Progress In Electromagnetics Research C, Vol. 26, 181–192, 2012

UHF RECTENNA USING A BOWTIE ANTENNA

G. Monti* **and F. Congedo**

Dept. Innovation Engineering, University of Salento, Via Monteroni, Lecce 73100, Italy

Abstract—In this paper, a rectifying antenna (rectenna) for energy scavenging applications is presented. The proposed device uses a modified bowtie antenna to collect the electromagnetic energy coming from UHF RFID systems, and RF Schottky diodes to convert it into DC power. Experimental results at 866 MHz demonstrating an RF-to-DC conversion efficiency of about 65% with an input power density of 60 μW/cm^2 will be presented and discussed.

1. INTRODUCTION

The proliferation of wireless communication devices suggests the possibility of harvesting the associated electromagnetic (EM) energy to feed devices with a low-power consumption. Accordingly, in the last years some design approaches have been proposed for rectenna systems [1–12], which are devices able to convert a free propagating EM wave into Direct Current (DC) power.

In its basic architecture (see Figure 1), a rectenna comprises:

- an antenna used to collect the EM energy (the harvester),
- a rectifying circuit used to rectify the (Radio Frequency) RF/microwave signal into a DC one (the rectifier),
- a low-power device as end-user (the load).

In order to improve the device conversion efficiency two filtering/matching sections can be added respectively between the antenna and the rectifier and between the rectifier and the load.

In this paper a rectenna designed to simultaneously harvest the EM energy associated to both the UHF (Ultra High Frequency) Radio Frequency Identification (RFID) systems and the Global System

Received 27 October 2011, Accepted 19 December 2011, Scheduled 24 December 2011

* Corresponding author: Giuseppina Monti (giuseppina.monti@unisalento.it).

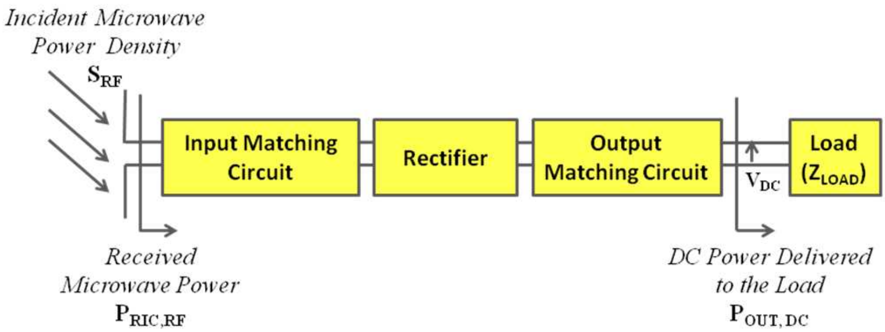

Figure 1. Schematic representation of a rectenna.

for Mobile Communications (GSM) is proposed. The rectenna here presented could be useful in industrial environments using UHF RFID systems and requiring low-power sensors such as temperature or humidity sensors.

In the literature some rectenna devices working in the same range of frequencies have been proposed [7–11]. In [7, 8] a low-cost rectenna for RFID systems is presented. In particular, in [8] a loop with a meander design is used as antenna; the measured conversion efficiency is 4.7% when the input power is 1 mW and the load is 5 kΩ. In [9] a rectifying circuit for UHF RFID tag is proposed, the measured conversion efficiency is higher than 30% when the RF input power is 0.1 mW.

In [10] by using three circular resonators to collect the EM energy, a rectenna able to work at three different frequencies (900 MHz, 1760 MHz, 2450 MHz) is described; the conversion efficiency obtained at 900 MHz is of about 40% when the input power is 2.1 mW.

In [11], a two-layer structure with a circular aperture coupled patch antenna working at 2.45 GHz is presented. The measured conversion efficiency has a maximum of 34% when the incident power density is 17 μW/cm^2.

The rectenna proposed in this paper consists of a compact modified bowtie antenna and four diodes in a bridge configuration. Reported experimental results demonstrate that at the working frequency of RFID systems (866 MHz) an RF-to-DC conversion efficiency of about 65% can be obtained when the incident input power is 60 μW/cm^2.

The paper is structured as follows. The proposed rectenna is briefly described in Section 2. Experimental results are given in Section 3. Some conclusions are drawn in Section 4.

2. PROSED RECTENNA ARCHITECTURE

The equivalent circuit of the proposed rectenna is illustrated in Figure 2, whereas some photographs of a realization are given in Figure 3. The rectifier is a full-wave bridge rectifier which consists of four Schottky diodes in a bridge configuration. More specifically the *1N 6263* diode of ST Microelectronics [13] has been used (see Figure 3(b)). From data sheet, this diode is well suited to work with small signals in the UHF/VHF band.

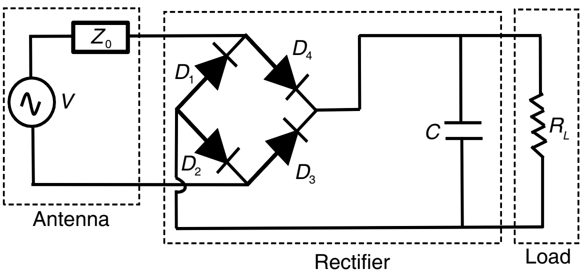

Figure 2. Lumped-element equivalent circuit of the proposed rectenna.

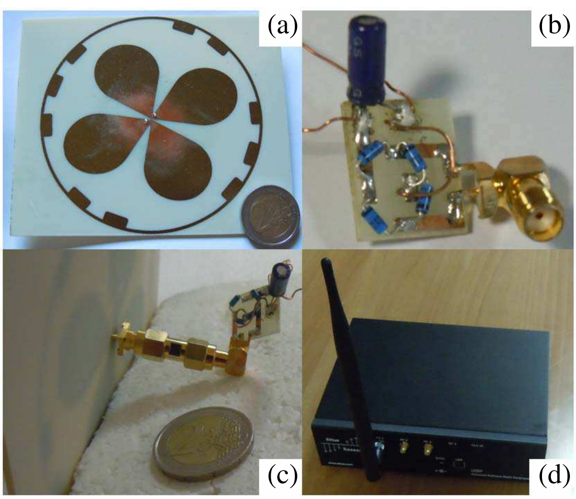

Figure 3. Photographs of the realized rectenna: (a) the antenna, (b) the rectifier, (c) the antenna connected to the rectifier, (d) the USRP adopted to generate the signal incident on the rectenna.

The adoption of a four-diode bridge configuration is related to the fact that this type of rectifier delivers a DC voltage two times greater than the one corresponding to a center-tapped full-wave rectifier which utilizes two diodes [14].

A capacitor of 1 μF in shunt configuration with the load is also drawn in Figure 2. The aim of this capacitor is to block the RF signal with respect to the load.

As for the antenna, it consists of two crossed bowties loaded with an annular ring [12]. The substrate is a 1.6 mm thick FR4 laminate with a relative permittivity of 3.7 and a loss tangent of 0.019. The steps of the antenna design process are illustrated in Figure 4. The starting geometry consists of two crossed bowties designed with rounded corners to obtain a broader bandwidth. A further consistent bandwidth enhancement has been obtained by loading this geometry with an annular ring. Finally, in order to reduce the overall dimensions of the antenna, some rectangles have been added to the annular ring and optimized in terms of number, position and shape. The size reduction is due to the capacitive coupling between the ring and the bowties antennas, which increases with the addition of the rectangles. All antenna dimensions have been optimized by using the full-wave

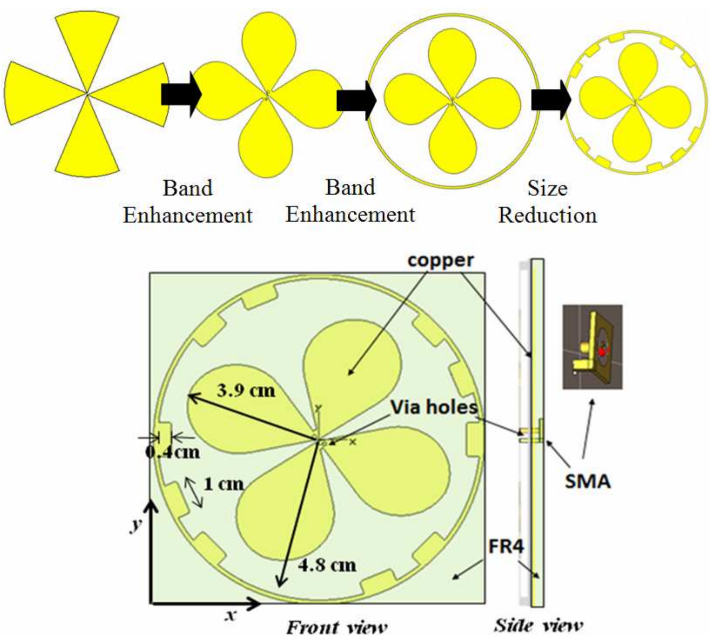

Figure 4. Design process and dimensions of the antenna.

simulator CST-Microwave Studio [15]; corresponding results are given in Figure 5. With respect to rectenna applications, the main advantage of the ring-loaded bowtie antenna presented in this paper is related to the fact that at the frequency range of interest (i.e., [860, 950] MHz) it exhibits high values of the gain (> 3 dB) and compact dimensions.

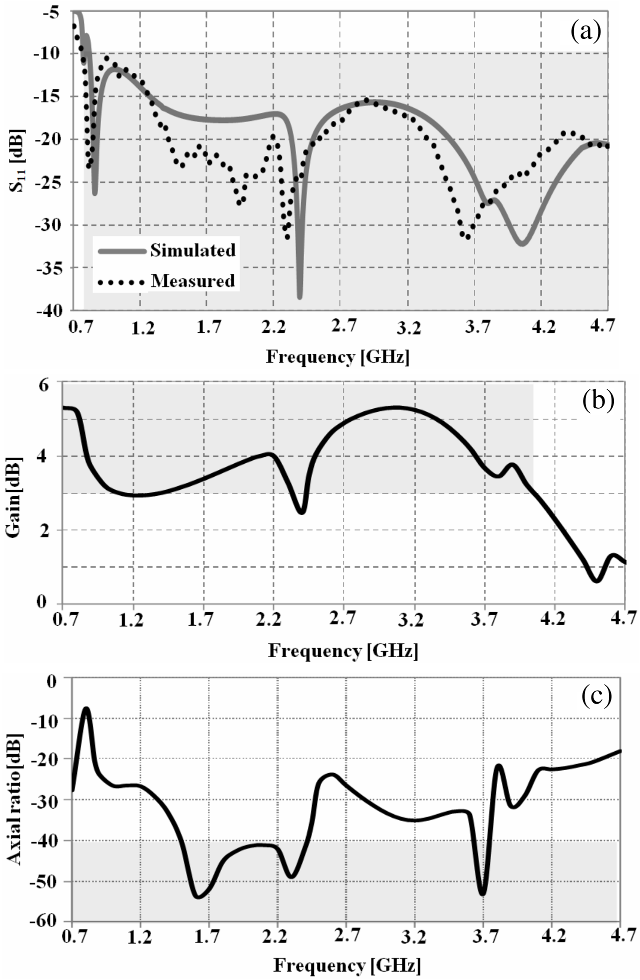

Figure 5. Parameters of the ring-loaded bowtie antenna. (a) Comparison between the simulated and the measured reflection coefficient. (b), (c) Gain and axial ratio calculated along the z direction by means of full-wave simulations performed with CST-Microwave Studio.

Figure 3(a) shows a photograph of a realization of the optimized layout whose dimensions are illustrated in Figure 4. The reflection coefficient normalized to a $50\,\Omega$ impedance is given in Figure 5(a) where a comparison between measured and simulated data is reported.

If we define the bandwidth of the antenna as the frequency range where the reflection coefficient is lower than -10 dB and the gain is greater than 2 dB, from Figure 5 it can be derived that the bandwidth of the proposed antenna is [0.74, 4.3] GHz corresponding to a relative bandwidth of 141%. It is worth observing that the area of the square circumscribing the antenna is $(9.8 \times 9.8)\,\text{cm}^2$, which at the lower frequency of the working band (i.e., 0.74 GHz) corresponds to $(0.24 \times 0.24)\,\lambda^2$.

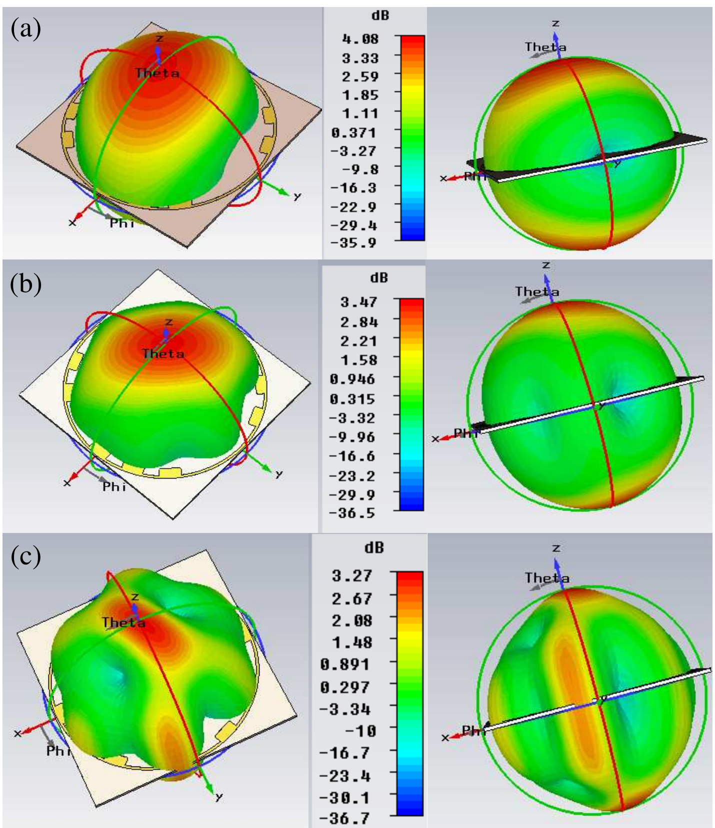

Figure 6. 3D gain calculated by CST Microwave Studio at the frequency of (a) 866.6 MHz, (b) 2.45 GHz, (c) 4 GHz.

As for the polarization, full-wave simulations results for the axial ratio are given in Figure 5(c). It is evident that over the entire bandwidth the antenna exhibits an elliptical or a y-directed linear polarization (in the case of the elliptical polarization the major axis is y-directed, see Figures 4 and 6 for the axis orientation). More specifically, the regions corresponding to a linear polarization are the ones highlighted in Figure 5(c) with a grey area, where the axial ratio is lower than -40 dB.

3. CONVERSION EFFICIENCY MEASUREMENTS

Measurements of the RF-to-DC conversion efficiency of the proposed rectenna were performed by using a Software-Defined Radio (SDR) platform. More specifically, in order to generate the microwave signal incident on the rectenna, the software toolkit GNU-Radio [16] and a Universal Software Radio Peripheral (USRP) were used; the USRP was equipped with a FLEX900 daughterboard which supports operating frequencies in the range of [750–1050] MHz [17].

In order to avoid spurious reflections, measurements were performed in a large outdoor area. More in detail, the antennas were mounted at a height of 2 m from the ground and placed at the center of a free space volume of $(4 \times 4 \times 4)\,\mathrm{m}^3$.

In all measurements the distance between the rectenna and the USRP transmitting dipole was equal to 60 cm, thus guaranteeing that both antennas were operating in their far-field region.

Furthermore, the relative position of the transmitting and receiving antenna was adjusted in order to minimize loss due to polarization mismatches. More specifically, the USRP dipole was oriented along the major axis of the polarization ellipse of the bowtie ring-loaded antenna, which, referring to Figure 4, is the y-direction.

Experimental data were taken for different values of: the resistive load, the power density and the frequency of the microwave signal incident on the antenna. Data collected this way have been used to calculate the RF-to-DC conversion efficiency (η_{RFtoDC}) according to the following definitions:

$$\eta_{\mathrm{RFtoDC,\ rectenna}} = \frac{P_{\mathrm{OUT,\ DC}}}{S_{\mathrm{RF}} A_G} = \left(\frac{V_{\mathrm{DC}}^2}{R_{\mathrm{LOAD}}}\right) \frac{1}{S_{\mathrm{RF}} A_G} \tag{1}$$

$$\eta_{\mathrm{RFtoDC,\ rectifier}} = \frac{P_{\mathrm{OUT,\ DC}}}{P_{\mathrm{RIC,\ RF}}} = \left(\frac{V_{\mathrm{DC}}^2}{R_{\mathrm{LOAD}}}\right) \frac{1}{S_{\mathrm{RF}} A_{\mathit{eff}}} \tag{2}$$

where S_{RF} is the power density incident on the antenna, V_{DC} is the DC output voltage (see Figure 1), R_{LOAD} is the resistive load. A_G is the geometric area of the antenna ($\sim 72\,\mathrm{cm}^2$), whereas A_{eff} is its effective area experimentally estimated as the ratio between the power received by the antenna and the incident power density S_{RF}.

In order to measure S_{RF} the PMM 8053A broadband field meter with the EP-183 isotropic probe was used.

By introducing the parameter η_{ANT} defined as:

$$\eta_{\mathrm{ANT}} = \left(\frac{A_{\mathit{eff}}}{A_G}\right) \tag{3}$$

we can derive:

$$\eta_{\mathrm{RFtoDC,\ rectenna}} = \left(\frac{A_{\mathit{eff}}}{A_G}\right) \eta_{\mathrm{RFtoDC,\ rectifier}} = \eta_{\mathrm{ANT}} \eta_{\mathrm{RFtoDC,\ rectifier}} \tag{4}$$

It can be noticed that η_{ANT} is the so called aperture efficiency which is an important figure of merit of aperture antennas.

It is evident that the two definitions (1) and (2) coincide if the geometric and the effective area of the antenna coincide ($\eta_{\mathrm{ANT}} = 1$); otherwise, if $\eta_{\mathrm{ANT}} > 1$ the first definition results in higher values of efficiency. The aim of the definition given in (1) is to highlight the efficiency of the antenna in collecting the electromagnetic radiation; in fact, it results in higher values of efficiency for compact antennas with high values of the gain. Therefore, we can conclude that $\eta_{\mathrm{RFtoDC,\ rectenna}}$ is a figure of merit that expresses the efficiency of the overall rectenna, whereas $\eta_{\mathrm{RFtoDC,\ rectifier}}$ expresses the efficiency of the rectifier.

In order to demonstrate the possibility of using the proposed rectenna for the scavenging of RF power associated with RFID systems, a first set of experiments was performed by setting to 866 MHz the frequency of the microwave signal generated by the URSP.

Results obtained this way are given in Figures 7–10. Values calculated for $\eta_{\mathrm{RFtoDC,\ rectenna}}$ are reported in Figure 7. In particular, Figure 7(a) shows the RF-to-DC conversion efficiency of the proposed rectenna as function of R_{LOAD}; from experimental data the best value of R_{LOAD} is 992 Ω. As for the dependence of $\eta_{\mathrm{RFtoDC,\ rectenna}}$ on the power density incident on the antenna, it is illustrated in Figure 7(b); a maximum of $\eta_{\mathrm{RFtoDC,\ rectenna}}$ of about 65% was obtained when the power density incident on the antenna was equal to 60.5 $\mu\mathrm{W/cm}^2$. It is worth underlining that this value of S_{RF} is the maximum that has been achieved with our measurement setup; by observing Figure 7(b) it is expected that greater values of $\eta_{\mathrm{RFtoDC,\ rectenna}}$ could be measured with greater values of S_{RF}.

Results obtained for the RF to DC conversion efficiency of the rectifier ($\eta_{\mathrm{RFtoDC,\ rectifier}}$) are given in Figure 8. The measured effective area at 866 MHz was approximately equal to 116 cm^2, which corresponds to a maximum of the conversion efficiency of about 40%.

The measured output DC voltage is also reported (see Figure 9). A maximum of V_{DC} of about 3 V was obtained with a resistive load of 10 kΩ, whereas, for the value of R_{LOAD} corresponding to the maximum of $\eta_{\mathrm{RFtoDC,\ rectenna}}$, a V_{DC} of about 1.67 V was measured.

In order to verify the level of matching between the antenna and the rectifier, and then the possibility of improving these results by using a matching network, measurements of the input impedance have been also performed both for the antenna and the rectifier. From experimental data, at 866 MHz the input impedance of the antenna is $(55+j20)\,\Omega$; as for the rectifier, a value of $(45-j17)\,\Omega$ has been obtained by using a resistive load of 992 Ω and an input power of about 10 dBm. From circuital simulations performed by using these measured values of impedances, the reflection coefficient between the antenna and the rectifier of about −18 dB, which is a good value of matching.

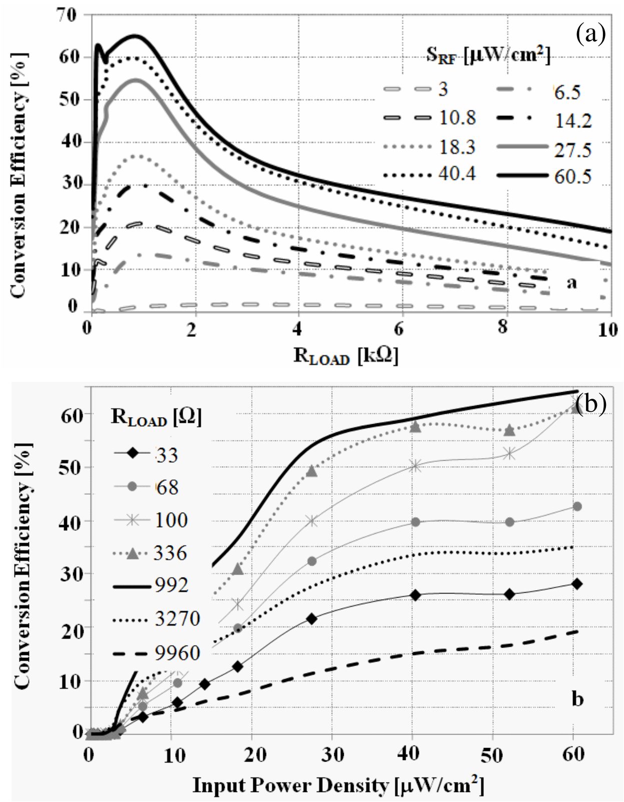

Figure 7. Measurements of $\eta_{\mathrm{RFtoDC,\ rectenna}}$: RF-to-DC conversion efficiency (a) as function of the load and (b) as function of the input power density.

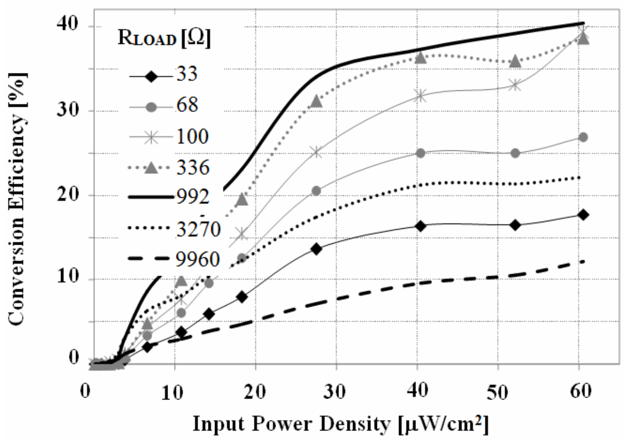

Figure 8. Measurements of $\eta_{\mathrm{RFtoDC,\ rectifier}}$ calculated by using the effective area of the antenna measured at 866 MHz.

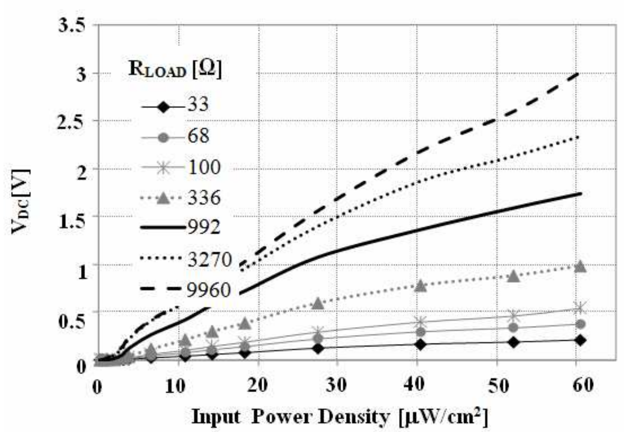

Figure 9. Measurements of the DC output voltage as function of the input power for different values of the resistive load.

Finally, some measurements by varying the frequency of the signal generated by the USRP were also carried out. In these measurements, the rectenna load was 992 Ω, while the power incident on the antenna was approximately kept constant at 60.5 μW/cm^2. Corresponding results are summarized in Figure 10; it can be noticed that by using (1) values greater than 60% were obtained over the entire operating frequency range of the FLEX900 daughterboard (i.e., [750, 1050] MHz).

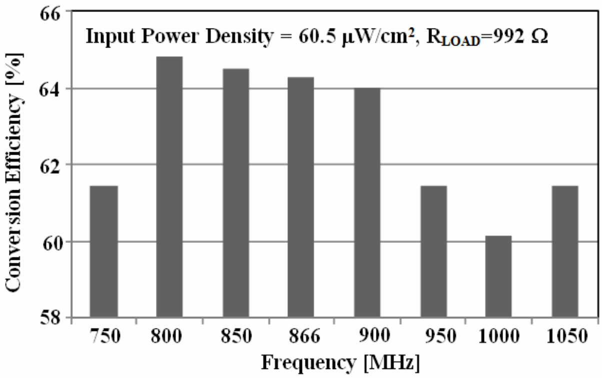

Figure 10. Measurements of $\eta_{\text{RFtoDC, rectenna}}$ for different values of the frequency of the RF input signal.

4. CONCLUSION

A rectifying antenna working in the UHF band has been presented. Reported experimental results demonstrate that the device here described is well suited to work at very low power level. In fact, from measurements performed with a 60.5 μW/cm^2 RF power density the conversion efficiency is greater than 60% over the entire frequency range [750 MHz, 1050 MHz], and it is approximately equal to 65% in the frequency range [850 MHz, 900 MHz]. These results suggest that the rectenna here proposed is an optimum candidate for the scavenging of signals associated to UHF RFID systems and to GSM devices.

REFERENCES

1. Takhedmit, H., et al., "A 2.45-GHz low cost and efficient rectenna," *Proc. of the 4th European Conference on Antennas and Propagation (EuCAP)*, Barcelona, Spain, Apr. 2010.
2. Monti, G., L. Tarricone, and M. Spartano, "X-band planar rectenna," *IEEE Antennas Wireless Propag. Lett.*, Vol. 10, 1116–1119, 2011.
3. Heikkinen, J. and M. Kivikoski, "Low-profile circularly polarized rectifying antenna for wireless power transmission at 5.8 GHz," *IEEE Microwave and Wireless Components Letters*, Vol. 14, No. 4, Apr. 2004.
4. Ali, M., G. Yang, and R. Dougal, "A new circularly polarized rectenna for wireless power transmission and data

communication," *IEEE Antennas Wireless Propag. Lett.*, Vol. 4, 205–208, 2005.

5. Heikkinen, J. and M. Kivikoski, "A novel dual-frequency circularly polarized rectenna," *IEEE Antennas Wireless Propag. Lett.*, Vol. 2, 330–333, 2003.
6. Strassner, B. and K. Chang, "Highly efficient C-band circularly polarized rectifying antenna array for wireless microwave power transmission," *IEEE Trans. Antennas Propag.*, Vol. 51, No. 6, 1347–1356, Jun. 2003.
7. Tikhov, Y., I.-J. Song, and Y.-H. Min, "Rectenna design for passive RFID transponders," *Proc. of the 37th European Microwave Conference*, Munich, Germany, Oct. 2007.
8. Chen, R.-H., Y.-C. Lee, and J.-S. Sun, "Design and experiment of a rectifying antenna for 900 MHz wireless power transmission," *Proc. of Asia-Pacific Microwave Conference, APMC 2008*, Macau, Dec. 16–20, 2008.
9. Seeman, K. and R. Weigel, "Ultra low power rectification in passive RFID tags at UHF frequencies," *Frequenz*, No. 59, 112–115, 2005.
10. Rizzoli, V., G. Bichicchi, A. Costanzo, F. Donzelli, and D. Masotti, "CAD of multi-resonator rectenna for micro-power generation," *Proc. of the 4th EuMIC*, Rome, Italy, Sep. 2009.
11. Riviere, S., F. Alicalapa, A. Douyere, and J.-D. Lan Sun Luk, "A compact rectenna device at low power level," *Progress In Electromagnetics Research C*, Vol. 16, 137–146, 2010.
12. Congedo, F., G. Monti, and L. Tarricone, "Broadband bowtie antenna for RF energy scavenging applications," *4rd European Conference on Antennas and Propagation (EuCAP)*, Rome, Apr. 11–15, 2011.
13. http://www.st.com.
14. Kuphaldt, T. R., *Lessons in Electric Circuits, Volume III — Semiconductors*, 5th edition, Apr. 2009, www.ibiblio.org/obp/electricCircuits.
15. http://www.cst.com/.
16. http://gnuradio.org/.
17. Ettus Research LLC website: http://www.ettus.com.