A High-Efficiency RF Rectifier-Booster Regulator for Ambient WLAN Energy Harvesting Applications

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***Abstract*—In this paper, a novel high-efficiency rectifier-booster regulator operating in radio frequency (RF) is firstly proposed. Then an entire WLAN energy harvesting system is demonstrated. A flower-shaped broadband dual-polarized cross dipole rectenna with a matching network is employed to harvest electromagnetic energy from a WiFi router. A novel rectifier-booster regulator (RBR) is proposed to rectify AC energy to DC and boost the output voltage. It evolves from a Greinacher rectifier and a Dickson charge pump to form a full wave rectifier. The measurement results show that the RBR can achieve up to ×3.4 voltage boosting with 85% voltage conversion efficiency (VCE) and provide over 1 V output voltage within a distance of 50 cm between a power amplifier (PA) with 20 dBm transmitting power and the rectenna. Maximum energy of 245 μW is harvested by the entire system. The good performance shows its wide practicality for Internet-of-Thing (IoT) applications.**

***Index Terms*—RF, WLAN energy harvesting, IoT, rectenna, Greinacher rectifier, Dickson charge pump**

I. Introduction

As internet of thing (IoT) becomes a hot research field, integrated circuits for smart home and health caring or environment monitoring have to meet explosive growth. In the meantime, power consumption and energy source of these circuits attract wide attention. Ultra-low power design and reliable power source are necessary for these circuits since they are designed to work for over ten years. The concept of harvesting energy from ambient environment has been raised for a long time. Several types of energy sources like solar energy and thermal energy have been adopted to power some low-power circuits. However, their drawbacks limited the applications of such sources. For instance, solar energy is not available at night and thermal energy breaks down in the environment with a stable temperature. Radio frequency (RF) signals, however, are widely used for mobile communications, radio/TV broadcasting systems and WiFi networks. RF energy can be harvested anytime and almost everywhere in urban environment. The feasibility of RF energy harvesting has been experimentally proved from hardware implementation viewpoint [1].

Many papers have been published dealing with the problems of RF energy harvesting. Ref. [2] focuses on the optimization of antennas to collect more power. Ref. [3] proposes a new rectifier to improve conversion efficiency. But these papers did not take the output voltage of a harvester into consideration. Normally, RF energy is weak, especially under outdoor conditions. The output voltage is very low, even with high energy conversion efficiency of the harvester. In this case, RF energy cannot be used directly to power the next stage which usually demands a supply voltage of several V and a power of several mW. A Greinacher rectifier can be used to rectify and boost output voltage, but the output voltage is still quite low for most circuits [2], [4], [5]. A conventional Dickson charge pump is generally employed as a DC-DC voltage multiplier to further boost the output voltage of the rectifier. But it suffers from the drawback of high reverse DC bias as the cascading stage increases. Also, a Dickson charge pump generates various odd harmonics, which requires complex filters in the circuit [4].

In this paper, an RF energy harvester focusing on indoor WLAN energy harvesting is described. Then, the circuit implementation of the system is given. Finally, experimental results demonstrating the design of the RF energy harvesting system are presented.

II. Design of RF Energy Harvesting System

A. Architecture of RF Energy Harvesting System

The architecture of the proposed entire RF energy harvesting system is shown in Fig. 1. Electromagnetic energy radiated from the antenna is harvested by a dual-polarized cross dipole rectenna with a matching network. A novel rectifier-booster regulator (RBR) is proposed to rectify AC power to DC and boost the output voltage. An energy storage unit temporarily stores energy and a voltage regulator further regulates the voltage for an IoT load.

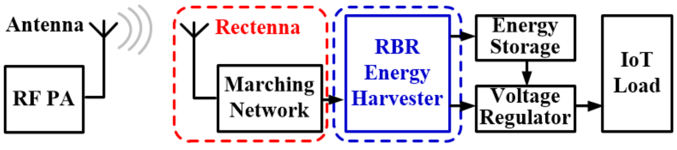

Fig. 1. Architecture of RF energy harvesting system

B. Rectenna design

A flower-shaped broadband dual-polarized cross dipole rectenna with a matching network [5] is employed to harvest electromagnetic energy from WiFi router and transform it into AC electric energy. The cross dipole rectenna is selected due to its planar shape and dual polarization which is suitable for incoming signals with arbitrary polarizations. A flower-shaped slot filter has been designed on the patch rectenna to suppress harmonics. A matching network is designed and optimized to match with a wide range of input power levels.

C. RBR implementation

Normally, a Greinacher rectifier, formed by $C_{1\sim4}$ and $D_{1\sim4}$ (shown in Fig. 2), works as a voltage quadrupler. During the positive cycle of the RF signal, C_2 is charged to V_N through the C_2-D_2 path. During the negative cycle, C_1 is charged to V_P through the C_1-D_1 path. Meanwhile, C_4 is charged to $2V_N$ through the C_4-D_4-C_2 path. During the next positive cycle, C_3 is charged to $2V_P$ through the C_1-D_3-C_3 path. The differential voltage between node A and B is four times of those rectifiers with four diodes and four capacitors.

Besides, a Greinacher rectifier can also be divided into two separated 2-stage Dickson charge pumps connecting to virtual ground (*gnd*). Even though a Greinacher rectifier can boost the output voltage of a rectenna, the voltage may still be too low to power the next stage directly, especially when the RF signal is weak. If more boosting stages are cascaded after nodes A and B, the output voltage will be further increased.

Therefore, a rectifier-booster regulator (RBR) is proposed in this paper, as shown in Fig. 2. It evolves from a Greinacher rectifier and a Dickson charge pump to rectify AC energy from rectenna to DC and boost the output voltage. The RBR combines the merits of both a Greinacher rectifier and a Dickson charge pump. Here, the Dickson charge pump is not simply connected after the Greinacher rectifier. The Greinacher rectifier not only functions as a rectifier but also forms initial stages of the Dickson charge pump.

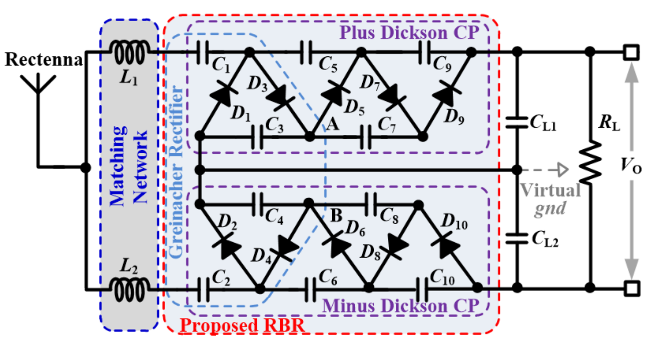

Fig. 2. Circuit implementation of the proposed rectifier-booster regulator

Ideally, the output voltage of the RBR would increase as the number of stages increases. But actually, the output voltage will decrease after several stages. This is caused by the threshold voltage of diodes. As a result, the voltage conversion efficiency (VCE) drops dramatically.

In order to optimize the number of stages and improve the output voltage efficiently, the open circuit voltage (OCV) and VCE of an up to 7-stage RBR are tested under about -8 dBm input power from the rectenna, as shown in Fig. 3 (Here, an SMS7630 series Schottky diode is used to implement the RBR shown in Fig. 2). At the beginning, the OCV increases with the increment of the boosting stages, and the VCE drops slightly. When the boosting stages exceeds 4, the OCV decreases and the VCE drops dramatically. This indicates the optimal result of our design. A 4-stage RBR is adopted to achieve 1.7 V OCV and 85% VCE, which means a voltage boosting of 3.4 is obtained.

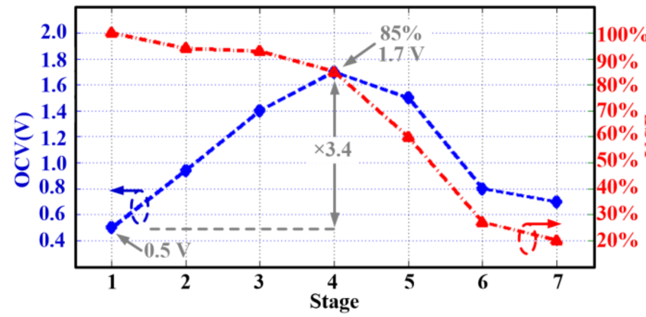

Fig. 3. Measured OCV and VCE versus the number of cascaded stages with an input power of -8 dBm from the rectenna

III. Measurement Results

The test platform is shown in Fig. 4. The RF signal is generated by a signal generator. An Power amplifier (PA) magnifies the RF signal with 11 dB gain. A DC source powers the PA. The input power from the rectenna can be changed by varying the magnitude of the RF signal or the distance between the radiating antenna and the proposed harvesting system (a 4-stage RBR adopted for the experiment).

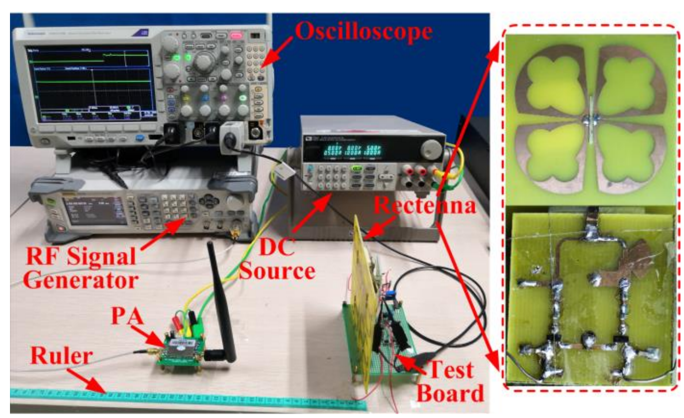

Fig. 4. Test platform of proposed RF energy harvester

Since the proposed harvester focuses on indoor RF energy harvesting, 2.4 GHz signals are commonplace in such an environment (WiFi network, ZigBee or Bluetooth communications) and are employed for the system test. Fig. 5 shows the measured results of the output power versus output voltage of the proposed system under different load impedance in three different input power levels. The distance between the Tx antenna and the rectenna is set to 15 cm, and the magnitude of the RF signal varies. When the output power of the signal generator is about 4 dBm, 6 dBm, 8 dBm, respectively, the measured

OCV and estimated maximum power conversion efficiency (PCE) of the entire harvesting system are 1.7 V and 45.6%, 2.6 V and 53.8%, 3.5 V and 61.6%, respectively. Compared with [2], [3], [4], the proposed harvester boosts the output voltage to a level more suitable for IoT loads. The system maintains similar or even higher power conversion efficiency. Also, as shown in Fig. 5, all three scatter curves of the output power exhibit a single peak characteristic, which indicates the maximum power point (MPP) when the load impedance matches with that of the rectenna. This feature leads the way to capture more power by carefully designing the RF energy harvesting system.

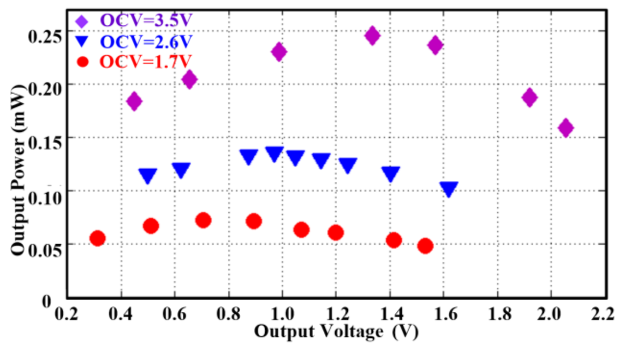

Fig. 5. Measured output power versus output voltage of the proposed harvester under different input power condition

Normally, the output power of a WiFi router is about 20 dBm. In this experiment, a PA is employed to simulate the operation of a WiFi router as an energy source, and the output power of the PA is set to 20 dBm. To facilitate comparison of our design, both a Greinacher rectifier and a 4-stage RBR energy harvester are implemented. Fig. 6 shows the measured results of the OCV versus distance, which indicate that the proposed system can provide over 1V output voltage within a distance of 50 cm between the antenna and the rectenna. Compared with the Greinacher rectifier, the proposed system can boost the output voltage up to 3.5 times higher.

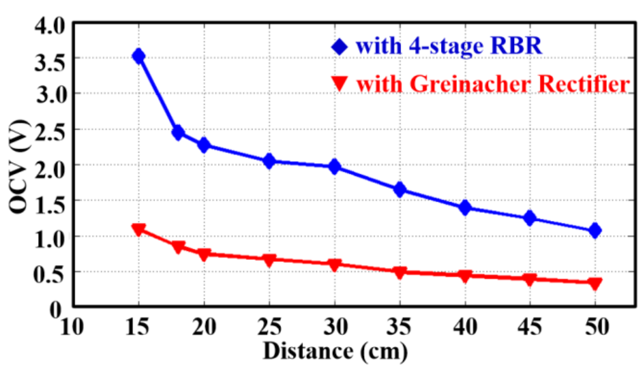

Fig. 6. Measured OCV of proposed system and Greinacher rectifier with different distance between antenna and rectenna

The proposed system is placed to harvest WLAN energy from a WiFi router (TP-LINK TL_WDR5620) with a distance of 15 cm while the router is downloading a big data file. Fig. 7 shows transient waveforms of the output voltage of the harvester with a Greinacher rectifier (with and without an output capacitor) and with the 4-stage RBR. It can be seen that the harvester with the RBR improves the output voltage significantly. Measured results further demonstrate the feasibility of harvesting WLAN energy by the proposed RF energy harvesting system.

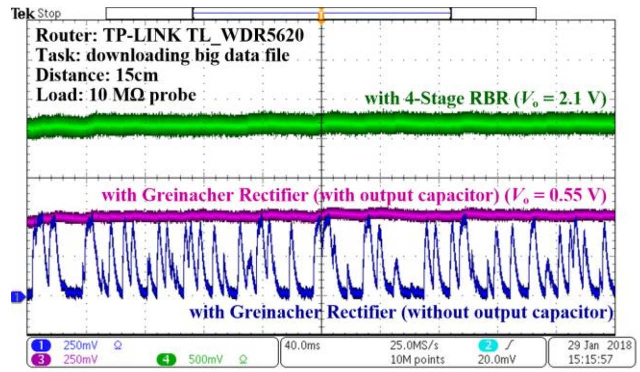

Fig. 7. Output voltage when harvesting WLAN energy from WiFi router

IV. Conclusion

A novel high-efficiency RF RBR has been proposed in the paper. It was evolved from a Greinacher rectifier and a Dickson charge pump to form a full-wave rectifier. It has dual paths with virtual ground connecting the booster architecture. Then, combined with a flower-shaped broadband dual-polarized cross dipole rectenna, an entire WLAN energy harvesting system is demonstrated by harvesting RF energy from a WiFi router and storing the electric energy in a capacitor. It shows a high VCE and PCR. These merits prove the good practicality of the proposed harvesting system for Internet-of-Thing applications.Acknowledgment

References

[1] T. Wu, and H. C. Yang, "RF Energy Harvesting with Cooperative Beam Selection for Wireless Sensors," *IEEE Wireless Communications Letters*, vol. 3, no. 6, pp. 585-588, Dec. 2014.

[2] Y. S. Chen, and C. W. Chiu, "Maximum Achievable Power Conversion Efficiency Obtained Through an Optimized Rectenna Structure for RF Energy Harvesting," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 5, pp. 2305-2317, May 2017.

[3] Y. Lu, H. J. Dai, M. Huang, M. -K. Law, S. –W. Sin, S. –P. U, and R. P. Martins, "A Wide Input Range Dual-Path CMOS Rectifier for RF Energy Harvesting," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 64, no. 2, pp. 166-170, Feb. 2017.

[4] H. Zhang, Z. Zhong, Y. X. Guo and W. Wu, "Differentially-fed charge pumping rectifier design with an enhanced efficiency for ambient RF energy harvesting," in *IEEE International Microwave Symposium (IMS)*, June 2017, pp. 613-616.

[5] C. Y. Song, Y. Huang, J. F. Zhou, J. W. Zhang, S. Yuan, and P. Carter, "A High-Efficiency Broadband Rectenna for Ambient Wireless Energy Harvesting," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 8, pp. 3486-3495, Aug. 2015.