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Rectenna Design for Radio Frequency Wireless Energy Harvesting

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ABSTRACT

The concept of wireless power transmission (WPT) has been introduced for nearly a century. Some of the achievements made so far have made energy harvesting a reality, capable of providing alternative sources of energy. This paper provides a summary of RF energy harvesting techniques to serve as a guide for designing RF energy harvesting units. Since energy harvesting circuits are designed to operate at relatively small voltages and currents, they rely on the latest electrical technology for high efficiency. Thus, thorough analysis and discussions of the various designs and trade-offs between them are included. Also, we introduce most of the recent applications of radio frequency (RF) energy harvesting. Also in this work, a rectenna, which is a combination between an antenna and a rectifier, with the purpose of energy harvesting, is designed and verified through simulation. The rectenna consists of two main components: the first is a microstrip patch antenna and the second is a rectifying circuit. The microstrip antenna gather the wireless power, then the received RF power is rectified to DC using the rectifier. In this work, we will design and simulate the microstrip antenna using HFSS software, and the rectifier circuit using ADS software.

Keyword: Rectenna, energy harvesting, Wireless power transmission (WPT), Radio Frequency (RF), Rectangular Microstrip Patch Antenna, Cockcroft-Walton Rectifier.

1. INTRODUCTION

Wireless power transmission (WPT) system is described as a device that sends electrical power between two points wirelessly without the usage of cables or any supporting medium [1]. The tenth history of free space radiofrequency energy extraction arose in the late 1950s using a microwave-powered helicopter system [2]. nowadays, harvesting is described as a way to harvest energy from the surrounding environment using various techniques such as thermoelectric conversion, vibrational excitement, solar energy transformation. This technology holds great potential for replacing small batteries in low-power electrical devices and systems. Figure 1 presents the structure of the RF energy harvesting system and the factors that contribute to the performance of the entire system. The Wireless Energy Harvesting (WEH) system has great potential to replace batteries or extend their lifespan. recently, the major of low-current sensors and embedded equipment is powered using batteries. In fact, batteries have a limited life and require periodic replacements. Utilizing energy harvesting technologies, such devices and equipment is turned onto self-sufficient in terms of the energy required for operation, thus obtaining an unlimited operating life. Thus, the demand for energy maintenance will become minimal.

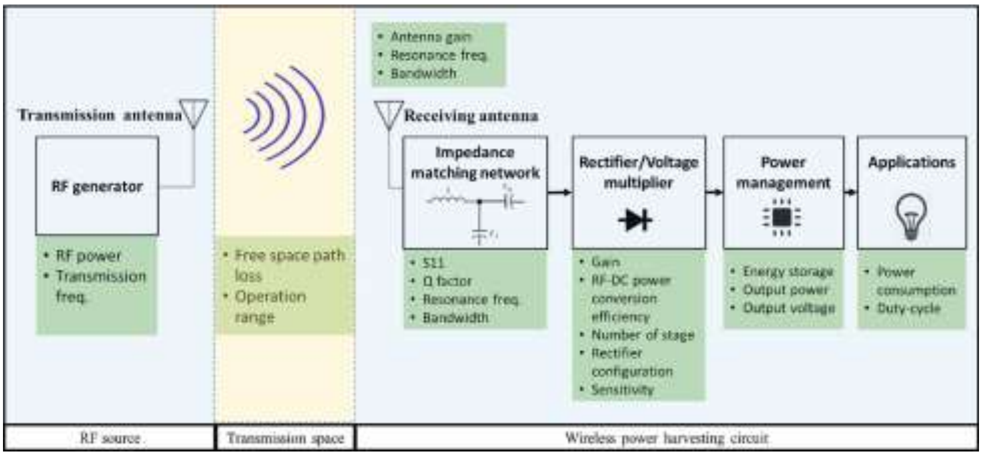

FIGURE 1: Experiment Block Diagram.

The concept of WEH can be applied in different forms, such as

1. Solar energy [3-5],
2. Wind power [6-8],
3. EM energy [9-11],
4. Thermal energy [12-14],
5. Kinetic energy [15-17], etc.

Among these methods, electromagnetic (EM) power is superabundant in space and can be gathered without limits. EM signals are generated from many different sources such as radio and broadcast stations, satellite stations, and wireless modems. The RF energy harvesting system can capture EM signal energy and turns it into a usable direct current (DC) voltage. The RF energy harvesting unit basically consists of the antenna section and the rectifier section, which is responsible for converting the RF energy to DC energy.

Authors in [18] designed a compact circularly polarized rectenna that operates at 5.8 GHz. the rectenna consisted of a feedback wide-slot antenna array of 5×5 that is depicted in Figure 2, and a rectifier that used a series of HSMS 286C Schottky diodes which are integrated on the back of the antenna to reduce the overall size of the system. The rectenna achieved a maximum efficiency of 62% and the DC output reached 26.81V.

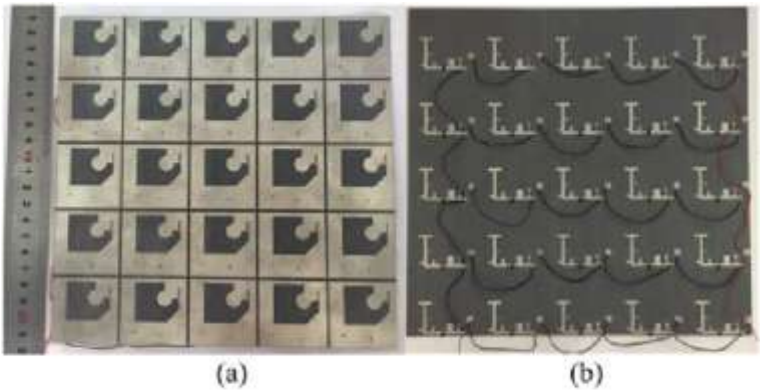

FIGURE 2: Top and bottom view of rectenna proposed in [18].

While in [19], authors analyzed and designed high output voltage energy harvesting rectenna that works at 2.45 GHz. It consisted of a microstrip patch antenna in combination with a Cockcroft-Walton rectifier. The simulation results showed that the rectenna gave high output voltage of 10 V with 20 dBm input RF power.

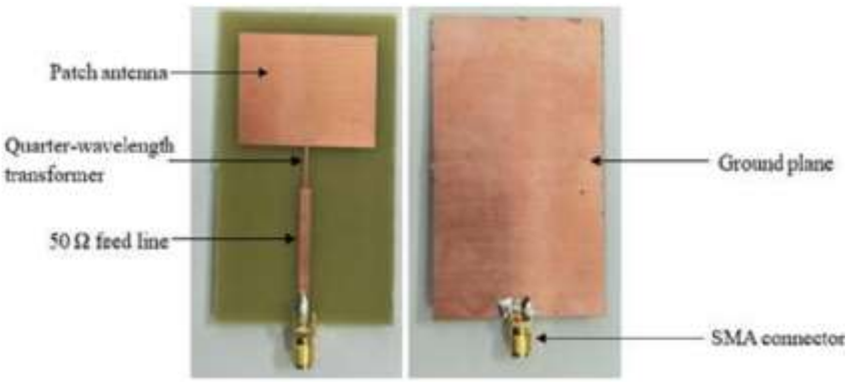

FIGURE 3: Top and bottom view of rectenna proposed in [19].

The motivation behind this work is that the treatment of waste batteries is a critical issue. Most batteries end up in landfills, polluting the land and water beneath. To get rid of such problems we need to avoid using these batteries by replacing them with a creative solution. The application of WEH will lead to a great reduction in our reliance on batteries, which will be positively reflected in the quality of the environment. Moreover, the process of harvesting EM energy generates no wastes because it is a clean energy source. Also, compared to all available forms of energy, the RF wave is available everywhere, all day long. The aforementioned features prompted us to investigate this point and work in the field of RF energy harvesting.

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The contribution of this work is basically to provide a design for the parameters and geometry of a rectangular microstrip patch antenna and a Three-stage Cockcroft-Walton, also we measure their performance through extensive simulation tests using high-frequency structure simulator (HFSS) and Advanced Design System (ADS) software.

This paper is organized as follows. A quick introduction and literature of the research and work that has been carried out in this regard is presented in section 1, the proposed antenna and rectifier design parameters and geometry, simulation results and discussion is explained in section 2 and 3, whereas the concluding remarks are presented in section 4.

2. ANTENNA DESIGN, RESULTS AND DISCUSSION

In this section, the simulation of the proposed antenna is introduced, then a discussion about the obtained results will be provided. The microstrip patch antenna is one of the most broadly used technologies in RF applications. It is gaining popularity compared to the other antennas because it is easy to fabricate, tune its input impedance, and attach it with the rectifier. Furthermore, it has a low profile, low cost, small size, and lightweight. The microstrip patch antenna has been chosen as a receiver element within the rectenna system for its advantages. The proposed antenna operates at 2.4 GHz when it is excited by a 50 Ω port. An important point to mention here is that the antenna impedance is optimized in order to be matched to the rectifier impedance.

The antenna was designed to operate at 2.4 GHz using the standard equation listed in [20]. The antenna designed was intended for the FR-4 substrate with dielectric constant 4.7, loss tangent 0.014 and thickness 1.6 mm. The dimensions of the patch antenna and the feed line are shown in Figure 4 and listed in TABLE I.

TABLE 1: Dimensions of the proposed antenna

Antenna Parameters	Dimensions (mm)
W_g	66
L_g	90.86
W_p	38.04
L_p	29.45
W_f	3.011
L_f	22
x_o	1.506
y_o	9.779

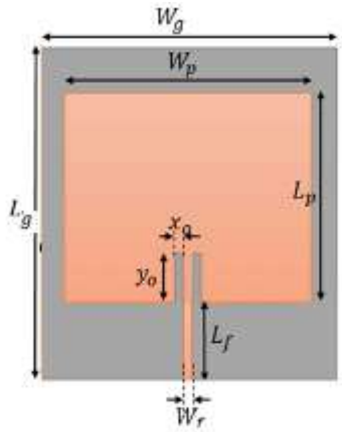

FIGURE 4: Dimensions of the proposed antenna

The values in TABLE 1 were used to draw a microstrip schematic of the antenna using HFSS as shown in Figure 5, which was then simulated to show both the antenna 3D gain and the return loss (S11) coefficient.

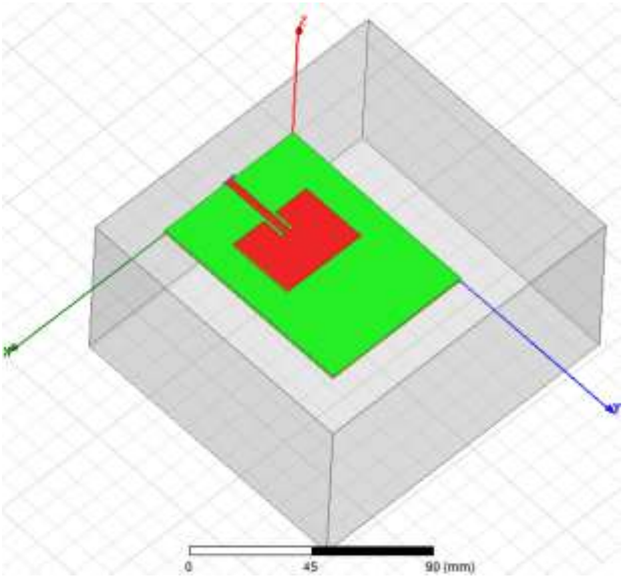

FIGURE 5: HFSS design of the proposed antenna.

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One of the important parameters in designing the antenna is the return loss which represents the amount of power that is reflected from the antenna. This S11 parameter is designed to be as low as possible so that the antenna transmits as much power as possible. Since an antenna is a reciprocal device, this equates to it receiving as much power as possible. The simulated S-parameters are compared in Figure 6. As we can notice from the figure that we reached about -33 dB return loss.

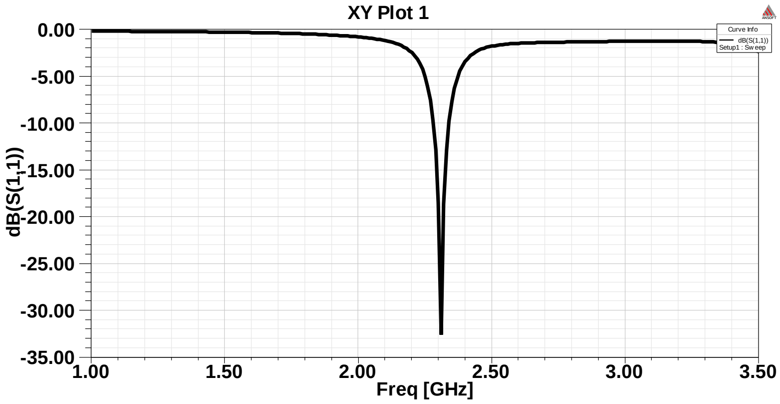

FIGURE 6: The return loss (S11) of the proposed antenna.

Another important parameter that measures the ability of the antenna to focus more or less power in any direction compared to a theoretical isotropic antenna is the 3D gain of the antenna. In Figure 7, we illustrate the 3D gain obtained from the simulation of the proposed antenna using HFSS.

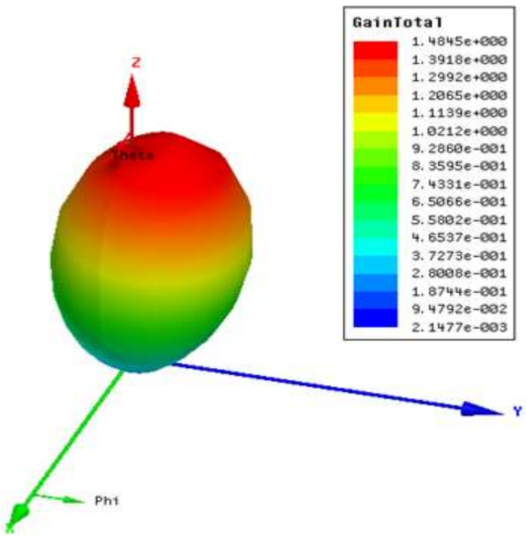

FIGURE 7: The 3D gain of the proposed antenna.

3. RECTIFIER DESIGN, RESULTS AND DISCUSSION

In this section, we will provide the design, simulation, and results analysis of the 2.4 GHz Cockcroft-Walton voltage rectifier [19]. The simulation is carried out using ADS software. The rectifier mainly consists of HSMS-2850 Schottky diodes, stages and load capacitors, and a load resistor. The load capacitor (or filter capacitor) is responsible for determining the value of the output voltage, we selected it as 100 nF. The schematic of the three-stages Cockcroft-Walton voltage multiplier is shown in Figure 8. The circuit was analyzed using the Harmonic Balance and S-parameter analysis tools.

The schematic was firstly analyzed using the S-parameter tool to find the return loss of the multiplier. Figure 9 shows the value of $|S_{11}|$ over the entire range of frequencies from 1 to 4 GHz, we can see that the return loss reaches its minimum of -23 dB approximately at a frequency of 2.45 GHz, which is the harvested frequency.

Another insight which we can make using the Harmonic Balance simulation which provides us with a relation between the input RF power in dBm to the output voltage. In Figure 10, we can see the obtained output voltage when the input RF power varies from -20 to 20 dBm, we can conclude that as the harvested power increases the output voltage increases as well. This relation is valid until input power of 14 dBm where the output voltage saturates at 11 voltages approximately.

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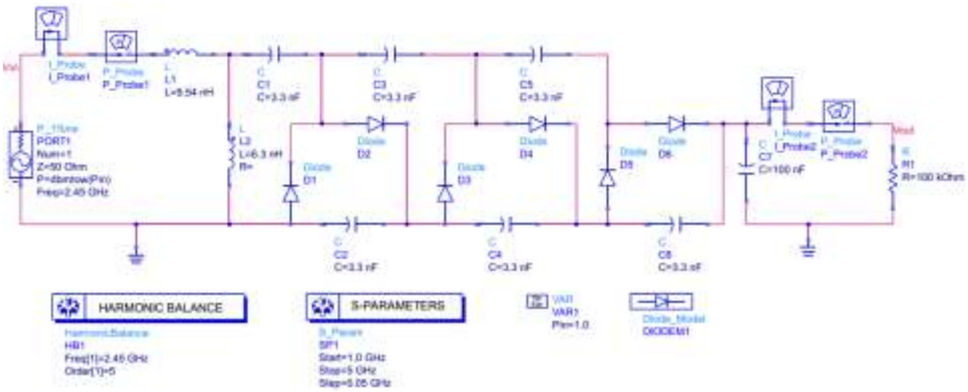

FIGURE 8: schematic of the three-stages Cockcroft-Walton voltage multiplier with matching network.

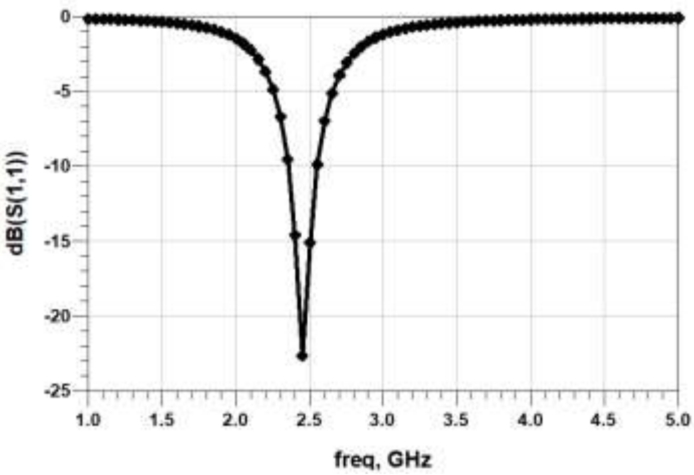

FIGURE 9: The return loss of three-stages Cockcroft-Walton voltage multiplier.

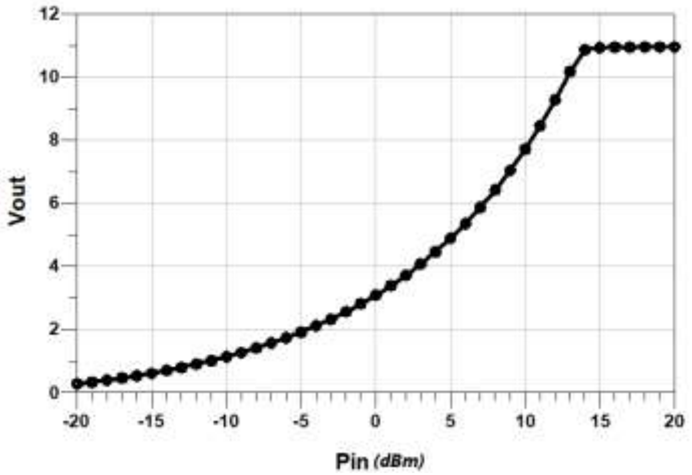

FIGURE 10: The output voltage of three-stages Cockcroft-Walton voltage multiplier.

4. CONCLUSION AND FUTURE WORK

In this paper we proposed the design of rectenna for RF energy harvesting that operates at 2.4 GHz. A microstrip patch antenna and three-stage Cockcroft Walton rectifier circuit were designed and simulated for operation at 2.4 GHz. The results of the simulation using HFSS, and ADS software indicated a relatively good return loss of the patch antenna and high output voltage of about 11 at 15 dBm input power. As a future work we intended to design a multi-band antenna to gather more input power.

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