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Jesus Argote-Aguilar, Muh-Dey Wei, Florin-Doru Hutu, Guillaume Villemaud, Matthieu Gautier, et al.. Low-input-power Sub-GHz RF Energy Harvester for Powering Ultra-low-power Devices. International Workshop on Integrated Nonlinear Microwave and Millimetre-wave Circuits, Nov 2023, Aveiro (Portugal), Portugal. hal-04312943v1

HAL Id: hal-04312943

<https://inria.hal.science/hal-04312943v1>

Submitted on 28 Nov 2023 (v1), last revised 19 Dec 2023 (v2)

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Ultra-low-input-power Sub-GHz RF Energy Harvester for Maintaining Operation of a Power Management Integrated Circuit

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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 an ultra-low-input-power RF harvester designed with off-the-shelf components and composed of a rectifier and a power management integrated circuit (PMIC). An inductive-matching technique is employed. In the RF rectifier, the inductive branch, composed of a lumped inductor together with a short stub due to sub-GHz frequency, and the DC load, limited by the PMIC, are well discussed and optimised. 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. 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 power 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 a continuous wave (CW) signal to date.

Index Terms—rectifier, RF energy harvesting, wireless power transfer, power management integrated circuit, ultralow 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 PMIC. An architecture of the rectification circuit has been presented in [3] and it is capable of powering a sub- μ W WURx from RF power. The RF signal received from an antenna is rectified with the rectification circuit depending on

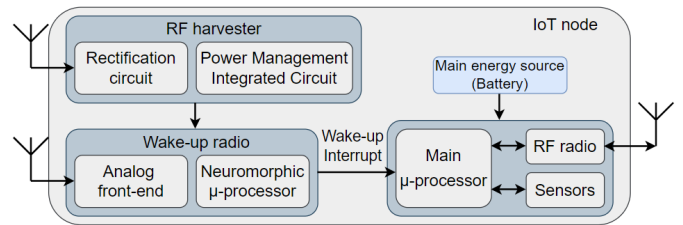


Fig. 1. Architecture aiming to reduce the dependency of an IoT node in the main energy source.

the input power. The obtained DC voltage is then regulated by a power management integrated circuit (PMIC). Good simulated performance has been shown in [3].

In this paper, an ultra-low-power RF energy 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.

II. RF ENERGY HARVESTER DESIGN

A. RF Rectifier Description

The RF energy harvester is composed of a 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 point tracking (MPPT) algorithm, the distribution of energy between an 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 [5].

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 power absorbed by 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, an optimal load higher than $10\text{ k}\Omega$ is designed in the rectifier.

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 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 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-nH leads to good matching between the rectifier and a $50\ \Omega$ RF power source and boosts the efficiency at -20 dBm when the rectifier is loaded with a $17\text{ k}\Omega$ resistor. This 128-nH inductance is achieved with a 2712sp-27N Coilcraft coil and a shorted 14 mm TL. The rectifier is implemented on a 0.7-mm -thickness Rogers RO4350 substrate, an RF choke is used to block the fundamental and harmonic frequencies from the load, and finally a 1 nF capacitor, C_1 , is used for smoothing the output DC voltage of the rectifier. For an input power of -20 dBm at a frequency of 889 MHz , an efficiency of 37% and an output DC voltage of 252 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 dimensions of the rectifier are $2.1 \times 1.9\text{ cm}^2$. S_{11} is measured using an R&S ZVA 50 vector network analyser with calibration. As showed in Fig. 4 measurement results are close to simulation and a $|S_{11}|$ of -28 dB at 888.7 MHz is obtained. Varying TL_1 , the frequency of operation can easily be designed and optimized to 868 MHz or 915 MHz which are common ISM bands. For measuring the RF-to-DC conversion efficiency, the rectifier is fed with an 888.7-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 dBm

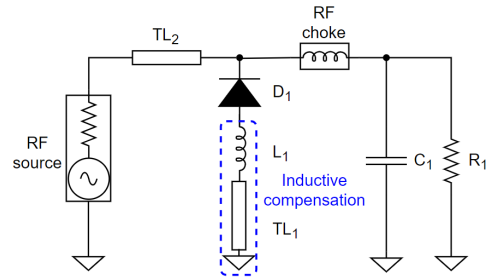


Fig. 2. Schematic of the implemented inductive-matching rectifier aimed for low-input-power.

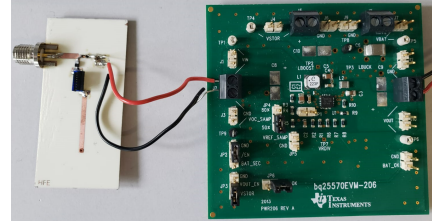


Fig. 3. Fabricated rectifier connected to a BQ25570 PMIC.

to find the optimal experimental load at this point of operation 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

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

where I_{meas} and V_{meas} are the measured output current in μA and output voltage in 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 mV for an input power of -20 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 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 . Differences between measurement and simulation are observed due to uncertainties introduced by the tolerance values of the lumped inductor as well as 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 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

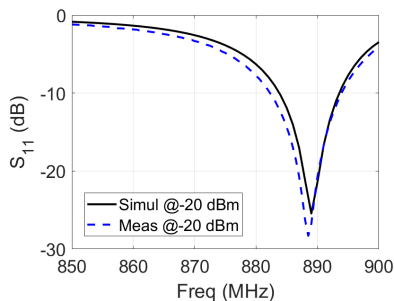


Fig. 4. Reflection coefficient S_{11} of the designed rectifier.

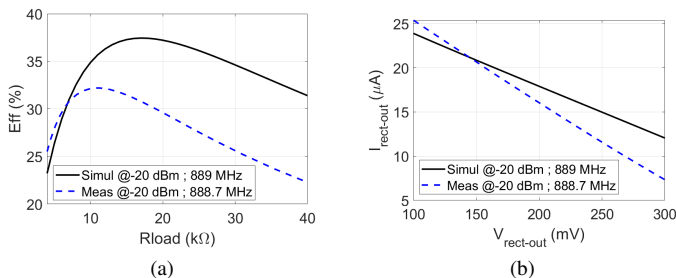


Fig. 5. Simulated and measured results, a) optimal load and b) I-V characteristic of the designed rectifier.

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, as a consequence the PMIC is loaded with an available load of 10 M Ω emulating a consumption of 324 nW. With an input power of -20 dBm at the rectifier, the PMIC is capable of working in the 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.

Although [6] is capable of harvesting a remarkable low power, it depends on other RF harvesters whose PMIC are connected in parallel. Moreover, it does not supply a regulated voltage. In [7], the system can operate at -20 dBm however using complex signals which increases the difficulty and power consumption in the transmitter.

To the best of authors' knowledge, the present work is the first discrete RF rectifier to be able to constantly keep the PMIC in the normal mode with an input power of -20 dBm to date.

IV. CONCLUSIONS AND FUTURE WORK

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

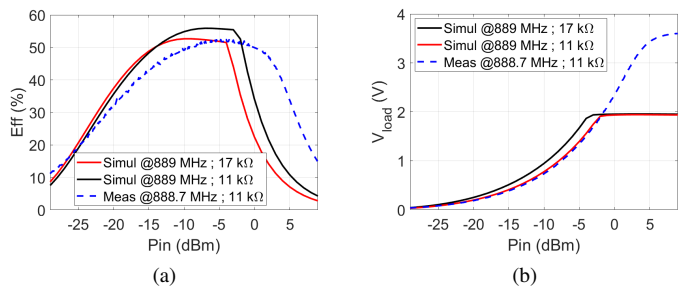


Fig. 6. Measurement results, a) efficiency and b) output voltage, V_{load} at 888.7 MHz with the rectifier loaded with 11 k Ω .

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

Ref.	RF power	Signal	PMIC	Regulation ¹
[6]	-29 dBm	-	BQ25504	No
[7]	-20 dBm	High PAPR ²	AEM30940	Yes
This work	-20 dBm	CW	BQ25570	Yes

¹Regulation of the DC output voltage.

²Peak-to-Average Power Ratio.

-20 dBm at 888.7 MHz. These results are sufficient to operate a commercial PMIC over 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 will be used for the architecture consisting in the association of two rectifiers, aiming to extend the range of RF power harvesting from -20 dBm to 0 dBm without degrading the performance at -20 dBm.

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