

A Comparison Study of Rectifier Designs for 2.45 GHz EM Energy Harvesting

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Abstract

Energy harvesting is a rapidly growing area in many scientific and engineering-related fields due to the demand for many applications. This paper focuses on the design and simulation of the voltage doubler rectifier circuit at 2.45 GHz operating frequency. The design of a rectifier is optimized based on the use of Schottky diode HSMS 286 B due to its low forward voltage at this frequency. 2 stages of the Schottky diode voltage doublers circuit are designed and simulated in this paper. The shunt capacitor and optimal load resistance are also introduced in the course to reduce signal loss. A multi-stage rectifier is used to produce maximum power conversion from AC to DC. The simulated results present that the maximum output voltage of 6.651 V with an input power of 25 dBm is produced, which presents a maximum power conversion efficiency of 73.13%, which applicable in small device applications.

Keywords

Energy Harvesting, Rectifier, Schottky Diode, Power Conversion Efficiency

1. Introduction

The ever-changing mix and growth of wireless devices that are accessing mobile networks worldwide are one of the primary contributors to global mobile traffic growth. The buildout of mobile devices has led to a multiply increase in mobile data traffic that shows no sign of being subsided. Globally, the total number of Internet users is projected to grow from 3.9 billion in 2018 to 5.3 billion by 2023 [1]. This is equivalent to almost 70 percent of the global population that will have mobile connectivity by 2023. Consequently, the emerging of Wi-Fi spectrum band (2.4 GHz and 5 GHz) to be used in 2023 by world population led to present of abundance of frequency signal in the surrounding [2]. The abundance

of this frequency signal has significant potential to be harvested then convert into electrical energy for many applications.

The concept of energy harvesting has been agreed upon as a technique for collecting energy from the external environment using various methods such as thermoelectric, vibration, solar energy conversion, and pressure gradients. This technique promises excellent scope for the replacement of small batteries in low power electrical devices and systems. The ambient EM energy has the advantage of availability all day and night, unlike solar energy, which is available only when sunlight is present [3]. In comparison with other energy, electromagnetic energy is not limited by space or time. The radio wave is available both indoors and outdoors, in rural and urban areas, throughout the day. Despite its low power density in the environment, an intentional source can be added for more efficient power transmission. A boosting unit or circuit can be built to suit the requirements of the loan application. This feature promotes research to realize many harvester technologies through applications such as RFID and the Internet of Things (IoT) [4].

Energy harvesting from Electromagnetic (EM) signals is obtained from the integrating of a receiving antenna and a rectifying circuit that converts EM to DC signals. Generally, energy harvesting consists of a microwave antenna, a rectifier, and a matching circuit [5]. A storage device could introduce to efficiently utilize the DC power to charge the battery depending on applications. The EM signals received by the antenna are transformed into DC signals by diode-based rectifying circuits. The impedance matching circuit between the antenna and rectifier is used to obtain an optimum power transfer [6].

Due to a low power threshold, the efficiency of the rectifier has reasonable efficiency. Nevertheless, the output voltage of the rectifier is not stable and consists of ripples. As to address this issue, a low pass filter is introduced at the output of the circuit to produce a more stable and smooth DC voltage. A rectifier load could be a resistor, capacitor, inductor, or a combination of all these. In this work design, a resistive load is used.

2. The Design of Rectifier Circuit

Initially, the first step in rectifying circuit design is to create a single-stage rectifier. As to select the best performance, the circuit was redesigned by considering three different diode models (HSMS 2820, HSMS 2850, and HSMS 286 B). According to [7], the selection of diodes should have a speedy switching time and the lowest possible turn-on voltage. Hence, Schottky diodes offer an ideal advantage in terms of speed. It does not rely on electrons or holes recombination when they enter the opposite regions, usually occurring in the conventional diode. Besides, the Schottky diode has better current density, resulting in low forward voltage drops, which means reducing energy losses, thus making them the most efficient choice. A matching network is required to allow a maximum power transfer between the antenna and the rectifier circuit [5]. In this work, the matching network is designed at 50 Ω .

Voltage Doubler Rectifier

One of the significant influences on the energy harvesting circuit's output voltage is the number of rectifier stages. In this work, Cockcroft-Walton rectifier topologies are employed to improve the output voltage. The previous work in [8] presented that the voltage doubler rectifier performs better than the series diode half rectifier. The maximum conversion efficiency is 70.06% for voltage doubler with 330 Ω and 40.17% with 220 Ω load resistance simultaneously. By using Agilent ADS, we simulate the effect of the load impedance with an input power of 20 to 25 dBm and the load value of 330 Ω .

Figure 1 shows that the schematic diagram consists of 50 Ω , input termination, matching circuit, voltage doubler circuit, and load resistance. The circuit simulation operates on a 1.5 mm, thick FR-4 substrate with dielectric constant, $E_r = 4.34$, and loss tangent of 0.0035. We set 25 dBm input power with the input impedance of 50 Ω by considering the 2.45 GHz at the input termination. The shunt capacitor and optimal load resistance are also introduced in the circuit to reduce the signal loss. **Table 1** tabulates all the components used in the rectifier circuit.

The HSMS286 B diode model is created in the schematic workspace based on manufacture properties which is shown in **Table 2**. The matching circuit is applied to the circuit to maximize the rectified output voltage. We used the smith chart available in the ADS tool to obtain the ideal impedance matching for the circuit operates at 2.45 GHz.

Table 1. List of components used in the rectifier circuit topology.

Name of the component	Symbol	Value
Diodes	$D_1 - D_2$	HSMS 286 B
Capacitor	C_1	10 pF
Load resistance	R_L	330 Ω
Shunt capacitor	C_S	100 pF

Table 2. HSMS286 B Schottky diode model parameters [9].

Parameter	Units	Value
B_V	V	7.0
C_j	pF	0.18
E_G	eV	0.69
I_{BV}	A	$1E^{-5}$
I_S	A	$5E^{-8}$
N		1.08
R_s	Ω	6.0
P_B (VJ)	V	0.65
P_T (XTI)		2
M		0.5

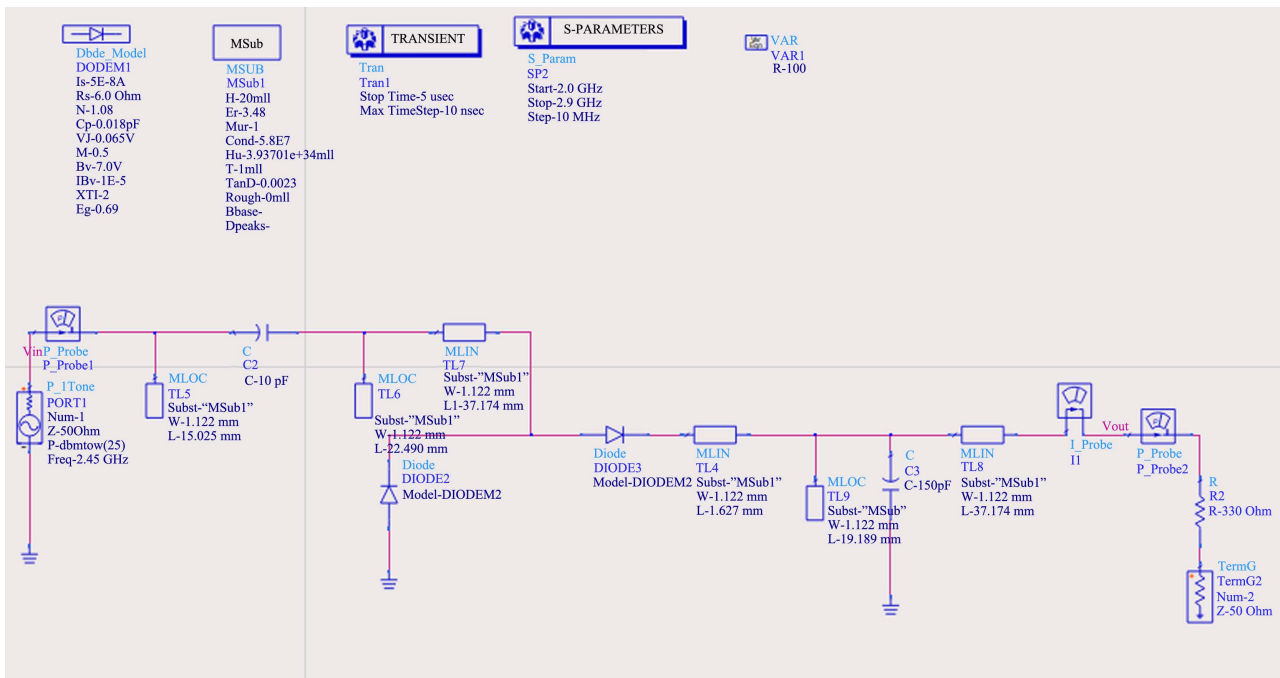


Figure 1. ADS schematic diagram of the voltage doubler rectifier circuit.

3. Result and Analysis

The rectifier circuit is simulated in ADS, and the result of the output voltage and power conversion efficiency were optimized analyzed.

3.1. Selection of Diode

The three most popular Schottky diodes were investigated using 20 and 25 dBm input power level in this work. Figure 2 and Figure 3 represent Schottky Diodes HSMS 2820, HSMS 2850, and HSMS 286 B at 20 dBm and 25 dBm, respectively. HSMS 286 B is selected due to its low forward voltage and ideally designed and optimized at 2.45 GHz. Overall, all the diodes can be used and HSMS-286 B fit the best selection used in the design of rectifier. The higher output voltage of 4.459 V and 6.366 V for 20 dBm and 25 dBm are obtained for the HSMS 286 B Schottky diode. The results are tabulated in Table 3.

3.2. Design and Simulation of Voltage Multiplier

Figure 4 shows a design of a 2-stage Cockcroft-Walton voltage multiplier circuit integrated with a matching circuit to maximize the performance of power conversion from EM to DC. 2 stages voltage multiplier selected in this work resulting in high output voltage and optimum return loss at the operating frequency.

Figure 5 presents the output voltages using different stages of the multiplier. The single-stage shows an excellent result. When the stages are added into two, the result presents better. The result was then confirmed by simulating the results shown in Figure 6, where the minimum return loss is obtained at the desired frequency. However, as the stages are increased from 3 until 8, the output

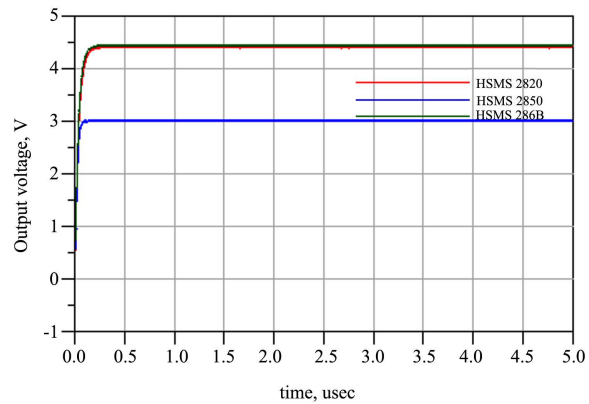


Figure 2. The output voltage of various diodes with 20 dBm input power.

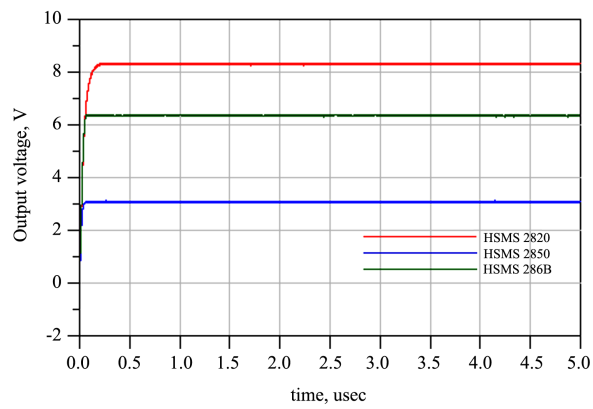


Figure 3. The output voltage of various diodes with 25 dBm input power.

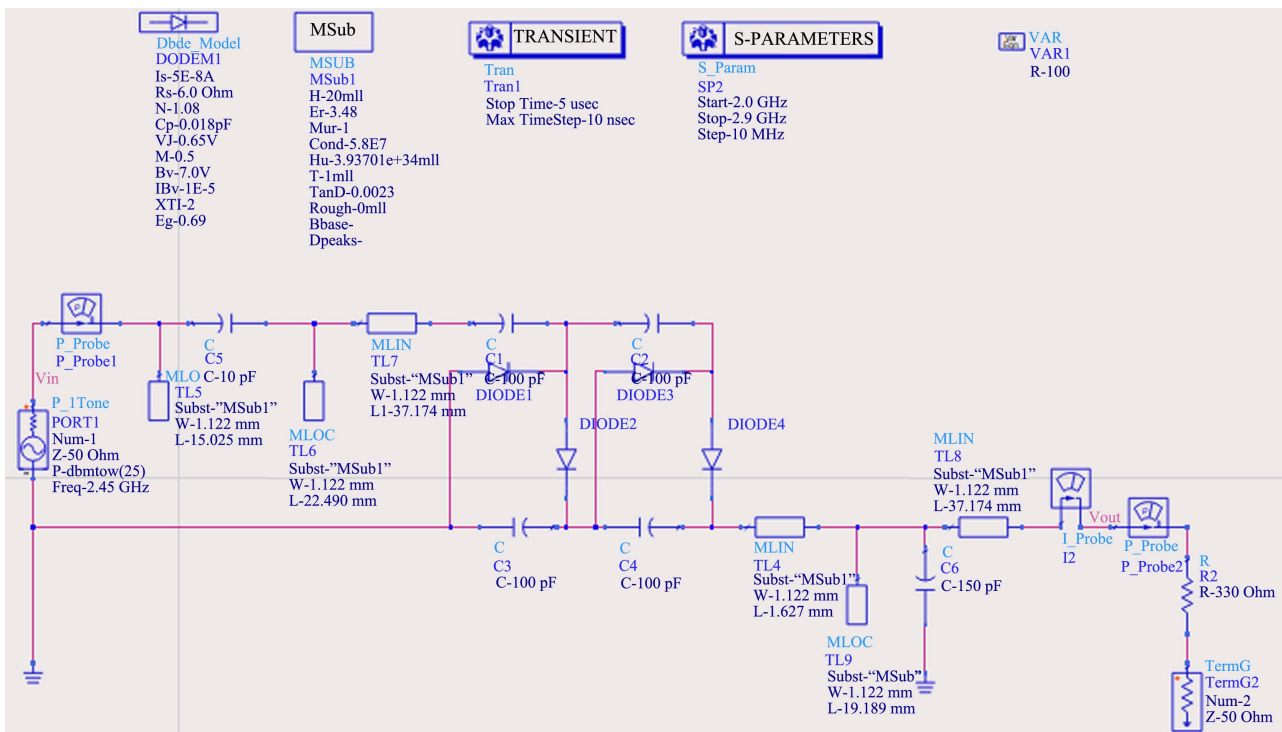


Figure 4. 2-stages rectifying circuit.

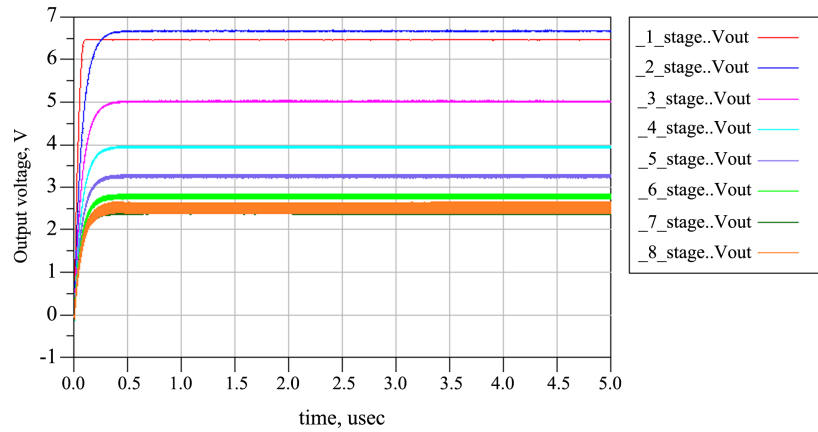


Figure 5. Output voltage at different stages with 25 dBm input power.

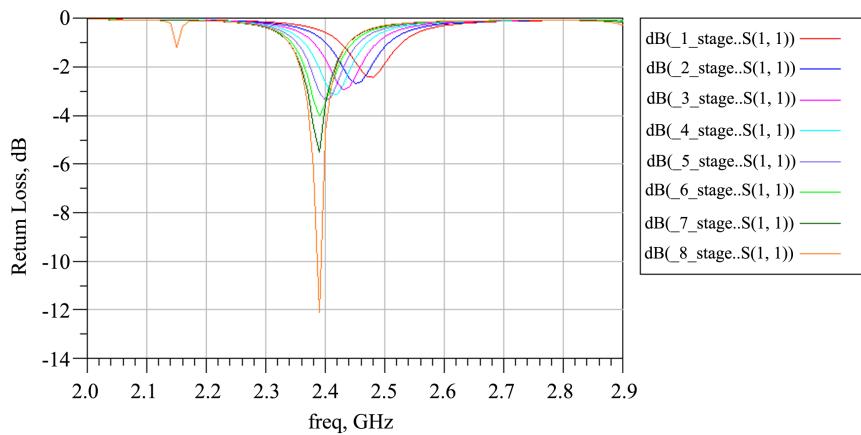


Figure 6. The simulated return loss of the rectifier at different stages.

Table 3. Performance of Schottky diodes at different input power.

Input power (dBm)	Output voltage (V)		
	HSMS 2820	HSMS 2850	HSMS 286 B
20 dBm	4.433	3.018	4.459
25 dBm	8.366	3.095	6.366

voltage is decreased, and the return loss increases. The reason is due to the voltage drop by the diodes at every stage.

Figure 6 shows the return loss obtained by each stage. The two stages rectifier is an ideal design to be used in this work for better performance of energy harvesting with 100 MHz bandwidth at the ISM band. The small return loss extracting more energy is to be converted as DC output. The result is tabulated in **Table 4**.

3.3. Power Conversion Efficiency

The power conversion efficiency for the rectifier can be calculated using Equation (1) as follows.

Table 4. Performance of different stages of voltage multiplier.

Stages	Voltage Output, V	Return loss (S11), dB
1	6.467	-2.413
2	6.651	-2.682
3	5.000	-2.933
4	3.972	-3.122
5	3.273	-3.371
6	2.828	-4.015
7	2.481	-5.575
8	2.470	-12.095

Table 5. The comparison between the proposed rectifier and the existing works for the ISM band.

Author	Year	Input power	Output voltage (V)	Power conversion efficiency (%)
[10]	2015	13 dBm	NA	>50%
[7]	2017	-5 dBm	2.13 V	86%
[11]	2019	NA	2.91 V	53.56%
This study	2020	25 dBm	6.651 V	70.13%

$$\eta = (P_{DC}/P_{in}) \times 100\% = \left((V^2 DC/R_L) \times P_{in} \right) \times 100\% \quad (1)$$

where P_{in} is the input power, R_L is the load resistance, and V_{DC} is the output DC voltage. We can study the simulated efficiency and DC output voltage simultaneously concerning the input power for a 330 Ω load resistance. The value of conversion efficiency at two stages rectifier is 70.13% at 25 dBm input power. This might be due to the input voltage being higher than the diode threshold voltage, 0.7 V.

The comparison on the performance metrics between the proposed rectifying circuit and other related circuit designs are shown in **Table 5**. It can be seen that the proposed work offers highest output voltage and higher conversion efficiency in comparison to all the other works. As in [10], the system needs 13 dBm input power to achieve a higher power conversion and the result for output voltage is not available. It is unclear what the results would be for the work in [11] as the input power range is not given. However, even though the input power level in [7] is lower than the proposed work, and the maximum conversion efficiency reached at 86%, the output voltage obtained is lower in comparison to the proposed design.

4. Conclusion

In this work, two stages of voltage multipliers associated with matching circuits have been designed using the ADS simulator. The simulation results have shown that the microwave rectifying circuit can rectify EM to multiple DC voltage by

employed Schottky diode HSMS 286 B. The performance of power efficiency conversion could be demonstrated if further research is done to figure out the effectiveness of this design throughout the measurement.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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