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AN INTERMODULATION RECYCLING RECTIFIER FOR MICROWAVE POWER TRANSMISSION AT 2.45 GHz

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Abstract—The microwave to direct current (MW-DC) conversion efficiency of a rectifier drops significantly in a dual-frequency microwave power transmission (MPT) system. The measured data show that the MW-DC efficiency of a rectifier drops from 67% to 53% when the microwave source is switched from a continuous wave to a dual-tone waveform at the same power level. It is mainly due to the intermodulation effects resulted from a nonlinear component, e.g., the diode, in a rectifier. A novel rectifier is designed to improve the MW-DC efficiency by recycling the intermodulation power besides the harmonic power. With the novel configuration, the maximum MW-DC conversion efficiency of 62% can be achieved for a dual-tone waveform input at 17 dBm. It implies that more than one half of the intermodulation power has been recycled to DC power.

1. INTRODUCTION

Studies of Microwave Power Transmission (MPT) systems are the first step to develop Space Solar Power Satellites (SSPS) aimed at solving global energy crisis [1]. As an essential part of a MPT system, microwave rectifiers have been extensively studied since W. Brown's successful demonstrations on energy transmission by beamed microwave [2–4]. Nowadays, kinds of rectifiers are designed for MPT systems. Most rectifiers are presented for single frequency applications at either 2.45 GHz or 5.8 GHz [5–7] besides some research on near field power transmission [8, 9]. Diodes are the most critical components in microwave rectifiers, in which Schottky diodes have been widely applied to converting MW to DC power [10–14].

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Previously microwave rectifiers were usually designed at a low input power less than 100 mW, e.g., 45 mW with the maximum conversion efficiency of 70.69% [15]. Rectenna arrays are finally constructed to convert more microwave power into DC power in a MPT system. An example of rectenna arrays consisting of 16 rectenna elements achieves a conversion efficiency of 74% with a input power of about 2 W [16]. A single rectifier at several watts level is also studied as well with the maximum input power of 2 W and an efficiency around 70% [17]. The harmonic recycling is a technique to convert the power at harmonics, e.g., doubled frequency.

A high power microwave source or a combination of multi-power-source leads to either higher output power or longer transmission distance. A practical way in a MPT system is to apply dual or more independent microwave power sources instead of coherent large power microwave sources, which are very expensive. The MW-DC of a conventional rectifier drops significantly under this situation. It is mainly due to the intermodulation effects. The conventional microwave rectifiers are designed to recycle harmonics which is produced during rectifying of continuous wave. The microwave power at difference frequency may not be recycled. This paper presents a novel rectifier to improve the MW-DC efficiency by introducing another rectifying circuit to recycle the microwave power at difference frequency. A microwave rectifier at 2.45 GHz, which is designed for dual-frequency microwave inputs with 2 MHz intervals, is fabricated and measured as an example. The measured results show that the proposed rectifier has an MW-DC efficiency about 20% higher than its original circuit when microwave sources at dual frequencies are applied.

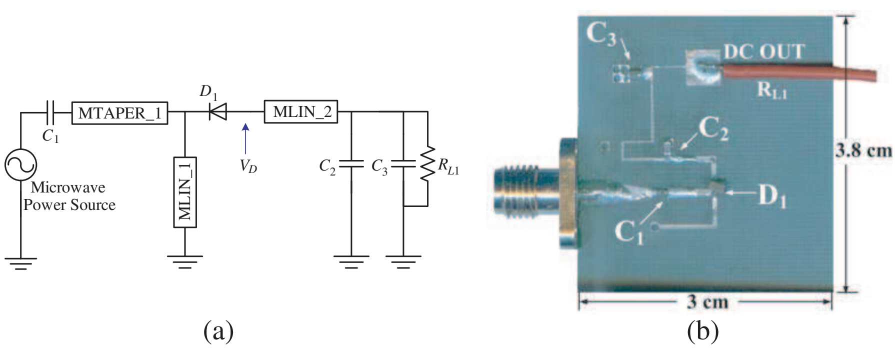


Figure 1. (a) Scheme and (b) photo of a continuous wave rectifier.

2. RECTIFIER ANALYSIS AND DESIGN

2.1. Single Frequency Rectifier

The scheme and photo of a rectifier, which we have designed for continuous microwave, are shown in Figure 1. It is a typical microwave rectifier with series diode. The series capacitor C_1 in Figure 1 is applied to isolate DC from the RF power source. The shunt capacitor C_2 is a low pass filter to pass DC signal, and reflect microwave back to the rectifier. The harmonics generated during rectifying are limited between MTAPER_1 and C_2. Thus, the harmonics are recycled by the diode D_1 to obtain a higher MW-DC efficiency. A microstrip line taper (MTAPER_1) and two microstrip lines (MLIN_1 and MLIN_2) are applied before and after the series diode D_1 to match to the source and load, respectively. This rectifier is designed at 2.45 GHz and optimized with Agilent ADS.

A Schottky diode (HSMS 282C by Avago Inc.) is applied to rectifying microwave into direct current. The basic parameters of the Schottky HSMS 282C diodes are the series resistance $R_s = 6$ ohm, zero-bias junction capacitance $C_{j0} = 0.7$ pF, forward bias turn-on voltage $V_{bi} = 0.65$ V, and reverse break-down voltage $V_B = 15$ V. The rectifier is realized on F4B substrate with dielectric constant of 2.65 and tangent loss of 0.001. The thickness of the substrate is 1 mm. C_1, C_2 and C_3 are all 15 pF. The length of MTAPER_1 is 4.64 mm and the left/right widths are 1.26 mm and 0.70 mm, respectively. The length and width of MLIN_1 and MLIN_2 are 11.16 mm and 0.70 mm, and 7.87 mm and 0.64 mm, respectively. The source impedance remains at 50 ohm, and the load resistance varies from 200 ohm to 1000 ohm to locate the best load for the maximum MW-DC conversion efficiency.

An Agilent E8267C vector signal generator is applied to measuring the MW-DC efficiency of the rectifier. We use an Agilent 34970A data acquisition to measure the output DC voltage. A standard resistor box is used to switch the load from 200 ohm to 1000 ohm. The maximum MW-DC efficiency of the conventional rectifier is 67.0% at 2.45 GHz, when the applied microwave power is 17 dBm and the load is 650 ohm.

2.2. Intermodulation Recycling Rectifier Design

In the case that dual-frequency microwave power is applied to the conventional rectifier in Figure 1, the intermodulation occurs due to the nonlinearity of the diode D_1. Not only harmonics but also difference and sum frequencies are produced. Figure 2 shows the simulated spectrums of the voltage V_D of the diode D_1 in Figure 1, when the applied dual-frequency microwave power are at center

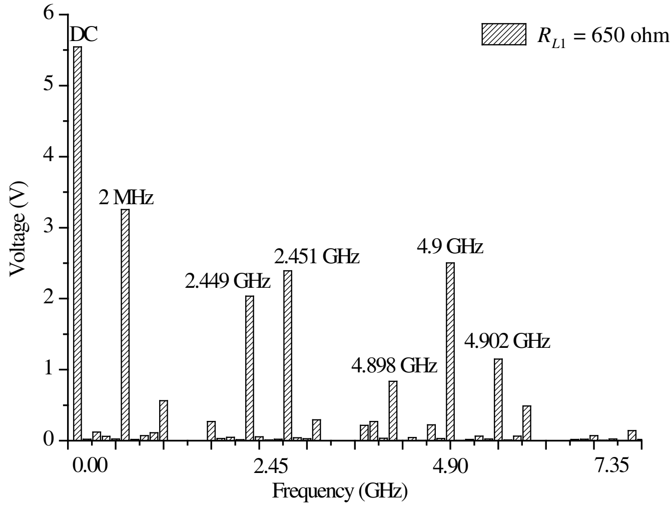


Figure 2. Spectrums of the diode voltage.

Table 1. Main intermodulation and harmonic frequencies of the rectifier with dual-frequency microwave input, i.e., $f_1 = 2449$ MHz and $f_2 = 2451$ MHz.

m	n	$mf_1 + nf_2$	Recycling
-1	1	2 MHz	No
2	0	4898 MHz	Yes
1	1	4900 MHz	Yes
0	2	4902 MHz	Yes

frequency 2.45 GHz with a frequency separation of 2 MHz. The applied microwave power at either frequency, i.e., 2449 MHz and 2451 MHz, is 14 dBm, and the average applied power is 17 dBm. The peak transient power is 20 dBm in this situation. The load resistance R_{L1} is 650 ohm. Figure 2 shows that the difference frequency (2 MHz) and sum frequency (4.9 GHz) besides the harmonics (4888 MHz and 4892 MHz) of the dual-frequency are produced in the rectifying. The difference frequency and the sum frequency are generated due to the intermodulation effects. The main intermodulation and harmonic frequencies are shown in Table 1. The power at the sum frequency is recycled, since the sum frequency is close to the first harmonic at the single-frequency situation. However, the power at difference frequency is too low to be recycled, since the rectifier is designed for 2.45 GHz

and its harmonics, which results in a significant MW-DC efficiency dropping of the rectifier.

A rectifier with broader band at center frequency is welcome in the dual-frequency microwave input situation so as to achieve better rectifying. However, it is still very hard to design a rectifier, which has high conversion efficiency at both the difference and sum frequency, i.e., 2 MHz and 4900 MHz in this example. A conventional low pass filter, of which the cut-off frequency is usually lower than the frequency of the input microwave, behind the diode can only block the input microwave and its harmonics generated by the nonlinear device [13]. The power at difference frequency is applied to the load directly, and is not converted to DC power. The output is measure by Agilent 34970A, which shows that the ratio between AC and DC power is about 1:5. In order to recycle the AC power, we have tried to apply a low pass filter with a cut-off frequency lower than the difference frequency, which blocks the power at difference frequency and reflect it to the rectifier. The recycling effects are poor, since the conversion efficiency of the rectifier is very low at the difference frequency. Thus, some additional circuits have to be applied to dealing with the difference frequency band in a dual-frequency microwave rectifying system.

In our proposed design, another rectifying branch is introduced to recover the power at the difference frequency. The basic idea is to introduce a band-pass filter to separate the difference frequency and rectify it with another circuit. Figure 3(a) shows the schematic of the proposed rectifier, in which a low-pass filter and a band-pass filter are introduced. The low-pass filter is composed of L_1 and C_3. The cut-off frequency of the low-pass filter is much lower than the difference frequency.

$$\frac{1}{2\pi\sqrt{L_1 C_3}} \ll f_{diff} \tag{1}$$

The band-pass filter is composed of L_2 and C_4, of which the center frequency is at the same order of the difference frequency

$$\frac{1}{2\pi\sqrt{L_2 C_4}} \sim f_{diff} \tag{2}$$

The low-pass filter and the band-pass filter present a low and high impedance at the difference frequency, respectively. Thus, the power at the difference frequency is led to the band-pass filter and recycled by D_2 and D_3. When the difference frequency is $f_{diff} = 2$ MHz, we choose $L_1 = 1120\,\mu$H (realized with two $560\,\mu$H inductors), $L_2 = 22$ nH, $C_3 = 15$ pF, and $C_4 = 1\,\mu$F as shown in Figure 3(a). The cut-off frequency of the low-pass filter is 1.23 MHz, and the center frequency of the band-pass filter is 1.07 MHz.

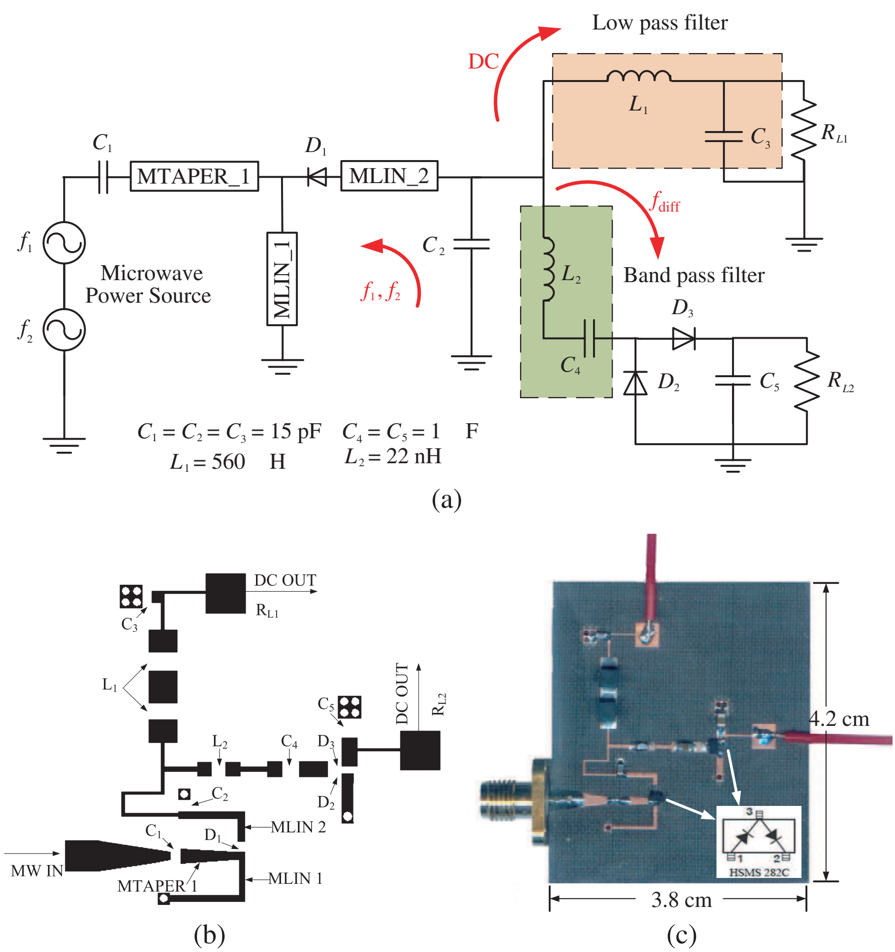


Figure 3. (a) Scheme, (b) layout and (c) photo of the proposed rectifier.

The scheme, layout and photo of the proposed intermodulation recycling rectifier are shown in Figures 3(a), (b), and (c), respectively. The intermodulation recycling rectifier is realized on F4B-2 substrate with a relative dielectric constant $\varepsilon_r = 2.65$ and thickness of 1 mm. Two HSMS 282 Schottky diodes (by Avago Inc.) are applied as the main component of the rectifying at the difference frequency. An HSMS 282C with SOT-323 packaged consists of two series diodes. A voltage doubler, which is composed of D_2, D_3, C_4, and C_5, is applied to rectify the difference frequency power. The new load R_{L2} varies from 200 ohm to 9500 ohm to gain the best rectifying efficiency.

3. EXPERIMENTS AND RESULTS

An Agilent E8267C microwave vector signal generator, which can produce a dual-frequency microwave output, is used as the microwave source. Two standard resistor boxes are applied to the DC load. An Agilent 34970A data acquisition provides two channels to measure the DC voltage of each output of the proposed intermodulation recycling rectifier, respectively. The maximum output power of the signal generator is 20 dBm. Thus, we choose 14 dBm dual-frequency signals in the following experiments so as to not exceed the power limitation of the signal generator.

3.1. Conventional Microwave Rectifier

The MW-DC conversion efficiency of a single-frequency conventional rectifier is defined as

$$\eta_1 = \frac{P_{\mathrm{DC1}}}{P_{\mathrm{MW}}} \times 100\% = \frac{(V_{\mathrm{DC1}})^2}{R_{L1}} \times \frac{1}{P_{\mathrm{MW}}} \times 100\% \tag{3}$$

where P_{DC1}, V_{DC1}, R_{L1}, and P_{MW} are the DC output power, DC output voltage, load resistance, and microwave input power, respectively.

The rectifier shown in Figure 1 is applied as a conventional microwave rectifier to compare its performance between the single- and dual-frequency input. Figure 4 shows the measured MW-DC

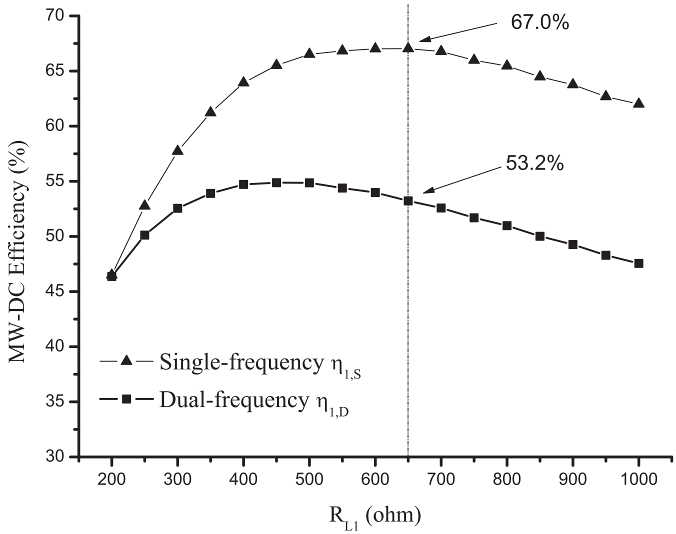


Figure 4. Measured MW-DC efficiency of the conventional rectifier with single- and dual-frequency microwave input at 17 dBm.

conversion efficiency of the single frequency rectifier with single-frequency and dual-frequency input, respectively. At dual-frequency input, the total power keeps at 17 dBm and the frequency separation is 2 MHz with a center frequency at 2.45 GHz. It shows a significant drop of the MW-DC conversion efficiency at the dual-frequency input situation mainly due to the intermodulation effects. When the load resistance R_{L1} is low, the MW-DC conversion efficiency is low. The efficiency difference between them becomes much less. Moreover, it indicates that DC load will magnify voltage of intermodulation signals, so as to effects the forward bias voltage of diode. For the single-frequency rectifier, the highest MW-DC efficiency is 67.0%, which is achieved at 17 dBm microwave input power and with the load resistance $R_{L1} = 650$ ohm. At the same condition, the MW-DC efficiency decreases to 53.2% with dual-frequency microwave input.

3.2. The Proposed Microwave Rectifier

The proposed microwave rectifier in Figure 3 is applied to comparing the performance with the conventional rectifier in Figure 1. At single-frequency input, there is no DC output at R_{L2}, and the MW-DC conversion efficiency is the same as the conventional rectifier.

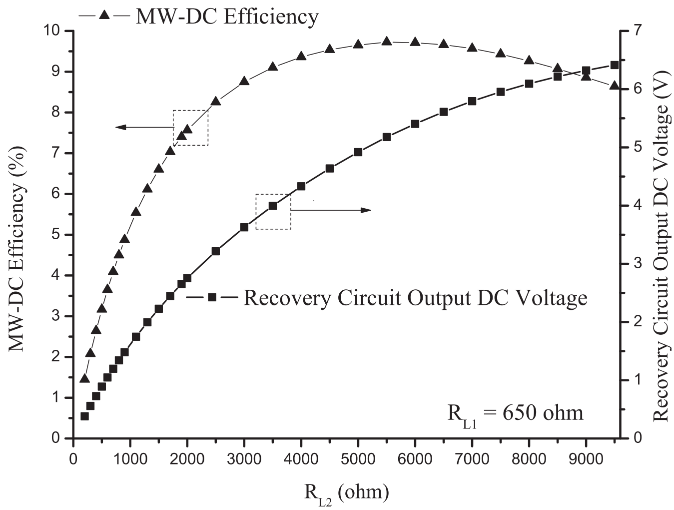
In the case that dual-frequency microwave input is applied, there is a DC output at R_{L2} due to the intermodulation effects. The load resistance of R_{L1} at the original DC output port keeps 650 ohm. When the input microwave P_{MW} is 17 dBm, the DC output voltage of the introduced rectifying circuit, i.e., the diodes D_2 and D_3, is measured with load resistance R_{L2} varying from 200 ohm to 9500 ohm. The measure results are shown in Figure 5(a).

The MW-DC efficiency of the introduced rectifying circuit for the difference frequency is hard to define, since the power at the difference frequency produced by the intermodulation is unknown. Therefore, we define the MW-DC efficiency of the introduced rectifying circuit (the diodes D_2 and D_3) by the microwave input power, as we have done in (3)

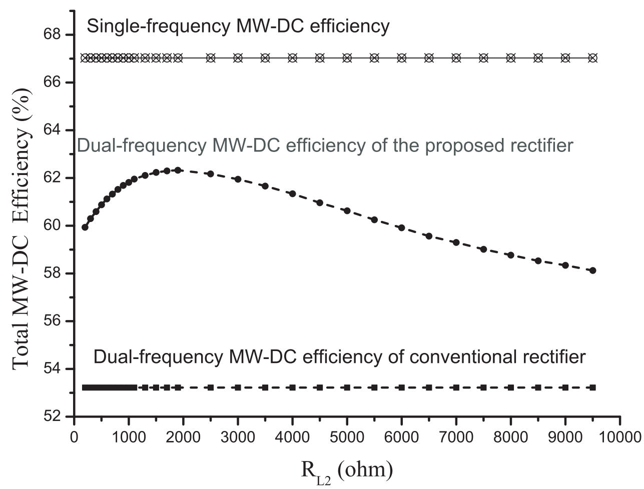
$$\eta_{2,D} = \frac{P_{\mathrm{DC2}}}{P_{\mathrm{MW}}} \times 100\% = \frac{(V_{\mathrm{DC2}})^2}{R_{L2}} \times \frac{1}{P_{\mathrm{MW}}} \times 100\% \tag{4}$$

where P_{DC2}, V_{DC2}, R_{L2}, and P_{MW}, are the DC output power, DC output voltage, load resistance, and input microwave power, respectively. Figure 5(a) shows the MW-DC efficiency with R_{L2} varying from 200 ohm to 9500 ohm. It shows that the MW-DC efficiency is dependent on the load R_{L2} as well, and the maximum efficiency reaches 9.7% at $R_{L2} = 5500$ ohm, which implies that the output voltage affects the conversion efficiency by varying its DC biasing voltage.

Figure 5(b) shows the measured total efficiency of the proposed rectifier compared with the conventional rectifier at both single- and dual-frequency with microwave input at 17 dBm. The total efficiency



(a)



(b)

Figure 5. (a) Measured DC output voltage and MW-DC conversion efficiency for the introduced rectifying circuit. (b) Measured total MW-DC efficiency of the conventional and proposed rectifiers.

is calculated as

$$\eta_{T,D}=\frac{P_{\mathrm{DC1}}+P_{\mathrm{DC2}}}{P_{\mathrm{MW}}}\times 100\%=\left(\frac{(V_{\mathrm{DC1}})^2}{R_{L1}}+\frac{(V_{\mathrm{DC2}})^2}{R_{L2}}\right)\times\frac{1}{P_{\mathrm{MW}}}\times 100\% \quad (5)$$

where P_{DC1}, P_{DC2}, V_{DC1}, and V_{DC2} are the DC output power and voltages, respectively. The maximum total conversion efficiency of 62.3% is achieved at $R_{L2} = 1900\,\mathrm{ohm}$. The load R_{L2} affects not only the DC biasing on diodes D_2 and D_3, but also the input impedance of diodes D_2 and D_3 at difference frequency. The load and the diode D_1 is affected, which leads to a variation of the output DC voltage V_{DC1}. Thus, the MW-DC conversion efficiency is affected. The maximum total MW-DC conversion efficiency does not agree to the condition of the maximum DC power output at R_{L2}.

The proposed intermodulation recycling rectifier is suitable for dual-frequency microwave input and achieves a higher MW-DC conversion efficiency than a conventional one. It improves the MW-DC conversion efficiency from 53.2% to 62.3% at dual-frequency applications with regard to the maximum MW-DC conversion efficiency of 67.0% at single frequency microwave input.

The effects of the proposed rectifier are quantitatively described with the recovery percent. The definition of the recovery percent η_{RP} is

$$\eta_{RP}=\frac{\eta_{T,D}-\eta_{1,D}}{\eta_{1,S}-\eta_{1,D}} \quad (6)$$

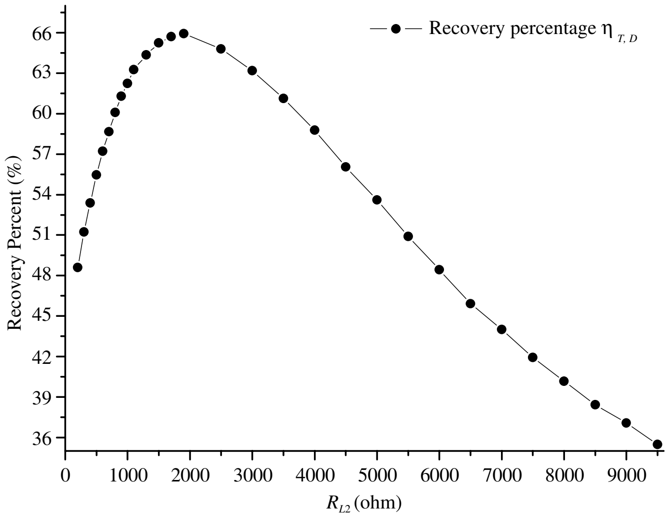


Figure 6. Measured recovery percentage for MW-DC conversion efficiency of the proposed rectifier.

where $\eta_{1,S} = 67.0\%$ and $\eta_{1,D} = 53.2\%$ are the efficiency of the conventional rectifier at 650 ohm load with single- and dual-frequency microwave input, respectively, and $\eta_{T,D}$ is the total MW-DC conversion efficiency of the proposed rectifier.

Figure 6 shows the calculated recovery percentage η_{RP} that describes the improvement of the proposed rectifier. The highest percentage of 65.9% is achieved at the load resistance $R_{L2} = 1900$ ohm, as shown in Figure 6. It shows that the proposed rectifier may recover about two third of the MW-DC conversion efficiency decrease due to the intermodulation at dual-frequency microwave input. The total MW-DC conversion efficiency can be further improved, if the rectifying efficiency at the difference frequency is enhanced.

4. CONCLUSIONS

This paper presents the MW-DC conversion efficiency drops of a conventional microwave rectifier with a dual-frequency microwave input with a small frequency interval, and proposed a novel rectifier with an introduced rectifying circuit branch for the difference frequency due to the intermodulation effects. The measured data show that the dual-frequency microwave input decreases the MW-DC conversion efficiency from 67.0% to 53.2% for a conventional microwave rectifier. The maximum total MW-DC conversion efficiency of 62.3% is achieved with the proposed rectifier, which may recycle the power at difference frequency much better. The recovery percentage of the proposed rectifier is 65.9%, which implies that about two thirds of the MW-DC conversion efficiency drop has been recovered.

In future, we will further expand the bandwidth and enhance the MW-DC conversion efficiency at the difference frequency so as to achieve a better overall performance of the proposed microwave rectifier. Moreover, artificial transmission lines may be applied to make the rectifier more compact [18, 19]. The improved microwave rectifier may be applied to large scale rectenna array of a MPT system with power sources with a possible frequency variation.

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