A Novel Single-Diode Microwave Rectifier With a Series Band-Stop Structure

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***Abstract*— A single-diode compact microwave rectifier with a series band-stop structure is presented in this paper. The band-stop structure is connected to the diode in series to block the harmonics produced during rectifying. It replaces the cascading bandpass or low-pass filter between the input and the diode in a conventional microwave rectifier. A microwave rectifier at 2.45 GHz with an HSMS 282 Schottky diode is realized based on the proposed design method. A short-ended eighth-wavelength microstrip transmission line is applied to the rectifier in series with the diode as a band-stop structure. The short-ended microstrip transmission line presents an inductive impedance to compensate the diode capacitive impedance at fundamental frequency and turns to an open circuit to block the second harmonic for power recycling. The proposed circuit shows a novel schematic for compact microwave rectifiers. The fabricated rectifier is compact with a dimension of $0.15\lambda_g \times 0.2\lambda_g$. A microwave-to-dc conversion efficiency of 80.9% is achieved at 20 dBm input power with a 580-Ω dc load.**

***Index Terms*— Microwave rectifier, Schottky diode, wireless power transmission.**

I. Introduction

THE microwave rectifier is an important component in wireless power transmission systems [1]–[4]. They convert microwave into direct current. They have been successfully applied to microwave power amplifiers for power recycling as well [5]. It has been applied to electromagnetic energy harvesting to obtain power from the environment [6]. Microwave wireless power transmission techniques have many applications [7]–[12]. The essential requirement of a microwave rectifier is its high microwave to direct current (microwave-to-dc) conversion efficiency, which is critical to a power transmission system. They should be compact and with reasonable power capacitance, since most microwave rectifiers are integrated to antennas and become rectennas in various microwave power transmission systems [13].

The harmonic recycling technique has found wide applications in microwave rectifiers to achieve high microwave-to-dc conversion efficiency. Usually, filters, e.g., bandpass filters, are applied between the diodes and the rectifier microwave input and dc output to reflect harmonics produced during rectifying. The reflected harmonics goes back to the diode for rectifying or mixing, which is called power recycling. The nonlinear component in a rectifier, e.g., a Schottky diode or a high electron mobility transistor, is usually shunt connected. A bandpass filter or a low-pass filter is applied between the diode and the rectifier input port. A low-pass or dc-pass filter is located between the diode and the dc output port [1], [3], [14]. The harmonics produced during rectifying are limited within the input and output filters and, then, recycled through either rectifying or mixing by the diode to obtain more dc output [1]. Currently, Class-F loads and harmonically terminated techniques are alternatives of the low-pass or dc-pass of rectifiers [15]–[17], which is quite a challenge, but it has good potential applications for high frequency microwave rectifiers. An interesting series diode rectifier is presented recently, which leads to a novel schematic [18]. The bandpass filter or low-pass filter at the input introduces extra insertion loss and occupies great area. A few novel microwave rectifiers have been developed recently, e.g., chip device rectifier [19], dual-diode or multidiode rectifier [20], [21], and rectifier with inkjet printed on paper or flexible substrate [22]–[24].

In this paper, a novel microwave rectifier using a series band-stop structure to realize harmonic recycling is presented. The design principle and procedure are discussed. A microstrip rectifier at 2.45 GHz is fabricated with an HSMS 282 Schottky diode in series connected to a short-ended eighth-wavelength microstrip line. The short-ended microstrip line compensates the diode capacitive impedance at the fundamental frequency and becomes an open circuit to block the second harmonic to enhance power recycling. Neither cascading bandpass filter nor low-pass filter is applied between the Schottky diode and rectifier input port. The proposed microwave rectifier is compact and with a high microwave-to-dc conversion efficiency without an input bandpass/low-pass filter. A microwave-to-dc conversion efficiency of 80.9% is achieved with 20.7 dBm microwave input power at 2.45 GHz with a 580 Ω dc load.

II. Principle and Design Method

A. Principle

A conventional microwave rectifying schematic is shown in Fig. 1(a), in which a cascading bandpass filter or low-pass filter and a dc-pass filter are applied to recycling the harmonics produced during rectifying. The diode is shunt connected between the rectifier input and output ports. Usually, the bandpass filter's center frequency is at the rectifier operational microwave frequency ω_0. The bandpass filter allows microwave power at ω_0 from the power source to pass through and reject the harmonics, e.g., $2\omega_0$, generated from the diode side. There is a low-pass or dc-pass filer before the dc load, which reflects

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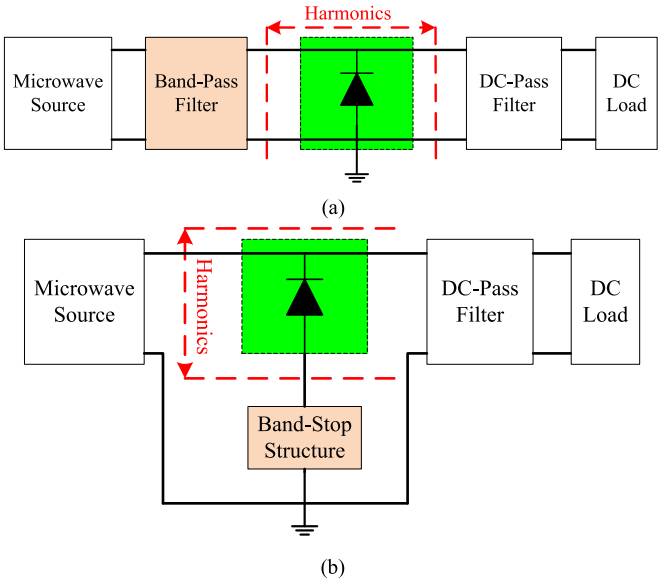

Fig. 1. Microwave rectifier with harmonic recycling by (a) conventional microwave rectifier with a cascading bandpass filter and (b) proposed rectifier with a series band-stop structure.

microwave power at both the fundamental frequency ω_0 and its harmonics $n\omega_0$ back to the diode. Thus, the harmonics produced during rectifying are limited between the input bandpass and output dc-pass filters, as shown in Fig. 1(a). Then, the harmonics are recycled through rectifying or mixing with other frequencies by the diode, and finally turn to dc power.

We propose another topology for harmonic recycling to remove the cascading bandpass or low-pass filter at the rectifier input, as shown in Fig. 1(b). The band-stop structure is applied to replace a bandpass/low-pass filter in a conventional rectifier. An ideal band-stop structure is series connected to the diode. The diode with series band-stop structure is parallel connected between the source and the dc load. The ideal band-stop structure has the following functions.

1) Blocking all harmonics produced during rectifying, i.e., presenting high reflections at harmonic frequencies $n\omega_0$ ($n \geq 2$), and reflecting them to the diode for power recycling.
2) Presenting a short circuit at dc, which is required by the rectification mechanism. There is no dc output without the dc path from the band-stop structure.
3) Compensating the diode inductive impedance. It is appreciated that the band-stop structure shows an inductive impedance to balance the diode capacitive impedance, which facilitates the impedance matching circuit of the rectifier.

Thus, it is a novel schematic compared with conventional microwave rectifiers. It is an alternative method to limit the harmonics inside the rectifier for power recycling.

From the viewpoint of impedance matching, the introduced band-stop structure should provide a reactive impedance to compensate the diode at the fundamental frequency ω_0, and switch to high reflections, e.g., an open circuit, to block microwave at harmonics $n\omega_0$. Therefore, the band-stop structure should be designed to achieve an impedance matching at the fundamental frequency ω_0 to minimize the reflection from the rectifier, and present an impedance mismatching at the harmonics $n\omega_0$ to result in high reflection and enabling the power recycling during rectifying.

B. Rectifying Circuit Design

An ideal band-stop structure to block all harmonics is hard to reach in practice. A complicated band-stop structure presents extra insertion loss at fundamental frequency ω_0 as well. Thus, we first focus on the main harmonic components produced during rectifying, e.g., the second harmonic, which contains most power among the harmonics. A practical microstrip band-stop structure to block the second harmonics is a short-ended eighth-wavelength transmission line. It is the simplest microstrip band-stop structure to block the second harmonic at frequency $2\omega_0$.

The input impedance Z_{IN} of the short-ended eighth-wavelength transmission line at dc, fundamental frequency, and harmonics are

$$Z_{\mathrm{IN}} = jZ_{\mathrm{SE}} \tan\left(\frac{\pi}{4}\frac{\omega}{\omega_0}\right) = \begin{cases} 0, & \omega = 0 \\ jZ_{\mathrm{SE}}, & \omega = \omega_0 \\ \infty, & \omega = 2\omega_0 \\ -jZ_{\mathrm{Se}}, & \omega = 3\omega_0 \\ \cdots & \cdots \end{cases} \quad (1)$$

where Z_{SE} is the characteristic impedance of the short-ended microstrip transmission line to build the band-stop structure. The short-ended transmission line presents zero impedance at dc, which provides a path for dc output. It has an inductive impedance jZ_{SE} at the fundamental frequency ω_0, and switches to an open circuit at the second harmonic $2\omega_0$, which blocks and reflects the second harmonic back into the diode. The power at the second harmonic is then recycled by the diode. It turns to capacitive impedance $-jZ_{\mathrm{SE}}$ at $3\omega_0$.

It is well known that Schottky diodes have been successfully applied to microwave rectifiers due to their low series resistance, low diode capacitance, and low forward voltage. An Avago HSMS 282 Schottky diode has been chosen for the rectifier due to the frequency and power capacitance consideration. Schottky diodes usually present a capacitive impedance due to its internal Schottky junction structures. The capacitance of a Schottky diode during rectifying is mainly determined by its own parameters, and rectifying state, e.g., the input microwave power and output dc voltage. The diode capacitive impedance may be compensated by the series short-ended microstrip transmission line by giving input microwave power and dc load.

The short-ended microstrip transmission line presents an inductive impedance jZ_{SE} at the fundamental frequency ω_0, as shown in (1). The inductive impedance compensates the Schottky diode capacitive impedance, which results in a pure real impedance to achieve better impedance matching performance and broaden the impedance matching bandwidth

$$\mathrm{Im}(Z_{\mathrm{IN}} + Z_D) = 0 \quad (2)$$

where Z_D is the diode impedance and Z_{IN} is the input impedance of the short-ended transmission line at the fundamental frequency ω_0. Thus, the characteristic impedance

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TABLE I
SPICE PARAMETER OF AN HSMS 282 DIODE

B_V	C_{J0}	I_S	R_S	V_{bi}
15 V	0.7 pF	0.022 μA	6 Ω	0.25 V

of the series short-ended microstrip transmission line is obtained from (1) as

$$Z_{\mathrm{SE}} = -\mathrm{Im}\{Z_D\}. \tag{3}$$

The length of the series short-ended microstrip transmission line is eighth-wavelength, and the microstrip linewidth is determined uniquely from (3).

At the second harmonic frequency $2\omega_0$, the series short-ended transmission line becomes a quarter-wavelength transmission line, and shows an open circuit, which functions as a perfect band-stop structure. The second harmonic microwave power is blocked by the band-stop structure, i.e., the short-ended microstrip transmission line, and is limited inside the rectifier. If one looks from the diode to either the rectifier input or output, the impedance is very high due to the series short-ended quarter-wavelength transmission line at the second harmonic $2\omega_0$. Then, the microwave power at $2\omega_0$ is reflected to the diode and recycled by the diode by either directly rectifying and/or mixing with microwave at other frequencies as a conventional rectifier does.

At the third harmonic frequency $3\omega_0$, the band-stop structure of the series short-ended transmission line has a capacitive impedance $-jZ_{SE}$. It leads to a higher reflection more or less at $3\omega_0$ compared with the reflection at fundamental frequency. A rough estimation of the reflection is

$$\Gamma(3\omega_0) \approx \frac{Z_D + j\mathrm{Im}\{Z_D\} - \mathrm{Re}\{Z_D\}}{Z_D + j\mathrm{Im}\{Z_D\} + \mathrm{Re}\{Z_D\}} = j\frac{\mathrm{Im}\{Z_D\}}{Z_D}. \tag{4}$$

When the real and imaginary parts of the diode impedance are comparable, (4) gives a voltage reflection coefficient around −3 dB.

C. Rectifier Implementation

We consider to implement a microwave rectifier with about 20-dBm input power at ISM frequency 2.45 GHz. The HSMS 282 series Schottky diode from Avago Technologies is selected, which is a low-cost surface-mounted microwave diode. The main SPICE parameters of an HSMS 282 diode are listed in Table I. The capacitive diode impedance is suitable for the proposed microwave rectifier.

The biasing voltage V_0, which is the output dc voltage as well, is estimated to be about one-half of the maximum reversed breakdown voltage Bv. This estimation is a rough approach to evaluate the diode impedance and lead to an initial design for further optimization. Thus, the biasing voltage of the diode or the output dc voltage of the rectifier is estimated to be 7.5 V. Then, the impedance of the diode Z_D is [1]

$$Z_D = \frac{\pi R_s}{\cos\theta_{\mathrm{on}}\left(\frac{\theta_{\mathrm{on}}}{\cos\theta_{\mathrm{on}}} - \sin\theta_{\mathrm{on}}\right) + j\omega R_s C_j\left(\frac{\pi-\theta_{\mathrm{on}}}{\cos\theta_{\mathrm{on}}} + \sin\theta_{\mathrm{on}}\right)} \tag{5}$$

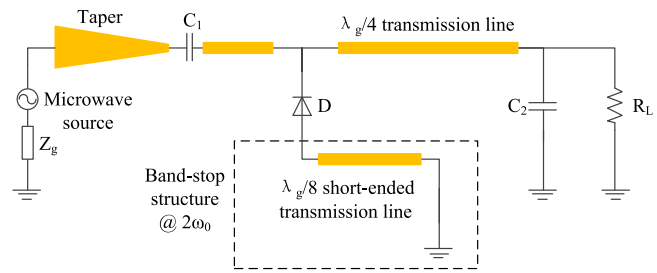

Fig. 2. Schematic of the proposed microwave rectifier.

where θ_{on} is the turn-on angle of the diode, and the junction capacitance of the diode is $C_j = C_{j0}((V_{bi}/(V_0 + V_{bi})))^{1/2}$. Then, the impedance of the HSMS 282 diode Z_{D} at ω_0 is evaluated to be $164 - j146\ \Omega$. Thus, the characteristic impedance of the series $\lambda_g/8$ short-ended microstrip line should be $Z_E = 146\ \Omega$ from (3).

The schematic of the proposed microwave rectifier with a series band-stop structure is shown in Fig. 2. The series $\lambda_g/8$ short-ended microstrip transmission line in a dashed rectangle is a band-stop structure at $2\omega_0$. The capacitor C_1 blocks the dc from the rectifier to the microwave source, and the capacitor C_2 and a $\lambda_g/4$ transmission line form a dc filter before the dc load. The $\lambda_g/4$ transmission line ended with capacitor C_2 and dc load R_L forms an open circuit at the fundamental frequency. The second harmonic microwave power is blocked by the band-stop structure and is not able to reach the dc pass filter. A tapered transmission line is applied to impedance matching from the rectifier to a microwave source at $Z_g = 50\ \Omega$.

The dc load is R_L. The best dc load is estimated to be $R_L \approx (V_0^2/P_{\mathrm{IN}}) \times \eta \approx 560\ \Omega$, where P_{IN} is the input microwave power and $\eta = 100\%$ is the ideal microwave-to-dc rectifying efficiency. R_L should be higher to maintain the same output dc voltage V_0 if the conversion efficiency η is less than 100% as in any real microwave rectifiers.

The schematic of the proposed microwave rectifier has been designed and optimized with the Agilent ADS to achieve a high microwave-to-dc conversion efficiency. The capacitors C_1 and C_2 are 6.8 and 20 pF, respectively, obtained from the ADS optimization. Two 0603 chip capacitors from Murata have been used. They are applied to dc blocking and dc filter, respectively. The $\lambda_g/8$ and $\lambda_g/4$ microstrip lines, whose widths are determined by their characteristic impedances, are bent to milder lines to miniaturize the microwave rectifier. Both the length and the width of the $\lambda_g/8$ and $\lambda_g/4$ microstrip lines have been adjusted slightly after optimization.

We have simulated the microwave-to-dc conversion efficiency and $|S_{11}|$ of the proposed rectifier with respect to the length of the microstrip line series to the diode from $\lambda_g/16$ to $\lambda_g/2$ at various input microwave power, as shown in Fig. 3(a). When the length of the microstrip line is $\lambda_g/8$, the maximum microwave-to-dc conversion efficiency is achieved. This means that the rectifier works well when the series microstrip line presents a band-stop behavior at the second harmonic. The conversion efficiency is very sensitive to the $\lambda_g/8$ microstrip line length. Moreover, the voltage reflection coefficient reaches the minimum. The effects of the width of the microstrip line

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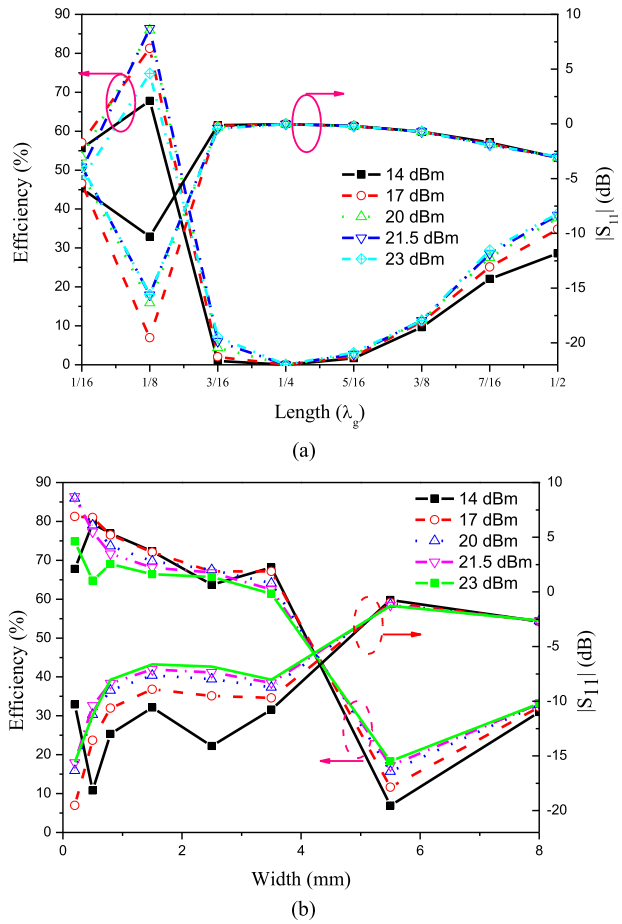

Fig. 3. Conversion efficiency and $|S_{11}|$ with respect to (a) length and (b) width of the series microstrip line to the diode.

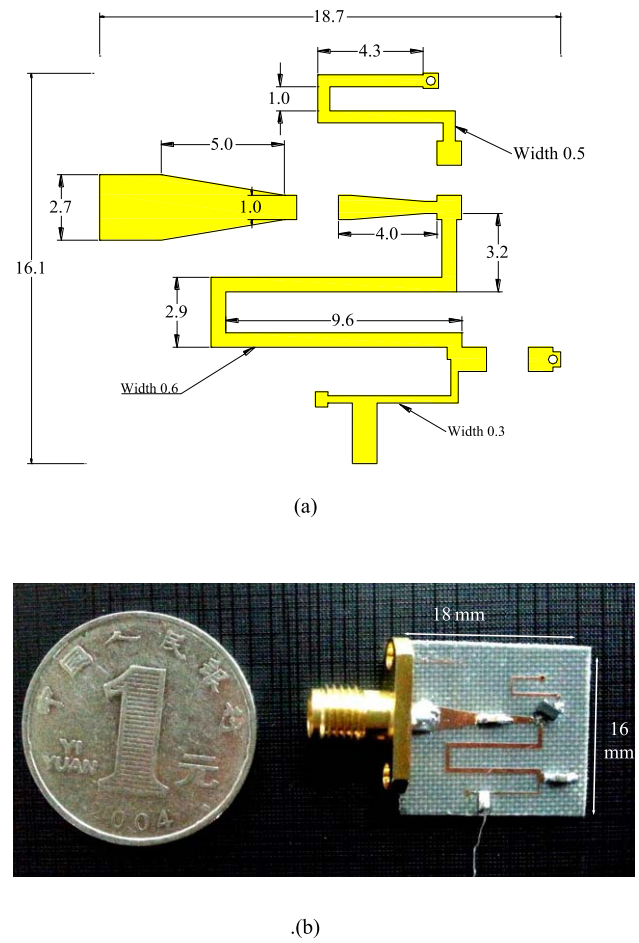

Fig. 4. Fabricated microwave rectifier. (a) Layout of the proposed microwave rectifier. (b) Fabricated microwave rectifier. The diameter of the coin is 25.0 mm.

are simulated as well, as shown in Fig. 3(b). When the width is 0.2 mm, better impedance matching and higher conversion efficiency are achieved. Thus, the microstrip line series to the diode with appropriate length and width not only achieves better impedance matching but also enhances the conversion efficiency.

The final layout of the proposed microwave rectifier is shown in Fig. 4(a). The fabricated microwave rectifier is shown in Fig. 4(b). The substrate is F4B-2 (PTFE microfiber glass) with a thickness of 1 mm and a relative dielectric constant of 2.65. The loss tangent is 0.0012 at S-band. The fabricated rectifier is about $0.23\lambda_g \times 0.2\lambda_g$, whose dimension is 18 mm × 16 mm. It is a compact structure due to the absence of the cascading bandpass/low-pass filter at the input port and the application of two bent microstrip lines. An SMA adapter is connected to the input port of the rectifier.

III. Experimental and Simulation Results

We have simulated the microwave-to-dc conversion efficiency η of the proposed rectifier with respect to the microwave source impedance Z_g at 14, 17, 20, 21.5, and 23 dBm input microwave power, respectively. The simulated results are shown in Fig. 5(a)–(e). When the microwave input power is low, e.g., 14 dBm, the turn-on angle of the diode is small and the equivalent impedance is high. A higher source impedance is expected to achieve high conversion efficiency. The maximum efficiency region shifts from right to left and from capacitive to slightly inductive. When the input microwave power is 20 dBm, the region of high conversion efficiency becomes the largest.

The $|S_{11}|$ of the proposed rectifier at 20-dBm input microwave power with respect to the source impedance Z_g is shown in Fig. 6. The real part of Z_g varies from 10 to 100 Ω, and the imaginary part of Z_g varies from −100 to 100 Ω. When the source impedance is $Z_g = (50 + j28)$ Ω, a lowest voltage reflection coefficient is achieved.

The simulated conversion efficiencies with respect to input microwave power and frequency are shown in Fig. 7. It shows that there is an optimal input microwave power and microwave frequency to obtain the maximum conversion efficiency.

A vector signal generator Agilent E8730C and a data acquisition device Agilent 34970A have been applied to microwave power source and dc voltage measurement, respectively. A standard resistance box is used as the output dc load. The microwave-to-dc conversion efficiency of the rectifier is defined as

$$\eta_{\text{MW-dc}} = \frac{P_{\text{dc}}}{P_{\text{IN}}} \times 100\% = \frac{V_0^2}{R_L} \times \frac{1}{P_{\text{IN}}} \times 100\% \qquad (6)$$

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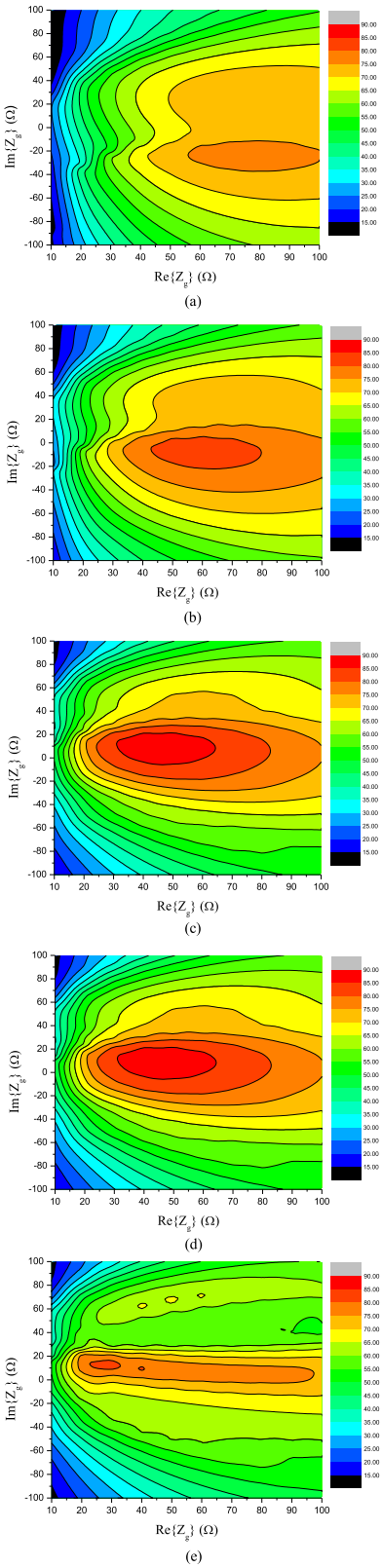

Fig. 5. Microwave-to-dc conversion efficiency contours as a function of the source impedance at different power levels from (a) 14, (b) 17, (c) 20, (d) 21.5, and (e) 23 dBm. The color bar stands for the microwave-to-dc conversion efficiency.

where P_{dc} is the dc output power at load R_L, P_{IN} is the available power from the microwave source, V_0 is the output dc voltage, and R_L is the dc load.

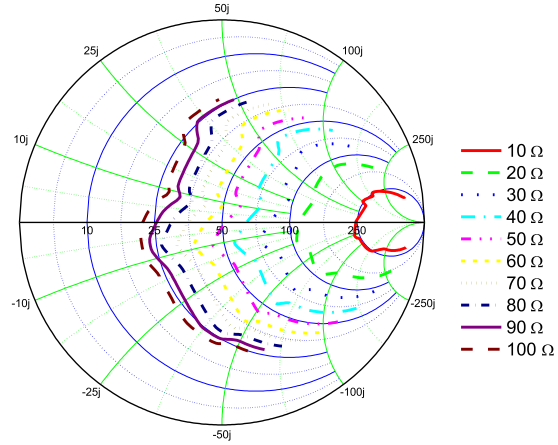

Fig. 6. $|S_{11}|$ of the rectifier at 20-dBm microwave input power with respect to the real part of source impedance from 10 to 100 Ω.

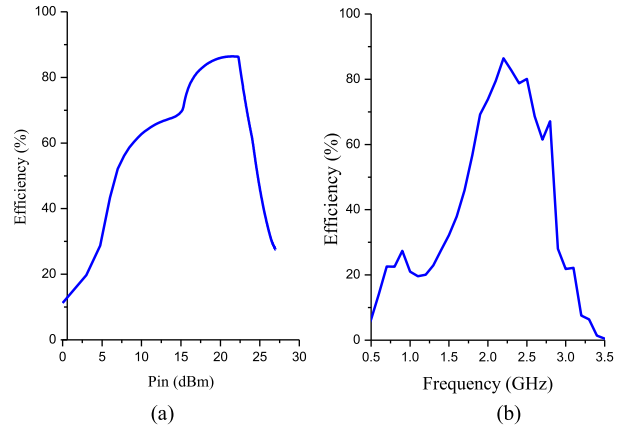

Fig. 7. Simulated conversion efficiency with respect to (a) microwave input power and (b) microwave frequency.

The rectifier has been measured at $P_{\mathrm{IN}} = 13$, 17, 20, and 22 dBm, respectively. The measured voltage and microwave-to-dc conversion efficiency are shown in Fig. 8(a) and (b). The microwave-to-dc conversion efficiencies are 64.6%, 73.0%, 80.9%, and 60.0%, when the input microwave power is 13, 17, 20, and 22 dBm, and the corresponding dc load R_L is 640, 600, 580, and 515 Ω, respectively. The output voltages are similar for 20 and 22 dBm input power in Fig. 8(a). However, the dc load R_L and input power P_{IN} are different, which leads to the difference of rectifying efficiency η in Fig. 8(b).

The results from Agilent ADS layout cosimulation are shown in Fig. 8(b) as well. The output dc voltages are close to the measurement results. The measured microwave-to-dc conversion efficiencies are a little lower than the simulation results around the optimal dc loads, since a few losses have not been taken into consideration in the simulation. Further, higher input microwave power has not been measured due to the limitation of the power capacitance of the HSMS 282 Schottky diode. The dc output voltage is 7.46 V at 850 Ω load with 20 dBm input microwave power, which is close to one-half of the reverse breakdown voltage Bv of the Schottky diode. When the input microwave power P_{IN} and the output dc voltage V_0 are high, the nonlinear model of the

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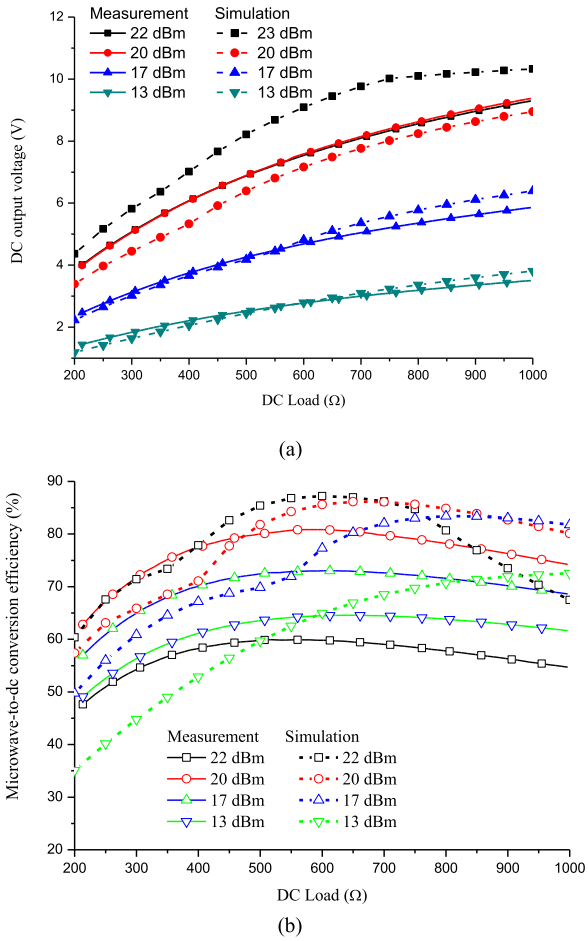

Fig. 8. Output dc voltage measured and simulated microwave-to-dc rectifying efficiency of the proposed rectifier with microwave input power of 13, 17, 20, and 22 dBm, respectively. (a) Measured dc output voltage. (b) Measured and simulated microwave-to-dc conversion efficiency.

TABLE II
COMPARISON BETWEEN RECTIFIERS

Ref.	*Size*	*Diode*	*Input Power*	*Efficiency*
[25]	45 mm × 25 mm	HSMS 2860	10.1 dBm	74.9%
[26]	45 mm × 35 mm	HSMS 286F	17 dBm	80.8%
[27]	20 mm × 10 mm	HMPS 2822	27 dBm	77.9%
[28]	40 mm × 20 mm	HSMS 2860	10 dBm	66.5%
This work	18 mm × 16 mm	HSMS 282C	20 dBm	80.9%

Schottky diode HSMS 282 in the ADS may become not so accurate, which leads to a higher simulation error.

Table II shows the comparison of rectifying efficiency, dimensions, input power with similar diodes at 2.45 GHz between the proposed rectifiers and recent publications. The proposed rectifier owns microwave-to-dc efficiency very close to [26], but is more compact. Reference [27] presents a very compact rectifier based on CPW structures with a reasonable microwave-to-dc efficiency.

IV. CONCLUSION

A novel compact microwave rectifier is designed, fabricated, and measured in this paper. The input cascading bandpass or low-pass filters in conventional microwave rectifiers have been replaced by a series band-stop structure, which leads to a compact design. The series band-stop structure is implemented with a $\lambda_g/8$ short-ended microstrip line, which provides a direct connection from the diode to ground at dc, presents a series inductive impedance to compensate the Schottky diode capacitive impedance at the fundamental frequency, and switches to an open circuit as a band-stop structure at the second harmonic.

A microwave-to-dc conversion efficiency of 80.9% has been achieved with 20-dBm microwave input power at 2.45 GHz. The dimension of the rectifier is only $0.23\lambda_g \times 0.2\lambda_g$. The input filter in a conventional microwave rectifier has been removed to reduce the extra insertion loss, and the impedance matching circuit has been facilitated to miniaturize the design. The series $\lambda_g/8$ short-ended microstrip line in the proposed rectifier functions as both a filter for harmonic recycling and an inductor for impedance matching.

The proposed rectifier design is suitable for Schottky diodes with relative high diode capacitive impedance. If the diode capacitive impedance is very low, the series $\lambda_g/8$ short-ended microstrip transmission line is too wide to fit the compact microwave rectifier design. The proposed rectifier design may be applied to microwave power transmission systems in the future.

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