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Compact 3D Rectenna for Low-Power Wireless Transmission

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Abstract

A novel compact rectenna with high sensitivity for low power has been designed, fabricated and tested. The proposed rectenna includes a 3D antenna design operating at the European Industrial Scientific Medical (ISM) 868 MHz frequency band. It includes a modified T-match antenna vertically connected to two metallic arms. An optimized differential rectifier was added to the antenna in order to form the rectenna with an overall size of 40 x 30 x 10 mm^3. The fabricated rectenna exhibits a harvested dc voltage of 155 mV and 740 mV (a RF to dc conversion efficiency 21 % and 44 %) across the load (10 kΩ) respectively with an illuminated power density of 0.1 µW/cm² and 1 µW/cm².

1 Introduction

The development of new wireless devices for Internet of Things (IoT) applications involves new challenges, including but not limited to self-powering capabilities [1]. Most IoT wireless devices use a battery as an energy source. The use of battery implies maintenance and environmental issues: the battery needs to be periodic replaced and recycled. In addition, batteries have important size and weight that are not compatible with IoT applications. One solution to dc-supply low-power wireless devices for IoT applications is to capture and convert the electromagnetic (EM) energy available into dc energy via Wireless Power Transmission (WPT) and Energy Harvesting (EH) approach. As well, a rectenna (**rect**ifying ant**enna**) was utilized in order to achieve this feature. In this work, is developed a rectenna featuring characteristics such as sensitivity and compactness. It was optimized for low power densities (bellow 1 µW/cm²) at the European Industrial Scientific Medical (IMS) frequency of 868 MHz. Simulations were carried out with Advanced Design System (ADS) from Keysight and Ansys HFSS software and verified with measurement in an anechoic chamber. Thus, the performances of the simulated rectifier were verified as presented in section 2.1. The compact three-dimensional (3D) antenna is presented in section 2.2 and then section III presents experimental results of the prototyped rectifier.

2 Proposed 3D rectenna

As shown in Fig. 1, the WPT is based on rectifying EM Field emitted by a Radiofrequency (RF) source to a dc power. The rectenna optimized for low power RF signals was designed as compact as possible. The prototyped design was fabricated on FR4 substrate (thickness of 0.8 mm, $\varepsilon_r = 4.3$).

2.1. Full wave Rectifier design

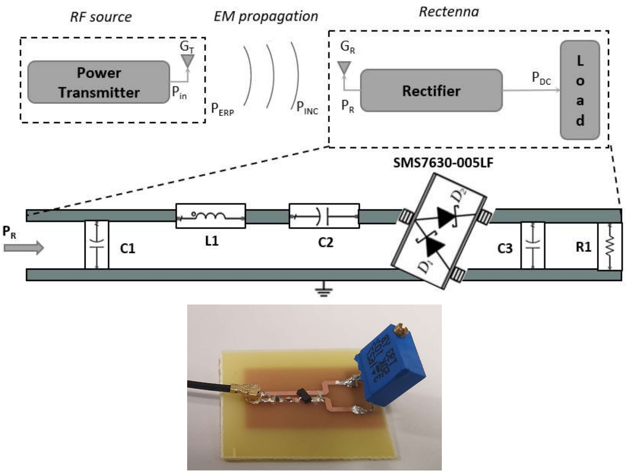

Figure 1. WPT diagram, electrical schematic and photo of the fabricated rectifier.

The proposed rectifier uses zero-bias Schottky diodes. Several types of diodes exist but the HMS285x series from Avago and SMS7630 series from Skyworks are commonly used for ISM 868 MHz designs due to their interesting features.

According to the datasheet [6] and investigation performed in [2-3], the Skyworks SMS7630 series provides better performances in terms of dc voltage and efficiency for low power range. The rectifier topology is also primordial in the performance results. A comparison of different topologies of rectifier was proposed in [4-5]. The voltage doubler topology increases the harvested dc voltage across the load (compared to the single diode rectifier). However, in terms of efficiency, single or half-wave rectifier is often preferred, mostly for very low power applications. The doubler rectifier architecture as shown in Fig. 1 is adopted in this paper. It consists of an LC matching network, a series pair Schottky diode (SMS7630-005LF) and a load of 10 kΩ (R1). The matching network consisted of a wire-wound inductor of 33 nH (L1-LQW15AN33NG00) and a shunt capacitor of 4 pF (C1-GRM1551X1H4R0CA01D)), was thoroughly designed and optimized with ADS Keysight software for low RF input power at the targeted frequency band.

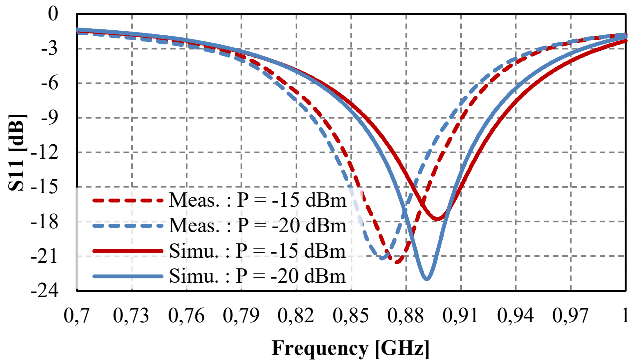

Figure 2. Comparison between the measured (dashed line) and simulated (solid line) reflection coefficient for two RF power (-15 dBm and -20 dBm) at the input of the rectifier.

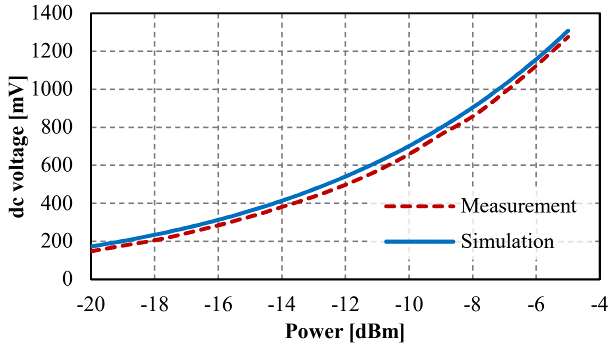

Figure 3. Measured and Simulated dc voltage as function of the RF power at the input of the rectifier at 868 MHz.

A capacitor of 100 pF was chosen for C2 and C3. For accurate simulation results, the Spice model of the diode [6] and the parasitic model of the SOT-23 plastic diode package [7] were included in the ADS simulation model. The non-linearity of the Schottky diode trend to modify the input impedance of the rectifier as a function of the input power. The prototyped rectifier (photo in Fig. 1) exhibits a good impedance matching for various low levels of the RF input power (-20 and -15 dBm) as illustrated in Fig. 2. There is a frequency shift between simulation and measurement due to an inaccurate model of the inductor and the manufacturing/soldering effect on the prototype. Concerning the harvested voltage, the presented design can exhibit a dc voltage of 200 mV for a RF input power of -18 dBm. As depicted in Fig. 3, the measured dc voltage fit well with the simulated results (offset of only 24 mV) and a measured efficiency of 51 % for an input power of -5 dBm.

2.2. 3D Dipole Antenna

In terms of compactness, a dipole antenna (at 868MHz) in 3D configuration was preferred in this design. Two different antennas (A1 and A2) were designed. The first design consists of a folded dipole antenna (FDA) commonly known as a modified T-match antenna [8]. A1 has a spline shape with a T-section in the driven port and the width of the line was optimized in order to obtain a good impedance matching (S11 under -10 dBm). A1 antenna was designed to operate at 1.15GHz as seen in Fig.4 (a).

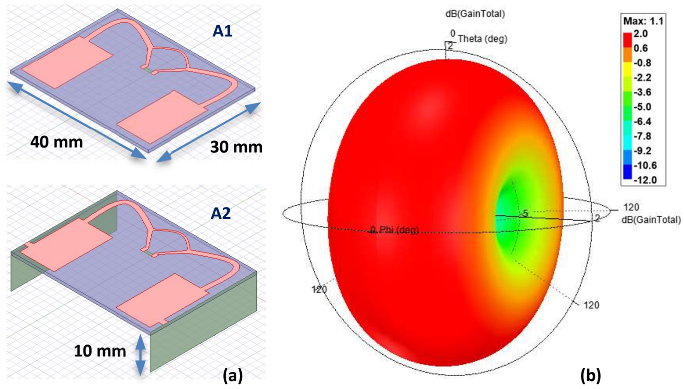

Figure 4: (a) Designed antennas on HFSS (A1: Flat FDA and A2: 3D FDA); (b) 3D polar plot of the radiation pattern of A2 antenna at the resonant frequency (HFSS results).

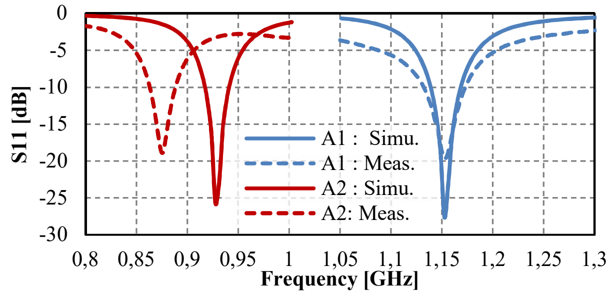

Figure 5. Measured (dashed line) and simulated (continuous line) reflection coefficient of the A1 (blue line) and A2 (red line) antennas.

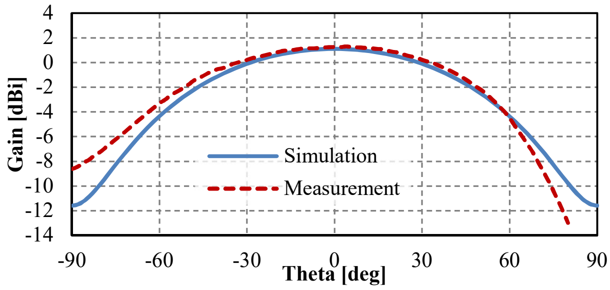

Figure 6. Simulated (red dashed line) and measured (continuous blue line) radiation pattern (gain plot in the E-plane) for the A2 antenna at the resonant frequency (868 MHz).

Therefore, two vertical metallic arms connected to the antenna with a short transmission line to the edge of the PCB, was added (A2). The size of A2 (represented in Fig.4 (a)) is only 40 x 30 x 10 mm and a maximum gain of 1.1 dBi was obtained as presented in Fig. 4 (b). Due to the vertical capacitive arms, A2 antenna resonates at 878 MHz as shown in Fig. 5. The measured and simulated gain in the E-plane are shown in Fig.6.

3 Experimental results

The integration between the rectifier and the antenna was done on the same Printed Circuit Board (PCB) as seen in the inset of Fig.8, which allows having great RF to dc conversion efficiency without any soldering effect.

Table I. Comparison with the state of the art

Ref.	Frequency (GHz)	Diode	Input Power (dBm)	Incident power density S (μW/cm²)	Efficiency (%)	Antenna gain (dBi)	Rectenna size (mm x mm x mm)	dc Voltage (mV) / Load
[10]	5.9	HSMS 286B	-10	--	22.5	7	NR	500 / 10 kΩ
[11]	2.45	SMS7630	--	1	NR	NR	100 x 100 (0.0055 λ^2)	140 / 10 MΩ
[12]	2.4	SMS7630	--	1	NR	NR	72.9 x 72.9 (0.0027 λ^2)	150 / 5.1 k Ω
[13]	0.868	HSMS285B	-12	1	33	1.43	24.4 x 24.4 x 29.85 (0.00043λ^3)	310 / 2.193 kΩ
This work	**0.868**	**SMS7630-005LF**	**--**	**1**	**44**	**1.1**	**40 x 30 x 10 (0.00029 λ^3)**	**740 / 10 kΩ**

NR: Non reported

The measurement setup placed in an anechoic chamber contains a Patch antenna (gain G_t of 9.44 dBi) connected to the RF signal generator (with RF output power P_t). It radiates an EM Field to the rectenna under test (distanced of 1.5 m, in the far-field region of the transmitting patch antenna).

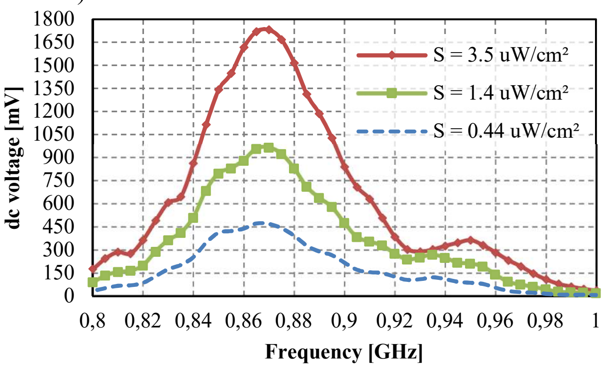

Figure 7. Measured dc voltage of the rectenna as function of the frequency and for various power density.

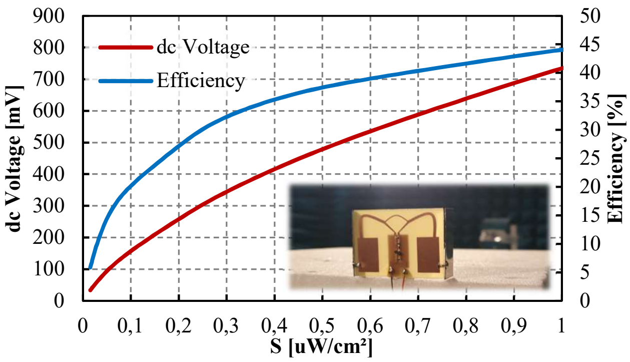

Figure 8. Measured dc voltage and RF-dc conversion efficiency as function of the power density at 868 MHz and inset of the fabricated rectenna.

The power density S (µW/cm²) and the rectenna efficiency η (%) can be computed from the two following relationships:

$$\eta = \frac{P_{DC}}{P_{RF}} = \frac{4 \cdot \pi \cdot P_{DC}}{S \cdot G_r \cdot \lambda^2} \cdot 100 \quad (1)$$

$$S = \frac{P_t \cdot G_t}{d^2 \cdot 4 \cdot \pi} \quad (2)$$

where P_{DC} is the dc harvested power, G_r is the receiving antenna gain and λ is the wavelength at the operating frequency. The insertion losses of the RF cable connecting the RF generator and the patch (about 3 dB) were removed from the patch gain. The maximum harvested dc voltage was measured at 868 MHz as represented in Fig. 7. With a power density of 0.44 µW/cm², the prototyped rectenna can exhibit a dc voltage of 468 mV at 868 MHz. The maximal measured RF to dc conversion efficiency is about 44 % with a power density of 1 µW/cm². These measured performances demonstrate the feasibility of powering an Integrated Circuit (IC) as the BQ25505 [9] (with a cold start voltage at least equals to 330 mV) with a low power density (0.3 µW/cm²) of the illuminating EM waves.

The Table I summarize key performances of the proposed rectenna and of the state-of-the-art rectennas operating with the same illuminating power density. It can be observed that the prototyped rectenna has a good conversion efficiency for low incident RF power densities and a good harvested dc voltage. Hence, it is a good candidate for achieving the best trade-off between compactness and efficiency.

4 Conclusion

A compact and sensitive rectenna is proposed in this paper with a size of 40 x 30 x 10 mm³. The proposed design combines a modified T-match antenna in 3D configuration and an optimized rectifier for low RF power levels (under -5 dBm). The experimental results confirm that the proposed 3D antenna (of the rectenna) exhibits a gain of 1.1 dBi in the operating frequency band (between 863 MHz and 889 MHz). The fabricated rectenna harvest a maximum dc voltage of 468 mV and an efficiency of 36% with a power density of 0.44 µW/cm² across a load of 10kΩ at 868 MHz.

5 References

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