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2.45 GHz rectenna with high gain for RF energy harvesting

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Abstract

This paper presents a high gain rectenna at 2.45 GHz. Two layers low cost FR4 substrate has been used with air-gap technology for this fabricated rectenna. The proposed designs contain antenna and open stub rectifying circuits with feedline. With the dimension of 100x100x5 mm^3, this rectenna can perform high gain. The technique of air gap approach has been used for this proposed rectenna design so as to increase the antenna gain. Second and third harmonics has been eliminated by the introducing of triangular slot and ground plane to the developed design. The proposed rectenna successfully achieved the output voltages reaches 0.46 V when the input power is 0 dBm respectively when the input power range is between -25 to 30 dBm. It is also can reach up to 6V when the maximum input power is applied. High gain, simple design, low profile and easy integration are the main advantages of this design of the rectenna when compared to past researchers.

Keywords: *antenna, rectenna, rectifying circuit*

1. Introduction

Energy harvesting is a rapidly growing area in many scientific and engineering related fields due to the need for finding solutions to the world's power issues [1]. Based on the previous works, there are many limitations and drawbacks exists in currently used technique such as only narrowband power is collected, expansion in the receiving band or an 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, harmonic rejection properties at the high-order frequency which limits the potential of further enhancement in the conversion efficiency [2]. This reseach work focuses on RF energy harvesting in which the abundant RF energy from surrounding sources, are captured by a receiving antenna and rectified into a usable DC voltage. The investigation involves the design of stacked receiving antennas to cover a wide-range of frequency spectrums and integrated them with power divider and rectifying circuit to obtain the optimum parameters such as return loss, gain and radiation pattern of the antenna. In this case, the use of rectifier which is crucial for the efficient RF-to-DC power conversion. Due to limitation of the different rectifier structure that produce low efficiency of around 18-37% [3-5], another rectifiers topology are developed to produce higher efficiency for the RF-to-DC power conversion [3] proposes a dual-band rectifier for RF energy harvesting systems that was designed to operate at 2.1 GHz and 2.45 GHz by using Schottky diode HSMS-285C of Avago Technology [4] has studied the rectifying circuit with single Schottky diode HSMS-2860 at 2.45 GHz. Based on an analysis of matching circuit, the rectifiers with single stub matching circuit, with radial stubs low pass filter, or with compact structure were designed by using circuit simulation and co-simulation in ADS and [5] proposes a dual-band rectifier circuit that uses Schottky diodes to convert DTV signals (470-770 MHz) and tag reader signals (950-956 MHz) to DC voltages for passive tag activation and enhanced range operation.

Figure 1 shows rectenna with conventional single series diode rectifying circuit configuration. High gain, acceptable reflection coefficient and good handling radiation pattern are some of the key parameters of an efficient antenna [6-9]. Nevertheless, the overall

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RF-to-DC conversion efficiencies is contributed by the rectifying circuit of the rectenna whole system [10-13]. Good power handling capability, a low power consumption and good power sensitivity are some characterization of a most suitable rectifying circuit [14-17].

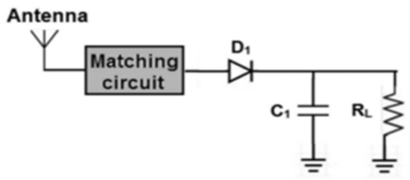


Figure 1. Rectenna with conventional single series diode rectifying circuit configuration

The objective of this paper is to demonstrate the new technique of rectenna development with high gain and high voltage performance capability. In addition, this paper also demonstrate the significant finding of the reduction size of rectifying circuit without degrading its performance and removal of the filter.

The design of the rectenna with the property of higher gain and its parametric study is presented in section 2. Section 3 demonstrated the proposed rectenna measured results along with its performance that has been optimized. The conversion efficiency from the measurement results are studied in section 4. Section 5 summarized all the achievement and conclusion and future work.

2. Geometry Design of the Proposed Rectenna

The top layer of the rectenna consist of rectangular patch receiving antenna. Followed by the second layer is the integration of microstrip feedline with digital capacitor rectifying circuit is etched in the middle layer and a triangular slot ground plane at the bottom layer. The air gap thickness,h between the substrate is 5 mm. The rectenna is fabricated on a low-cost FR-4 substrate with thickness, t is 1.6 mm and relative permittivity, ε_r of 4.6. The radiated patch antenna is fabricated on single layer substrate and the rectifying circuit integrated with the feedline is printed on another layer as shown in Figure 2. The plastic spacers of 5 mm are drilled at the corner of the substrate to hold both layers. The measured output DC voltage and conversion efficiency of this rectenna with the optimized value of the resistor is 900Ω and at the operating frequency, *f* of 2.45 GHz are depicted in Figure 2 when the input power range is between -25 to 30 dBm. The dimension of the antenna is 100x100 mm^2.

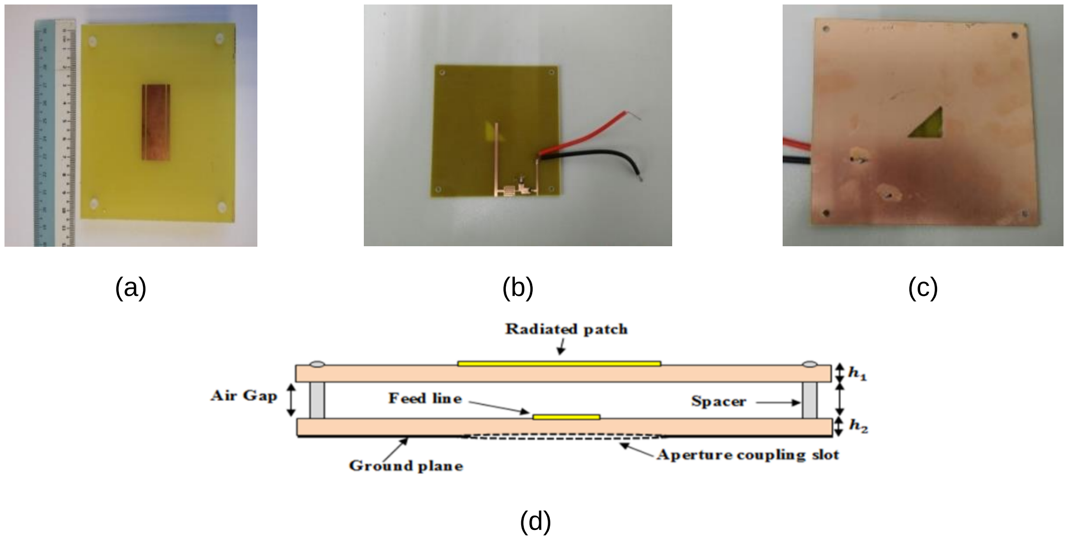


Figure 2. Geometry of the proposed rectenna (a) top view (b) middle layer (c) bottom layer (d) side view

The rectifying circuit is simulated by using ADS and CST is used for antenna simulation process. The simulated and measured reflection coefficient for the proposed antenna are plotted in Figure 3. We observe that the measured results shifted compared to the simulated value due to devices and human force. The gain of the simulated antenna reaches 8.36 dB. By comparing with the existing values, this developed rectenna has some very important parameters that are suitable for wireless power transfer.

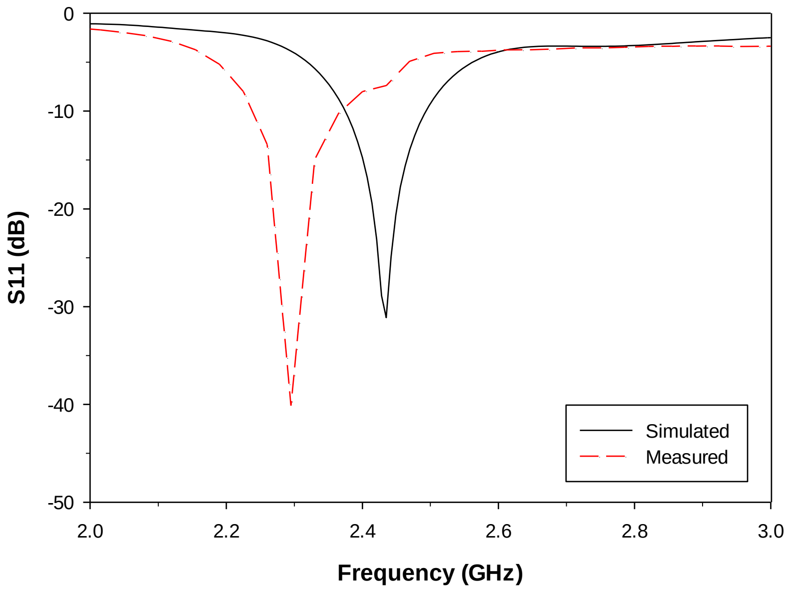


Figure 3. Proposed antenna simulated and measured return loss

3. Results and Analysis

In this section, it is explained the results of this work and at the same time is given the comprehensive discussion. Results are presented for antenna, rectifying circuit and rectenna.

3.1. Performance of the Proposed Antenna

The proposed antenna design that has been chosen is rectangular slot microstrip patch stacked antenna. This antenna produced -40 dB return loss when the antenna is resonates at 2.45 GHz as shown in Figure 3 when the frequency range is between 2 to 3 GHz. This antenna design improved the return loss much more if compared to the previous antenna designs. From the simulation result shows that the power radiated at the designing frequency or fundamental frequency is increased with the improvement of the return loss result. Due to the permittivity variation of the FR4 substrate, there is a slight frequency shifting for the measurement result. This is the strongest property of this type of antenna design as it is matched at 2.45 GHz frequency.

The method that has been used in this research work to enhance the gain of the antnna is the tehnology of two layers substrate separated by the air gap. The simulated gain of the rectangular slot stacked antenna with aperture coupling slot is illustrated as in Figure 4. This antenna design achieved gain of 8.36 dB when the antenna operate at 2.45 GHz. This type of antenna still acceptable and can still consider antenna with high gain property. After analysis and optimization process, the distance between the two layer substrate has been chosen to be 5 mm.

Figure 5 shows the E-plane and H-plane radiation patterns of the rectangular slot stacked antenna with aperture coupling slot. The simulated results of the radiation pattern show the antenna radiates directionally towards the transmitter antenna.

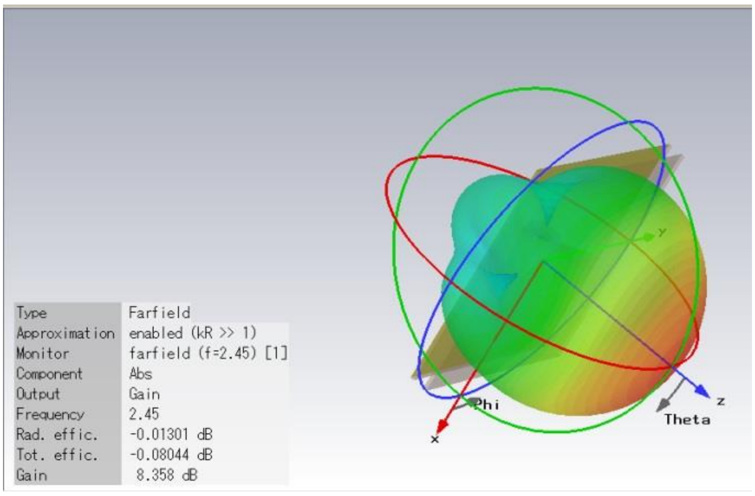
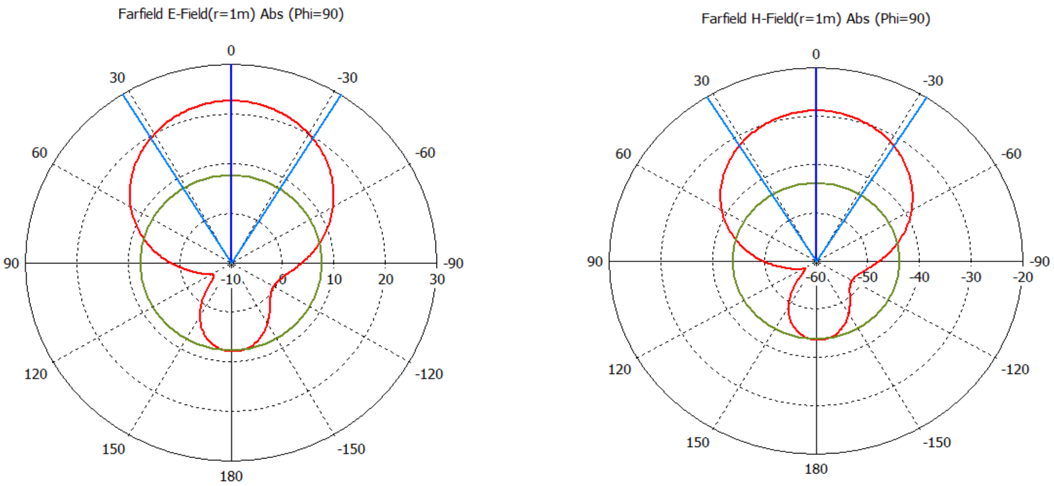


Figure 4. Proposed antenna simulated gain



(a) (b)

Figure 5. Proposed antenna radiation patterns
(a) e-plane radiation pattern. (b) h-plane radiation pattern

3.2. Rectifying Circuit

Rectifier is one of the most significant part in the development of the rectenna. From previous studies have shown that there are several different forms of rectifier configuration and designs. Rectifier is used to convert AC signals into DC voltage or current. The configuration of voltage doubler rectifying circuit for this work is shown in Figure 6.

The rectifier circuit has been designed and oprimized by using Advanced Design System (ADS) software. Figure 7 shows the fabricated of feedline integrate with voltage doubler rectifying circuit by using low cost FR4 substrate which can be operate at 2.45 GHz. The dimension of the rectifying circuit is 100 x 100 mm^2. This voltage doubler rectifying circuit consist of interdigital capacitor, two HSMS 286B Schottky diodes and load impedance.

Measured output voltage at different input power when the load resistance is 900Ω is shown in Figure 8. The input power supplied for this circuit is range from -25 up to 30 dBm. during measurement, this rectifying circuit can achieve up to 6V when the input power signal is 30 dBm. This voltage doubler rectifying circuit is the improvement from the previous work in terms of its size. They still can perform at their optimum performance eventhough the size has been reduced.

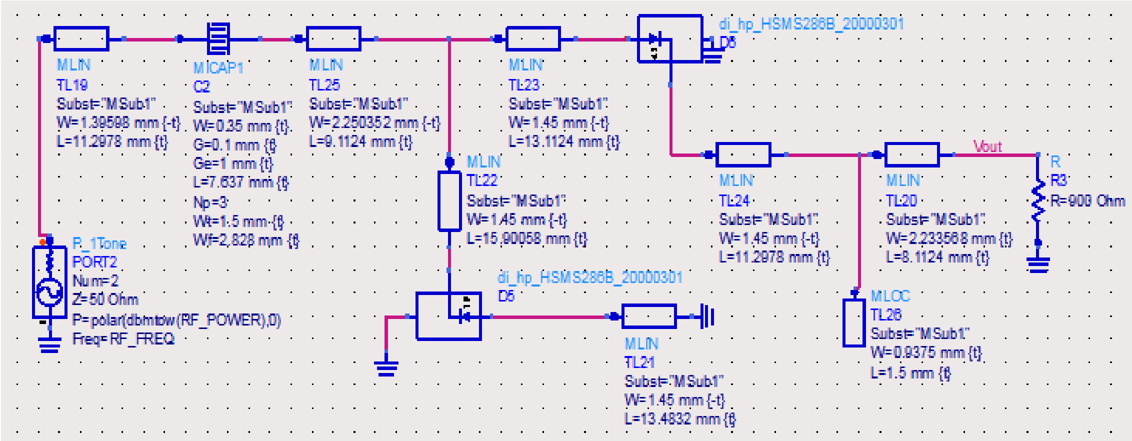


Figure 6. Rectifying circuit design in ADS

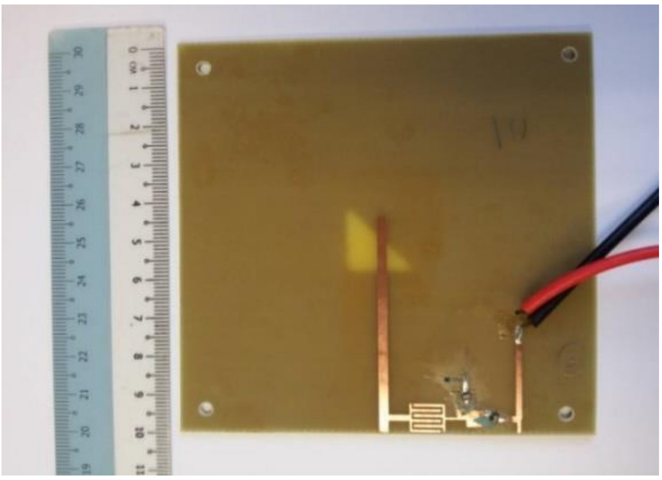


Figure 7. Proposed rectenna rectifying circuit

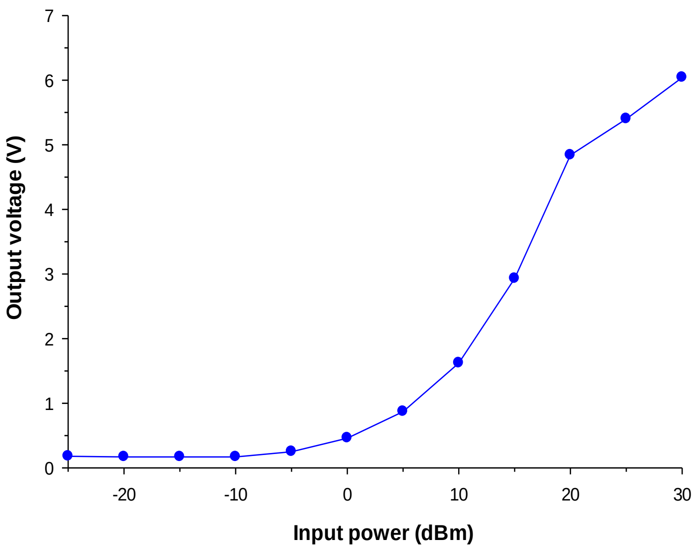


Figure 8. Measured output voltage at different input power (dBm) when the load resistance is 900Ω

3.3. Integrated Rectenna Analysis

Several advantages such as high gain, stable radiation pattern and high DC output voltage has been verified by using ADS and CST software. The overall RF-to-DC conversion efficiency of the proposed rectenna is calculated by using (1).

$$\eta = \left(\frac{P_{DC}}{P_{in}}\right) X100\% = \left(\frac{V^2{}_{DC}}{R_L}.Pin\right) X\ 100\% \quad (1)$$

where P_{in} is the input power, V_{DC} is the output DC voltage and R_L is the load resistance. Figure 9 demonstrated measurement setup of the proposed rectenna The measured output DC voltage and conversion efficiency of the proposed rectenna with the optimized value of the resistor is 900 Ω and at the operating frequency of 2.45 GHz are depicted in Figure 8 when the input power range is between -25 to 30 dBm. It shows that when the input power is 30 dBm, the measurement of DC output voltage reaches its maximum value of 6 V. When the power of the input is decreased to 20 dBm, the DC output voltage is able to remain 5 V. The rectenna DC output voltage consistent increasing with the incremental of the input power power as shown in Figure 8. It gets 0.46 V for power of the input at 0 dBm. The peak DC output voltage 6 V can be achieved for a resistor of 900 Ω. With a 900 Ω resistor, when the powerof the input is more than 15 dBm, the overall DC output voltage is remain higher than 3 V, proved that this rectenna well suited for RF energy harvesting apllications. Table 1 shows parameters of the antenna and Table 2 shows past research proposed rectennas compared with the proposed rectenna based on reseach study and results presented in this paper [18-26].

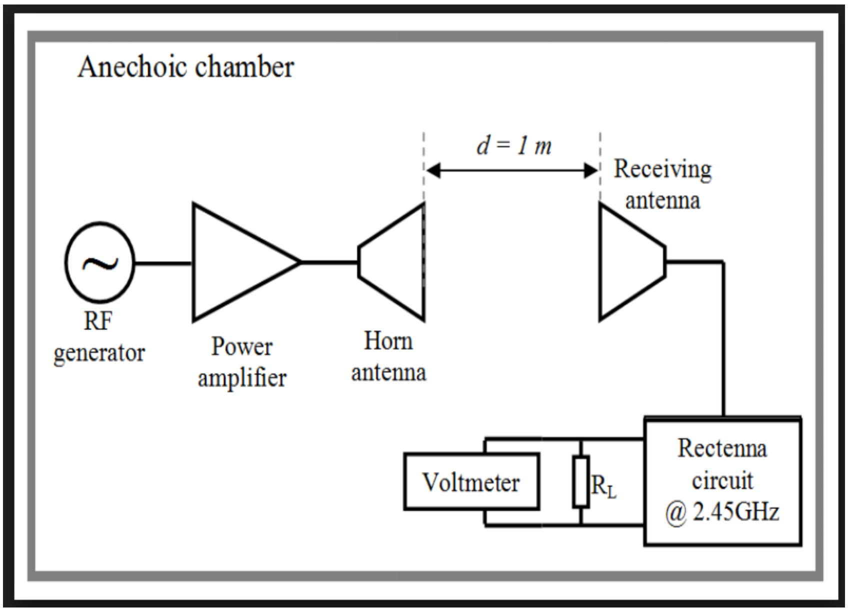


Figure 9. Measurement setup of the proposed rectenna

Table 1. Parameters of the Antenna

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	5 mm
Air gap thickness	t	1.6 mm
FR4 board pemittivity	ε_r	4.6

Table 2. The Proposed Rectenna with Past Research Work Comparison

Author	Type of antenna	Polarization of antenna	Substrate type	Gain of antenna (dB)
[18]	Microstrip antenna	Dual linear polarized	Rogers 4003c	NA
[19]	3×3 array antenna	Circular polarization	FR4	9.14 dB
[20]	2 × 2 planar array antenna	Linearly polarized	A 10.2 permittivity substrate	4.5 dB
[21]	GCPW Broadband slot antenna	Linearly polarized	F4B-2	NA
[22]	Microstrip antenna	Linearly polarized	FR4	NA
[23]	Annular ring slot Antenna	Circularly Polarized	Arlon 25N	4.7 dB
[24]	patch antenna	Linear polarized	Rogers Duroid 5880	6.2 dB
[25]	Aperture coupled antenna	Circularly Polarized	Arlon A 25N	7.5 dB
[26]	Single patch antenna	Circular polarization	FR4	7.68 dB
This work	Single patch antenna	Linear polarization	FR4	8.36 dB

4. Conclusion

A compact and efficient rectenna has been developed in this paper. This research work had introduced the new designs of rectenna with feedline integrating with voltage multiplier rectifying circuit and antenna with triangular-shape slot ground. The insertion loss is vanish due to the repealed of the filter in the circuit. The proposed rectenna successfully achieved the output voltages reaches 0.46 V when the input power is 0 dBm respectively when the input power range is between -25 to 30 dBm. A good overall performance has been presented for this proposed rectenna. Besides of its high gain property, this rectenna also has advantage of simplicity and low cost. This makes the rectenna approachable to be applied in variety wireless communication and RF energy harvesting applications. By the extension and further studies of this developed structure, multi-frequency rectenna can be invented.

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