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# Low-input-power Sub-GHz RF Energy Harvester for Powering Ultra-low-power Devices

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**Abstract**—Using RF energy to power ultra-low-power devices is an appropriate solution to reduce the dependency on conventional sources (e.g. batteries); however, providing a regulated DC voltage from low RF power is a challenging task. This work presents a low-input-power RF harvester designed with off-the-shelf components and composed of an RF rectifier and a power management integrated circuit (PMIC). In the rectifier, an inductive-matching technique is employed which consists of an inductive branch composed of a lumped inductor together with a short-circuited stub due to sub-GHz frequency. The rectifier is designed to present an optimal DC load in function of the PMIC operation at low powers. Measured RF-to-DC conversion efficiency of 32 % and DC output voltage of 186 mV with an input power of  $-20$  dBm at 888.7 MHz are achieved in the rectifier. Measured peak efficiency is 52 % at  $-4$  dBm. At  $-20$  dBm, a relatively high efficiency and output DC voltage are obtained compared to other discrete rectifiers. For this power level, this performance is sufficient to maintain the operation of the PMIC that delivers a power of 324 nW aiming to supply an ultra-low-power wake-up receiver. The required RF power to deliver a regulated DC voltage is so far the lowest reported in the literature for an RF harvester using off-the-shelf components and a continuous wave (CW) signal to date.

**Index Terms**—rectifier, RF energy harvesting, wireless power transfer, power management integrated circuit, ultra-low-power wake-up radio.

## I. INTRODUCTION

In a context of an increasing deployment of the Internet of Things (IoT), the long term operation of these devices is limited by their batteries. Duty cycled IoT consume high energy due to the idle listening of their transceivers. The use of wake-up radio receivers (WURx), driving the IoT on demand, reduces the required energy since most of the time the main node is in a deep sleep state [1]. Moreover, making the WURx independent of the main battery and powering it with harvested RF energy will extend the battery lifetime [2]. The targeted application is depicted in Fig. 1. One of the main goals to power a WURx with RF energy is to efficiently transform this fluctuating kind of power into a regulated DC voltage. The RF energy harvester is composed of a rectification circuit and a power management integrated circuit (PMIC).

In [3] an architecture of a rectification circuit has been presented in simulation. This architecture is capable of powering sub- $\mu$ W devices with a regulated DC voltage from a wide RF power level range. Depending in the input RF power level,

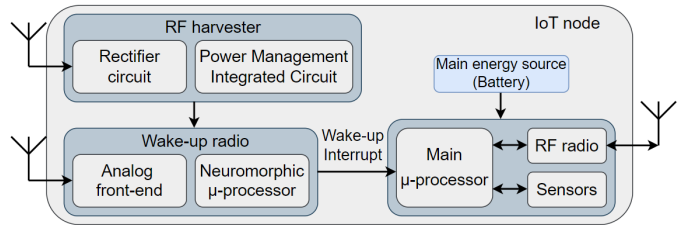


Fig. 1. Architecture aiming to reduce the dependency of an IoT node in the main energy source.

the RF signal received is rectified by a power dependent part of the the circuit. The obtained DC voltage is then regulated by a PMIC. For RF harvesting from the environment, except when being close to a base station (e.g., a mobile phone base station), RF power density is very low. When transmitting RF power from a dedicated wireless RF energy source, increasing the distance of transmission is necessary. However, regulations limit the amount of RF power to be transmitted. In both scenarios, a low RF power is expected at the input of the RF harvester circuit.

In this paper, a low-power RF harvester is demonstrated. A rectifier is implemented and optimised at low-input-power using the inductive-matching technique [4]. Minimal requirements of a commercial TI BQ25570 PMIC are taken into account in the design of the rectifier. Measured RF-to-DC conversion efficiency of 32 % and DC output voltage of 186 mV with an input RF power of  $-20$  dBm at 888.7 MHz are achieved in the rectifier. For this input power level, a relatively high voltage, compared to other rectifiers fabricated with off-the-shelf components, is obtained while reaching good efficiencies. This performance is sufficient to maintain the operation of the PMIC that regulates the DC output voltage of the rectifier and delivers a power of 324 nW aiming to power an ultra-low-power WURx which power consumption is estimated to be around the tens to hundreds of nW [5].

## II. RF ENERGY HARVESTER DESIGN

The RF energy harvester is composed of an RF rectifier and a PMIC as depicted in Fig. 1. Because of its low quiescent current, the commercial BQ25570 PMIC from TI is chosen. This PMIC offers three main functions. A maximum power

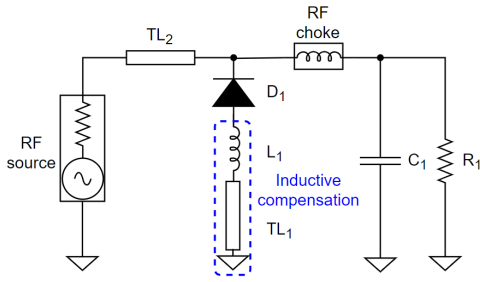


Fig. 2. Schematic of the implemented inductive-matching rectifier aimed for low RF input power.

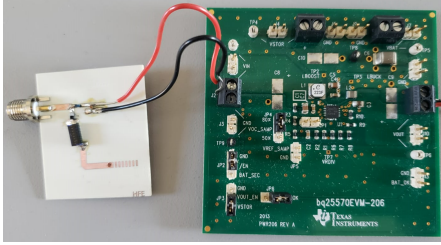


Fig. 3. Fabricated rectifier connected to a BQ25570 PMIC.

point tracking (MPPT) algorithm, the distribution of energy between a storage element and its load and the regulation of the output voltage. All the functionalities are enabled when the PMIC is in the normal mode state. To study the characteristics of the PMIC connected with a rectifier, the latter is modeled as a voltage source with its internal resistor  $R_{int}$  as in [6].

This model is used in [3] to measure the impact of  $R_{int}$  in the minimal input power and voltage required by the PMIC to output a regulated voltage and hundreds of nW. The authors suggest that  $R_{int}$ , which evidently is the output load of the rectifier in the model, must be higher than  $10\text{ k}\Omega$  to limit the quiescent power of the PMIC. Higher loads than  $10\text{ k}\Omega$  do not reduce substantially the power absorbed by the PMIC. As a result, in the present work, the rectifier is designed with an optimal load higher than  $10\text{ k}\Omega$ . In [4] a shorted transmission line (TL) which acts as an inductance is used in series with the diode to compensate its capacitive behaviour in a shunt topology. The advantage of the approach is to reduce ohmic losses in the input matching network as much as possible. The rectifier reported in [4] is at  $2.45\text{ GHz}$ , resulting in a reasonable shorted TL length. In the present work, a similar principle is used; however, the rectifier is designed at a frequency of  $889\text{ MHz}$ , leading to a significantly long shorted TL length which reduces the quality factor ( $Q$  factor), consequently reducing the RF-to-DC conversion efficiency.

To reduce the length of the shorted TL, a high  $Q$ -factor inductance,  $L_1$ , is used in combination with  $TL_1$  as showed in Fig. 2. Using Keysight ADS, the values of the required components are determined in simulation. A BAT15 Infineon diode,  $D_1$ , is used due to its low forward threshold voltage and low series resistance which reduce the losses at low power. A  $50\ \Omega$  TL,  $TL_2$ , is placed for the connector solely. In simulation, the use of an ideal inductance of  $128\text{ nH}$  leads

to good matching between the rectifier and a  $50\ \Omega$  RF power source and boosts the efficiency at  $-20\text{ dBm}$  when the rectifier is loaded with a  $17\text{ k}\Omega$  resistor. This  $128\text{ nH}$  inductance is achieved with a 2712sp-27N Coilcraft coil and a shorted  $14\text{ mm}$  TL. The value of the coil inductance is selected making a trade-off between which section of the inductive branch introduces higher losses. Indeed, too high inductance coils have a reduced  $Q$ -factor and too long lengths of  $TL_1$  become preponderant in terms of losses at a certain length value.

The rectifier is implemented on a  $0.7\text{ mm}$ -thickness Rogers RO4350 substrate, an RF choke is used to block the fundamental and harmonic frequencies from the load, and finally a  $1\text{ nF}$  capacitor,  $C_1$ , is used for smoothing the output DC voltage of the rectifier. For an input power of  $-20\text{ dBm}$  at a frequency of  $889\text{ MHz}$ , an efficiency of  $37\%$  and an output DC voltage of  $252\text{ mV}$  are obtained in simulation when the rectifier is loaded with a  $17\text{ k}\Omega$  resistor,  $R_1$ , which is suitable for the PMIC.

### III. MEASUREMENT RESULTS

The prototype of the proposed energy harvester is shown in Fig. 3. The width of the RF rectifier is  $0.019\lambda$  and its length is  $0.062\lambda$ .  $S_{11}$  is measured using an R&S ZVA 50 vector network analyser.

As shown in Fig. 4, measurement results are close to simulation and a  $|S_{11}|$  of  $-28\text{ dB}$  at  $888.7\text{ MHz}$  is obtained. Varying  $TL_1$ , the operation frequency can be optimized to  $868\text{ MHz}$  or  $915\text{ MHz}$  which are common ISM bands. For measuring the RF-to-DC conversion efficiency, the rectifier is fed with an  $888.7\text{-MHz}$  CW signal using an R&S SMBV100A vector signal generator. A Krytar directional coupler and an RF power meter with a power sensor are employed to acquire the exact input power to the rectifier.

First, using a Yokogawa GS610 source measurement unit, the load of the rectifier is varied at input power of  $-20\text{ dBm}$  to find the optimal experimental load at this operating point as showed in Fig. 5a. As aforementioned, the rectifier is modeled as a voltage source. Fig. 5b shows the measured I-V characteristic of the designed rectifier. Indeed, this characteristic corresponds to a voltage source in series with its internal resistor which equation is

$$I_{meas} = -0.09 \cdot V_{meas} + 34.2, \quad (1)$$

where  $I_{meas}$  and  $V_{meas}$  are the measured output current in  $\mu\text{A}$  and output voltage in  $\text{mV}$  of the rectifier, respectively. The inverse of the slope is the experimental optimal load found in Fig. 5a and corresponds to  $11\text{ k}\Omega$ . Then for a  $11\text{ k}\Omega$  load, the input power is swept. The DC voltage is measured at the output of the rectifier using a Keithley 195 DC meter. Measurement results are shown in Fig. 6.

These results show an efficiency of  $32\%$  and an output voltage,  $V_{load}$ , of  $186\text{ mV}$  for an input power of  $-20\text{ dBm}$ . For this power level, a relatively high voltage, compared to other rectifiers fabricated with off-the-shelf components, is obtained while reaching good efficiencies. The peak of

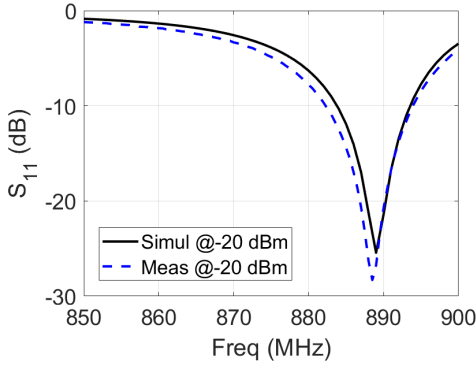


Fig. 4. Reflection coefficient  $|S_{11}|$  of the designed rectifier.

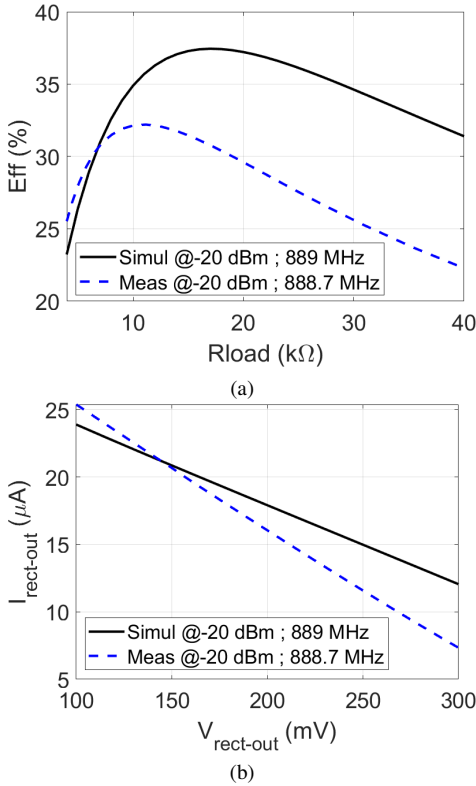


Fig. 5. Simulated and measured results, a) optimal load and b) I-V characteristic of the designed rectifier.

efficiency is 52% at  $-4$  dBm which corresponds to an output voltage of 1.5 V and at  $-29$  dBm, the rectifier has an efficiency of 11% and an output voltage of 40 mV. At  $-20$  dBm the measured efficiency is 5% lower than simulations. The value of the experimental optimal load is shifted of  $7$  k $\Omega$  to lower values face to the simulated optimal load. However, the  $11$  k $\Omega$  experimental optimal load obtained is still higher than  $10$  k $\Omega$  and suitable for limiting the quiescent current of the PMIC. Differences between measurement and simulation are observed due to uncertainties introduced by the tolerance values of the lumped inductor, and the diode model, *i.e.* breakdown voltage in Fig. 6b.

Finally, the rectifier is connected to a BQ25570 PMIC. The latter uses a fractional MPPT algorithm to load its source

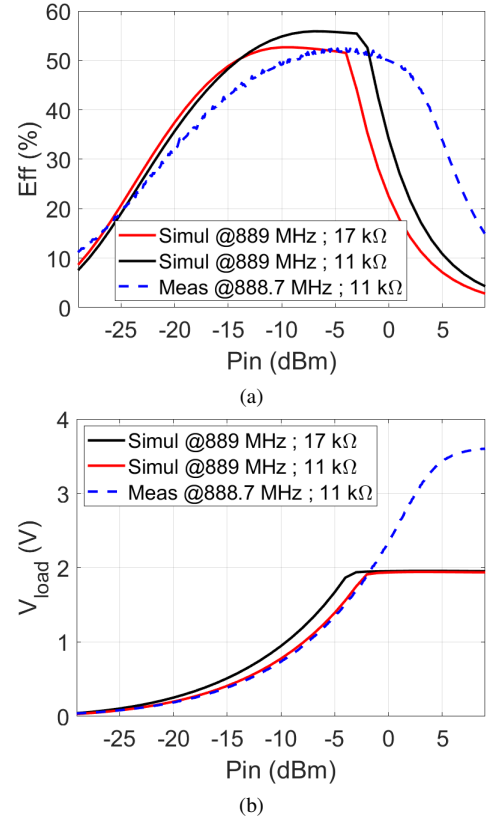


Fig. 6. Simulated and measured results, a) efficiency and b) output voltage,  $V_{load}$  at 888.7 MHz with the rectifier loaded with  $11$  k $\Omega$ .

with its optimal load. This algorithm consists in sampling and presenting to the source a fraction of its open circuit voltage. Depending on the source being used, the most appropriate fraction can be settled. To determine the most appropriate open voltage fraction for the designed rectifier, from (1), a rectifier open voltage of 378 mV is obtained when making  $I_{meas}$  equal to 0. The half of this open circuit voltage is 189 mV which is almost the voltage that the rectifier delivers at its optimal load. As a consequence, the MPPT of the BQ25570 is fixed to 50%. The PMIC used is embedded in an evaluation board and the regulated DC voltage is settled to 1.8 V which is the minimum value allowed by the evaluation board without performing major modifications. The estimated consumption of an ultra-low power WURx is around the tens to hundreds of nW [5], as a consequence the PMIC is loaded with an available load of  $10$  M $\Omega$  emulating a consumption of 324 nW. With an input power of  $-20$  dBm at the rectifier, the PMIC is capable of working in its normal mode without disabling its load, and hence, providing a continuous regulated voltage of 1.8 V and an output power of 324 nW.

Table I compares the similar works found in the literature. In [7] an end-to-end efficiency (RF rectifier + PMIC) of 40% is reported at  $-25$  dBm, inferring a 37% rectifier efficiency; however, these results are obtained in function of predicted input RF powers and the efficiency of the rectifier with a controlled source is not given. An RF harvester with an end-

TABLE I  
COMPARISON OF LOW-INPUT-POWER RF ENERGY HARVESTERS

Ref.	RF power	Signal	Rectifier efficiency	Regulation <sup>1</sup>
[7]	-25 dBm <sup>2</sup>	3G	37 %	No
[8]	-20 dBm	High PAPR <sup>3</sup>	-	Yes
[2] [10]	-23 dBm	CW	30 %	Yes
[9]	-20 dBm	Chaotic	38 %	-
[11]	-20 dBm	CW	28 %	-
<b>This work</b>	-20 dBm	CW	32 %	Yes

<sup>1</sup>Regulation of the DC output voltage.

<sup>2</sup>Predicted input RF power.

<sup>3</sup>Peak-to-Average Power Ratio.

to-end efficiency over 10 % is obtained with a high peak-to-average power rate (PAPR) signal [8], whereas it is not able to operate with a -20 dBm CW source. A chaotic waveform as an input source of a rectifier is demonstrated in [9]. It can achieve efficiency of 38 %. It however leads to the the complex waveform design reducing efficiency of power amplifier in the transmitter side. MMIC rectifier is also reported such as a 130-nm CMOS rectifier reported in [2], which has an efficiency of 30 % at -23 dBm input power. High cost MMIC process is expected.

#### IV. CONCLUSIONS

A prototype of the RF energy harvester is demonstrated in this paper. An inductive-matching rectifier aimed for low input power is proposed. Measured efficiency of 32 % and a DC voltage of 186 mV are achieved at input power of -20 dBm at 888.7 MHz. These results are sufficient to operate a commercial PMIC under its minimum limits specified on its data-sheet. Under -20 dBm the PMIC delivers a power of 324 nW which is sufficient for the targetted application. The RF input power required to deliver a regulated voltage from an RF power as low as -20 dBm is so far the lowest reported in the literature using off-the-shelf components with a CW signal. This design strategy is being used in an architecture consisting in the association of two rectifiers which increases the RF power range harvesting capability without degrading the performance at -20 dBm.

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