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Compact Harmonic Feedback Rectennas for Low Power Battery-Free IoT Applications

Jinyao Zhang(1)(3), Chaoyun Song* (1)(2), Yejun He(1), Jiupei Shi(1), Jiafeng Zhou(3) and Yi Huang(3)

(1) State Key Laboratory of Radio Frequency Heterogeneous Integration, Sino-British Antennas and Propagation Joint Laboratory, Guangdong Engineering Research Center of Base Station Antennas and Propagation, Shenzhen Key Laboratory of Antennas and Propagation, College of Electronics and Information Engineering, Shenzhen University, Shenzhen, China. Emails: cysong@szu.edu.cn, heyejun@126.com

(2) Department of Engineering, King's College London, London, UK.

(3) Department of Electrical Engineering and Electronics, University of Liverpool, Liverpool, UK.

***Abstract*—We propose a novel design of rectennas with harmonic feedback capability, tailored for battery-free IoT applications that operate at low input power levels. This rectenna design is based on the voltage doubler rectification topology. By integrating a quarter-wave stub, the rectifier achieves both DC conversion and harmonic feedback using just two Schottky diodes. We also introduce a single-port design that employs an impedance transformation network. This design allows the RF input and the harmonic output of the harmonic feedback rectifier to share the same port. Consequently, it reduces the number of transceiver antennas required. Preliminary measurement results presented in this work confirm and demonstrate the circuit's capability to efficiently perform RF to DC conversion and harmonic feedback even at lower input power levels.**

I. INTRODUCTION

With the development of the Internet of Things (IoT), low-power sensors are becoming increasingly popular. Achieving battery-free and self-sustainability in a limited size is a challenging problem [1-2]. Wireless Power Transfer (WPT) is a promising technology that wirelessly transmits energy to the receiver via radio frequency (RF). It converts this energy into DC power to replace traditional batteries in platforms [3-4]. Conventional rectifier designs for WPT typically provide only DC power. The harmonic components generated by the rectifier are mostly suppressed to improve performance. However, diode-based harmonic feedback rectifiers utilize their nonlinearly generated harmonics for additional functions like positioning, power tuning, and information transmission. Attempts to exploit these harmonics have been reported, including a duplexing rectenna proposed in [5]. This rectenna sends harmonics back to the RF transmitter for positioning, steering the radiation direction from the transmitter antenna array. Existing WPT systems usually use directional high-gain antennas. An alignment system based on returning harmonics can direct the beam precisely at the receiver for optimal transmission efficiency. In [6], a rectifier with harmonic recovery capability for WPT has been reported. This rectifier communicates with the transmitter using the second harmonic to determine the load status at the receiver and to control the direction and power level of the transmit beam. However, these systems face issues like low DC conversion efficiency, low harmonic feedback power at low input power levels (< 0 dBm), and large circuit size. The limited DC power and harmonic power restrict communication distance and functionality in low-power IoT applications.

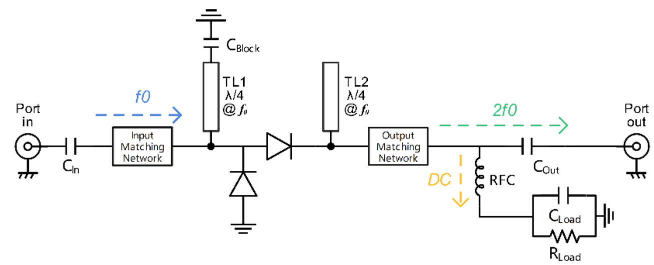

Fig. 1. Schematic of the two-ports harmonic feedback rectifier.

This work proposes a new design for a rectifier with second harmonic feedback capability, tailored for battery-free IoT applications with low input power levels. The design integrates a WPT circuit with a harmonic feedback circuit. It can simultaneously harvest wireless RF energy and feedback the second harmonic. The rectifier and the second harmonic feedback parts share most of the circuit layout to minimize size [7]. A single-port optimized design reduces the number of transceiver antennas. The quarter-wave impedance transformer network allows the input and output of the harmonic feedback rectifier to share a port while maintaining a small size and good performance.

II. HARMONIC FEEDBACK CIRCUIT DESIGN AND ANALYSIS

The schematic of a two-port harmonic feedback rectifier is illustrated in Fig. 1. This design is particularly suited for batteryless IoT systems, which are typically designed for low received power (< 0 dBm). A voltage doubler topology is employed to enhance the DC voltage level of the output, facilitating the operation of other modules. The diode, serving as a rectifying element, distorts the input waveform at the fundamental frequency due to its inherent nonlinearity, thereby generating higher harmonics. To optimize the generation of the second harmonic for effective feedback while rectifying, short-circuited and open-circuit quarter-wave stubs at the fundamental frequency f_0 (named TL1 and TL2, respectively) are strategically positioned on either side of the diode. To minimize the number of antennas required, a λ/8 transmission line TL3 (at f_0) is incorporated between point A and the input impedance matching network, as depicted in Fig. 2. This configuration allows the same port to be used for both the fundamental frequency input and the harmonic output of the harmonic feedback rectifier. For performance evaluation, a prototype of this single-port harmonic feedback rectifier was designed using the Advanced Design System (ADS) and operates at 2.4 GHz. The prototype was built on an FR4 substrate with a relative permittivity of 4.3 and a thickness of 1.57 mm. A pair of Schottky barrier diodes, HSMS2852 from Skyworks, with a low threshold voltage, was selected. The performance was simulated using a nonlinear diode SPICE model, including parasitics. The results of these simulations are presented in Figs. 3 and 4. The RF to DC conversion efficiency of this system can be expressed by:

$$\eta = V_{out}^2/(R_{Load} \times P_{in}) \times 100\% \quad (1)$$

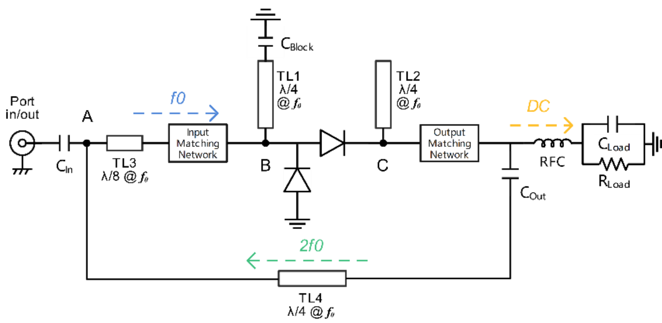

Fig. 2. Schematic of the single-port harmonic feedback rectifier.

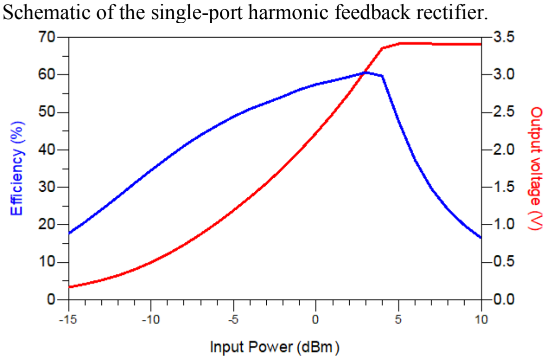

Fig. 3. Simulated RF-DC performance in ADS.

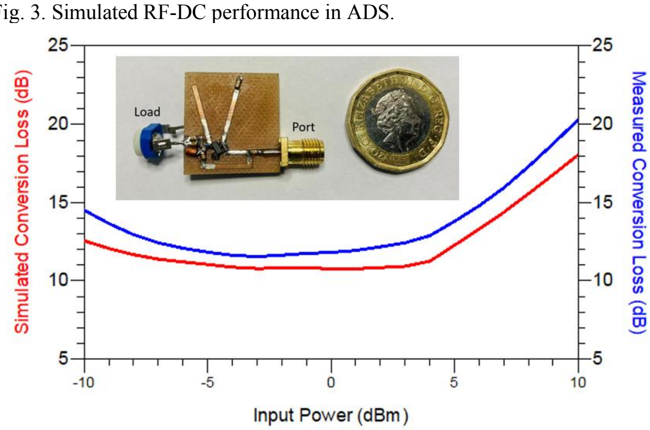

Fig. 4. Simulated and measured power conversion loss of second harmonic generation with the fabricated prototype example.

where P_{in} is the incident power and V_{out} is the output DC voltage across the load R_{Load}. As the simulation result shows in Fig. 3, the proposed single-port harmonic feedback rectifier achieves 60% peak RF-to-DC conversion efficiency at 3 dBm input power and can provide up to 3.4V DC output voltage. The simulated power conversion loss of second harmonic generation of the proposed single-port harmonic feedback rectifier by harmonic balance (HB) simulation in ADS is shown in Fig. 4. The power conversion loss CL is given by:

$$CL\ (in\ dB) = P_{f_0}(dBm) - P_{2f_0}(dBm) \quad (2)$$

where P_{f0} is the incident power at the fundamental frequency in dBm and P_{2f0} is the output power of the harmonic feedback rectifier at the 2nd harmonic frequency. As shown by the red line in Fig. 4, the simulated power conversion loss is lower than 10 dB when the input power is around -4 dBm and 4 dBm. The photograph of the fabricated prototype is depicted in Fig. 4. The design of both matching networks incorporates lumped-element components, optimizing for a minimal board size of approximately 22 mm in length and 20 mm in width. This compact design is a crucial aspect of the prototype, especially for applications where space is a limiting factor.

III. Conclusion

In this work, we have proposed a single-port rectifier design featuring second harmonic feedback capability, adept at simultaneously harvesting wireless RF energy and feeding back the second harmonic. To evaluate its performance, we designed a harmonic feedback rectifier utilizing a pair of HSMS2852 Schottky diodes, operating at a frequency of 2.4 GHz. Both simulated and measured results demonstrate the effectiveness of the proposed topology. Impressively, at an input power of 0 dBm, the design achieved a conversion loss of 12 dB and an RF to DC conversion efficiency of 53%.

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