A High-Efficiency Rectenna Design at 2.45 GHz for RF Energy Scavenging

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***Abstract*—A high conversion efficiency rectenna at 2.45 GHz is proposed in this paper. Two layers low cost FR-4 substrate has been used to fabricate the rectenna. The proposed designs contain patch antenna and open stub rectifying circuits. The dimension for the proposed rectenna design is 100 x 100 x 5 mm^3. The technique of air gap approach has been used in order to increase gain of the antenna. The ground plane is added with the triangular slot has eliminate second and third harmonics which results enhancement of the conversion efficiency. The measured conversion efficiency reaches 79.29% when the input power at 17 dBm. This rectenna takes advantages of low profile, easy integration, high gain and high power conversion efficiency from previous proposals.**

***Index Terms*— Antenna; Conversion efficiency; Rectenna; Rectifying.**

I. INTRODUCTION

RF energy harvesting system plays important role in gathering clean energy from surrounding environment. Rectifying antenna or rectenna is one of the primary components in the RF energy harvesting system, which is used to capture RF signals and convert it into a DC voltage [1]. Despite significant progress, batteries still have a limited lifetime and their replacement is quite difficult. There are several studies have been conducted to design rectenna for the RF energy harvesting [2]. However, most of the designs suffer from low RF-DC conversion efficiency, low output DC voltage and large size [3]. This is due to low captured ambient RF signals and the nonlinear behavior from the active component i.e. diode which generates harmonics which causes losses and less efficiency for the RF-DC conversion. In addition, the mismatch impedance between antenna and rectifier also the factor that will contribute to low performance of the rectenna [4]. This paper is focus on developing new rectifier integrated with stacked air-gap antenna that can exhibit power in milliwatts and produce sufficient and reliable energy for an output voltage in the range of 3 – 20 V, that are suitable to be implemented for RF energy harvesting especially in wireless sensor applications.

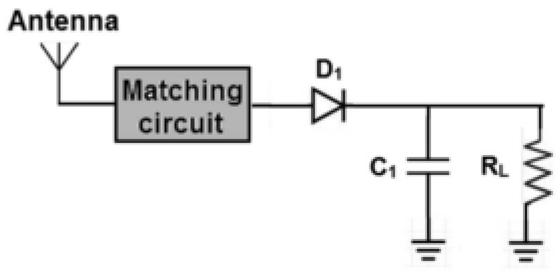


Figure 1: Conventional single series diode rectifying circuit rectenna configuration.

A conventional overall rectenna system single series diode rectifying circuit is depicted in Figure 1. A good antenna must have a high gain, acceptable reflection coefficient and good handling radiation pattern [5-8]. On the other hand, the rectifying circuit also plays an important role since it contribute to the overall conversion efficiencies of the rectenna whole system [9-12]. A low power consumption, good power handling capability and good power sensitivity are some characterization of a good rectifying circuit [13-16].

Section II presented the design of the rectenna with the property of higher gain and its parametric study. The proposed rectenna measured results are given in Section III along with its performance that has been optimized. Section IV, we study the conversion efficiency from the measurement results. We summarize all the achievement and draw a conclusion in Section V.

II. THE PROPOSED RECTENNA GEOMETRY DESIGN

The proposed receiving antenna consists of a radiating rectangular patch at the top layer, an open stub with interdigital capacitor rectifying circuit joined with the microstrip feeding line is etched in the middle layer and a triangular slot ground plane at the bottom layer. The proposed rectenna geometry is shown in Figure 2. Both layers are fabricated on the 1.6 mm-thick low cost FR4 substrate with a dielectric constant of 4.6 (ε_r = 4.6) and loss tangent of 0.02. This rectenna is designed to operate at 2.45 GHz. The dimension of the rectangular patch is 12 x 38.6 mm^2. The width of the feeding line is 2.34 mm at the middle layer as

shown in Figure 2 (b). The simulation experiment has been done in ADS and CST 2013. Figure 3 shows the simulated and measured reflection coefficient for the proposed antenna gives good agreement with gain reaches 8.36 dB. By presenting this performance shows that this developed rectenna promises wireless power transfer effectively.

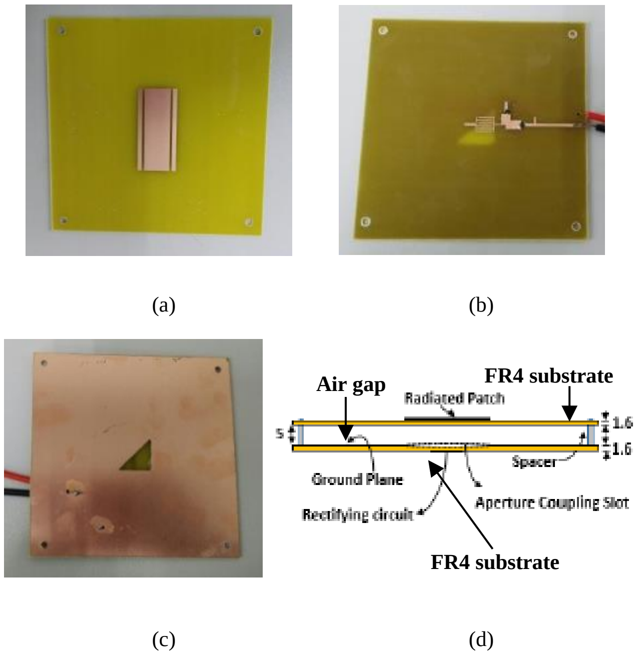


Figure 2: Geometry of the proposed rectenna (a) top view, (b) middle layer (c) bottom layer (d) side view

Table 1
Antenna Parameters

Specification Parameters	Symbol	Value
Centre frequency	*f*	2.45 GHz
Cavity material	–	FR4 and Air Gap
Radiating patch material	–	Copper
Ground plane material	–	Copper
Air gap thickness	h	5mm
FR4 board thickness	t	1.6 mm
FR4 board pemittivity	ε_r	4.6

III. Results Analysis Of The Proposed Rectenna

A. *Performance of the proposed antenna*

The air gap width, *h* = 5 mm is chosen as this is the optimal value to radiate maximum power from the patch antenna to the rectifying circuit. The 50 Ω microstrip lines has been replaced with rectifying circuit. The input port is at the open end. The simulated and measured return loss is shown in Figure 3. Straight curves represent measured data while the dotted curves are simulated by using CST 2013. During the fabrication process, material precariousness would happen and there is slightly difference between the simulation and measurement results. Good impedance matching can be found in Figure 3 at the designated operation frequency. The bandwidth is about 120 MHz (2350 – 2470 MHz).

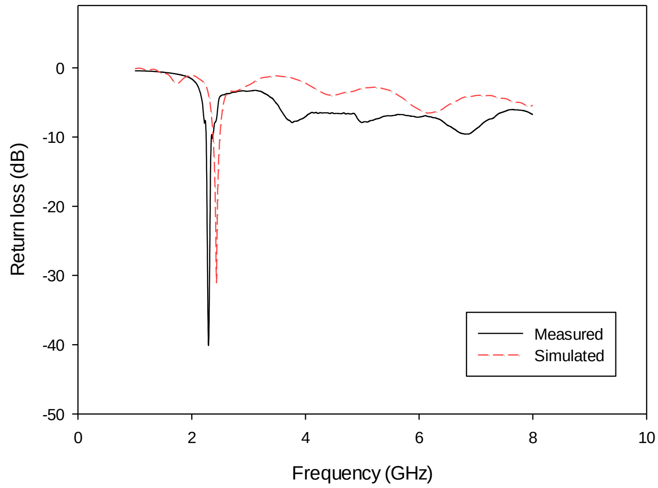


Figure 3 : Simulated and measured return loss of the proposed antenna

The antenna gain is increased by using the separated two layers substrate by an air gap as shown in Figure 4. By utilizing the concept of air gap at 2.45 GHz frequency, the antenna gain can reached > 8 dB as shown below. The variation of the air gap distance can cause shifting of the frequency in higher or lower range. Therefore, 5 mm has been chosen as the optimized distance to maintain the efficient performance of the antenna.

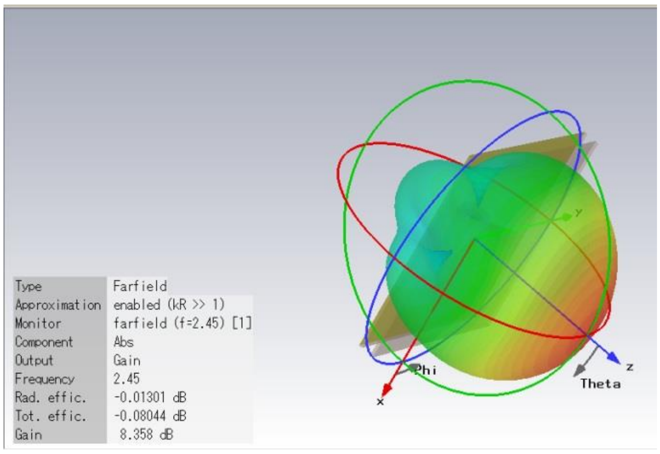
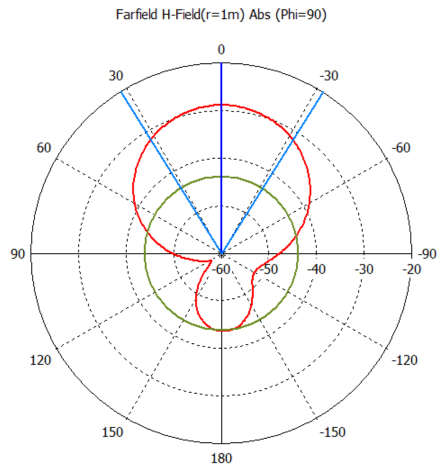
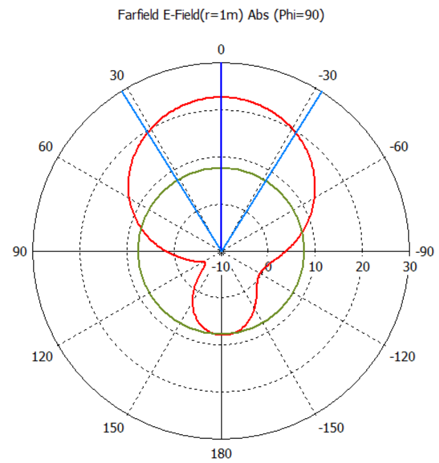


Figure 4: Simulated gain of the proposed antenna.

The simulated radiation pattern of the proposed antenna at 2.45 GHz for E-plane and H-plane are shown in Figure 5 (a) and (b). It can be seen that the radiated fields of the antenna are high indeed the antenna is able to receive RF waves effectively. Additionally, the proposed antenna radiation patterns can be said approximately constant at the operating frequency. Therefore the antenna is very suitable for wireless energy harvesting at the selected frequency of 2.45 GHz.



(a)



(b)

Figure 5: Radiation patterns of the proposed antenna. (a) H-plane radiation pattern. (b) E-plane radiation pattern.

B. *Rectifying circuit*

The rectifying circuit is the significant part of the proposed rectenna as it will effect the overall conversion efficiency of the RF energy harvesting system. We can say the rectifier is a good one if it only consume low power, efficient and produced high output voltage [16-17]. Therefore, a voltage doubler rectifier is designed as shown in Figure 6 below. The series diode D1 rectified the first positive half cycle of the wave and the shunt diode D2 rectified the negative half cycle of the wave.

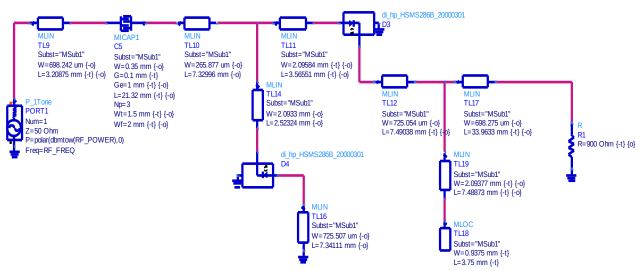


Figure 6 : ADS rectifying circuit

This voltage doubler rectifying circuit has been designed and optimized by using Advanced Design System (ADS) software. Figure 7 shows the fabricated proposed rectenna and measuring process has been done to validate the design concept. In order to transmit the power, a gain horn antenna by default setting has been used. The detachment distance between the rectenna and the standard gain horn antenna is 50 cm. The optimal load resistance (R_L) happened to be exactly 900Ω and the output DC voltage at the load of the rectenna is measured by using multimeter. The measurement setup of the proposed rectenna is shown in Figure 8. The maximum measured output voltage has reached to 6.31 V when the input power of 25 dBm being supplied.

The rectifying circuit consists of open stubs in order to get the circuit matched at 2.45 GHz. The schottky diode HSMS 286B is selected for this rectifying circuit due to its low forward voltage and it is ideally designed and optimized for use at 2.45 GHz.

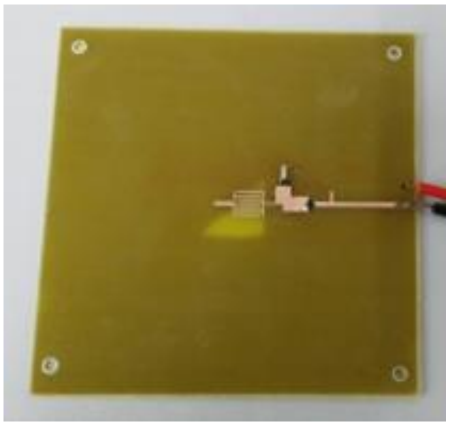


Figure 7 : Rectifying circuit of the proposed rectenna.

IV. Integrated Rectenna Analysis

The CST 2013 and ADS softwares has been used to simulate the proposed rectenna. The conversion efficiency for overall system can be calculated by using

$$\eta = \left(\frac{P_{DC}}{P_{in}}\right) X100\% = \left(\frac{V^2{}_{DC}}{R_L}.Pin\right) X100\% \qquad (1)$$

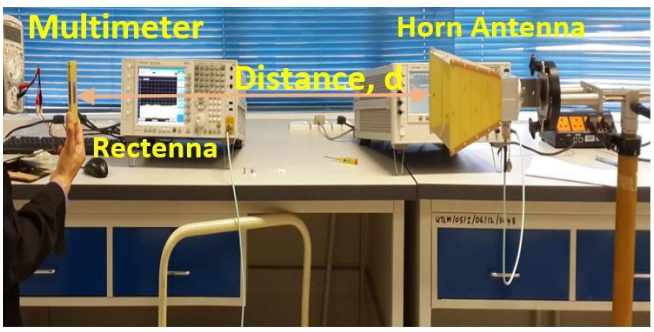


Figure 8 : The proposed rectenna measurement setup.

where P_{in} is the input power, R_L is the load resistance and V_{DC} is the output DC voltage. For measurement setup, the input power level is around -25 to 25 dBm. The total power measurement and the output voltage was measured by using multimeter. The overall conversion efficiencies are found to be as high as 79.29% at the operating frequency of 2.45 GHz and when supplied with an input power of 17 dBm as shown in Figure 9.

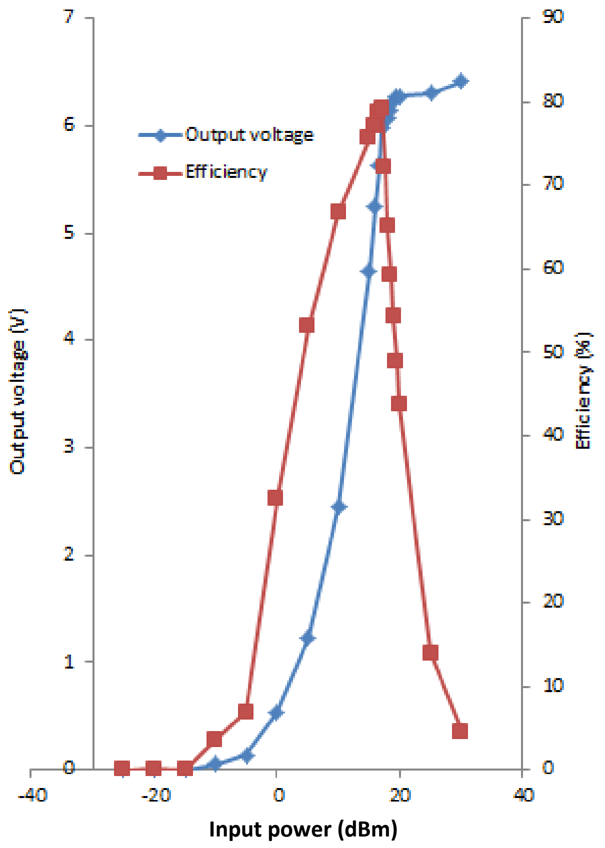


Figure 9 : Measured output voltage and conversion efficiency at different input power (dBm) when the load resistance is 900Ω.

V. CONCLUSION

We have proposed the rectenna in this paper that consists of a receiving antenna and voltage doubler rectifying circuit with high gain, high conversion efficiency and triangular-shape slot ground. For transformation of RF power into DC power, the feeding line connecting the rectifying circuits and the slot is responsible. Both antenna and rectifying circuits are integrated on a low cost FR-4 substrate. The input RF power is free from the insertion loss because of the removal of the filters. At the input power 17 dBm, the proposed rectenna conversion efficiency reaches 79.29% and 5.98 V output voltages. Therefore, this rectenna will significantly benefit to the society in providing green and sustainable technology for a wide range of sensing applications. In conclusion, the proposed rectenna has advantage such as simple structure, easy to fabricate, low profile and high efficiency. The design method of this proposed rectenna can be further devoped to cover multi-frequency rectennas.

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