Design of a capacitor-less 5.8-GHz microwave rectifier for microwave power transmission

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Design of A Capacitor-Less 5.8-GHz Microwave Rectifier for Microwave Power Transmission

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***Abstract*— A microwave rectifier for 5.8 GHz operation without any capacitors is presented, which has a measured MW-to-DC conversion efficiency of 61%. A coupled band pass filter and a class-F load are utilized to suppress diode harmonics and replaced the capacitors in conventional microwave rectifiers. The imaginary part of the diode impedance is canceled by a parallel microstrip line to enhance its rectifying efficiency at fundamental frequency. The measured conversion efficiency matched well to the simulated result.**

Keywords—capacitors; microwave rectifiers; band pass filters; class-F load

I. INTRODUCTION

A microwave rectifier is a rectifying circuit which converts microwave power into DC power. It is an essential component for a microwave power transmission (MPT) system, and it has been widely applied in rectennas [1-3], RFID tags [4], wireless sensor [5], space energy harvesting [6], and so on. Microwave rectifiers at 5.8 GHz have been extensively studied [7], and most of them are composed of a DC blocking capacitor, which is a lumped component, an input filter, a rectifying diode, and a output filter[8,9].

This paper presents a novel microwave rectifier, as shown in Fig. 1, in which it consists of a microstrip band pass filter, a Schottky diode, a $\lambda_g/8$ microstrip line, and a microstrip class-F load. Lumped capacitors are removed from the design, which may find more applications in high frequency microwave rectifiers.

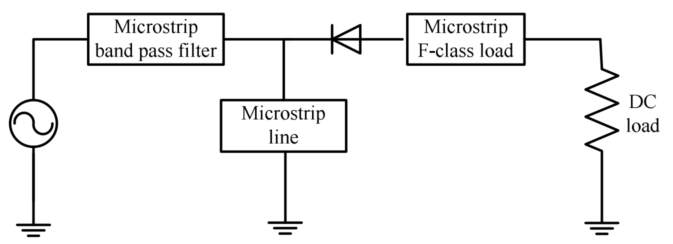

Fig.1. Proposed rectifying circuit scheme.

II. RECTIFYING CIRCUIT DESIGN

A. Band-Pass Filter

A microstrip band pass filter is introduced for the capacitor-less microwave rectifier. The filter is composed of two parallel coupled microstrip lines, which blocks the DC voltage and current to protect the microwave generator. The center frequency of this band-pas filter is at 5.8 GHz. Fig. 2 and Fig. 3 show the fabricated band pass filter and the experimental results, respectively. The insertion loss of the filter is 0.4 dB at 5.8 GHz, 14.2 dB at 11.6 GHz and 3.2 dB at 17.4 GHz, respectively. The fundamental frequency is located in the pass-band, and its harmonics are rejected by the band-pass filter. The input and output impedance are 50 ohm to match the microwave generator impedance.

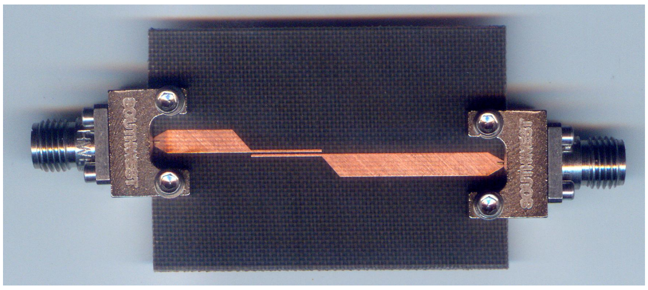

Fig.2. The proposed microstrip band pass filter

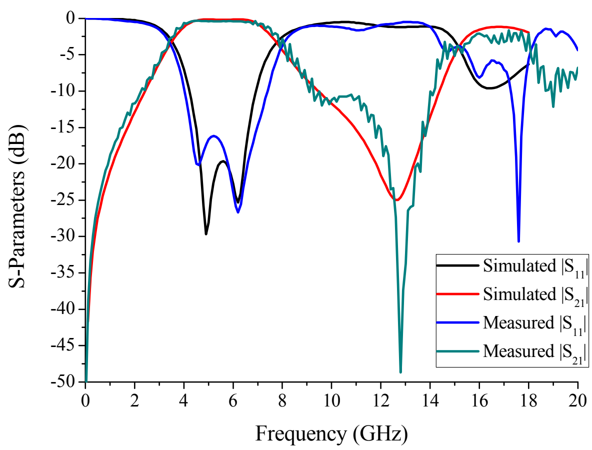

Fig.3. The simulated and measured results of the band-pass filter.

B. Diode Impendance and Parallel Inductor

In the proposed design, the large signal model of HSMS-286 Schottky diode is used. The impedance of the diode [2] is defined as

$$Z_d = \frac{\pi R_s}{\cos\theta_{on}\left(\frac{\theta_{on}}{\cos\theta_{on}} - \sin\theta_{on}\right) + j\omega R_s C_j\left(\frac{\pi-\theta_{on}}{\cos\theta_{on}} + \sin\theta_{on}\right)} \tag{1}$$

where C_j, R_s and θ_{on} are the junction capacitance, the series resistance, and the forward-bias turn-on angle, respectively. A $\lambda_g/8$ short-ended microstrip line is equivalent to an inductance at the fundamental frequency and a $\lambda_g/4$ resonator at the second harmonic. Therefore, this microstrip line cancels the imaginary part of diode impedance to enhance the rectifying efficiency at the fundamental frequency [10]. The inductive reactance of the microstrip line is defined as

$$jX_L = j2\pi f_0 L = jZ_0 \tan(\beta l) \tag{2}$$

where Z_0 and β are the characteristic impedance and propagation constant, respectively. The equivalent inductance $L = Z_0 / 2\pi f_0$, while $l=\lambda_g/8$. At the second harmonic, the equivalent resonator rejects the harmonic wave generated by the diode during rectifying.

The MW-DC conversion efficiency is greatly dependent on the length of the parallel microstrip line. Fig. 4 shows the relation between the conversion efficiency and the length of the parallel microstrip line with the optimum load resistance of the rectifier. In Fig. 4, the maximum conversion efficiency is 68.5%, when the line's length is 5.7 mm, which approximately is $\lambda_g/8$. The MW-to-DC conversion efficiency falls down obviously, while the length deviates from $\lambda_g/8$.

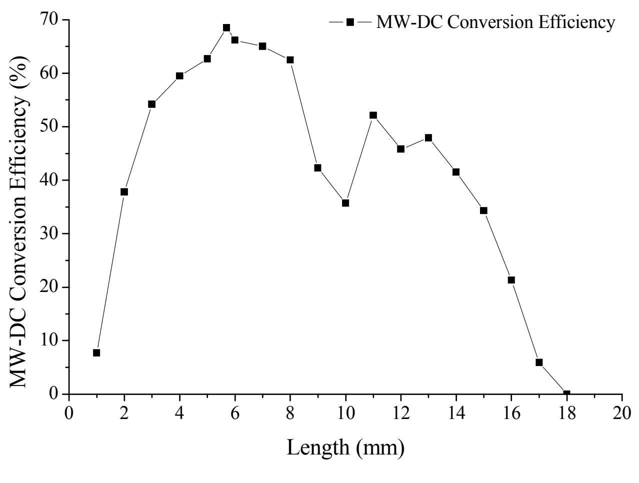

Fig.4. MW-to-DC conversion efficiency according to the length of the parallel microstrip line.

C. Class-F Load

Conventional output filter of the rectifier is composed of a $\lambda_g/4$ microstrip line and a capacitor. However, a real capacitor cannot produce 100% efficiency because its capacitance is not infinity and the loss cannot be neglected especially at high microwave frequencies. Thus, a class-F load [11] is proposed to satisfy the reflection conditions of a low-pass filter, which presents a short circuit for fundamental microwave and its harmonics. Fig. 4 shows the detailed microstrip structure of the class-F load.

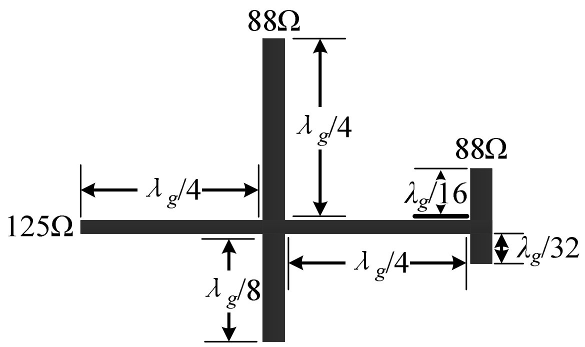

Fig.5. Microstrip structure of the class-F load.

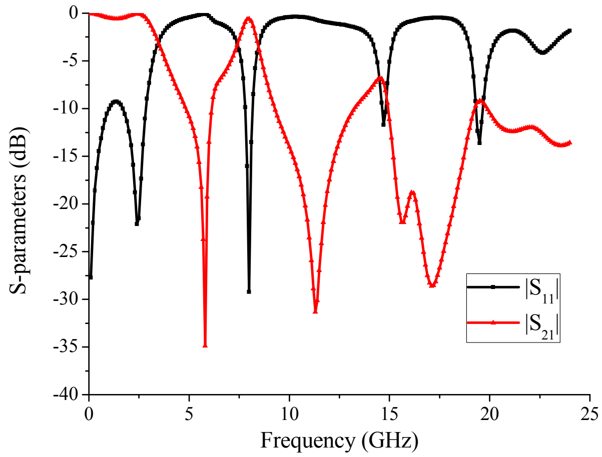

Fig.6. Reflection and transmission characteristics of the class-F load.

The reflection and transmission characteristics of the applied class-F load are shown in Fig. 5. The reflection and the transmission coefficients at the fundamental frequency of 5.8 GHz are -0.1 dB and -34.8 dB, respectively. Furthermore, the reflection and the transmission characteristics are -0.8 dB and -24.1 dB at the second harmonic, -0.5 dB and -27.5 dB at the third harmonic, and -3.3 dB and -13.6 dB at the forth harmonic, respectively. The class-F load obtains a good performance of preventing the fundamental frequency microwave and its higher order harmonics from leaking to the DC output port.

III. EXPERIMENTAL RESULTS

The proposed microwave rectifying circuit is realized on a F4B-2 substrate with $\varepsilon_r = 2.65$, thickness of 1 mm, and cooper foil 17 μm . Fig. 5 shows the photo of the fabricated capacitor-less 5.8 GHz microwave rectifier. The presented design applies the band pass filter and the class-F load as discussed in the above to replace the lumped capacitor of the input part and the output circuits in most conventional microwave rectifiers, respectively. The capacitors in both the input and output have been removed.

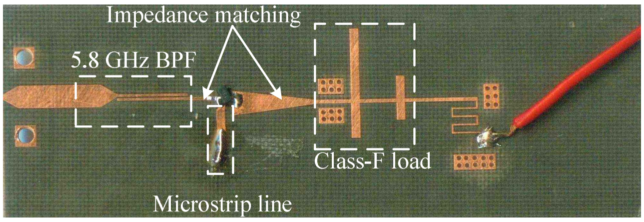

Fig.7. The fabricated microwave rectifier.

The simulated and measured DC output voltage and MW-DC conversion efficiency at 17 dBm input power are shown in Fig. 8. The rectangle- and triangle- marked lines show the conversion efficiency and the output DC voltage, respectively. This figure shows that the measurements agree well to the simulated results. When the maximum MW-to-DC conversion efficiency achieves 60% at 17 dBm microwave input power, the experimental DC output voltage reaches 2.3 V with a 180 Ohm DC load.

Fig. 9 shows the measured conversion efficiency with respect to various input power. Its highest MW-to-DC efficiency of 61% achieved at a microwave input power of 20 dBm and a DC load at 140 ohm. When the input power is between 17 dBm and 21 dBm and the load is at one hundred Ohm level, microwave to DC conversion efficiency above 50% is realized. The maximum power that the rectifier may handle is 21 dBm. When the input MW power increases, the optimal DC load decreases to achieve the best MW-to-DC conversion efficiency. Moreover, it indicates that the DC load and MW-to-DC efficiency relation become sharper as well.

The output DC voltage of a diode varies as the operating power level changes. Fig. 10 shows the DC voltage of the proposed rectifier dependent on the input microwave power. The curves of the output voltage with respect to the load become steeper while the input power increases. Finally, the voltage is limited to 3.7 V which approximates to the half of the breakdown voltage of HSMS-286 Schottky diode. Thus, the critical input power determined by the breakdown effects of the diode is expressed as $V_{br}^2/4R_L$ [12]. The maximum output DC voltage of a rectifier which based on a single-diode rectifier is about $V_{br}/2$.

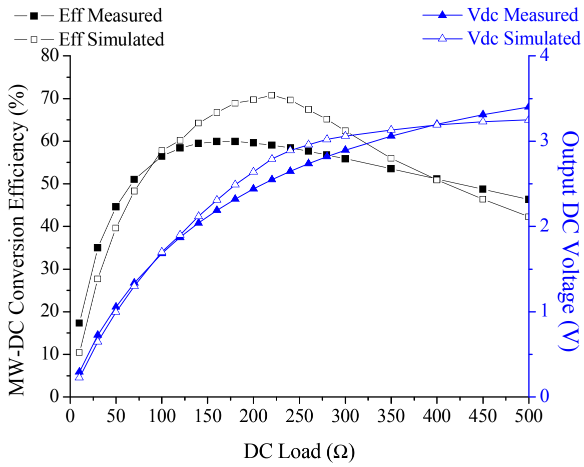

Fig.8. Simulated and measured DC output voltage and MW-DC conversion efficiency at 17 dBm.

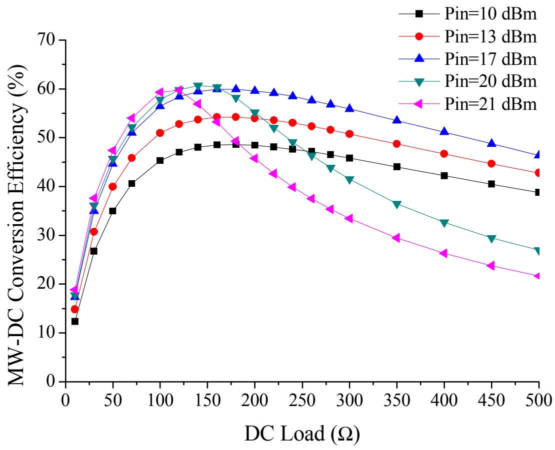

Fig.9. Measured MW-DC conversion efficiency with respect to the load at different input power.

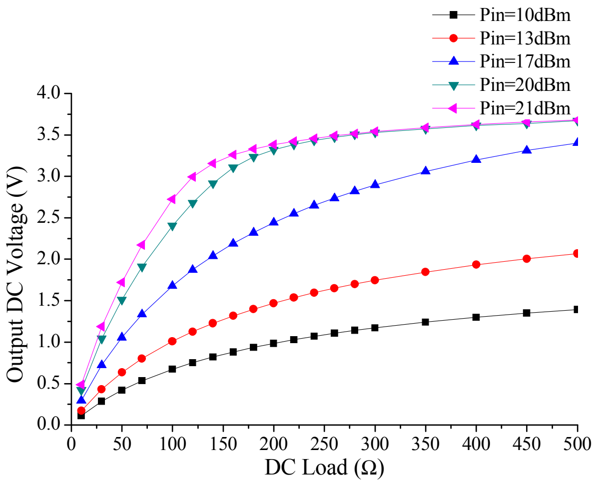

Fig.10. Measured DC output voltage with respect to the load at different input power.

IV. CONCLUSION

In this paper, we investigated a 5.8 GHz microwave rectifier with no lumped capacitors to achieve a high MW-to-DC conversion efficiency. In this design, the conversion efficiency is widely regulated with various lengths of the parallel microstrip transmission line. The maximum conversion efficiency achieves when the length of the short-ended transmission line is $\lambda_g/8$. A microstrip band pass filter and a class-F load are applied to replacing the lumped capacitors in the input and output circuits of a conventional rectifier to enhance the conversion efficiency. This rectifying circuit realized a high conversion efficiency of 61% at 20 dBm input microwave power, and the conversion efficiency is greater than 50% from 17 to 21 dBm input microwave power. This structure can be conveniently applied to the rectifier design at other frequencies.

ACKNOWLEDGMENT

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