Two-Port Five-Band Rectenna for Ultralow Ambient RF Energy Harvesting

Zhen Li, Jing-Wei Zhang, *Member, IEEE*, Yu-Chao Wang, Da-Ping He, and Cheng Zhang, *Member, IEEE*

***Abstract*—A two-port rectenna is proposed to harvest the ambient RF power from five commercial bands, including 1.8, 2.1, 2.4, and 2.65 and 3.5 GHz for GSM, LTE, WLAN, and 5G, respectively. The novel rectenna comprises a hybrid half-wave rectifier and two back-to-back slot antennas. The rectifier consists of a series rectifier branch and a parallel rectifier branch to extend its multiband coverage, only sharing one diode. With this design strategy, its RF-dc power conversion efficiency (PCE) can reach 23.1% at 1.8 GHz, 26.4% at 2.1 GHz, 27.2% at 2.4 GHz, 20.7% at 2.66 GHz, and 19.1% at 3.47 GHz with −20 dBm input power level. Notably, once a five-tone signal is input simultaneously with the identical power level of −20 dBm, the PCE of rectifying circuit can be improved to 43.7%, breaking the existing record to the best of authors' best knowledge. The designed slot antennas can also receive omnidirectional RF power at five corresponding frequencies. The experimental results demonstrate that our proposed rectenna is competitive in band coverage and PCE with ultralow input power, indicating enormous potential for RF energy harvesting and powering sensors, wearables, and other low-power scenarios.**

***Index Terms*—Five-band rectifiers, hybrid rectifiers, rectennas, RF energy harvesting, two-port rectennas.**

I. Introduction

RF ENERGY harvesting is a potential solution to alleviate the requirement for battery replacement in the Internet of Things [1]. Compared with renewable energy, such as solar and wind, the significant advantage of RF energy harvesting as a power supplier is implantable and sustainable [2]. In addition, with the rapid development of wireless communications in the last decade, RF sources in the environment, especially Wi-Fi and cellphone base stations, are gradually increasing. Therefore, harvesting ambient RF energy has more potential to power devices [3].

The rectenna is the core device of an RF energy harvesting system, which can convert RF signal into dc power. The ideal rectenna should have high efficiency and provide enough power. However, due to the low ambient power level (<−20 dBm) and diode loss, it is incredibly challenging to improve the power conversion efficiency (PCE) of the rectennas at ultralow power levels. One practical approach is to use wideband or multiband rectennas, which collect more ambient power from multiple or continuous frequency spectrums. Currently, a group of wideband and multiband rectennas is presented, and the critical element for wideband and multiband rectennas are rectifiers [4], [5], [6], [7], [8], [9], [10], [11], [12]. Note that the available ambient power in the air is always discontinuous [13]. Due to the nonlinear impedance characteristics of the diode, it is a bottleneck to design such a broadband rectifier covering several available bands. In addition, multiband rectennas can avoid interference with other undesired signals within bands.

Therefore, it is necessary to investigate advanced multiband rectennas to boost the PCE at ultralow power levels. For instance, a seven-band rectenna with a three-branch rectifier was proposed [14], of which only three diodes have been adopted to match seven operation bands. Even like this, its average PCE is just about 16.5% at −20 dBm due to the increased losses of excessive diodes. Further, an eight-band rectenna with a single-branch rectifier (containing two diodes) was reported [15]; but as a result of the complex impedance matching network, the PCE is low at several working frequencies (7.5% at 1.68 GHz, 5% at 4.31 GHz, 3.5% at 5.11 GHz, and 1% at 5.49 GHz) with the power level of −20 dBm. In addition, a triple-band rectenna with a conjugate-matched rectifier was presented [16], and its PCE is around 21% at −20 dBm. A state-of-the-art research has proved that the challenge for enhancing the PEC of multiband rectennas is simplifying the matching network and limiting diode losses.

This letter presents a five-band dual-port rectenna to efficiently harvest the ambient RF energy from the available primary spectrum (GSM 1.8 GHz, LTE 2.1 GHz, WLAN 2.4 GHz, and 5G 2.65 and 3.5 GHz). To simplify matching networks and reduce the diode loss, the novel dual-port five-band rectifier is hybridized by a series rectifier branch and a parallel rectifier branch, sharing the same diode. The experimental results illustrate that our proposed rectifier performs well at ultralow input power levels of −35 to −20 dBm. With −20 dBm input power, the PCE is 23.1% at 1.8 GHz, 26.4% at 2.1 GHz, 27.2% at 2.4 GHz, 20.7% at 2.66 GHz, and 19.1% at 3.47 GHz. Moreover, the proposed rectifier can improve the PCE of a five-tone signal input to 43.7% at −20 dBm.

II. Dual-Port Hybrid Rectifier

Since the rectifying diode is a nonlinear element, multiband impedance matching for a rectifier with one brunch is challenging. A dual-port hybrid rectifier is proposed to simplify the matching network and decrease diode loss. This rectifier consists of series and parallel rectifier branches. As shown in Fig. 1, two branches share the same diode (SMS7630-079LF) and output load (2.7 kΩ). The substrate material is F4BM-2 ($\varepsilon_r = 2.65$,

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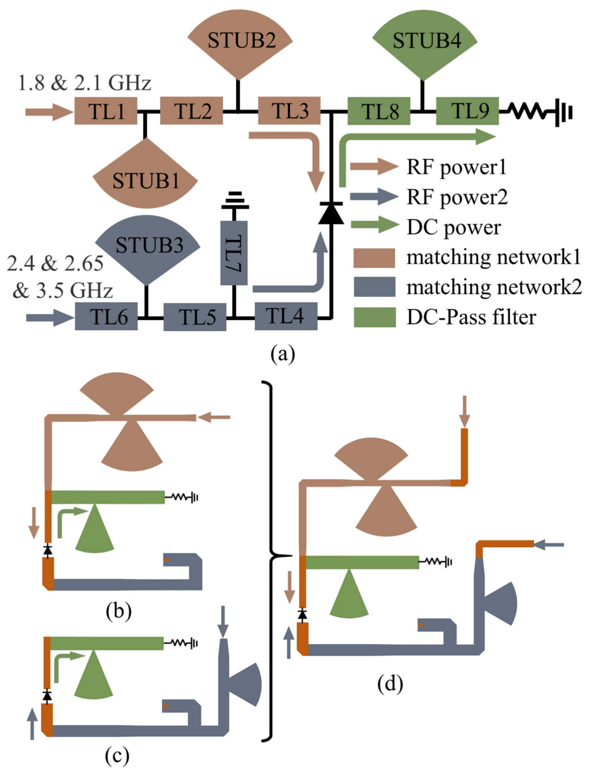

Fig. 1. Design process and schematic diagram of hybrid dual-port rectifier. (a) Schematic diagram of hybrid dual-port rectifier. (b) Shunt rectifier. (c) Series rectifier. (d) Hybrid dual-port rectifier.

$\tan\theta = 0.0008$) with a thickness of 0.764 mm. Besides that, each of them contains an impedance matching network and dc-pass filter. Both input ports are designed to match with a 50 Ω to match with the harvesting antenna. The rectifier is designed and optimized by using Keysight ADS software harmonic balance and large signal *S*-parameters simulation methods.

The first step is to design a dual-band shunt rectifier. Fig. 1(b) illustrates the topology of the shunted rectifier. The RF power (1.8 and 2.1 GHz) passes through its impedance-matching network into the negative diode terminal. Then, a series rectifier is designed, as shown in Fig. 1(c), and the RF power (2.4, 2.65, and 3.5 GHz) passes through the series impedance matching network into the positive diode terminal. In order to hybridize the two rectifiers, it is crucial to building a bridge. In this design, we choose a shorted stub (TL7) as the bridge, which is the matching element in the series rectifier and the grounding part in the parallel rectifier. Power converted by hybrid circuits is combined into dc energy by a dc-pass filter (TL8, TL9, and Stub4), which can suppress fundamental frequency signal to the load. Fig. 2 shows the simulated *S*-parameters of the hybrid rectifier with −20 dBm input power. It is obtained that good impedance matching and port decoupling are achieved at 1.8, 2.1, 2.4, 2.65, and 3.5 GHz, and therefore, the high PCE can be observed in Fig. 3(a). In addition, the simulated PCE of the proposed rectifier for 1–5 tones is plotted in Fig. 3(b). The average 1-tone PCE reached 25.2% with −20 dBm input power in the desired frequencies, revealing the rectifier's performance to harvest wireless power for GSM, Wi-Fi, LTE, and 5G. The attractive point of this design is that power captured from five bands is concentrated into one rectifying diode, which can effectively increase the PCE with

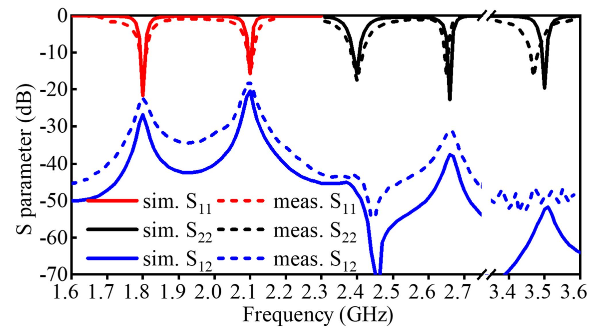

Fig. 2. Simulated *S*-parameters of the dual-port rectifier.

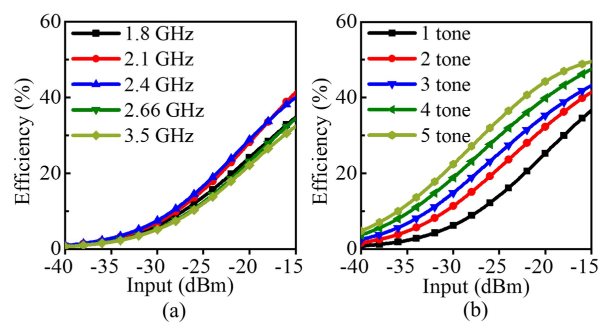

Fig. 3. Simulated PCE of the hybrid dual-port rectifier for one–five tones. (One-tone for the average, two-tone for 1.8 and 2.4 GHz, three-tone for 1.8, 2.1, and 2.4 GHz, and four-tone for 1.8, 2.1, 2.4, and 2.66 GHz).

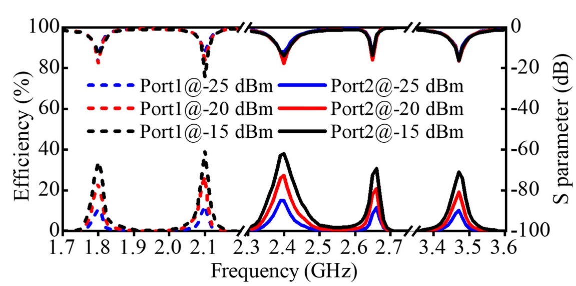

Fig. 4. Measured PCE and S-parameters of the proposed rectifier.

ultralow input power. As the input tones increase, the five-tone PCE improves to 44.2% at −20 dBm.

Fig. 4 plots the measured S-parameters and PCE at three input power levels. The rectifier has suitable impedance matching over five operational frequencies with the input power from −25 to −15 dBm. We can calculate the PCE using

$$\mathrm{PCE} = V_L^2/R_L P_{\text{in}} \tag{1}$$

where V_L is the output voltage measured by a multimeter, R_L is the load resistance, and P_{in} is the input RF power provided by a signal generator. The measured PCE of the rectifier is 23.1% at 1.8 GHz, 26.4% at 2.1 GHz, 27.2% at 2.4 GHz, 20.7% at 2.66 GHz and 19.1% at 3.47 GHz with −20 dBm input power, respectively. Because of fabrication error, parasitic properties of the diodes and the SMA connector used in the circuit, the simulated results are slightly different from the measured results.

We also measured the rectifier performance with multitone signals to evaluate multitone rectification performance. The

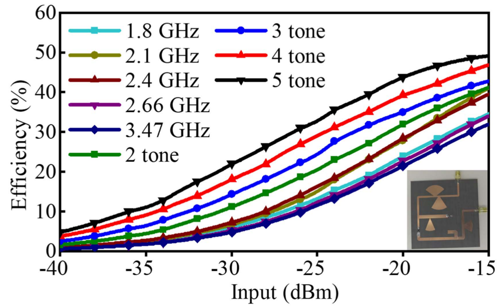

Fig. 5. Measured PCE of the hybrid dual-port rectifier. (One-tone for the average, two-tone for 1.8 and 2.4 GHz, three-tone for 1.8, 2.1, and 2.4 GHz, and four-tone for 1.8, 2.1, 2.4, and 2.66 GHz). Inset: photograph of the fabricated rectifier.

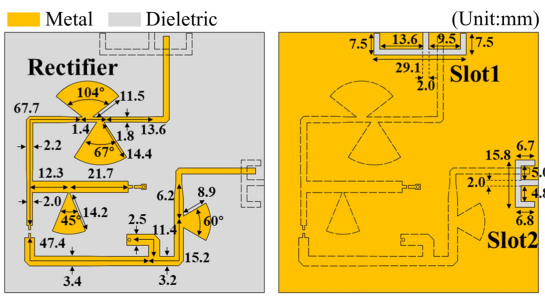

Fig. 6. Structure and dimensions of the rectenna.

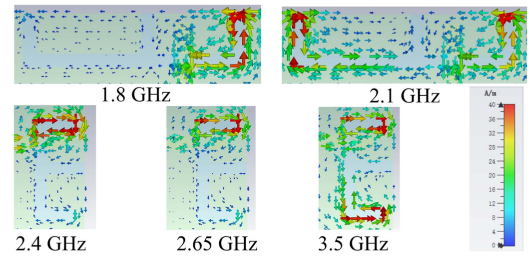

Fig. 7. Current distribution of the antennas at different frequency.

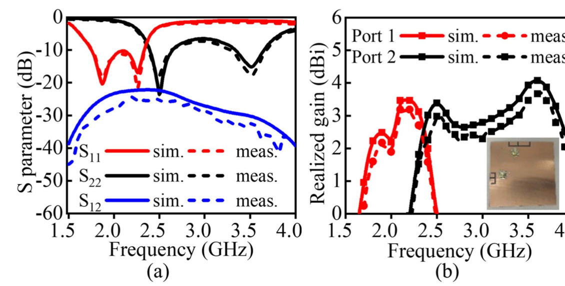

Fig. 8. Simulated and measured results of the proposed antenna. (a) *S*-parameter. (b) Realized gain.

signal is provided by an RF power combiner, which combines single-tone signals from different bands generated by signal generators. The system has been calibrated and adjusted to the same power level for each frequency. The total input power of the rectifier $P_{\text{in\_all}}$ can be calculated by using

$$P_{\text{in\_all}} = P_{\text{in\_}f1} + P_{\text{in\_}f2} + \ldots + P_{\text{in\_}fn} \quad (2)$$

and the measured PCE of the proposed rectifier for one–five tones are plotted in Fig. 5. The PCE of multitone can be calculated by (1) and (2). The multitone PCE is 23.2% at one-tone, 31.8% at two-tone, 34.9% at three-tone, 39.3% at four-tone, and 43.7% at five-tone at -20 dBm input power. As the input energy increases from single to five-tone, the PCE can increase from 6.1% to 22.4% at -30 dBm, 12.3% to 32.4% at -25 dBm, and 23.6% to 43.7% at -20 dBm.

III. Five-Band Rectenna

A. Antenna Design

As shown in Fig. 6, two E-slot antennas are designed on the back of the rectifier to harvest RF power at the desired frequencies. The proposed E-slot antennas adopt the open terminal structure and are carved on the edge of the floor, making the rectenna structure more compact. Each E-slot antenna consists of a 0.25λ open slot and a 0.5λ traditional slot, which can generate dual-frequency characteristics. The current distribution of the slot antenna at different operating frequencies is shown in Fig. 7. It can be observed that the proposed antennas operate in the 0.25λ open-slot resonant mode at 1.8, 2.4, and 2.65 GHz, while in the 0.5λ traditional slot resonant mode at 2.1 and 3.5 GHz, respectively. The parameters of the resonant path can control the resonant frequency. We can calculate antenna frequency using the following:

$$f_{\text{open\_slot}} = \frac{c}{4L_{\text{Path}}\sqrt{\varepsilon_{\text{eff}}}} \quad (3)$$

$$f_{\text{trad.\_slot}} = \frac{c}{2L_{\text{Path}}\sqrt{\varepsilon_{\text{eff}}}} \quad (4)$$

where f is the antenna resonant frequency, L_{Path} is the resonant path length, c is the speed of light, and ε_{eff} is equivalent dielectric constant.

An antenna prototype was fabricated on a 0.764 mm F4BM-2 substrate to verify our design. The measured and simulated *S*-parameters of the slot antennas are given in Fig. 8(a). The experimental results are consistent with the simulated results and achieve good impedance matching (S_{11} & $S_{22} < -10$ dB) at the corresponding five bands (1.8, 2.1, 2.4, 2.65, and 3.5 GHz). The simulated and measured realized gains of the slot antennas are also shown in Fig. 8(b), which has good agreements. Fig. 9 demonstrates the radiation patterns of slot antennas at their operational frequencies. It is shown that both the slot antennas have omnidirectional radiation patterns and broadside beamwidth at desired frequencies, suitable for ambient energy harvesting.

B. Rectenna Implement

To verify the performance of this two-port five-band rectenna, an integrated rectenna is fabricated and tested in an anechoic chamber based on the dimensions shown in Fig. 6. We can calculate receiving power using

$$P_r = P_t + G_r + G_t + 20log_{10}\left(\frac{\lambda}{4\pi d}\right) \quad (5)$$

where P_t is the energy from a generator, G_t is the gain of reference horn, and d (2.9 m) is the distance between the horn and the rectenna. The realized gain of the receiving antenna G_r

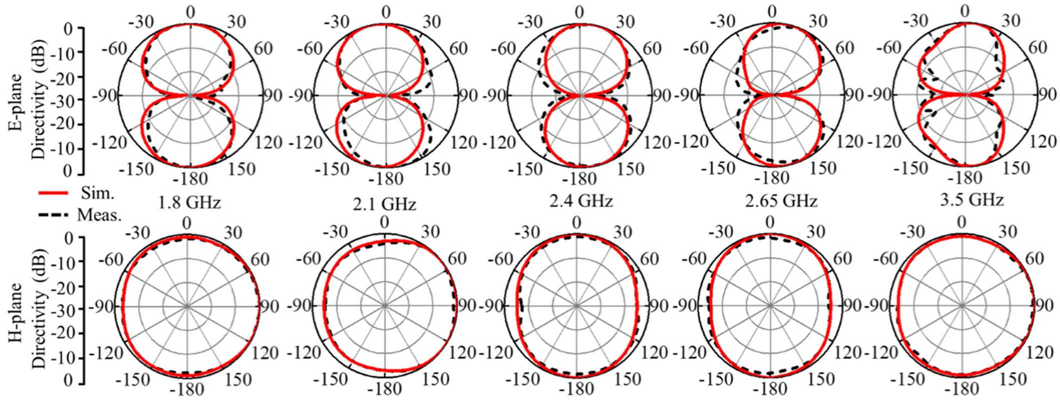

Fig. 9. Radiation patterns of the slot antennas at operational frequencies.

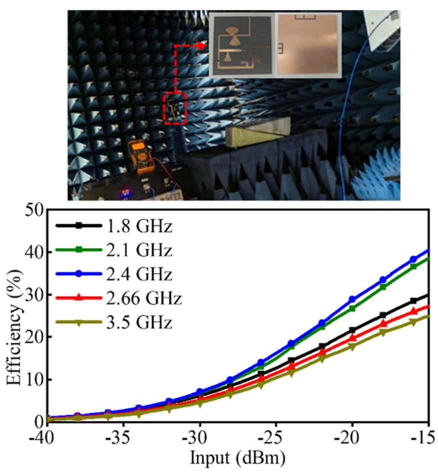

Fig. 10. Measured PCE of the rectenna.

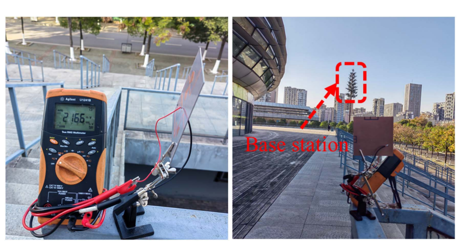

Fig. 11. Outdoor experimental photograph.

is 1.59 dBi at 1.8 GHz, 3.18 dBi at 2.1 GHz, 2.25 dBi at 2.4 GHz, 2.41 dBi at 2.65 GHz, and 3.46 dBi at 3.5 GHz. The PCE of the rectenna is obtained by (1) and (5).

As shown in Fig. 10, the measured highest PCE of the proposed rectenna is 21.6% at 1.8 GHz, 26.7% at 2.1 GHz, 28.8% at 2.4 GHz, 19.8% at 2.66 GHz, and 17.9% at 3.5 GHz with −20 dBm input power.

Moreover, the proposed rectenna is measured in an outdoor ambient environment at the campus to evaluate the rectenna performance, as shown in Fig. 11. With an overall ambient input power level of −13.2 dBm, the measured rectenna dc output voltage is roughly 200 mV, corresponding to 30.2% of average PEC. The proposed rectenna can achieve a peak value of 216.6 mV (the load is 2700 Ω), corresponding to an output dc power of 17.4 μW. Table I gives a comparison between this design and other works. Our design uses only one diode but covers five operating frequency bands while maintaining 23.2% average PCE at −20 dBm input. Moreover, the proposed rectifier can improve the PCE of a five-tone signal input to 43.7% at −20 dBm input, which is better than other published designs. Therefore, the proposed rectenna can cover multiple frequency bands and maintain high PCE at ultralow input power, which is a very good candidate to power low-power devices in many practical applications.

TABLE I
COMPARISON OF THE PROPOSED RECTIFIER AND RELATED DESIGNS

Ref.	Topology	Rectifier size (mm × mm)	Diode no.	Band no.	Average PCE at -20 dBm	Multitone PCE at -20 dBm
[6]	single (series)	44×81	1	3	24.1%	35.4%
[15]	single (doubler)	80×80	1	8	12%	Nor
[14]	stacked (shunt)	54×42	3	7	15%	Nor
[8]	stacked (doubler)	Nor	6	4	16%	36%
This work	hybrid (half-wave)	75×75	1	5	23.2%	43.7%

IV. CONCLUSION

A five-band dual-port hybrid half-wave RF rectenna has been presented theoretically and experimentally. The results demonstrate that the proposed rectenna has achieved overall high PCE at low input power and multiple frequency-band coverages. Furthermore, the topology of the proposed rectenna can improve the PCE of the five-tone signal input to 43.7% at −20 dBm. In conclusion, the proposed rectenna can achieve multiband coverage and high efficiency, making it suitable for RF power harvesting and powering sensors, wearables, and other low-power scenarios.

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