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A Broadband Rectifying Circuit with High Efficiency for Microwave Power Transmission

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Abstract—A broadband rectifying circuit with high microwave-direct current (mw-dc) conversion efficiency is designed based on the voltage doubling circuit. The rectifying circuit consists of a broadband match network, a capacitance, a diode, a dc-pass filter formed by three fan-shaped stubs and a resistive load. The measured results show a maximum mw-dc conversion efficiency of 78.3% at 2.45 GHz centre frequency on a 900 Ω load. When the input power is 15 dBm, the bandwidth of efficiencies higher than 50% is about 57% (1.65 GHz–3.05 GHz). The simulated results agree with the measured ones. The rectifying circuit has the characteristics of simple structure and easy integration, which can be applied in the microwave power transmission systems.

1. INTRODUCTION

Microwave power transmission (MPT) has attracted lots of attention in a wide range of applications, such as energy harvesting [1], radio frequency identification (RFID) [2] and wireless sensor networks [3]. As a key component in the MPT systems, rectifying circuits are used to convert the microwave power to dc power. The performance of the rectifying circuit is evaluated by its power conversion efficiency. The diode used for rectification is a nonlinear device, so the power conversion efficiency is sensitive to the frequency and the input power. Published studies have shown that high mw-dc conversion efficiency demands high input power and about 80% efficiency has been obtained at a narrow bandwidth and a fixed input power higher than 20 dBm [4, 5]. However, the manufacture errors may cause the shifts of the operation frequency and the optimized input power, which results in a rapid decrease of the efficiency [6, 7]. Besides, for energy harvesting, rectifying circuits should operate on wide bandwidth.

In [8], rectifying circuits were connected to a broadband antenna array to collect the microwave energy over a broad frequency band from 2 GHz to 18 GHz. However, only a 20% maximum efficiency was reached at 3 GHz with the input power density of 0.1 mW/cm^2. A dual section stepped impedance broadband network was designed to improve the bandwidth of the rectifying circuit [9]. The rectifying circuit covered the band from 800 MHz to 2.5 GHz and the maximum conversion efficiency was 8%. The rectifying circuit reported in [10] obtained a maximum efficiency of 71.9% at 17 dBm input power. A broadband matching circuit was designed by using two radial stubs, and the bandwidth of efficiencies higher than 50% is about 10.5%. A voltage doubling rectifying circuit [11] with 3rd order harmonic rejection radial stub obtained efficiencies of 53% and 75% when the input powers were 10 dBm and 17 dBm, respectively. However, the bandwidth was narrow.

In this paper, a broadband rectifying circuit with high conversion efficiency is presented based on the voltage doubling circuit. Furthermore, the rectifying circuit has the characteristics of simple structure and easy integration, which is suitable for the MPT systems.

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2. RECTIFYING CIRCUIT DESIGN

Figure 1 shows a basic model of the voltage doubling circuit. The packaged Schottky diode HSMS-2862 of Avago Technologies is adopted. There are two diodes in series-parallel connection in a single SOT-23 package. The equivalent circuit parameters of the diode are $V_F = 0.3\,\text{V}$, $R_S = 6\,\Omega$, $C_{j0} = 0.18\,\text{pF}$ and $V_B = 7\,\text{V}$, which are derived from its datasheet [12]. The voltage doubling circuit is simulated and analysed by Agilent Advanced Design System (ADS) [13]. The input impedance Z_{in} of the diode pair versus the frequency is shown in Figure 2. It is observed that the input impedance Z_{in} changes slowly with the frequency in a relatively broad bandwidth and it is close to the standard impedance of $50\,\Omega$. This characteristic is good for designing the impedance matching network with a broad band. The Z_{in} of the diode pair is calculated to be $(64.2 + j9.8)\,\Omega$ at 2.45 GHz when the input power is 15 dBm. The following design of the microwave rectifying circuit is based on this voltage doubling circuit.

The layout of the designed microwave rectifying circuit is shown in Figure 3. It consists of a broadband matching network, a 47 pF capacitor C_1, a HSMS-2862 diode, a dc-pass filter and a resistive load R_L. The capacitor C_1 is part of the basic voltage doubling circuit as shown in Figure 1. It also can be considered as a dc-block, which prevents the dc power from returning back to signal source. To maximize the conversion efficiency, the circuit containing only a packaged diode, a dc-pass filter and a load is optimized with the goal of high efficiency over a broad band. Then the rectifying circuit is matched to $50\,\Omega$ at the input port by designing the broadband match network and the microstrip line L_5. The open stub is used to cancel out the imaginary part of Z_{in}. Microstrip lines L_1, L_2 and L_3 are three section stepped impedance transformers, which help to enhance the bandwidth. A resistive load R_L is attached to the output port for collecting the dc power.

Three fan-shaped stubs with different radii are designed to act as the dc-pass filter to block the fundamental frequency and high harmonics generated by the diode. According to the radii sizes from large to small, the fundamental frequency, the second and the third order harmonics are inhibited respectively. The fourth and higher order harmonics are very low and do not significantly contribute to

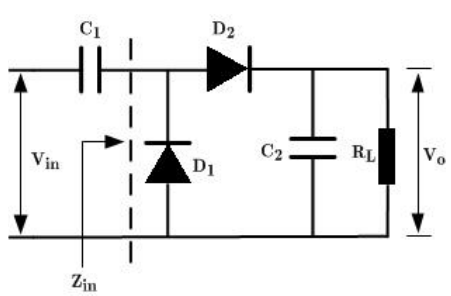

Figure 1. Basic model of the voltage doubling circuit.

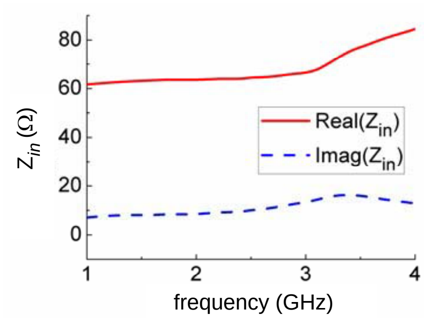

Figure 2. Input impedance Z_{in} vs. frequency simulated by ADS.

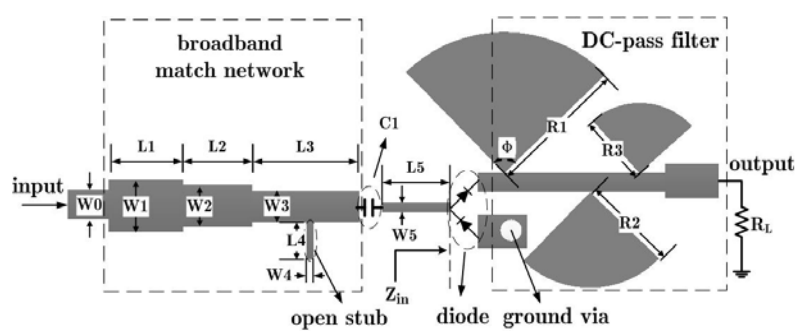

Figure 3. Layout of the designed voltage doubling rectifying circuit.

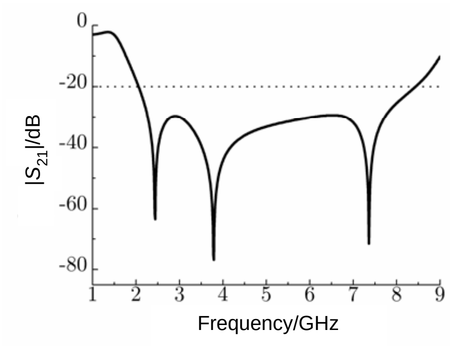

Figure 4. $|S_{21}|$ of the dc-pass filter simulated by ADS.

the power loss. The three fan-shaped stubs have the same angles of 120°. Figure 4 presents the $|S_{21}|$ of the dc-pass filter versus the frequency. It can be found that the $|S_{21}|$ is under −20 dBm within the band from the fundamental frequency 2.45 GHz to the third order harmonic 7.35 GHz. So the fundamental frequency, the second and the third order harmonics are inhibited effectively.

3. SIMULATION AND MEASUREMENT RESULTS

The proposed rectifying circuit is designed on an F4B-2 substrate with the relative dielectric constant ε_r of 2.65, thickness h of 0.8 mm and $\tan\sigma$ of 0.001. The geometric parameters of the rectifying circuit are listed in Table 1. The simulated $|S_{11}|$ of the rectifying circuit is shown in Figure 5. It is well matched at 2.45 GHz with a minimum $|S_{11}|$ of −38.8 dB and the −10 dB bandwidth is 33.2% (from 2.07 GHz to 2.9 GHz).

Table 1. Dimensions of the proposed rectifying circuit.

Geometrical Parameters (mm)						
W_0	W_1	L_1	W_2	L_2	W_3	L_3
2.2	4.2	8.4	3.4	8.9	2.2	12
W_4	L_4	W_5	L_5	R_1	R_2	R_3
1	1.6	0.6	8.5	12.6	8.5	4.6

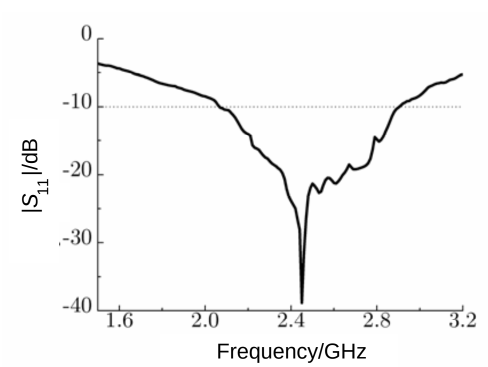

Figure 5. $|S_{11}|$ of the rectifying circuit simulated by ADS.

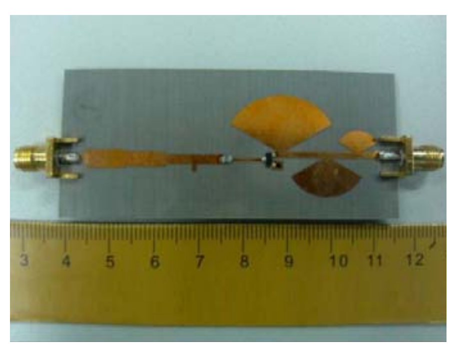

Figure 6. Photograph of the fabricated rectifying circuit.

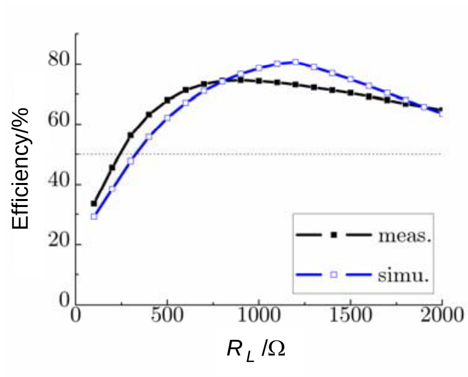

Figure 7. Simulated and measured efficiency vs. load.

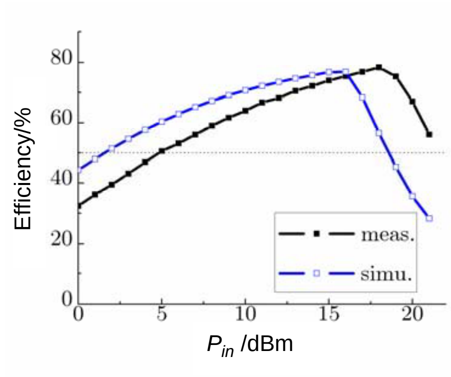

Figure 8. Simulated and measured efficiency vs. input power.

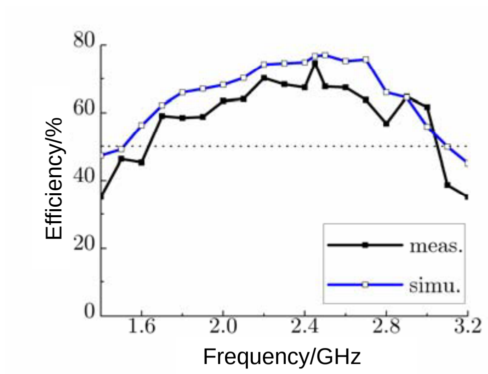

Figure 9. Simulated and measured efficiency vs. frequency.

The rectifying circuit is fabricated and tested. The fabricated rectifying circuit is shown in Figure 6. The mw-dc conversion efficiency of the rectifying circuit is calculated by the following formula,

$$\eta = \frac{V_{DC}^2}{P_{in} R_L} \times 100\% \tag{1}$$

where V_{DC} is the voltage across the resistive load R_L, P_{in} is the input power of the rectifying circuit.

The simulated and measured mw-dc conversion efficiencies versus the load, input power and frequency are displayed in Figures 7–9. The load characteristic for the rectifying circuit is investigated at the centre frequency 2.45 GHz as shown in Figure 7. It can be found that the measured conversion efficiency changes slowly with the load after 700 Ω and the highest efficiency is measured on the load of 900 Ω. In Figure 8, the efficiency increases with the input power and a peak value of 78.3% is obtained on the conditions of 18 dBm input power and 900 Ω load at 2.45 GHz. Then the efficiency gradually decreases. This is because the voltage across the diode exceeds its maximum reverse voltage, which causes a decrease in the diode performance. Figure 9 shows that the efficiency keeps higher than 50% over the frequency band from 1.65 GHz to 3.05 GHz at a lower input power of 15 dBm, which also reveals a broadband performance of the rectifying circuit. Compared with the simulated results, about 10% error can be observed, which could be induced by the manual welding process of the diode and capacitors.

4. CONCLUSION

In this paper, a broadband rectifying circuit with high conversion efficiency has been presented based on the voltage doubling circuit. The measured results have shown that the proposed rectifying circuit has a maximum conversion efficiency of 78.3% at 2.45 GHz centre frequency, and the bandwidth of efficiencies higher than 50% is about 57% (1.65 GHz–3.05 GHz). Furthermore, the rectifying circuit possesses the characteristics of simple structure and easy integration, which can be applied in the MPT systems.

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