INVITED PAPER *Special Section on Microwave and Millimeter-Wave Technology*

Rectenna Design and Signal Optimization for Electromagnetic Energy Harvesting and Wireless Power Transfer

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SUMMARY This work addresses two key topics in the field of energy harvesting and wireless power transfer. The first is the optimum signal design for improved RF-DC conversion efficiency in rectifier circuits by using time varying envelope signals. The second is the design of rectifiers that present reduced sensitivity to input power and output load variations by introducing resistance compression network (RCN) structures.

key words: *rectenna, energy harvesting, wireless power transfer, resistance compression network, rectifier*

1. Introduction

The massive development of concepts such as the smart cities and the Internet of Things (IoT) require a large amount of sensors to be spread in the surrounding environment in order to provide us with useful information. In order to make these concepts a reality this large quantity of sensors and devices need to be autonomous and self-sustained in order to avoid the costly maintenance of battery replacement [1], [2].

In order to achieve the required sensor energy autonomy the use of energy harvesting and wireless power transfer solutions have been proposed. When considering energy harvesting the main drawback is that the amount of available energy from the available energy sources (solar, electromagnetic, thermal or mechanic) is variable and sometimes unpredictable. As the harvesting systems are designed for specific operating conditions deviation from them may cause a dramatic drop in the harvester efficiency. Several advances aiming at improving the efficiency of energy harvesters have been proposed in the literature [3]–[9] focusing both on the antenna and the rectifier circuits.

Energy harvesters are designed to operate at certain input power levels and certain output load values, however real scenarios may not match the optimum operation conditions at all times. Structures that aim at maintaining the RF-DC conversion efficiency independently of variations in the input power level and output load time variations have been proposed [10], [11] based on resistance compression networks (RCN). Originally they have been used in DC-DC converter circuits to compensate for variations in the rectifier loads [10]. In [11] the use of a dual band RCN was proposed to be used in dual band rectifier circuits for energy harvesting and wireless power transfer.

Another field that is attracting attention is the use of time-varying envelope signals to improve the RF-DC conversion efficiency in wireless power transfer systems. Several works have shown that under certain operating conditions it is possible to obtain improvement in the efficiency if using multi-sine, chaotic or modulated signals [12]–[19].

In this paper several aspects and advances in these two topics will be presented.

2. Signal Selection for Optimum Rectifier Performance

It has been shown in the literature that signals with time-varying envelope and high peak-to-average power ratio (PAPR) may under certain conditions operate rectifier circuits in a more efficient manner, which leads to improved performance in terms of RF-DC conversion efficiency [12]–[19]. The underlying motive for this is that high PAPR signals take advantage of the nonlinear dynamics of rectifying devices and make them operate in a region of their (i-v) curve that lead to larger mixing products at the desired DC output.

Several experiments have been performed using a 433 MHz rectifier (Fig. 1). The selected topology is an envelope detector with a Schottky diode as the rectifying element (Skyworks SMS7630-02LF). The rectifier operates at 433 MHz using a suitable LC matching network, and has an output RC filter with C = 100 pF and R_{load} = 5.6 KOhm.

The selected time-varying envelope signals used in the experiments are a chaotic signal, a white noise signal and an OFDM signal, all of them presenting a high PAPR (Table 1). A single carrier signal is also used in the experiments for comparison.

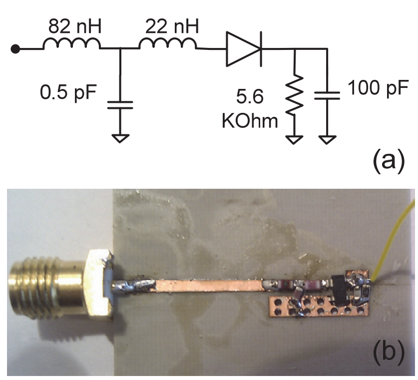

Fig. 1 Rectifier circuit at 433 MHz. (a) Schematic of the envelope detector rectifier, (b) photo of the prototype.

Manuscript received April 3, 2015.

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DOI: 10.1587/transele.E98.C.608

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The performance of the rectifier circuit under different input signals is evaluated in terms of RF-DC conversion efficiency (see Eq. (1)). In order to make a fair comparison both the single carrier and all the time varying signals used (Table 1) have the same average power in a 6 MHz bandwidth around 433 MHz. A commercial band-pass surface acoustic wave (SAW) filter was used to limit the signal bandwidth to 6 MHz.

The used measurement set-up is depicted in Fig. 2, where a power splitter is used to divide the signal between the rectifier circuit and an oscilloscope that is used to accurately measure the amount of power that reaches the rectifier circuit. The measured power is used to calculate the RF-DC conversion efficiency in Eq. (1).

$$\eta = \frac{P_{DC}}{P_{RF\_in}} = \frac{V_{DC}^2/R_L}{P_{RF\_in}} \tag{1}$$

The obtained measured results are shown in Fig. 3, where it can be seen that for this specific experiment the signals with higher PAPR lead to larger improvement in the RF-DC conversion efficiency. Specifically, in the case of a chaotic signal with a PAPR of 14.8 dB the efficiency is approximately 20% larger compared to a single carrier signal. The precise theoretical conditions corresponding to circuit design parameters and signal parameters which result in an efficiency improvement at a given average input power represent the object of future work.

Table 1 Measured PAPR of selected signals.

Type	PAPR (dB)
Single carrier	3
Chaotic	14.8
White noise	13.7
OFDM	12

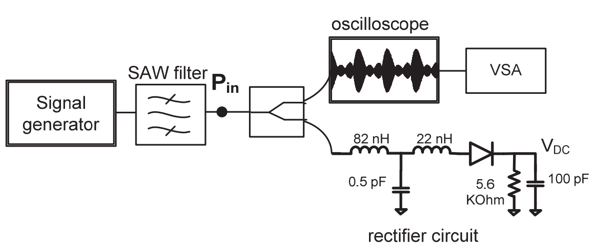

Fig. 2 Measurement set-up.

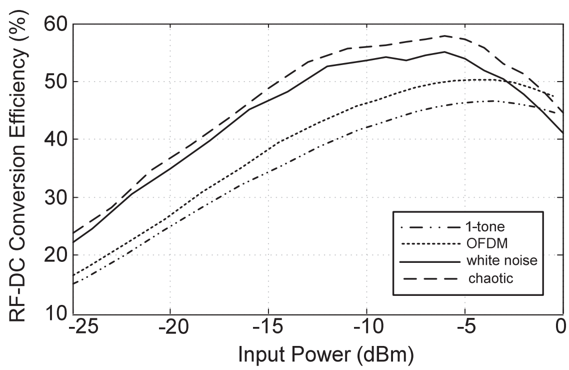

Fig. 3 Comparison of RF-DC of the rectifier in Fig. 1 under different input signals.

3. Resistance Compression Networks for Improved Rectifier Performance

One of the major issues to address when designing rectifier circuits is the fact that they are usually designed to operate for a certain level of input power and for certain load conditions. However, real scenario conditions suffer from variations in the received power levels and also in the load which due to the nonlinearity of the rectifying device may also cause load variations. Deviation from the design conditions causes the performance of the rectifier to degrade causing un-matching of the circuit and consequently reduction in RF-DC conversion efficiency. A circuit topology that has been proposed to overcome this problem is the use of resistance compression networks (RCN) [10], [11].

Resistance compression networks are circuits that are capable to minimize their input resistance variation under large output load variations. RCN are formed by two parallel braches, each of them loaded with the same load. Each of the branches is formed by reactive elements that produce resistance compression and transformation. The main characteristic that the two branches have to fulfill to achieve the resistance compression is that their input impedance has to be of equal magnitude and opposite phase at the design frequency.

When designing RCN based rectifiers the output load of the two branches of the RCN is the rectifying element together with the output DC load (Fig. 4), which is a com-

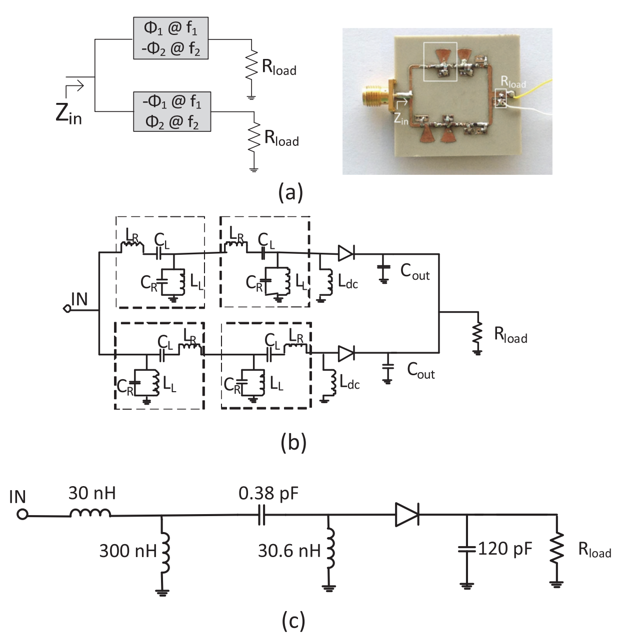

Fig. 4 Dual band rectifier with resistance compression network, a) circuit block diagram and fabricated prototype, b) circuit topology (L_R = 8.7 nH, L_L = 100 nH, C_R = 0.8 pF, C_L = 2.7 pF), c) dual band envelope detector rectifier used in the comparisons.

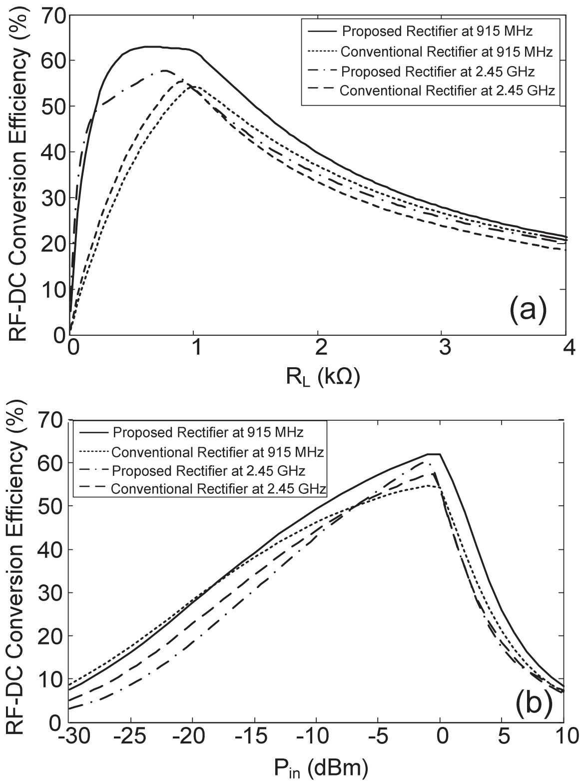

Fig. 5 RF-DC conversion efficiency versus (a) output load, (b) input power.

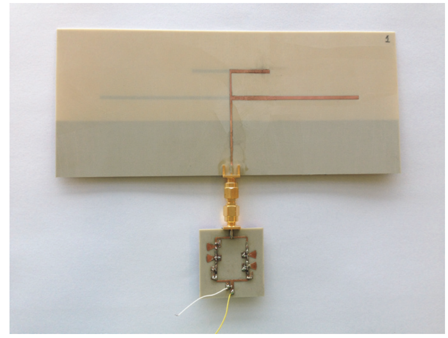

Fig. 6 Prototype of the RCN-based rectenna element.

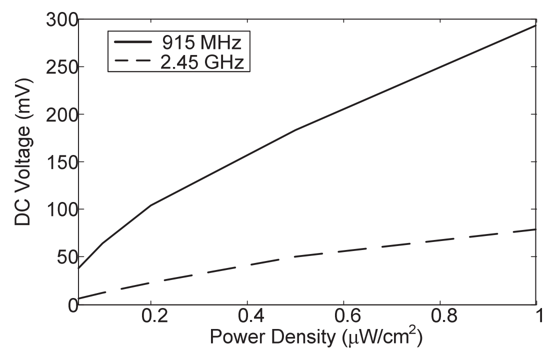

Fig. 7 Obtained DC voltage using the RCN-based rectifier versus power density.

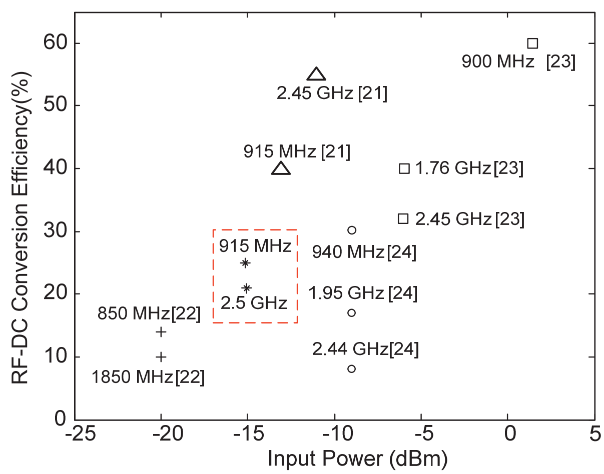

Fig. 8 Comparison of RF-DC conversion efficiency in multi-band rectifiers.

plex load. Here a dual band RCN-based rectifier is presented that operates at 915 MHz and 2.45 GHz. The two branches of the RCN are designed to present compression properties at both operation frequencies by using reactive circuits formed by series and shunt LC networks. In order to achieve equal magnitude and opposite phase response the reactive circuitry in the lower branch is the same network as in the upper branch but mirrored. The proposed structure for the RCN is shown in Fig. 4. Instead of considering only one reactive cell per branch, two cells have been used in order to have more flexibility in the design. The fabricated prototype is shown in Fig. 4 (a).

In order to evaluate the performance of the RCN-based rectifier, it has been compared to the performance of a conventional envelope detector rectifier also operating in the 915 MHz and 2.45 GHz frequency bands. Figure 5 shows the RF-DC conversion efficiency for both circuits. The proposed RCN-based rectifier presents less variation in the RF-DC conversion efficiency versus variations in the input power level (Fig. 5 (b)) and in the output load (Fig. 5 (a)).

Using the designed RCN-based rectifier, a rectenna element has been designed and its performance evaluated for different incoming power densities (Fig. 6). The used antenna in a series fed printed dipole pair antenna [20] designed to have dual-band operation at 915 MHz and 2.45 GHz. The antenna is fabricated in the same Arlon A25N substrate used for the RCN-based rectifier and presents 4 dB gain at 915 MHZ and 4.8 dB gain at 2.45 GHz.

The obtained DC voltage by using this RCN-based rectenna is measured for different power densities (Fig. 7) showing that the harvested DC voltage can reach 300 mV at 915 MHz and 75 mV at 2.45 GHz for power densities of 1 μW/cm^2.

A comparison of different multiband rectifiers in the literature has been made in order to evaluate the performance of the presented RCN-based rectifier with respect to the state-of-the-art. Figure 8 shows the RF-DC conversion efficiency of different multi-band rectifier designs versus input power levels. The presented RCN-based rectifier performance is highlighted in a dashed square.

4. Conclusion

There has been significant progress recently in the design of wireless power transfer systems. Nonetheless, further developments are foreseen addressing issues such as the optimum signal and device characteristics which result in higher RF-DC conversion efficiency, multiband operation, and reducing the sensitivity of the rectifying circuits to input power and output load variations. This paper highlights recent results in the above topics. It is shown that signals with high PAPR can lead, under certain input power and output load conditions, to higher RF-DC conversion efficiency compared to continuous wave signals. Resistance compression networks can be employed to reduce the sensitivity of a rectifier to output load. In this paper, dual band operation of a resistance compression network is demonstrated.

Acknowledgments

This work was supported by the Spanish Ministry of Economy and Competitiveness and FEDER funds through the project TEC2012-39143, the Generalitat de Catalunya under grant 2014 SGR 1551 and the EU COST Action IC1301 Wireless Power Transmission for Sustainable Electronics.

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