An Efficient 2.4 GHz Differential Rectenna for Radio Frequency Energy Harvesting

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Abstract – **This paper presents a rectenna to harvest RF energy at the ISM band of 2.4 GHz. A differential topology for the rectifier, along with microstrip patch antennas, are adopted to eliminate a power splitter at the input and a voltage adder at the output reducing the ohmic loss and leakage. The rectenna is prototyped on Rogers 4003C substrate. The measurement results indicate that the proposed rectenna achieves the peak power conversion efficiency (PCE) of 69.3 %, while delivering 5.1 mW to the load.**

Keywords— RF energy harvesting, rectenna, differential rectifier, microstrip patch antenna, power conversion efficiency.

I. Introduction

The rampant growth of internet of things (IoT) technologies has led to the rise in demand for adc ubiquitous renewable energy source. Spectrum surveys conducted in major urban areas indicate that ambient RF energy through digital television (DTV), cellular, and Wi-Fi transmissions can be utilized to satisfy this demand **Error! Reference source not found.**. While RF energy harvesting (EH) technology has the potential to provide wireless power and information transfer, a high-performance design can be difficult.

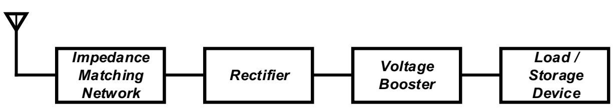


Fig. 1. Block Diagram for a typical RF EH.

A conventional RF energy harvester is shown in Fig. 1. The antenna receives the incoming RF energy, and the rectifier converts it to dc energy. A major design challenge is low input power received by the antenna. The Federal Communication Commission (FCC) limits equivalent isotopically radiated power (EIRP) in the 2.4 GHz ISM band to 36 dBm, and typical RF EH sources exhibit lower transmit power [2]. For example, a typical Wi-Fi router in an office environment transmits a mere 20 dBm [3]. This signal is significantly attenuated when it is received by the RF energy harvester. For RF EH to be a practical energy source, a high RF to dc power conversion efficiency (PCE) is vital.

Various publications have investigated and developed designs to function in the 2.4 GHz band. Andia Vera et al. developed a compact rectenna system based on a dual polarized antenna [4]. The rectifier consists of a four-stage voltage multiplier and achieves the RF to dc conversion efficiency (PCE) of a 42.1% at the input power of -10 dBm. Noteworthily, the rectifier offers satisfactory efficiency at low input power, but the small output power for a low input power level is insufficient to drive the load in many applications. Olgun et al. proposed a differential rectifier that is able to achieve peak conversion efficiency of 68% given -5 dBm RF input power [5]. The power splitter at the input distributes power between two rectifier branches and adds loss to decrease the delivered input power to the splitter. In another approach researchers demonstrated a RF EH system with a 58% conversion efficiency at 6 dBm input power [6]. While the design does not achieve as high power conversion efficiency (PCE) as other works, it utilizes a Wilkson power divider to harvest power from multiple patch antennas [6]. Multiple antennas enable it to harvest a good amount of energy. Tafekirt et al. implemented three single-ended rectifiers in parallel [7]. Each rectifier matches to a specific frequency and the dc output voltages of three rectifiers are combined at the output. Although collecting power from different input RF signals with different frequencies increases the overall dc output voltage, the power splitter at the input degrades the PCE. The power splitter causes the ohmic loss and leakage of the input power to undesired rectifier branches.

To address the low PCE issue in the abovementioned works, this paper proposes a differential RF energy harvester structure. The RF EH developed in this paper utilizes a modified Greinacher rectifier topology to achieve RF to dc conversion efficiency of 69.3 % at the input power of 5.2 dBm and the frequency of 2.4 GHz by removing the power splitter and combiner.

This paper is organized as follows. Section II describes the basic operation of a diode rectifier. Section III presents the design methodology of the proposed rectenna. Section IV and V shows the post layout simulation and measured results, respectively. Section VI concludes the paper.

II. Voltage Reectifier

A voltage rectifier, also called as voltage multiplier or doubler, is commonly used for RF EH. A single stage voltage rectifier is shown in Fig. 2. Assuming ideal diodes, the capacitor C_1 is charged to the peak amplitude $V_{i,p}$ of the RF input voltage ($V_{i,p}$) during the negative voltage cycle as shown in Fig. 2 (a). Then, during the positive voltage cycle, the capacitor C_2 is charged to $2V_{i,p}$ as shown in Fig. 2 (b). The voltage rectifier doubles the peak RF voltage while rectifying the RF input. The threshold voltage of the diodes is the most sensitive to the performance of the voltage rectifier, and other parameters such as conduction resistance, saturation current, and junction capacitance also affect the performance, making the selection of diodes important for the rectifier design [8].

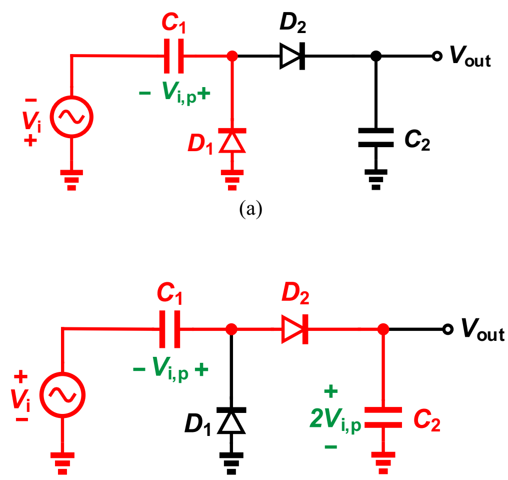


Fig. 2. Voltage rectifier. (a) negative V_i (b) positive V_i.

III. Design Methodology

This section presents a differential rectenna, which is composed of two patch antennas and two voltage rectifiers. The design procedure is described in this section. The target frequency for the proposed rectenna is the 2.45 GHz ISM band.

A. Rectifier Design

Fig. 3 shows the proposed differential rectifier topology for RF EH in the ISM band. Two patch antennas supply the input RF power to the differential rectifier. The output voltage of each branch is stored differentially across the corresponding output capacitor $C_{2,4}$. The load voltage across the load resistor R_L is two times the voltage of the individual capacitors $C_{2,4}$ due to its differential topology. The power delivered to the load is double compared with a single stage rectifier. Note that the PCE of the proposed rectifier is the same as the single stage one, as the input power is also double for the rectifier.

The Skyworks 7630 Schottky diodes are used for the proposed rectifier [9]. The diodes offer a low threshold voltage and series resistance. The specifications of the diodes are listed in Table I. The threshold voltage of the diodes called “Junction Potential” in the table is 0.34 V. We observed that diodes are more efficient than similar low threshold diodes often used in RF energy harvesting [2]. Once capacitors and the diodes are selected, the rectifier was laid out using rectifier Keysight ADS.

Table I: Spice Model Parameters of the Schottky Diode

Parameter	Value
Saturation Current (I_s)	5 µA
Ohmic Resistance (R_s)	20 Ω
Transient Time (TT)	10 psec
Zero Bias Junction Cap. (V_{j0})	0.14 pF
Forward Bias Depletion Cap. Coeff. (F_C)	0.5
Junction Potential (V_j)	0.34 V

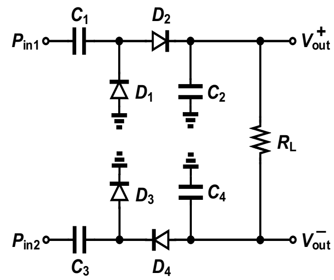


Fig. 3. Schematic of proposed rectifier.

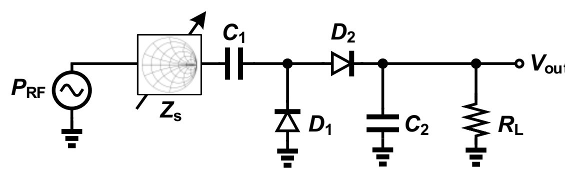


Fig. 4. Schematic diagram for source pull simulations.

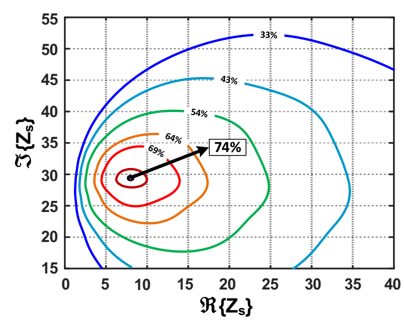


Fig. 5. Simulated source-pull contours.

B. Impedance Matching Design

To allow for maximum power transfer, the rectifier input impedance must be equal to the conjugate of the source impedance Z_S. The impedance of the rectifier can vary depending on the power level, frequency, and load resistance [10]. Also, the relationship is nonlinear at high input power. To account for the nonlinear operation of the rectifier, the source pull (SP) method was used to design the input matching network [11]. Fig. 4 shows the schematic diagram for SP simulations. The source impedance Z_S is swept, and the efficiency is plotted for each impedance value.

Fig. 5 shows the simulation results for an input power of 10 dBm and an output load of 11 kΩ. If Z_s is the innermost contour of 7.5+j29 Ω, the rectifier achieves the maximum efficiency of 74%. The efficiency gradually decreases as the contours move further away from the inner most one. The simulation results show that the input impedance of the rectifier circuit is 7.5 – j29 Ω. The proposed rectenna adopts an open circuit T- branch structure for the matching, and Fig. 6 shows the proposed structure with dimensions in the mm scale, along with the rest of the rectifier.

C. Patch Antenna Design

The patch antenna can be implemented on a printed circuit board making it attractive for RF EH. Fig. 7 (a) shows the proposed patch antenna with its dimensions in the mm scale. It utilizes an inset feed to match to 50 Ω impedance. We followed the process described in [12] for the antenna design. Fig. 7 (b) shows the S_{11} parameter versus frequency. The S_{11} stays below -10 dB over the bandwidth of 25 MHz around the center frequency of 2.45 GHz. EM simulation using Momentum Microwave of Keysight ADS shows the proposed antenna achieves the gain of 5.9 dBi.

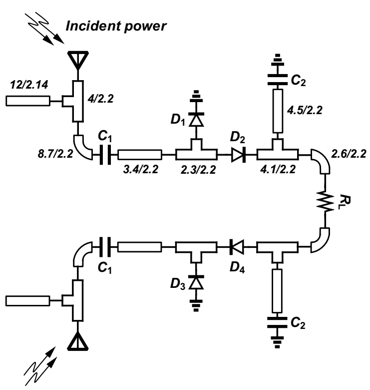
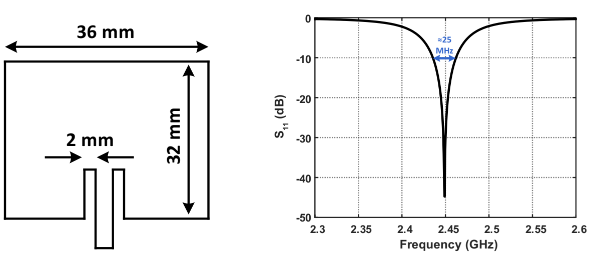


Fig. 6. Schematic of the proposed rectifier with the dimensions (length/width) in mm.



(a) (b)

Fig. 7. (a) Dimensions of the developed patch antenna and (b) its corresponding S-parameter.

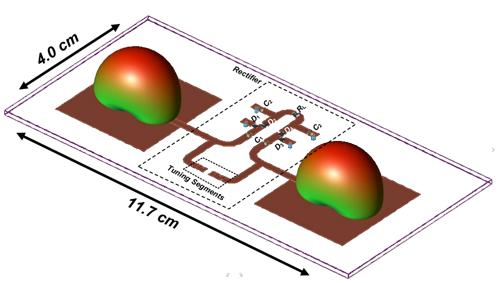


Fig. 8. Layout of the proposed rectenna.

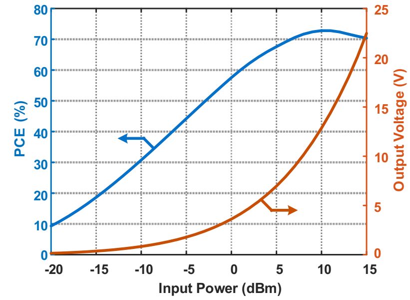


Fig. 9. Rectifier PCE and output voltage over input power range at 2.45 GHz.

IV. Post Layout Simulation Results

The proposed rectenna and the patch antenna was laid out and simulated using Keysight ADS. Fig. 8 shows the layout along with the radiation pattern of the patch antenna. Fig. 9 shows the simulation results for the differential output voltage (= V_{out}^{+} - V_{out}^{-}) across the load resistor of 11 kΩ versus RF power input to each rectifier branch. As expected, the output voltage increases steadily with increase of the input power. The power delivered to the load resistor is 5.8 mW at the input power of 0 dBm, and 14.2 mW at the input power of 10 dBm.

The RF to dc conversion efficiency, PCE, is calculated from (1).

$$PCE = \frac{P_{DC}}{P_{RF}} = \frac{1}{P_{RF}} \frac{\left(V_{out}^{+} - V_{out}^{-}\right)^2}{R_L} \quad (1)$$

where P_{RF} is the RF power at the input of the rectifier and P_{DC} the power delivered to the load resistor R_L. The PCE is also shown in Fig. 9. The PCE increases with the input power while the input power is reaching its optimum value and then starts to decrease as the input power passes its optimum. The peak PCE is 72.8 % at the input power level of 10 dBm with the optimal load resistance of 11 kΩ. The PCE is 30.7% at the low input power level of -10 dBm, and the PCE is quite high. The proposed rectifier is capable of harvesting power at the input power of -20 dBm. The measured efficiency of the rectifier is slightly lower than the predicted value through SP simulations as described in the following section.

Fig. 10 shows the large signal S_{11} parameter, which indicates the structure of the proposed rectenna is optimized to an input power of 0 dBm. The S_{11} graph enables us to trade the minimum input power level and maximum PCE. In other words, a rectenna could be designed to harvest energy from lower RF input power at the cost of lower PCE at higher RF input power. Fig. 11 shows the relationship of the PCE, RF input power and the load resistance of the proposed rectenna. It can be noticed that the load resistance is sensitive to the PCE and hence the power delivered to the load.

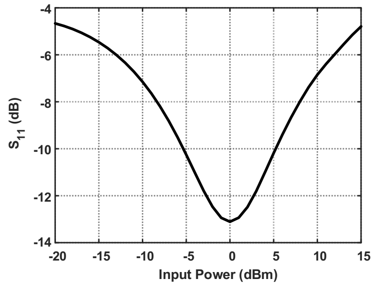


Fig. 10. S_{11} versus input power at 2.45 GHz.

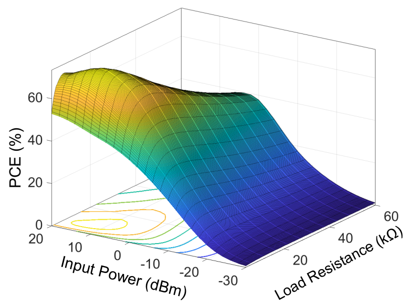


Fig. 11. Rectifier PCE versus input power and load resistance at 2.45 GHz.

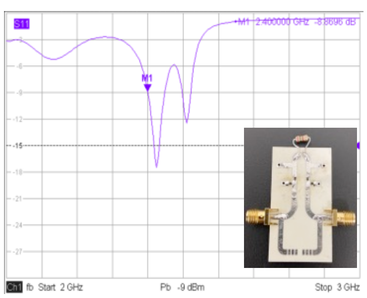


Fig. 12. Measured S_{11} for the rectifier.

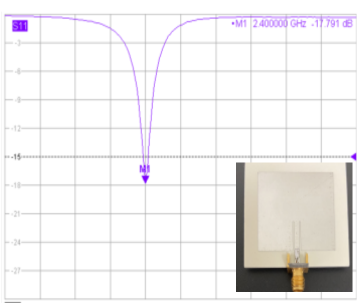


Fig. 13. Measured S_{11} for the developed rectifier

V. Measurement Results

The proposed rectenna was prototyped on Rogers 4003C substrate with dielectric constant $\varepsilon_r = 3.55$. This material offers a stable frequency response at the frequency band of interest [13]. The size of the rectenna is 4.0 cm × 11.7 cm, and its thickness is 1.6 mm. We measured S_{11} parameters of the antenna and the rectifier to obtain the matching frequency and used a R&S ZVA 67 vector network analyzer for the measurements. Fig. 12 shows the measurement result for the rectifier without the antenna. The input port of the rectenna is matched over a 100 MHz bandwidth around the center frequency of 2.45 GHz. The achieved bandwidth covers the WiFi frequency band (e.g. IEEE 802.11g). Fig. 13 shows the measurement result for the antenna alone. The result indicates a frequency shift in the S_{11} parameter from 2.45 GHz in simulations to 2.4 GHz in the prototype. The shift is mainly due to process variations. So we set the center frequency of the proposed rectenna to 2.4 GHz in the following experiment.

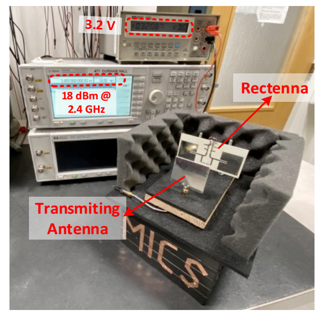


Fig. 14. Measurement setup for the rectenna.

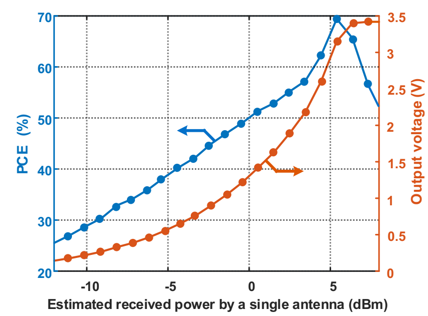


Fig. 15. Rectenna PCE and output voltage for given transmitted power.

A patch antenna identical to the one for the proposed rectenna was fabricated and used as the transmitting antenna. Note that the proposed rectenna has two identical patch antennas. Fig. 14 shows the measurement setup for the proposed rectenna. An Agilent EE438C ESG vector signal generator is connected to a patch antenna, and the rectenna is placed 10 cm away from transmitting antenna. The Friis formula for free space loss is used to calculate the received power at the patch antennas of the rectenna, in which the gain of the transmitting and receiving antennas is 5.9 dBi as described in Section III.C. Refer to [14] for Friis formula. The measured loss of cables and connectors is also considered in the calculation. The effective path loss between the transmitter and the receiver is obtained as 9.33 dB. The process variations of the PCB and the diode change the matching performance of the rectifier and hence small signal and large signal S-parameters. The deviation from the desired small signal S-parameter is compensated using the tuning segments that were implemented on the fabricated board. Note that the simulation results in Section III.B indicate the optimal load resistance is 11 kΩ. However, due to the variations in the large signal s-parameters (LSSP) of the fabricated board compared to the

TABLE II: COMPARISON BETWEEN RF ENERGY HARVESTING CIRCUITS

Specification	RWS '10 [4]	[5]AWPL '11 [5]	[6]ICSE '14 [6]	[7]IEEEA '20 [7]	This Work
Frequency (GHz)	2.45	2.45	2.42	2.45	2.4
Diode	SMS7630	HSMS2852	HSMS285B	HSMS2852	SMS7630
Substrate	Arlon A25N	RO3206	RO3206	FR4	RO4003C
Output resistance (kΩ)	8.2	10	NA*	3.8	2
dc output power (mW)†	0.48	0.60	0.50	0.48‡	1.0
Peak PCE (%)	46 @ 0 dBm	68 @ -5 dBm	58 @ 8 dBm	47.5 @ 3 dBm	69.3 @ 5.5 dBm

* NA indicates not available. † For the input power of 0 dBm ‡ Combined output power of 1.5 mW at the three input frequencies.

simulated one, the optimum load resistance needs to be adjusted. The load resistance R_L of the rectifier is swept to find the optimal load resistance under several different transmitting power levels. The optimal load resistance for the delivery of the maximum power is obtained to be about 2 kΩ and rather independent of the power levels.

The PCE and the output voltage of the proposed rectenna was measured for the frequency of 2.4 GHz with the load resistance of 2 kΩ, and Fig. 15 shows the measurement results. The PCE increases steadily as the received power increases and then decreases rapidly after reaching the peak point. The peak PCE is 69.3 % under the received power of 5.2 dBm for a single antenna or 8.2 dBm for two antennas of the rectenna. The transmitter power is 18 dBm at the peak PCE and the output power delivered to the load resistor is 5.1 mW. The measured peak PCE is lower than the simulated one by 3.5 %, which is reasonable considering process variations. The output voltage across the load resistor increases steadily with increase of the received power and saturates to nearly 3.5 V after the received power of 7 dBm.

Table II compares the proposed rectenna with other RF energy harvesters. The proposed rectenna achieves the highest PCE among all of them. In addition, the proposed rectenna achieves highest dc output power at the input power ranging from 0 dBm to 8 dBm. This can be attributed to the higher PCE than others and the use of two antennas to collect the power.

VI. CONCLUSION

This paper presents a 2.4 GHz rectenna for RF energy harvesting. The rectifier adopts a differential topology to eliminate the power splitter at the input and the voltage adder at the output. The source pull matching technique is used to match the input impedance of the rectifier to the 50 Ω patch antenna. The rectenna is prototyped with Rogers 4003C substrate. The measurement results indicate that the rectenna achieves the peak power conversion efficiency of 69.3 % at the center frequency of 2.4 GHz. The high efficiency is due to removal of the power splitter and the voltage adder, resulting reduction of the loss.

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