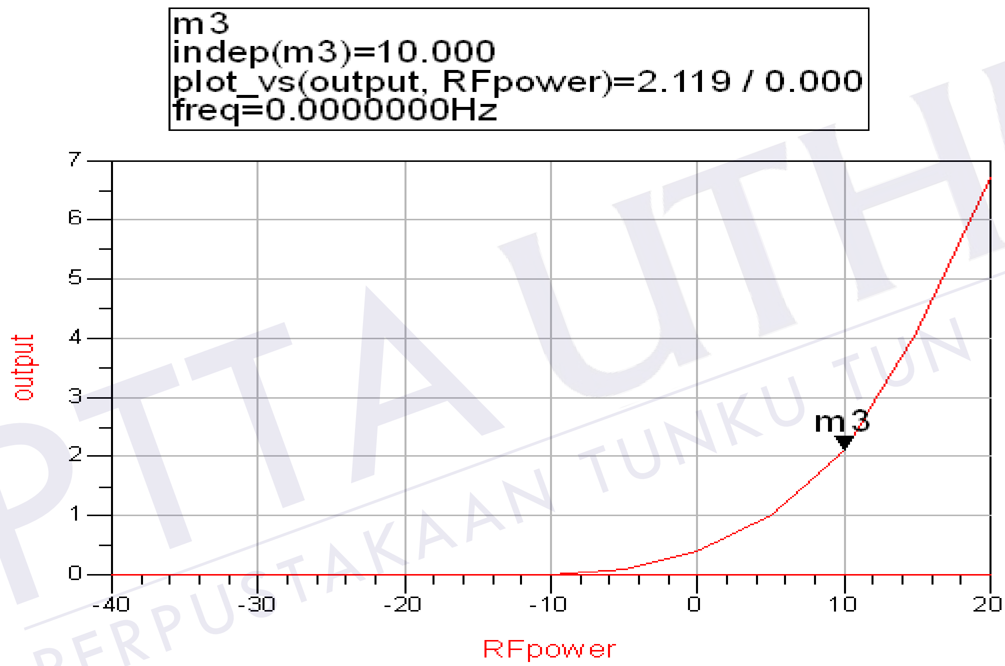

Figure 2.9: Output DC voltage versus received RF power

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2.8.4 RF Energy Harvesting System and Rectennas

In this paper, a study of various methods used for RF-energy harvesting has been made. It is found that we can harvest energy in micro watt range from ambient RF sources. Here the harvested power highly depends on the distance between the transmitter and RF harvesting system. By using an array of harvesting antennas we can harvest considerable amount of power.

As shown in the Figure 2.10 shows the frequency response of an 899 MHz rectenna. Here the peak is at 895 MHz at this frequency we obtained an output dc voltage of 3.2V. In general it is difficult to predict how the rectenna system is optimized for the maximum conversion efficiency. However, there are several theoretical methods to overcome this problem.

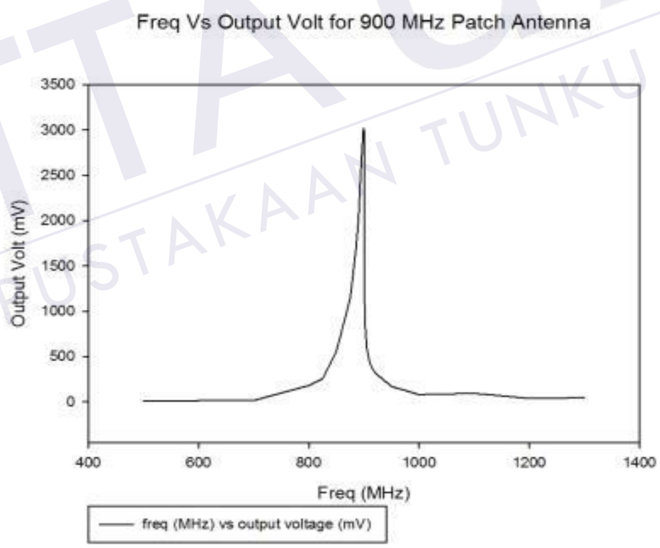

Figure 2.10. Frequency Response of an 899 MHz Rectenna

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2.8.5 Study on an S-Band Rectenna Array for Wireless Microwave Power Transmission

The measured conversion efficiency of the rectifier is over 60% with 10 dB dynamic range of input power and highest efficiency reaches 83.1%. The maximum DC output power and highest conversion efficiency of rectenna array are 7.1W and 67.6%, respectively.

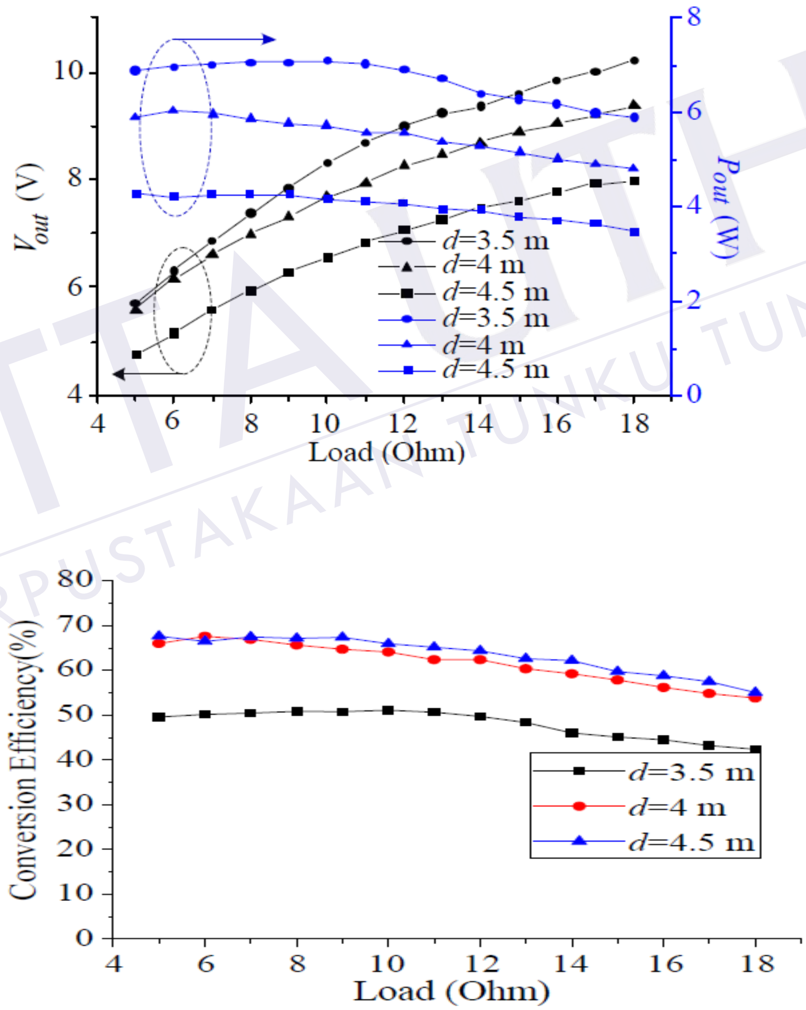

Figure 2.11: Measured DC voltage and conversion efficiency

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2.8.6 Design of Wideband Antenna for RF Energy Harvesting System

In this paper shown, the performance of a coplanar ice cream cone antenna has been presented. The simulation and measurement result of the single diode rectifier is shown in Figure. 2.12. From the graph, it can be observed that the maximum output voltage of both process are in line where they obtained an output voltage of approximately 3.174 V despite of the different rising time. From these tables2.1, it can be observed that the variation of load and input power will affect the output DC voltage. The voltage increased when the load of the rectifying circuit is reduced.

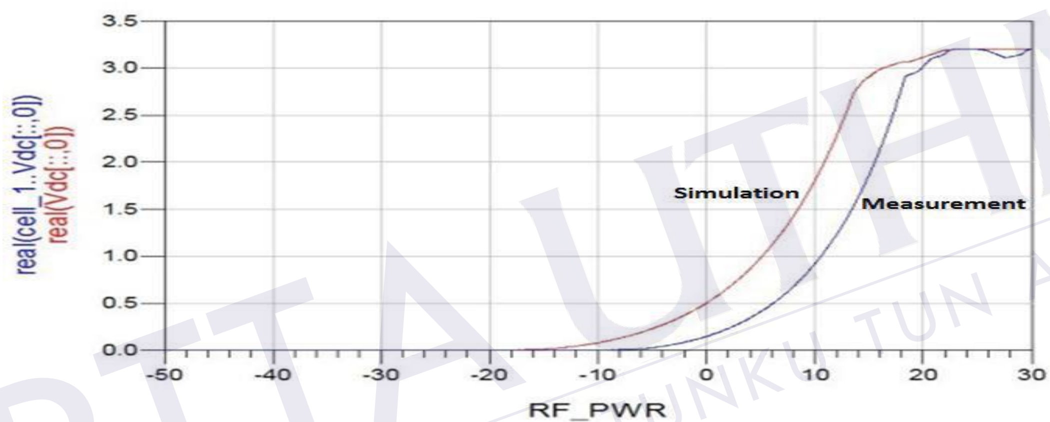

Figure 2.12: The simulated and measured output voltage of the rectifying circuit

Table 2.1.The measured output voltage for different loads, R

Power transmit (dBm)	Output voltage (V)		
	R=1MΩ	R= 820KΩ	R = 20KΩ
-15	0.049	0.082	0.09
-10	0.050	0.081	0.09
-5	0.049	0.081	0.09
0	0.049	0.081	0.09
5	0.046	0.076	0.09
10	0.047	0.081	0.09
15	0.048	0.080	0.09
20	0.050	0.081	0.09

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