Analysis of Low-Power Rectifiers Based on Tunnel Diode for Energy Harvesting

Zhongqi He[1], Xin Zhang[1], Liping Yan[1], Wenquan Che[2], Changjun Liu[1]
1. School of Electronics and Information Engineering, Sichuan University, Chengdu 610064, China
2. School of Electronic and Information Engineering, South China University of Technology, Guangzhou, China

***Abstract*-Microwave rectifier design with tunnel diodes for energy harvesting are presented in this paper. Addressing the low efficiency of rectifiers based on common Schottky diodes in low power level, rectifiers with tunnel diodes show higher efficiency at low power levels. The I-V characteristic curve of a tunnel diode is different from that of a Schottky diode, marking the conventional rectifier model unsuitable for rectifiers based on tunnel diodes. To address this issue, this study conducted simulations and calculations using a new rectifier model based on the I-V characteristic curve of diodes, which was verified by the proposed rectifier.**

Keywords—energy harvesting, I-V characteristic curve, rectifier, tunnel diode.

I. Introduction

Due to the rapid development of wireless networks, electromagnetic signals from wireless communication, Bluetooth, broadcast, and WIFI are distributed in every corner of our lives, which leads to an increasing of electromagnetic power density in space. The emergence of the Internet of Things requires the use of a large number of wireless sensors, and the power supply for large-scale sensor networks remains a restricting factor in its development[1]. The harvesting and utilization of electromagnetic wave energy in space can power these sensors. Therefore, researchers are studying energy harvesting (EH) technology[2] as well as large power and dynamic range rectifiers [3][4].

In the context of low-power rectifying technology, the power density of the receiving antenna is typically in the range of μW/cm^2, and the input power of the rectifier is usually in the μW range. The primary objective of rectifier design is to maximize the output of DC power[5][6]. However, achieving high-efficiency rectification at low-power levels is challenging due to the limited nonlinearity of diodes.

To enhance the efficiency of rectifier circuits at low power, researchers have explored numerous viable approaches, with one of the most common being the selection of diodes known for their superior performance. Currently available options include the HSMS285x series by Avago Technologies and the SMS7630 series by Skyworks. However, these diode series suffer from the disadvantage of elevated threshold voltage, which consequently leads to reduced rectification efficiency, particularly at extremely low power levels.

Hence, searching for a Schottky diode with a low turn-on voltage can effectively improve rectification efficiency at low power. According to reference [7], the VDI ZBD diode demonstrates promising characteristics. At a forward current of 100 μA, it exhibits an opening voltage ranging from 45 mV to 95 mV. When operating at a frequency of 1.9 GHz and with an input power of -30 dBm, the rectification efficiency reaches 11.2%, whereas the rectification efficiency of the SMS7630 diode is 8%. Moreover, the VDI ZBD diode finds application in low-power rectifiers covering frequencies from 24 GHz to 81 GHz and 94 GHz.

Apart from Schottky diodes, researchers are also exploring alternative types of low-power rectifier diodes. They have developed models for the tunnel diode MBD2057, implemented them in low-power rectifiers operating at 28 GHz. According to reference [8], a comparison was made regarding the rectification efficiency of the GI401A tunnel diode and the HSMS285B Schottky diode at 2.4 GHz. Across the power range from -10 dBm to -40 dBm, tunnel diodes can achieve up to a maximum rectification efficiency of 12.6%, whereas Schottky diodes exhibit an efficiency of only 6.53%. In reference[9], researchers designed a GaAs tunnel diode for low-power rectification, eventually achieving an efficiency of 18.2% at -30 dBm.

Firstly, this study shows the SPICE model of a tunnel diode and discusses its corresponding I-V characteristic curve. Next, the study performs calculations, simulations, and discussions on rectifiers based on tunnel diodes.

II. SPICE Model of Tunnel Diode

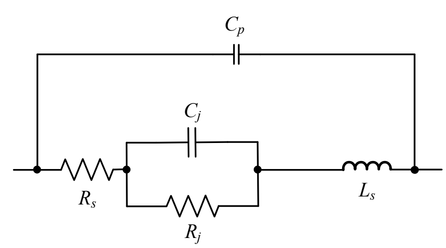

Fig. 1 SPICE model of tunnel diode

Fig. 1 illustrates the equivalent circuit model of a tunnel diode, comprising five components, namely, diode core parameters and packaging parameters. Here, C_j represents the junction capacitance of the diode. R_j correlates with the nonlinear I-V characteristic curve of the diode and regulates the current through voltage control. R_s denotes the series resistance. Additionally, C_p and L_s introduce parasitic capacitance and inductance to the diode's packaging.

2023 16th UK-Europe-China Workshop on Millimetre Waves and Terahertz Technologies (UCMMT) | 979-8-3503-3940-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/UCMMT58116.2023.10310633

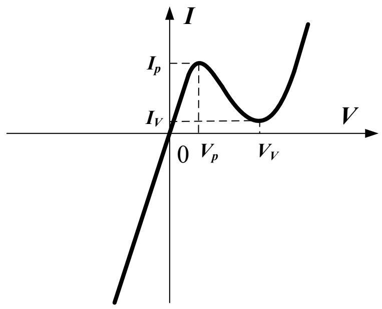

Fig. 2 I-V characteristic curve of tunnel diode

The I-V characteristic curve of the tunnel diode is shown in Fig. 2, which differs significantly from the I-V characteristic curve of the Schottky diode. Under reverse bias, the diode current increases monotonically with voltage. Under forward bias, owing to the quantum tunneling effect, the current initially increases with voltage, reaching its maximum value, I_p, at $V=V_p$. Subsequently, the current value decreases with increasing voltage, reaching its minimum value, I_V, at $V=V_V$, where the resistance in this region exhibits differential negative resistance. With further voltage increase, the current exhibits characteristics similar to a Schottky junction.

III. SIMULATION AND CALCULATION

With its lower power loss compared to other tunnel diodes, the tunnel diode MBD2057 offers advantages in low-power rectifier circuits. This study will present the design of a low-power rectifier circuit utilizing the tunnel diode MBD2057 as the rectifier diode and perform calculations and analyses of the losses and efficiency during the rectification process.

TABLE I
PARAMETERS OF MBD2057

R_s	15 Ω	C_j	0.3 pF
C_p	0.12 pF	L_s	0.61 nH

Table I presents the key parameters of tunnel diode MBD2057, with the model shown in Fig. 1. The characteristics of R_j closely resemble the I-V characteristic curve, and therefore, it can be simulated using polynomials. In this study, a 6th-order polynomial is utilized:

$$I_{Rj} = a_0 + a_1 V_{Rj} + a_2 V_{Rj}^2 + a_3 V_{Rj}^3 + a_4 V_{Rj}^4 + a_5 V_{Rj}^5 + a_6 V_{Rj}^6 \quad (1)$$

The coefficient a_i is given in Table II.

TABLE II
POLYNOMIAL COEFFICIENT OF MBD2057

a_0	a_1	a_2	a_3	a_4	a_5	a_6
0	0.01154	-0.1269	0.4509	-0.319	-1.124	1.638

The rectifier circuit employs a straightforward parallel diode configuration, as depicted in Fig. 3. The parallel rectification circuit utilizing tunnel diode MBD2057 comprises an input isolation capacitor, a matching network, a parallel diode, an output low-pass filter network, and a DC load. We utilize electromagnetic simulation software for simulating the rectifier, with a particular emphasis on observing the efficiency trend of the rectifier circuit as power varies. To accurately simulate the rectification performance of the tunnel diode, other circuit components introduce no losses except for the diode.

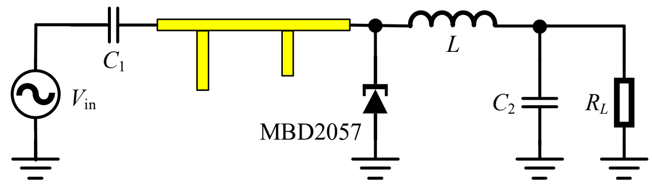

Fig. 3 Schematic of rectifier based on tunnel diode

The rectifier operates at a frequency of f=2.4 GHz, with a load resistance (R_L) of 1000 Ω. The input power range is P_{in} = -20 dBm to 0 dBm. Firstly, the matching network at the input port is optimized to match the source impedance of 50 Ω. The $|S_{11}|$ of the rectifier, shown in Fig. 4, demonstrates that when the input power is between -17 dBm and -2 dBm, the $|S_{11}|$ of the circuit is less than -10 dBm, indicating a good match.

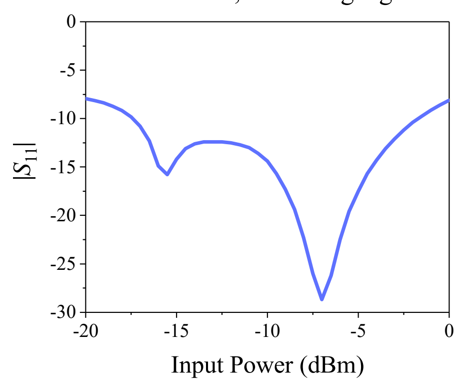

Fig. 4 $|S_{11}|$ of the rectifier

Regarding tunnel diode rectification, research in this area is currently limited, with no comprehensive circuit model analysis available. Since tunnel diodes have no conduction angle and reverse breakdown angle, conventional rectifier models based on the conduction angle of Schottky diodes are no longer applicable to tunnel diode rectifier. In this section, we employ the rectifier model based on the diode I-V characteristic curve [10] for calculating and analyzing the tunnel diode rectifier. The simulation and calculation efficiency are illustrated in Fig. 5(a).

Fig. 5(a) illustrates the output DC voltage and efficiency of the tunnel diode MBD2057 rectifier within the power range from -20 dBm to 0 dBm. The figure demonstrates the consistency between the calculation and simulation results. The rectification efficiency reaches its maximum of 28% at an input power of -12 dBm. However, the rectification efficiency rapidly decreases when the input power is below -12 dBm. Furthermore, at an input power of approximately -10 dBm, a notable discrepancy is observed between the calculation and simulation results. To analyze the underlying reasons, we conducted a simulation of the spectrum for the tunnel diode MBD2057 during the rectification process, with the results displayed in Fig. 5(b).

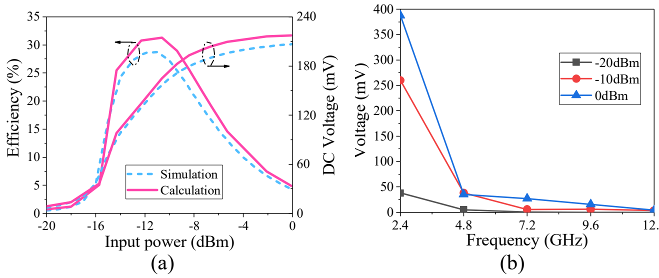

Fig. 5 (a)Simulation and calculation results of efficiency and dc voltage and (b) simulated spectrum of the rectifier when f=2.45 GHz

At both -20 dBm and 0 dBm power levels, the harmonics generated by diode rectification exhibit significantly smaller amplitudes compared to the fundamental wave, aligning with the assumption of harmonic behavior in the circuit model based on the diode's I-V characteristic curve. As a result, the calculation and simulation results exhibit relatively consistent behavior, considering the assumption of a perfectly matched circuit during calculation, with the calculation results tending to be slightly larger than the simulation results. At an input power of -10 dBm, the amplitude of diode harmonic becomes relatively significant, leading to a notable discrepancy between the calculation and simulation results. While, the overall trend of change remains consistent.

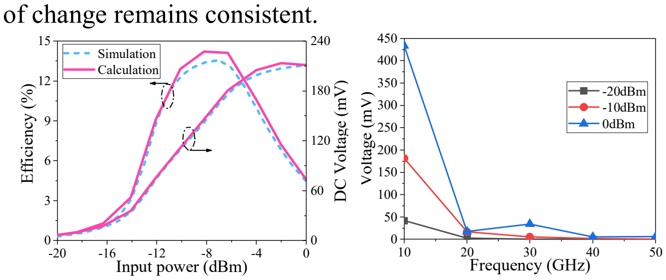

Fig. 6 (a)Simulation and calculation results of efficiency and dc voltage and (b) simulated spectrum of the rectifier when f=10 GHz

Because the tunnel diode exhibits excellent performance at high frequencies, it can be effectively utilized in the rectifier of the X band. Therefore, we once again employ the tunnel diode MBD2057 in the X-band rectifier. The circuit structure remains consistent with Fig. 3, operating at a frequency of f=10 GHz, a load R_L of 1000 Ω, and an input power range of P_{in}=-20 dBm to 0 dBm.

Similarly, we initially optimized the matching network to achieve optimal impedance matching, resulting in very small reflection coefficient. Subsequently, we simulated and calculated the rectifier. Fig. 6(a) shows the simulated and calculated DC voltage and efficiency, indicating a high level of agreement between the simulation and calculation results. The efficiency of this circuit surpasses 12% at an input power of -8 dBm. However, the efficiency of the circuit significantly decreases for power levels below -12 dBm.

Fig. 6(b) displays the spectrum of the tunnel diode MBD2057 during the rectification process at various input power levels, where the higher harmonics exhibit significantly smaller amplitudes compared to the fundamental wave. This characteristic contributes to the consistency between the simulation and calculation results.

IV. Conclusions

This study proposed an analysis of rectifiers based on tunnel diode in low-power level. Firstly, by studying the SPICE model and I-V characteristic curve of tunnel diodes, it is demonstrated that tunnel diodes are suitable as rectifying diodes for low-power applications. Next, the simulation and calculation of rectifiers based on tunnel diodes operating at different frequencies are presented. When the rectification harmonics are low, the results of simulation and calculation show good agreement.

Acknowledgment

This research is supported in part by the National Nature Science Foundation of China U22A2015, 62071316, and 61931009.

References

[1] T. Paing, E. Falkenstein, R. Zane and Z. Popovic, "Custom IC for Ultra low Power RF Energy Harvesting," 2009 Twenty Fourth Annual IEEE Applied Power Elect ronics Conference and Exposition, Washington, DC, USA, 2009, pp. 1239 1245.

[2] T. Le, K. Mayaram and T. Fiez, "Efficient Far Field Radio Frequency Energy Harvesting for Passively Powered Sensor Networks," *IEEE Journal of Solid State Circuits*, vol. 43, no. 5, pp. 1287 1302, May 2008.

[3] B. Zhang, X. Zhao, C. Yu, K. Huang, and C. Liu, A Power Enhanced High Efficiency 2.45 GHz Rectifier Based on Diode Array, Journal of Electromagnetic Waves and Applications, 2021, 25:5-6, 765-774

[4] Z. He, J. Lan and C. Liu, Compact Rectifiers with Ultra-wide Input Power Range Based on Nonlinear Impedance Characteristics of Schottky Diodes," in IEEE Transactions on Power Electronics, vol. 36, no. 7, pp. 7407-7411, July 2021

[5] Z. He, H. Lin, H. Zhu and C. Liu, "A Compact High-Efficiency Rectifier With a Simple Harmonic Suppression Structure," *IEEE Microw. Wireless Compon. Lett.*, vol. 30, no. 12, pp. 1177-1180, Dec. 2020.

[6] Z. He, H. Lin and C. Liu, "A Novel Class-C Rectifier With High Efficiency for Wireless Power Transmission," *IEEE Microw. Wireless Compon. Lett.*, vol. 30, no. 12, pp. 1197-1200, Dec. 2020.

[7] C. H. P. Lorenz, S. Hemour and K. Wu, "Physical Mechanism and Theoretical Foundation of Ambient RF Power Harvesting Using Zero-Bias Diodes," *IEEE Trans. Microwave Theory Tech.*, vol. 64, no. 7, pp. 2146-2158, July 2016.

[8] V. Manev, H. Visser, P. Baltus and H. Gao, "A Comparison of Tunnel Diode and Schottky Diode in Rectifier at 2.4 GHz for Low Input Power Region," 2019 IEEE Wireless Power Transfer Conference (WPTC), London, UK, 2019, pp. 274-277.

[9] C. H. P. Lorenz et al., "Overcoming the efficiency limitation of low microwave power harvesting with backward tunnel diodes," 2015 IEEE MTT-S International Microwave Symposium, Phoenix, AZ, USA, 2015, pp. 1-4.

[10] Z. He, S. Trovarello, F. Benassi, D. Masotti, C. Liu and A. Costanzo, "Analysis of Rectifiers Under Various Multitone Excitations and Using Different Diodes in Low-Power Conditions," 2022 IEEE 12th International Conference on RFID Technology and Applications (RFID-TA), Cagliari, Italy, 2022, pp. 157-160.