Efficient RF Harvesting for Low-Power Input with Low-Cost Lossy Substrate Rectenna Grid

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***Abstract*—An efficient, low-cost and low-complexity rectenna-grid is analyzed, fabricated and measured, for low-power RF input and RF density. The design consists of two single series rectifier circuits that add the currents from each diode, in order to increase the offered power at the load. Despite the fact that a lossy and low-cost FR-4 substrate was used, the rectenna-grid offers $200\ \mu\text{W}$ at load for $1\ \mu\text{W/cm}^2$ ambient power density, while for $0.01\ \mu\text{W/cm}^2$ the power at load reaches $0.8\ \mu\text{W}$. Furthermore, RF-to-DC rectification efficiency of 20.5% and 35.3% is achieved at -20 and -10 dBm power input, respectively. Measurements of the proposed RF harvester agree well with simulations. Finally, the rectenna was connected to a DC-to-DC converter and the open voltage was increased from 298 mV to 1.4 V, charging a 1 mF capacitor at 37 min. The stored energy could supply a sensor in a wireless network, with consumption 20 mW, rate 1 kbps and word-length of 20 bits.**

***Index Terms*—Energy harvesting, rectifiers, rectennas.**

I. Introduction

Energy harvesting has become an increasingly attractive research topic due to the proliferation of radio frequency emitters. The goal is to collect unused ambient RF energy and supply with power small electrical devices, such as sensors. Three decades have passed since the rectenna (i.e. antenna and rectifier) was first proposed for transformation of RF energy to DC [1]. Recently, considerable research effort has been directed towards high-efficiency. However, most prior art designs operate optimally at *high* input power, e.g. greater than 0 dBm [2]–[6]. In order to increase the efficiency at *low* power input, e.g. less than 0 dBm [7]–[13], substrates with low losses [8], [9], [11] or hybrid designs [10] have been used, raising the total cost or the fabrication complexity, respectively. In [7], [13] power is harvested from a Digital TV power station and wide-band efficiency is estimated, while in [14] ambient RF power is collected and the end-to-end efficiency is estimated, as the ratio of the obtained DC energy to the captured RF energy. Table I presents analytically the achieved efficiency versus input power (or power density) and frequency, for various prior art designs.

The goal of this work was: a) high efficiency design for low-power input and b) as much power as possible offered at the load. Hence, a rectenna-grid consisting of two low-cost and low-complexity single circuits [12] and a pair of custom antennas, was utilized. RF-to-DC efficiency of 20.5% is achieved, for total power input -20 dBm, or equivalently, for power density $0.019\ \mu\text{W/cm}^2$, as explained bellow. Next, the rectenna was connected to a DC-to-DC converter in order to enhance the open circuit DC voltage, from 298 mV to 1.4 V. Finally, a 1 mF capacitor was charged in 37 min and the stored energy of 0.98 mJ could supply a wireless sensor with power consumption 20 mW, rate 1 kbps and word-length 20 bits (0.4 mJ per packet).

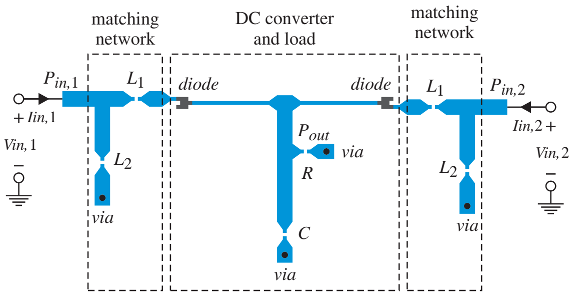

Fig. 1. Two-input microstrip rectifier-grid design (top layer).

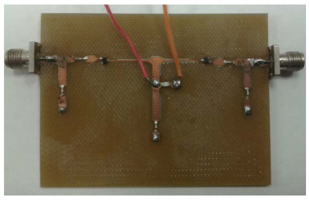

Fig. 2. The fabricated rectifier.

TABLE I
RF-TO-DC CONVERSION EFFICIENCY VERSUS POWER INPUT/DENSITY AND FREQUENCY

work	efficiency	power input (dBm)	frequency (MHz)
[2]	65%	25	2450
[3][1]	20%	13.27	2000 – 18000
[4]	77.8%	10	2400
[5][2]	54%	9.54	1960
[6]	40%	0	2450
[7]	21%	−4.74	512 – 566
[8]	56.4%	−10	900
[9]	50%	−17.2	2450
[10]	15%	−20	850, 1850
[11]	15.3%	−20	2450
[12]	17%	−20	868
[13]	18.1%	−20	470 – 770
[14][3]	40%	−25.4	2110 – 2170

[1] $A_{\text{eff}} = A = 18.5\times18.5\ \text{cm}^2$, $S = 62\ \mu\text{W/cm}^2$.
[2] $A_{\text{eff}} = A = 7.5\times6\ \text{cm}^2$, $S = 200\ \mu\text{W/cm}^2$.
[3] The end-to-end efficiency as the ratio of the obtained DC energy to the captured RF energy.

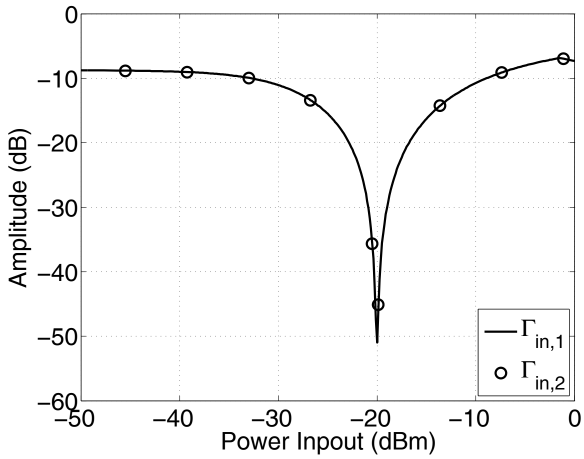

Fig. 3. Γ_{in} coefficient for two ports at 868 MHz.

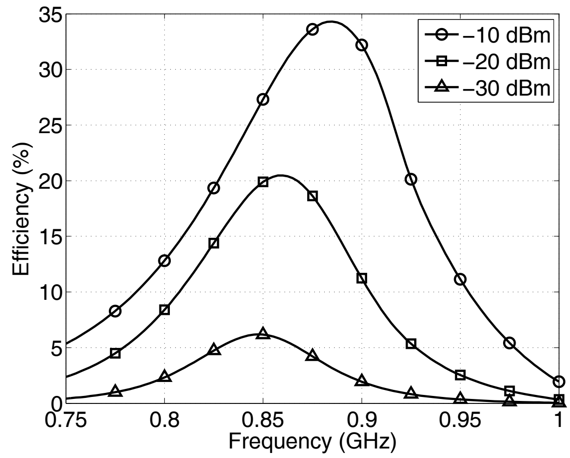

Fig. 5. Rectifier efficiency versus frequency for different power inputs.

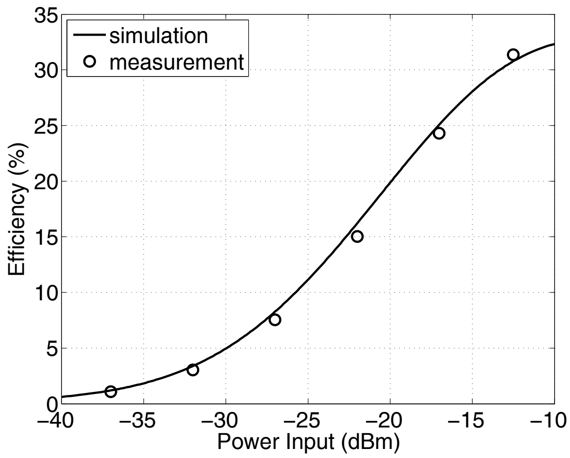

Fig. 4. Rectifier efficiency versus total power input.

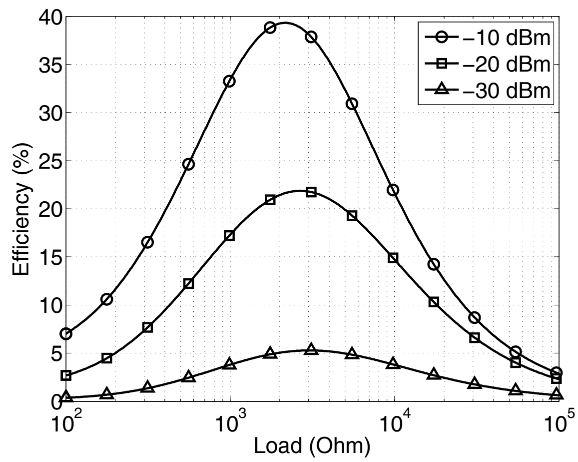

Fig. 6. Rectifier efficiency versus load for different power inputs.

II. RECTIFIER

In this work a high-efficiency for low-power input, low-cost and low-complexity rectifier is designed, analyzed and fabricated. In order to decrease the total cost, a lossy substrate is used, although losses reduce efficiency. The efficiency is increased using a single series circuit with a single diode [12], while the total power on load is enhanced through a rectenna-grid design, for low-power density, bellow 1 $\mu\mathrm{W/cm}^2$.

Specifically, rectification of the received RF power to DC power is achieved using two single series rectifier circuits, consisting of a matching network and a single diode, in each input port. Their outputs are joined together, adding the currents from each diode and finally, feeding the load R. The latter leads to enhancement of the power which is offered to the load, for low-power RF density. The whole geometry is depicted in Fig. 1 and 2. The diodes are the low-cost "HSMS285B", while the substrate is (lossy) FR-4 with $\epsilon_r = 4.4$, $\tan\delta = 0.025$, copper thickness 0.35 μm and height 1.5 mm.

A. Design and Analysis

For simulations, Agilent Technologies' ADS software is employed, with harmonic-balance and the method of moments solver. Full electromagnetic analysis takes simultaneously into account the losses from the low-cost FR-4, the fringing fields and the non-linear behavior of the rectifier due to the diodes. It is assumed that the rectifier ports will be connected to antennas with input impedance equal to 50 Ohm, while the (low) power input P_{in}, varies from -30 dBm to -10 dBm. The system was chosen to operate at 868 MHz, which is the UHF ISM center frequency in Europe. In order to design the rectifier (i.e. trace dimensions and lumped elements L_i) an optimization procedure was applied. The goal was the minimization of term,

$$\Gamma_{in,1} = \frac{Z_{in,1} - 50}{Z_{in,1} + 50}, \tag{1}$$

for power input at port "1", $P_{in,1}$, -20 dBm at 868 MHz, where

$$Z_{in,1} = \frac{V_{in,1}}{I_{in,1}}, \tag{2}$$

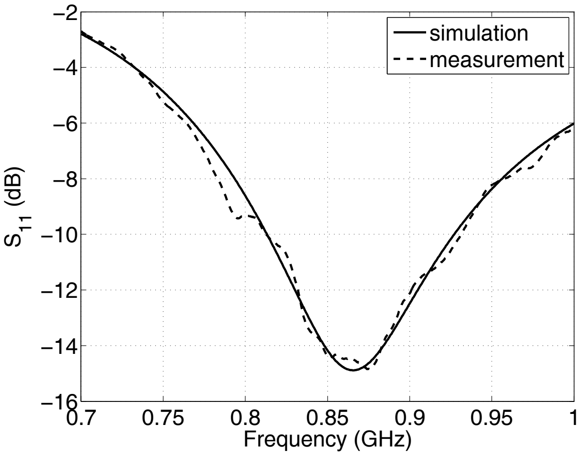

Fig. 7. Reflection coefficient of the bow-tie antenna.

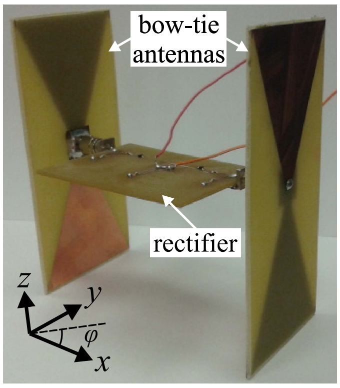

Fig. 8. The proposed rectenna-grid consisting of two identical bow-tie antennas.

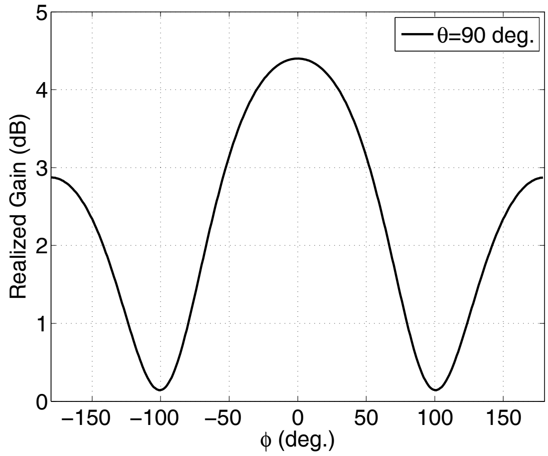

Fig. 9. The estimated rectenna realized gain. Only one antenna was radiated and the other, with the rectifier, acted as parasitic elements.

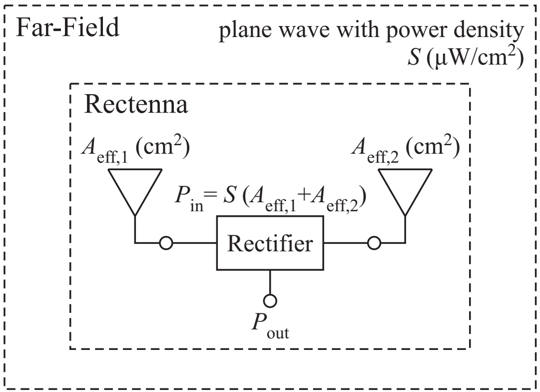

Fig. 10. Rectenna topology at far-field.

is the input impedance at port "1", with port "2" matched at 50 Ohm. After simulation, the obtained lumped element values were $L_1 = 27$ nH and $L_2 = 1.5$ nH. The load and capacitor were initially fixed at 5 kOhm and 100 pF, respectively. The results, $\Gamma_{in,i}$, are depicted in Fig. 3. It is observed that the two-port rectifier circuit operates (i.e. the reflection coefficient, $\Gamma_{in,i}$, is less than -10 dBm) from about -33 dBm to -9 dBm power input.

The RF-to-DC efficiency,

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_R^2/R}{P_{in,1} + P_{in,2}}, \tag{3}$$

with P_{in} the total power input at the rectifier, P_{out} the power output at load and V_R the voltage across the load, R, is estimated and depicted in Fig. 4. When $P_{in} = -20$ dBm, η is equal to about 20%, while for $P_{in} = -10$ dBm η reaches the peak of about 32.3%. It is noted that η is a function of power input, operation frequency and load, hence, the relation between them should be tested. Next, the relation between η, frequency and load will be shown.

Fig. 5 shows the rectifier efficiency versus frequency for different power inputs. When $P_{in} = -20$ dBm, it is observed that the rectifier is tuned at 868 MHz, as expected. The highest efficiency 34.3% is achieved for $P_{in} = -10$ dBm but at 885 MHz. For $P_{in} = -30$ dBm the peak $\eta = 6.2\%$ occurs at 850 MHz, while $\eta = 5.2\%$ at 868 MHz. It is noted that load was fixed at 5 kOhm.

Finally, the relationship between efficiency and load is studied. Frequency is now fixed at 868 MHz, and the results are shown in Fig. 6. It is observed that for $P_{in} = -20$ dBm and R at about 2.7 kOhm, the efficiency is slightly increased from 20% to 22%, and for this reason the load remained fixed at 5 kOhm. The maximum $\eta = 39.3\%$ occurs for $P_{in} = -10$ dBm when R is equal to about 2.2 kOhm.

B. *Rectifier Measurements*

For validation purposes, the rectifier design is fabricated (Fig. 2) and tested. A Wilkinson power divider, which was also analyzed and fabricated, is connected to a signal generator. First, a spectrum analyzer is connected to each divider output, measuring the received power. Next, the spectrum analyzer is removed and power divider outputs were connected to the proposed rectifier. The total power, P_{in}, is considered as the sum of $P_{in,1}, P_{in,2}$, which are the two divider output ports.

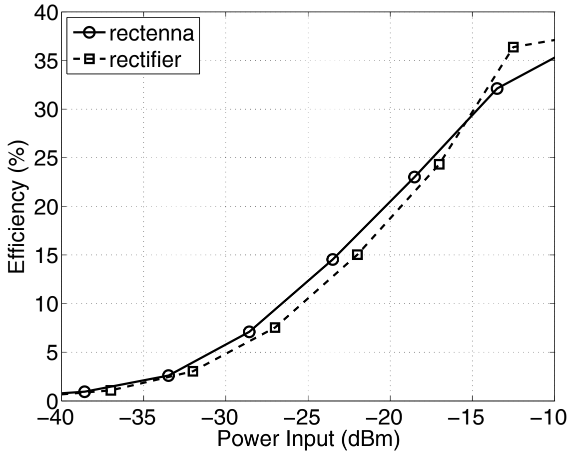

Fig. 11. Rectenna measured efficiency.

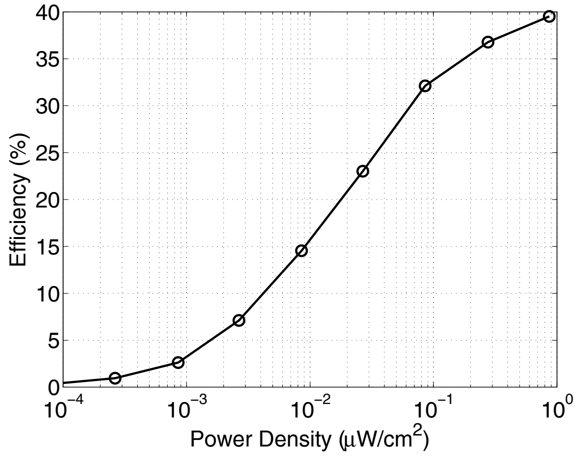

Fig. 13. Efficiency versus ambient power density.

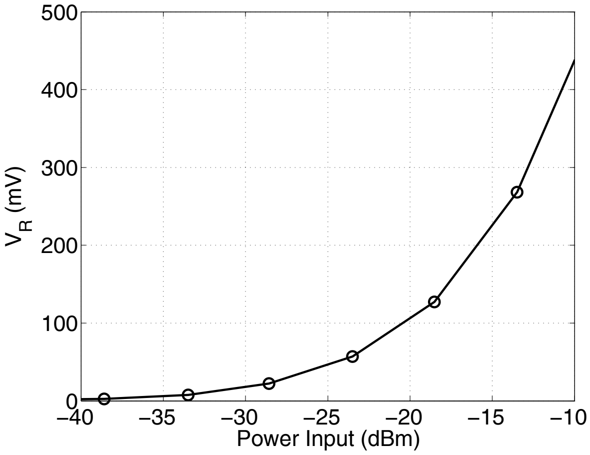

Fig. 12. Measured voltage across the 5 kOhm load.

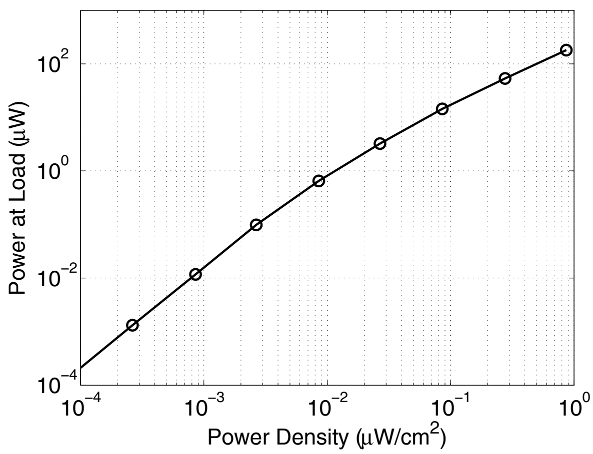

Fig. 14. The power at the load versus ambient power density.

A voltmeter measures the voltage across the load, which is fixed at 5 kOhm. Fig. 4 depicts the simulated/measured results. Good agreement between simulation and measurements is observed.

III. Rectenna Grid

A crucial rectenna parameter, apart from the efficiency, is the amount of power offered at the load. The ambient power density is usually below $1\ \mu\mathrm{W/cm}^2$ [7], [13], [14]. Given such low offered ambient power density, it becomes an engineering challenge for rectenna design to harvest as mush power as possible. In this work a rectenna-grid scheme is used in order to provide the load with enhanced power for low-power density. The combination point took place at DC-area, simplifying the matching network design process. The proposed rectifier is now connected to a pair of custom designed antennas, eventually forming a rectifying antenna, i.e. a rectenna.

It is noted that the use of rectenna grids operating on the same frequency is not new [2], [3]. In contrast to prior art designs, our goal was to fabricate a low-cost rectenna grid which operates adequately, in terms of efficiency and offered power at load, for low power density and power input. The RF-to-DC efficiency was measured according to a specific procedure which took into account the rectenna radiation pattern and utilizes a signal generator, a spectrum analyzer and a calibrated antenna.

A. Rectenna Design and Radiation Pattern

A bow-tie antenna is designed to operate at ISM band (around 868 MHz) and the simulated/measured reflection coefficient is depicted in Fig. 7. The design is an enhanced variation of a dipole antenna in terms of wide-band operation and low fabrication complexity. The rectifier is accompanied by two such identical bow-tie antennas, forming a rectenna device (Fig. 8). Due to proximity of the antennas and rectifier, the total rectenna radiation pattern is not omni-directional and should be estimated. For far-field simulation, Ansys HFSS was used. Especially, the whole geometry was analyzed at 868 MHz when only one antenna was radiated and the other, with the rectifier, acted as parasitic elements. After simulations a maximum gain, $G = 4.4$ dB is achieved at horizontal plane, in front of each bow-tie antenna ($\phi = 0°$, $\theta = 90°$). The realized gain versus ϕ-angle is presented in Fig. 9.

B. Rectenna Efficiency

The rectenna RF-to-DC efficiency is calculated by,

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_R^2/R}{S \cdot A_{\text{eff}}}, \tag{4}$$

where S is the power density of the incident to the rectenna plane wave and A_{eff} the total antenna effective area:

$$A_{\text{eff}} = \frac{\lambda^2}{4\pi} G, \tag{5}$$

where λ is the wave length and G the antenna gain.

Fig. 10 shows schematically the terms S, A_{eff}, P_{in} and P_{out}. The total RF power P_{in}, to be transformed to DC by the rectifier, is the sum of the power which is captured by the two antennas. It is clear that when the antenna gain is increased, the captured power will also increase. The same result can be obtained by increasing the number of the antennas, hence the idea which is presented here could be expanded and applied in $n \times 1$ rectenna grids, where $n \geq 2$. According to (5), the effective rectenna area from the both antennas, $A_{\text{eff}} = A_{\text{eff},1} + A_{\text{eff},2}$, is equal to 522.86 cm^2.

Next, the RF-to-DC efficiency was estimated: A log-periodic antenna, connected to a signal generator was the transmitter. At a specific point in the far-field area, one commercial and calibrated monopole antenna with gain $G_{\text{cal}} = 1.8$ dBi was placed, and connected to a spectrum analyzer, measuring the received power, P_{cal}. The power density S, is estimated from,

$$S = \frac{4\pi}{\lambda^2} \frac{P_{\text{cal}}}{G_{\text{cal}}}. \tag{6}$$

Afterwards, the spectrum analyzer and monopole antenna was removed and the proposed rectenna was placed at exactly the same point. Now, the voltage across the load was measured. The RF-to-DC efficiency is depicted in Fig. 11. Firstly, it is observed that the rectenna and the rectifier efficiency, measured with different procedures, agree well. The slight difference is mainly due to the estimation via simulation of G. Especially for the rectenna, for $P_{in} = -20$ dBm efficiency of 20.5% is achieved, while for -10 dBm efficiency of 35.3%. Fig. 12 shows the measured voltage across the 5 kOhm load. For $P_{in} = -20$ dBm, voltage of 110 mV across the load is measured, while for -10 dBm voltage is equal to 450.5 mV. It is noted that load was fixed to 5 kOhm.

Fig. 13 depicts the rectenna efficiency versus the ambient power density S, of the incident plane wave. For $S = 1$ $\mu\text{W}/\text{cm}^2$ the efficiency is about 40%. For 0.01 $\mu\text{W}/\text{cm}^2$ efficiency is 15.7%.

Similar conclusions are drawn when the offered power at the load versus power density is studied. Fig. 14 depicts the results: a rectenna offers 200 μW to load when it is placed in space with power density equal to 1 $\mu\text{W}/\text{cm}^2$. For extra low power density 0.01 $\mu\text{W}/\text{cm}^2$, the rectenna offers at load 0.8 μW.

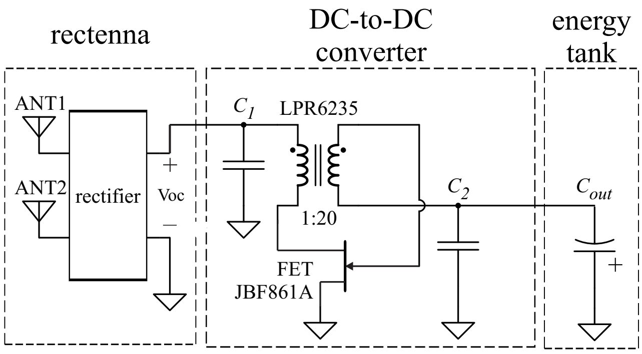

Fig. 15. Autonomous low-voltage and ultra-low power converter schematic with $C_1 = C_2 = 1$ nF and $C_{out} = 1$ mF.

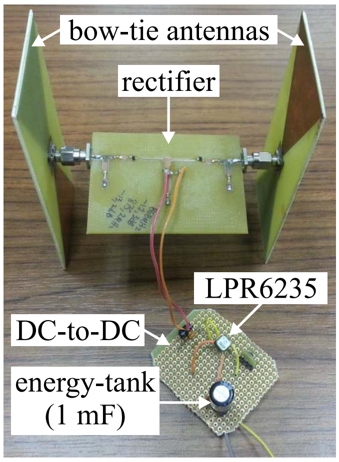

Fig. 16. The fabricated rectenna and the DC-to-DC converter.

C. The DC-to-DC Converter

In this section, a DC-to-DC converter is fabricated and used in order to enhance the output voltage of the RF-to-DC rectifier. Specifically, the converter design is inspired from the classical Armstrong oscillator topology and was presented in [15]. It is an autonomous low-voltage and ultra-low power converter. The converter topology is presented in Fig. 15. For the circuit is used the transformer $1:20$ (Coilcraft "LPR6235-253PMB") and the "BF861A" N-channel JFET. The oscillations start-up conditions satisfied due to the low gate-source cut-off voltage (V_p) and low drain current (I_{DSS}) of the "BF861A" component. Fig. 16 depicts the fabricated RF-to-DC rectifier and the DC-to-DC converter. The rectenna is placed at a specific distance from signal generator in order to achieve P_{in} equal to -20 dBm. The 5 kOhm is removed and the DC-to-DC converter is connected through cables. The open voltage at the output of the rectifier and the converter is now 298 mV and 1.4 V, respectively. Finally, a 1 mF electrolytic capacitor is connected at the output of the converter. and is measured the total charging time. After about 37 minutes the voltage across the capacitor is increased from 0 to 1.4 V and

0.98 mJ was stored. Assuming a wireless with rate 1 kbps, power consumption 20 mW and 20 bits length-packet, the required energy per packet is equal to 0.4 mJ, hence, the stored energy is capable to supply the sensors of this network.

IV. Conclusion

In this paper a high efficiency, low-cost (with lossy FR-4 substrate), low-complexity (single diode in a series configuration) rectenna-grid is presented. The performance is evaluated via two ways; the rectifier is connected directly to a signal generator or the latter radiates through a log-periodic antenna and the rectenna grid receives energy at far-field. Measurements from both procedures agree with simulation and demonstrate high efficiency rectification, for low-power density, low-power input and low-cost. Emphasis was given on collecting and offering as much power as possible at the load. Finally, the rectenna was connected to a DC-to-DC converter and the energy stored in a capacitor is able to supply a sensor.

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