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Dual-Band RF-to-DC Rectifier with High Efficiency for RF Energy Harvesting Applications

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***Abstract*—Radio Frequency (RF) energy harvesting is emerging as a potentially reliable method to replace the costly and, difficult to maintain, source of low-power wireless sensors networks. In this paper, a dual-band RF-to-DC rectifier, that operates at LoRaWAN and GSM-900 cellular communication frequency bands, is presented. The system is composed of an impedance matching circuit, an RF-to-DC rectifier, that converts the ambient RF energy into DC voltage able to feed low power devices, and an output load. The proposed system resonates at two different frequencies of 866 MHz and 937 MHz. Numerical results demonstrate that the overall system exhibits an efficiency of 80% with 4.32 V of output voltage at 0 dBm of input power.**

***Index Terms*—RF to DC rectifier, dual-band, wireless sensors, energy harvesting, voltage multiplier, impedance matching**

I. INTRODUCTION

Ambient RF sources in an urban environment are mostly incident sources like TV/radio broadcast stations, mobile base stations and, handheld stations. Ambient Electromagnetic (EM) energy harvesting is emerging as a potentially reliable method to replace the costly and, difficult to maintain, source of wireless sensors networks. Unlike other harvesting techniques that are strongly dependent on the climate and/or environmental conditions, RF energy harvesting can be somewhat predictable, so it is better suited for supporting quality-of-service (QoS) based applications [1].

Recently, dual-band rectifier designs have been proposed in the literature. In 2014 [2], the authors presented a rectifier for RF energy harvesting applications that was operated at 2.10 GHz and 2.45 GHz. The rectifier was comprised of a multi-stub impedance matching network, a Schottky diode and a DC pass filter. The authors reported that their proposed rectifier achieved an efficiency of 24% and 18% at 2.10 GHz and 2.45 GHz, accordingly, for an input power of 10 dBm and a load impedance of 1.6 kOhms. In 2015 [3], the authors presented a rectifier that was operated at 2.45 GHz and 5.8 GHz. The rectifier consisted of a matching circuit, a Schottky HSMS-2850 diode, a DC-pass filter, and a load. The authors achieved an efficiency of 57.6% and 33.62% for an input power of 0 dBm and 30% and 28% for an input power of 10 dBm, at 2.45 GHz and 5.80 GHz, respectively. In 2017 [4], Tissier et.al. introduced a dual-band rectifier in the GSM900 and GSM1800 bands. The rectifier topology was based on Latour doubler. The efficiency obtained was greater than 30% at 942 MHz and greater than 20% at 1805 MHz for an input power greater than – 10 dBm and an output load equal to 15 kOhms. In 2018 [5], the authors introduced a voltage doubler circuit as a rectifier, which was consisted of two Avago HSMS2850 Schottky diodes and two capacitors. The results demonstrated that the RF-to-DC maximum efficiency was 63% at 1.95 GHz and 69% at 2.50 GHz, for an input power of 7.0 dBm and 3.5 dBm, respectively, and a resistive load of 1.0 kOhm. In 2019, Huang et al. [6] utilized a $\lambda/4$ T-junction power divider to connect two branches of a rectifier, in order to extend the range of input power of the system with high conversion efficiency. They applied their proposed technique to both single- and dual-band rectifiers. They reported a measured peak efficiency of 68% for the single-band (915 MHz) rectifier, and an input power range from -5 dBm to 31 dBm, by setting an efficiency threshold $> 70\%$ of its peak value. Consequently, they measured a peak efficiency of 66% for an input power range from -6 dBm to 33 dBm (efficiency threshold $> 70\%$)

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at 915 MHz, and a peak efficiency of 58% for an input power range from 10 dBm to 32 dBm (efficiency threshold $> 70\%$) at 2450 MHz.

In this paper, a novel dual-band rectifier that operates at LoRaWAN and EGSM-900 mobile communication frequency bands is presented. The RF-to-DC rectifier resonates at two different frequencies (866 MHz and 937 MHz). For the rectification unit, a single layer voltage doubler circuit is utilized that operates in the previously mentioned frequencies. The proposed system can harvest the ambient RF electromagnetic radiation at two different frequency bands simultaneously by the implementation of a single rectifying circuit.

The remainder of the paper is as follows. In Section II, a description of the proposed Radio Frequency Energy Harvesting system is outlined, which focuses on the Schottky diode-based dual-band rectifying circuit. Section III summarizes the main results of the proposed rectifier and evaluates its performance. Finally, Section IV concludes the findings of the paper.

II. RADIO FREQUENCY (RF) ENERGY HARVESTING DESIGN

A. Rectenna System Design

The rectifying antenna (rectenna) is a joint system of an antenna and an RF-to-DC rectifier. The antenna is responsible for capturing the ambient RF electromagnetic energy, whereas the rectifier is converting the input AC voltage into DC voltage, able to run low-power electronic devices. In many cases, an impedance matching network is inserted prior to the RF-to-DC rectifier and after the antenna, to adjust the impedances between these two elements. Brown [7] invented the first rectenna in the early 1960s. Since then, the technological revolution has encouraged researchers to design and build more efficient and sophisticated circuits. Fig. 1 illustrates the basic block diagram of a rectenna system.

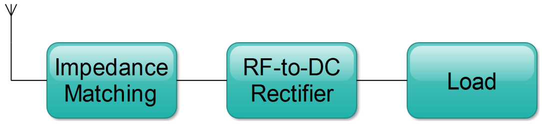


Fig. 1. Basic block diagram of a rectenna system.

B. Dual-Band Rectifier Design

The rectifier circuit is the heart of an energy harvesting module. It is responsible for converting the received RF power into DC voltage, sufficiently enough to charge a battery or run battery-free low-power electronics. It is decisive to provide high values of RF-to-DC power conversion efficiency and to operate in multi-frequency bands for converting as much ambient RF energy as possible. One of the most established approaches to design an RF-to-DC rectifier is the Schottky diode-based rectifying circuit. Fig. 2 illustrates the design process of the proposed Schottky diode-based rectifier, as well as the main considerations that were taken into account. Based on Fig. 2, the first steps of a rectifier design are to select the appropriate circuit type and elements (Schottky diodes, resistors, capacitors), given the application it will be used for. The Schottky diode, that is attributed with a low forward voltage drop and low substrate leakage, can improve the RF-to-DC conversion efficiency, as well as the DC output voltage.

In this paper, the HSMS-285C (SOT-323) Schottky barrier diode, which has a low forward voltage value of V_F = 150 mV, is utilized [8]. The configuration of the proposed rectifier is illustrated in Fig. 3. Two different impedance matching circuits are designed to interconnect the antenna module with the branches of the rectifier. The system is designed using the harmonic-balance (HB) method in Advanced Design System software (ADS - © Keysight Technologies 2000 - 2020). An FR4 substrate (dielectric constant (ϵ_r) = 4.4, substrate thickness = 1.6 mm, dielectric loss tangent $(\tan\delta)$ = 0.02, and copper thickness = 0.07 mm) is utilized to design the proposed system.

Fig. 4 portrays the configuration of the Greinacher voltage doubler that has been utilized in the proposed rectifier. The voltage doubler uses two (2) zero bias Schottky surface mount Avago HSMS-285C series diodes and two (2) capacitors C_1 = C_2 = 100 pF (AVX 08053K) of 1% tolerance. The rest of the voltage doubler components are several conductor lines of appropriate width (W) and length (L) to ensure compact layout design and impedance matching. The input RF AC signal is rectified by the voltage doubler circuit. The latter is comprised of a voltage clamp (diode D_1 and capacitor C_1) and a peak rectifier (diode D_2 and capacitor C_2).

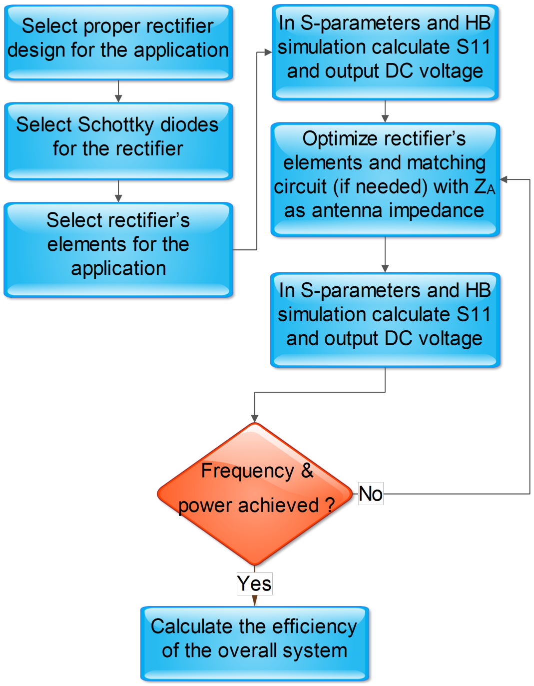


Fig. 2. Design process of the proposed Schottky diode-based dual-band rectifier.

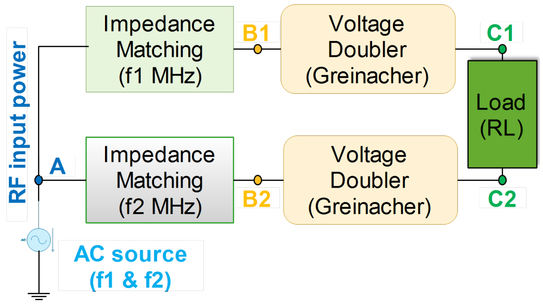


Fig. 3. The proposed dual-band rectenna system block diagram.

C. Impedance Matching Design

To ensure that maximum power conversion efficiency and maximum sensitivity will be achieved, an impedance matching network should be utilized. We consider a standard antenna port of Z_A = 50 Ohms. The overall system performance can be evaluated by the RF-to-DC power conversion efficiency versus the incident RF signal (P_{in}) at the input port A. Fig. 5 illustrates the proposed impedance matching circuits for the corresponding operating frequencies of the rectifying circuit.

III. NUMERICAL RESULTS

The voltage doubler input impedance has been computed using the S-parameters simulator of the Advanced Design System (ADS). The derived values are $11.42 - j * 66.36$ and $27.1 - j * 65.4$ at 886 MHz and 937 MHz, respectively. The size of the impedance matching circuits have been optimized and adjusted to the input impedance of the overall system derived to $44.3 + j * 6.1$ and $55.0 + j * 8.5$ at the two frequencies of interest. To obtain the impedance matching of the overall system, a simple short-circuited stub has been included, as depicted in Fig. 5.

Fig. 6 illustrates the S_{11} magnitude (reflection coefficient) of the proposed RF-to-DC dual-band rectifier vs frequency. From the presented graph, we can derive that the proposed rectifying circuit operates satisfactorily in the European LoRaWAN frequency band (863 - 870 MHz), as well as in the EGSM-900 mobile communication frequency band (925 - 960 MHz). The proposed rectifier has a dual-frequency operation (-21.9 dB at 869 MHz and -20.9 dB at 940 MHz) within the previously mentioned frequency bands. It is also noticeable, that the operational bandwidth (-10 dB bandwidth) of the proposed rectifier extends to 121.1 MHz (845.8 - 966.9 MHz).

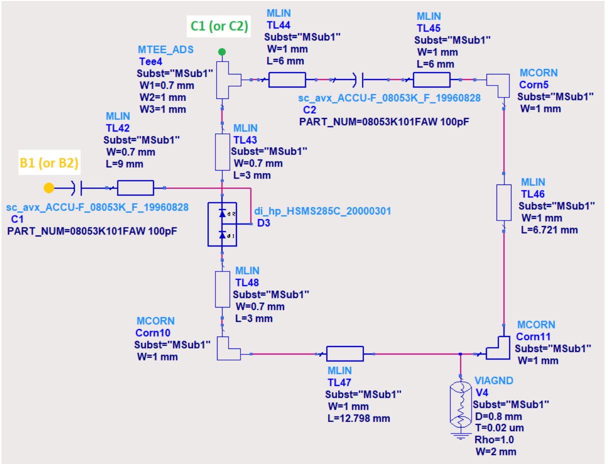
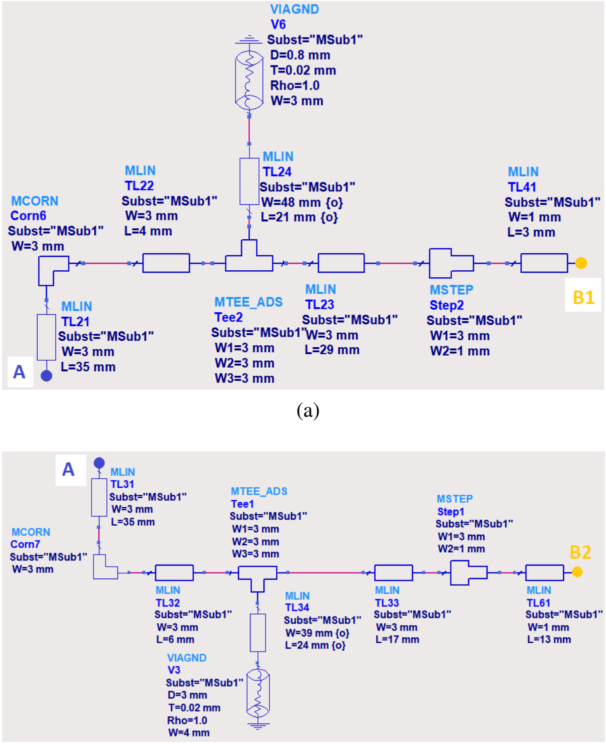


Fig. 4. The proposed Greinacher voltage doubler configuration.



(a)

(b)

Fig. 5. Proposed impedance matching circuits of the rectifying circuit at (a) 866 MHz and (b) 937 MHz.

The overall system RF-to-DC efficiency n is computed as

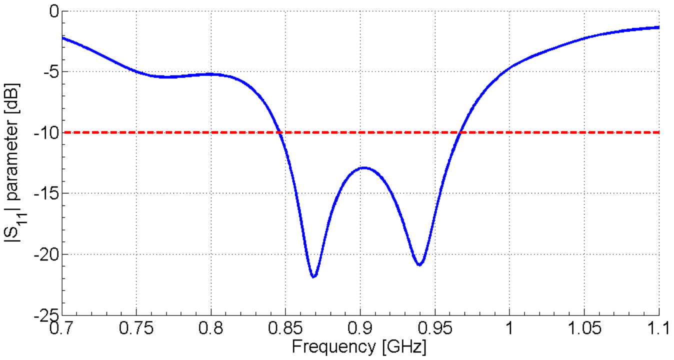


Fig. 6. Obtained S_{11} parameter (reflection coefficient) of the proposed Schottky diode-based dual-band rectifier for R_L = 13 kOhms (blue solid line: S_{11} parameter, red dash line: -10 dB limit).

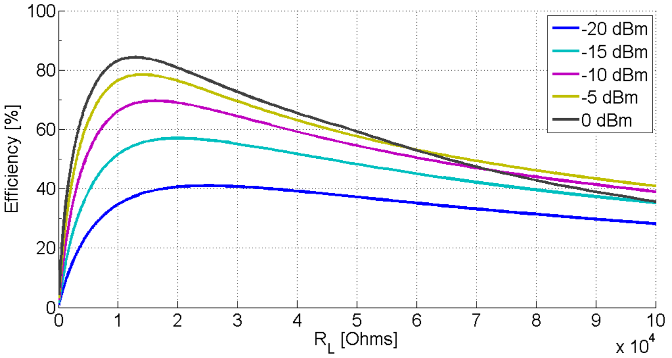


Fig. 7. RF-to-DC efficiency vs R_L output load of the demonstrated dual-band rectifying circuit for various RF input power values (P_{in}).

follows:

$$n = P_{DC}/P_{in} \tag{1}$$

$$P_{DC} = V_{DC}^2/R_L \tag{2}$$

where P_{DC} is the DC output power, P_{in} is the RF input power, V_{DC} is the output DC voltage, and R_L is the load resistance.

Fig. 7 displays the RF-to-DC efficiency versus the R_L output load. From the presented graph, we can easily derive that the maximum efficiency of the proposed rectifier is 85% for an input power of 0 dBm and a load of 13 kOhms. At -20 dBm, -15 dBm, -10 dBm, and -5 dBm the obtained conversion efficiencies for 13 kOhms are 38%, 55%, 69%, and 78%, accordingly.

Finally, Fig. 8 portrays the DC output voltage V_{out} versus the RF input power P_{in}. From the depicted graph, we can observe that the output DC voltage for RF input power of -10 dBm, -5 dBm, and 0 dBm is 1.17 V, 2.28 V, and 4.32 V, respectively.

Additional numerical results, including a comparative study with the latest dual-band designs, an evaluation of topology's sensitivity, as well as the plot of the simulated efficiency versus frequency will be reported in the extended paper.

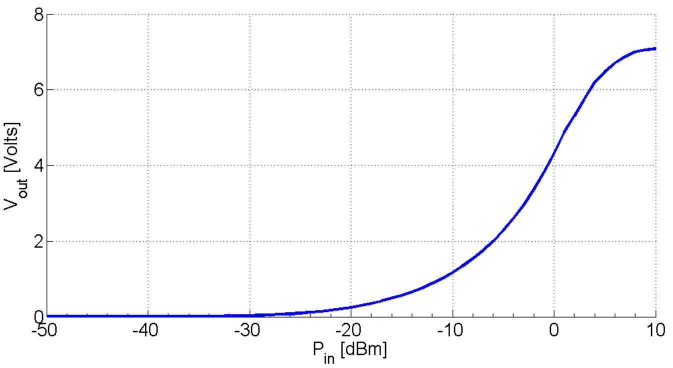


Fig. 8. DC output voltage vs input power of the proposed dual-band rectifier for R_L = 13 kOhms.

IV. CONCLUSIONS

In this paper, a Schottky diode-based dual-band rectifier is proposed. The system operates at LoRaWAN and EGSM-900 cellular communication frequency bands and consists of an impedance matching circuit, an RF-to-DC rectifier, that converts ambient RF energy into DC voltage and, an output load. The obtained input impedance matching network to adjust the rectifier's impedance with the antenna impedance has been computed using Advanced Design Systems (ADS). The proposed system resonates at two different frequencies of 866 MHz and 937 MHz. Numerical results demonstrate that the overall system provides an efficiency of 80% for input power of 0 dBm. Future work involves a thorough study of the rectenna topology (a combination of an antenna and the proposed rectifier) to broadband designs for more efficient energy harvesting applications. Also, the proposed dual-band rectifier can be easily combined with a low power DC/DC converter to develop an RF sensor module.

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