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Design a Compact Single Stage Rectifier Circuit for Ambient RF Energy Harvesting

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Abstract

In this paper, a compact rectifier capable of harvesting ambient radio frequency (RF) power is presented. Controlling the resonant frequency of the antenna allows the designer to target the available sources of electromagnetic energy, such as Wi-Fi, WLAN, and Wi-MAX, altering current (AC) by the antennas and converting it into direct current (DC) by the receiver. The receiver is designed on an FR-4 substrate using a single-stage voltage multiplier at 2.4, 3.6, and 5 GHz. This is among the favorable RF Energy Harvesting (RFEH) energy sources that span over a wide range with minimal path loss and high input power. The proposed RFEH rectifier at 2.4 GHz achieves a simulated RF-to-DC (RF to direct current) power conversion efficiency (PCE) of 45.22% for 10 dBm input power. Additionally, the rectifier attained a 2.2 V DC output voltage across the 3 kΩ load terminal. The input power level is changed from -10 to 25 dBm. ADS software (Advanced Design System) is used to simulate the proposed structures.

Keywords: *RF Energy Harvesting, Impedance Matching Network (IMN), Power Conversion Efficiency (PCE), Rectifier, IoT (Internet of Things)*

1 Introduction

Over the years, researchers from all over the world have become increasingly interested in and involved in wireless communication technology because of its pervasiveness (Chen et al., 2018; Pardue et al., 2018). In addition, GSM900/1800, 3G, 4G, WiFi, and the impending promising 5G are some of the key wireless technologies. Everyday generation works to meet demand and meet human needs (Mansour et al., 2018; Pardue et al., 2018). New and developing technological developments have emerged as a result of recent advancements in wireless communication technology. One or more application drivers in the fields of IoT, industrial IoT, autonomous driving, smart farming, smart cities, and many more were created as a result of the rising need for such inventions (Awais et al, 2018; Wong et al., 2018). By 2023, this will equate to over 70% of the world's population having mobile access. As a result, the emergence of the Wi-Fi spectrum bands (2.4 GHz and 5 GHz), which the world's population will use in 2023, has caused an abundance of frequency signal to be present in the environment (Naik et al., 2018). This frequency signal's abundance offers tremendous potential for energy harvesting and conversion into electrical energy for a variety of uses. It has been determined that energy harvesting is a useful notion for using a variety of techniques, including thermoelectric, vibration, solar energy conversion, and pressure gradients, to capture energy from the surrounding environment. For the replacement of small batteries in low-power electrical systems and devices, this approach has significant potential. Unlike solar energy, which is only available when sunlight is present, ambient EM energy has the advantage of being accessible day and night (Lakhal et al., 2016). This paper proposes a method for the design and implementation of a voltage doubler rectifier for ambient RF energy harvesting. The designed rectifier circuit was simulated using ADS Software. Three different designs of Rectifier Circuit at 2.4, 3.6, and 5 GHz were designed and simulated.

2 Design a Single Stage Rectifier

Voltage double rectifier and matching circuit design and simulation are carried out at 2.4 GHz, 3.6 GHz, and 5 GHz using Advanced Design System (ADS) software. Wireless Power Transmission (WPT) is a reliable method of transferring power from a source to an end system without the need for cables or connections. This task is performed by rectennas, which are antennas coupled with rectifiers. Undoubtedly, the rectifier, which converts RF power received into DC power, is the most important component of the rectenna.

Several rectifier topologies are designed for RF use (rectenna applications) in this paper. RF energy is taken in by the antenna and sent into the matching circuit. The antenna and rectifier's impedances will be matched using a matching circuit, while the Schottky diode type HSMS-2820 is utilized for rectification. It is worth mentioning that choosing the right diode is one of the most vital factors, and HSMS-2820 is used in this paper due to its fast diode. The simulation results, including DC output voltage (Vout) with respect to the input power and efficiency with respect to the input power, are recorded and plotted at three frequencies.

Features of Schottky diode type HSMS-2820:

- Low Turn-On Voltage (As Low as 0.34 V at 1 mA).
- Low FIT (Failure in Time).
- Single, Dual and Quad Versions.
- Increase flexibility.
- save board space.
- reduce cost.

2.1 Matching Network Circuit

There are Two Method for matching network will be discussed in details in this paper:

1- LC (Inductance and Capacitance)-Matching Network Circuit (shown in Figure 1).

2- TL (Transmission Lines) - Matching Network Circuit.

2.1.1 LC- Matching Network Circuit:

This LC-Matching Method is solved using the Q matching technique.

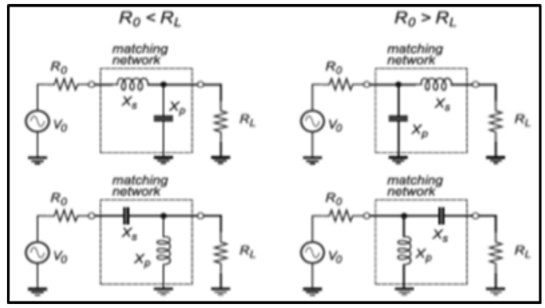

Figure 1: LC-Matching Network.

One of the drawbacks of this technique is its use of reactive components, meaning that the matching is possible at only one frequency.

An LC section placed between two resistive terminations creates a serial subnetwork and a parallel subnetwork as shown in Figure 2. When the two subnetworks are conjugate matched to each other, their Q factors are equal.

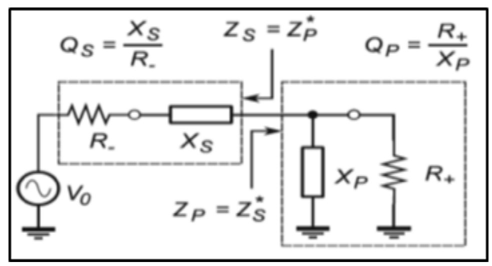

Figure 2: Equivalent Circuit for LC-Circuit.

These equations are used to compute L and C.

$$Q_s = {}^{X_s}/_{R\,-} \quad \text{and} \quad Q_P = {}^{R_+}/_{Xp} \qquad \text{... (1)}$$

And also

$$Q_s = Q_p = \sqrt{\frac{R_+}{R_-} - 1} \qquad \text{… (2)}$$

To find the input impedance (Zin) of the rectifier circuit, ADS simulations were with any matching network as shown in Figure 3. The input impedance is plotted over the frequency range 1.2 GHz to 3.4 GHz and it is found that Zin at 2.4 GHz is equal 3.196-j38.638 Ω.

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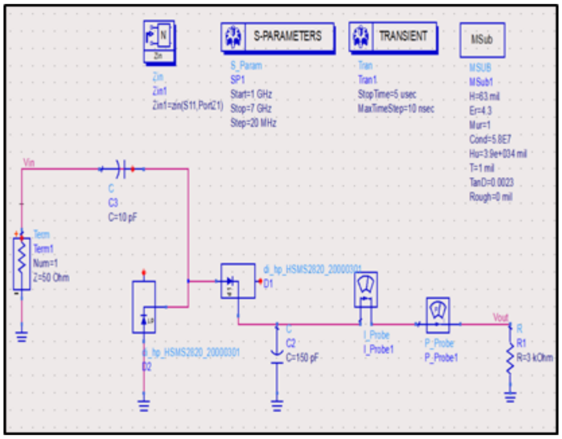

Figure 3: Simulated circuit to find Zin.

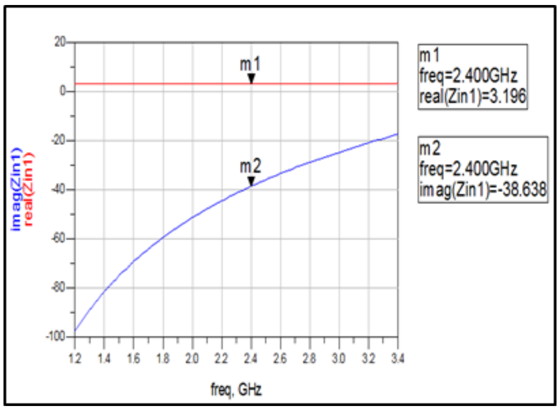

Figure 4: Simulated value of Zin

To validate the simulation results of Zin, the value of input impedance was found analytically by using the equivalent circuit of the diode as shown in Figures 5 and 6.

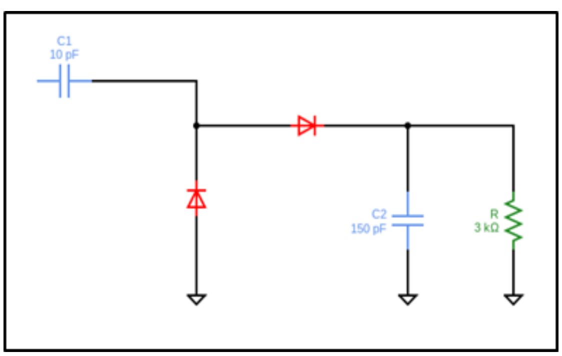

Figure 5: Rectifier Circuit.

Compensate for each diode with its equivalent circuit shown in Figure 6 below.

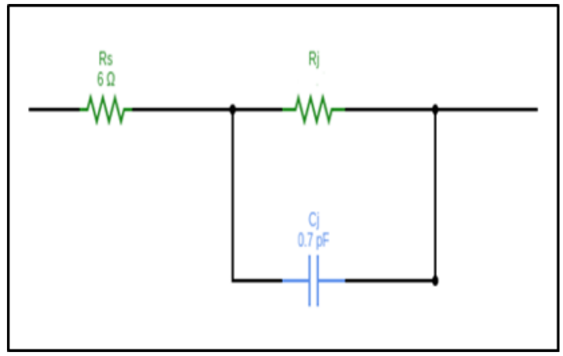

Figure 6: Equivalent Circuit for Diode.

The following equation for computing R_j

$$R_j = \frac{8.33 \times 10^{-5} \times n \times T}{I_s} \quad \dots \quad (3)$$

$$R_j = \frac{8.33 \times 10^{-5} \times 1.5 \times 300}{2.2 \times 10^{-8}}$$

$$R_j = 1.7\ M\Omega$$

Where I_s=2.2× 10^{-8} A, n=1.5, T=300 c, R_s=6 Ω and C_j=0.7 pF all values are taken from Data sheet for HSMS-2820 Schottky Diode.

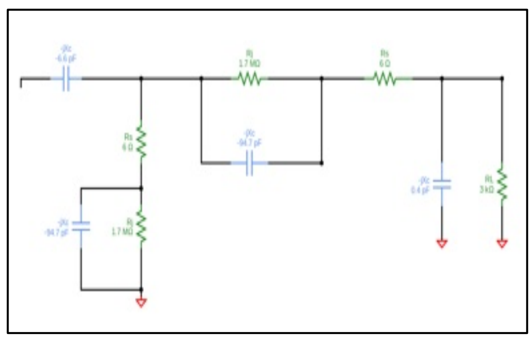

Figure 7: Analysis circuit to compute Zin.

The value of R_j is neglected because it has great value, then the circuit arrangement becomes as follows.

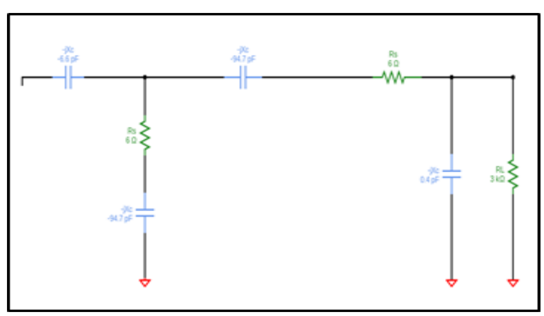

Figure 8: Final Analysis Circuit after neglecting R_j

Z_{in} = 6-j95.14 // 6-j94.7

$Z_{in} = \frac{8973.7 - j1139}{12 - j189.84}$ = 3-j47.4

It is clearly seen that the analytical value of Zin is very close to the simulated value (3.19-j38.6 Ω), which validates our simulation procedure.

2.1.2 TL (Transmission Lines) Circuit:

ADS is employed again to find the matching network at a specific frequency but this time a TL matching is used instead of the LC matching. The matching network at 2.4 GHz consists of four block of TL is illustrated in Figure 9.

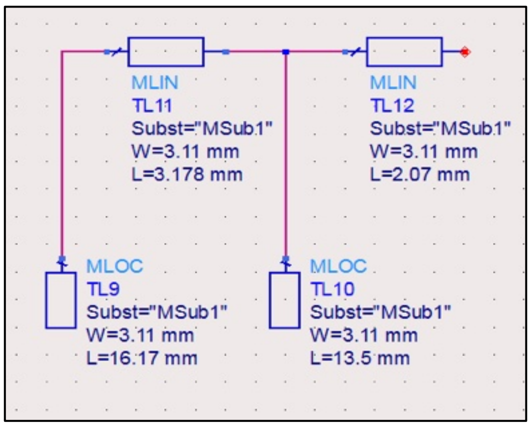

Figure 9: Simulated Block diagram of Transmission Lines (TL) at 2.4 GHz.

2.2 Rectifier Circuit Operating at 2.4 GHz with LC-Circuit Matching Network

As shown in Figure 10, a single-stage rectifier is simulated in Advanced Design System (ADS). A power source which in such systems anticipated as the antenna component is found in the employed circuit. The power source has an internal impedance of 50 Ω and transmits an RF power of 25 dBm at 2.4 GHz. The matching network circuit for the rectifier circuit, which consists of two methods, LC-Circuit and Transmission Line (TL), is chosen to match between the antenna and the rectifier. Furthermore, HSMS-2820 diodes were used, which contributed to rectifying the coming RF signal and transforming it from alternating current AC to direct current DC. At the input, the series capacitance acts as a voltage doubler. Additionally, the output has a capacitance to smooth the DC output before it is fed to the load as DC power or stored in a battery, as illustrated in Figure 10. It is necessary to note that the circuit below is intended to be printed on an FR-4 substrate with a 4.3 dielectric constant that is set in the Er MSub block and a thickness of 1.57 mm that is set in the H MSub block, where 63 mil equals 1.57 mm. The matching network has done the job perfectly, where excellent matching is achieved, as shown in the S-parameters curve in Figure 11.

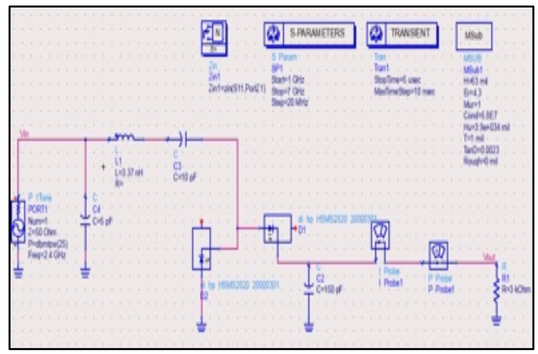

Figure 10: Rectifier circuit operating at 2.4 GHz with LC-Circuit.

Table 1: Show the DC Voltage output and Efficiency (η) for different input power (Pin).

Pin (dBm)	Vout (dc)	Efficiency (η)
-10	53 mV	0.88 %
-5	200 mV	21.7 %
0	430 mV	6.2 %
5	0.9 V	9.4 %
10	2.2 V	45.22 %
15	3.6 V	13.37 %
20	5.9 V	11.2 %
25	9 V	27.8 %

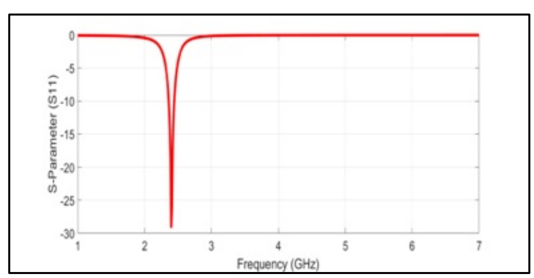

Figure 11: Simulated S11 of rectifier circuit at 2.4 GHz with LC-Circuit.

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Figure 12, Displays the input voltage waveform that is fed to the rectifier circuit at 2.4 GHz frequency band, which is simulated by ADS.

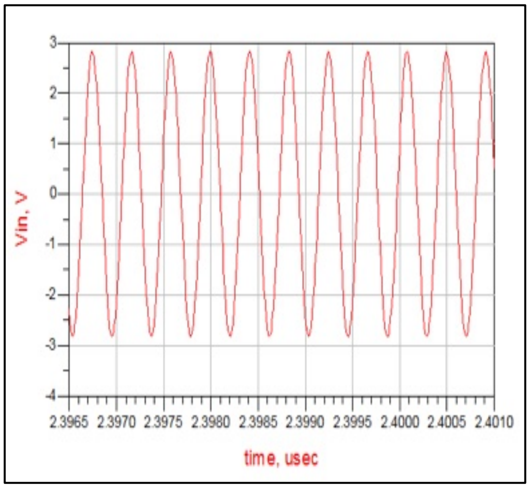

Figure 12: Vin (V) of Rectifier Circuit at 2.4 GHz with LC-Circuit.

Figure 13 illustrates the output voltage waveform for rectifier circuit at 2.4 GHz. The achieved DC output voltage is around 3 V as shown in Figure 13, as observed that the ripple is acceptable in this application.

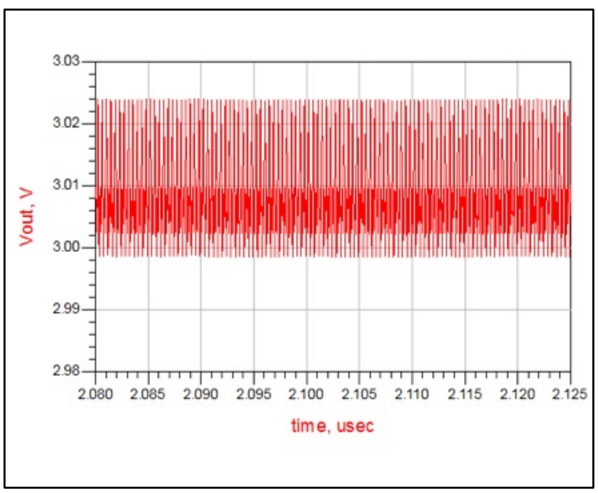

Figure 13: Vout (V) of Rectifier Circuit at 2.4 GHz with LC-Circuit.

Figure 14, Displays the waveform of output current for the rectifier circuit at 2.4 GHz . The output current is about 9 mA, and with changing the load value will change the output current also.

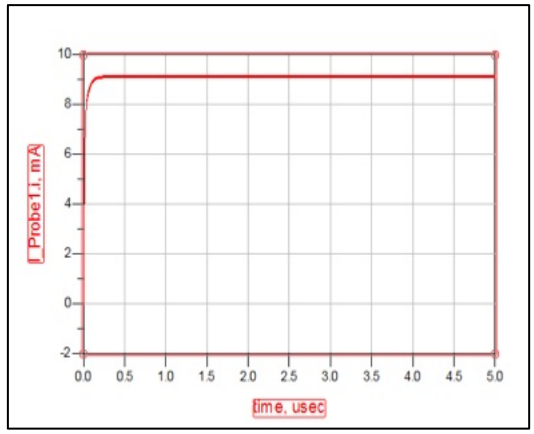

Figure 14: Output current of Rectifier Circuit at 2.4 GHz with LC-Circuit.

Figure 15 shows the measurement of the rectifier's performance. It has been investigated how the input power Pin impact the output voltage. The relationship between the input power (Pin) and the output voltage (Vout) of rectifier circuit at 2.4 GHz is recorded. It is clearly seen the output voltage increases exponentially with increasing the input power (Pin). A maximum output voltage is around 9 V is achieved at input power of 25 dBm, which is equivalent to 25 mW.

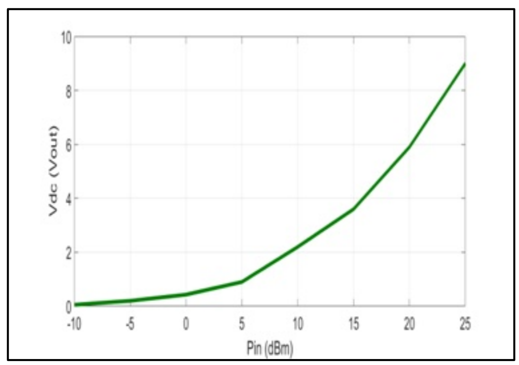

Figure 15: Vout (V) versus Pin (dBm) of Rectifier Circuit at 2.4 GHz with LC-Circuit.

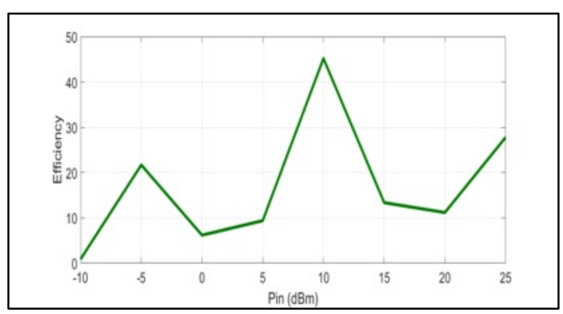

Figure 16: Efficiency versus input power of Rectifier Circuit at 2.4 GHz with LC-Circuit.

Figure 16 shows that when the input power increases, the efficiency gradually rises. It also suggests that a slight increase must produce significant improvement in system performance. In other words, the efficiency behaviour changes due to losses in power.

2.3 Rectifier Circuit Operating at 3.6 GHz with LC-Circuit Matching Network

A rectifier circuit can be operated at 3.6 GHz by setting the source of power to 3.6 GHz, as illustrated in Figure 17. The S-parameters results show that the rectifier circuit has an excellent matching at 3.6 GHz due to the matching LC-circuit as shown in Figure 18.

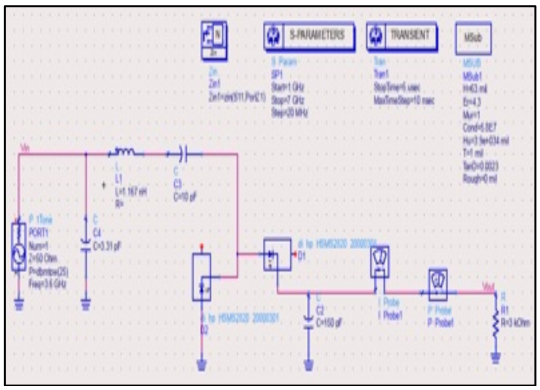

Figure 17: Rectifier circuit operating at 3.6 GHz with LC-Circuit.

Table .2: Show the DC Voltage output and (Vdc) and Efficiency (η) for different input power (Pin) at 3.6 GHz with LC-Circuit.

Pin (dBm)	Vout (dc)	Efficiency (η)
-10	16 mV	0.077%
-5	170 mV	3.06%
0	500 mV	27.5%
5	1 V	29.89%
10	1.6 V	8.33%
15	2.5 V	6.7%
20	3.7 V	4.55%
25	5.5 V	3.33%

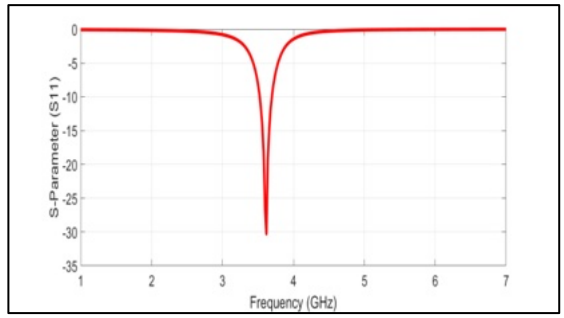

Figure 18: Simulated S11 of Rectifier Circuit at 3.6 GHz with LC-Circuit.

Figure 19, Displays the input voltage waveform that is fed to the rectifier circuit at a 3.6 GHz frequency band, which is simulated by ADS.

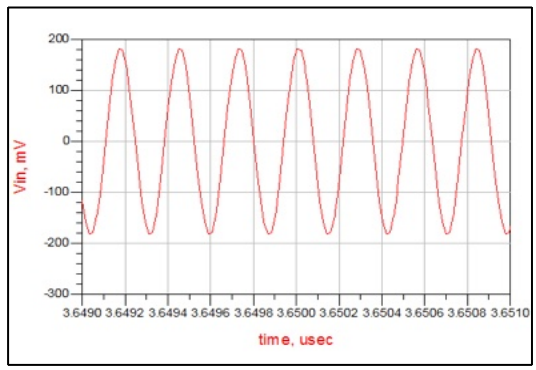

Figure 19: Vin (V) of Rectifier Circuit at 3.6 GHz with LC-Circuit.

Figure 20 illustrates the output voltage waveform for rectifier circuit at 3.6 GHz. The achieved DC output voltage is around 1.6 V, as can be shown below in Figure 20, as observed that the ripple is very small.

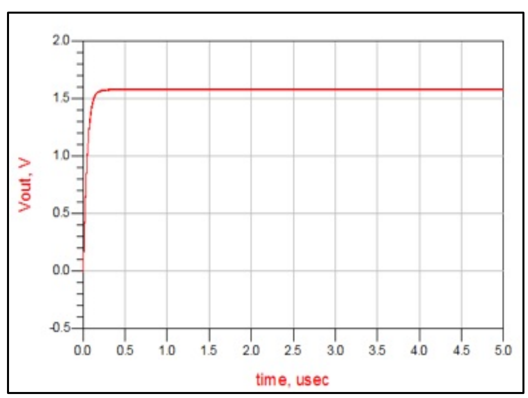

Figure 20: Vout (V) of Rectifier Circuit at 3.6 GHz with LC-Circuit.

Figure 21 displays the waveform of output current for the rectifier circuit at 3.6 GHz. The output current is about 530 uA, and changing the load value will change the output current also.

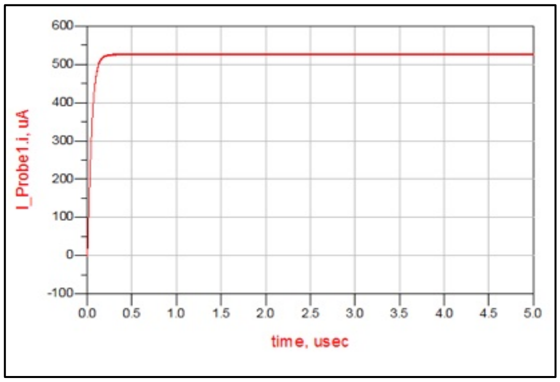

Figure 21: Output current of Rectifier Circuit at 3.6 GHz with LC-Circuit.

Figure 22 shows a measure of the rectifier's performance in addition Vout value and quality, it has been investigated how the input power Pin impacts the output voltage. The relationship between the input power (Pin) and the output voltage (Vout) of the rectifier circuit at 3.6 GHz. It may be clearly seen the output voltage increases exponentially with increasing the input power (Pin). A maximum output voltage is around 5.7 V is achieved at an input power of 25 dBm.

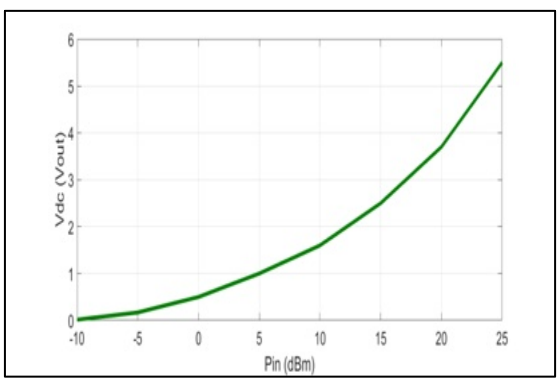

Figure 22: Vout (V) versus Pin (dBm) of Rectifier Circuit at 3.6 GHz with LC-Circuit.

Figure 23 shows that when the input power increases, the efficiency gradually rises. Also, it suggests that a slight increase must produce significant improvement in system performance. In other words, increasing the input power from -10 to 25 dBm produces an output voltage rise from 0 to 5.7 V and an efficiency rise from 0% to 27%.

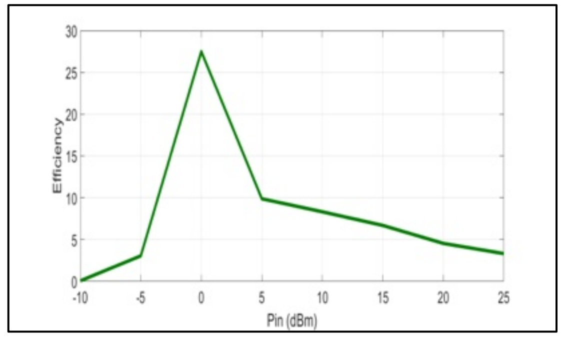

Figure 23: Efficiency versus input power of Rectifier Circuit at 3.6 GHz with LC-Circuit.

2.4 Rectifier Circuit Operating at 5 GHz with LC-Circuit Matching Network

A rectifier circuit can be operated at 5 GHz by setting the source of power to 3.6 GHz, as illustrated in Figure 24. The S-parameters results show that the rectifier circuit has an excellent matching at 5 GHz due to the matching LC-circuit as shown in Figure 25.

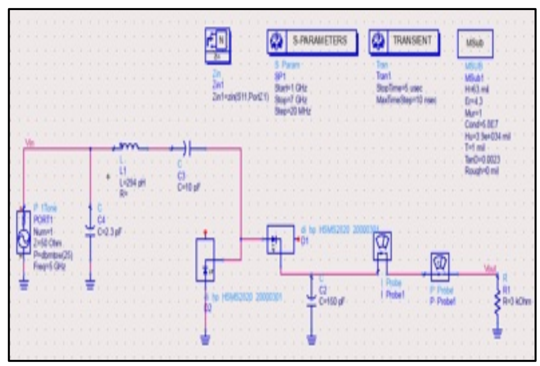

Figure 24: Rectifier circuit operating at 5 GHz with LC-Circuit.

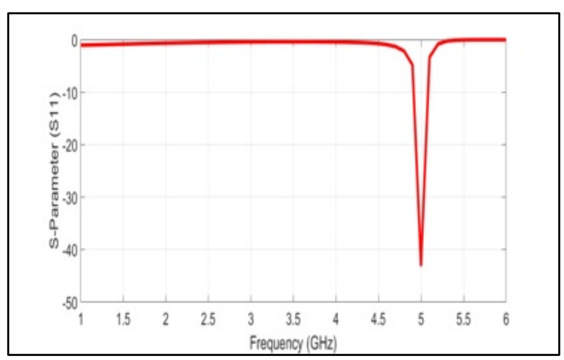

Figure 25: Simulated S11 of Rectifier Circuit at 5 GHz with LC-Circuit.

Table .3: Show the DC Voltage output and (Vdc) and Efficiency (η) for different input power (Pin) at 5 GHz with LC-Circuit.

Pin (dBm)	Vout (dc)	Efficiency (η)
-10	3 mV	0.0002 %
-5	60 mV	0.35 %
0	350 mV	3.9 %
5	0.8 V	16 %
10	1.7 V	27 %
15	2.7 V	13.37 %
20	4.5 V	11.2 %
25	7 V	33.8 %

Figure 26 displays the input voltage waveform that is fed to the rectifier circuit at 5 GHz frequency band, which is simulated by ADS.

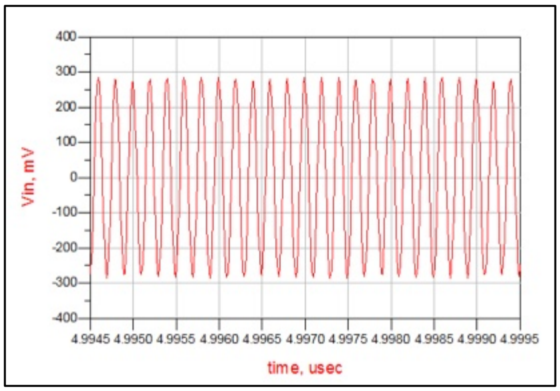

Figure 26: Vin (V) of rectifier circuit at 5 GHz with LC-Circuit.

Figure 27 illustrates the output voltage waveform for rectifier circuit at 5 GHz. The achieved DC output voltage is around 1.7 V, as can be shown in Figure 27, as observed that the ripple is very small.

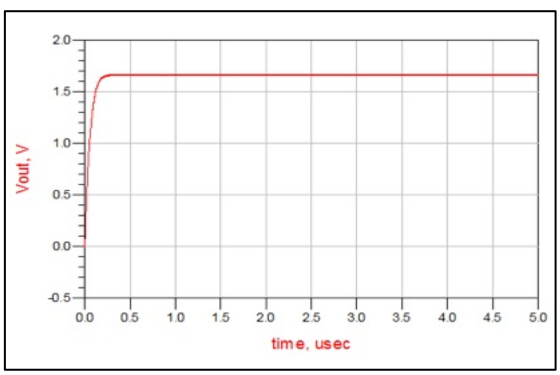

Figure 27: Vout (V) of rectifier circuit at 5 GHz with LC-Circuit.

Figure 28, Displays the waveform of output current for the rectifier circuit at 5 GHz. The output current is about 550 uA.

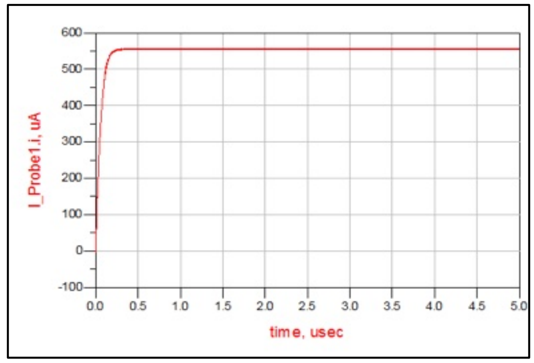

Figure 28: Output current of rectifier at 5 GHz with LC-Circuit.

Figure 29 shows the measure of the rectifier's performance in addition Vout value and quality, it has been investigated how the input power Pin impact the output voltage. The relationship between the input power (Pin) and the output voltage (Vout) of rectifier circuit at 5 GHz. It can be clearly seen the output voltage increases exponentially with increasing the input power (Pin). A maximum output voltage is around 7 V is achieved at input power of 25 dBm.

From Figure 30, it is shown that when the input power increases, the efficiency gradually rises. Also it suggests that a slightly increase produces significant improvement in system performance. In other words, increasing the input power from -10 to 25 dBm produce an output voltage rise from 0 to 7 V and efficiency rise from 4 % to 26 %. This demonstrates that increasing the input power improves the efficiency.

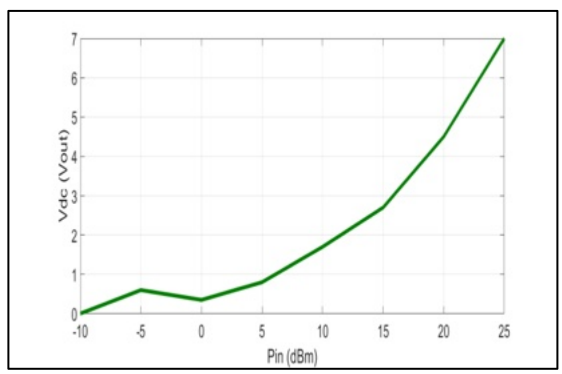

Figure 29: Vout (V) virsus Pin (dBm) of rectifier circuit at 5 GHz with LC-Circuit.

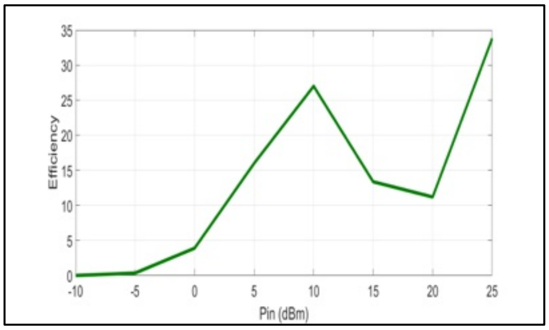

Figure 30: Efficiency versus input power of rectifier at 5 GHz.

2.5 Rectifier Circuit Operating at 2.4 GHz with TL-Circuit Matching Network

Another way of impedance matching is applied by using the Smith Chart capability in ADS software. In this way, a transmission line stub is employed at the input part of the circuit to match the source to the rectifier circuit as illustrated in Figure 31. Figure 32 shows the simulated S11 of the Rectifier Circuit at 2.4 GHz with TL-Circuit, where the return loss value went below -14 dB.

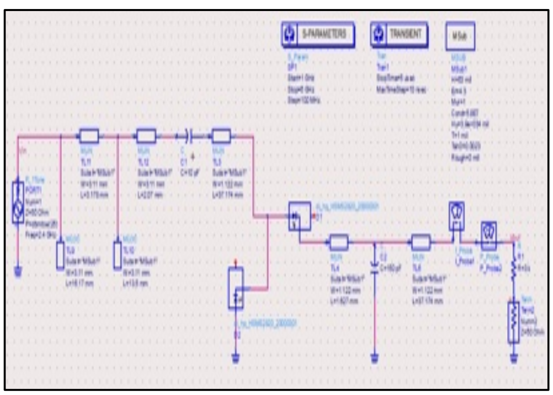

Figure 31: Rectifier circuit operating at 2.4 GHz with TL-Circuit.

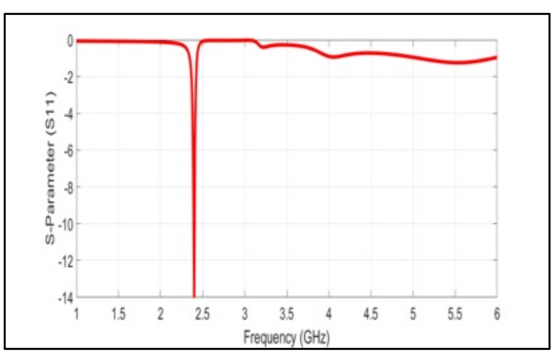

Figure 32: Simulated S11 of Rectifier Circuit at 2.4 GHz with TL-Circuit.

Figure 33 displays the input voltage waveform that is fed to the rectifier circuit with TL-Circuit at 2.4 GHz frequency band, which is simulated by ADS.

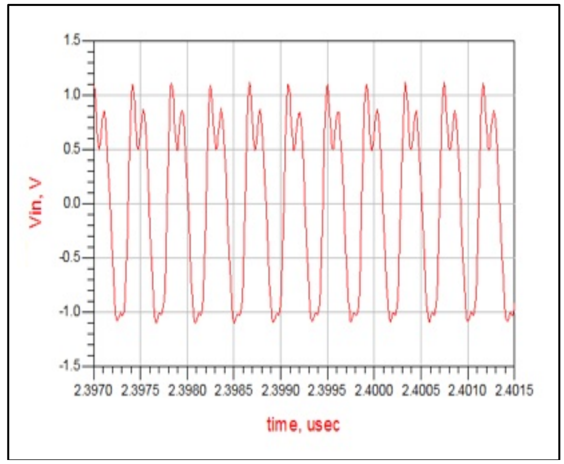

Figure 33: Vin (V) of Rectifier Circuit at 2.4 GHz with TL-Circuit.

Figure 34, on the other hand, illustrates the output voltage waveform for the rectifier circuit with TL-Circuit at 2.4 GHz. The achieved DC output voltage is around 11.3 V as shown in Figure 34. As observed the ripple is acceptable in this application.

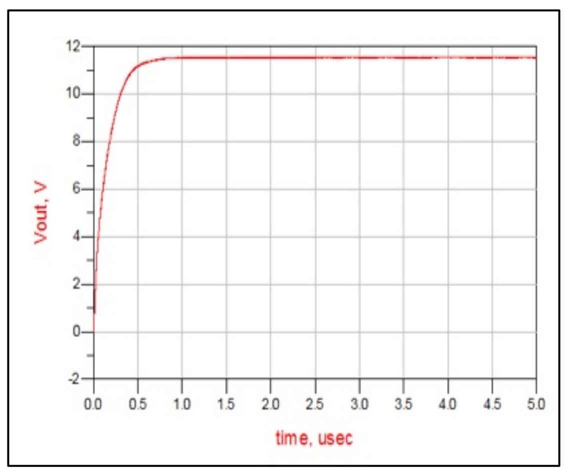

Figure 34: Vout (V) of Rectifier Circuit at 2.4 GHz with TL-Circuit.

Figure 35, Displays the waveform of output current for the rectifier circuit with TL-Circuit at 2.4 GHz. The output current is about 3.44 mA, and changing the load value will change the output current and the current ripple in this case is 0.008 mA.

Figure 35: Output current of Rectifier Circuit at 2.4 GHz with TL-Circuit.

Figure 36, shows the measurement of the rectifier's performance. It has been investigated how the input power Pin impacts the output voltage. The relationship between the input power (Pin) and the output voltage (Vout) of the rectifier circuit with TL-Circuit at 2.4 GHz is recorded. It is clearly seen the output voltage increases exponentially with increasing the input power (Pin). A maximum output voltage of around 10.5 V is achieved at an input power of 25 dBm.

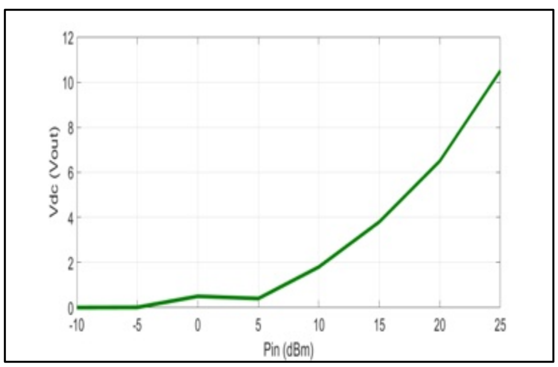

Figure 36: Vdc (Vout) versus input power of rectifier at 2.4 GHz with TL-Circuit.

Figure 37 shows that when the input power increases, the efficiency gradually rises. It also suggests that a slight increase must produce significant improvement in system performance. In other words, increasing the input power from -10 to 25 dBm may produce an output voltage rise from 0 to 10.5 V and efficiency rise from 2% to 27%.

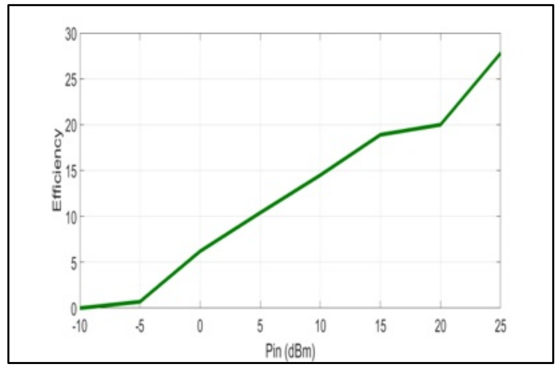

Figure 37: Efficiency versus input power of Rectifier Circuit at 2.4 GHz with TL-Circuit.

2.6 Rectifier Circuit Operating at 3.6 GHz with TL-Circuit Matching Network

A rectifier circuit can be operated at 3.6 GHz by setting the source of power to 3.6 GHz, as illustrated in Figure 38. The simulated S11 is depicted in Figure 39, where the matching circuit has achieved the goal.

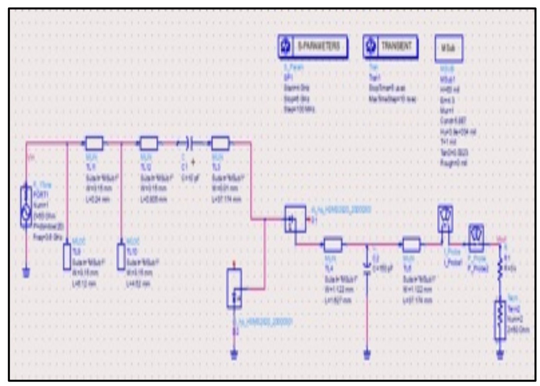

Figure 38: Rectifier circuit operating at 3.6 GHz with TL-Circuit.

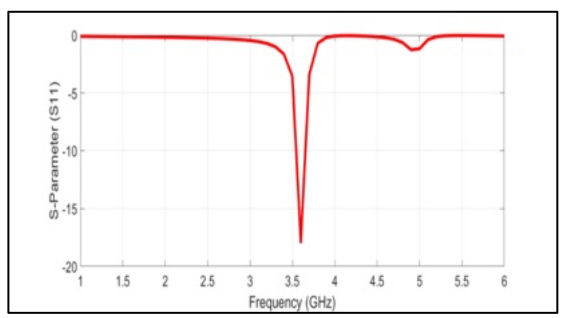

Figure 39: Simulated S11 of Rectifier Circuit at 3.6 GHz with TL-Circuit.

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Figure 40 displays the input voltage waveform that is fed to the rectifier circuit with TL-Circuit at 3.6 GHz frequency band, which is simulated by ADS.

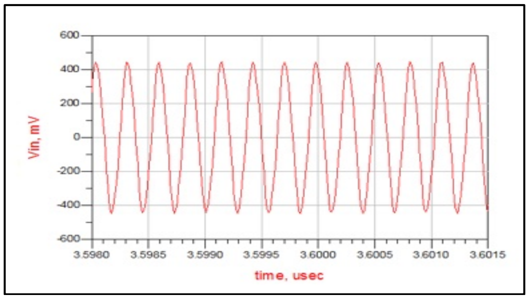


Figure 40: Vin (V) of Rectifier Circuit at 3.6 GHz with TL-Circuit.

Figure 41 illustrates the output voltage waveform for the rectifier circuit with TL-Circuit at 3.6 GHz. The achieved DC output voltage is around 1.7 V as shown in Figure 41, as observed that the ripple is acceptable in this application.

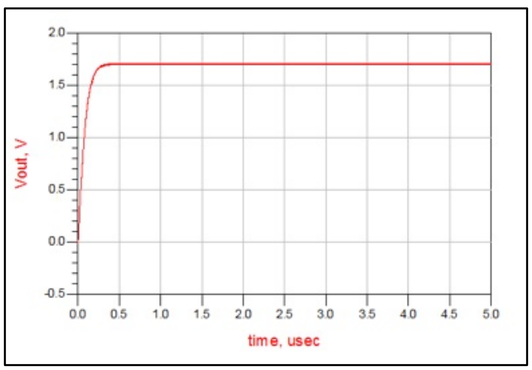


Figure 41: Vout (V) of Rectifier Circuit at 3.6 GHz with TL-Circuit.

Figure 42 displays the waveform of output current for the rectifier circuit with TL-Circuit at 3.6 GHz. The output current is about 560 uA, and changing the load value will change the output current, and the current ripple in this case is 4 uA.

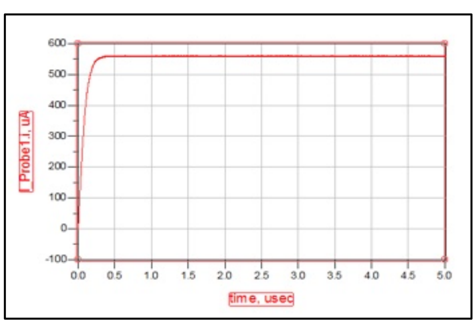
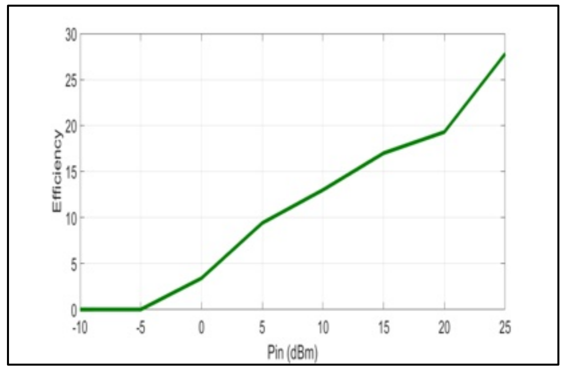


Figure 42: Output current of Rectifier Circuit at 3.6 GHz with TL-Circuit.

Figure 43 shows the measurement of the rectifier's performance. It has been investigated how the input power Pin impacts the output voltage. The relationship between the input power (Pin) and the output voltage (Vout) of the rectifier circuit with TL-Circuit at 3.6 GHz is recorded. It is clearly seen the output voltage increases exponentially with increasing the input power (Pin). A maximum output voltage is around 2.6 V is achieved at an input power of 25 dBm.



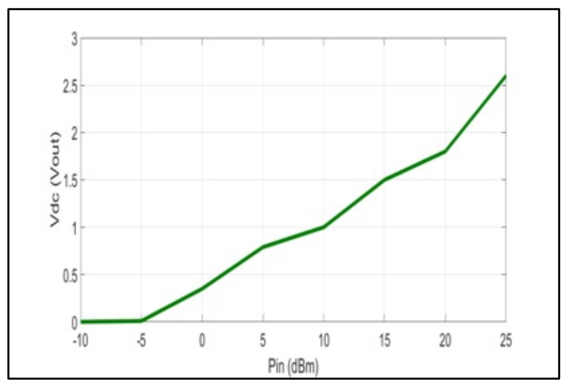


Figure 43: Vdc (Vout) versus input power of rectifier at 3.6 GHz with TL-Circuit.

Figure 44 shows that when the input power increases, the efficiency gradually rises. It also suggests that a slight increase must produce significant improvement in system performance. In other words, increasing the input power from -10 to 25 dBm may produce an output voltage rise from 0 to 2.6 V and efficiency rise from 2% to 27%.

Figure 44: Efficiency versus input power of Rectifier Circuit at 3.6 GHz with TL-Circuit.

2.7 Rectifier Circuit Operating at 5 GHz with TL-Circuit Matching Network

A rectifier circuit can be operated at 5 GHz by setting the source of power to 5 GHz, as illustrated in Figure 45. Figure 46 shows the simulated S11 of the Rectifier Circuit at 5 GHz with TL-Circuit.

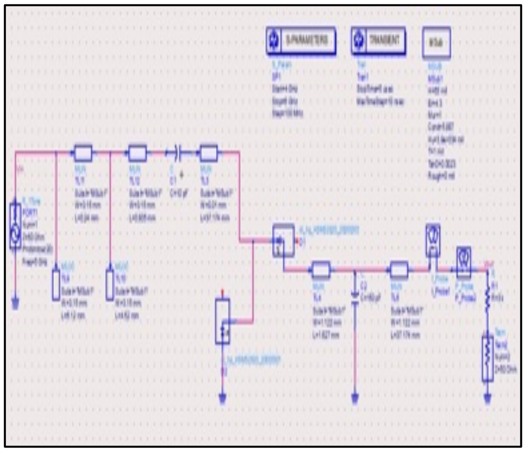


Figure 45: Rectifier circuit operating at 5 GHz with TL-Circuit.

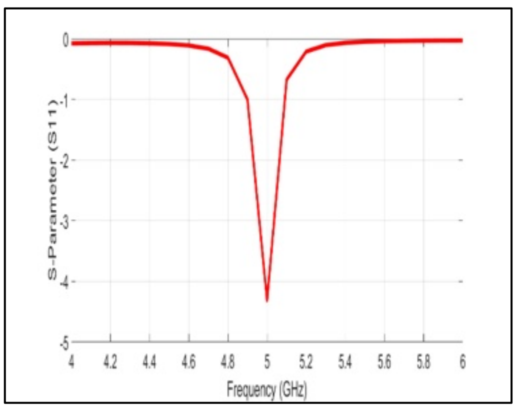


Figure 46: Simulated S11 of Rectifier Circuit at 5 GHz with TL-Circuit.

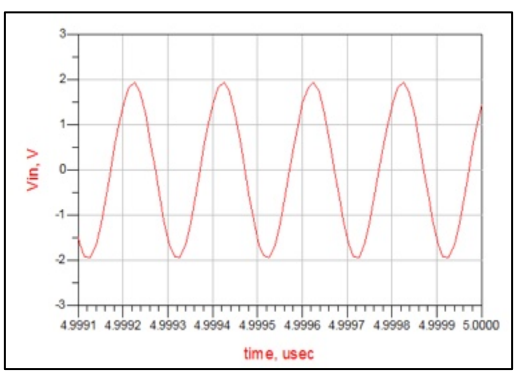


Figure .47: Vin (V) of Rectifier Circuit at 5 GHz with TL-Circuit.

Figure 47 displays the input voltage waveform that is fed to the rectifier circuit with TL-Circuit at 5 GHz frequency band, which is simulated by ADS.

Figure 48 illustrates the output voltage waveform for rectifier circuit with TL-Circuit at 5 GHz. The achieved DC output voltage is around 6.5 V as shown in Figure 48, as observed that the ripple is acceptable in this application.

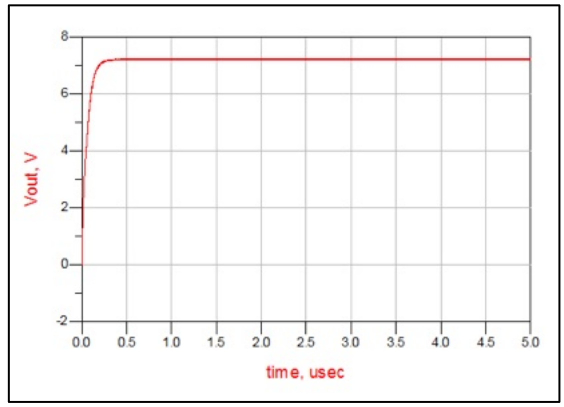


Figure 48: Vout (V) of Rectifier Circuit at 5 GHz with TL-Circuit.

Figure 49 displays the waveform of output current for the rectifier circuit with TL-Circuit at 5 GHz . The output current is about 2.4 mA, and with changing the load value will change the output current also.

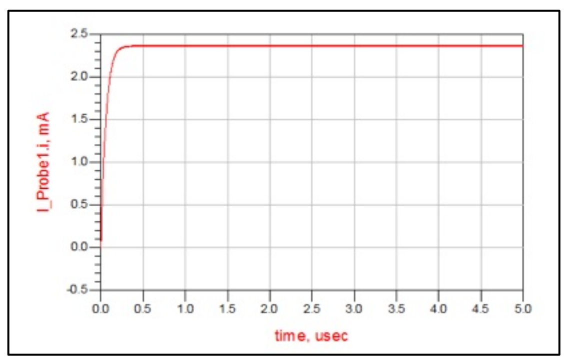


Figure 49: Output current of Rectifier Circuit at 5 GHz with TL-Circuit.

The relationship between the input power (Pin) and the output voltage (Vout) of rectifier circuit with TL-Circuit at 5 GHz is recorded in Figure 50. It is clearly seen the output voltage increases exponentially with increasing the input power (Pin). A maximum output

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voltage is around 6 V is achieved at input power of 25 dBm.

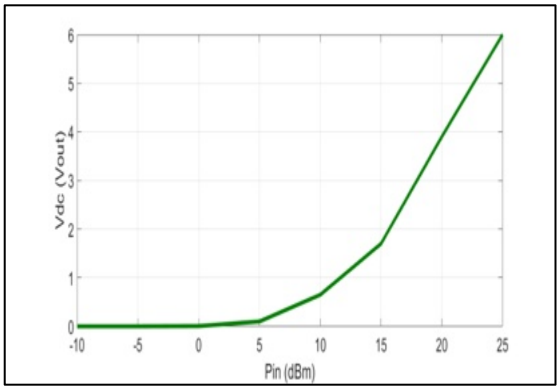

Figure 50: Vdc (Vout) versus input power of Rectifier Circuit at 5 GHz with TL-Circuit.

Figure 51 shows that when the input power increases, the efficiency gradually rises. It also suggests that a slight increase must produce significant improvement in system performance. In other words, increasing the input power from -10 to 25 dBm may produce an output voltage rise from 0 to 6 V and efficiency rise from 0% to 18%.

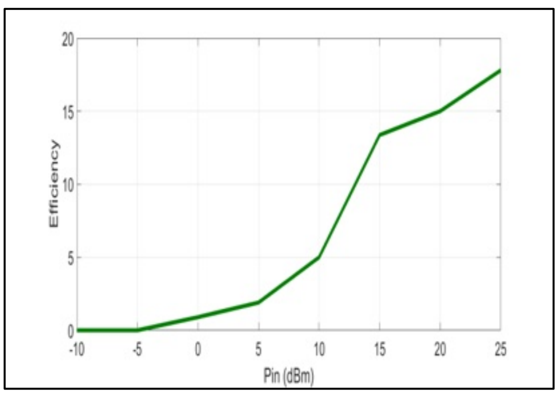

Figure 51: Efficiency versus input power of Rectifier Circuit at 5 GHz with TL-Circuit.

3 Fabrication and Experimental Validation

To validate the concept and for experimental validation, the rectifier circuit that operates at 2.4 was fabricated using PCB technology. FR-4 substrate with a dielectric constant of 4.3 and thickness of 1.6 mm is employed. Figure 52 illustrates the PCB schematic diagram of the fabricated circuit which is a double-layer circuit with a full ground plane at the back of the substrate. All the circuit components were available in the market.

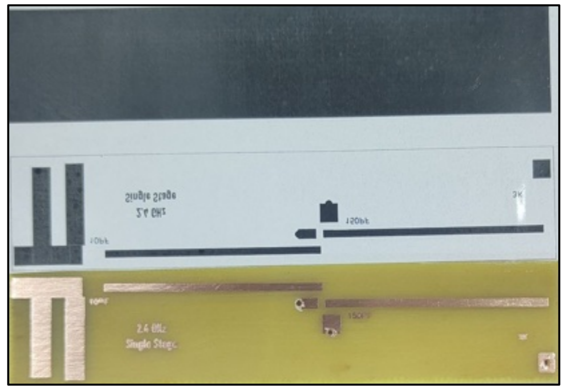

Figure 52: Rectifier circuit layout for fabrication.

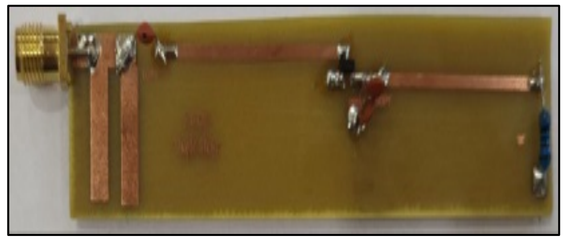

Figure 53: Photo of the front layer of the rectifier circuit.

Figure 54: Photo of the back layer of the rectifier circuit.

The fabricated rectifier circuit was fed by TGR6000 1GHz Synthesized RF Signal Generator with a variable input power level (in dBm) through a rigid microwave coaxial cable. SMA connector is attached to the input port of the fabricated circuit and the S11 (Reflection Coefficient) is measured by Network Analyzer as shown in Figure 55, and then the output voltage is measured using a multipurpose digital AVO meter as illustrated in Figure 56. It can be seen from Figure 55 that the best impedance matching is achieved at 1.87 GHz, not 2.4 GHz. This difference is due to the fabrication tolerance, which causes to slight change in the resonant frequency of the circuit and alters the impedance-matching characteristics. Thus, in the measurement phase, the circuit was operated at 1.87 GHz, and the output voltage was recorded at different input power. Furthermore, the employed TGR6000 1GHz Synthesized RF Signal Generator has a maximum input power of 7 dBm so that our measurements were limited to this value.

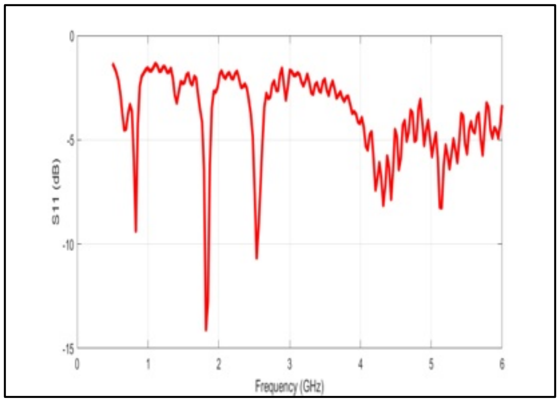

Figure 55: Measured S11 for the fabricated rectifier circuit.

Figure 56: Photograph of the experimental setup showing the measurement of Vdc (Vout) Versus Pin (dBm).

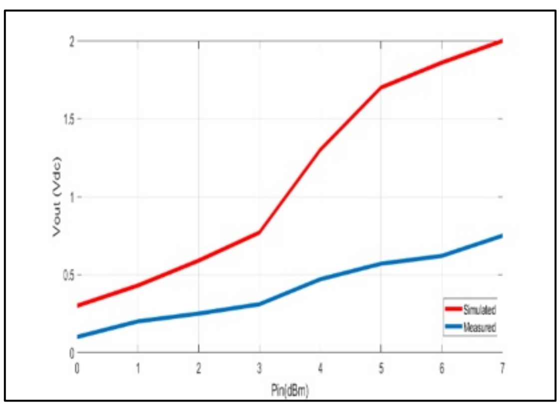

Figure 57: Comparison between simulated and Measured Vdc (Vout) versus Pin (dBm) at 3 kΩ.

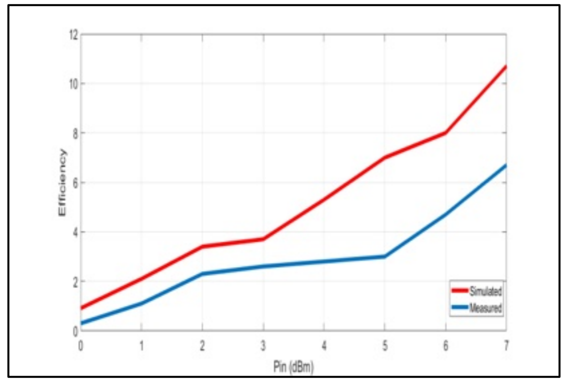

Figure 58: Comparison between simulated and Measured Efficiency (η) versus Pin (dBm) at 3 kΩ.

4 Conclusions

This work proposes the design and construction of a compact single-stage rectifier circuit for energy harvesting applications at 2.4, 3.6, and 5 GHz bands, using an HSMS-2820 Schottky diode. An LC-section impedance matching network and a Transmission Lines (TL) circuit are designed to match the input impedance of the rectifier with the 50 Ω source. The circuit undergoes parametric tuning from an ideal to a model component to achieve better performance and minimize the effects of the transmission line in the network. The simulated results of the rectifier with LC-Circuit at 2.4 GHz can receive an ambient RF signal at 10 dBm and achieve 45.22% maximum PCE and 2.2 V of output DC voltage using a 3 kΩ load terminal.

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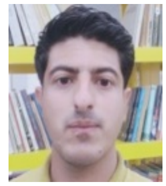
Biography



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