Wide Input Power Range X-Band Rectifier With Dynamic Capacitive Self-Compensation

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***Abstract*— A microwave rectifier composed of a pair of Schottky diodes with dynamic capacitive self-compensation is proposed in this letter. The impedance of a Schottky diode usually varies with the input power. A method using paired diodes for capacitive self-compensation is presented to enhance the rectifier's dynamic power range. The imaginary part of one diode's impedance is compensated using another identical diode with a section of transmission line by impedance transforming. The proposed method reduces the effect of the input power on the diode impedance. An X-band rectifier using a pair of HSMS-286 Schottky diodes based on the proposed method is designed and fabricated. This rectifier, with a dc load of 300 Ω, achieves power conversion efficiency of 64.5% at 9.7 GHz and has a 15.3-dB input power dynamic range with efficiency exceeding 50%. The rectifier is expected to be used in wireless power transmission systems with flexible distance requirements.**

***Index Terms*— Imaginary impedance part, microwave rectifier, Schottky diode, self-compensation.**

I. Introduction

RECENT advances in wireless power transmission (WPT) technology are enabling various engineering applications with the potential for product implementation [1]. As environmentally friendly and effective alternative power system for future power systems and WPT systems are attracting increasing attention from researchers [2], [3]. When the transmission distance of the WPT system changes, the power received by the antenna also varies. Therefore, as a crucial WPT system component mounted on the antenna, a rectifier with a wide dynamic input power range is critically important. A wide input power dynamic range for a rectifier can enable efficient circuit operation with complex environmental changes.

With the rapid development of radio frequency (RF) circuits, rectifier working frequencies are becoming increasingly high, e.g., in the X-band or higher frequencies [4]–[7]. Schottky diodes are commonly used as rectifying diodes in rectifier design because of their high cutoff frequencies and short reverse recovery times [8]–[16]. However, the input power affects the impedance of the diode and input power variations can result in impedance mismatching, which is the main reason for the limited input power dynamic range. Therefore, to increase the rectifier's input power dynamic range, several approaches have been proposed [17]–[19]. In [20], a GaAs pHEMT was used to achieve a low threshold voltage and high breakdown voltage for the rectifier simultaneously. In [21], one Schottky diode was connected directly to a dipole antenna. Methods have also been proposed to enhance the power dynamic range using the diode impedance, e.g., using a $\lambda/8$ section of transmission line to counteract the imaginary part of the diode impedance that achieved a dynamic range from 6 to 25 dBm with conversion efficiency of over 50% at 2.45 GHz [22]. In [23], an impedance compression network (ICN) was designed to compress the undesired input impedance variations. This circuit realized efficiency of more than 50% from 28 to 35 dBm at 2.45 GHz, which is a 4-dB dynamic power range improvement when compared with the circuit without the ICN. In [24], the rectifier array used two rectifier cells operating at low- and high-power levels to achieve peak the conversion efficiency of over 50% when the input power ranged from 2.2 to 26.5 dBm at 2.45 GHz. However, more work is required to enhance the dynamic power ranges of rectifiers, especially in higher frequency bands.

In this work, a microwave rectifier operating in the X-band using capacitive compensation is proposed to give a wide input power dynamic range. The proposed capacitive self-compensation circuit uses a pair of diodes to cancel the imaginary parts of each other's impedance. The two diodes share the same dc output as the biasing voltage and their impedances vary simultaneously with respect to the input microwave power. Therefore, the capacitive impedance of one diode will compensate for the impedance of the other dynamically. The theoretical analysis and the design equations are presented in Section II while measurement results and discussions are presented in Section III. These results show that a wide dynamic input power range of 15.3 dB is achieved for the designed rectifier from 7.1 to 22.4 dBm when the dc load is 300 Ω. Conclusion is then presented in Section IV.

II. Design of the Microwave Rectifier

A schematic of the proposed microwave rectifier is shown in Fig. 1. The rectifier is mainly composed of parts A and B. Part A includes diode D_1 with a section of transmission line TML_1; part B includes diode D_2. The two diodes are identical. TML_1 transforms the impedance of D_1 into an inductive impedance. D_2 has a capacitive impedance to compensate for the impedance of part A.

A diode's input impedance is usually influenced by the input power, the working frequency, and the dc load. It is thus

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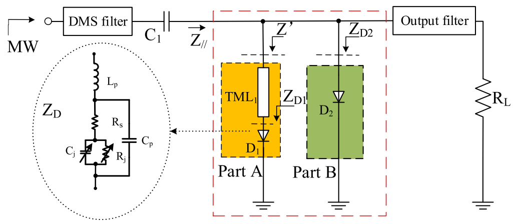

Fig. 1. Schottky diode model and schematic of the proposed rectifier.

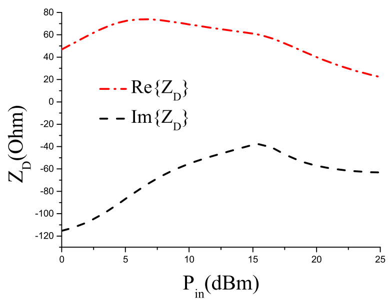

Fig. 2. Diode impedance variations with the input power.

important to study the relationship between diode impedance and input power at a fixed working frequency with a dc load. The real and imaginary parts of a Schottky diode at various input power levels can be obtained from simulations using ADS software with a harmonic balance and large-signal S-parameter.

A Schottky diode (HSMS-286F, Avago Tech. Inc.) is selected as the rectifying diode. Its equivalent circuit elements are $R_s = 6\ \Omega$, $C_{j0} = 0.18$ pF, $B_v = 7$ V, and $V_{bi} = 0.35$ V. Variations in the real and imaginary parts of the impedance Z_D with the input microwave power are illustrated in Fig. 2. To determine the influence of the input power on the real and imaginary parts of the diode impedance, the diode impedances were selected from the figure at input powers of 5, 10, 15, and 20 dBm, and the corresponding points are shown in a Smith chart. Simultaneously, only the real parts of the impedance for the selected diode are plotted in the same Smith chart, as shown in Fig. 3. As the chart shows, without the imaginary part, the impedances are in the circle with voltage standing wave ratio (VSWR) = 1.3 while the impedances with imaginary parts are located between the circles with VSWR = 1.3 and 5. This shows that when the input power varies, the imaginary part of the impedance has a greater effect on impedance matching.

The microstrip transmission line TML_1 is connected directly to the diode D_1 and transforms its impedance into its conjugate impedance. Another identical diode D_2 is then added in parallel with the impedance-transformed diode D_1 to counteract the imaginary part of its impedance. The impedances of the diodes D_1 and D_2 both vary simultaneously with respect to the output dc voltage, which is the biasing voltage and is dependent on the input microwave power. The input impedance remains real because of the cancellation of the imaginary part. Therefore, a wide input power dynamic range is obtained because the real part of the diode impedance with respect to the input power is not as sensitive as the imaginary part of the diode impedance.

As indicated by Fig. 1, by transforming the impedance of D_1 using transmission line TML_1, the input impedance Z' is

$$Z' = Z_T \frac{Z_{D1} + jZ_T \tan\beta l}{Z_T + jZ_{D1}\tan\beta l} \tag{1}$$

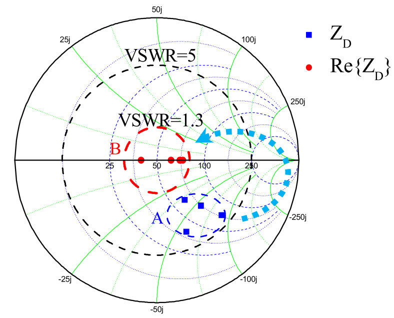

Fig. 3. Diode impedances at different power levels. A: Diode impedance with the imaginary parts. B: Diode impedance without the imaginary parts.

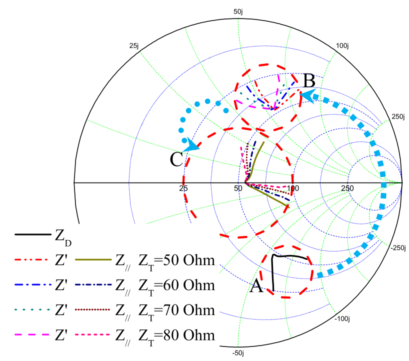

Fig. 4. Diode impedance transforming with different Z_T. Region A: Z_D Diode impedance at various power levels. Region B: Z' Impedance of diode in series with the transmission line. Region C: $Z_{//}$ Parallel impedances of the two diodes in the rectifier.

where Z_T and Z_{D1} are the characteristic impedance of transmission line TML_1 and the impedance of diode D_1 at the fundamental frequency, respectively. After serial connection with TML_1, the imaginary part of the diode impedance Z' can be changed from a capacitive value into an inductive value. Furthermore, Z' is supposed to be equal to the conjugate of Z_{D1}, which is then connected in parallel with the identical diode D_2 with impedance Z_{D2} to counteract the imaginary part, that is,

$$Z' = (Z_{D1})^* \tag{2}$$

$$Z_{//} = \frac{Z' \times Z_{D2}}{Z' + Z_{D2}}. \tag{3}$$

The length of the microwave transmission line is

$$\beta l = \arctan \frac{2jZ_T \mathrm{Im}\{Z_{D1}\}}{|Z_{D1}|^2 - Z_T^2} \tag{4}$$

where β is equal to $2\pi/\lambda_g = 0.33\ \mathrm{mm}^{-1}$.

To determine the microstrip line impedance, parallel impedance calculations can be performed for parts A and B. Fig. 4 indicates that when the characteristic impedance Z_T of TML_1 is 50, 60, 70, or 80 Ω, the variation in the corresponding parallel impedance $Z_{//}$ is quite small. Therefore, 60 Ω is selected as the characteristic impedance Z_T of TML_1. According to Fig. 2, the diode impedance at $P_{\mathrm{in}} = 17.8$ dBm and $R_L = 600\ \Omega$ is 46.8 − j59.6 Ω, i.e., $Z_{D1} = Z_{D2} = 46.8 - j59.6\ \Omega$. According to (1), $Z' = 46.8 + j59.6\ \Omega$. Therefore, the length of TML_1 of 5.5 mm is calculated from (4) and $Z_{//}$ is approximately 61.35 Ω from calculations using (3). These results will be used in the initial design to perform further optimizations.

TABLE I

MAIN PARAMETERS OF THE PROPOSED RECTIFIER

Parameter	W_1	W_2	W_3	W_4	W_5	W_6
Value (mm)	1.0	1.0	0.63	3.98	2.50	2.13
Parameter	W_7	W_8	W_9	L_1	L_2	L_3
Value (mm)	2.04	0.60	0.20	3.83	0.61	1.43
Parameter	L_4	L_5	L_6	L_7	L_8	L_9
Value (mm)	2.94	5.90	4.1	4.73	4.5	5.0

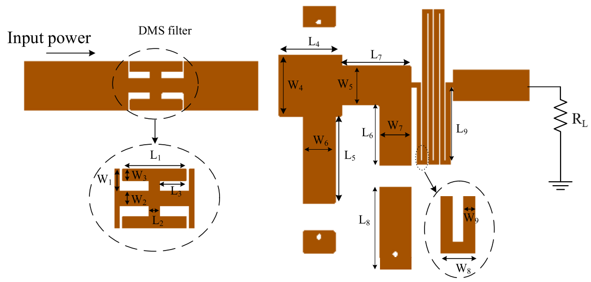

Fig. 5. Fabricated prototype of the proposed circuit.

III. RECTIFIER REALIZATION AND RESULTS

Based on the analyses above, the proposed rectifier consists of a series of microwave transmission line, two identical diodes, a dc load, and a defected microstrip structure (DMS) filter [25]. The DMS filter is used to miniaturize the rectifier and is slotted on a 50-Ω microstrip line in the input part of the rectifier. The DMS filter's frequency response can be tuned by adjusting the slot lengths and widths to achieve better harmonic recycling in the rectifier. The proposed rectifier is designed on an F4B substrate. The parameters of the proposed circuit are optimized in ADS to tune the return loss and conversion efficiency within the band of interest (centered at 9.7 GHz), as shown in Table I.

The rectifier dimensions are 30 mm × 16 mm and the blocking capacitors C_1 and C_2 (American Technical Ceramics, ATC) have values of 100 and 0.3 pF, respectively. The final circuit layout is shown in Fig. 5.

The microwave (MW)-dc conversion efficiency (η) of a microwave rectifier is defined as the ratio of the rectified dc output power to the microwave incident power and is given by

$$\eta = \frac{P_{\mathrm{DC}}}{P_{\mathrm{in}}} \times 100\% \tag{5}$$

where P_{DC} is the dc output power at load R_L and P_{in} is the power available from the microwave source.

An Agilent E8730C vector signal generator with output power of up to 25 dBm in the *X*-band was used to test the proposed circuit. An adjustable resistance box was connected to the rectifier output and a data acquisition instrument (Agilent 34970A) was used to measure the output dc voltage. The simulated and measured conversion efficiencies with respect to the input microwave power are shown in Fig. 6.

Both power and load sweeping were performed to achieve optimal performance. Fig. 7(a) shows the conversion efficiency for a fixed dc load R_L from 200 Ω to 500 Ω at f_0 = 9.7 GHz with various input power levels. Fig. 7(b) shows the variations in the measured conversion efficiency of the microwave rectifier with the dc load at the fundamental frequency and at fixed input power levels of P_{in} = 17, 18, 19, and 20 dBm. The figure shows that the conversion efficiency

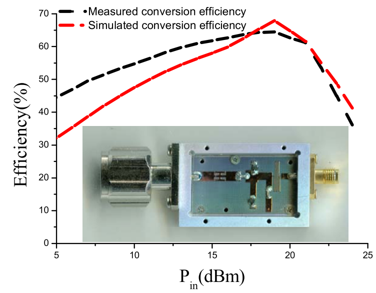

Fig. 6. Simulated conversion efficiency and measured conversion efficiency variations with microwave input power when R_L = 300 Ω.

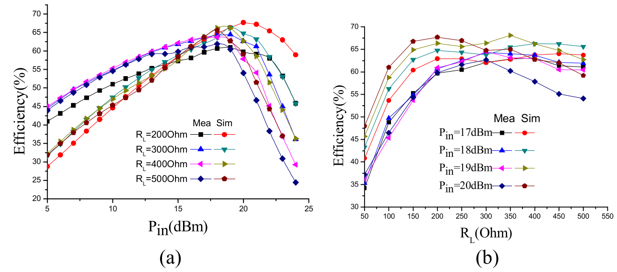

Fig. 7. Measured efficiency versus (a) input power and (b) load.

TABLE II

COMPARISON WITH PRIOR RECTIFIERS

Reference	[5]	[6]	[8]	This work
Frequency	9.5 GHz	9.3 GHz	10 GHz	9.7 GHz
Power Range (PCE>50%)	14 dB	N.A.	~13 dB	**15.3 dB**
Peak efficiency	67%	60%	72.2%	64.5%
Diode Type (HSMS)	8101	8202	286C	286F
Optimal input power	15 dBm	N.A.	19.4 dBm	19 dBm
Dimensions (mm^2)	70×40	N.A.	40×40	**30×16**

improves as the power level increases because of the nonlinear characteristics of the diodes. When the input power is between 7.1 and 22.4 dBm and the load is 300 Ω, the rectifying efficiency is more than 50%, which represents an input power dynamic range of 15.3 dB. When the input power is 19 dBm, the rectifying circuit reaches its highest efficiency of 64.5%.

To further demonstrate the advantages of this work, a performance comparison with previously published rectifier results is shown in Table II, mainly in terms of the input power range. Obviously, the proposed rectifier is compact in size and has a wide input power range.

IV. CONCLUSION

An *X*-band rectifier with a wide dynamic input power range is presented, in which a capacitive self-compensation structure is proposed. Using a direct serial connection to a microstrip line, the capacitive imaginary part of the diode impedance can be transformed into its conjugate. The diode with the serial microstrip line is then connected in parallel with an identical diode. In this way, the imaginary part of the rectifier's input impedance can be canceled effectively to provide a good input power dynamic range. The proposed rectifier realizes an input power dynamic range of 15.3 dB (conversion efficiency >50%) from 7.1 to 22.4 dBm. It also has compact dimensions of 30 mm × 16 mm which will enable easy integration with a planar antenna for potential applications in WPT systems.

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