2.45 GHZ RECTENNA DESIGN FOR RF ENERGY HARVESTING

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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 mm3. 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.

KEYWORDS: *Antenna; Conversion Efficiency; Rectenna and Rectifying*

1.0 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]. Based on the previous works, there are many limitations and drawbacks exists in currently used technique such as low RF-to-DC power conversion efficiency or increase in the number of antenna elements enlarges the overall aperture size of the rectenna, the resulting devices are large and more difficult to install which limits the potential of further enhancement in the conversion efficiency [2]. 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.

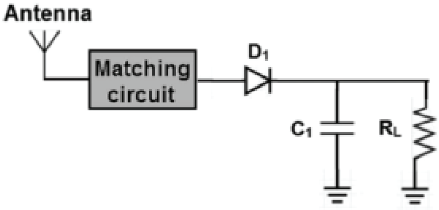


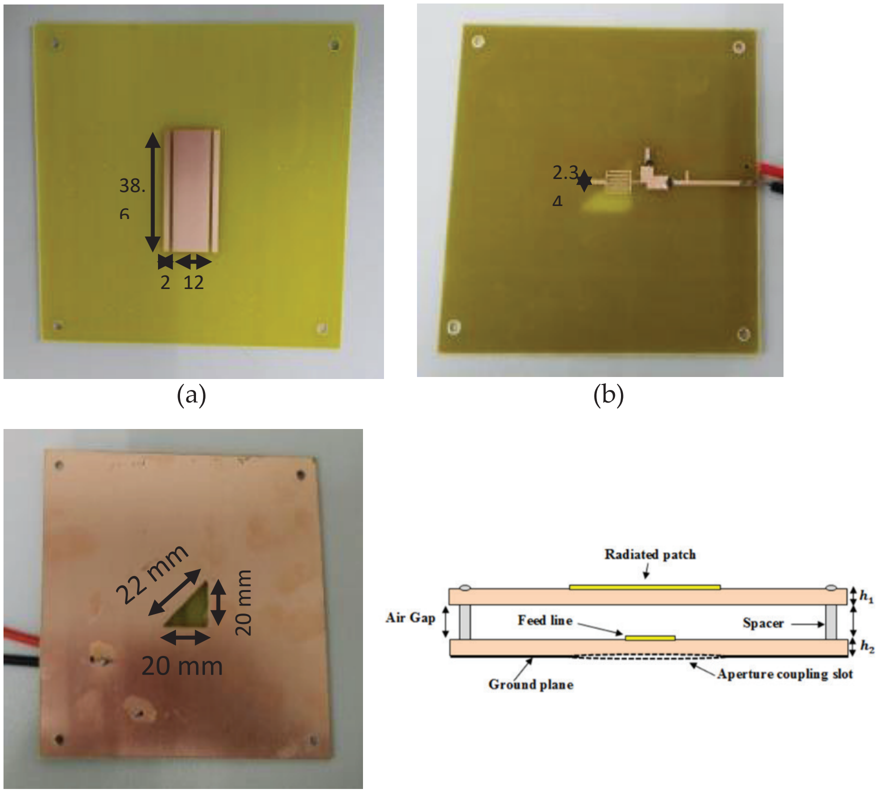
Figure 1: Conventional single series diode rectifying circuit rectenna configuration [18]

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 2 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 3 along with its performance that has been optimized. Section 4, we study the conversion efficiency from the measurement results. We summarize all the achievement and draw a conclusion in Section 5.

2.0 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.



(a) (b)

(c) (d)

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

Both layers are fabricated on the 1.6 mm-thick, t low cost FR4 substrate with a dielectric constant of 4.6 (Ɛr = 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 (Advance Design System) ADS and (Computer Simulation Technology) CST. By presenting this performance shows that this developed rectenna promises wireless power transfer effectively. This geometry design of the rectenna is significant for solving the research problem because it provides high gain, high efficiency and matching at the resonant frequency. The antenna parameters can be found in Table 1.

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

3.0 RESULT ANALYSIS OF THE PROPOSED RECTENNA

3.1 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. Figure 3 shows the simulated and measured reflection coefficient for the proposed antenna gives good agreement with gain reaches 8.36 dB. Straight curves represent measured data while the dotted curves are simulated by using CST. During the fabrication process, material precariousness would happen and there is slightly difference between the simulation and measurement results. The amount of error for the simulation and measurement result is 25%.

Good impedance matching can be found in Figure 3 at the designated operation frequency. The bandwidth is about 120 MHz (2350 – 2470 MHz).

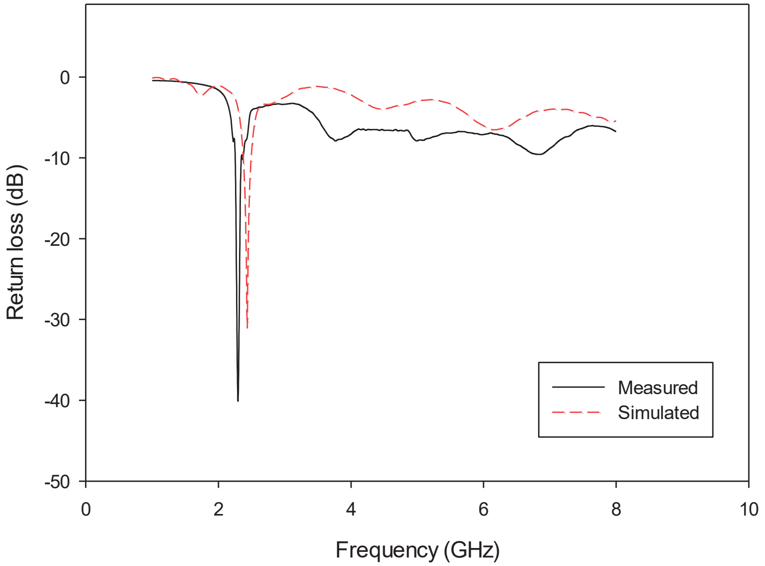
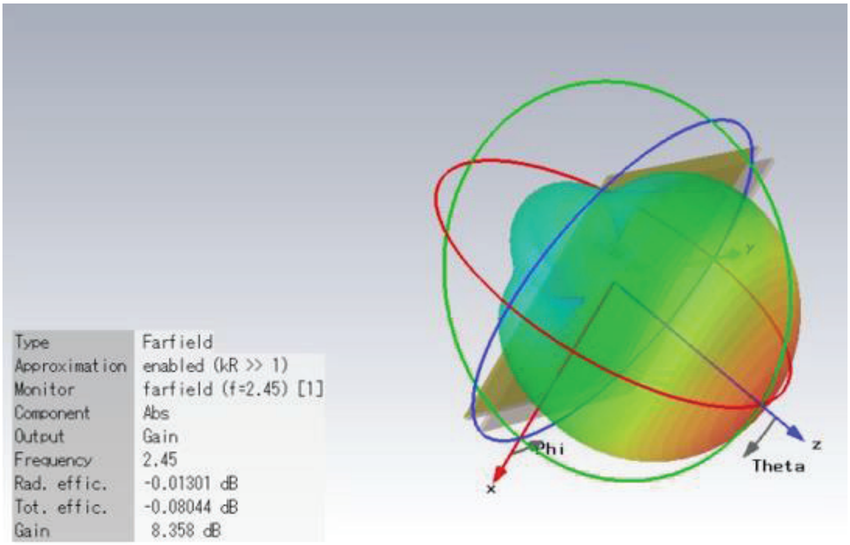


Figure 3: Simulated and measured return loss of the proposed antenna

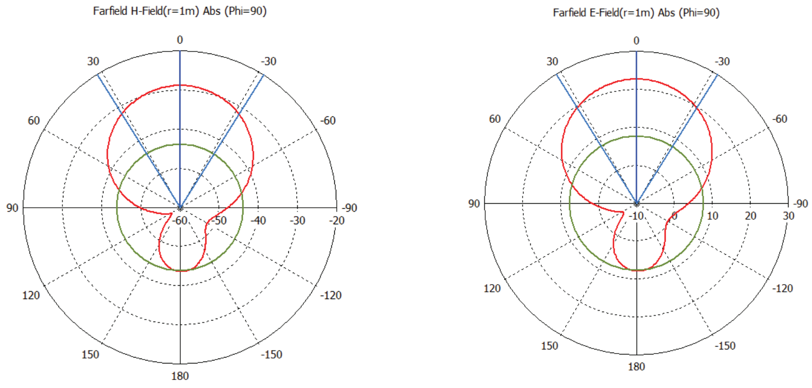
The antenna gain is increased by using the separated two layers substrate by an air gap as shown in Figure 4. By utilizing the concept of air gap at 2.45 GHz frequency, the antenna gain can reached > 8 dB as shown below. The variation of the air gap distance can cause shifting of the frequency in higher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

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 radio frequency 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.



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=2.45) [1]
Component	Abs
Output	Gain
Frequency	2.45
Rad. effic.	-0.01301 dB
Tot. effic.	-0.08044 dB
Gain	8.358 dB

Figure 4: Simulated gain of the proposed antenna



(a) (b)

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

3.2 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. 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.

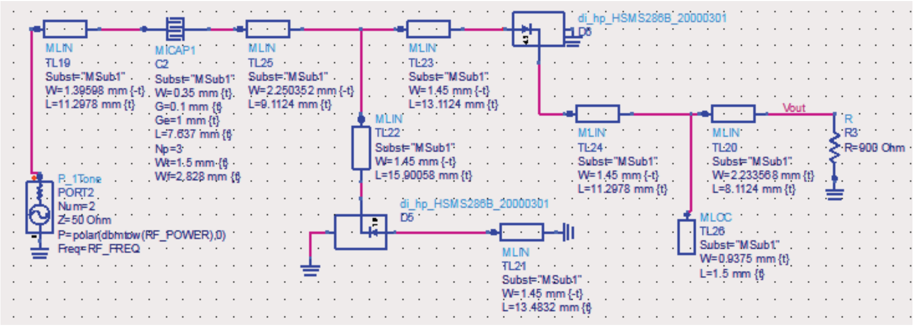


Figure 6: ADS rectifying circuit

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 900 Ω and the output DC voltage at the load of the rectenna is measured by using multimeter. 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.

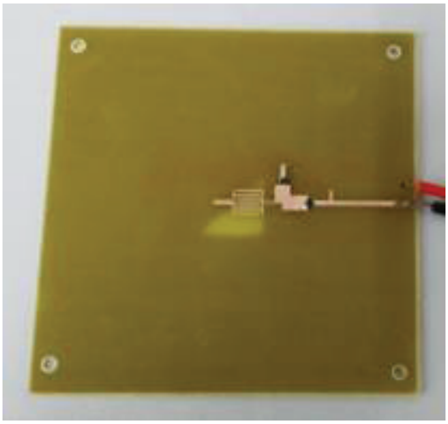


Figure 7: Rectifying circuit of the proposed rectenna

4.0 INTEGRATED RECTENNA ANALYSIS

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

$$\eta = (\frac{P_{DC}}{P_{in}}) \times 100\% = (\frac{V_{DC}^2}{R_L} \times P_{in}) \times 100\% \quad (1)$$

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 measurement setup of the proposed rectenna is shown in Figure 8 consisted of signal generator, horn antenna, rectenna and multimeter. The total power measurement and the output voltage was measured by the multimeter.

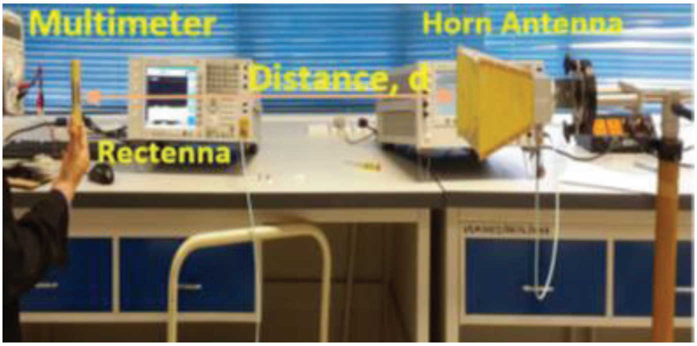


Figure 8 : The proposed rectenna measurement setup

Figure 8 also shows that when the power of the input is 17 dBm, the measurement of the efficiency reaches its maximum value of 79.29 %. When the power of the input is decreased to 0 dBm, the efficiency is still remaining at 50%. The rectenna DC output voltage consistent increasing with the incremental of the input power as shown in Figure 9. The rectenna gives 0.16 V for the input power at 0 dBm. The peak efficiency 79.29 % can be achieved for a resistor of 900 Ω. With a 900 Ω resistor, when the input power is more than 0 dBm, the overall efficiency is remain higher than 50%, proved that this rectenna capability for RF energy harvesting appllications. The comparison of proposed rectenna with the previous works is shown in Table 2.

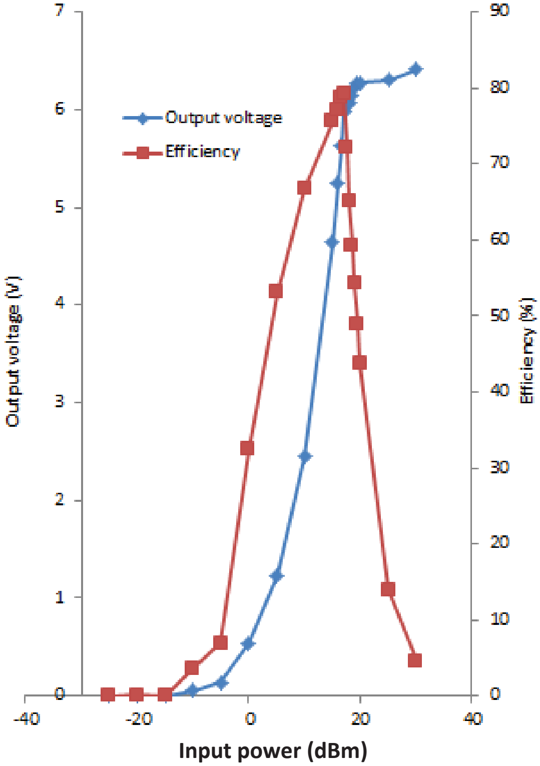


Figure 9: Measured output voltage and conversion efficiency at different input power (dBm) when the load resistance is 900 Ω

Table 2: The comparison between the proposed rectenna and the previous works

Author	Type of antenna	Polarization of antenna	Substrate type	Gain of antenna (dB)	Efficiency (%)
[19]	Microstrip antenna	Dual linear polarized	Rogers 4003c	NA	54 %
[20]	3×3 array antenna	Circular polarization	FR4	9.14 dB	65.8 %
[21]	2 × 2 planar array antenna	Linearly polarized	A 10.2 permittivity substrate	4.5 dB	68 %
[22]	GCPW Broadband slot antenna	Linearly polarized	F4B-2	NA	72.5 %
[5]	Microstrip antenna	Linearly polarized	FR4	NA	37.8 %

[15]	Annular ring slot Antenna	Circularly Polarized	Arlon 25N	4.7 dB	50 %
[23]	patch antenna	Linear polarized	Rogers Duroid 5880	6.2 dB	52 %
[17]	Aperture coupled antenna	Circularly Polarized	Arlon A 25N	7.5 dB	38.2 %
[24]	Single patch antenna	Circular polarization	FR4	7.68 dB	76.84%
The study	Single patch antenna	Linear polarization	FR4	8.36 dB	79.29%

5.0 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 feed in line connecting the rectifying circuits and the slot is responsible. Both antenna and rectifying circuits are integrated on a low cost FR4 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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