IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 28, 2020, accepted March 20, 2020, date of publication April 9, 2020, date of current version May 1, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2986797

A Sensitive Triple-Band Rectifier for Energy Harvesting Applications

HAMZA TAFEKIRT[1], JOSE PELEGRI-SEBASTIA[2], (Senior Member, IEEE), ADEL BOUAJAJ[1], AND BRITEL MOHAMMED REDA[1], (Member, IEEE)

[1]Department of Electrical and Industrial Engineering, National School of Applied Science of Tangier, Tangier V6B1G8, Morocco
[2]IGIC Institute, Universitat Politècnica de València, Campus Gandia, 46730 Gandia, Spain

Corresponding author: Jose Pelegri-Sebastia (jpelegri@upv.es)

This work was supported in part by the EMMAG Program, 2014, funded by the European Commission.

ABSTRACT This paper presents a novel sensitive triple-band power rectifier for RF energy harvesting systems. The proposed rectifier can simultaneously harvest RF energy from GSM-900, GSM-1800, and Wi-Fi-2450 bands at relatively low and medium ambient power densities. Previously, a few multi-band rectennas have been reached a stable conversion efficiency overall frequency bands of interest because of the nonlinearity and the distinct input impedance of the rectifying circuit at these frequencies. The originality of this paper is on the improved impedance matching technique that enhances the efficiency and performance of the rectifier. The proposed high-efficiency triple-band rectifier consists of three parallel branches. Each branch comprises an input matching circuit designed to provide maximum RF power transferred to rectifying diodes, a single voltage doubler using Schottky diode HSMS-2852, and a DC-pass filter to smooth the DC output voltage. A prototype of the proposed rectifier circuit is fabricated and tested to verify its performance against the simulation results. With an optimum load resistance of 3.8 kΩ at -10 dBm input power level, the measured RF to DC conversion efficiency achieves 33.7%, 21.8%, and 20% at 0.9, 1.8 and 2.45 GHz respectively. The efficiency is above 46.5 % overall bands of interest under 0 dBm input power.

INDEX TERMS RF energy harvesting, RF to DC conversion efficiency, Schottky diode, triple-bands rectifier.

I. INTRODUCTION

On one hand, wireless applications (FM, TV, GSM, WIFI, WIMAX ....) used by wireless communication systems such as portable entertainment systems and health care devices, are widely presented in the urban environment. Most of these emissions are omnidirectional and permanent. On the other hand, the power consumption of electronic devices is reduced due to the development of micro-technologies systems. These systems are electronic devices of reduced size often consists of an ultra-low power microcontroller of very low power consumption, sensors and antennas. However, there is also in these devices an embedded power source in the form of batteries or batteries that require replacement operations or periodic recharging which can penalize the mobility and deployment of these systems. The classic sustainable energy is solar or wind power that unfortunately does not correspond to the challenge of conceiving a wireless communication system with simple structure, compact-size and low-cost. This situation offered a fertile field of research to use the radio-frequency (RF) energy. This energy can power these low-power electronic devices and replace the batteries, which saves maintenance cost that gives birth to RF energy harvesting.

Rf energy harvesting consists of converting energy from the electromagnetic (EM) field into the electrical domain which is a challenging task for researchers. The main drawback of the RF energy harvesting is the very low RF power density in the ambient environment, which penalize the RF to DC conversion efficiency. Indeed, and despite the low available power density, RF energy recovery has certain advantages, among which is the fact that radio waves can propagate through materials such as plastic, wood, plasterboard and concrete. So, we can consider this energy as a renewable source of energy that is available in several frequencies, that propagates in all directions and present at all times. To maxi-

The associate editor coordinating the review of this manuscript and approving it for publication was Rami Ghannam.

mize harvested ambient RF energy, the device used should be able to receive the RF signals from multiple frequency bands in the ambient environment. The solution that emerged to meet these requirements is the rectenna (rectifying antenna). A multi-band rectenna can be an appropriate solution to collect energy from several standards with often unbalanced power levels, therefore the amount of harvested energy is increased. It has several advantages amongst which, the lack of replacement due to its unlimited lifetime and environment-friendly as no deposition pollutes the environment.

In the literature, several rectifier topologies are investigated. Single narrow bands frequencies rectifiers with high efficiency are reported in [1]–[3]. In [1], authors used a rectenna operated at 889 MHz with a maximum RF to DC conversion efficiency of 45.9% is achieved for -10dBm input power. In [2], a rectifier showed an efficiency of 65% for 0-dBm input power at 1.8GHz. Finally, the rectenna in [3] with Differentially-Fed Rectifier showed a maximum efficiency of 73.9% under the input power of 10dBm at 2.45 GHz. Despite the high efficiency of these rectifiers, the DC output voltage is still limited and is not able to provide enough energy to supply microsystems or wireless sensor network (WSN), and needs a high input power level. To collect more surrounding energy from several frequency bands simultaneously, many research teams have carried out numerous designs, such as broadband [4], [5], and multi-band rectifiers [6]–[11] with different topologies. In [4], authors have used a broadband reconfigurable rectenna with a tunable matching network. The measured rectifier efficiency was varied between 42.7% and 54.3% when frequency increases from 5.1 to 5.8 GHz, for 16.5 dBm input power level. Another broadband rectifier was investigated in [5], the obtained conversion efficiency was around 50% within the band from 1.6 GHz to 2.8 GHz at 18 dBm received power. The broadband approach often suffers from poor impedance matching, which affects the overall RF to DC conversion efficiency. Therefore, the multi-band approach comes out as the optimal alternative for rectifier design. A dual-band harvesting system was used in [6], the obtained rectifier efficiency was 48% and 39% for an input power level of 0 dBm at 915 MHz and 2.45 GHz, respectively. Another dual-band rectifier was investigated in [7], operating at 2.1 GHz and 2.45 GHz, for an input power of 10 dBm. The achieved maximum efficiency was 24% and 18%, respectively. In [8], a dual-band rectenna was used, and a peak RF to DC conversion efficiency of 64% and 52% for an input power of 4 dBm was achieved at 0.89 GHz and 1.88 GHz, respectively. A dual-port triple-band rectenna operating at GSM-900, GSM-1800, and UMTS-2100 was presented in [9]. The peak conversion efficiency at the three bands are 35%, 30%, and 25%, respectively, when the input power was −10 dBm. Reference [10] reported a four-band rectifier using a resonant matching network. When the input power was 10 dBm, the maximum RF-to-dc conversion efficiency was only 50%, 54%, 24%, and 18% at 1.3 GHz, 1.7 GHz, 2.4 GHz, and 3.6 GHz, respectively. Finally, the rectenna in [11] was designed on a paper substrate, with the obtained RF-to-dc conversion efficiency was comprised between 40% and 32% for the available input power of 0 dBm over the frequency band from 1.71 GHz to 2.69 GHz. Unfortunately, most reported rectifiers are bulky or reach a high conversion for high input power density. Nevertheless, they achieve very low conversion efficiency for low input power, Since the ambient RF energy resources are usually available only at a low power level. Thus, more studies are still needed to satisfy the requirements of micro-devices, such as sensitivity at low input power, total size, and fabrication cost.

In this Letter, based on the surveys performed in different countries, which indicate that GSM-900, GSM-1800, and WiFi-2450 are the most promising bands for RF energy harvesting [12]–[14]; we present a novel efficient triple-band power rectifier which works well at GSM-900, GSM-1800, and WiFi-2450. The realized rectifier was optimized for low input power conditions and has the advantage of compact size, low cost, and provides a higher output voltage. The designed rectifier is consisting of a typical voltage doubler optimized for low input power from -20 dBm to 0 dBm. Besides, a novel three-branches matching network is also designed to ensure maximum power transfer to the rectifier. Finally, a DC-pass filter to smooth the DC output voltage is introduced.

The rest of this paper is organized as follows. Section 2 introduces the design procedure of the triple-band rectifier, including details about the novel impedance matching technique, rectifier topology, and DC-pass filter. The simulated and measured results of the proposed rectifier are presented in Section 3. Finally, the conclusion is drawn in Section 4.

II. TRIPLE-BAND RECTIFIER CIRCUIT DESIGN

The proposed triple-band rectifier circuit can convert RF signals from GSM-900, GSM-1800, and WiFi-2450, of alternating current (AC) type into a DC power. To reach sufficient DC output power to supply micro-devices, a rectifying circuit with high efficiency, low power consumption, and good power sensitivity is required [15]. A typical rectifying circuit consists of an impedance matching circuit for maximum power transfer, a rectifying diode to perform the RF-to-dc conversion, a DC-pass filter for smoothing the output DC voltage and a load resistor.

A. RECTIFIER TOPOLOGY

In the literature, several rectifier topologies are used such as the single serial [16], [17], shunt diode [18], [19], Villard doubler and full-wave Greinacher rectifier [20]–[22]. According to the comparison done in [23], the single-stage full-wave voltage doubler rectifier is selected considering his higher efficiency and DC output voltage. It is well known that the single diode rectifiers reject the negative half-wave and provide high efficiency at a very low input power density, but the DC output and the breakdown voltage is still limited which could affect the power handling capability of the circuit.

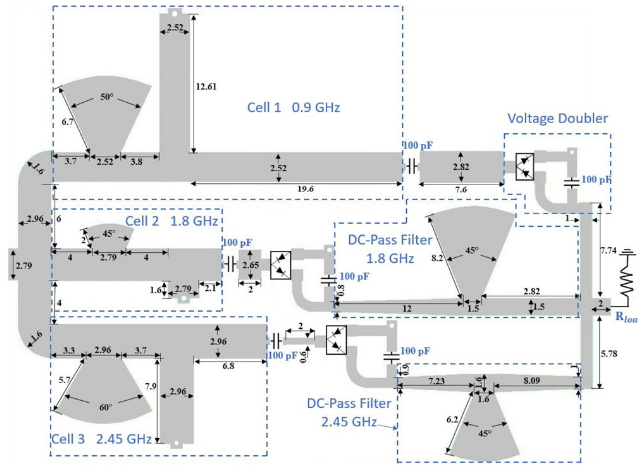

FIGURE 1. Topology of the proposed rectifying circuit with a three-branch impedance matching network (unit: mm).

on the contrary, the multistage rectifiers provide a high output voltage but the sensitivity and efficiency of the rectifier are decreased due to the increased lose at each stage. Fig. 1 illustrates the equivalent circuit of the used voltage doubler, which consists of two surface-mounted devices (SMD) capacitors of 100 pF and a rectifying Schottky diode HSMS2852. The circuit operates as follows: When the input RF signal is negative, the diode D2 turns-on, the current passes from the ground through the diode D2 toward the capacitor C1, so C1 charges with a voltage. When the input RF signal is positive, the diode D1 turns-on, at this moment, the positive input voltage and the voltage stored in C1 added together to charges capacitor C2. Thus, the peak voltage on the output capacitor C2 is approximately two times the peak voltage of the diode [24]. The dual-series-diodes configuration of HSMS-2852 in a SOT-23 is selected, taking into consideration their high efficiency at low/medium power input. According to the datasheet [25], HSMS-2852 has an equivalent series resistance of 25 Ohm, low threshold voltage of 150 mV, the low junction capacitance of 0.18pF and high breakdown voltage of 3.8V. A nonlinear model for the Schottky diode package imported from the ADS components library was used in the simulation.

B. IMPEDANCE MATCHING

In order to provide a maximum power to the rectifying circuit, we must achieve a good impedance matching over a large bandwidth of frequency. As a consequence, it was very challenging to reach a high efficiency with a single branch rectifier, especially when we take into account the nonlinearity behavior of diodes and the dependency between the input impedance of the rectifying circuit and frequency. For this reason, it was opted to develop three branches rectifying circuit in parallel. Each branch contains a narrow band matching network connected to voltage doubler. In this manner, the captured RF signals can be processed only by the cell with the right frequency and be rejected by the other cells.

The RF matching network is the crucial part of this design. It is usually designed to provide maximum RF power

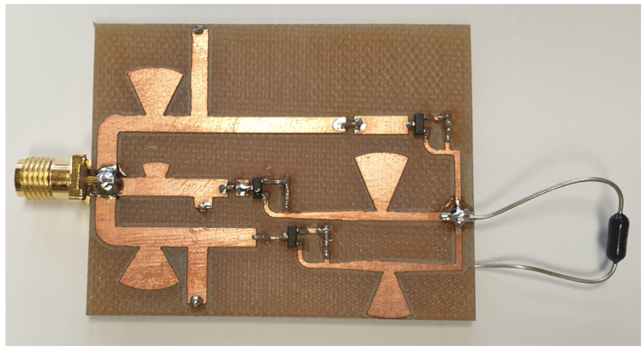

FIGURE 2. Fabricated prototype of the proposed triple-band rectifier.

transferred from antenna to rectifier circuit at a dynamic operating conditions, which are frequency band, input power level and load impedance. Therefore, a novel three-branch impedance matching circuit located between the input port and three rectifying branches is designed. At first, the input impedance of each rectifying circuit is determined as a function of the frequency and for fixed input power (−20dB). After that, each complex impedance is matched with 50 Ohm representing the input port. Finally, the overall matching network is optimized using ADS.

The proposed triple-band (0.9Ghz, 1.8Ghz and 2.45Ghz) input matching circuit consists of three cells. Each cell comprises of a radial stub, a short stub, and several transmission lines optimized in order to get the circuit matched around 0.9,1.8 and 2.45 GHz respectively. As depicted in Fig. 1, the three cells are distributed in three branches, each cell is connected to a single voltage doubler circuit to increase the DC output voltage.

C. DC-PASS FILTER

The DC-pass filter placed in the second and third branch just after the rectifier circuit is composed of radial stubs and transmission lines in series. These latter are used to remove the fundamental frequency signal and harmonics generated by the nonlinear behavior of the diodes. As a result, the DC output voltage is smoothed and the power transfer efficiency is enhanced. To obtain the best performance over the power range from -20dbm to 0dBm, the simulation and optimization process of the whole rectifier circuit has been made using the advanced design system (ADS) software from Agilent Technologies. To take into account the non-linear characteristic of the rectifier, harmonic balance (HB) and large signal scattering parameter (LSSP) simulators are employed. Subsequently, the best performance is obtained for a resistive load of 3.8Kohm.

III. MEASURED RESULTS OF THE RECTIFIER

To verify our design a prototype with size of 54 mm × 42 mm is printed on a low-cost FR-4 substrate with relative permittivity of 4.4, loss tangent of 0.02 and thickness of 1.6 mm as shown in Fig. 2.

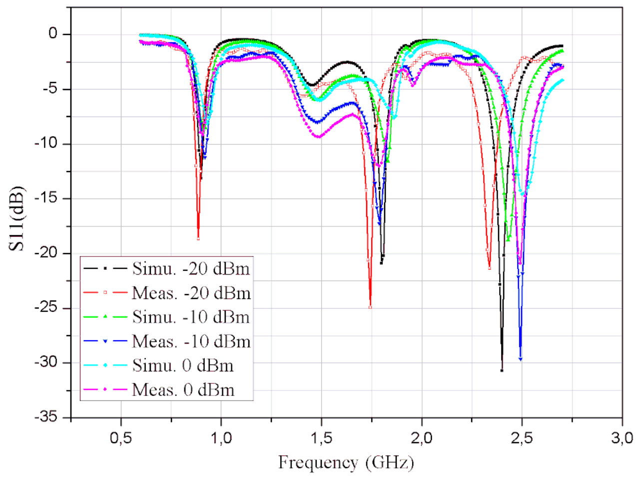

FIGURE 3. The measured and simulated S11 of the proposed rectifier at three input power levels for the load resistance of 3.8 kΩ.

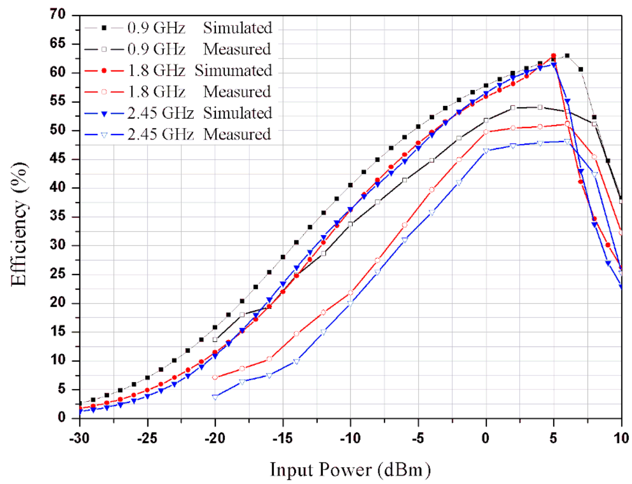

FIGURE 4. The measured and simulated RF-to-DC conversion efficiency of the proposed rectifier versus input power level at three frequencies for the load resistance of 3.8 kΩ.

Fig. 3 depicts the measured and simulated reflection coefficients of the triple-band rectifier versus frequency at different input power levels from −20 to 0 dBm. Better performance can be achieved at low input power, and the optimal value of reflection coefficient is reached to be -17dB, -22dB and -31dB at 0.9, 1.8 and 2.45 GHz respectively for an input power of −20 dBm. The slight difference between simulated and measured results was mainly due to fabrication tolerances and the mismatch due to the measurement connectors. We can conclude that a good impedance matching across all frequencies of interest at different power level from −20 to 0 dBm is achieved.

Fig. 4 reports the simulated and measured RF-to-dc conversion efficiency of the rectifier as a function of the RF input power, which has been calculated from the measured output

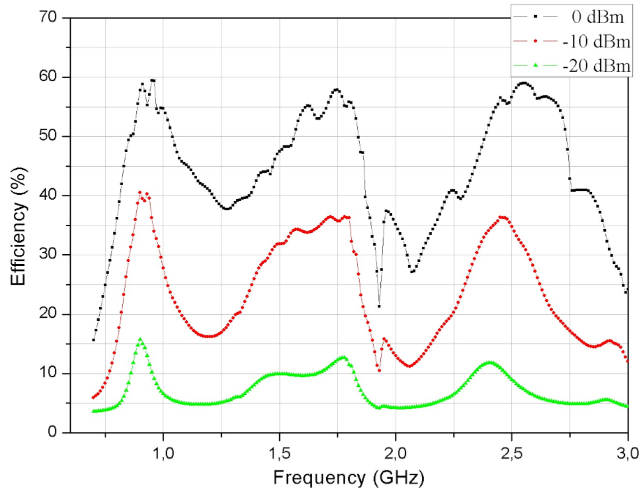

FIGURE 5. The simulated RF-to-DC conversion efficiency of the proposed rectifier at three input power levels for the load resistance of 3.8 kΩ.

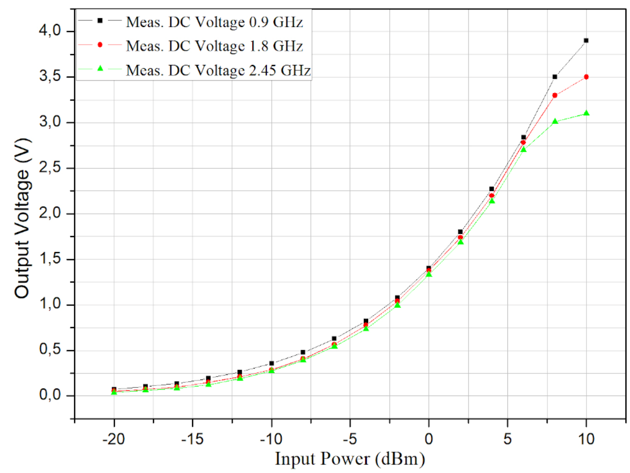

FIGURE 6. The measured DC output voltage of the proposed rectifier versus input power level at three frequencies for the load resistance of 3.8 kΩ.

voltage, according to:

$$\eta_{RF-DC} = \frac{P_{DC}}{P_{RF}} = \frac{{V_{DC}}^2}{P_{RF}R_L} \tag{1}$$

where V_{DC} is the DC output voltage measured by a multimeter, P_{RF} is the RF input power provided by the signal generator, and R_L is the load resistance.

When we set the load value at 3.8 KΩ, we can observe that the peak measured efficiency at 0.9, 1.8 and 2.45 GHz are 13.6%, 7 %, and 3.8 % for −20dBm, 33.7 %, 21.8 %, and 20% for −10dBm, and 51.7 %, 49.7 %, and 46.5 % for 0dBm, respectively. The maximum measured conversion efficiency was achieved when the input power level is 4 dBm, with the respective values of 54%, 51%, and 48 %. On the other hand, the simulated efficiency versus frequency is shown in fig. 5. We can see that the efficiency at the three center frequencies is higher than 53% under 0 dBm input power.

TABLE 1. Comparison of the experimental results for the proposed rectifier and related work.

Ref.	RF bands (GHz)	Substrate	Diode	RF-DC Conversion efficiency (%)		
				-15	-10	0
[3]	2.45	Rogers 4350B	HSMS-2860	8	26	58
[6]	0.915 and 2.45	Arlon 25N	SMS7630	24 and 15	35 and 28	48 and 38
[7]	2.1 and 2.45	FR4	HSMS-285C	4.5 and 2.5	10 and 6	19 and 13
[9]	0.9, 1.8 and 2.1	RT/Duroid 5880	SMS7630-079	35, 25 and 18	41, 30 and 25	—
[10]	1.3, 1.7, 2.4 and 3.6	FR4	SMS7630-005	12, 7, 1 and 1	25, 17, 5 and 2	43, 40, 14 and 9
This Work	0.9, 1.8 and 2.45	FR4	HSMS-2852	22, 13 and 9	33.7, 22 and 20	52, 50 and 46.5

This demonstrates that the proposed triple-band rectifier has a good power sensitivity at relatively low input power.

The DC output voltage of the rectifier can be measured by using a multimeter connected to the load resistor. As depicted in figure 6, the DC output voltage at the three frequencies is greater than 1.3 V for an input power level of 0 dBm.

Table 1 illustrates a performance comparison of the proposed work with other reported rectifier designs. It can be seen that the proposed triple-band rectifier works efficiently over a wide input power range and reaches a good conversion efficiency at three frequencies in comparison to other designs. In addition, our design has the advantage of low fabrication cost and small size. Therefore, we can consider that our design is suitable for energy harvesting applications.

IV. CONCLUSION

In this paper, an efficient power rectifier operating at GSM-900, GSM-1800, and WiFi-2450 bands is able to gather the ambient RF energy available with low and medium power densities simultaneously. A novel three-branches impedance matching network was designed to ensure a maximum transfer to the rectifying circuit. As a result, good performance was achieved under different conditions, such as multiple-frequency bands and a wide input power range. The simulated conversion efficiencies under 0 dBm are 57.8%, 55.8%, and 56.5% at three frequencies of 0.9, 1.8, and 2.45 GHz, respectively. The measured results have shown that the efficiency is above 46% in every band when the input power is 0 dBm. Final results confirm that the improved impedance matching can effectively improve the rectenna conversion efficiency. Moreover, the output voltage level is also increased by simultaneously accumulating energy from multiple RF sources at three well-conceived matching frequencies. Regarding the prominent performance of the rectifier, its compact size, and multi-operating frequencies, the proposed design is very suitable to be used in RF energy harvesting applications.

REFERENCES

[1] S. D. Assimonis, S.-N. Daskalakis, and A. Bletsas, "Sensitive and efficient RF harvesting supply for batteryless backscatter sensor networks," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 4, pp. 1327–1338, Apr. 2016.

[2] M. Zeng, A. S. Andrenko, X. Liu, Z. Li, and H.-Z. Tan, "A compact fractal loop rectenna for RF energy harvesting," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2424–2427, Jul. 2017.

[3] H. Sun, "An enhanced rectenna using differentially-fed rectifier for wireless power transmission," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 32–35, Apr. 2015.

[4] P. Lu, X.-S. Yang, J.-L. Li, and B.-Z. Wang, "Polarization reconfigurable broadband rectenna with tunable matching network for microwave power transmission," *IEEE Trans. Antennas Propag.*, vol. 64, no. 3, pp. 1136–1141, Mar. 2016.

[5] M.-J. Nie, X.-X. Yang, G.-N. Tan, and B. Han, "A compact 2.45-GHz broadband rectenna using grounded coplanar waveguide," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 986–989, Dec. 2015.

[6] K. Niotaki, S. Kim, S. Jeong, A. Collado, A. Georgiadis, and M. M. Tentzeris, "A compact dual-band rectenna using slot-loaded dual band folded dipole antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 1634–1637, Dec. 2013.

[7] E. Khansalee, Y. Zhao, E. Leelarasmee, and K. Nuanyai, "A dual-band rectifier for RF energy harvesting systems," in *Proc. ECTI-CON*, Nakhon Ratchasima, Thailand, May 2014, pp. 1–4.

[8] M. Zeng, Z. Li, A. S. Andrenko, Y. Zeng, and H.-Z. Tan, "A compact dual-band rectenna for GSM900 and GSM1800 energy harvesting," *Int. J. Antennas Propag.*, vol. 2018, pp. 1–9, Juul. 2018.

[9] S. Shen, C.-Y. Chiu, and R. D. Murch, "A dual-port triple-band L-probe microstrip patch rectenna for ambient RF energy harvesting," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 3071–3074, Oct. 2017.

[10] C.-Y. Hsu, S.-C. Lin, and Z.-M. Tsai, "Quadband rectifier using resonant matching networks for enhanced harvesting capability," *IEEE Microw. Wireless Compon. Lett.*, vol. 27, no. 7, pp. 669–671, Jul. 2017.

[11] V. Palazzi, J. Hester, J. Bito, F. Alimenti, C. Kalialakis, A. Collado, P. Mezzanotte, A. Georgiadis, L. Roselli, and M. M. Tentzeris, "A novel ultra-lightweight multiband rectenna on paper for RF energy harvesting in the next generation LTE bands," *IEEE Trans. Microw. Theory Techn.*, vol. 66, no. 1, pp. 366–379, Jan. 2018.

[12] M. Pinuela, P. D. Mitcheson, and S. Lucyszyn, "Ambient RF energy harvesting in urban and semi-urban environments," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 7, pp. 2715–2726, Jul. 2013.

[13] T. Beng Lim, N. M. Lee, and B. K. Poh, "Feasibility study on ambient RF energy harvesting for wireless sensor network," in *IEEE MTT-S Int. Microw. Symp. Dig. Workshop Ser. RF Wireless Technol. Biomed. Healthcare Appl. (IMWS-BIO)*, Singapore, Dec. 2013, pp. 1–3.

[14] M. Pinuela, D. C. Yates, P. D. Mitcheson, and S. Lucyszyn, "London RF survey for radiative ambient RF energy harvesters and efficient DC-load inductive power transfer," in *Proc. EuCAP*, Gothenburg, Sweden, Apr. 2013, pp. 2839–2843.

[15] S. Hemour, Y. Zhao, C. Henrique Petzl Lorenz, D. Houssameddine, Y. Gui, C.-M. Hu, and K. Wu, "Towards low-power high-efficiency RF and microwave energy harvesting," *IEEE Trans. Microw. Theory Techn.*, vol. 62, no. 4, pp. 965–976, Apr. 2014.

[16] Z. Harouni, L. Cirio, L. Osman, A. Gharsallah, and O. Picon, "A dual circularly polarized 2.45-GHz rectenna for wireless power transmission," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 306–309, Apr. 2011.

[17] J. Zbitou, M. Latrach, S. Toutain, "Hybrid rectenna and monolithic integrated zero-bias microwave rectifier," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 1, pp. 147–152, Jan. 2006.

[18] Q. He and C. Liu, "An enhanced microwave rectifying circuit using HSMS-282," *Microw. Opt. Technol. Lett.*, vol. 51, no. 4, pp. 1151–1153, Apr. 2009.

[19] H. Sun, Y.-X. Guo, M. He, and Z. Zhong, "Design of a high-efficiency 2.45-GHz rectenna for Low-Input-Power energy harvesting," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 929–932, Aug. 2012.

[20] M. Arrawatia, M. S. Baghini, and G. Kumar, "Broadband bent triangular omnidirectional antenna for RF energy harvesting," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 36–39, Apr. 2015.

[21] C. Song, Y. Huang, J. Zhou, J. Zhang, S. Yuan, and P. Carter, ''A high-efficiency broadband rectenna for ambient wireless energy harvesting,'' *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3486–3495, Aug. 2015.
[22] J. Heikkinen and M. Kivikoski, ''A novel dual-frequency circularly polarized rectenna,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 330–333, 2003.
[23] C. R. Valenta and G. D. Durgin, ''Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems,'' *IEEE Microw. Mag.*, vol. 15, no. 4, pp. 108–120, Jun. 2014.
[24] J. Wang, Q. Gao, Y. Yu, H. Wang, and M. Jin, *Radio-Triggered Power Management in Wireless Sensor Networks Wireless Sensor Networks-Technology and Applications*, 1st ed. Rijeka, Croatia: InTech, Jul. 2012. [Online]. Available: https://www.intechopen.com/books/wireless-sensor-networks-technology-and-applications/radio-triggered-power-management-in-wireless-sensor-networks
[25] *Surface Mount Zero Bias Schottky Detector Diodes, HSMS-285x Series*, Agilent Technol., Santa Clara, CA, USA, 1999.

HAMZA TAFEKIRT was born in Fez, Morocco, in 1990. He received the engineering degree in mechatronic systems engineering from Abdelmalek Essaadi University, Tetouan, Morocco, in 2013. He is currently pursuing the Ph.D. degree in RF energy harvesting systems with the National School of Applied Sciences, Tangier, Morocco. His current research interest includes antennas and rectifier circuits.

JOSE PELEGRI-SEBASTIA (Senior Member, IEEE) received the M.Sc. degree in physics, the degree in electrical engineering, and the Ph.D. degree in physics from Universitat de Valencia, Valencia, Spain, in 1994, 1998, and 2002, respectively. He is currently an Associate Professor with the Electronic Engineering Department, Universitat Politècnica de València, Campus de Gandia, Spain. His current research interests include instrumentation systems, characterization sensors (especially magnetic sensors and its industrial applications), low-power embedded systems, and wireless sensor networks.

ADEL BOUAJAJ received the Ph.D. degree in materials science from University Claude Bernard Lyon I, France, in 1994. He was a Postdoctoral Fellow with CNR-IFN, Trento, Italy. He is currently a Professor of physics with the University Abdelmalek Esaadi (UAE), Tangier, Morocco. His current research focuses on the development and characterization of dielectric materials doped rare earth for optoelectronics and photonics. He is responsible for the training of engineers in photovoltaic solar energy in the UAE-Tangier.

BRITEL MOHAMMED REDA (Member, IEEE) was born in Rabat, Morocco, in 1968. He received the B.S. degree in solid state physics from Mohammed V University, Rabat, in 1990, the D.E.A. and Ph.D. degrees in physics from Joseph Fourier University, Grenoble, France, in 1994, and the Ph.D. degree in physical engineering from the Polytechnic School of Montreal, Canada, in 2000. Since July 2000, he has been the North American telecommunications leader, Appolo Microwaves, as a Designer of microwave devices. Since 2002, he occupied, at that date, the function of Teacher–Searcher at the National School of Applied Sciences, Abdelmalek Essaadi University (UAE), Tangier. He worked on several fields as the energy collection, the improving the efficiency of photovoltaic cells, the magnetic sensors, and the microwave devices based on magnetic materials. He is currently the Director of the Laboratory for Innovative Technologies, UAE.