High-Efficiency Rectifier Circuit at 2.45 GHz for Low-Input-Power RF Energy Harvesting

Bruno R. Franciscatto[#*1,2], Vitor Freitas[#*1], Jean-Marc Duchamp[#1],
Christian Defay[*], Tan Phu Vuong[#1]

[#]*Université Grenoble-Alpes, IMEP-LAHC laboratory*
3 Parvis Louis Néel, CS 50257- 3801, Grenoble, France
[1]{bruno.franciscatto,freitasv,duchamp,tan-phu.vuong}@minatec.inpg.fr
[*]*Multitoll Solutions*
250 avenue des Grésillons, 92601, Asnières, France
[2]bruno.franciscatto@multitoll.fr

***Abstract*— this paper presents a new approach for a high-efficiency rectifier circuit design at 2.45 GHz. Due to nonlinear behavior it is not trivial to predict a correct model of a Schottky diode. When modeling, one should take into account the presence of the harmonics. To increase the conversion efficiency an electromagnetic resonant phenomenon is necessary. To validate this method, we developed a rectifier circuit capable of recovering signals at 2.45 GHz with a high RF-DC efficiency conversion. The prototype shows a maximum conversion efficiency of 70.4% for a RF input power of 0 dBm at 2.45 GHz.**

***Keywords*— rectifier circuit, RF-DC conversion efficiency, Schottky diode, wireless power transmission, harvesting.**

I. INTRODUCTION

Nowadays wireless power transfer is a promising technique for the long-term power supply of embedded wireless systems; e.g. health applications (glucose, body temperature and heart rate measurements) or industrial applications (gas detection sensor, temperature measurement, …). These systems need low power electronic and alternatives for battery feeding. Several research teams are working on the possibility to create autonomous systems by ambient energy harvesting (electromagnetic, solar, vibration, thermal, etc ...). The photovoltaic energy can provide a significant recovered power, 5 µW (panel size: 150 µm x 150 µm) [1]. A second solution is the vibration energy available, this source can provide up to 335 µW (piezoelectric, 2.25 ms^{-2}) [2]. Another possibility is the use of thermal energy with a possible recovery of about 250 µW (ambient indoor temperature) [3]. An interesting solution is based on the recovery of a radio frequency (RF) signal for supplying a DC power. It is possible to consider collecting up to 100 µW/cm ².

The first wireless power transmission can be dated back to many years ago when Tesla conducted his first successful experiment [4]. A good review in the context of high-power beaming, 1950s, is given in [5]. Recently, the RF energy harvesting has been the subject of numerous studies especially concerning the combination of an antenna and a rectifier circuit: *rectenna* [6], [7] and more recently in [8], was presented an interesting result of a rectenna at 2.45 GHz with a maximum conversion measured efficiency of 75% for a RF input power of about 0 dBm, but the result presented in [8] already takes into account the high-gain of the antenna to improve the conversion efficiency. In [9], another lately results where a compact rectenna using a double diode was presented.

This paper focuses on a new detailed approach for the design of a high-efficiency rectifier circuit. As the diode is not a linear device and may produce harmonic signals, it is not easy to formulate a perfectly correct model. Because of this nonlinear behavior, when the RF signal reaches the diode, harmonic signals will be generated and as a result this energy could be lost on the DC load or irradiated by the antenna. However, these harmonics can be trapped and remixed producing more DC power; a resonance phenomenon is created. Therefore, a careful combination of the rectifier circuit elements has to be considered. For our system, we consider an operating frequency of 2.45 GHz. This frequency is included in the ISM band (license-free industrial, scientific, and medical) where the maximum radiated power is in general 20 dBm. We assume a received RF power level of 0 dBm and this value is less than expected for practical applications in this frequency band. The rectifier circuit introduced in this paper has a high RF-DC conversion efficiency, 70.4%. In section II, we detail how to design a high-efficiency circuit, based on an electromagnetic resonance phenomenon in a rectifier circuit. Comparisons between the simulated and measured results are presented in section III. A summary of the results and a discussion on future work are given in Section IV.

II. RECTIFIER CIRCUIT DESIGN

A rectifier circuit RF-DC can be implemented with one or more Schottky diodes, a low-pass filter at the input of the circuit, a DC load (RF-block capacitor + resistor) and a matching network, as shown in Fig.1.

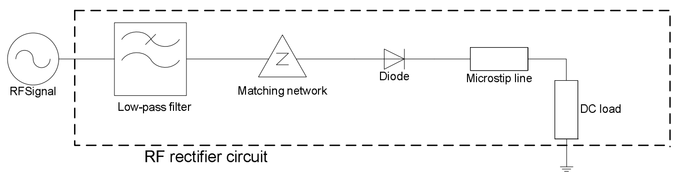


Fig.1: RF energy rectifier circuit.

Depending on the application, some elements of the rectifier circuit can be fused, e.g. low-pass filter and the matching network.

In the literature, different approaches have been proposed [10–12] to explain the best method to obtain a high conversion efficiency with a simple Zero-bias Shottky diode. Commonly, with a single diode (V-I quadratic), we expected a maximum 50% RF-DC conversion efficiency; instead, by applying different HF methods we can achieve a RF-DC efficiency up to 70%.

A. Conversion efficiency

The RF-DC conversion efficiency (η) is directly proportional to the DC power (P_{DC}) at the DC load terminals, divided by the RF input power (P_{RF}), (1). It is essential to increase the DC power in order to amplify the RF-DC efficiency.

$$\eta = \frac{P_{DC}}{P_{RF}} \quad (1)$$

In this paper the central point of the analysis is the rectifier circuit design, but a co-design with an antenna is also possible to set up a rectenna ("rectifying antenna").

B. Zero-bias Shottky diode modeling

The main component of the rectifier circuit is the Schottky diode; for this work the AGILENT HSMS-2855 [13] zero-bias Schottky detector diode was used. Zero-bias diodes are needed because they have relatively low barrier (high saturation current), which compared to externally biased detector diodes, results in a higher output voltage for low power inputs levels.

First an analytical equivalent model was developed to determine the input impedance of the diode Z_D at 2.45 GHz (f_0). This model has been validated by the diode S-parameters measurements. Then, from the Z matrix the input and output impedances of the diode were determined.

The analytical model was validated by using the diode model proposed by Agilent ADS software in a LSSP (Large Signal S-Parameter) simulation. Because of the nonlinear characteristics of the diode, the diode impedance should be observed as a function of RF input power.

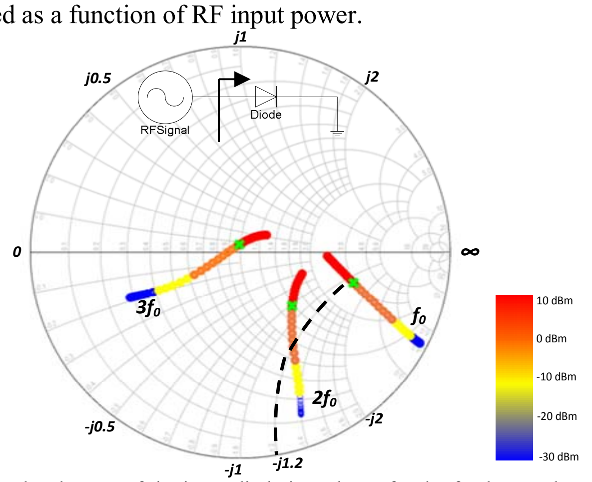


Fig.2: Simulated range of the input diode impedance for the fundamental RF signal (f_0), 1st ($2f_0$) and 2nd ($3f_0$) harmonics from -30 dBm to +10 dBm input RF power.

Fig. 2 shows the range of the input diode impedance for the fundamental RF signal (f_0), 1st ($2f_0$) and 2nd ($3f_0$) harmonics from -30 dBm to +10 dBm input RF power. A color gradient was used to indicate the input power variation; blue corresponds to low input power and red to high input power. The magnitude of the diode impedance becomes smaller with the increasing incident power. The marker X in Fig.2 corresponds to the diode impedance Z_D for a RF input power of 0 dBm. The impedance values (in Ω) are: $Z_{D(f0)}$= 147-j*63, $Z_{D(2f0)}$= 68-j*41 and $Z_{D(3f0)}$= 51+j*4.8.

C. Analysis of the electromagnetic resonance phenomenon in a rectifier circuit

In the simple case of a quadratic detector diode it is possible to show that in the frequency domain the result of a RF signal f_0 passage leads to two lines: a continuous (DC) and a second $2f_0$. The conversion efficiency is 50%. To increase the RF-DC conversion efficiency (1), using a Shottky diode it is necessary to remix the second line $2f_0$ then the $3f_0$ and so on. Therefore, the diode must be placed in a RF resonant structure. This is what we propose in this article. On the antenna side, a low-pass filter allows the RF excitation signal to pass but avoids that the harmonics be radiated by the antenna. Finally, on the load side we need a resistor, a specified microstrip line and a capacitor to short the RF energy. Furthermore, the microstrip line between the capacitor and the diode can increase the efficiency conversion. The optimization of these RF functions will be described below.

The resonance effect is generated when the imaginary part of the diode impedance (Z_D) is canceled out by the microstrip line together with the RF-block capacitor.

When the RF signal at 2.45 GHz passes through the diode, the signal is rectified. This means that in time domain, the negative part of the voltage cycle is canceled and at the frequency domain, some harmonics of the fundamental 2.45 GHz are generated. Subsequently, in order to deliver a DC voltage, this signal gets to a capacitive load, optimized to rectify the fundamental 2.45 GHz. Hence, when we analyze the output impedance of the diode, we are interested on a good match for the fundamental frequency, but it is important to present high mismatched impedance for the other harmonics, in order to reflect back, this creates a remix phenomenon that enables the regeneration of more DC energy.

Based on the diode impedance for a RF input power of 0 dBm (Fig.2), a microstrip line was designed to cancel out the imaginary part of the diode impedance (Z_D). The RF-block capacitor value was also optimized to achieve this resonant effect. Therefore, the impedance of the harmonics generated by the diode should also be studied.

Fig.3 shows the load impedance (Z_{Load}) for the fundamental RF signal (f_0), and harmonics $2f_0$, $3f_0$, $4f_0$.

For the fundamental f_0, the imaginary part of the load impedance (Z_{Load}) is the symmetric of the imaginary part of $Z_{D(f0)}$, for the $2f_0$ harmonic the load is viewed as an open circuit, for $3f_0$ harmonic the impedance load has a capacitive behavior and the $4f_0$ harmonic is a short-circuit, as shown in Fig.3.

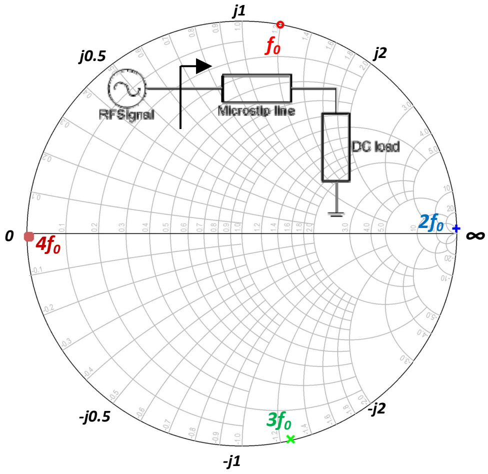


Fig.3: Simulated range of the load impedance (Z_{Load}) for the fundamental RF signal (f_0), harmonics $2f_0$, $3f_0$, $4f_0$.

Fig4. shows how the RF-DC efficiency changes according to the microstrip line length. In fact, by modifying the microstrip line length, we are varying the imaginary part of the microstrip line impedance. For an electrical length of 0.15 λg, the RF-DC efficiency is 68%.

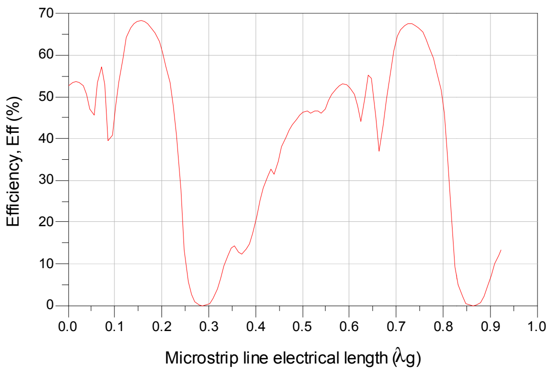


Fig.4: RF-DC conversion efficiency as function of the microstrip line length.

To exploit the maximum RF-DC conversion efficiency of the HSMS-2855 Shottky diode, an optimum load should be used. In Fig.5 the load impedance optimal for maximum RF-DC efficiency is presented. The optimum amplitude load impedance is exactly the opposed imaginary part of the diode impedance at f_0, i.e., $Z_{Load(f0)} = 63\ \Omega$.

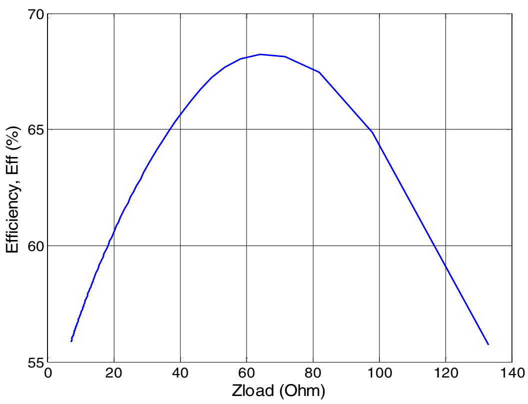


Fig.5: RF-DC efficiency versus load impedance

To achieve high RF-DC conversion efficiency careful combination of rectifier circuit elements has to be considered. For this purpose, Fig.6 shows the efficiency for each combination block in a rectifier circuit. Each curve is designed by connecting block by block in order to have the system complete.

When the diode is combined with a matching network and an optimized load (case #2), the theoretical RF-DC efficiency of 50% is achieved. With an optimized microstrip line added (case #3), i.e. the imaginary part of $Z_{D(f0)}$ is cancelled out, the efficiency increases by 16%. In case #4, a low-pass filter is added and we reach an efficiency of 68%. The filter blocks the harmonics generated by the diode and sends them back to the diode, contributing to the remix of energy.

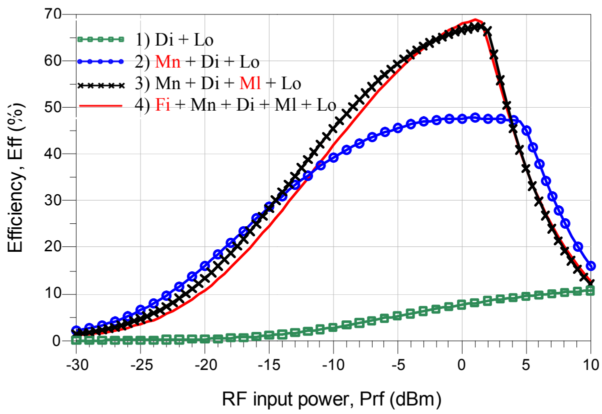


Fig.6: Efficiency by adding block by block in a rectifier circuit. *Di= diode, Lo=load, Mn=Matching network, Ml=Microstrip line, Fi=filter.

D. Optimized final circuit

The rectifier circuit has been designed and optimized using the "Harmonic Balance" (HB) method of AGILENT ADS. It is a frequency-domain simulator developed to take into account the nonlinear effects of the diode. The substrate used was Rogers RO4003; $\varepsilon r = 3.55$, $tan(\delta) = 0.0027$ and 0.8mm of thickness. The capacitor and the resistor values optimizing the performances of the system were selected to be 10 nF and 1.8 kΩ.

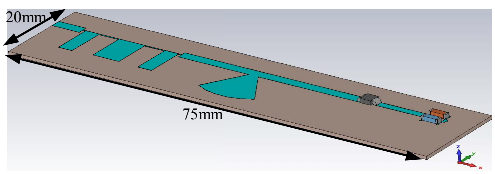


Fig.7: Layout of the final optimized rectifier circuit.

The simulated optimal RF-DC efficiency and the output DC voltage of the rectifier are 68 % and 1.2 V respectively, for a RF input power of 0 dBm.

III. Circuit Performance and Measurement Results

The prototype, Fig.9(b), has been fabricated in accordance with the layout shown in Fig.7. The measurement setup was as follows, Fig.8: a signal generator was connected on the SMA connector at the circuit input; by varying the RF input power the DC voltage was measured across the resistance load, and then the RF-DC conversion efficiency was derived from (1). In Fig.9(a) we compare the simulated and measured results.

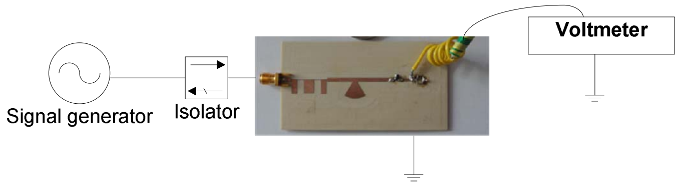
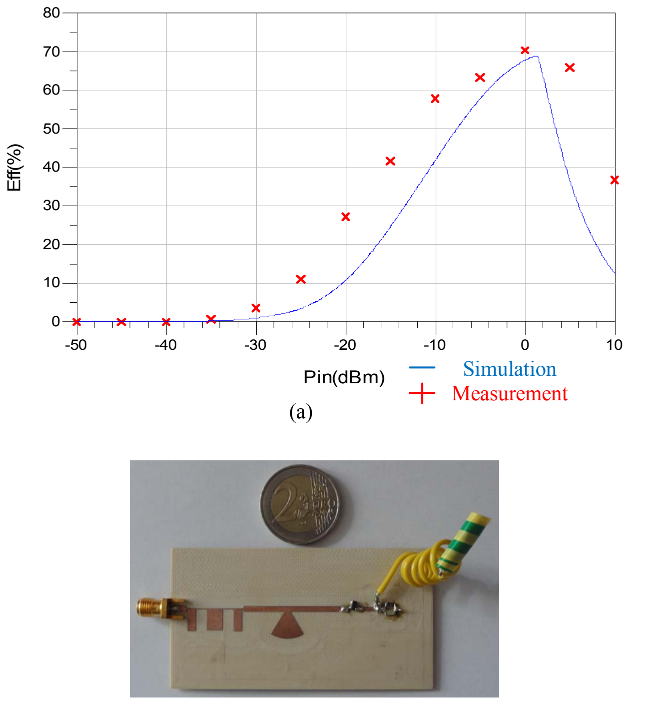


Fig.8: Rectifier circuit measurement setup.



(a)

(b)

Fig.9: (a) Measurement of the conversion efficiency as a function of the RF input power. (b) Photograph of the fabricated rectifier circuit.

Conversion efficiency measured was of 70.4% for 0 dBm input RF power. The authors think that the shift between the measurement and simulation comes from the diode model on the simulator, as because of the nonlinear behavior, predicting a fully correct model is not trivial. The energy remix in the real prototype can be more significant than on simulation.

IV. Conclusion and Perspectives

In this paper we presented a different approach to design a rectifier circuit with a high RF-DC conversion efficiency. Predicting a correct model for a Shottky diode is not obvious, due to nonlinear characteristics; the model should take into account the harmonics. To increase the conversion efficiency, a resonant phenomenon is necessary. The prototype measurements show a high RF-DC measured conversion efficiency of over 70% for a 0 dBm input RF power.

Future work is expected to switch the peak of RF-DC conversion efficiency for a lower-input RF power signal.

Acknowledgment

The authors are grateful to Multitoll Solutions Company for its support on this project.

References

[1] N. Guilar, A. Chen, T. Kleeburg, and R. Amirtharajah, “Integrated Solar Energy Harvesting and Storage,” *Proc. Int. Symp. Low Power Electronics and Design*, pp. 20–24, Oct. 2006.

[2] S. Roundy, E. Leland, J. Baker, E. Carleton, E. Reilly, E. Lai, B. Otis, J. Rabaey, P. Wright, and V. Sundararajan, “Improving power output for vibration-based energyscavengers,” *IEEE Pervasive Computing*, vol. 4, no. 1, pp. 28–36, Jan.-March 2005.

[3] V. Leonov, T. Torfs, P. Fiorini, and C. Van Hoof, “Thermoelectric Converters of HumanWarmth for Self-Powered Wireless Sensor Nodes,” *IEEE Sensors Journal*, vol. 7, no. 5, pp. 650–657, May 2007.

[4] M. Cheney, Tesla Man Out of Time. Englewood Cliffs, NJ: Prentice- Hall, 1981.

[5] W. C. Brown, “The history of power transmission by radio waves,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 1230–1242, Sept.1984.

[6] Y. H. Suh and K. Chang, “A high-efficiency dual-frequency rectenna for 2.45- and 5.8-GHz wireless power transmission,” *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 7, pp. 1784–1789, Jul. 2002.

[7] A. Slavova and A. S. Omar, “Wideband rectenna for energy recycling,” *in Proc. IEEE Antennas and propag. Society Int. Symp.*, Jun. 2003, vol. 3, pp. 954–957.

[8] H. Sun, Y. Guo, He, and Z. Zhong, "Design of a High-Efficiency 2.45-GHz rectenna for Low-Input-Power Energy Harvesting," *IEEE Antennas and Wireless Propagation Letters*, vol. 11, p. 929 -932, 2012.

[9] S.Ladan; N. Ghassemi; A. Ghiotto; Ke Wu, "Highly Efficient Compact Rectenna for Wireless Energy Harvesting Application," *Microwave Magazine, IEEE* , vol.14, no.1, pp.117,122, Jan.-Feb. 2013

[10] J. A. G. Akkermans, M. C. van Beurden, G. J. N. Doodeman, and H. J. Visser, “Analytical models for low-power rectenna design,” *IEEE Antennas Wireless Propag. Lett.*, vol. 4, pp. 187–190, 2005.

[11] T.-W. Yoo and K. Chang, “Theoretical and experimental development of 10 and 35 GHz rectennas,” *IEEE Trans. Microw. Theory Tech.*, vol. 40, no. 6, pp. 1259–1266, Jun. 1992.

[12] J. Joe and M. Y. W. Chia, “Voltage, efficiency calculation and measurement of low power rectenna rectifying circuit,” *IEEE AP-S Int. Symp.*, Jun. 1998, vol. 4, pp. 1854–1857.

[13] Diode Agilent HSMS-2850, Datasheet.