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OPTIMUM DESIGN OF RECTIFYING CIRCUIT WITH RECEIVING ANTENNA FOR RF ENERGY HARVESTING

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ABSTRACT

Recently, wireless communication has been a crucial part of our daily life. Hence, this study focuses on RF energy harvesting where a small amount of the electrical power is generated to drive circuits in wireless communication electronics devices. This paper presents an optimum design of microstrip rectangular 2x2 patch array antenna with air gap and integrated with a double stage rectifying circuit which has the potential to be used for the RF energy harvesting system. A single and double stage rectifying circuit are designed and simulated. A prototype is then fabricated and measured to validate the simulation results. Simulation process mainly used EM simulator and measurement is carried out for various input power levels at frequency 2.45 GHz. An experimental measurement has been conducted by varying the load, R of the rectifying circuit. From the experimental measurement, it has been observed that the maximum DC voltage of 13.556 V and RF-DC efficiency of 78.57% are obtained from the energy harvesting system.

Keywords: RF Energy harvesting, 2x2 patch array antenna, rectifying circuit, RF-DC conversion, schottky diode, impedance matching.

INTRODUCTION

Passively powered devices are becoming increasingly important for a wide range of sensing applications. Also known as remotely powered devices, passively powered devices do not require any internal power source. They instead extract their power from ambient for instance propagating radio waves, sunlight, mechanical vibration, thermal gradients, convection flows or other forms of harvestable energy. One of the most popular power extraction methods used for passively powered devices is to harvest power from propagating radio frequency (RF) signals. RF energy harvesting is the process of capturing ambient electromagnetic energy and converting into suitable DC power [1].

The concept of harvesting DC power from RF signals is obtained from a combination of a receiving antenna and integrated to a rectifying circuit that efficiently converts RF energy to DC signals. Thus, the RF energy harvesting is made up of a microwave antenna, a matching circuit with low pass filter, rectifying circuit, the next stage of low pass filter for DC path and a resistive load. The RF signals received by the antenna will be transformed into DC signals by a diode based rectifying circuit. Depending on applications, a storage device could be introduced in order to efficiently utilize the DC power to charge the battery and depending on techniques it is enough to drive small electrical or low power consumption devices [2, 3]. Several researchers have conducted studies on designing RF energy harvesting system for instance in [4-6].

In this paper, we propose an integration of high gain microstrip 2×2 array antenna with a rectifier at 2.45GHz to harvest energy from RF ambient. A matching circuit is used to enhance the efficiency of the system, hence producing better amount of DC output voltage which is sufficient for low-powered device applications.

METHODOLOGY

a) Rectifying circuit design

1) Rectifier circuit: Advanced Design System (ADS 2011) software is used for the nonlinear simulation of rectifiers. Rectification circuits were designed, simulated, and evaluated in order to convert RF input signals into a DC signal via Schottky diodes. At the same time, these circuits were optimized to obtain a higher efficiency and eventually to increase the overall system performance. Studies on various rectifier configurations show that the conversion efficiency cannot be considered without matching circuit. In fact, the input power from antennas may not be transferred entirely to rectifiers and consequently, the mismatching maybe lead to a low efficiency. Figure-1 shows the single stage structure of rectifier where Pin, Pt, Pr, PDC are output power from power resources, actual power inside the diode, reflected power at diode input, DC output power, respectively.

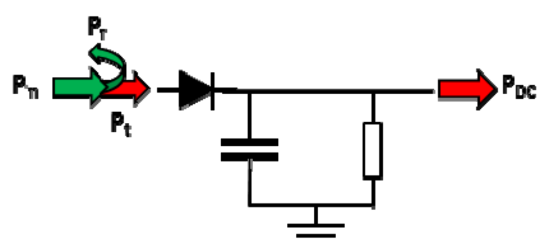


Figure-1. Single stage structure of rectifier.

The rectifier's performance can be determined by calculating the RF-DC efficiency of the overall system (η_o),

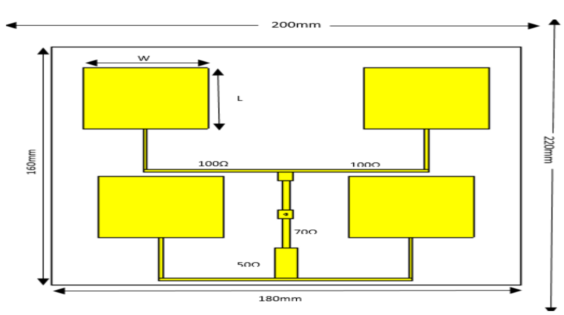
$$\eta_o = \frac{P_{DC}}{P_{in}} \times 100 \quad (1)$$

In this paper, two rectifiers with different number of stages is designed and their performance is compared. Schottkey diode of HSMS286B is used due to its advantage of better switching time and it is also suitable to be used at lower frequency. A comparison of loads for the rectifying circuit performance has been done and based on the preliminary output DC voltage, the 10 kΩ load is further used.

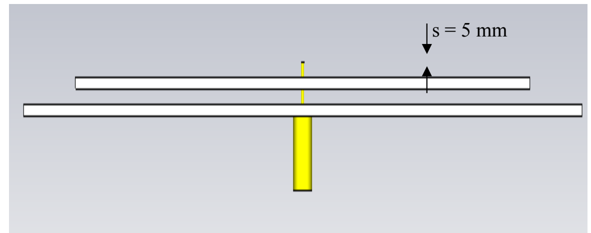
2) Rectifying and matching circuit: The impedance matching stage of the RF harvesting circuit is an essential in optimizing power transfer from the antenna to the rectifier. In general, matching networks are constructed with reactive components only, which act as filters so that no loss is added to the overall network. However, the design of the associated matching network is challenging since the rectifier is a nonlinear load, the complex impedance varies with frequency, input power level, and load resistance [7]. In this paper, a simple stub matching circuit was proposed due to its convenience and lumped element avoidably. Analytical models are employed to acquire a conjugate match between the rectifier and antenna, and its effect of RF-DC conversion efficiency was investigated. The rectifier circuit is simulated using Parameter Sweep simulator as the input impedance varies due to the nonlinearity of diodes. In this design, double stub matching network is applied.

b) Antenna design

A microstrip rectangular 2x2 patch array antenna with air gap is chosen due to its ability to produce a high gain at 2.45 GHz frequency by using Computer Simulation Tool 2011 (CST 2011). The overall physical dimension of radiating antenna is 200 mm × 220 mm as shown in Figure-2. The dimension of radiating patches of this antenna array with 2×2 element distributed on the FR-4 substrate is 160mm × 180 mm. The patch array antenna and air gap technique are used to increase the gain and improve the return loss (RL) of the antenna. Table-1 shows the specifications of the microstrip 2×2 array antenna. Microstrip array antenna design begins with defining the dimensions of the patch. The width, W and length, L of the microstrip patch can be found using the equation in [8].



(a)



(b)

Figure-2. Microstrip 2×2 array antenna structure (a) front view (b) side view

Table-1. Antenna design specifications.

Centre Frequency, f_o.	2.45 GHz
Substrate	FR-4
Dielectric Constant of FR-4	4.4
Dielectric Constant of Air	1
Thickness of substrate	1.6 mm
Loss Tangent	0.019
Thickness of Copper	0.035 mm

RESULT AND DISCUSSION

a) Rectifying circuit

Figure-3(a) shows a single stage rectifier circuit that has been designed. The circuit consists of two Schottky diodes HSMS286B, two capacitors and one input. The simulation result of this single stage rectifier circuit design as shown in Figure-3(b). The range of input signal for this rectifier circuit has been set from -40 dBm to 40 dBm in ADS simulation. From the simulation result, the output voltage started to increase from 0V at -18 dBm. The maximum output voltage produce is around 6.778 V at 20 dBm and remains constant even though the input signal achieves 40 dBm.

Figure-4(a) shows double stages rectifier circuit. The circuit design consists of four Schottky diode HSMS286B, four capacitor and two inputs. The simulation result for this rectifier circuit design is shown in Figure-4(b). The range of input signal for this rectifier circuit has been set from -40 dBm to 40 dBm in ADS simulation. From the simulation result, the output voltage started to increase from 0 V at -18 dBm. The maximum output voltage produce is around 13.556V at 15.2 dBm, which is two times higher than the output voltage from a single stage rectifier circuit. The voltage remains constant even though the input signal exceeds 40 dBm input powers.

An experimental measurement also has been made to validate the simulation results. The maximum output voltage for measurement result is 6.01 V and 13.65 V for single stage and double stage rectifier circuit respectively. While the output voltage at the distance of 30 cm from the transmitting antenna is 3.801 V for single stage circuit and 6.01 V for the double stage circuit.

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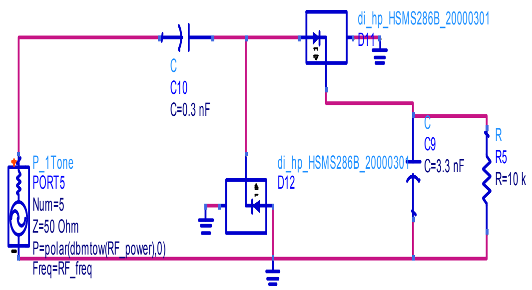
Figure-5 shows the efficiency for both single stage and double stage rectifier with different value of loads.



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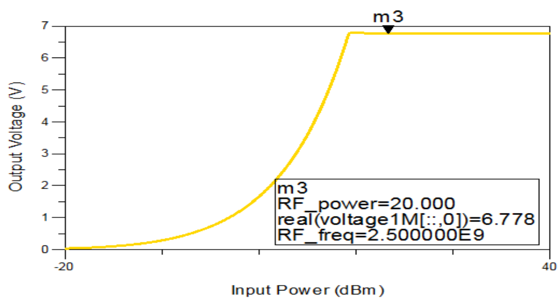
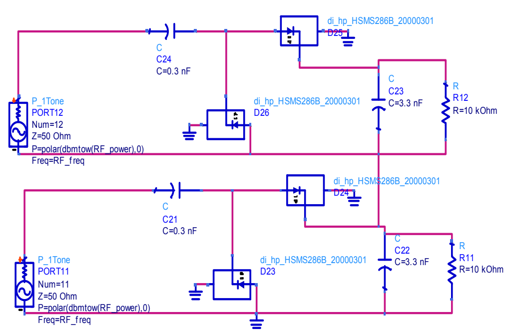
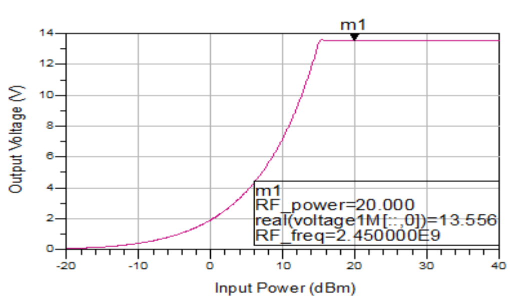


(b)

Figure-3. Single stage rectifier (a) Schematic circuit (b) Output DC voltage.

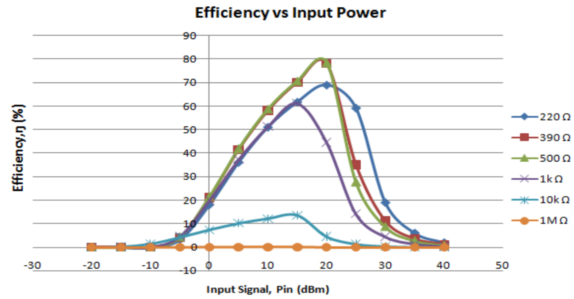


(a)



(b)

Figure-4. Double stage rectifier (a) Schematic circuit (b) Output DC voltage.



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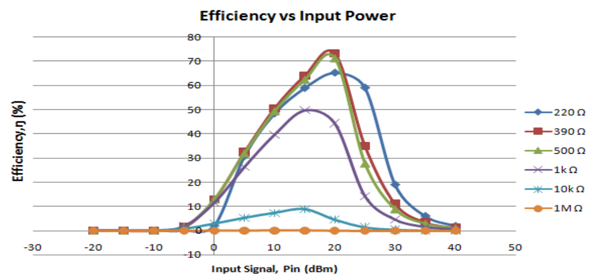

(b)

Figure-5. Efficiency vs. Input power (a) Single stage rectifier (b) Double stage rectifier.

b) Microstrip 2×2 array antenna

Table-2 shows the changes that occur when the height of air gap changed the height in the range 2.0 mm ≤ h2 ≤ 6.0 mm where, when the air gap is 4mm, the antenna has obtained the highest gain at 14.16 dB with return loss and bandwidth are 24.536 dB and 87.1 MHz respectively. Figure-6 shows the return loss graph for a microstrip rectangular 2x2 patch Array antenna with air gap. From the graph it can be seen that the height of the air gap affected the return loss and center frequency of the antenna. The air gap is chosen to be at 4 mm because the frequency shifting is minimal at that height. Nevertheless, the return loss is good with 24.54 dB. Figure-7 shows the radiation pattern for air gap at height of 4 mm where the antenna radiates more power at z-axis compared to the radiation from other directions. The microstrip 2×2 array antenna is then fabricated in-house and the photograph of the prototype can be seen in measurement setup.

Table-2. Frequency, return loss, gain and bandwidth at different air gap height.

Air Gap (mm)	Frequency (GHz)	Return Loss (dB)	Gain (dB)	Bandwidth (MHz)
2.0	2.294	15.525	13.81	59.9
3.0	2.394	20.472	14.13	79.8
4.0	2.450	24.536	14.16	87.1
5.0	2.482	18.220	14.08	88.6
6.0	2.498	15.245	13.94	85.7

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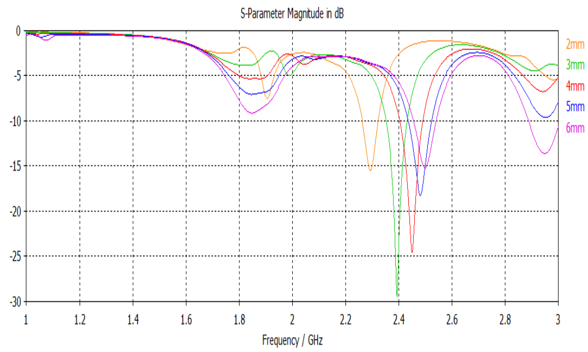

Figure-6. Simulated return loss at different air gap height.

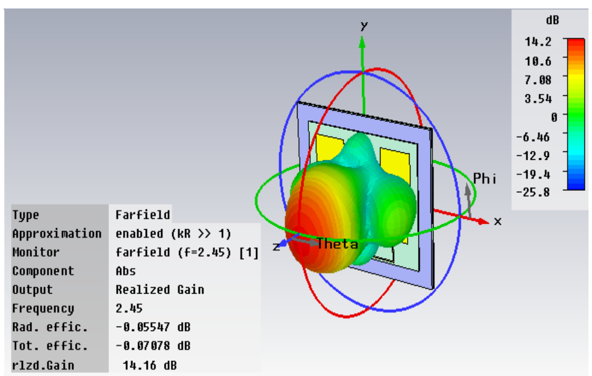

Figure-7. Radiation pattern of microstrip 2×2 array antenna at h2=4mm.

c) Measurement of antenna with rectifying circuit

Figure-8 shows the measurement setup for the integration of the antenna with the rectifying circuit in the laboratory. An experimental measurement has been conducted by varying the distance, D, between the transmitting and receiving antenna. The input power of transmitting antennas is injected directly from a signal generator ranged from -15 dBm to 20 dBm. The output DC voltage is then measured by using a digital multimeter. Table-3 and Table-4 below show the measurement results of the output voltage with various distances are recorded from the observation.

Figure-8. The measurement setup for integrated antenna with rectifier circuit experiment.

Table-3. Output voltages of antenna with single stage rectifier circuit for various input power and specified distances.

Input Power (dBm)	Output Voltage of Double Stage Rectifier Circuit (V)			
	D=300 mm	D=600 mm	D = 900mm	D=1200mm
-20	0.0487	0.0168	0.0147	0.0117
-15	0.0483	0.0168	0.0146	0.0115
-10	0.0483	0.0178	0.0145	0.0114
-5	0.1192	0.0480	0.0398	0.0311
0	0.2589	0.1163	0.1008	0.0081
5	0.4290	0.2774	0.2494	0.0021
10	0.9560	0.4660	0.4210	0.0036
15	2.0006	1.0020	0.9510	0.0081
20	3.8010	2.0450	1.9090	0.0164

Table-4. Output voltages of antenna with double stages rectifier circuit for various input power and specified distances.

Input Power (dBm)	Output Voltage of Double Stage Rectifier Circuit (V)			
	D = 300 mm	D = 600 mm	D = 900 mm	D=1200 mm
-20	0.0786	0.0351	0.0225	0.0173
-15	0.0781	0.0346	0.0224	0.0172
-10	0.0809	0.0360	0.2310	0.0177
-5	0.2015	0.0963	0.0630	0.0484
0	0.2861	0.2333	0.1555	0.1226
5	0.7660	0.3960	0.3822	0.3107
10	1.6330	0.8950	0.6080	0.4950
15	3.2460	1.8500	1.3150	1.0910
20	6.0700	3.5870	2.6080	2.1950

From the tables, it can be observed that the variation input power will affect the output DC voltage. The output voltage and power are increased when the input power increased. Hence, it can be concluded that the output voltage and output power are directly proportional to the input power. This experimental work is an early effort done for the antenna of an energy harvester. The performance may be improved by designing antennas with optimum performance to capture as much energy as possible and able to capture more energy even further.

CONCLUSIONS

In this paper, the development of RF energy harvesting that consists of antenna with a rectifying circuit to operate at 2.45 GHz has been presented. It has been observed that the maximum DC voltage of 13.556 V and RF-DC efficiency of 78.57 % are obtained during the measurement in the laboratory. This study is useful to be implemented for low power wireless sensor network applications such as agriculture and health monitoring system as well as Earthquake disaster detection.

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