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Reconfigurable Nonlinear Circuit for Wireless Power Harvesting and Backscattering

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Abstract — Scarcity of accessible energy compels battery-less micro-energy wireless devices to embed energy harvesting, backscattering modulation, and even harmonic operation to avoid self-jamming. However, since those Internet of Things (IoT) devices are meant to be ubiquitous, keeping a low level of complexity of nonlinear operation, and also a small footprint circuit is becoming an ever-challenging task. This paper presents a hybrid IoT frontend architecture capable of rectification, second-harmonic generation and modulation using a single diode controlled by harmonic terminations. The proposed solutions of re-configurability are validated by measurements.

Keywords — backscattering, energy harvester, harmonic transponder, Internet of Things (IoT)

I. INTRODUCTION

A large-scale integration of ubiquitously connected and well-rounded low-power sensor/communication platforms is the foundation of Internet of Things (IoT) applications [1]. It is projected that the number of IoT connected devices worldwide will be reaching 75.44 billion in the year of 2025 [2]. As the footprints of such sensor/communication platforms are continuously becoming smaller, powering them turns out a challenging problem. Thus, higher-energy-density batteries are always a first choice at this moment for these distributed platforms for an extended life span [3]. However, considering battery recharging or replacement issues at a large scale, an ultimate long-lasting solution is to develop and deploy self-sustainable sensor/communication platforms [4]. Making a full use of ambient radiofrequency (RF) power to create self-sustainability is a straightforward idea, since this pervasive energy form is actually wasted if not used immediately [5]. Currently, there exist two different ways to recycle the ambient RF power as described in Fig. 1. Converting ambient RF power into dc energy which replaces conventional batteries in the platforms is the first one. The other is to modulate an injecting ambient RF power signal and deliver the modulated signal information, thus realizing a backscattering communication.

Harvesting ambient RF power was proposed decades ago and has now been going through a rapid development [6]. Due to a low energy density, the ambient RF power harvesting still has its power conversion efficiency below 10% [7, 8]. With this

issue in mind, researchers around the world have been developing techniques and taking measures from multiple aspects. For example, advanced semiconductor process has been continuously rolled out to enhance device nonlinearity [9, 10].

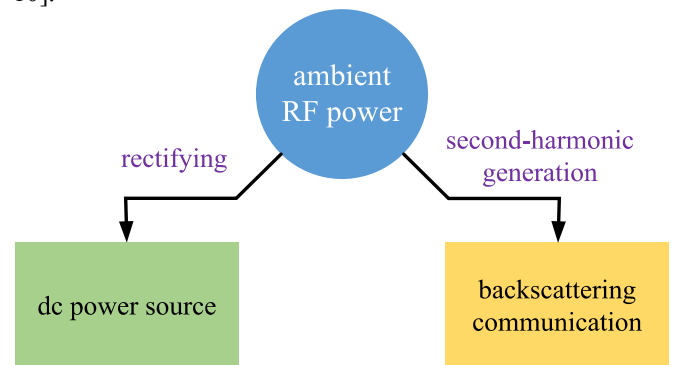


Fig. 1. Two ways to create self-sustainability of sensor/communication platforms based on ambient RF power.

Eliminating matching network to reduce any inherent mismatch loss can boost the power conversion efficiency [11]. As for the technique of backscattering communication including sensing functions, it is another promising technique, which requires no specific transmitter [12, 13]. The use of a second-harmonic generation to avoid radar clutter interference and self-jamming has been proved an efficient backscattering communication scheme [14]. In this work, a reconfigurable nonlinear circuit-based frontend is proposed and studied with a reduced system complexity and small form factor to meet the requirements of IoT applications. It combines both harmonic transponder and power harvester but still remains a multifunction compact design, featuring the use of only one diode for both functionalities. The harmonic transponder and power harvester share most of the circuit layout to minimize the circuit size. In this work, preliminary circuit design details are revealed. Also, measurement results related to the circuit performance of this multifunction scheme are provided and discussed in the paper, showing its potential to implement reconfigurable IoT tasks.

II. CIRCUIT ARCHITECTURE AND DEMONSTRATION

A. Diode Role

Diode is the core component of the proposed circuit to produce dc and higher-order harmonics. For example, the relationship of current I and voltage V of a Schottky diode can be expressed by:

$$I_{diode} = I_s \cdot \left[e^{\frac{V_{on}}{n \cdot V_t}} - 1 \right] \quad (1)$$

where I_s , n , and V_t are saturation current, ideality factor and thermal voltage of the diode, respectively. V_{on} is the voltage across diode junction. This $I - V$ relationship can be expanded by Taylor series around the zero bias point [15]:

$$I_{diode} = I_s \cdot \left[\frac{V_{on}}{n \cdot V_t} + \frac{V_{on}^2}{(n \cdot V_t)^2 2!} + \dots + \frac{V_{on}^k}{(n \cdot V_t)^k k!} + \dots \right] \quad (2)$$

Let us assume that injecting power is a single-tone signal. Thus, V_{on} can be expressed as $V_{f_0} \cos(\omega_0 t)$, where V_{f_0} is the voltage magnitude and ω_0 is the angular frequency. For a low-power injecting case, the first two terms in (2) can be used as a good approximation for simplicity. Then, by substituting V_{on} expression into (2), we have:

$$I_{diode} = \frac{I_s \cdot V_{f_0}^2}{4(n \cdot V_t)^2} + \frac{I_s \cdot V_{f_0}}{n \cdot V_t} \cos(\omega_0 t) + \frac{I_s \cdot V_{f_0}^2}{4(n \cdot V_t)^2} \cos(2\omega_0 t) \quad (3)$$

First and third terms in (3) represent the dc and second-harmonic output in connection with the diode frequency conversion. There, the diode can realize both functionalities of power harvester and harmonic transponder utilizing the second-harmonic generation by selecting a desired output power as shown in Fig. 2. To maximize the diode operation efficiency and at the same time to make a full use of the RF power, only one functionality works at one time.

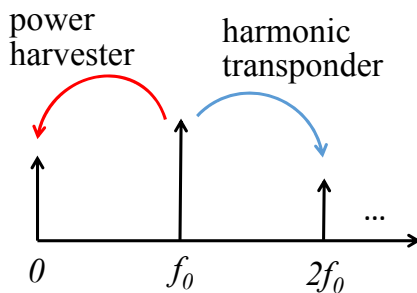


Fig. 2. Selecting desired nonlinear components generated by diode for different functionalities.

B. Harmonic Transponder

As mentioned earlier, the proposed harmonic transponder using the second-harmonic signal features a high robustness to radar interference clutter [14]. To fully comply with ISM band rules for its operation, the fundamental frequency (uplink) in

this work is set at 910 MHz, and thus the second-harmonic frequency (downlink) becomes 1820 MHz. Fig. 3 presents a schematic of a typical harmonic transponder layout. Besides the input and output matching networks, a set of quarter-wave open-circuited and short-circuited stubs are introduced to enhance the diode frequency conversion from f_0 to $2f_0$ [14, 16].

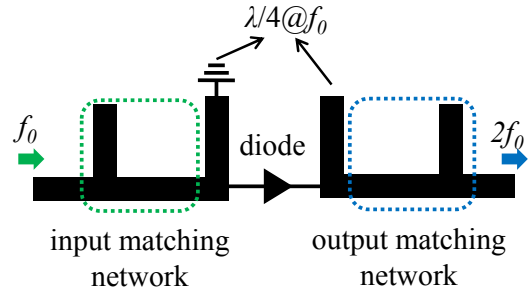


Fig. 3. Schematic of the proposed harmonic transponder using the second-harmonic generation.

C. Rectifier

To make a full use of the circuit layout of the harmonic transponder and also to achieve a compact design, a rectifier circuit of interest evolves based on the schematic of the harmonic transponder as shown in Fig. 4. As the core idea devised in this work, only one diode suitable for both functionalities is considered, which is the diode SMS7630 from Skyworks in this demonstration. Its key SPICE parameters are listed below in Table I. This diode has been widely used in low-power rectifier design [17]. Also, it has been reported that SMS7630 is a suitable candidate for a fully passive harmonic transponder design to reduce conversion loss [14].

TABLE I
KEY SPICE PARAMETERS

Parameters	SMS7630-079LF
C_{j0} (pF)	0.14
I_s (A)	5e-6
R_s (Ω)	20
n	1.05
V_j (V)	0.34
M	0.4
C_p (pF)	0.16
L_p (nH)	0.7

In this work, the rectifier loading part that includes a load resistor and a filtering capacitor, is placed at the end of the output matching stub. An RF switch will be considered to control the reconfigurable circuit. Other forms of ambient energy such as solar or thermal energy can be introduced to enable the operation of the RF switch in a more mature design afterwards. Once the switch is connected, a dc path is created in the circuit as indicated in Fig. 4 and a power harvesting starts at this moment. When the switch is disconnected, the circuit then

becomes a harmonic transponder which can be represented by Fig. 3.

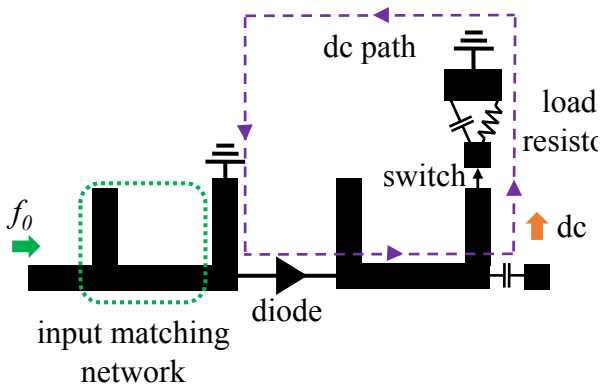


Fig. 4. The proposed circuit working as rectifier when switch is connected with dc path.

The proposed design is first verified by our ADS schematic simulation. Rogers RT/duroid 6010 with a thickness of 10 mils is selected as the substrate for prototyping. Simulation results are presented in Fig. 5. As expected, both functionalities work properly. For example, the conversion loss at an input power of -30 dBm is 19.7 dB. Rectifying efficiency under the same input level is 8.5 %.

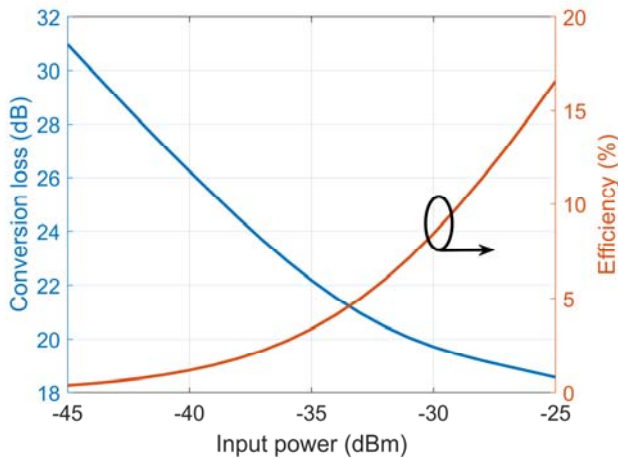


Fig. 5. Performance evaluation of the proposed circuit working as harmonic transponder and energy harvester. Simulation results of conversion loss (left side) and rectifying efficiency (right side).

III. MEASUREMENT RESULTS AND DISCUSSIONS

Fig. 6 shows the experimental prototype of the proposed circuit, whose size is about $73 \text{ mm} \times 45 \text{ mm}$. Major components of the circuit including the diode, harvester load and capacitor located at the output port of the harmonic transponder are labelled. The circuit layout enabling power harvester and harmonic transponder is also highlighted. It can clearly be seen that the circuit layout is efficiently shared by the two different functionalities and the common area accounts for more than 90

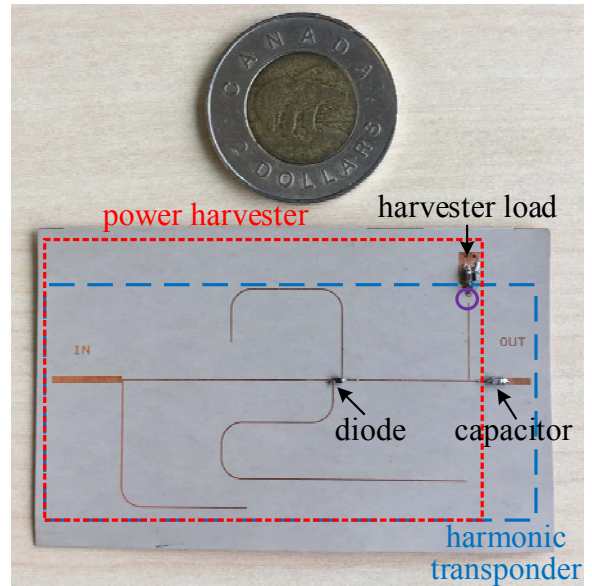


Fig. 6. Photo of the proposed nonlinear circuit prototype. The place reserved for an RF switch is labeled by a circle.

%. Also, we note that the RF switch is not included at this stage, and a 0Ω resistor is used to mimic the situation when the RF switch is connected.

Performances of the harmonic transponder and power harvester are tested separately with results as shown in Fig. 7. In this design, microstrip lines with a characteristic impedance of 100Ω is adopted, leading to a narrow linewidth. It may introduce more fabrication errors and transmission losses and thus the matching network performance does not work as well as expected. Finally, as we can see from Fig. 7, measured conversion loss results are slightly higher than simulated counterparts. Meanwhile, harvesting efficiency results are lower compared with simulation ones. However, both conversion loss and harvesting efficiency curves agree with simulation results in a very reasonable manner. Moreover, these

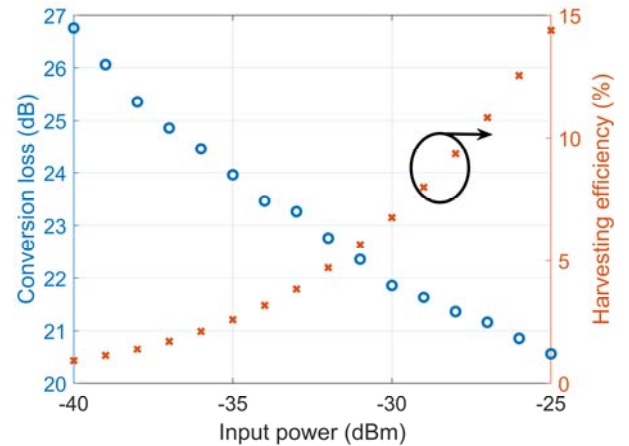


Fig. 7. Measurement results of the proposed circuit working as harmonic transponder and energy harvester. Conversion loss (left side) and harvesting efficiency (right side).

measurement results indicate that this nonlinear circuit utilizing only one diode can work properly as both harmonic transponder and power harvester. It is believed that through the introduction of an RF switch, this reconfigurable circuit would present a promising design for future IoT applications.

IV. CONCLUSION

This work proposes and demonstrates a reconfigurable nonlinear circuit for wireless power harvesting and harmonic transponder-based backscattering. This nonlinear circuit features the use of only one Schottky diode to realize both functionalities. More than 90 % of the circuit layout is shared by the passive harmonic transponder and rectifier, thereby showing a super compact design. Preliminary measurement results in this work confirm and demonstrate that this circuit can realize both functionalities of harmonic transponder and rectifier. It is anticipated that an RF switch can then be introduced to make this circuit switchable between both functionalities for future IoT applications.

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