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A Self-biased Adaptive Reconfigurable Rectenna for Microwave Power Transmission

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***Abstract*—A self-biased adaptive reconfigurable rectenna, consisting of a microstrip patch antenna and a self-biased reconfigurable rectifying circuit, is proposed. To eliminate the need of bias networks, a DC power routing structure is introduced to link the reconfigurable matching stub and the load. Hence the output DC current obtained by the rectifier can be divided/split, thereby letting a part of the DC current flow back to the matching stub for providing a bias voltage. According to the input power level, the states of the PIN switch can be automatically changed in order to connect/disconnect the matching stub to the rectifying circuit for achieving improved matching performance at different power levels. Simulated and measured results show that the proposed rectenna reaches more than 50% conversion efficiency over a broadened input power range from 0~20 dBm with the peak efficiency of 68% at 9 dBm. It is evident that the proposed self-biased reconfigurable matching scheme is a promising and effective solution to facilitate the less-complicated reconfigurable rectenna integration and realize high efficiency at higher operating frequency bands (e.g. > 5 GHz).**

Index Terms—Adaptive antenna, reconfigurable rectenna, self-biased, microwave power transmission.

I. Introduction

Rectenna, which receives radio frequency (RF) power and converts it into DC power, is a key component for Microwave Power Transmission (MPT) systems. The rectennas with different rectifier topologies, such as half-wave rectifier, voltage-doubler rectifier and bridge rectifier, have been reported. But, all these conventional rectennas could only achieve high conversion efficiency within a limited power range while the peak efficiency is typically obtained at an optimal power level [1-2]. The efficiency of such conventional rectifiers could drop down quickly due to the circuitry saturation and mismatch at higher input powers. Hence, it is desirable to maintain high conversion efficiency for a wider input power range, i.e. improved impedance matching between the antenna and rectifier at different input powers.

In order to adapt to the electromagnetic waves with dynamic input powers, some technologies, such as the transmission line-based resistance compression network (TLRCN), branch-line coupler, power divider, cooperative structure and reconfigurable distributed rectification topology, were introduced for rectenna designs [3-16]. However, the rectifiers with the aforementioned structures normally need several sub-rectifier branches, therefore more microstrip lines and circuit components are needed, which increases the rectifier size and complexity. Besides, extra loss associated with these components would dramatically decrease the overall power conversion efficiency of the rectifier, especially at high frequency [3]-[8].

To avoid the multiple sub-rectifier branches, reconfigurable technology has been implemented in the rectenna design [9-17]. Some reconfigurable rectennas integrated with passive RF switches [single-pole 4-throw (SP4T) or single-pole double-throw (SPDT) switch] were proposed for a wider input power range. However, complex circuit topologies and matching networks were introduced to the design whilst extra bias networks will be required to drive these switches, which leads to a bulky size and high fabrication cost [9]-[10].

To facilitate compactness and simplicity, some self-biased structures were introduced to avoid the bias network [11]-[16]. A self-biased system was designed by using the rectified DC power from a rectenna to power the radio receiver without the need of an external power supply. However, the rectenna is a typical design that has a limited operating power range [11]. Lately, some self-biased adaptive reconfigurable rectennas have been proposed using active devices, such as FET, MOFET and E-pHEMT transistors [12]-[16] etc. Without using the extra biasing network, the switch-based rectifier can be automatically reconfigured to the favorable circuit topology depending on the input power level and/or the operation frequency. Since these active switches could consume more power, the overall conversion efficiency could be lower at high frequencies (> 3 GHz). Thus, they are inadequate for high-frequency rectifying circuits. Also, the price of FET, MOFET and E-pHEMT diodes is typically expensive.

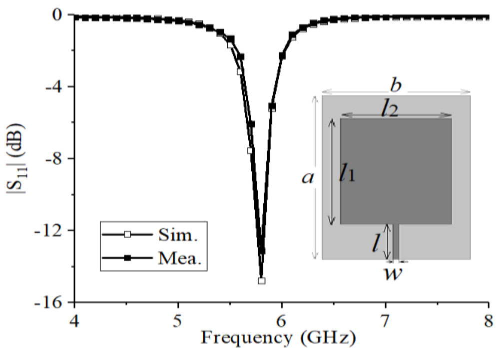

Fig. 1. Simulated and measured S-parameter of the receiving antenna. The metal in dark gray is on the top side, and the partially ground in light gray is on the back side. (a = 44 *mm*, b = 24 *mm*, l_1 = 24.4 *mm*, l_2 = 18 *mm*, l = 9.8 *mm*, w = 1 *mm*.)

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Especially, the starting operational power level of Class-E power amplifier is normally high, and it suffers from the heat dissipation and thermal management, which increases the complexity of such rectifying circuits [13].

In this letter, a self-biased adaptive reconfigurable rectenna based on a PIN-switch (passive diode) and an L-shaped shorted stub is proposed at 5.8 GHz for a wide input power range. Owing to the DC power routing structure, the bias current for the switch can be directly extracted from the rectified DC power to achieve the self-biased structure. According to the incident power level, the reconfigurable stub can be automatically connected to or disconnected from the circuit to achieve good impedance matching. Compared to other passive diode-based reconfigurable structures [9]-[10], [17], the proposed rectenna can be automatically tuned without the need of extra biasing networks. Also, the proposed rectenna has a reasonable price, typically lower than that of the active diode-based ones [12]-[16]. The proposed rectenna has advantages in term of simplicity, reconfigurability, low-cost and easiness for integration.

II. Self-biased Reconfigurable Rectenna Design

The proposed reconfigurable rectenna consists of a rectangular patch receiving antenna and a self-biased reconfigurable rectifying circuit with a DC power routing structure.

A. Rectenna Structure

A rectangular patch with a size of $l_1 \times l_2$, is used as a receiving antenna. It is printed on the top layer of a grounded Rogers 4003C substrate (ε_r=3.38, $tan\delta$=0.0027) with a thickness of 0.813 *mm*, as displayed in Fig. 1, where the receiving antenna is fed by a quarter-wavelength microstrip feedline. The simulated and measured return loss of the proposed antenna, as shown in Fig. 1, where the simulated$|S_{11}|$ is -14.8 dB@5.8 GHz, which agrees reasonably well with the measured value of -13.1 dB@5.8 GHz, and the proposed antenna can achieve good impedance matching at 5.8 GHz. The simulated (measured) maximum gain G_r of the proposed antenna reaches 7.78 (7.18) dBi, and the antenna radiation efficiency η_a is up to 97.2% (96.1%) at 5.8 GHz. The decrease of the measured gain and antenna efficiency may be caused by the deviation of the dimensional error and the loss of SMA connector.

A self-biased reconfigurable rectifying circuit is proposed to operate at 5.8 GHz for a wide input power range, as shown in Fig. 2, where the rectifying circuit with an overall size of $l_3 \times l_4$ is printed by using the identical PCB substrate of the antenna. In this design, a 150-pF pre-capacitor is used to keep the receiving antenna from the reverse current. A Schottky diode HSMS 2850 with a low junction capacitance (C_{j0} = 0.18 pF) is connected in parallel to the rectifying circuit. Two microstrip radial stubs are used as a dc-pass filter, and it is used to suppress the high-order harmonics and smooth the output DC voltage waveform, cooperated with the pre-capacitor. Some stepped-impedance matching microstrip lines are inserted between the antenna, the rectifier diode and the load to achieve good impedance matching.

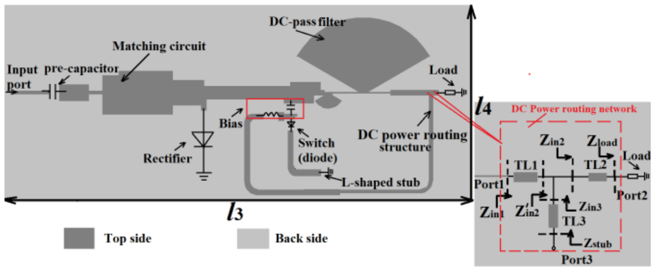

Fig. 2. Proposed rectifying circuit structure with DC power routing network. Z_{load} is the load impedance, and it is equal to the load resistance R_L. The input impedance Z_{stub} of the reconfigurable stub has different values when the rectifying circuit operates in different modes, i.e. Z_{stub_on} at ON-state and Z_{stub_off} at OFF state. The size of the rectifying circuit is $l_3 \times l_4$.

B. Self-biased Reconfigurable L-shaped Stub

To achieve good matching with a varying input power, a reconfigurable matching stub is designed to be tuned flexibly. To miniaturize the circuit size, the matching stub is bent into the L-shaped stub, where a PIN diode switch (SMP1345-SC-79) with low insertion loss (0.4 dB) is deployed in series to construct the reconfigurable matching stub. When the PIN diode switch is ON/OFF, it can be equivalently represented by a resistor or a capacitor, with a resistance value of 1.5 Ω or a capacitance of 0.2 pF. Due to the passive PIN diode switch, the problem of linearity and thermal effect at high frequency brought by the active switches (FET and E-pHEMT) can be solved. Also, the rectifier with PIN diode is more compact and much easier for integration if compared with the prior-art rectifiers with passive switching networks [9]-[10].

By controlling the switch, the L-shaped stub can be connected to/disconnected from the rectifying circuit when the rectifying circuit operates at high/low input power, thereby enabling the reconfigurable stub for adaptive matching in accordance with the varying input power. In this design, a DC power routing structure is introduced to connect the radial stubs to the load and reconfigurable matching stub for providing the bias voltage. The DC power output from the dc-pass filter is respectively divided for the load and the matching stub. The division ratio can be determined by the ratio of Z_{in2} and Z_{in3} (see in Fig. 2). One part of the rectified DC power

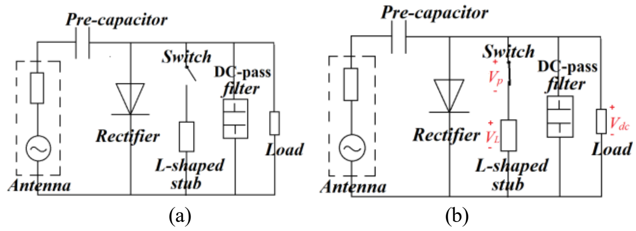

Fig. 3. Equivalent circuit of the proposed rectifying circuit structure. The dc-pass filter is equivalent to a by-pass capacitor. (a) OFF-state; (b) ON-state.

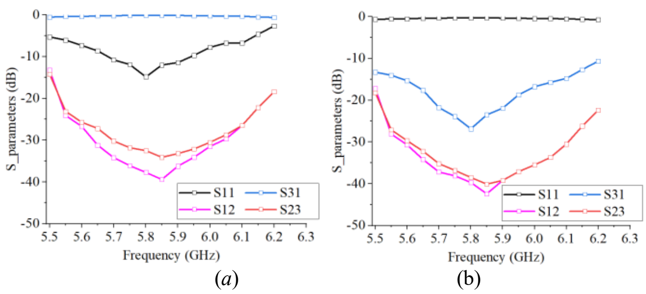

Fig. 4. Conversion efficiency of the proposed rectenna with different input power. (a) OFF state. (b) ON-state.

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flows to the load for recharging the battery, and another part of the rectified DC power is delivered back to the matching stub for driving the switch. Due to the DC power routing structure, the additional bias network is eliminated, and the bias power is provided by the rectifying circuit itself, forming the self-biased structure. In the bias circuit, an inductor of 22 nH and a capacitor of 100 pF are collaboratively implemented to isolate the DC power from RF power.

When the input power is low, i.e. the output DC voltage is lower than the forward voltage of PIN diode ($V_{dc} < V_f = 1.1$ V), the L-shaped matching stub with OFF-state diode is disconnected from the rectifying circuit, and the equivalent circuit is displayed in Fig. 3(a), where the switch on the branch of the bias power is open; therefore all the rectified DC power will be delivered to the load. As the input power increasing, i.e. $V_{dc} > V_f = 1.1$ V, the PIN diode switch becomes ON-state, and the L-shaped matching stub is connected to the rectifying circuit. In this case, the ON-state switch can be equivalently modelled as a resistor (r = 1.5 Ω), where its equivalent circuit is displayed in Fig. 3(b). It can be seen that the voltage of PIN diode V_p with that of L-shaped stub V_L is equal to the output DC voltage on the load V_{dc}. By adjusting the size of the L-shaped stub, V_L can be changed for obtaining higher output DC power, subsequently, high conversion efficiency can therefore be obtained under a high input power (e.g., > 10 dBm). However, the power handling capability of this reconfigurable circuitry is dependent on the threshold voltage of the PIN diode switch, which can be chosen in accordance with specific applications. Also, the maximum power handling capability is limited by the breakdown voltage with the lower value of the PIN diode and rectifier diode.

C. DC Power Routing Network Design

To realize the DC power routing network for DC power feedback loop, a three-port network is implemented, as displayed in Fig. 2, where a three transmission lines TL1, TL2 and TL3 are used to construct the DC power routing network. The input impedance Z_{in1} at Port 1 can be obtained at different input power levels using load-pull simulation. By using the Keysight ADS software, the size of TL1, TL2 and TL3 can be optimized. When the rectifying circuit works at OFF-state (under low input power), the size of the three transmission lines can be dimensioned, whilst at ON-state (under high input power) the size of the reconfigurable stub can be found. The frequency dependences of the designed DC power routing network at the two states are shown in Fig. 4. At OFF-state, the reflection coefficient of Port 1 (S_{11}) at 5.8 GHz is smaller than -10 dB and the transmission loss from Port 1 to Port 3 (S_{31}) at 5.8 GHz is around 0 dB. This indicates that the RF component of the signal injected at Port 1 can be transmitted to Port 3 and then flows back to the rectifier, therefore enhancing the effective utilization of RF power. The parameters (S_{21} and S_{32}) at 5.8 GHz are smaller than -25 dB, meaning that only the DC power injected at Port 1 or Port 3 can be guided to Port 2. While at ON-state, by adjusting the size of the reconfigurable stub, S_{11} becomes to 0 dB, and S_{31} is smaller than -25 dB. This means no RF component of the power can be transmitted to the DC power routing network, and only DC can be guided from Port 1 to Port 3 or Port 2, and so DC power can flow back to the matching stub for the bias voltage. Therefore, the designed network can effectively route the RF and DC components of the power at the three ports.

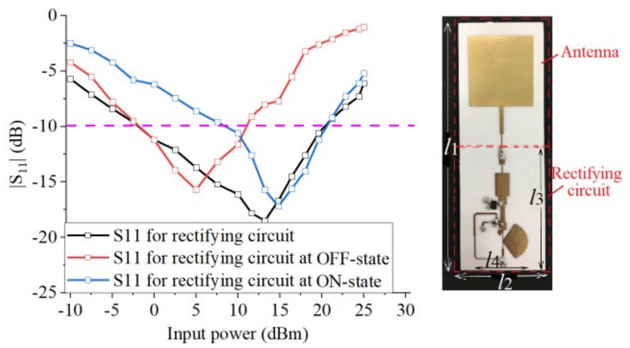

Fig. 5. Simulated $|S_{11}|$ of the proposed rectifying circuit. An equivalent capacitor (C=0.15 pF) is used to represent the OFF-state switch for the rectifying circuit at OFF-state. An equivalent resistor (r=1.5 Ω) is used to represent the ON-state switch for the rectifying circuit at ON-state. Fabricated rectenna is also presented. (l_1=8.6 cm, l_2=2.4 cm, l_3=4.1 cm, l_4=1.4 cm.)

III. PERFORMANCE OF RECONFIGURABLE RECTENNA

The conversion efficiency η_c of the rectifying circuit can be written by

$$\eta_c = V_{dc}^2 / P_{in} R_L \tag{1}$$

where R_L is the load resistance of 220 Ω and P_{in} is the input power of the rectifying circuit. From the above analysis, the operating state of switch will be changed when the input power varies from low to high. The S parameters versus input power at 5.8 GHz for the proposed rectifying circuit are simulated, as displayed in Fig. 5. It can be seen that the proposed rectifying circuit at OFF-state can only provide good input return loss ($|S_{11}|$<-10 dB) in the power range of 0-10 dBm, and the circuit at ON-state achieves good return loss within the input power range from 10 to 20 dBm. Due to the DC power routing network, the input power range of the self-biased circuit can be significantly widened through the combination of two working states, good impedance matching ($|S_{11}|$<-10 dB) is obtained from 0 to 20 dBm. Such input power levels can be used for charging low-power electric devices, such as RF identification devices (RFID), the implantable devices and wireless sensor networks [16]-[19].

The output and self-biased voltages of rectifying circuit versus input power at 5.8 GHz is shown in Fig. 6 (a). Under a low input power, the prominence of the rectifying circuit at OFF-state is revealed for high conversion efficiency. As the input power increases, the rectifying circuit with ON-state reconfigurable stub will take the dominant position for high

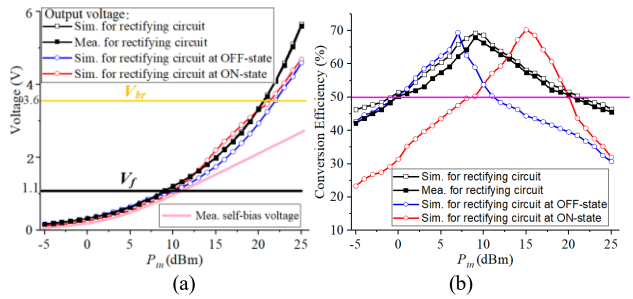

Fig. 6. Simulated and measured output voltage and conversion efficiency of the rectenna with different input powers. (a) Output voltage and self-bias voltage. (b) Conversion efficiency.

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conversion efficiency. Since some of the voltages travel across the L-shaped stub, the voltage on the load is therefore divided, and the self-biased voltage on the diode is smaller than the output voltage. In this case, the selected diode HSMS 2850 cannot be easily broken down, since the voltage across the diode is well below its breakdown voltage (V_{br} = 3.6 V).

Also, the conversion efficiency versus input powers at 5.8 GHz is shown in Fig. 6 (b). It can be observed that when the rectifying circuit is at OFF-state, high conversion efficiency above 50% can be achieved at the input power ranging from 0-11 dBm. While at ON-state with reconfigurable stub, the input power range with high conversion efficiency (η_c>50%) is from 9 to 20 dBm. By using the DC power routing network, the reconfigurable stub can be connected to, or disconnected from the rectifying circuit for good matching in accordance with the appropriate input powers. Subsequently, high conversion efficiency (η_c>50%) can be achieved under a wider input power from 0 to 21 dBm, where the peak efficiency of 69.2% is achieved at 9 dBm. Due to the actual parasitic of PIN diode, η_c is lower than that at ON-state (red line in Fig. 6 (b)) under high input power.

The fabricated rectenna is shown in Fig. 5. According to the Friis equation, the received power P_r by the rectenna can be estimated using [16]

$$P_r = P_t G_r G_t \left(\frac{\lambda}{4\pi L}\right)^2 \tag{2}$$

Considering the total efficiency η_a of the receiving antenna, the power input to the rectifying circuit (P_{in}) is expressed by,

$$P_{in} = P_r \eta_a \tag{3}$$

where λ is the wavelength in free space. G_t and G_r are the gain of the transmitter and receiver, respectively. In the measurement, the distance L between the transmitter and rectenna is set to 1 m to satisfy the far-field condition of RF radiation at 5.8 GHz. As the input power to the rectifying circuit P_{in} was configured at -5~25 dBm, a standard gain horn antenna with G_t = 10 dBi was used for transmitting power P_t of 0.37~371 W at 5.8 GHz, according to (2)-(3). The measured conversion efficiency and output voltage is also displayed in Fig. 6, where the measured result agrees well with the simulated one. The measured efficiency is above 50% for input power between 0~20 dBm. The maximum efficiency is around 68% at 9 dBm. The measured efficiency is a bit lower than the simulated one. Such a discrepancy could be caused by the variation in parasitic elements of the actual Surface-Mounted Device (SMD) components (e.g. diode, capacitor, inductor and PIN diode switch), leading to the mismatch in the measurement.

The performance of this work has been fairly compared with some recently published wide-input-power rectifying circuit, as displayed in Table I. Although the conversion efficiency of our work is not the highest, our design has achieved a reasonably high efficiency at a higher operating frequency (with larger component loss), which is comparable with that of the state-of-the-art 5.8 GHz rectennas in such as [17] (64.8%) and [20] (61%). Moreover, the same topology of our design is expanded for operating at 2.45 GHz as a simulation example (as shown in Fig. 7). By adjusting the matching network and filtering network, the operation frequency of the proposed rectifying circuit can be shifted to 2.45 GHz. Since the L-shaped stub (ON-state at high input power) plays an important role in impedance matching, when the frequency is decreased to 2.45 GHz, the rectifier size can be scaled down to 0.42λ×0.15λ by mainly adjusting the stubs rather than the main circuit structure at high input power. The simulated conversion efficiency of the two rectifiers at 2.45 GHz and 5.8 GHz is displayed in Fig. 7 versus input power. It can be seen that the maximum conversion efficiency of 78.2% can be observed at 7.5 dBm (for 2.45 GHz), and a wider input power range of -6~21 dBm has been realized for η_c>50%. Due

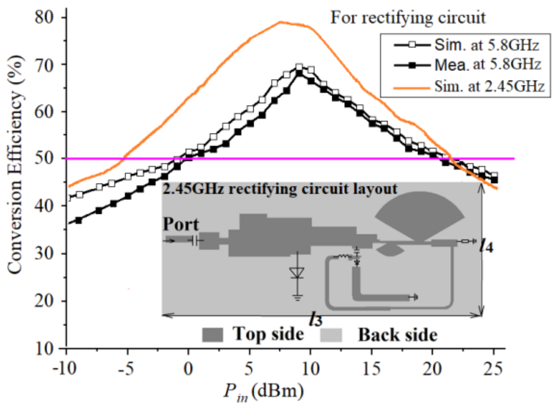

Fig. 7. Conversion efficiency of the rectifying circuit with different input powers at 2.45 GHz and 5.8 GHz. The layout of the rectifying circuit at 2.45 GHz is illustrated. The circuit size has been changed to l_3=5.2 cm×l_4=1.9 cm.

TABLE I
COMPARISON OF WIDE-INPUT-POWER RECTIFYING CIRCUIT

Ref.	Freq. (GHz)	P_{in} (dBm) range for conversion efficiency > 50%	Max. Eff. (%)	Size of rectifying circuit (cm^2)	Methods
[3]	0.915 /2.45	-8~5	74.9 /71.2	24.1×8.8 (1.97λ×0.72λ @2.45GHz)	TLRCN
[4]	2.45	20~30	70	-	TLRCN
[5]	2.45	2.9~20.2	80.8	14.2×6.8 (1.16λ×0.56λ)	Coupler
[6]	2.45	8.5~32.5	63	-	Coupler
[7]	2.45	-	48.9	8.2×6.0 (0.67λ×0.5λ)	Power divider
[8]	2.4	-3.5~26	72.8	5.5×3.8 (0.44λ×0.3λ)	Cooperative
[9]	1.8	-4~30	75	-	Reconfigurability
[10]	2.45	-3~22	78	6.1×2.2 (0.49λ×0.18λ)	SPDT
This work	5.8	0~20	68	4.1×1.4 (0.79λ×0.27λ)	PIN
	2.45*	-6~21	78.2	5.2×1.9 (0.42λ×0.15λ)	PIN

*Simulated values at 2.45 GHz for evaluation.

TABLE II
COMPARISON OF SELF-BIASED ADAPTIVE WIDE-INPUT-POWER RECTIFYING CIRCUIT

Ref.	Freq. (GHz)	P_{in} (dBm) range for η_c >50%	Size of rectifying circuit (cm^2)	Max. Eff. (%)	Switch diode
[12]	1	-4~20	5.3×2.6 (0.18λ×0.08λ)	80	FET
[13]	2.45	-5~20	-	77	E-pHEMT
[14]	0.1	-14~21	5.4×5.4 (0.02λ×0.02λ)	75	FET
[15]	0.05	-13.5~16.7	5.0×3.8 (0.01λ×0.006λ)	70	MOSFET
[16]	0.915	-12~28	-	80	Transistors
This work	5.8	0~20	4.1×1.4 (0.79λ×0.27λ)	68	PIN
	2.45*	-6~21	5.2×1.9 (0.42λ×0.15λ)	78.2	PIN

*Simulated values at 2.45 GHz for evaluation.

to the frequency-dependent RF power loss associated with the circuit components [21]-[22], the conversion efficiency and power range of the proposed rectifying circuit at 2.45 are greatly improved, which are comparable with that of the state-of-the art rectennas at 2.45 GHz. Besides, although the physical size of the rectifying circuit at 2.45 becomes larger if compare with the prototype at 5.8 GHz, the circuit size of our work is smaller than that of the prior-art rectennas at 2.45 GHz.

Furthermore, due to the proposed self-biased structure of this work, some additional bias networks, TLRCNs, couplers, power dividers and sub-rectifier branches used in the state-of-the-art work can be avoided, which makes our rectenna more simplified and miniaturized. Also, extra components including additional diodes will need to be installed in those previously published rectennas using sub-rectifier branches, which leads to more loss. Our design generally does not have such a problem.

Meanwhile, the performance of this work is compared with some recently published self-biased wide-input-power rectifying circuit, as displayed in Table II. It should be emphasized that our design is not aimed for achieving a best number in terms of conversion efficiency and input power range. In contrast, we have taken the overall design complexity, cost and loss into account. As a consequence, our design is much simpler and of low-cost compared with the published ones using transistors, power amplifiers (PAs) and active switches. Moreover, if these self-biased designs in [12-16] are scaled and expanded for the high frequency of 5.8 GHz, the conversion efficiency and operation input power range would be decreased significantly due to the high loss of the components and topologies [21]-[22]. This has been further verified by our rectifier simulation comparison at 2.45 and 5.8 GHz (see Fig. 7). Evidently, the proposed rectenna has the merits of compactness, low cost, simplicity and reconfigurability. In addition, our design can be easily switched to different power levels at other frequency bands by using diverse diodes (e.g., spin diodes, Metal Insulator Metal (MIM) diodes and new material-based semiconductor diodes). At higher frequency and large input power, our rectenna design does not suffer from the design challenges of the active switches (e.g., Fin-FET transistors) in terms of linearity and thermal effects, and the performance can be also comparable with that of the state-of-the-art work at lower frequencies (< 3 GHz). As future work, alternative low-loss diodes such as BGS12SN6 can be used as the switch for high efficiency.

IV. CONCLUSION

A self-switchable reconfigurable rectenna has been proposed for MPT at 5.8 GHz. The extra biasing network is eliminated by using an uncomplicated shunt feedback structure, thereby improving the simplicity and integration of rectenna significantly. The design method of this rectenna can be further developed to cover the emerging high-performance rectifying diodes to exploit for other reconfigurable rectennas (at different frequency bands and power levels for high efficiency) with a much-simplified structure and easiness to integration.

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