A compact 2.45 GHz, low power wireless energy harvester with a reflector-backed folded dipole rectenna

Ignacio Ramos *Student Member, IEEE,* and Zoya Popović *Fellow, IEEE*
University of Colorado, Boulder, CO 80309, U.S.A.

***Abstract*—This paper paper describes the design procedure as well as the experimental performance of a 2.45 GHz 10 μW wireless energy harvester (WEH) with a maximum total efficiency of $\approx$ 30 % at 1 μW/cm^2 incident power density. The WEH integrates a shunt high-speed rectifying diode with a folded dipole. A metal reflector increases the gain of the rectenna and a quarter wavelength differential line is used as a choke. Both a VDI WVD and a Skyworks GaAs Schottky diode are integrated with the antenna and their performance is compared.**

***Index Terms*—Rectenna, rectifiers, energy harvesting, wireless power.**

I. INTRODUCTION

With the increased interest in wireless energy transfer in recent years, bolstered by the ever increasing use of low power sensors and the Internet of Things, there has been a significant interest in the design of compact low power energy harvesters. In environments with no sunlight and vibration, harvesting of very low power densities in the radio frequency of the spectrum is possible for low-power low duty cycle applications [2]. The WEH presented in this paper won second place at the third annual student wireless energy harvesting design competition held at the 2014 IEEE International Microwave Symposium (IMS2014). The competition requires the design of a WEH capable of harvesting a minimum of 10 μW of DC power from a power density of 1 μW/cm^2 at 2.45 GHz. The polarization of the source is specified to be linear vertical, the general location of the source is known, and the DC load is chosen by the designer. The maximum weight of the harvester cannot exceed 20 g and the figure of merit used to evaluate the WEH is defined by

$$FOM = 10\log_{10}\left[\frac{\left(\frac{P_L(\mu W)}{10(\mu W)}\right)^2}{\frac{D^2(cm^2)}{25(cm^2)}}\right](dB) \qquad (1)$$

where D refers to the largest dimension of the WEH and P_L is the output DC power across the load.

The figure of merit implies certain specifications and trade-offs in the design: lightweight materials should be used, the antenna and rectifier need to be as compact as possible while providing gain in the direction of the source; the rectifier efficiency needs to be maximized at very low power levels; and the load needs to be chosen to maximize the total rectified power. These constraints motivated the prototype shown in Fig. 1. A single shunt Schottky diode is chosen as the rectifying element due to the very low power density requirement which would imply reduced efficiency for a rectifier with more diodes, such as a charge pump. The overall dimensions are shown in millimeters and the largest linear dimension in Eq.(1) is $D = 52$ mm. Additionally, for in-building applications we imposed a form-factor that allows non-obtrusive placement of the harvester in any corner inside a building. The corner reflector shields the rectenna from power management and sensor circuitry that can be placed on the back side of the reflector.

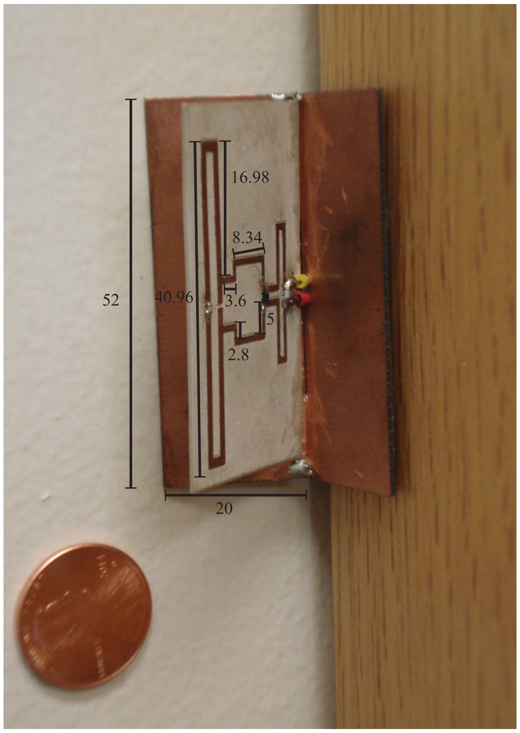

Fig. 1. Photograph of energy harvester prototype wtih a Skyworks SMS7630-079. All dimensions are given in millimeters.

II. DESIGN AND INTEGRATION OF RECTIFIER AND ANTENNA

The RF harvesting component consists of an antenna, rectifier, RF matching circuit and DC collection circuit with DC load. The first step in the design is the characterization of the non-linear rectifying device [1]. Initially, the W-Band ZBD Schottky diode from VDI is chosen. A nonlinear model provided by Modelithics is used to perform a load pull

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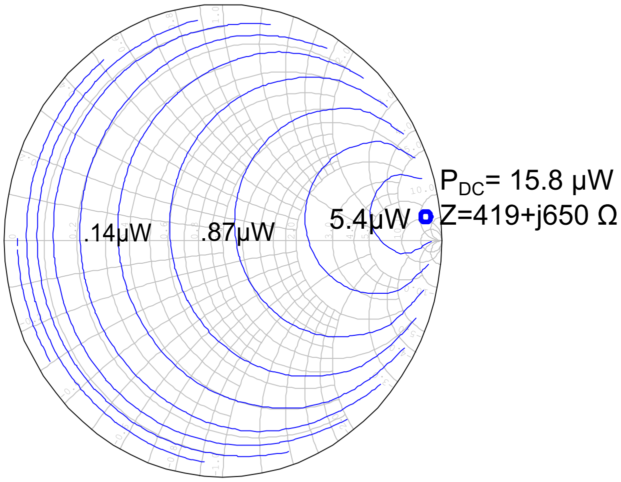

Fig. 2. Simulated load pull contours for the W-band ZBD diode from VDI, performed with an incident power of -15 dBm and a DC load of 2.2 kΩ. Maximum rectified power achieved is 15.8 μW at an impedance of 419+650 Ω. The contours represent constnat DC rectified power in μW.

simulation in NI-AWR. The initial load pull is performed with a DC load of 2.2 kΩ and a minimum incident power of -15 dBm. The results of the load pull are shown in Fig. 2. The simulations show that both the real and imaginary parts of the optimum impedance for maximum efficiency are very large, making matching challenging. Assuming an initial rectifying efficiency of 50 %, a minimum effective area of 20 cm^2 would be required to harvest 10 μW from a 1 μW/cm^2 power density, which translates to a minimum 2.24 dB antenna gain.To minimize matching circuit size, an antenna with a high impedance is a good choice. A folded dipole with an arm separation $d = 4.2\,\text{mm} \ll \lambda$ is chosen, since its input impedance is on the order of several hundred ohms and given by [5].

$$Z_{in} = N^2 Z_d \tag{2}$$

where Z_d is the impedance of a single resonant dipole, and $N = 2$ is the number of elements for a single folded dipole.

An inductive feed [4], [3] is used to match the antenna to the highly reactive diode. An equiavalent schematic of the circuit is shown in Fig. 3. For reduced size, the circuit was designed on a high-permitivity 25-mil thick RT/duroid 6010.2LM substrate with a ϵ_r= 10.2 ± 0.25. A model of the WEH is created in HFSS for fine tunning with full-wave simulations. To further increase the power received by the diode, a thin metallic corner reflector is added behind the rectenna to increase the gain of the folded dipole. Fig. 4 shows the simulated circuit, the peak gain of the antenna alone is 7.48 dBi. The inductive match is simulated together with the antenna in HFSS, and results in an impedance presented at the diode of 248.5+j628 Ω, which is slightly off the maximum DC power contour of Figure 2. The length of the folded dipole is 39 mm which is approximately 1λ, the length of the reflectors and the distance from the antenna to the reflector is adjusted for maximum gain while maintaining a compact design. Each reflector measures 52 mm ($\approx$1.35λ) by 20 mm ($\approx$0.5λ) and the two reflectors form an angle between them of 100°. Considering the position of the diode to be the feed, the distance from the reflectors is 11 mm or 0.29 λ.

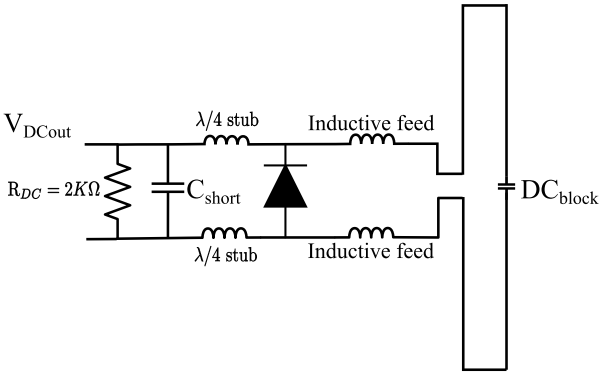

Fig. 3. Simplified schematic of rectenna circuit. C$_{short}$ = 10 pF, a DC blocking capacitor DC$_{block}$ is placed at the symmetry plane of the dipole to behave as a short circuit at 2.45 GHz and avoid short circuiting the diode.

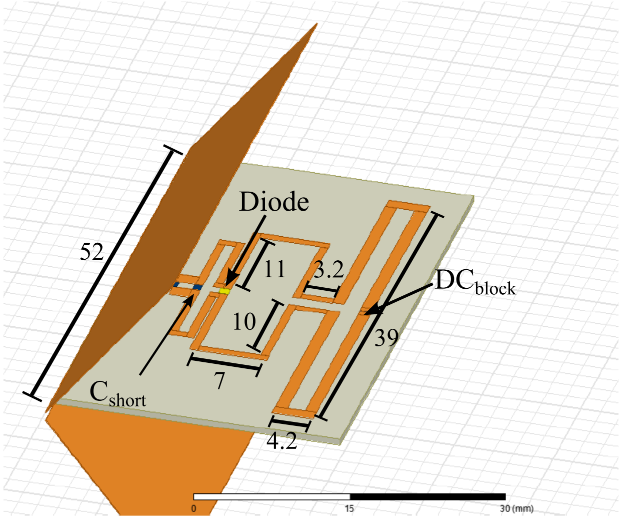

Fig. 4. Layout of the rectenna with the VDI diode match, corresponding to the circuit diagram in the previous figure. The DC load is connected on the back of the reflector though vias. All dimensions are given in mm.

III. MEASUREMENTS AND RESULTS

The implemented prototype has a mass of only 7.5 g. The WEH is measured in an anechoic chamber calibrated to provide a power density of approximately 1 μW/cm^2 at the location of the receiver. A low frequency 2.2 kΩ resistor is attached to the DC load terminals and the voltage measured for different azimuth angles. The maximum rectified power is 15.05 μW at approximately 25° from the symmetry plane. Power rectified by the diode seems to be considerably lower than expected, probably due to the high optimal impedance that is difficult to reach with a compact matching circuit. The rectenna design is not symmetrical, resulting in the pattern

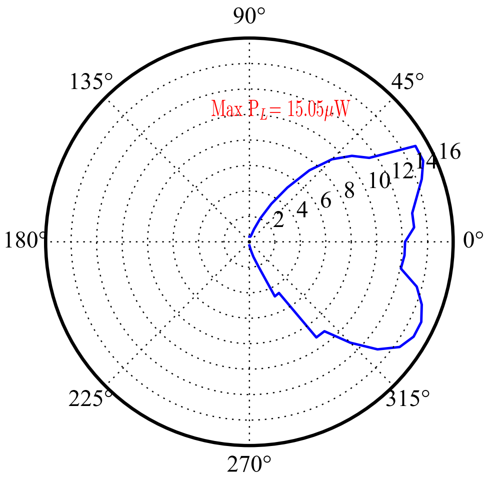

Fig. 5. Measured radiation pattern of the rectenna is obtained by measuring the DC power across the load and includes the efficiency change over angle. The incident power density is 1 μW/cm^2 and the DC load is 2.2 kΩ. The rectified power is shown in μW, with a peak of 15.05 μW.

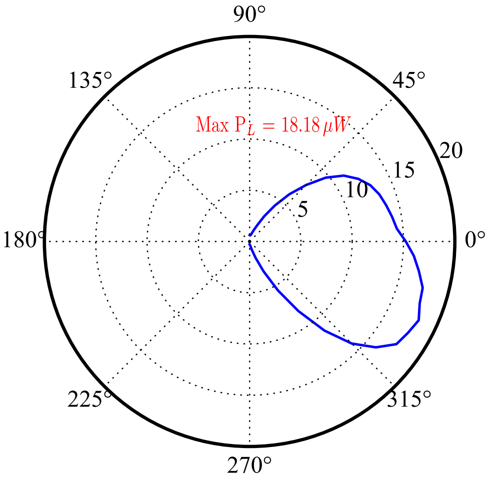

Fig. 6. Pattern of rectified power as a function of azimuth angle for Skyworks SMS7630-079 diode. Measurements are performed with a 1 μW/cm^2 incident power density and a 2.2 kΩ DC load. Rectified power is shown in μW. The maximum rectifed power is 18.05 μW.

with a split lobe, which is not a disadvantage for harvesting applications.

A. Alternate Design with the Skyworks SMS7630-079 Diode

As previoulsy mentioned,the high impedance required for the W-band ZBD diode becomes a problem for high efficiency energy harvesters. A modified version of the WEH using the Skyworks SMS7630-079 GaAs Schottky diode is designed as a modification of the WEH from Figure 4. The impedance required for maximum efficiency is lower in this case, about 50+j250 Ω obtained by load-pull simulations with a Modelithics nonlinear model [3]. The design is modified to maximize gain with different inductive feed dimensions and angle of the corner reflector of 116°, compared to 100° for the first design. The dimensions are shown in Fig. 1.

The measurements results are shown in Fig. 6. The rectified power is increased by 20 % compared to the VDI diode prototype, with a maximum rectified power of 18.05 μW at $\approx$ 25° from the symmetry plane.

The following table shows the rectified power for higher power densities, which increases linearly with incident power density while the efficiency remains relatively constant.The efficiency can be estimated from the power density and geometric area of the rectenna as in [1], and the lower bound on efficiency is calculated to be 30% based on the antenna gain of 7.5 dB.

Power density (μW/cm^2)	Maximum rectified power (μW)
1	18.2
1.26	23.22
1.58	29.32
2	35.64
2.5	42
3.16	47.7

The 20 % increase in rectified power results in an inrease in the figure of merit from 7.164 dB to 9.07 dB. Because the two designs have similar dimensions and similar gain, it is safe to assume that the increase in rectified power is mainly due to the appropriate impedance matching of the diode.

IV. CONCLUSION

In this paper, the design of two wireless energy harvesting rectennas is presented. Each WEH consists of a folded dipole with an inductive feed and a corner reflector. Two different diodes are used, and the high impedance needed for maximum efficiency for the VDI ZBD diode proves difficult to achieve and therefore matching to the Skyworks SMS7630-079 results in a more efficient design. The WEH can easily be positioned in any corner for harvesting while not being overly intrusive. The WEH presented in this paper won second place in the student wireless energy harvesting design competition held at the 2014 IEEE International Microwave Symposium. The tens of microwatts of available rectified power in an environment that has 1-2 μW/cm^2 incident power density can be used to trickle-charge a storage element for low-energy electronic applications [6].

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