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Compact High-Efficiency Broadband Microwave Rectifier for Free-Space RF Energy Harvesting

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Abstract. This paper presents a compact high-efficiency broadband microwave rectifier for free-space Radio Frequency (RF) energy harvesting. Lumped-element components and voltage-doubling circuits are used to improve output efficiency and power, widen frequency bandwidth, and reduce circuit size. The theoretical model and numerical model of the rectifier circuit are established, and the mechanism of the microwave voltage-doubling rectifier is revealed by using Advanced Design System (ADS) EM simulator. The simulated results exhibit that the rectification efficiency is larger than 60% with the highest efficiency of 84% under the input power of 16 dBm-30 dBm and the frequency of 600 MHz-1600 MHz. Moreover, the overall size is 4cm×2cm, smaller than some recently published literatures, proving the circuit structure's superiority. On this basis, for the lower operating frequency band, the circuit structure is further simplified without reducing bandwidth and efficiency by reducing the number of circuit components, and the overall size is only 2cm×2cm. For validation, two broadband rectifiers fabricated by utilizing FR4 dielectric substrate and Printed Circuit Board (PCB) technology, are implemented and tested using Vector Signal Generator (VSG), DC resistance, and multimeter. The measure results are in good agreement with simulation ones within the measuring range of the equipment.

Keywords. RF energy harvester, voltage-doubling rectifier, high efficiency, broadband

1. Introduction

With the improved environmental protection awareness, the concept of energy conservation and emission reduction has been deeply rooted in people's hearts. Collecting wasted energy is an effective way of energy conservation and emission reduction. Electromagnetic waves energy collection of the environment is an energy collection method, which directly collects RF energy from the environment and converts it into renewable energy without the support of batteries and cables. Compared with traditional energy technology, this technology has the advantages of green, environmental protection, wide application range, and no need for artificial substitution. The key of this technology is to harvest RF energy into DC power available to the

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equipment through a microwave rectifier circuit, which ensures the application of radio equipment and power. Therefore, the study of microwave rectifier circuits is of great significance.

However, it is difficult for most microwave rectifier circuits to ensure high efficiency, broadband and high output power with small size [1-5]. The rectifier circuit based on lumped-parameter elements and microstrip lines can significantly reduce the circuit size, but it is only suitable for point frequency [6, 7], it cannot meet various energy acquisition requirements in space. The microwave rectifier circuit based on impedance compression network [8] demonstrated by Du and others shows the method to improve the relative working bandwidth of the circuit. Still, its rectifier circuit has a large size and high center frequency, which is not suitable for space RF energy collection. Generally, the difficulty of improving the efficiency and bandwidth of microwave rectifier circuits is to study the nonlinearity [9] of the circuit and find a method to balance various parameters.

This paper proposes a voltage-doubling rectifier circuit model based on a CLC structure, the rectifier circuit uses an SMA connector [10] to introduce RF energy, and it uses a CLC structure for matching and voltage-doubling to reduce the circuit size and improve the output bandwidth and power. Furthermore, this paper proposes a simplified rectifier circuit without the CLC structure for the lower operating frequency band, and the overall size is only 2cm×2cm. We reveal the mechanism of microwave voltage-doubling rectification and use the ADS EM simulator to establish these two rectifiers' theoretical and numerical models. We have processed and manufactured these two rectifiers to realize broadband and high-efficiency rectification within the measuring range of the equipment.

2. Circuit Design and Analysis

2.1. Circuit Design

To achieve large power output and increase the output DC voltage to meet the power demand of the load, a voltage-doubling rectifier circuit is designed, as shown in Figure 1. The circuit uses two diodes in series to realize the efficient utilization of electric energy. Its principle is that when the negative half cycle of input power, diode D1 is on, diode D2 is off, and the current will charge capacitor C1 through diode D1. At this time, ideally, the conduction of diode D1 can be regarded as a short circuit, so the voltage of capacitor C1 can be charged to V_m. In the positive half cycle of the input power, the diode D1 will be cut off, and the diode D2 will be turned on. The input power charges the capacitor C2 through C1 and D2. Due to the voltage discharged by the capacitor C1 is V_m and the RF power source's voltage is V_m, the actual voltage reached by the final charging of the capacitor C2 is $2V_m$, so the voltage-doubling rectification is realized. It can be seen from this process that the voltage-doubling rectifier can effectively use the energy of the positive half cycle and the negative half cycle of input power. In fact, these two diodes are encapsulated in SOT-23 or SOT-323, the integration of the two diodes is realized.

Based on this voltage-doubling rectifier circuit, to further improve the rectification efficiency and working bandwidth, an LC matched filter network of the front end of capacitor C1 is added, as shown in Figure 2. LC network and capacitor C1 form a compact CLC structure, which improves the working bandwidth and rectification efficiency without increasing the circuit size.

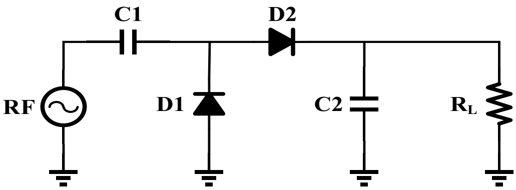


Figure 1. Voltage-doubling rectifier circuit.

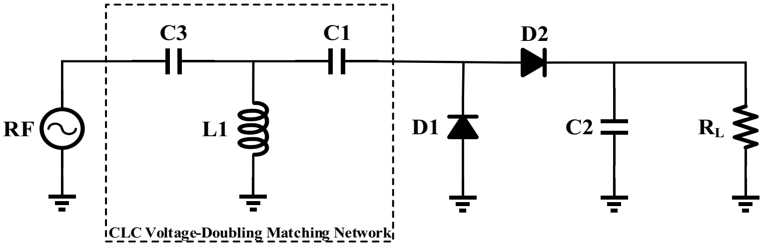


Figure 2. CLC voltage-doubling rectifier circuit.

2.2. Model and Simulation

The schematic diagram and layout of the circuit are established by using the ADS EM simulator. Based on the calculation method of transmission line theory, the schematic diagram is simulated, and the simulation model of the rectifier circuit is established. Based on the numerical 2.5-dimensional simulation method, the numerical model of the rectifier circuit is established. After parameter optimization and adjustment, the schematic model is shown in Figure 3. On this basis, the layout simulation is shown in Figure 4, and the simulated results are shown in Figure 5. This circuit works in the frequency band of 600 MHz-1600 MHz, when the input power is 16 dBm-30 dBm, the rectification efficiency is more than 60%, the maximum is 84.2%, the results are well.

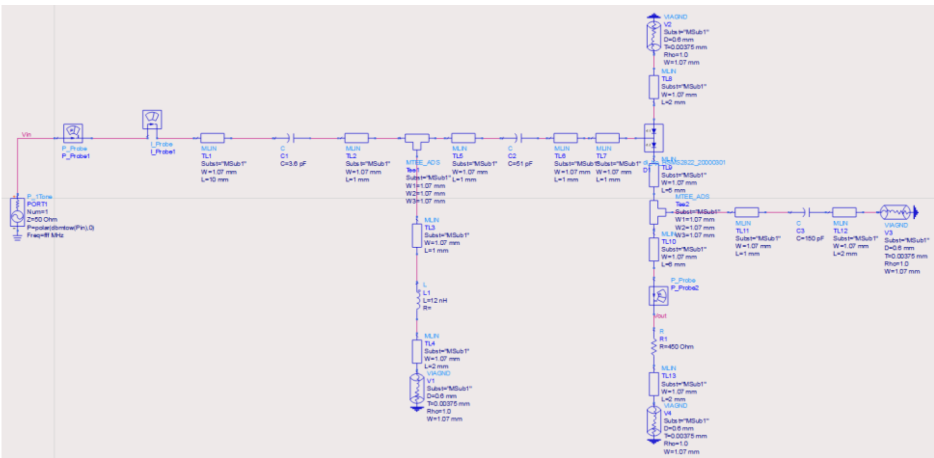


Figure 3. Schematic model.

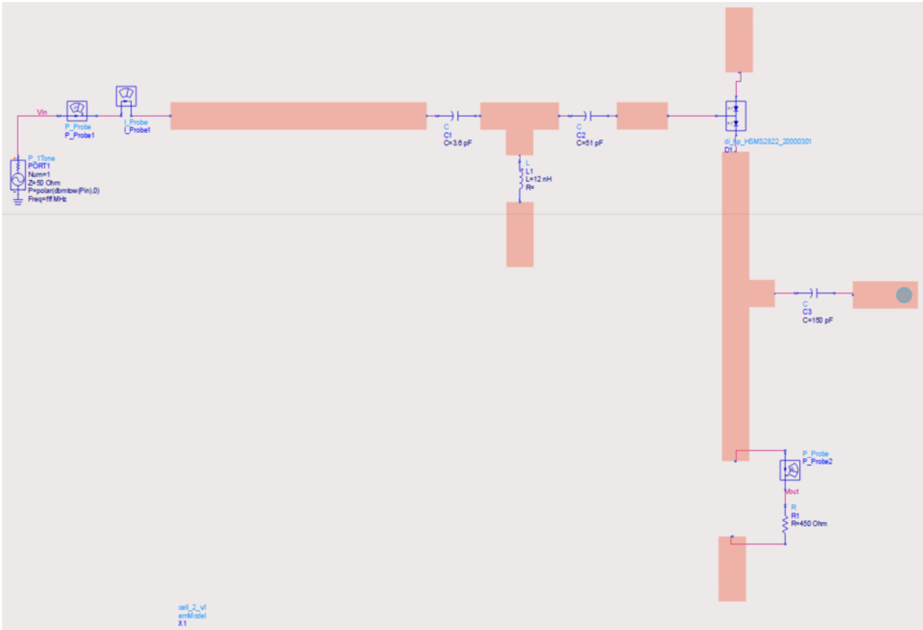


Figure 4. Layout model.

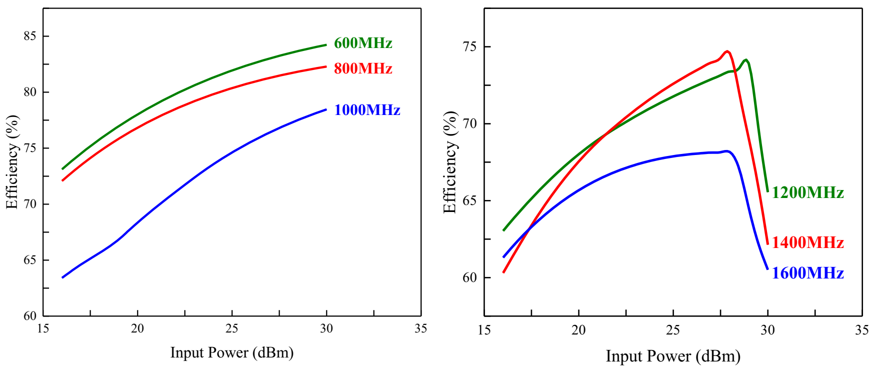


Figure 5. Simulation results.

2.3. Simplified Rectifier Circuit

On this basis, for the lower frequency energy harvester, this paper improves the circuit structure by reducing the number of circuit elements which further reduces the circuit size. In the range of 100 MHz-1100 MHz, without adding microstrip lines, we find that removing the LC matched filter structure has little effect on the performance of the rectifier circuit. Therefore, a simplified rectifier circuit model is designed, and the schematic diagram and layout are shown in Figures 6 and 7, respectively. The simulated results are shown in Figure 8, when the input power is 15 dBm-30 dBm and the frequency is in the range of 100 MHz-1100 MHz, the rectification efficiency is larger than 62%, the maximum is 79.8%.

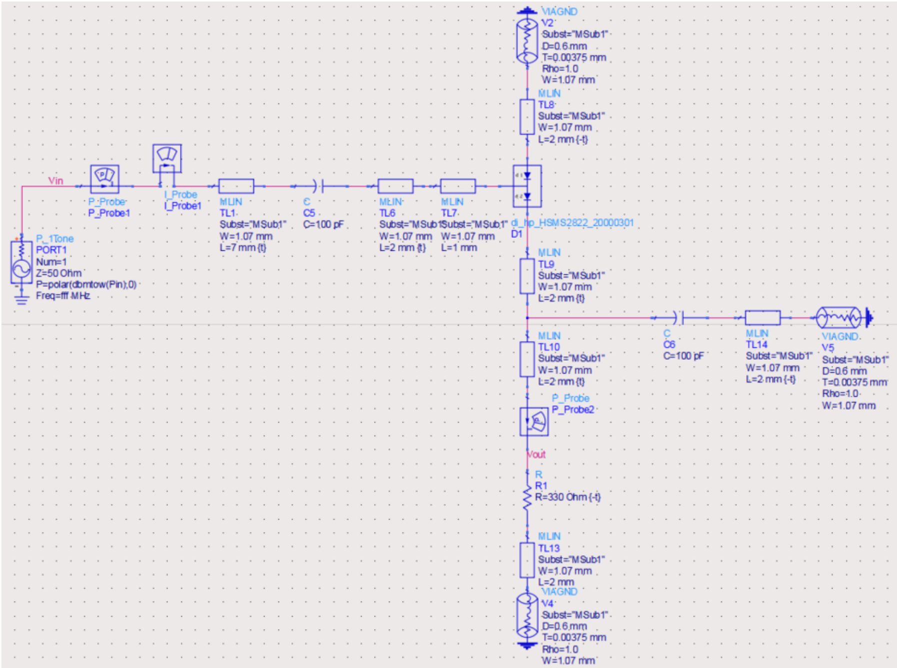


Figure 6. Simplified schematic model.

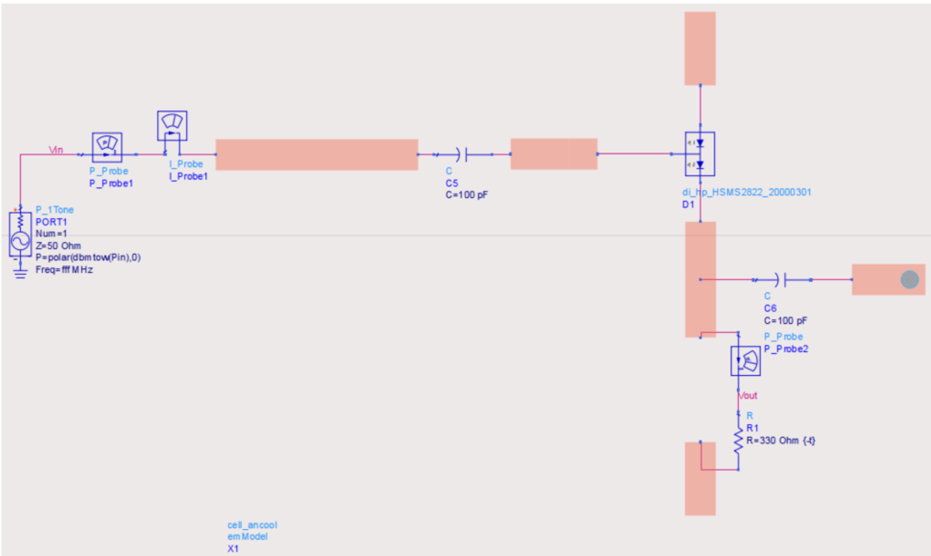


Figure 7. Simplified layout model.

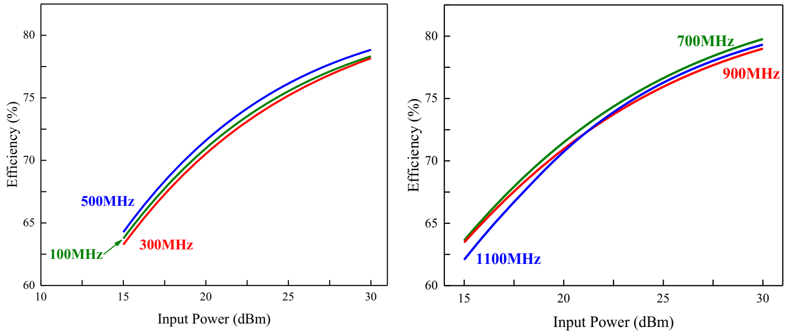
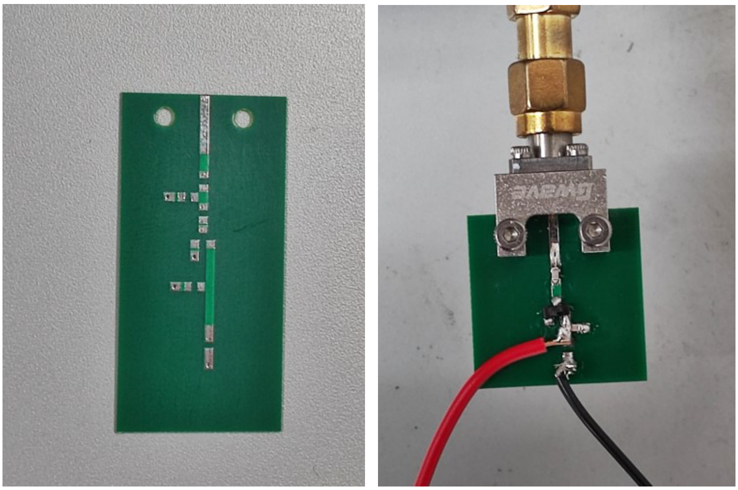


Figure 8. Simulation results of the simplified circuit.

3. Results

In this paper, 0.6 mm FR4 is used as the substrate, and the PCB is used to process the circuits, as shown in Figure 9. The Agilent E4438C microwave power source used in the test, its range is -10 dBm-22 dBm, 250 kHz-6 GHz. Therefore, the experiment can only supply the power to 22dBm to verify the accuracy of the simulation. The experimental device is shown in Figure 10. We use a multimeter and DC resistance to measure DC output power. The measurement results of the CLC rectifier circuit and simplified circuit are shown in Figures 11 and 12, respectively, and we compare them with the simulated results. The results show that there is little difference between them.



(a) (b)

Figure 9. (a): Rectifier circuit board; (b): simplified rectifier circuit board.

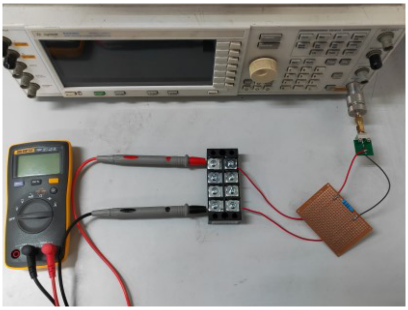


Figure 10. Experimental device.

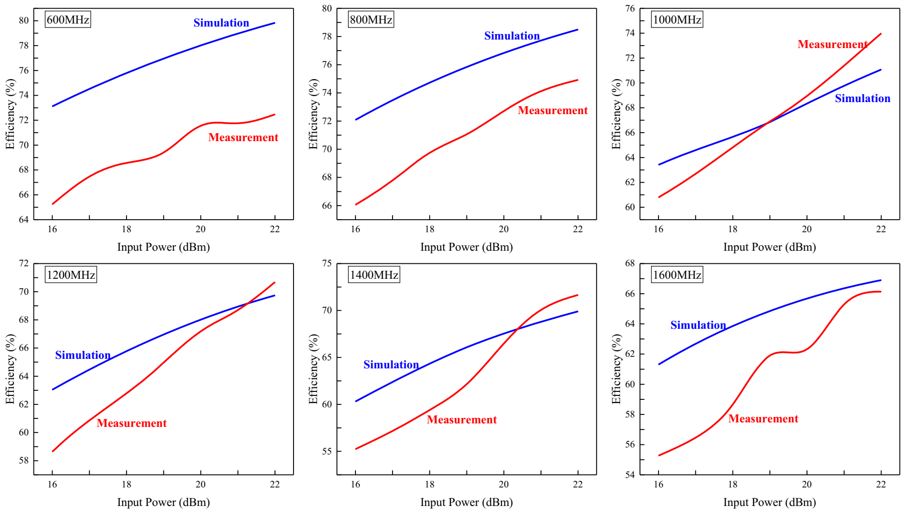


Figure 11. Comparison between simulation results and experimental results for the circuit.

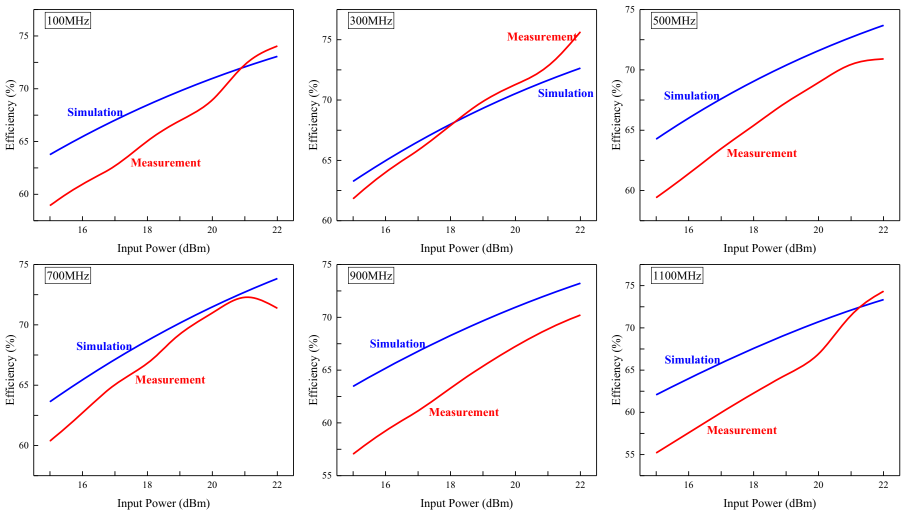


Figure 12. Comparison between simulation results and experimental results for the simplified circuit.

4. Conclusion

This paper proposes a microwave voltage-doubling rectifier circuit model based on CLC structure and a simplified low-frequency voltage-doubling rectifier circuit model. Simulation and experiments show that these rectifier circuits are conducive to improving the efficiency and power of free-space RF energy harvesters, expanding the bandwidth, and reducing the size.

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