Compact High-Efficiency Broadband Rectifier Based on Coupled Transmission Line

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***Abstract*—In this brief, a compact high-efficiency broadband rectifier with an extended range of input power is proposed for the applications in wireless energy harvesting (EH). In the rectifier, a coupled transmission line is connected in series with a Schottky diode to compensate its capacitive reactance, compress its impedance variation when the frequency or input power varies. The coupled transmission line facilitates the impedance matching circuit and reduces the insertion loss. High RF-dc conversion efficiency will be achieved consequently. A rectifier is fabricated and measured based on analysis and simulation on the coupled transmission line. The measured results show a good agreement with the simulation results. The rectification efficiency of the rectifier is over 70 % from 1.6 to 2.8 GHz (a bandwidth of 54.5%) with the input power range from 11 to 14 dBm. The efficiency remains above 50% from 1.5 to 2.85 GHz with input power from 5 to 18 dBm,and over 40% within 1.7–2.8 GHz when the input power decreases to 0 dBm. The maximum measured efficiency is 78.63% at an input power of 16 dBm.**

***Index Terms*—Coupled transmission line, broadband, energy harvesting, rectifier, high-efficiency, wide input power range, wireless power transmission.**

I. Introduction

ENERGY harvesting (EH) and wireless power transmission technology is getting a great amount of attention due to the capability to charge electronic devices that are difficult to reach wired power [1]–[4]. It can extend the battery life of a wide range of electronic devices, including Internet of Things (IoT), biomedical implant devices and wireless sensor networks [5], [6]. With the rapid development of wireless techniques, the electromagnetic energy sources are more and more available for EH, such as WIFI [7], cellular networks, AM/FM, TV [8], ISM 2.4 GHz devices, and so on. Thus, the EH rectifiers should operate in a wide band to harvest as much energy as possible. However, designing a wideband rectifier [9], [10] or multi-frequency rectifier [11], [12] with high efficiency and wide input power range [13] is challenging. The reason is that the input impedance of the rectifying diode varies nonlinearly with respect to the operating frequencies and input power levels, which make broadband input impedance match difficult. As a result, complex matching networks are required, which introduce additional insertion loss and result in low RF-dc power conversion efficiency (PCE).

To solve the problems, several research groups have proposed various efficient solutions to improve rectifier efficiencies efficiency in a wide frequency range. Conti *et al.* [14] proposed a rectifier with wide bandwidth and input power range based on branch circuit couplers. A high conversion efficiency was successfully achieved with introducing an extra coupler and two sub-rectifiers. Martínez and Bullo [15] designed a broadband rectifier based on a proposed impedance matching network, consisting of a high impedance transmission line, two open stubs in parallel and a capacitor, which realizes rectification efficiency over 80% in an operating bandwidth of 300 MHz. A novel matching network based on non-uniform transmission is proposed [16]. In this design, the rectification efficiency is more than 60% from 470 to 860 MHz when the input power is 10 dBm. The transmission line is long and introduces additional insertion loss. A novel impedance matching technique to extend the operating bandwidth is proposed in [17], which is capable of manipulating the impedance over a wide frequency band. A microstrip line, a shunt stub, and a coupled line to compress the diode impedance and match to microwave source. The compact broadband rectifier operating at 0.57-0.9 GHz at an input power lever of 12.8 dBm is with an efficiency above 70%. In [18], a two-stage impedance matching network is proposed, which has an output direct pass filter with two capacitors connected in parallel at the end of a $\lambda/4$ transmission line. The rectification efficiency is more than 70% from 1.80 to 2.72 GHz when the input power is 19.5 dBm.

Khojasteh *et al.* [19] utilized a $\lambda/8$ short-ended microstrip line to connect a diode, which makes the impedance matching easier and realizes more than 70% rectifying efficiency from 1.8 to 2.62 GHz when the input power is 20 dBm. Subsequent, [20] and [21] use similar structures to compensate diode impedance at the center frequency and build a wideband rectifier. The input impedance of a diode in series with a $\lambda/8$ shorted microstrip line is pure resistance at the center frequency, and the impedance is inductive at high frequency and capacitive at lower frequency. The imaginary part of the impedance is symmetric about the real axis, and, then, the broadband impedance matching is achieved. In [20], a broadband rectifier circuit based on multi-stage transmission line extends the efficiency to more than 70% from 2.0 GHz to 3.05 GHz. In [21], the proposed rectifier shows a bandwidth from 2.1-3.3 GHz for efficiency over 70% at an input power of 14 dBm. The inductive impedance a $\lambda/8$ of a short-ended microstrip line compensates the capacitive impedance of Schottky diode, and achieve better impedance matching performance and wider bandwidth.

Compared to a $\lambda/8$ shorted transmission line, a coupled transmission line (CTLIN) has more tunable parameters with

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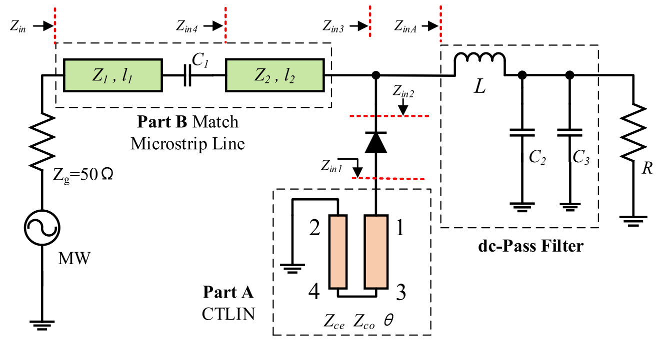

Fig. 1. Proposed rectifier with a wide bandwidth range.

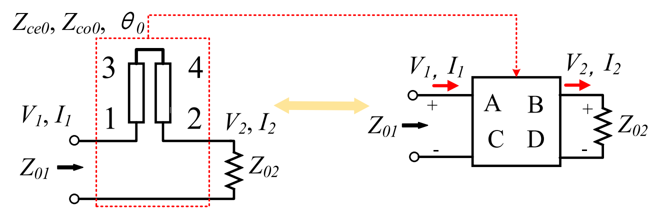

Fig. 2. Schematic diagram of the proposed coupled line and its equivalent two-port network.

greater freedom, thus, achieving better performance, e.g., impedance matching over a wider frequency range. In this brief, we propose a novel broadband high-efficiency rectifier for EH. This rectifier utilizes a coupled transmission line to series with a diode to compensate its capacitive reactance over a wide frequency band. The circuit facilitates the impedance matching network and reduces its insertion loss. The rectifier realizes a conversion efficiency above 70% at an operating frequency from 1.6 to 2.8 GHz. The efficiency is above 50 % when the input power ranges from 5 to 18 dBm from 1.5 to 2.85 GHz. The detailed theoretical analysis and design steps are presented in Section II. In this design, a broadband rectifier is realized successfully. The fabrication and measurements of the proposed rectifier are presented in Section III. Finally, a conclusion is drawn in Section IV.

II. Design Methodology and Simulation

Fig. 1 shows the schematic diagram of the proposed wideband rectifier, which consists of a broadband impedance matching network (Part B), a Schottky diode HSMS286, a coupled transmission line (Part A, CTLIN), a dc-pass filter, and a dc load R. In the rectifier design, the CTLIN is proposed to compensate the diode imaginary impedance, and Part B is an impedance transformer for matching Z_{in3} to 50 Ω.

A. Analysis of the Coupled Line

When two transmission lines are close to each other, the coupling occurs due to the interaction of the electromagnetic fields from each transmission line [22]. Such lines are referred to coupled transmission lines. For various frequencies, the coupling effects of the adjacent transmission lines vary as well.

Fig. 2 shows the schematic diagram of the proposed coupled line and its equivalent two-port network, where Z_{co0} and Z_{ce0} are the odd- and even-mode characteristic impedance, respectively. The electrical length at this frequency is noted as θ_0. Port 3 and 4 of this coupled line are directly connected, turning it into a two-port component. As shown in [23], the ABCD matrix of the coupled line is

$$A = D = \frac{Z_{ce0} - Z_{co0}\tan^2(\theta_0)}{Z_{ce0} + Z_{co0}\tan^{2\cdot}(\theta_0)} \tag{1}$$

$$B = \frac{2Z_{ce0}Z_{co0}j\tan(\theta_0)}{Z_{ce0} + Z_{co0}\tan^{2\cdot}(\theta_0)} \tag{2}$$

$$C = \frac{2j\tan(\theta_0)}{Z_{ce0} + Z_{co0}\tan^{2\cdot}(\theta_0)}. \tag{3}$$

Calculating the ABCD matrix, the input impedance of port 1 is obtained from (4):

$$Z_{01} = \frac{AV_2 + BI_2}{CV_2 + DI_2} = \frac{AZ_{02} + B}{CZ_{02} + D}, \tag{4}$$

where Z_{01} and Z_{02} are the input impedance of port 1 and terminal impedance of port 2, respectively. V_1, I_1 and V_2, I_2 are the voltage and current of port 1 and port 2, respectively. When port 2 is a short circuit, i.e., $Z_{02} = 0$, the input impedance of port 1 is

$$Z_{01} = \frac{B}{D} = \frac{2Z_{ce0}Z_{co0}j\tan(\theta_0)}{Z_{ce0} - Z_{co0}\tan^{2\cdot}(\theta_0}. \tag{5}$$

We manage to change the coupled line odd-mode impedance Z_{co0} and even-mode impedance Z_{ce0} to tune the input impedance Z_{01} of port 1 by varying the coupled line widths, gap distance and electrical length.

B. Coupled Line Design

A Schottky diodes usually exhibits capacitive impedance due to its internal Schottky junction structure. It is difficult to design a broadband rectifier since the diode's capacitive reactance varies at different frequencies, which makes the design of impedance matching network at dual frequencies or in a wide band is complex and difficult.

As previously stated, a coupled transmission lines have more design parameters and greater freedom in design. Therefore, the coupled line is capable to be completed at multiple frequencies to compensate for the nonlinear impedance behavior of the diode. We may tune the parameters of the impedance of coupled line and make its impedance satisfy the dual-frequency or broadband requirements.

As shown in Fig. 1, according to (5), $Z_{\mathrm{in}1} = Z_{01}$ and $Z_{\mathrm{in}4} = \infty$ at all frequencies of interest. Z_{in2} can be obtained as

$$Z_{in2} = Z_d + Z_{in1} = Z_d + \frac{2Z_{ce}Z_{co}j\tan(\theta_i)}{Z_{ce} - Z_{co}\tan^{2\cdot}(\theta_i)} \quad i = 1, 2 \tag{6}$$

where Z_d is the input impedance of the diode, θ_1 and θ_2 are the electrical length of the coupled transmission line in Part A at frequency f_1 and f_2, which are operating frequency of beginning and ending, set to 1.6 GHz and 2.8 GHz, respectively. The variation of diode impedance Z_d with frequency and input power is shown in Fig. 3. The purpose of Part A to be designed is to reduce the imaginary impedance of Z_{in2}. Therefore, there is an option for us to compensate the Z_{in2} to zero at both f_1 and f_2, and limit Z_{in2} to be close to the real axis in the Smith chart at all the operating frequency due to the continuous variation of the impedance $Z_{\mathrm{in}2}$.

Therefore, at a given input power level, the parameters of Part A can be determined by calculating the equation below:

$$\mathrm{Im}(Z_{in2}(f_1)) = \mathrm{Im}(Z_{in2}(f_2)) = 0 \tag{7}$$

In this broadband rectifier design,an Avago HSMS286F Schottky diode is chosen due to its low build-in voltage and

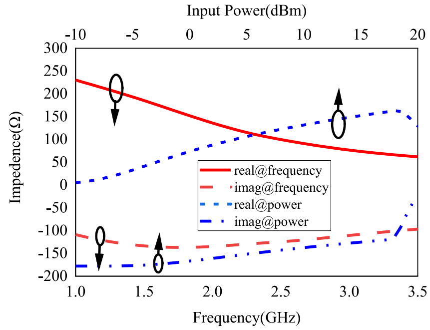

Fig. 3. The variation of Z_d with frequency and input power.

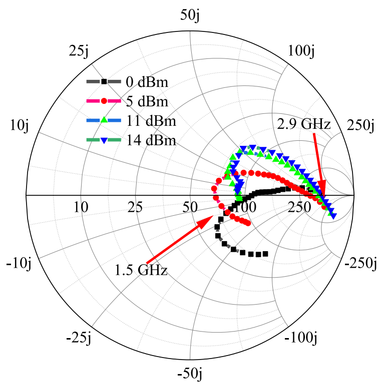

Fig. 4. Z_{in2} over 1.5-2.9 GHz at various input power levels.

low junction capacitance. The input impedance Z_{in2} was simulated using the large signal S-parameter (LSSP) model in the Advance design system (ADS, Keysight) based on its nonlinear diode model. The variation of Z_{in2} over 1.5 to 2.9 GHz at different input power levels is shown in Fig. 4. As shown in Fig. 4, we can observe that the imaginary part of Z_{in2} is zero at both 1.6 GHz and 2.8 GHz. Meanwhile, Z_{in2} at all frequencies of interest are located in the vicinity of the real axis. This allows us to design a broadband rectifier with impedance matching over certain input power range.

C. Design of the Matching Network

Part B is an impedance transformer consisting of two sections of microstrip lines and a capacitor C_1, as shown in Fig. 1. The characteristic impedance and length of the microstrip line are Z_1, Z_2 and l_1, l_2, respectively. In the Smith chart, the impedance Z_{in3} of the diode series connected with the CTLIN, is able to be tune to 50 Ω vicinity by a single section of transmission line, since the CTLIN has compensated the diode capacitive impedance well at both f_1 and f_2 and compress its impedance into a small region, as shown in Fig. 4.

There are two sections of transmission lines in Section B, i.e., Z_1 and Z_2. A capacitor C_1 is inserted between the two transmission lines to block the dc voltage generated by the diode from reaching the microwave source. The input impedance Z_{in4} of the second transmission line Z_2 is

$$Z_{in4}(f_{\mathrm{i}}) = Z_2 \frac{Z_{in3}(f_i) + jZ_2 \tan\theta_i(f_i)}{Z_2 + jZ_{in3}(f_i)\tan\theta_i(f_i)} \quad i = 1, 2 \tag{8}$$

where $\theta_i(f_i) = \beta(f_i)l_2$ is the electrical lengths of the impedance transformer in Part B at f_1 and f_2, respectively. The relationship between f_1 and f_2 can be expressed by denoting a frequency ratio k, where $k = f_2/f_1$. Thus, we may tune its

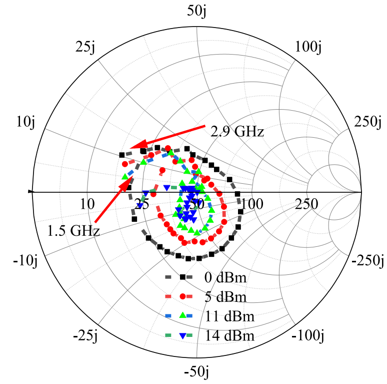

Fig. 5. Z_{in} over 1.5-2.9 GHz at different input power level.

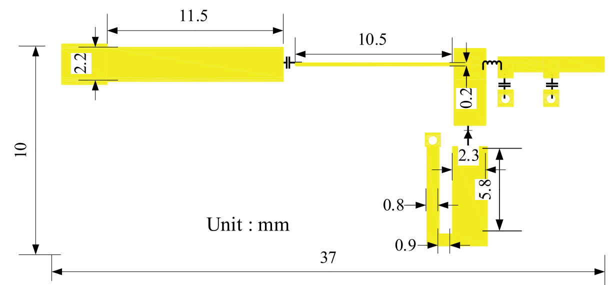

Fig. 6. Layout of the proposed broadband rectifier.

characteristic impedance Z_2 and physical length l_2 to make its input impedance Z_{in4} at all interested frequencies and power levels are close to the vicinity of $Z_0 = 50$ Ω.

The other transmission line Z_1 in Section B presents a further tuning as well. The characteristic impedance Z_1 is very close to Z_0. Thus, minor optimization may be performed here. Finally, the input impedance Z_{in} of the proposed rectifier with various input power levels can be obtained, as shown in Fig. 5. It shows that Z_{in} at the operating frequencies matched to $Z_0 = 50$ Ω well.

III. Implementation and Measurement

To experimentally validate the proposed design, a rectifier from 1.6 GHz to 2.8 GHz was designed, fabricated, and measured. Its substrate is F4B-2 (PTFE microfiber glass) with a thickness of 1 mm and a relative dielectric constant of 2.65. Its loss tangent is 0.0012 at *S*-band. The dc-block capacitor C_1 is 15 pF. The dc-pass filter includes an inductor L (68 nH) and two capacitors C_2 (5 pF) and C_3 (20 pF). Part number of all the capacitor is muRata COG C0603, and the inductor is muRata LQW18AN4N3D00D L0603. The characteristic impedance Z_1 and Z_2 of the impedance matching transmission line are 57 Ω and 158 Ω, respectively. The odd- and even-mode characteristic impedance Z_{co} and Z_{ce} of the CTLIN are 57.6 Ω and 79.0 Ω at 1.6 GHz, and 57.2 Ω and 78.4 Ω at 2.8 GHz, respectively.

The layout of the proposed rectifier is shown in Fig. 6 with detailed dimensions, and the fabricated rectifier is shown in Fig. 7. Its total size is 37 mm by 10 mm.

An Agilent N5230A network analyzer was used for $|S_{11}|$ measurement. Its maximum output power is 13 dBm. Thus, the voltage reflection coefficient of the rectifier may be measured at higher power levels. The simulated and measured voltage reflection coefficient with various frequencies at 0 dBm and 11 dBm input power is shown in Fig. 8. $|S_{11}|$ is better

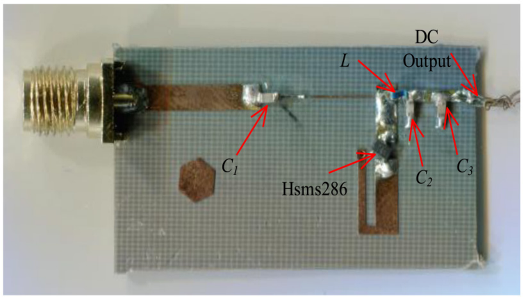

Fig. 7. A photograph of the fabricated rectifier.

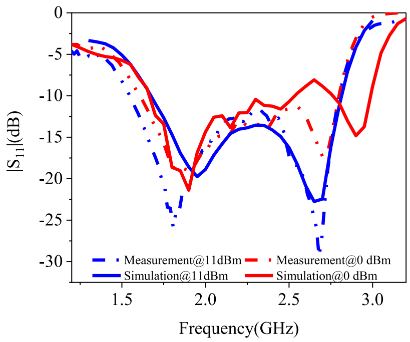

Fig. 8. The reflection coefficient $|S_{11}|$ versus frequency at the input power of 0 dBm and 11 dBm.

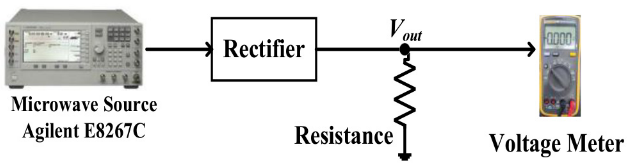

Fig. 9. Diagram of the measurement system.

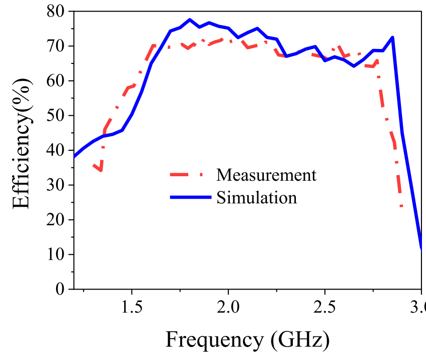

Fig. 10. Measured and simulated RF-dc conversion efficiency versus frequency at the input power of 11 dBm.

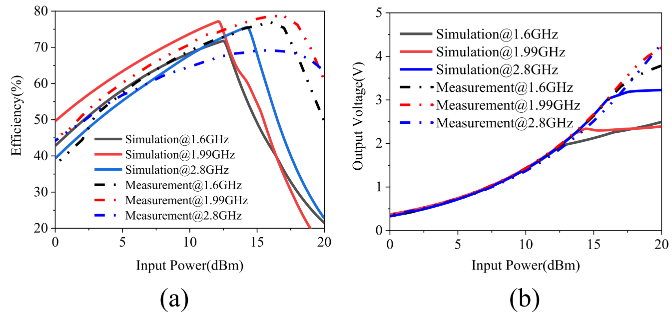

Fig. 11. (a) Conversion efficiency (b) Output Voltage from 0 dBm to 20 dBm at 1.6 GHz, 1.99 GHz, and 2.8 GHz.

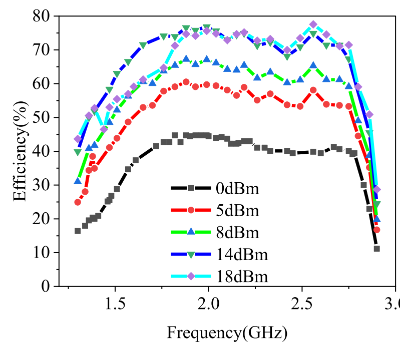

Fig. 12. Measured RF-dc conversion efficiency versus frequency with input power from 0 to 18 dBm.

than −10 dB from 1.6 GHz to 2.8 GHz at 11 dBm input power, which indicates that the rectifier is well matched in the operating frequency band.

An Agilent E8267C microwave source was used to generate microwave power for rectifying efficiency measurement. The output voltage of the rectifier was measured by a voltage meter. A standard resistor box was employed as the output dc load. The diagram of the measurement system is shown in Fig. 9. The dc-load resistance R_{dc} in the measurement is set to 290 Ω. By varying the output power and frequency of the microwave source, the dc output voltage V_{out} was measured across the dc load. The measured power conversion efficiency (PCE) $\eta_{\mathrm{RF-dc}}$ is calculated by (9), where P_{IN} is the input power of the rectifier.

$$\eta_{RF-dc} = \frac{P_{dc}}{P_{IN}} \times 100\% = \frac{V_{OUT}^2}{R_{dc}} \times \frac{1}{P_{IN}} \times 100\% \qquad (9)$$

where P_{dc} is the output dc power, V_{OUT} is the output dc voltage, and P_{IN} is the input microwave power.

The simulated and measured RF-dc conversion efficiency versus frequency with an input power of 11 dBm are shown in Fig. 10. It can be observed that the measured efficiency is in good agreement with the simulated efficiency. At an input power of 11 dBm, the measured efficiency is higher than 70% from 1.6 to 2.8 GHz with a fractional bandwidth of 54.5%. The measurement results of voltage reflection coefficient and rectification efficiency at various frequencies show that the bandwidth is consistent with the design. In addition, there is a slight frequency shift between the simulated and measured results, which may be caused by manufacturing tolerances and differences between the diode model and the real one.

Fig. 11 illustrates the effects of input power on rectification efficiency and output voltage at 1.6 GHz, 1.99 GHz, and 2.8 GHz. The results show that the measured highest efficiency is 78.63% with an input power 16 dBm at 1.99 GHz and the rectifier remains high efficiency above 60%, when the input power varies from 4 to 16 dBm. Furthermore, it is noticed that the measured rectification efficiency is a little higher than the simulated results, when the input power is higher than 15 dBm at 1.6 GHz and 1.99 GHz. This may be due to the frequency shift. The optimal operating frequency of the rectifier is shifted, which causes the optimal power level of the rectifier at that frequency shifts as well.

To further evaluate the performance of the proposed broadband rectifier, the efficiency versus frequency with

TABLE I
COMPARISON WITH PREVIOUS RECTIFIERS

Ref	[14]	[15]	[17]	[20]	[21]	This work
PCE > 70% (GHz)	2.08 -2.58	1.47 -1.77	0.57 -0.90	2.0 -3.05	2.1-3.3	1.6-2.8
Fraction Bandwidth	21.5%	18.5%	44.9%	41.5%	44.4%	54.5%
Power (dBm)	15.5	10	12.8	10	14	11
PCE > 40% at 0 dBm (GHz)	2.03 -2.75	N/A	N/A	1.9- 3.1	NA	1.7-2.8
Fraction Bandwidth	30%	N/A	N/A	48%	NA	49%
Maximum Efficiency	80.80%	80.00%	76.00%	75.80%	76.30%	78.63%
Size (mm^2)	126×68	71×20	60×88	36×35	31×18	37×10

various input power levels are also measured as illustrated in Fig. 12. The rectifier efficiency stays above 50% in the range of 1.5-2.85 GHz, when the input power varies from 5 to 18 dBm. And it reminds over 40% within 1.7–2.8 GHz when the input power decreases to 0 dBm. In particular, the rectifier maintains 70% rectification efficiency in the range of 1.7-2.7 GHz for all input power level from 11 dBm to 18 dBm.

Table I shows the performance comparison with previous publications. The results show that the fractional bandwidth (with efficiency $> 70\%$) of the proposed rectifier is 54.5%, which is the highest among them. Meanwhile, the rectifier is very compact and has the physical size of 37 mm $\times$ 10 mm.

IV. CONCLUSION

In this brief, a compact microwave broadband rectifier with extended input power range is proposed. The theoretical analysis of the rectifier was presented. It was designed, fabricated, and measured to verify its performance. The proposed rectifier reduces the impedance matching difficulty of a wideband rectifier greatly by using a coupled line to compensate the capacitive impedance of a Schottky diode. The diode impedance variation with respect to frequency and input power level was compressed greatly.

Experimental results show that it has a wide fraction bandwidth of 54.5%, when the rectifying efficiency is greater than 70%. The rectifying efficiency stays above 50% from 1.5 to 2.85 GHz when the input power varies from 5 to 18 dBm. The experimental results are in good agreement with the analytical predictions. It has a higher fractional bandwidth and is compact with minimal physical dimensions. The proposed design can also be applied to WPT systems as well.

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