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A POWER ENHANCED HIGH EFFICIENCY 2.45 GHz RECTIFIER BASED ON DIODE ARRAY

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Abstract—A novel microwave (MW) rectifier based on a diode array is presented in this paper. The diode array composed with sixteen HSMS-282 Schottky diodes is applied to enhance the MW input power. The proposed configuration improves the rectifier power capacitance from 20 dBm level of a single-diode rectifier up to 30 dBm level. The presented design is to use a diode array to replace a single diode without significant modification on the original rectifying circuit. When the input power is between 23 dBm and 33 dBm and the load is at hundred Ohm level, microwave to direct current (MW-DC) conversion efficiency above 60% is realized. The DC output voltage of the rectifier achieves 20.4 V at a load 600 Ohm, when the input MW power is at 30 dBm. The MW-DC conversion efficiency reaches 69.4% in this situation. The maximum power that the rectifier can handle is greater than 33 dBm. The measured temperature of the rectifier shows the power consumption distributed among the diode array evenly.

1. INTRODUCTION

The microwave transmission technology (MPT) has been developed for Space Solar Power System to solve the global energy crisis in 1960s [1, 2], which realizes to transmit the power generated by Solar Power Satellites to the ground with microwave [3]. Microwave rectifier is an essential part of a microwave power transmission (MPT) system, which converts the received MW power into DC power. Recently, a variety of rectifiers has been designed for MPT system [4–12].

Most previous rectifiers based on solid state component were designed at an input power less than 20 dBm mainly due to its low power capacitance. However, in some MPT systems, a rectifier at

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several watt level is convenient and useful. There are some efforts to enhance the power capacitance of a solid state rectifier. Suh and Chang have applied a GaAs FET to a rectifier and achieved a power level around 30 dBm [13]. The high cost of large power GaAs FET and its power capacitance limit the applications. Japanese Naoki Shinohara have built a rectifier with multi-diode to obtain a higher power level [14]. Its power capacitance is limited not only by the number of diodes but also the thermal dissipation problem.

In this paper, we made a diode array to enhance the input microwave power. The diode array consists of 16 Schottky diodes to extend the power capacitance up to 2W at 2.45 GHz. The diode array is designed to have identical impedance of a single diode so as to replace it. Thus, the well-studied single diode rectifying circuit can be referred as good prototype. The MW-DC conversion efficiency drops only less than 10% compared with its original single diode rectifier prototype [4]. Thermal problems have been taken into consideration as well for large power handling. The diode packages are physically separated to improve the heat dissipation.

2. RECTIFIER DESIGN

2.1. Single Diode Rectifier

The schematic diagram and the photo of single diode rectifier we've designed is shown in Fig. 1. According to the large signal model [15], the diode junction consists of a series resistance and a parallel

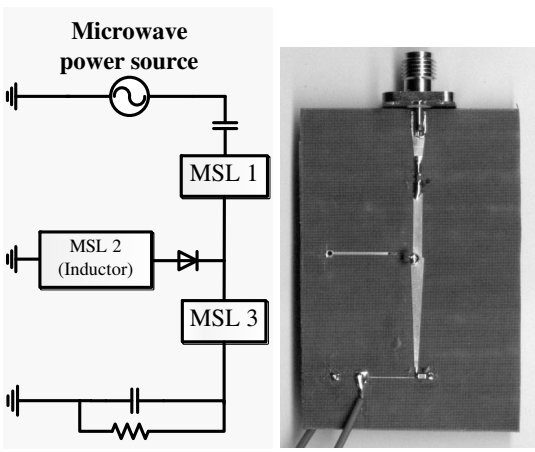
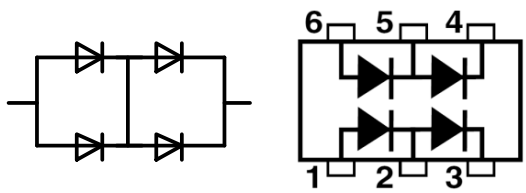


Figure 1. The schematic and photo of a single diode rectifier.

capacitive reactance. We use a series-connected short-ended microstrip line (MSL) to cancel the imaginary part of the diode junction impedance [4]. This technique is applied to the diode array identically. The maximum efficiency of a sing-diode rectifier, in which an HSMS-282 Schottky diode is applied, is 78% at 2.45 GHz while the microwave input power is 20 dBm.

We can series connect two Schottky diodes to extend the voltage and power limitation. At this situation, the diode impedance doubles due to series connection. The input and output matching networks are required to be completely redesigned. Thus, we introduce another two identical diodes to parallel connect to previous diodes and form them into a 2×2 diode array, as shown in Fig. 2(a). The advantage is the total impedance of the diode array is close to a single diode. Then we can use the previous single diode rectifier design as a good prototype.

An HSMS 282P is a special packaged component, which has four diodes to form an array as in Fig. 2(a). We use HSMS 282P to enhance the power capacitance of a single-diode rectifier. Fig. 2(b) shows the internal structure and the package of HSMS 282P.



(a) Structure profile (b) HSMS 282P

Figure 2. A 2×2 Schottky diode array.

It is not valid to use more diodes directly by series and parallel connection due to the parasite effects and the heat dissipation problems. Thus, we will develop a novel method to use more diodes, i.e., applying a 4×4 diode array to replace the diode of the rectifier in Fig. 1, to further extend the power capacitance of a microwave rectifier.

2.2. Rectifier Based on Diode Array

In our design, one Schottky diode HSMS-282P packages four single HSMS 282 diodes. The equivalent parameters of each single diode are shown as follows: the series resistance $R_S = 6\,\Omega$, zero-bias junction capacitor $C_{j0} = 0.7\,\text{pF}$, forward bias turn-on voltage $V_{BI} = 0.65\,\text{V}$, and reverse breakdown voltage $V_B = 15\,\text{V}$. The large signal model of Schottky diode is presented in [15].

In rectifier, the voltage of single diode is:

$$V_d = \begin{cases} -V_{d0} + V_{d1}\left(\cos\omega t - \varphi\right), & \text{if diode is off} \\ V_f, & \text{if diode is on} \end{cases} \tag{1}$$

where V_{d0} and V_{d1} are the DC and the fundamental frequency components of diode junction voltage V_d, respectively, when the diode is under reverse basing. V_f is the forward voltage drop of the diode when the diode is under forward basing. The power loss of diode is mainly due to the diode resistance R_s. The output DC voltage is $V_{OUT} = V_{d,DC}/(1 + R_s/R_{Load})$, $V_{d,DC}$ introduced is the average value of V_d [15]. So if we increase the input microwave power, V_d rises as well. V_d on a single diode is limited by its reverse breakdown voltage V_B.

In our experiment, we used four HSMS 282P to form a larger array as shown in Fig. 3. When we input high microwave power, the thermal dissipation of the diodes becomes a serious problem. In order to avoid overheating of the diodes, we introduce two half-wavelength microstrip lines between them to separate them physically. The half-wavelength microstrip line duplicates the impedance of one port to another. Thus, it not only helps the heat dissipation, but also compensates the parasite effects of the diodes. As shown in Fig. 3, sixteen diodes have been applied to form a 4×4 array.

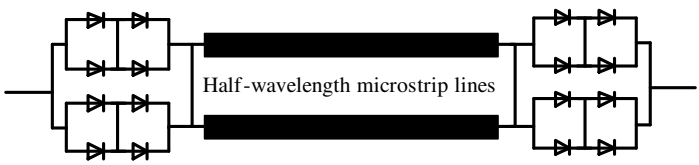


Figure 3. Structure of a 4×4 diode array.

The impedance of the single diode and the diode array is simulated by Agilent ADS. In the 4×4 diode array, the applied power is 16 times (about 12 dB) compared with the single diode rectifier, which keeps the applied microwave power on each diode equals to the single diode condition. The real and imaginary parts of the single diode and the diode array are almost the same as shown in Fig. 4, when the input power of diode array is 12 dB higher than the single diode. It means that a single diode could be replaced with a 4×4 diode array without significant modification on its original rectifying circuit.

The rectifier is simulated and optimized by the Agilent ADS software. The final dimensions are shown in Fig. 5.

Figure 5 shows the layout and the photo of the proposed diode-array rectifier. The presented design applies a diode array to

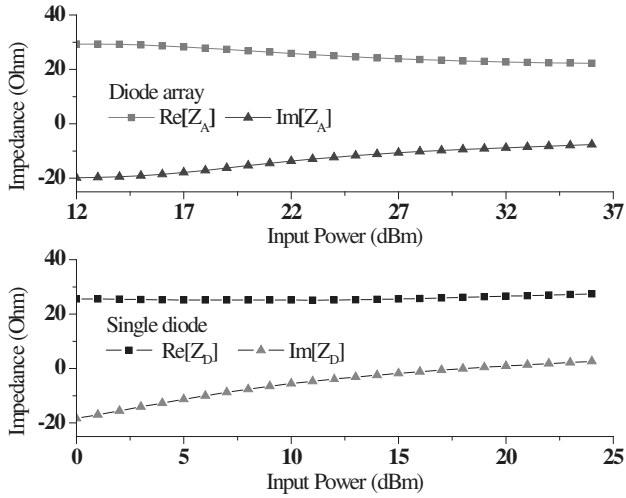


Figure 4. Simulated impedance of the single diode and diode array.

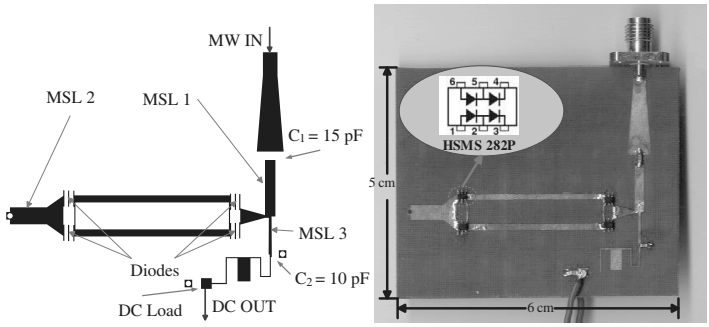


Figure 5. Layout and photo of the proposed rectifier.

replace the single-diode without significant modification on the original rectifying circuit. The rectifying circuit is realized on a F4B-2 substrate with $\varepsilon_r = 2.65$ and thickness of 1 mm. The high impedance microstrip lines on both sides of capacitor C_2 with C_2 itself form a low pass filter to reflect the harmonics produced in rectifying back to the diode array. Microstrip lines before and after the capacitor C_1 are applied to match the impedances of diode array and input interface.

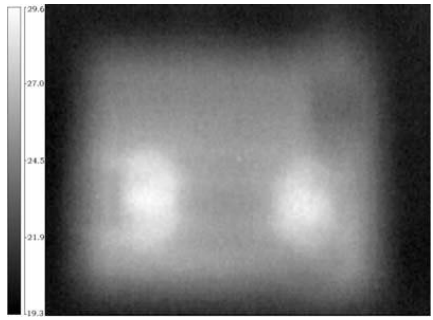
3. EXPERIMENTAL RESULTS

A 2.45 GHz solid state microwave power generator, which has a maximum output power of 100 W, is used as the microwave source. An

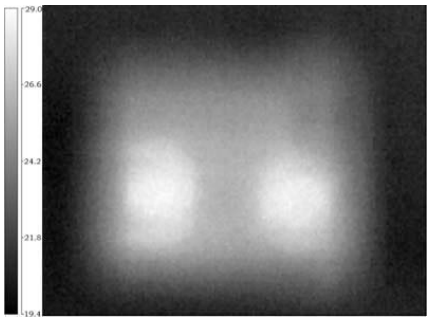
AV2433 dualchannel microwave power meter and a 20 dB bi-directional coupler are applied to monitoring the input microwave power. A resistance box is used as the DC load, and the DC voltage is measured by an Agilent 34970A Data Acquisition/Data Logger. The MW-DC efficiency of the proposed rectifier is measured with the above equipments. A Fluke Ti30 Thermal Imager is applied to monitoring the temperature variation of the rectifier board.

3.1. Thermal Effects

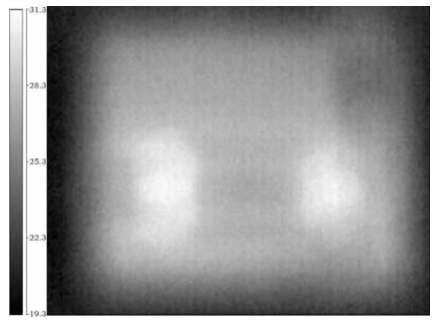
Figures 6(a), (b) and (c) show the temperature distribution of the whole circuit board working under 33 dBm microwave input for 5 minutes, 10 minutes, and 30 minutes, respectively. The room temperature was 19.3 degree centigrade, when the experiments were performed. These photos show the main thermal sources are the Schottky diodes. The highest temperature of the circuit is 31.3 degrees centigrade after working for 30 minutes. The highest temperature



(a) 5 minutes



(b) 10 minutes



(c) 30 minutes

Figure 6. Measured temperature distribution on the rectifier.

appears at those diodes, which are physically separated by two half-wavelength microstrip lines. It shows that the two half-wavelength transmission lines play an important role for better cooling effects. The rectifier worked stably under input microwave power 33 dBm for 150 minutes without significant temperature rise compared with the temperature at 30 minute. Thus, the rectifier may work for hours at input microwave power 33 dBm.

3.2. Conversion Efficiency

The MW-DC conversion efficiency is defined as

$$\eta = \frac{P_{DC}}{P_{MW}} \times 100\% = \frac{(V_{DC})^2}{R_{Load}} \times \frac{1}{P_{MW}} \times 100\% \tag{2}$$

where P_{DC} is the DC output power, V_{DC} is the DC output voltage, R_{Load} is the load and P_{MW} is the input MW power.

The simulated and measured DC output voltage and MW-DC conversion efficiency at 30 dBm input power are shown in Fig. 7(a). The rectangle and triangle marked lines show the efficiency and the output voltage, respectively. This figure shows that the measurements agree well to the simulated results. When maximum MW-DC conversion efficiency achieves 69.4% at 30 dBm microwave input, the experimental DC output voltage achieves 20.4 V at a 600 Ohm load.

Figure 7(b) shows the measured conversion efficiency with respect to different input powers. The highest efficiency of 69.4% achieved at

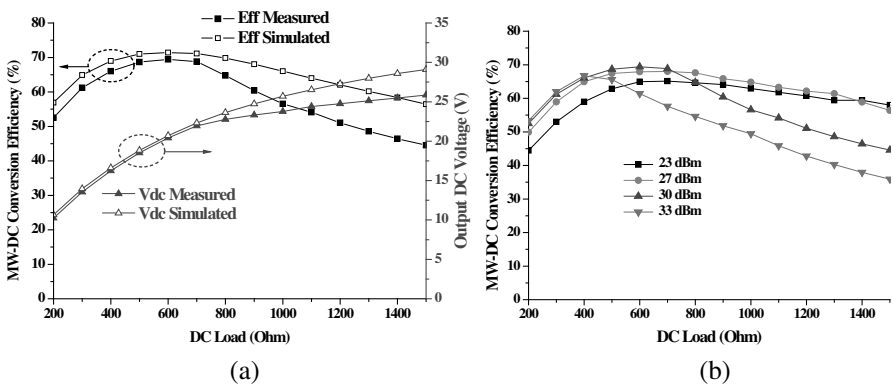


Figure 7. Measured and simulated MW-DC efficiency. (a) Simulated and measured DC output voltage and MW-DC conversion efficiency at 30 dBm. (b) Measured MW-DC conversion efficiency with respect to the load at different input power.

an input power of 30 dBm and DC load at 600 Ohm. The maximum power that the rectifier can handle is 33 dBm; the highest conversion efficiency is 66.8% at 33 dBm microwave input power. When the input MW power increases, the optimal DC load decreases to achieve the best MW-DC conversion efficiency. Moreover, it indicates that DC load and MW-DC efficiency relation curve become sharper as well.

4. CONCLUSION

In this paper, a novel microwave rectifier based on diode array has been developed to extend its power capacitance. We have advanced the concept of a diode array rectifier to solve the heat dissipation problems of a large power microwave rectifier. Moreover, the parasite effects of the diode array have been taken into consideration and minimized by means of introducing series connected half-wavelength microstrip lines. The diode array is to replace the diode in a sing-diode rectifier. Thus, the techniques in conventional rectifier can be well referenced.

We have realized the MW-DC conversion efficiency of 69.4% at 30 dBm input microwave power with the proposed diode array rectifier. It works well at even 33 dBm microwave input power. Both the simulations and experiments confirm that it is an efficient way to enhance the input power and keep high conversion efficiency simultaneously. The diode array can be easily extended to handle higher microwave power level. The drawback of the proposed design is not compact due to the half-wavelength microstrip lines. In further work, we will use artificial transmission lines or defected ground structures [16–18] to replace those half-wavelength microstrip lines so as to finish a compact design. This rectifier will be applied to large scale rectenna array of a microwave power transmission system in future.

ACKNOWLEDGMENT

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