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A High Conversion Efficiency Millimeter-Wave Rectifier Based on Modified Equivalent Model

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***Abstract*—one rectifying diode equivalent model calibration method is proposed firstly, and a 24GHz rectifier is designed based on the modified model accordingly. The calibration method uses the resonant characteristic of the diode to identify the difference between commonly used diode model and the real model. Compared to the other calibration methods, the proposed method provides a simple calibration process and an accurate equivalent model. For validation, the calibration circuits are fabricated and the diode model is then modified and given according to the proposed calibration method. A 24GHz rectifier is designed using the modified model, while the simulated results indicate a 72% conversion efficiency maximum.**

***Index Terms*—millimeter-wave, rectifier, equivalent model, calibration method, wireless power transfer**

I. Introduction

Rectifier is an essential component in wireless power transmission (WPT) system which converts microwave energy into dc power. The conversion efficiency of one rectifier is vital to the overall system efficiency.

Currently, most of the reported designs work at L to X band. However, with the rapid development of wireless communication and radar techniques, more and more researches have been focused on millimeter-wave frequency design due to the intrinsic advantage of compact size. However, only a few millimeter-wave rectifier researches were reported with relatively low efficiency compared to centimeter-wave designs.

According to authors' knowledge, state-of-the-art reported works are introduced as below. In [3], a harmonic recycling configuration was utilized to improve the power conversion efficiency and 34% maximum rectifying efficiency is obtained at 35 GHz. [4] realized 63.2% maximum rectifying efficiency at 34.8 GHz in measurement. [5] designed a compact rectenna and the conversion efficiency of the utilized rectifier is up to 61.5%. In order to deduce the high loss of microstrip line at millimeter-wave band, [6] explored the design method of shielded microstrip-line based rectifier and obtains a 67% maximum conversion efficiency at 35GHz. In [7], a CMOS rectifier was proposed which working at 160 GHz. Due to the difficulty to realize a typical Schottky diode in CMOS technology, the diode is realized in form of diode-connected MOSFETs. However, the performance is not as good as commercial GaAs technology based Schottky diode. [8] used CMOS integrated Schottky diode to design a rectifier with 53% maximum conversion efficiency. [9] designed a rectifier without Schottky diode in 65 nm CMOS technology. The novel idea of the structure is to use mixer to eliminate IO and RF when they are at the same frequency. However, the process of frequency mixing consumes a high portion of power and the conversion efficiency of this design is up to 36% at 35GHz.

As the conversion efficiency of millimeter-wave rectifier is relatively low compared to centimeter-wave rectifier, previous works mostly focused on simplifying the topology of circuit or using low-loss substrate structure. However, with all these means, the conversion efficiency of millimeter-wave rectifier is still low. It is noted that in all these millimeter-wave reported works, the measurements hardly agreed with the simulation while the agreement is usually good in centimeter-wave bands. One of the key reasons is that the software model of rectifying diode is not accurate due to the high frequency. In this case, a method to calibrate the equivalent model of diode in high frequency is needed to achieve a high conversion efficiency.

In this paper, a calibration method is proposed to acquire the accurate equivalent model of rectifying diode with simple calibration process. The calibration circuit with simple topology is utilized to test the S21 which is directly related to the parameters of the equivalent model. By tuning those parameters, good agreement between the simulation result of calibration circuit and the measurement can be achieved. In this way, the equivalent model is modified. Moreover, a high efficiency millimeter-wave rectifier is designed based on the modified equivalent model for validation.

II. Working Process Of Calibration

Firstly, the working mechanism of the proposed calibration circuit should be discussed. The schematic is shown in Fig. 1(a). Port 1 and 2 are connected by a microstrip line while a

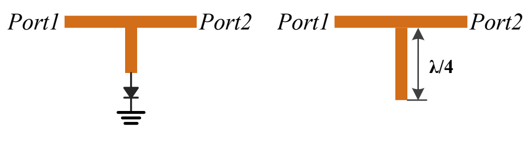

Fig. 1. Block diagrams of (a) proposed calibration circuit and (b) the equivalent circuit.

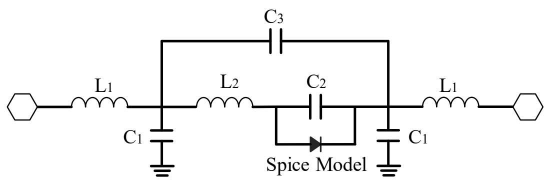

Fig. 2. Diode model considering the affection of package and soldering.

TABLE I

	$C_1(fF)$	$C_2(fF)$	$C_3(fF)$	$L_1(pH)$	$L_2(nH)$
Current model	4	16	17	4.3	0.28
Modified model	25	16	17	85	0.28

branch line with a diode connected to ground is in shunt. It is known that the rectifying diode is considered as a complex LC circuit with a resonant frequency, the equivalent model is shown in Fig. 2. By properly designing the length of the branch line, the calibration circuit is equivalent to the circuit shown in Fig. 1(b) at the designed resonant frequency. The whole branch performs as a 1/4 wavelength open stub hence a zero point of S21 can be observed.

This resonance characteristic can be used to carry out the calibration. As the length of branch line is a designed value, the resonance frequency is only related to the parameters of the model. Thus, by testing the resonance frequency of the fabricated circuit we can tell if the used model is accurate enough to predict the performance.

The calibration steps are given as below:

Step 1: use the current model to build the proposed calibration circuit, make sure that there is a zero point of S21 at resonance frequency by proper designing the length of branch line.

Step 2: fabricate the circuit, verify that if the measurement agrees with the simulation.

Step 3: If the measurement agrees with the simulation, it suggest that the currently used model is accurate. Otherwise, tuning the parameters of the model to match the measurement.

Step 4: fabricate the circuit designed with modified model to verify the results.

The simulation result in step 1 is shown in Fig. 3. The circuit is designed with the model provided by the producer and the resonance frequency is set at 24 GHz. The parameters of the model are given in Table I. The measurement of the fabricated verification circuit is also illustrated in Fig. 3. As can be seen the measured resonance frequency is 20.7 GHz, which does not agree with the simulation. According to the result in step 2, the model parameters are modified to make

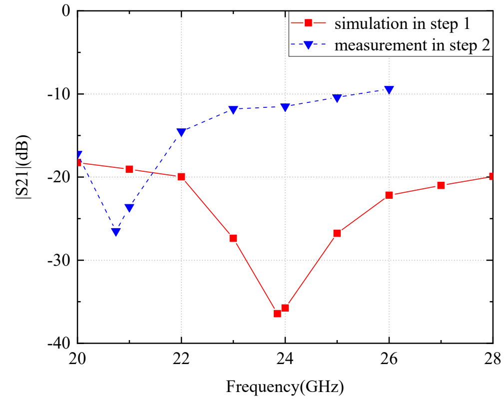

Fig. 3. Simulation results of the calibration circuit in step 1 and measurements of fabricated circuit in step 2.

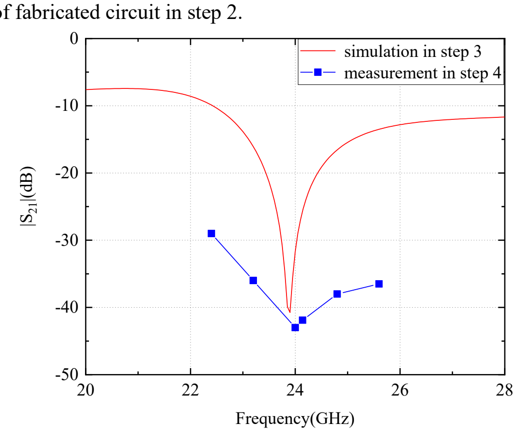

Fig. 4. Simulation results of the calibration circuit in step 3 and measurements of fabricated circuit in step 4.

the simulation result match to the measurement. The parameters are given in Table I. By tuning the length of the branch line, the resonance frequency is also set at 24 GHz in step 3. The simulation and measurement result of calibration circuit designed with the modified model are shown in Fig.4. The results show that the modified model is accurate.

The merits of the proposed method are discussed below. Firstly, the cost of the proposed method is less than the other methods. Only one kind of calibration circuit is needed in this method. For comparison, a TRL calibration method needs 3 kinds of circuits (through, reflect and line) totally to do the calculation and calibration. Secondly, the proposed calibration process is much simpler. In order to eliminate the error caused by cables or connectors, the TRL calibration method uses a lot of data to do the complex calculation to put the reference plane on the device under test (DUT). However, in the proposed method, the influence of connectors and cables is neglectable since the resonance frequency of shunt resonance circuit is hardly affected by the component in series. The testing object resonance frequency is only related to the parameters of the model. In this case, no complex calculation is needed to acquire the real performance of the DUT.

III. RECTIFIER DESIGN

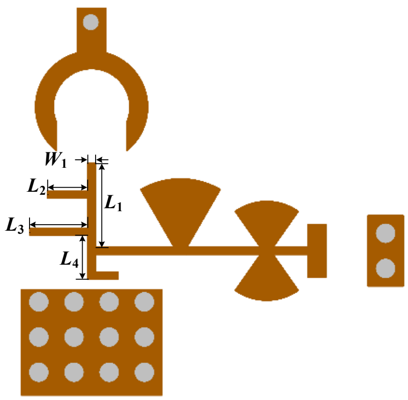

Fig. 5. Layout of the designed rectifier based on the modified model.

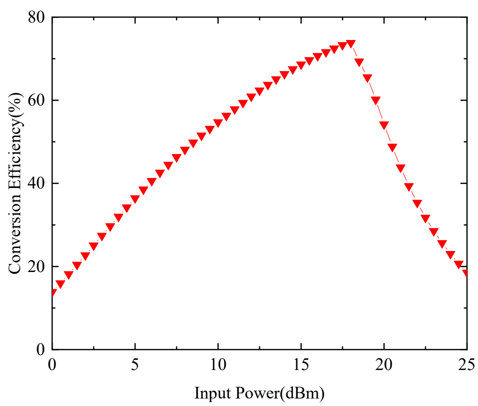

Fig. 6. Conversion efficiency of the designed rectifier based on the modified model.

The layout of the designed rectifier based on the modified rectifying mode is shown in Fig. 5. It consists of a ground for connector, an impedance matching network, a shunt Schottky diode, and a harmonic compression network. Due to the high frequency, a SMPM mount connector 3287-6101 is used to reduce the power loss caused by the connector. The utilized rectifying diode is Ma4e1317 which is also designed for high frequency usage. The diode has a low series resistance 4Ω and a low junction capacitance. The harmonic compression network is design to provide a reflection at the output port in order to improve the amount of rectified power. It also helps to smooth the waveform of output voltage.

The impedance matching network consists of a two stage T-type matching topology. This is to compensate the parasitic effect of the T junction. In addition, on the shunt diode branch a T-type topology is also deployed for compensation.

The optimum input power, the characteristic impedance of microstrip line and the resistance of load resistor are optimized to acquire a high conversion efficiency. The parameters are given as below: W_1=0.2 mm, L_1=2.4 mm, L_2=1.15 mm, L_3=1.65 mm, L_4=1.25 mm. The conversion efficiency versus input power is shown in Fig. 6. As we can see, the maximum conversion efficiency is 72% when the input power is 18 dBm.

IV. Conclusion

This paper presents a simple and effective calibration method to extract the equivalent model of one rectifying diode. By taking the advantage of the resonance characteristic of rectifying diode, neither multiple calibration circuit nor complex calculation is needed. The calibration process is given and executed for validation. For demonstration, one high efficiency rectifier working at 24 GHz is also designed based on the modified diode model.

References

[1] T.-W. Yoo and K. Chang, “Theoretical and experimental development of 10 and 35 GHz rectennas,” *IEEE Trans. Microw. Theory Techn.*, vol. 40, no. 6, pp. 1259–1266, Jun. 1992.

[2] S. Hemour and K. Wu, “Radio-frequency rectifier for electromagnetic energy harvesting: Development path and futureoutlook,” *Proc. IEEE*, vol. 102, no. 11, pp. 1667–1691, Nov. 2014.

[3] S. Ladan and K. Wu, “Nonlinear modeling and harmonic recycling ofmillimeter-wave rectifier circuit,” *IEEE Trans. Microw. Theory Techn.*,vol. 63, no. 3, pp. 937–944, Mar. 2015.

[4] H. Mei, X. Yang, B. Han, and G. Tan, “High-efficiency microstrip rectenna for microwave power transmission at Ka band with low cost,” *IET Microw., Antennas Propag.*, vol. 10, no. 15, pp. 1648–1655, Dec. 2016.

[5] P. Pang, X. Lin, S. Liu, X. Jia, and R. Xu, “A high-efficiency 35GHz rectenna with compact structure for rectenna arrays,” in *Proc. IEEE Asia–Pacific Conf. Antennas Propag. (APCAP)*, Aug. 2018, pp. 303–305.

[6] Q. Chen, X. Chen, H. Cai and F. Chen, "A Waveguide-Fed 35-GHz Rectifier With High Conversion Efficiency," in IEEE Microwave and Wireless Components Letters, vol. 30, no. 3, pp. 296-299, March 2020, doi: 10.1109/LMWC.2020.2968237.

[7] P. Zhu, Z. Ma, G. A. E. Vandenbosch and G. Gielen, "160 GHz harmonic-rejecting antenna with CMOS rectifier for millimeter-wave wireless power transmission," 2015 9th European Conference on Antennas and Propagation (EuCAP), 2015, pp. 1-5.

[8] H. Chiou and I. -. Chen, "High-Efficiency Dual-Band On-Chip Rectenna for 35- and 94-GHz Wireless Power Transmission in 0.13-μm CMOS Technology," in IEEE Transactions on Microwave Theory and Techniques, vol. 58, no. 12, pp. 3598-3606, Dec. 2010, doi: 10.1109/TMTT.2010.2086350.

[9] P. He and D. Zhao, "High-Efficiency Millimeter-Wave CMOS Switching Rectifiers: Theory and Implementation," in IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 12, pp. 5171-5180, Dec. 2019, doi: 10.1109/TMTT.2019.2936566.