Dual-Band Rectifier Based on Resistance Compression Networks

Kyriaki Niotaki, Apostolos Georgiadis, Ana Collado
Centre Tecnologic de Telecomunicacions de Catalunya (CTTC), Castelldefels, 08860, Spain
kniotaki@cttc.es, ageorgiadis@cttc.es, acollado@cttc.es

Abstract — This work presents the design of a dual-band rectifier operating at 915 MHz and 2.45 GHz with minimized sensitivity to input power and load variations. The rectifier is designed using a dual-band resistance compression network (RCN) for minimizing the effect of input power and load changes and it is based on Composite Right/Left-Handed (CRLH) to implement the dual band operation. The resulting rectifier has shown good RF-DC conversion efficiency and reduced sensitivity to variations.

Index Terms — CRLH, resistance compression network, rectenna, energy harvesting, metamaterial, dual-band rectifier.

I. INTRODUCTION

Ambient energy harvesting has received special attention recently due to the need of autonomous and self-sustained devices and sensors towards the implementation of the internet of things, smart cities and machine to machine communications concepts, to name a few. Aiming to maximize the amount of harvested energy, several approaches have been followed for the design of rectenna circuits with multi-band or broadband capabilities [1- 5], as these circuits can harvest simultaneously the available power from different frequency bands.

However, the rectennas are usually designed for a specific value of input power and consequently variations in the amount of available power in the surrounding environment, produce changes in the input impedance of the rectifier and additionally in the rectifier performance [5]. The same applies to variations in the output load of the rectifier.

The design of matching networks for multi-band or broadband operation of the rectifier is of great importance in order to deliver maximum power from the source to rectifying device. One of the main challenges in the design of dual band rectifiers is to match the rectifier in two frequency bands and at the same time minimize the sensitivity of the rectifier to changes in the input power level or in the output load.

A solution to minimize the sensitivity of the rectifier is to use resistance compression networks (RCN) that allow achieving small variations in the input impedance of the rectifier even under large variations of input power levels and output load values. Until now, resistance compression networks that operate at a single frequency have appeared in the literature [6]. In this work a dual band RCN is proposed.

Additionally, taking advantage of the properties of metamaterial transmission lines that allow synthesizing dual-band networks with arbitrary frequencies [7], a dual-band metamaterial RCN (MRCN) is designed.

The implemented prototype is a dual-band MRCN rectifier operating at 915 MHz and 2.45 GHz that shows good RF-DC conversion efficiency and minimized sensitivity to input power and output load variations.

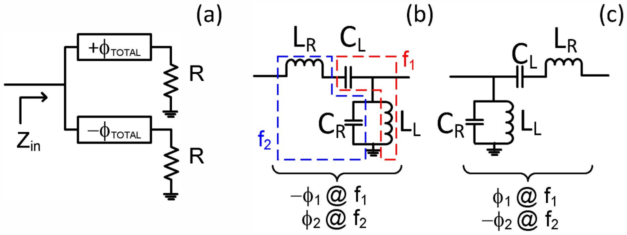

Fig. 1. Dual-band resistance compression network.

II. DUAL-BAND RESISTANCE COMPRESSION NETWORK THEORY

Due to the nonlinear nature of rectifying devices, variations in the input power (P_{in}) and output load (R_{load}) produce changes in the input impedance of the rectifier circuit and consequently the overall performance of the rectifier circuit is affected.

In order to minimize the effect of these variations in the input impedance of the rectifier, a resistance compression network (RCN) is designed. The RCN [6] allows minimizing the sensitivity of the rectifier to changing input power and load conditions. The basic structure of the RCN consists of two branches that present opposite phase conditions at the design frequency (Fig. 1a). The input impedance Z_{in} of the RCN will suffer very small variations independently of the large variations in R_{load} or P_{in}, which allows maintaining the matching of the rectifier circuit to the selected source independently of the variations in R_{load} or P_{in}.

In order to design a dual-band rectifier operating at f_1 and f_2, a metamaterial based resistance compression network (MRCN) is designed taking advantage of the properties of the CRLH metamaterial transmission lines that allow synthesizing arbitrary dual-band frequency responses [7]. The CRLH basic cell consists of series connected left-handed (LH) and right-handed (RH) cells with different propagation properties [7] (Fig. 1b). The CRLH structures exhibit a LH behavior at the low frequency (f_1) and RH response at the high operating frequency (f_2) as C_R (C_L) and L_R (L_L) tend to be open (short) and short (open) at f_1 (f_2).

In terms of implementing the RCN using the CRLH metamaterial cells one has to take into account that the unit cell in Fig. 1b presents a negative phase response $-\phi_1$ at f_1 (ϕ_2 at f_2), while the unit cell in Fig.1c where the components have been rearranged presents a positive phase response ϕ_1 at f_1 ($-\phi_2$

978-1-4799-3869-8/14/$31.00 ©2014 IEEE

at f_2). Taking advantage of this equal but opposite phase response in the units cells in Fig. 1b and Fig. 1c, a MRCN can be designed to be used as matching network in a dual-band rectifier circuit, in order to reduce the sensitivity of the rectifier to output load and input power variations.

III. DUAL BAND MRCN RECTIFIER

The dual-band MRCN is used here as the impedance matching network that needs to be placed between the antenna and the rectifier circuit. The proposed MRCN rectifier circuit is shown in Fig. 2 and its performance is compared with the operation of a conventional envelope detector rectifier (Fig. 3) in order to verify that the proposed rectifier is less sensitive to input power and load variations. The selected rectifying device in both circuits is the Skyworks Schottky diode SMS7630. The rectifiers are designed to have a dual band operation, maximizing their RF-DC conversion efficiency at 915 MHz and 2.45 GHz.

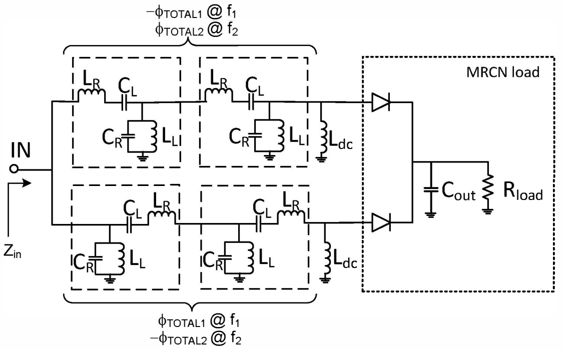

Fig. 2. Schematic of the MRCN rectifier circuit.

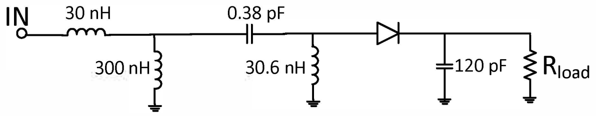

Fig. 3. Schematic of the comparison single diode rectifier circuit.

In the proposed MRCN rectifier (Fig. 2) each of the branches in the MRCN is composed of two CRLH metamaterial cells and a Schottky diode. The CRLH metamaterial cells are placed in such a way that the total phase in each of the branches has the same magnitude but opposite sign (Fig.2) at the two operating frequencies. The rectifier is designed to be resistive at the operating frequencies by cancelling the imaginary part of the diode impedance. The outputs of the two branches are connected to a common output load (R_{load}). The output capacitance C_{out} provides an RF short that isolates the two branches at RF frequencies. The two branches however are DC coupled, which affects the diode impedance and is taken into account during the circuit simulation. A 50 Ohm source is assumed at the input.

The MRCN rectifier is optimized to maximize the RF-DC conversion efficiency at f_1 and f_2 and to minimize the sensitivity of the rectifier to variations in the input power levels and load resistance values. The optimization is done using harmonic balance in combination with optimization goals to impose constraints on the minimum RF-DC conversion efficiency [4,8] and large signal scattering parameter (LSSP) analysis is used to impose constraints on the input matching (Z_{in}) to minimize its variation versus R_{load} or P_{in}. The resulting components values for the MRCN rectifier are shown in Table I.

TABLE I

MRCN RECTIFIER COMPONENT VALUES

Components	Values	Components	Values
L_R	8.7 nH	C_R	0.8 pF
L_L	100 nH	C_L	27 pF
L_{dc}	100 nH	C_{out}	120 pF

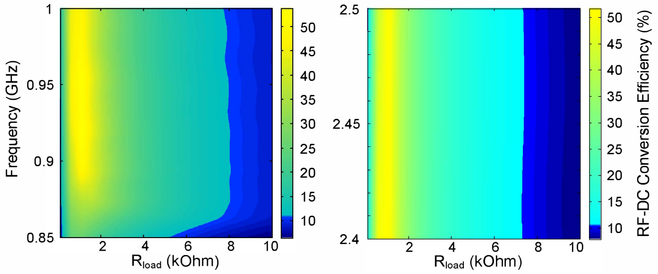

Fig. 4. RF-DC conversion efficiency of the single-diode rectifier for an input power of 0 dBm.

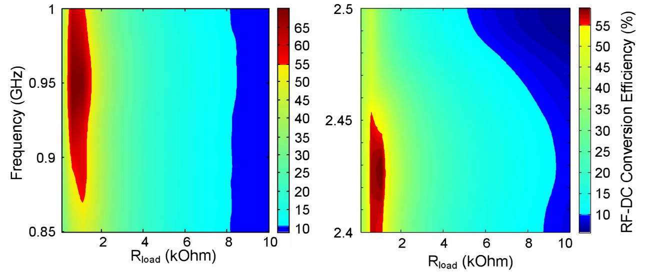

Fig. 5. RF-DC conversion efficiency of the MRCN rectifier for an input power of 0 dBm.

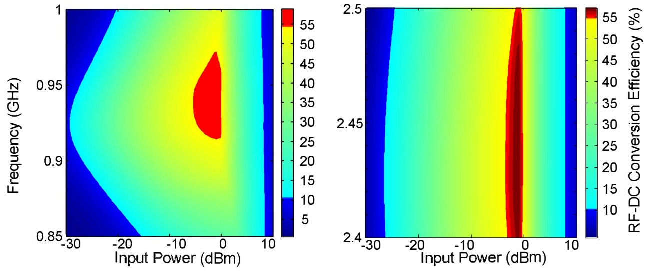

Fig. 6. RF-DC conversion efficiency of the single-diode rectifier for R_{load}=1 kOhm.

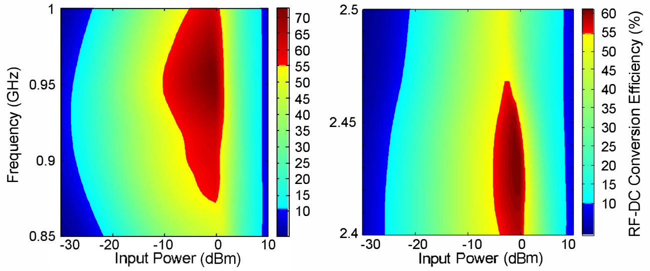

Fig. 7. RF-DC conversion efficiency of the MRCN rectifier for R_{load}=1 kOhm.

The performance of the proposed topology is compared with the performance of the dual-band single diode rectifier circuit in Fig. 3. This rectifier uses a dual band matching network and is optimized for maximum RF-DC conversion efficiency at the two selected frequencies.

Fig. 4 and Fig. 5 show the simulated RF-DC conversion efficiency of the two rectifiers versus R_{load} for an input power level of 0 dBm. Fig. 6 and Fig. 7 show the RF-DC conversion efficiency for an output load of 1 kOhm versus the input power. It can be observed that the MRCN rectifier circuit shows improved performance in terms of RF-DC conversion efficiency compared to the single diode rectifier and it is less sensitive to input power and output load variations.

IV. EXPERIMENTAL RESULTS OF THE MRCN DUAL-BAND RECTIFIER

The designed MRCN rectifier was implemented and tested (Fig. 8). The capacitor C_R was implemented as a radial stub with width W=1.05 mm, length L=4.55 mm and angle 45°. A comparison of the simulated and measured values of the RF-DC conversion efficiency and input matching for an input power level of – 15 dBm is shown in Fig. 9 and Fig. 10 respectively showing reduced sensitivity to variations in the output load. Fig. 11 shows the RF-DC conversion efficiency versus input power level for the two frequencies of operation.

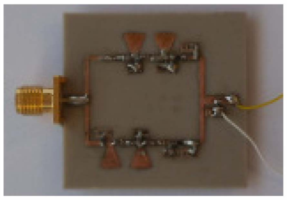

Fig. 8. Fabricated MRCN rectifier prototype.

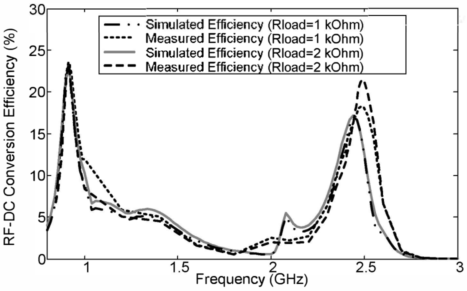

Fig. 9. Simulated and measured RF-DC conversion efficiency versus frequency for an input power of -15 dBm.

V. CONCLUSION

This paper presents the design of a dual-band rectifier with reduced sensitivity to input power and output load variations. The design is based on the use of a resistance compression network for minimizing the sensitivity and metamaterial cells for achieving dual-band operation. The result is a metamaterial resistance compression network (MRCN) rectifier that shows improved performance when compared to classical rectifier implementations.

VI. ACKNOWLEDGMENT

This work was supported by the Spanish Ministry of Economy and Competitiveness and FEDER funds through the project TEC2012-39143, and the EU Marie Curie FP7-PEOPLE-2009-IAPP 251557. This work was also supported by the COST Action IC1301 Wireless Power Transmission for Sustainable Electronics (WIPE).

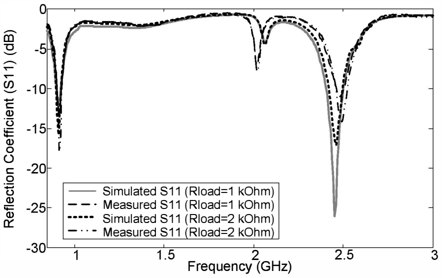

Fig. 10. Simulated and measured S_{11} for R_{load}=1 kOhm and 2 kOhm

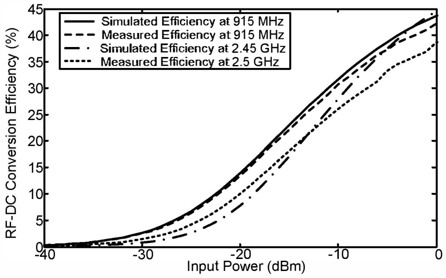

Fig. 11. Simulated and measured RF-DC conversion efficiency versus input power level for 1 kOhm load value.

REFERENCES

[1] J. A. Hagerty, F. B. Helmbrecht, W. H. McCalpin, R. Zane, and Z. B. Popovic, "Recycling ambient microwave energy with broad-band rectenna arrays," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 3, pp. 1014–1024, Mar. 2004.

[2] 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.

[3] A. Collado and A. Georgiadis, "Conformal Hybrid Solar and Electromagnetic (EM) Energy Harvesting Rectenna," *IEEE Trans. Circuits Syst. I*, vol. 60, no. 8, pp. 2225-2234, Aug. 2013.

[4] V. Rizzoli, G. Bichicchi, A. Costanzo, F. Donzelli, and D. Masotti, "CAD of multi-resonator rectenna for micro-power generation," *in Proc. EuMC*, Rome, Italy, Oct. 2009, pp. 1684–1687.

[5] A. Boaventura, A. Collado, N.B. Carvalho, and A. Georgiadis, "Optimum behavior: Wireless power transmission system design through behavioral models and efficient synthesis techniques," *IEEE Microwave Mag.*, vol. 14, no. 2, pp.26–35, 2013.

[6] Y. Han, O. Leitermann, D.A. Jackson, J.M. Rivas, and D.J. Perreault, "Resistance Compression Networks for Radio-Frequency Power Conversion," *IEEE Trans. Power Electron.*, vol.22, no.1, pp. 41-53, Jan. 2007.

[7] C. Caloz, T. Itoh, Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications, Ed. New Jersey: Wiley, 2006.

[8] A. Georgiadis, G. Andia-Vera and A. Collado, "Rectenna design and optimization using reciprocity theory and harmonic balance analysis for electromagnetic (EM) energy harvesting," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 444-446, 2010.