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Comparing Different Rectifier Circuits Using Different Impedance Matching Methods for RF energy Harvesting

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Abstract:

This study compares rectifier circuits of many kinds that harvest radio frequency energy by utilizing the TL-match approach with those that use the LC-match method. The main purpose of doing the comparison between different types of rectifier circuits under the same frequency of 2.4 GHz is to ease the way for researchers to consider choosing a suitable rectifier circuit from these comparison results that match their application demands. Six different types of rectifier circuits are designed and simulated in this work including: full-wave, half-wave, voltage doubler, Villard charge pump, Graetz charge pump, and Dickson charge pump. These different types of rectifier circuits consist of a standard substrate material with different εr, an HSMS2820 diode, and a 3 kΩ resistance load. Initially, using a single-stage TL-match technique at 2.4 GHz, the rectifiers are constructed on a FR-4 substrate with a thickness of 1.6 mm and a dielectric constant of 4.3. The resistance load was 1 kΩ, the input power range under test was 0 dBm to 30 dBm, and the HSMS2820 diode was employed. The results showed that the Graetz charge pump has the greatest recorded output voltage of about 27 V at 1 kΩ and the best recorded efficiency of 73% at 1 kΩ. Advanced Design System (ADS) is used to design and simulate the rectifier circuits.

Keywords: *RF Energy Harvesting (RFEH), Rectifier Circuits, Impedance Matching Network (IMN), Advanced Design System (ADS).*

1 Introduction

A rectifier is an electronic device that converts an alternating current into a direct current by using one or more P-N junction diodes. In this paper, six different designs of rectifier circuits at 2.4 GHz with TL-match circuit are half-wave, full-wave, voltage doubler; Villard charge pump, Graetz charge pump, and Dickson charge pump were designed and simulated. An antenna for receiving radio frequency signals, a matching network for adjusting the antenna and rectifier's impedance, an AC to DC converter, a DC pass filter to prevent higher-order harmonics, and a load for measuring the rectenna's final output make up a rectenna system. Impedance Matching Network (IMN) uses fewer components in order to minimize losses.

An efficient rectifier was designed using methods including choosing an ideal load resistance value and incorporating a resistance compression network within the rectifier (Trikolikar A. and Lahudkar S., 2020). Different rectifier designs exist, including single- and dual-frequency operation. A transmission line rectifier using an HSMS2850 diode and operating at 0.9 GHz was proposed by (Muhammad S et al., 2020). At 2 dBm input power, the rectifier achieved a conversion efficiency of 50.2%. High-efficiency more than (70%) single-frequency rectifiers were proposed by (Xiao et al., 2019) and (Kasar et al., 2020), although they require more input power higher than 7 dBm to function. (Ismail N and Abd KE, 2021) increased Power Conversion Efficiency (PCE) and attained 42% efficiency at -10 dBm input power using a reversed L-type matching impedance approach.

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Pinto et al. proposed a 2.45 GHz rectifier with a 7-stage Villard voltage doubler and a boost circuit was described in (Pinto D et al., 2021); the output voltage was 0.204 V before the boost circuit. The boost circuit generated an output value of 3.3 V. (Narayanan S. and Thangavel S., 2021) proposed a 2.45 GHz rectenna with a rectifier created by a Cockcroft-Walton voltage doubler. At 10 dBm input power, a 45% conversion efficiency was achieved. Using a metamaterial matching impedance circuit (IMN) operating at 2.4 GHz and 5 GHz, (Coskuner et al., 2021) presented a rectifier with an input power of -30 dBm and an efficiency of 22% and 12% at corresponding frequencies. They drew the conclusion that metamaterial transmission lines provide more design flexibility and enable matching of impedance over several bands. (Yusoff et al., 2021) have presented a rectifier operating at the GSM 900 and 1800 MHz bands. For the 950 MHz and 1850 MHz bands, the author claimed power conversion efficiencies (PCEs) of 43.51% and 25.98%, respectively. (Li et al., 2021) to increase circuit efficiency in rectifiers that operate at 2.45 GHz and 915 MHz used a stepping impedance stub-matched network. The suggested rectifier, according to the author, has the benefits of a high frequency ratio, a straightforward design, and a small dimension.

The designed rectifier circuits were simulated using Advanced Design System (ADS) Software.

2 Single Stage Rectifier Circuits

Advanced Design System (ADS) software is used for simulating half-wave, full-wave, voltage doubler, Villard, Graetz and Dickson charge pump rectifier circuits at 2.4 GHz. A dependable way to move power from a source to an end system without the use of wires or connectors is wireless power transmission (WPT). Rectennas, which are antennas connected to rectifiers, handle this job. The rectifier, which transforms received RF power into DC power, is without a doubt the most crucial part of the rectenna. The antenna receives and transmits radio frequency energy to the corresponding circuit. A TL-matching circuit will be used to match the impedances of the antenna and rectifier, and the Schottky diode type HSMS-2820 will be used in this work for rectification. It is important to note that one of the most essential tasks is selecting the appropriate diode. Additionally, a thickness of 1.6 mm is utilized for all six types of rectifier PCB substrate, and the dielectric constants are chosen for a number of materials, such as FR-4 with a 4.3 for comparative reasons between rectifier circuits using the TL-match technique and also using the LC-match method. The 2.4 GHz frequency range is used to record and plot the simulation results, which include DC output voltage (Vout) with respect to the input power and efficiency with respect to the input power at 3 kΩ of resistance load, HSMS-2820 diode, and substrate with (ε_r) equal to 4.3.

2.1 Impedance Matching Circuit using TL-match method

ADS is utilized to determine the matching at a certain frequency; however, this time, a TL matching for instance, the Graetz charge pump is utilized as a substitute for an LC matching since it produces a superior match and is simpler to manufacture.

2.2 Half-wave rectifier circuit using TL-match method

Impedance matching can also be done by applying the Smith Chart feature found in ADS software. As shown in Fig. 1, this technique matches the rectifier circuit to the source by using transmission line stubs at the circuit's input port. The transmission line stubs' length (L) and width (W) are critical factors in determining the quality of impedance matching. The rectifier circuit's simulated S11 at 2.4 GHz with TL-match method is shown in Fig. 2. At the given frequency, the return loss value dropped to below -29 dB.

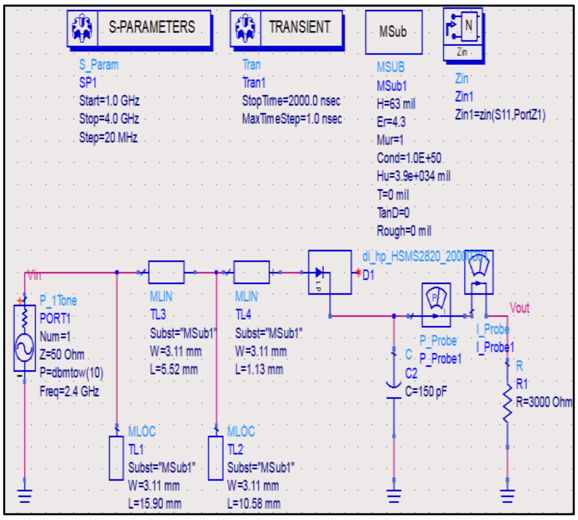

Fig.1: Half-wave rectifier circuit operating at 2.4 GHz with TL-circuit.

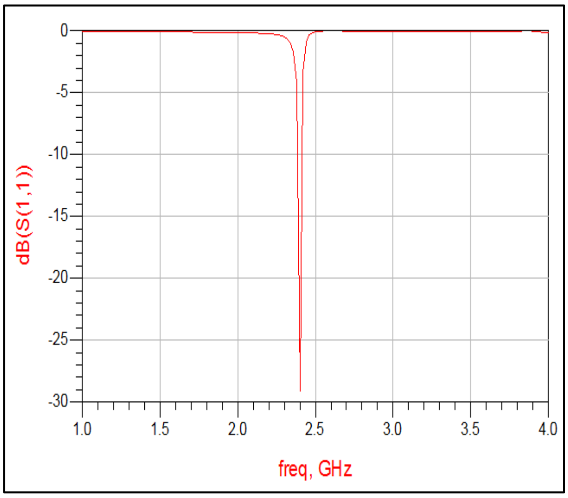

Fig.2: Simulated S11 of half-wave rectifier circuit at 2.4 GHz with TL-circuit.

Fig. 3 illustrates the output voltage waveform for a half-wave rectifier circuit at 2.4 GHz. The achieved DC output voltage is around 10.8 V, as shown in Fig. 3.

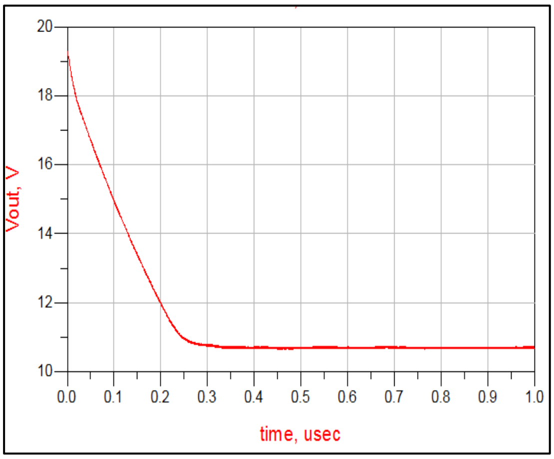

Fig.3: Vout (V) of half-wave rectifier circuit at 2.4 GHz with TL-circuit.

Fig. 4 displays the waveform of output current for the half-wave rectifier circuit at 2.4 GHz. The output current is about 3.6 mA.

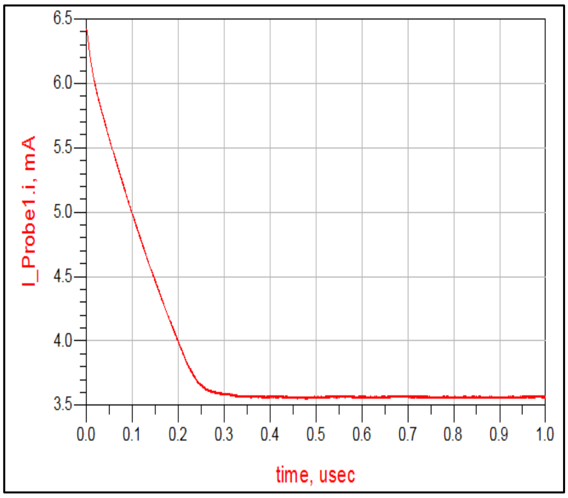

Fig.4: Output current of half-wave rectifier circuit at 2.4 GHz with TL-circuit.

Fig. 5 shows the comparison in Vout of the rectifier's performance when using the LC-match method and the TL-match method. It has been investigated that there is little impact on the Vout at low input power (Pin) on the contrary at high input power (Pin), where using the TL-match method is bigger in terms of Vout than using the LC-match method.

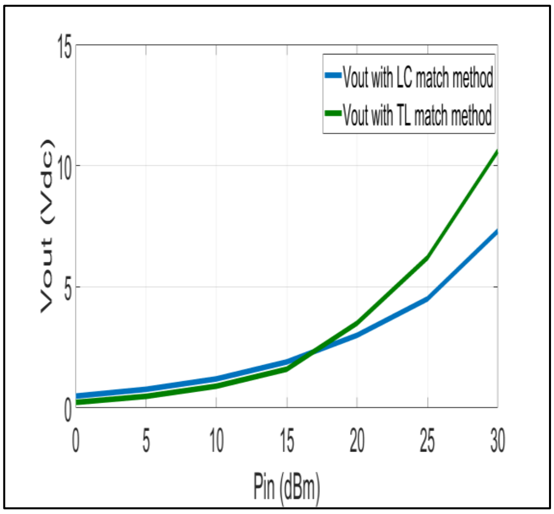

Fig.5: Vout versus Pin of comparison between a half-wave rectifier circuit with an LC-circuit and a TL-circuit at 2.4 GHz.

Fig. 6 shows the comparison in efficiency (η) of the rectifier's performance when using the LC-match method and the TL-match method. It has been investigated that using the LC-match method is higher in terms of efficiency (η) than using the TL-match method at low input power (Pin), on the other hand, at high input power (Pin), where using the TL-match method is bigger in terms of efficiency (η) than using the LC-match method.

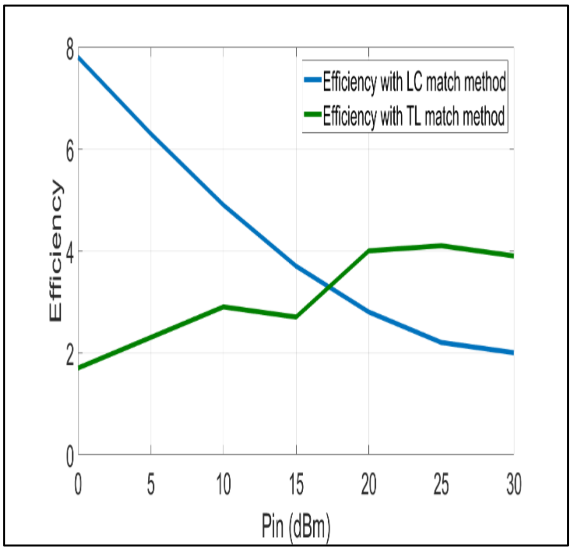

Fig.6: Efficiency (η) versus Pin of comparison between a half-wave rectifier circuit with an LC-circuit and a TL-circuit at 2.4 GHz.

2.3 Full-wave rectifier circuit using TL-match method

The Smith Chart feature of ADS software may also be used to design the full-wave rectifier circuit with transmission line (TL) impedance matching. This method uses transmission line stubs at the circuit's input port to match the rectifier circuit to the source, as seen in Fig. 7. The width (W) and length (L) of the transmission line stubs are important parameters that affect how well the impedance matching works. Fig. 8 displays the rectifier circuit's simulated S11 at 2.4 GHz using the TL-match approach. The reflection coefficient value decreased to less than -4 dB at the specified frequency.

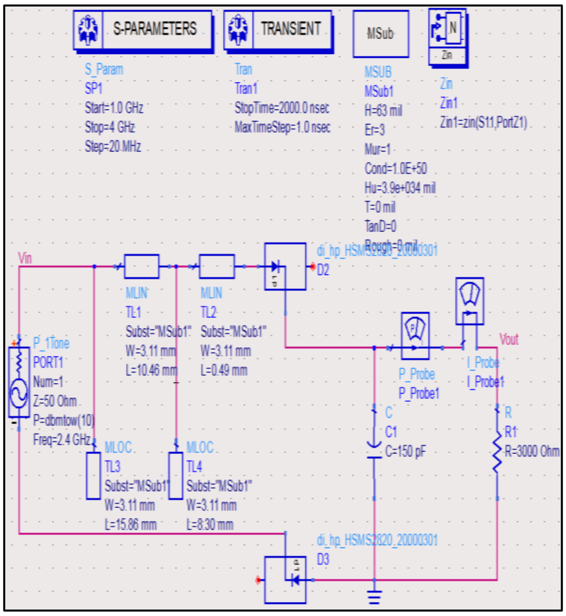

Fig.7: Full-wave rectifier circuit operating at 2.4 GHz with TL-circuit.

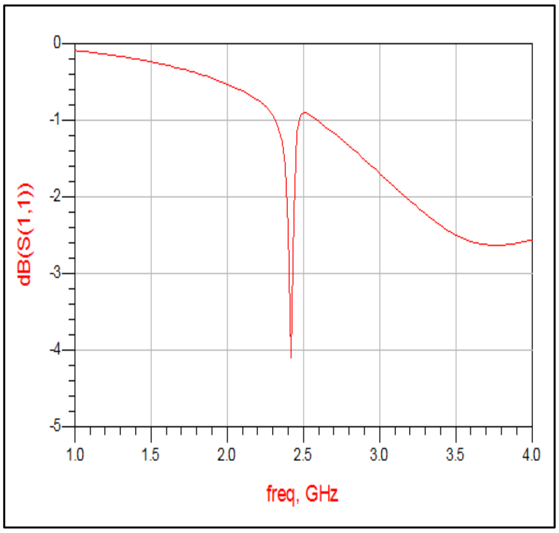

Fig.8: Simulated S11 of full-wave rectifier circuit at 2.4 GHz with TL-circuit.

Fig. 9 shows the comparison in Vout of the rectifier's performance when using the LC-match method and the TL-match method. It has been investigated that using the TL-match method is higher in terms of Vout than using the LC-match method almost for all input power (Pin), except for high input power (Pin) between 25 and 30 dBm.

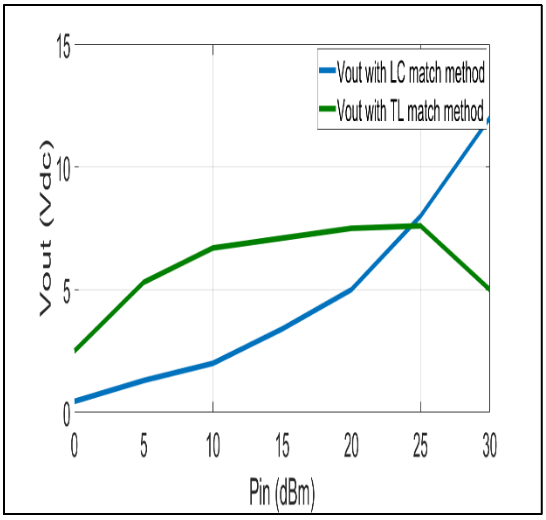

Fig.9: Vout versus Pin of comparison between a full-wave rectifier circuit with an LC-circuit and a TL-circuit at 2.4 GHz.

Fig. 10 shows the comparison in efficiency (η) of the rectifier's performance when using the LC-match method and the TL-match method. It has been investigated that using the LC-match method is higher in terms of efficiency (η) than using the TL-match method at low input power (Pin); on the other hand, at high input power (Pin), using the TL-match method is bigger in terms of efficiency (η) than using the LC-match method. And the better efficiency was 13% at 5 dBm of pin when using the LC-match method.

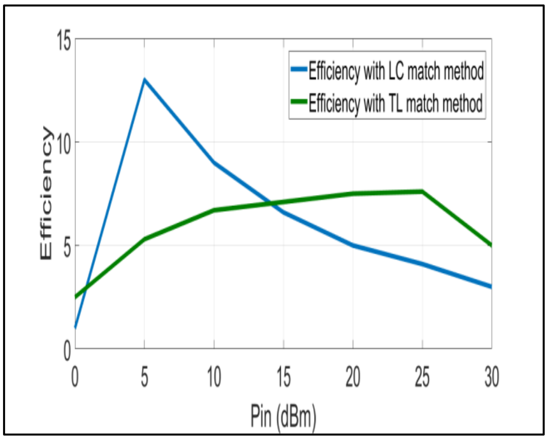

Fig.10: Efficiency (η) versus Pin of comparison between a full-wave rectifier circuit with an LC-circuit and a TL-circuit at 2.4 GHz.

2.4 Voltage doubler rectifier circuit using TL-match method

It is also possible to construct the voltage doubler rectifier circuit with transmission line (TL) impedance matching using the Smith Chart function of the ADS program. As shown in Fig. 11, this technique matches the rectifier circuit to the source by means of transmission line stubs at the circuit's input port.. The simulated S11 of the rectifier circuit using the TL-match method is shown in Fig. 12 at 2.4 GHz. At the given frequency, the reflection coefficient value dropped to less than -38 dB, which means the validity of the execution procedure of the simulation in ADS software.

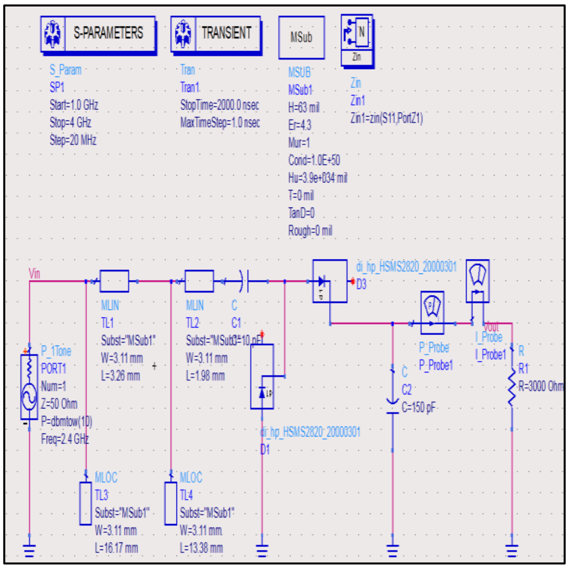

Fig.11: Voltage doubler rectifier circuit operating at 2.4 GHz with TL-circuit.

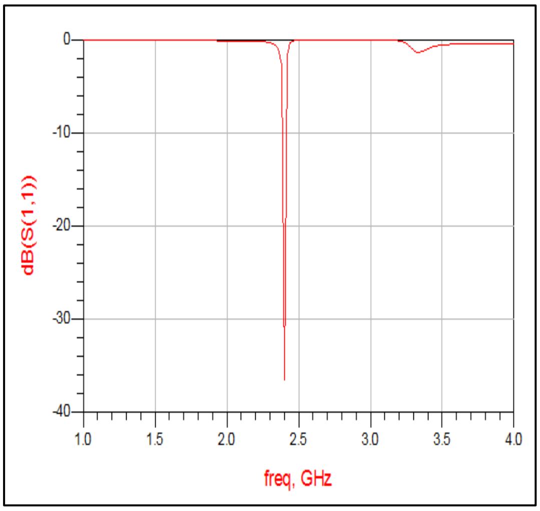

Fig.12: Simulated S11 of voltage doubler rectifier circuit at 2.4 GHz with TL-circuit.

Fig. 13 shows the comparison in Vout of the rectifier's performance when using the LC-match method and the TL-match method. It has been found that there is little difference in terms of Vout at low input power (Pin). On the other hand, for high input power (Pin), the TL-match method has higher values than the LC-match method.

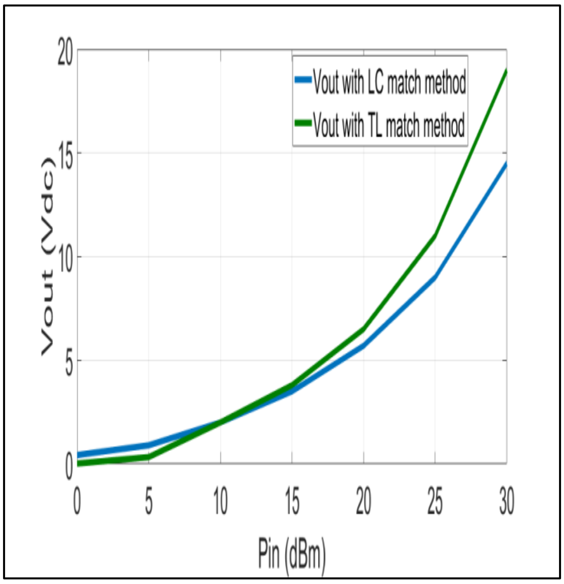

Fig.13: Vout versus Pin of comparison between a voltage doubler rectifier circuit with an LC-circuit and a TL-circuit at 2.4 GHz.

Fig. 14 shows the comparison in efficiency (η) of the rectifier's performance when using the LC-match method and the TL-match method. It has been investigated that values vary between both the LC-match and TL-match in efficiency (η) at low input power (Pin); on the other hand, at high input power (Pin), using the TL-match method is higher in terms of efficiency (η) than using the LC-match method. And the better efficiency was 16% at 15 dBm of pin when using the LC-match method.

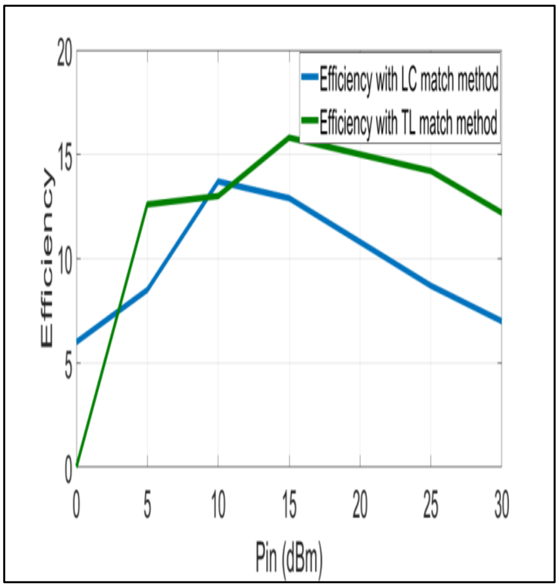

Fig.14: Efficiency (η) versus Pin of comparison between a voltage doubler rectifier circuit with an LC-circuit and a TL-circuit at 2.4 GHz.

2.5 Villard charge pump rectifier circuit using TL-match method

Using the ADS program's Smith Chart tool, a Villard charge pump rectifier circuit with transmission line (TL) impedance matching may also be built. This method uses transmission line stubs at the circuit's input port to match the rectifier circuit to the source, as seen in Fig. 15. Fig. 16 at 2.4 GHz displays the rectifier circuit's simulated S11 using the TL-match approach. The reflection coefficient value decreased to less than -31 dB at the specified frequency, indicating that the ADS software's simulation execution process was valid.

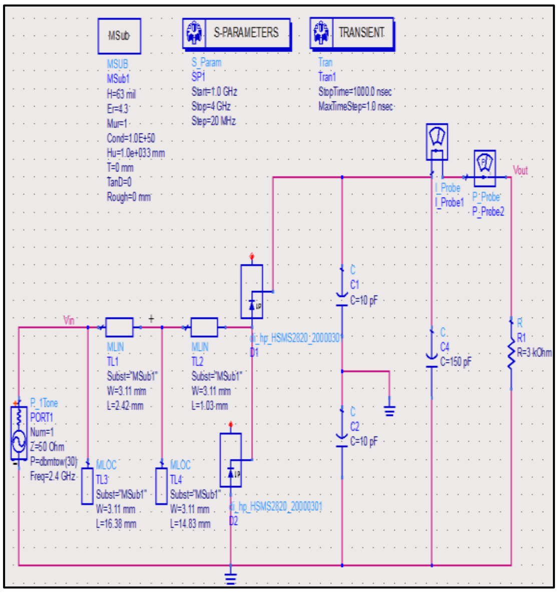

Fig.15: Villard charge pump rectifier circuit operating at 2.4 GHz with TL-circuit.

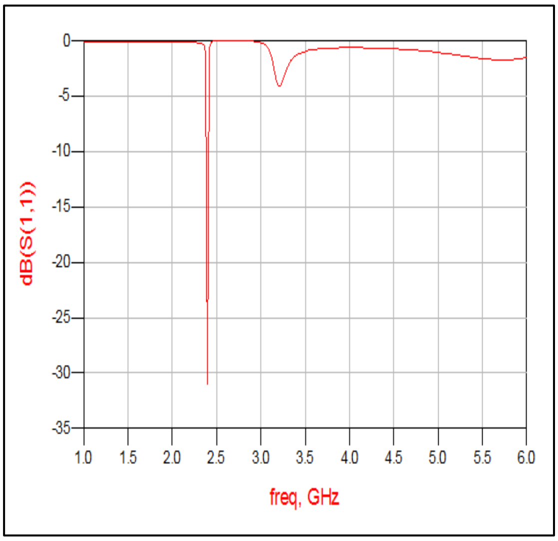

Fig.16: Simulated S11 of Villard charge pump rectifier circuit at 2.4 GHz with TL-circuit.

Fig. 17 shows the comparison in Vout of the rectifier's performance when using the LC-match method and the TL-match method. It has been demonstrated that the LC-match method has higher values than the TL-match method at all input power Pins.

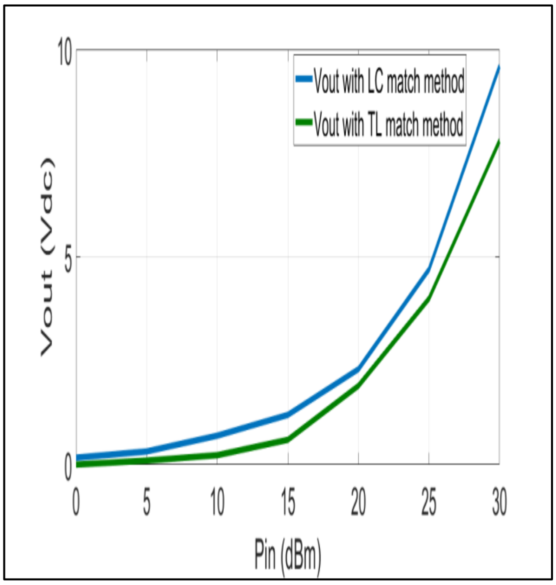

Fig.17: Vout versus Pin of comparison between a Villard charge pump rectifier circuit with an LC-circuit and a TL-circuit at 2.4 GHz.

Fig. 18 shows the comparison in efficiency (η) of the rectifier's performance when using the LC-match method and the TL-match method. It has been investigated that the LC-match method has higher values than the TL-match method at all input power Pins. And the better efficiency was 7% at 30 dBm of pin when using the LC-match method. Overall, the efficiency was low in this kind among other rectifier circuits. Where the efficiency (η) is between 2 and 7%.

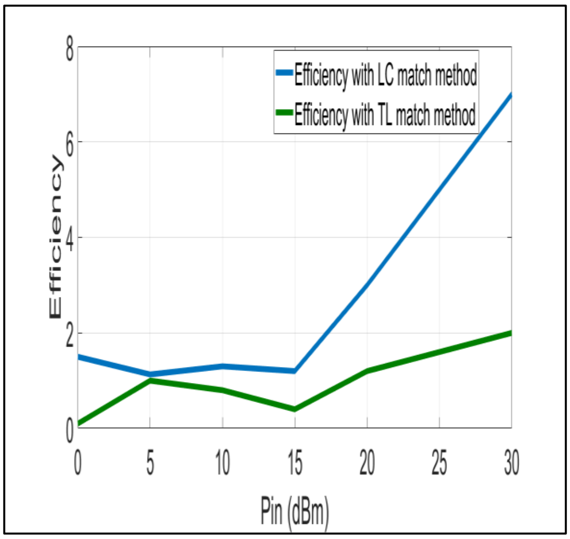

Fig.18: Efficiency (η) versus Pin of comparison

between a Villard charge pump rectifier circuit with an LC-circuit and a TL-circuit at 2.4 GHz.

2.6 Graetz charge pump rectifier circuit using TL-match method

A graetz charge pump rectifier circuit with transmission line (TL) impedance matching may also be constructed using the Smith Chart tool included in the ADS software. To match the rectifier circuit to the source, this method shown in Fig. 19 uses transmission line stubs at the circuit's input port. Important parameters that determine how well the impedance matching works are the transmission line stubs' width (W) and length (L). The simulated S11 of the rectifier circuit using the TL-match technique is shown in Fig. 20 at 2.4 GHz. The simulation execution procedure of the ADS program was valid when the reflection coefficient value dropped to less than -10 dB at the designated frequency.

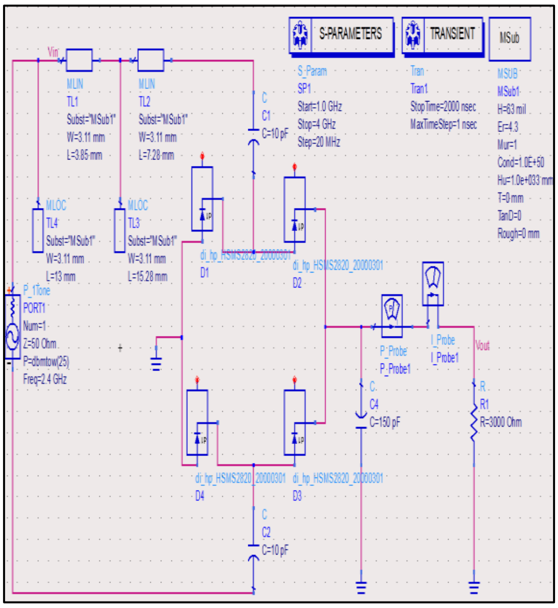

Fig.19: Graetz charge pump rectifier circuit operating at 2.4 GHz with TL-circuit.

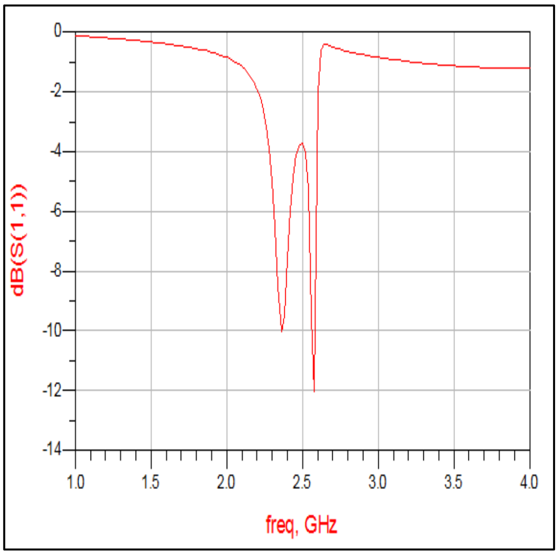

Fig.20: Simulated S11 of Graetz charge pump rectifier circuit at 2.4 GHz with TL-circuit.

Fig. 21 shows the comparison in Vout of the rectifier's performance when using the LC-match method and the TL-match method. It has been demonstrated that the TL-match method has higher values than the LC-match method at all input power Pin, except at low input power beginning from 0 to 10 dBm, where there is little difference between them.

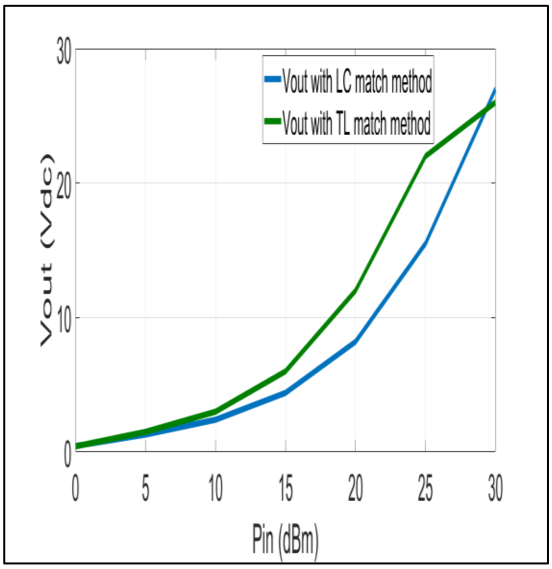

Fig.21: Vout versus Pin of comparison between a Graetz charge pump rectifier circuit with an LC-circuit and a TL-circuit at 2.4 GHz.

Fig. 22 shows the comparison in efficiency (η) of the rectifier's performance when using the LC-match method and the TL-match method. It has been investigated that the TL-match method has higher values than the LC-match method at all input power Pins. And the better efficiency was 50% at 20 dBm of Pin when using the TL-match method. Overall, the efficiency of this type of rectifier circuit was higher than that of other rectifier circuits. Where the efficiency (η) is between 7 and 50%.

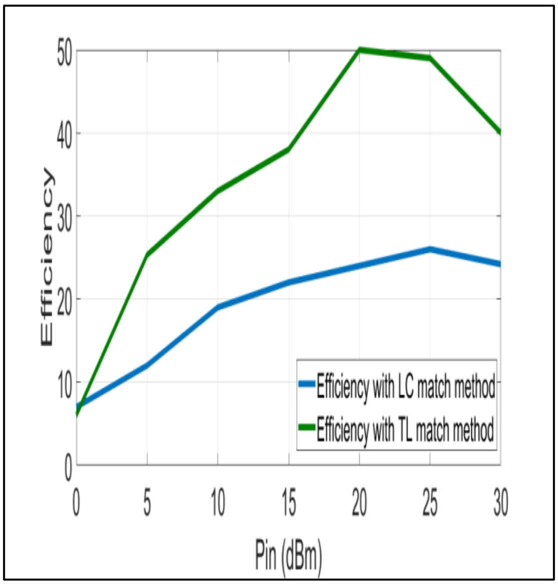

Fig.22: Efficiency (η) versus Pin of comparison between a Graetz charge pump rectifier circuit with an LC-circuit and a TL-circuit at 2.4 GHz.

2.7 Dickson charge pump rectifier circuit using TL-match method

Lastly, Dickson charge pump rectifier circuit with transmission line (TL) impedance matching is built as illustrated in Fig. 23, making use of transmission line stubs at the circuit's input port to match the rectifier circuit to the source. Significant factors that dictate the effectiveness of impedance matching are the width (W) and length (L) of the transmission line stubs. Fig. 24 displays the rectifier circuit's simulated S11 at 2.4 GHz using the TL-match approach. The ADS program's simulation execution process was deemed valid when the reflection coefficient value at the assigned frequency fell to less than -35 dB.

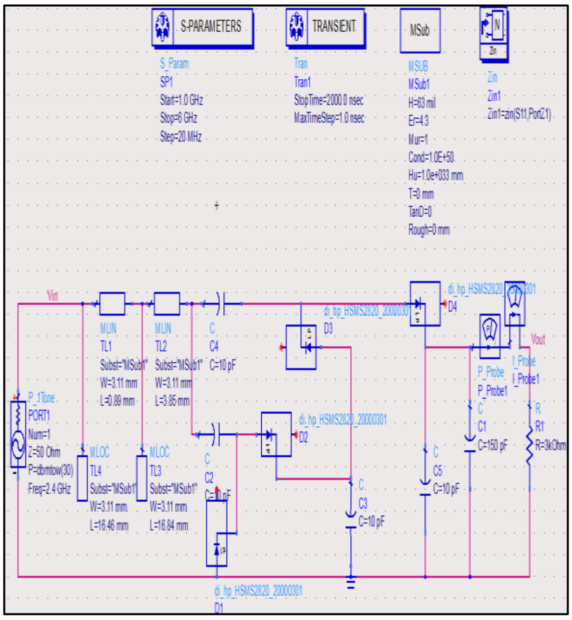

Fig.23: Dickson charge pump rectifier circuit operating at 2.4 GHz with TL-circuit.

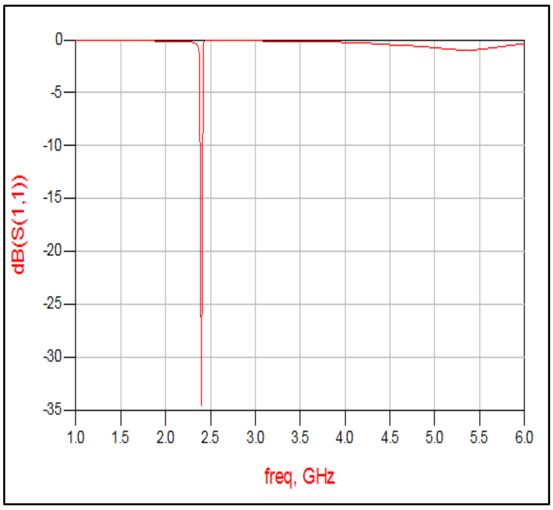

Fig.24: Simulated S11 of Dickson charge pump rectifier circuit at 2.4 GHz with TL-circuit.

Fig. 25 shows the comparison in Vout of the rectifier's performance when using the LC-match method and the TL-match method. It has been investigated that the LC-match method has higher values than the TL-match method at all input power Pins, where the high values with the LC-match method and the highest value are about 21 V at 30 dBm of Pin.

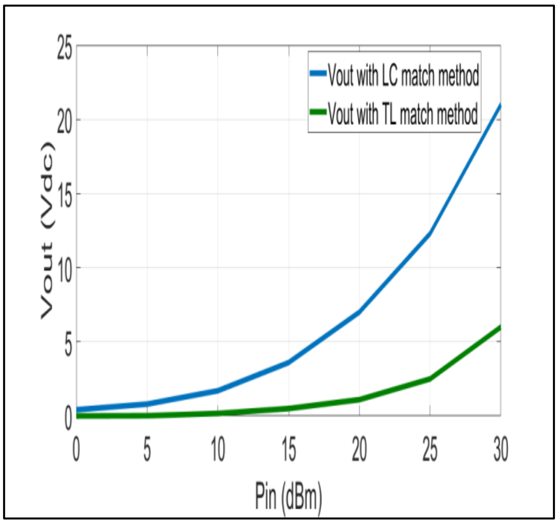

Fig.25: Vout versus Pin of comparison between a Dickson charge pump rectifier circuit with an LC-circuit and a TL-circuit at 2.4 GHz.

Fig. 26 shows the comparison in efficiency (η) of the rectifier's performance when using the LC-match method and the TL-match method. It has been investigated that the LC-match method has higher values than the TL-match method at all input power Pins. And the better efficiency was 17% at 20 dBm of Pin when using the LC-match method. Overall, the efficiency of this type of rectifier circuit was smaller than that of the Graetz charge pump rectifier circuit.

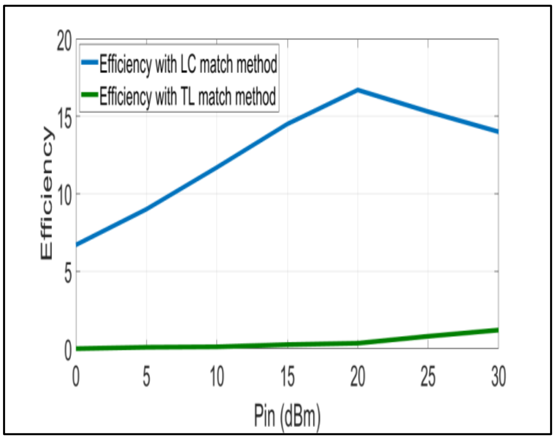

Fig.26: Efficiency (η) versus Pin of comparison between a dickson charge pump rectifier circuit with an LC-circuit and a TL-circuit at 2.4 GHz.

Fig. 27 shows the comparison in Vout performance of the rectifier circuits using the TL-match method at the resistance load (3 kΩ), HSMS2820 diode, and ε_r equal to 4.3. It has been investigated that the highest Vout with the Graetz charge rectifier circuit is about 27 V, followed by the voltage doubler rectifier circuit with a value around 19.7 V, followed by the full-wave rectifier circuit, then by the half-wave rectifier circuit. On the other hand, the smallest value between them was the Dickson charge pump rectifier circuit.

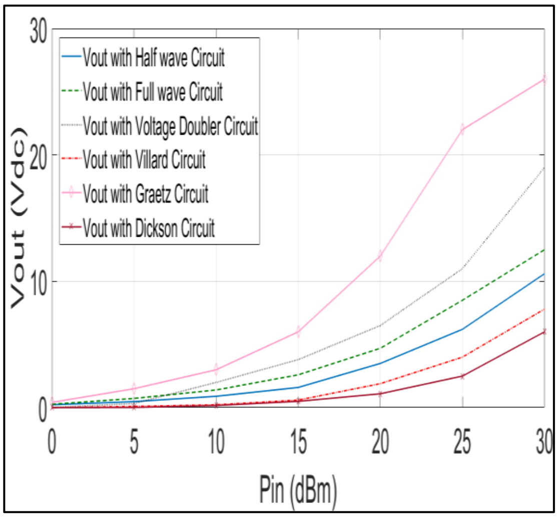

Fig.27: Vout (V) versus Pin (dBm) of different rectifier circuits at 2.4 GHz with TL-circuit.

Fig. 28 shows the comparison in efficiency performance of the rectifier circuits using the TL-match method at the resistance load (3 kΩ), HSMS2820 diode, and ε_r equal to 4.3. It has been investigated that the highest efficiency with the Graetz charge rectifier circuit is about 50% at 20 dBm of input power Pin, followed by the voltage doubler rectifier circuit with a value around 16.7 % at 15 dBm of input power Pin, followed by the full-wave rectifier circuit, then by the half-wave rectifier circuit. On the other hand, the smallest value between them was the Dickson charge pump rectifier circuit.

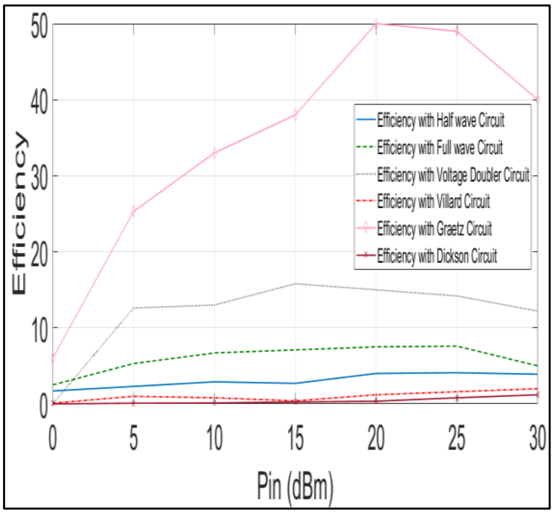

Fig.28: Efficiency (η) versus Pin (dBm) of different rectifier circuits at 2.4 GHz with TL-circuit.

A parametric study is conducted on the Graetz charge pump rectifier circuit using Transmission lines (TL)-match method; the comparison of the rectifier's performance efficiency (η) when the load resistance (from 1 to 5 kΩ) is changed is shown in Fig. 29. Research has shown that when load resistance increases, efficiency (η) declines. The maximum efficiency (η) of 73% is found at a load resistance equal to 1 kΩ at 25 dBm of Pin. Additionally, this efficiency rating is outstanding in comparison to other rectifier circuits that have relatively low efficiency.

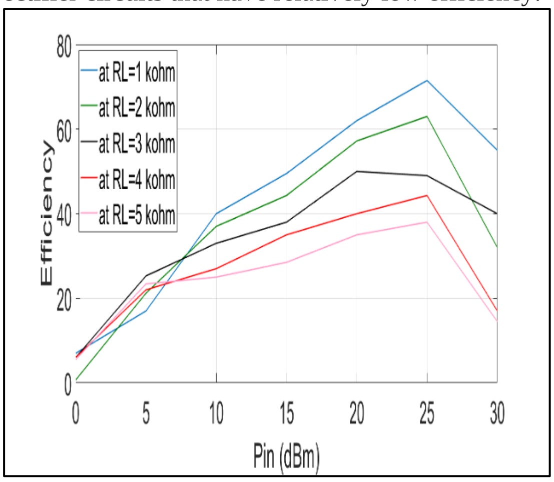

Fig.29: Efficiency (η) versus Pin (dBm) of Graetz charge pump rectifier circuit for different values of resistance load (R_L) at 2.4 GHz with TL-circuit.

For fair comparison, a comparison in normalized values of Vout of the rectifier circuits using the TL-match method at the resistance load (3 kΩ), HSMS2820 diode, and εr equal to 4.3 is shown in Fig. 30. It is noted that the all rectifier gradually increased in Vout with an increase in the Pin and appeared to have the same trends except that the normalized Vout for the Villard charge pump increased in the middle of the pin, but still Graetz circuit has the better performance among all other circuits.

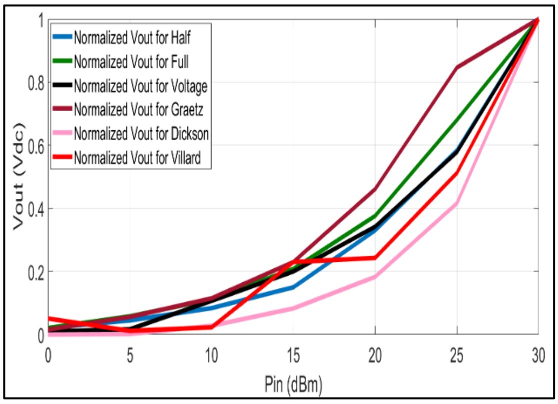

Fig.30: Normalized Vout (V) versus Pin (dBm) of different rectifier circuits at 2.4 GHz with TL-circuit.

Fig. 31 shows the comparison in normalized efficiency performance of the rectifier circuits using the TL-match method at the resistance load (3 kΩ), HSMS2820 diode, and ε_r equal to 4.3. It has been investigated that the all rectifier gradually increased in Vout with an increase in the pin and appeared to have the same trends except that the normalized efficiency for the Villard charge pump decreased in the middle of the pin.

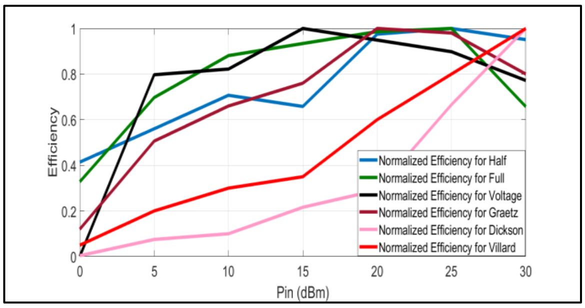

Fig.31: Normalized efficiency (η) versus Pin (dBm) of different rectifier circuits at 2.4 GHz with TL-circuit.

Fig. 32 shows the comparison in normalized Vout performance of the rectifier circuits using the LC-match method at the resistance load (3 kΩ), HSMS2820 diode, and ε_r equal to 4.3. It has been investigated that the all rectifier gradually increased in Vout with an increase in the pin and appeared to have the same trends except that the normalized Vout for the Dickson charge pump decreased in the low of the_pin.

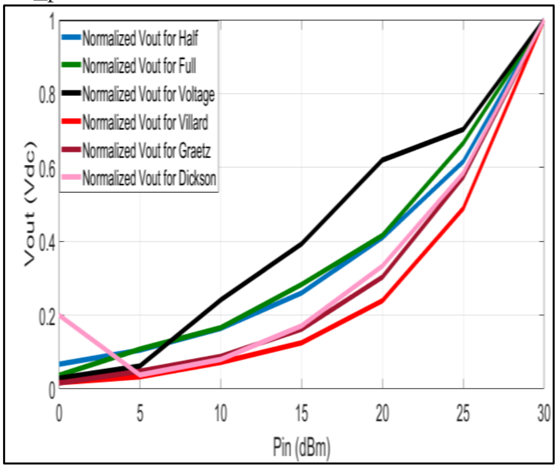

Fig.32: Normalized Vout (V) versus Pin (dBm) of different rectifier circuits at 2.4 GHz with LC-circuit.

The comparison of the rectifier circuits' normalized efficiency performance using the LC-match technique at a resistance load of 3 kΩ, using an HSMS2820 diode and an εr of 4.3, is displayed in Fig. 33. Investigations have revealed that there seem to be differences in patterns among all rectifiers.

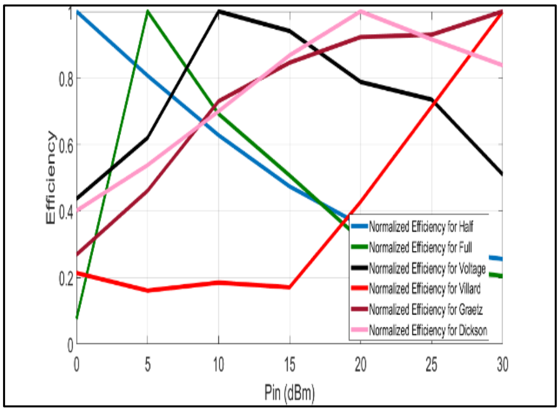

Fig.33: Normalized efficiency ($\boldsymbol{\eta}$) versus Pin (dBm) of different rectifier circuits at 2.4 GHz with LC-circuit.

3 Discussion and Results

A comparison of several rectifier circuit types is presented in Table 1, and it is discovered that the Greatz charge pump rectifier circuit, when equal to 50%, achieves the maximum efficiency, while the Villard charge pump and Dickson charge pump rectifier circuit, when equal to 2%, achieve the lowest. Additionally, the Dickson charge pump rectifier circuit produces the lowest Vout at 6 volts, while the Graetz charge pump produces the best Vout at 27 volts. Conversely, each rectifier circuit featured four matching blocks (stubs) in all. Depending on the chosen frequency and additional parts that make up the rectifier circuit, each stub has width and length measurements that are different from the others.

4 Conclusion

In this paper, six different rectifier circuits are compared in terms of output voltage and efficiency when two different impedance matching methods are applied. It has been investigated that the highest Vout is achieved with the Graetz charge rectifier circuit and it was about 27 V, followed by the voltage doubler rectifier circuit with a value around 19.7 V in terms of Vout. Also, the smallest value between them was the Dickson charge pump rectifier circuit in terms of Vout. On the other hand, it has been investigated that the highest efficiency with the Graetz charge rectifier circuit is about 73% at 25 dBm of input power Pin, followed by the voltage doubler rectifier circuit with a value around 16.7 % at 15 dBm of input power Pin. Lastly, the smallest performance between them was the Dickson charge pump rectifier circuit. The Graetz charge pump showed the best performance among the other rectifier circuits, using both the LC-match method and the TL-match method. Furthermore, when the LC-match method and the TL-match method were compared for the same circuit, it is found that in general and for most case the TL-matched circuits have shown a better performance and outperformed the LC-match method. Finally, this paper throughout the presented comparison have showed a road map for the designers to choose the appropriate rectifier circuit based on the available input power levels and to select the proper impedance matching method.

Table.1 demonstrate the comparison between different rectifier circuits in term of efficiency, Vout and TL-match method.

Rectifier Circuits	TL_match (stubs) all dimensions in milimeter	Efficiency (%)	Vout (volt)
Half wave	L1=15.9, L2=10.58, L3=5.52, L4=1.13 And (W1,W2,W3 ,W4)=3.11	4	10.5
Full wave	L1=10.46, L2=0.4 L3=15.86, L4=8.30 And (W1,W2,W3 ,W4)=3.11	7	7.5
Voltage Doubler	L1=3.26, L2=1.98 ,L3=16.17, L4=13.38 And (W1,W2,W3 ,W4)=3.11	16	18
Villard charge pump	L1=2.42, L2=1.03, L3=16.38, L4=18.83 And (W1,W2,W3 ,W4)=3.11	2	7.5
Graetz charge pump	L1=3.85, L2=7.28, L3=15.28, L4=13 And (W1,W2,W3 ,W4)=3.11	50	27
Dickson charge pump	L1=0.89, L2=3.85, L3=16.84, L4=16.46 And (W1,W2,W3 ,W4)=3.11	2	6

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