Jurnal
Teknologi

Full Paper

DEVELOPMENT OF CASCADED VOLTAGE DOUBLER RECTIFIER FOR RF ENERGY HARVESTING

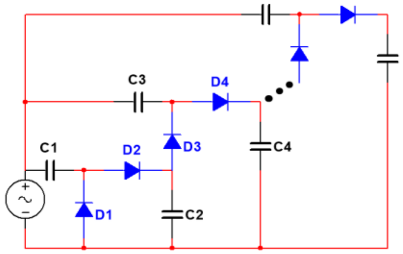
Ismahayati Adam[a]*, Mohd Najib Mohd Yasin[a], Siti Zuraidah Ibrahim[a], Norshakila Haris[b]

[a]Fakulti Teknologi Kejuruteraan Elektronik, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia
[b]Universiti Kuala Lumpur Malaysian Institute of Marine Engineering Technology, 32200 Lumut, Perak, Malaysia

Article history
Received
25 August 2021
Received in revised form
9 November 2021
Accepted
3 December 2021
Published Online
21 February 2022

*Corresponding author
ismahayati@unimap.edu.my

Graphical abstract



Abstract

Radio Frequency (RF) energy harvesting is a process where RF energy from the ambient source is collected and converted into an electrical energy by using a rectifier circuit. However, the collected RF energy only supplies very low input power. Therefore, it is important to design a circuit that not only rectified the RF signal, but also with amplified characteristic to obtain a higher output voltage from a low input power. Driven by the increasing use of Internet of Things (IoT) devices operating in the 2.4 GHz Industrial, Scientific, and Medical (ISM) band, the presented rectifier circuit in this paper is designed in the same band as well. Initially, the voltage doubler circuit is chosen as the primary rectifier circuit, afterward cascaded into several stages until the most optimized result is obtained. The optimization is investigated across -30 dBm to 0 dBm of RF input power by varying the value of capacitor and resistor at a single stage. Based on the topology analysis, Dickson topology yields slightly higher voltage compared to Villard. In turn, the optimized number of stages is 6 because higher stages resulted to less output power. The measured reflection coefficient of the fabricated prototype is better than 40 dB at the center frequency with 240 MHz bandwidth. The rectified voltage is 3.4 V with 0 dBm input power. When it is supplied by 5 dBm input power, the green LED that connected to rectifier circuit output is light-up, confirming the RF energy harvesting application.

Keywords: ISM band, multistage, rectifier circuit, RF energy harvesting, schottky diode, voltage doubler

Abstrak

Penuaian tenaga Frekuensi Radio (RF) adalah proses di mana tenaga RF dari sumber ambien dikumpulkan dan diubah menjadi tenaga elektrik dengan menggunakan litar penerus. Walau bagaimanapun, tenaga RF yang dikumpulkan hanya membekalkan daya input yang sangat rendah. Oleh itu, adalah penting untuk merekabentuk satu litar yang tidak hanya membetulkan isyarat RF, tetapi juga dengan ciri yang diperkuat untuk mendapatkan voltan keluaran yang lebih tinggi dari daya input yang rendah. Didorong oleh peningkatan penggunaan peranti IoT yang beroperasi di jalur Industri, Ilmiah, dan Perubatan (ISM) 2,4 GHz, rangkaian penyearah yang disajikan dalam makalah ini juga dirancang pada jalur yang sama. Pada mulanya, rangkaian penggandaan voltan dipilih sebagai litar penyearah utama, setelah itu dilancarkan ke beberapa tahap sehingga hasil yang paling optimum diperoleh. Pengoptimuman disiasat di antara -30 dBm hingga 0 dBm kuasa input RF dengan mengubah nilai kapasitor dan perintang pada satu tahap. Berdasarkan

84:2 (2022) 153–161 | https://journals.utm.my/jurnalteknologi | eISSN 2180–3722 | DOI:
https://doi.org/10.11113/jurnalteknologi.v84.17405 |

analisis topologi, topologi Dickson menghasilkan voltan yang sedikit lebih tinggi berbanding dengan Villard. Seterusnya, bilangan tahap yang dioptimumkan adalah 6 kerana tahap yang lebih tinggi menghasilkan daya output yang lebih sedikit. Pekali pantulan yang diukur dari prototaip buatan lebih baik daripada 40 dB pada frekuensi tengah dengan lebar jalur 240 MHz. Voltan yang diperolehi ialah 3.4 V dengan kuasa masukan 0dBm. Apabila ia dibekalkan oleh daya input 5dBm, LED hijau yang disambungkan ke keluaran litar penerus akan menyala, mengesahkan aplikasi pengambilan tenaga RF.

Kata kunci: Band ISM, berperingkat. Litar penerus, Penuaian tenaga RF, diod Schottky, pengganda voltan

1.0 INTRODUCTION

Wireless technology is experiencing tremendous growth owing to technological advancements and rising number of subscribers. Signal such as Television (TV) and radio broadcasting, wireless Local Area Network (LAN) and mobile communication signal have triggered significant interest in radio frequency (RF) energy harvesting. RF energy harvesting has caught research attention as promising approaches in providing power with relatively small voltages and currents applications. Some argued on whether there is enough energy to be harvested and how this harvested energy could be applied to current electronic devices. Still, on the bright side, this technology will be significant soon once the Internet of Things (IoT) is implemented as it will create more opportunities for energy harvesting. Wireless LAN 2.4 GHz and 5.8 GHz bands are expected to be the core communication links for IoT, which a lot of researchers [1]–[4] reported working on rectifier in the said bands.

The concept of harvesting direct current (DC) power from RF signal is obtained from a combination of receiving antenna and rectifier circuit, also known as rectenna. Figure 1 illustrates the concept of RF energy harvesting, from an RF input into DC output. Main element that determines the effectiveness of the system, is the rectifier circuit. Rectifier is an electrical device that will convert alternating current (AC) into direct current (DC) which only flows into single direction. This process is known as rectification.

Figure 1 RF Energy Harvester Block Diagram

Rectifying elements such as diode and Complementary Metal-Oxide-Semiconductor (CMOS) technology are the fundamental components in rectifier circuit. In terms of simplicity and small input signal, schottky diode technology is better choice compared to CMOS technology as designer need to consider more parameters in designing rectifier based on CMOS technology [5]-[7]. For instance, 4 stage CMOS rectifier is proposed in [5]-[6], where Saffari *et al*. (2019) obtained a maximum PCE of 43% with -11 dBm input power of 1 MΩ load [5], while PCE of 66% with 100 kΩ load is achieved by Almansouri *et al*. 2018 by proposing double sided topology [6]. According to [7], CMOS technology required a high threshold voltage that would lead to the reduction of the circuit efficiency.

From a single to multistage rectification techniques, designed for either devoted source or the ambient, [1]-[4] reported on development of rectifier for energy harvesting. For a low power RF input, a single stage rectification might not sufficient to provide enough DC voltage, which driven the design of multistage rectification [8]–[13]. Even though a multistage rectifier will improve the output DC voltage, however, it has certain limits which eventually will affect the power conversion efficiency. A 7-stages rectifier circuit is presented in [8], where the rectified voltage is 2.22 V at 0 dBm RF input by utilizing HSMS2850. The same diode also been employed by [2], with the achievement of 70 mV with 24.3% at -20 dBm input power for a single stage rectifier. Efficiency above 65% is achieved by [9] with the cost of high input power of 16 dBm. Najeeb *et al.* (2019) presented a 8-stage rectifier operated at 1800 MHz, the output voltage of 3.5 V is attained for a load of 5 MΩ [11]. On the other hand, [15] and [16] proposed a voltage doubler rectifier design by implementing SMS3670 diode as rectification element. An efficiency of 39% at 0 dBm is achieved in [15], while 50.7% efficiency is obtained with an input power of -10 dBm, by later authors. Table I shows the comparison of literature works on rectifier for 2.4 GHz applications. Out of ordinary configuration, Nazari *et al*. (2018) proposed a phase cascade lattice rectifier array to overcome the nonlinear issues in the rectifier performance [17]. Each stage is consisting of an AC source with controllable phases in a bridge-rectifier like configuration. This method generates ripple-free DC power.

Table 1 shows a comparison works on the RF rectifier circuit based on Schoktky diode technology. The comparison were made on a basis of diode, technique, efficiency, load and the rectified voltage. The rectified voltage in Table 1 are referred to input power stated at the stated efficiency.

Table 1 Comparison works on RF rectifier circuit

Ref.	Diode	Technique	Efficiency (η) @ power	Load (Ω)	Rectified Voltage
[8]	HSMS 2850	7-stages	Not stated @ 0 dBm	100k	2.22 V
[9]	HSMS 2862	2-stages	75% @ 16 dBm	1k	4.705 V
[13]	HSMS 2860	Single stage	66.5% @ 10 dBm	1.3 k	2.94 V
[14]	SMS 3670	Single stage	39% @ 0 dBm	2.2k	Not stated
[15]	SMS 3670	Voltage doubler	50.7% @ -10 dBm	5k-75k	Not stated
This work	SMS 3670	6-stages	63% @ -10 dBm	820k	0.9 V

In this paper, steps in developing the rectifier circuit starting from the technical specification consideration of the key components, circuit simulation and measurement process are comprehensively explained. The rectifier circuit is designed at 2.4 GHz ISM band because most of IoT devices are operated in this band. The output of the rectifier circuit is investigated across -30 dBm to 0 dBm RF input power.

2.0 METHODOLOGY

The aim of this work is to design a rectifier circuit that will produce an efficient DC output voltage and power. The circuit is designed using Advanced Design System (ADS) software by Keysight. In this section, the design process of the rectifier circuit will be explained in detail.

A. Diode

Diode carries an important role in rectifier design as its characteristic influences the performance of rectifier. Schottky diode is the most suitable diode in rectifier circuit as it has a low voltage drop and high switching rate. Compared to normal silicon diode which has a voltage drop between 0.6V to 1.7V, Schottky diode provides a voltage drop approximately between 0.15V to 0.24V only.

Table 2 Schottky diode parameters comparison

Diode	V_t (V)	R_s (Ω)	J_c (pF)	Is (A)
HSMS-2850	0.35	25	0.18	3e-6
HSMS-2860	0.65	6	0.18	5e-8
SMS-7630	0.34	20	0.14	5e-6
SMS- 7621	0.55	12	0.1	2.6e-8

Table 2 shows the comparison of main parameters in diode which are threshold voltage (*Vt*), series resistance (*Rs*) and junction capacitor (*Jc*). For high conversion efficiency at high frequency with low powers, the diode should have low *Vt*, *Rs* and *Jc* values, but high saturation current, *Is* [11]. Hence, in this work, SMS7630 Schottky diode is used as it offers low parasitic impedance at high frequency with great sensitivity (-30 dBm) [18].

B. Capacitor

Capacitor also carries an important role in this rectifier design. Capacitor is used to store potential energy in the amplification process. As the input is in AC signal, therefore the signal will be in positive and negative. The proposed rectifier is a full wave rectification, which in each stage of rectifier circuit is consist of two diodes and capacitors. The first capacitor is used to charge the voltage when the signal is positive, and the other capacitor is used to charge the voltage when the signal is negative. This is to ensure that the voltage always presence in the rectifier circuit so that the rectifying process is working continuously. In this work, the capacitor used is the Surface-Mount Device (SMD) ceramic capacitor by AVX where it uses X7R as the dielectric [19].

C. RF input Power

RF input can be find from source frequency domain pallete, the source can be choosen from a single or multitone frequency. In this work, a single frequency sinusoid is used, thus P_1Tone tool was chosen. Among parameters need to be defined are frequency, impedance, power level and modulation. The values define here should be identical as defined in HB tools. The input of this source is in dBm, hence different value of power in dBm will be tested in the circuit. In order to investigate the response of the designed circuit, input power are varied range from -30 dBm until 0 dBm with a step of 5. Figure 2 shows the P_1 Tone setup in ADS.

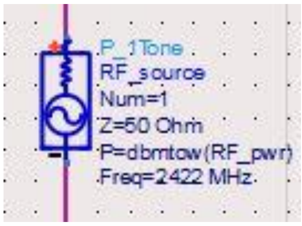

P_1Tone
RF_source
Num=1
Z=50 Ohm
P=dbmtow(RF_pwr)
Freq=2422 MHz

Figure 2 RF source in ADS

D. Rectifier Topology

In order to rectify a low RF power with amplification power, the voltage doubler topology is chosen. There are two common topologies adopted in RF rectifier design, which are Dickson topology and Villard topology. They are also known as voltage doubler as in each stage, 2 diodes and capacitors are adopted to double the output voltage. It's works as a full wave rectifier, where diode (D1) active during negative cycle which then charge the C1. D2 is forward biased during positive cycle together with discharging of C1, resulting a voltage charging by C2 is twice as input voltage. Cascading the voltage doubler stages will resulted to a greater voltage multiplication. In Villard topology, the stages increase in series form while in Dickson, the stages are increase in parallel form [13].

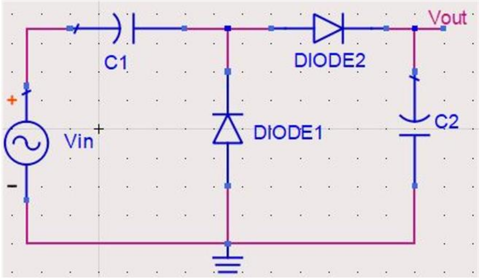


Figure 3 Voltage doubler topology

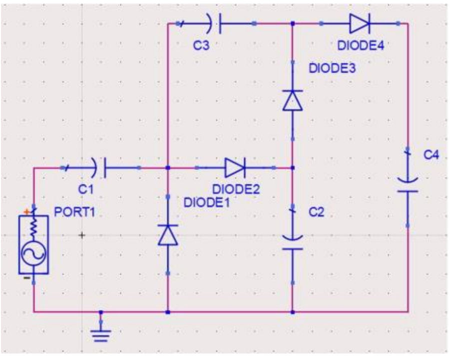


Figure 4 2 stages of villard topology

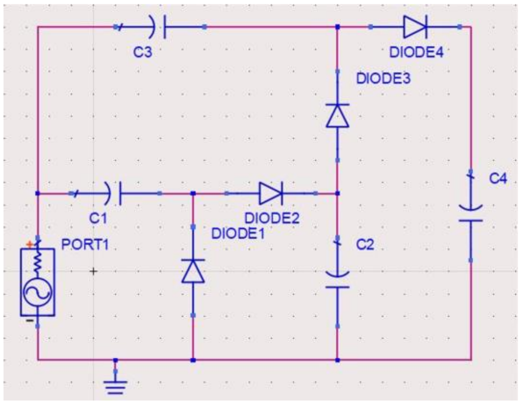


Figure 5 2 stages of dickson topology

In Dickson topology, a parallel cascading will allowed the stages to be excited simultaneously. Whereas, the stages are invoked after one another in Villard topology. 2 stages Villard and Dickson topology are illustrated in Figure 4 and Figure 5 respectively. The output voltage and the output power of each topology is considered and the most optimized topology and stages is selected.

3.0 RESULTS AND DISCUSSION

In order to obtain an optimized design, parameters study on rectifier are carried out. The parameters are capacitor value, type of topology, number of stages, variation in load capacitor and load resistor. A voltage doubler circuit is consists of TWO (2) capacitors and TWO (2) diodes as shown in Figure 3. A single tone source is used as shown in Figure 6. Simulations of circuit under different input and circuit parameters is executed to observe the performance of the circuit particularly the gain and efficiency. In this works, the input voltage, input power, output power and output voltage were monitored, where voltage gain and efficiency are calculated by using equation (1) and (2).

$$Voltage\ Gain = Vout\ /\ Vin \qquad (1)$$

$$RF\ to\ DC\ efficiency\ (\eta) = \frac{P_{out}}{P_{in}} \times 100 \qquad (2)$$

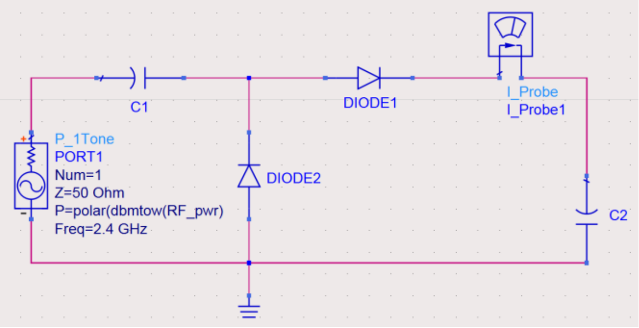


Figure 6 RF source in ADS.

A. Capacitor

Variation of capacitor values effect the rectifier performance. Based on the simulation, 0.1pF and 1pF produced a maximum gain of less than ONE (1) with an efficiency not more than 25% for an input of 0 dBm. While, for higher capacitor values, between 1nF to 47µF, 50% efficiency with a gain of 1.4 are achieved as shown in Figure 7 and Figure 8. Increase the capacitor values higher than 1nF does not increase the output voltage more than the output produces by 1nF. This can be relates by the theory of more energy is stored from higher capacitance value, where it depends on the time to charge and discharge to its maximal value. However, the charging and discharging time is effected by the operating frequency. Thus, deploying a higher capacitance value does not affect the output voltage. Thus, 1nF capacitor is used in the designed rectifier as the higher value does not provide any improvement in the circuit performance.

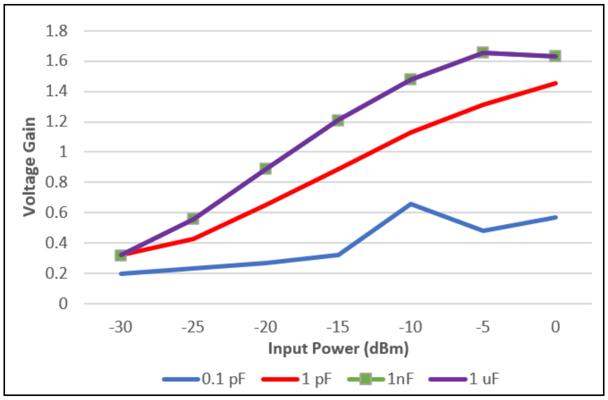


Figure 7 Capacitor gain comparison

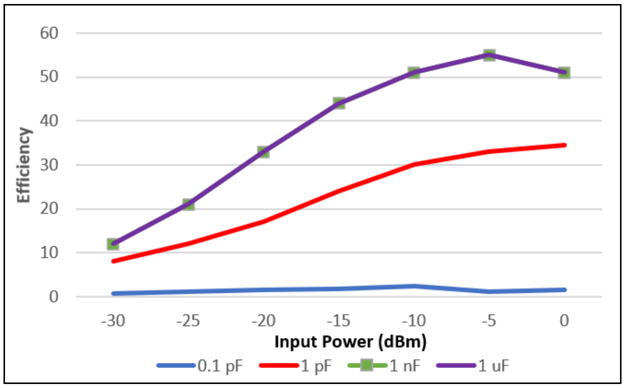
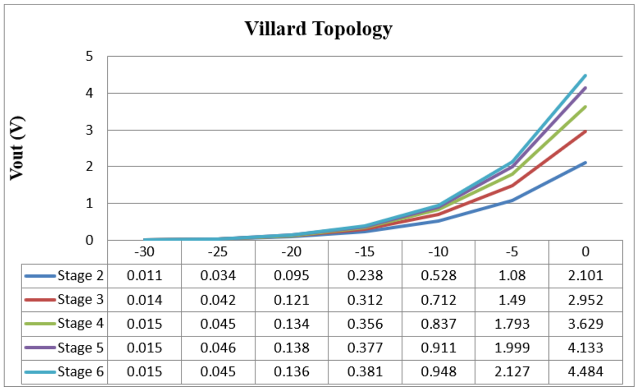


Figure 8 Capacitor efficiency comparison.

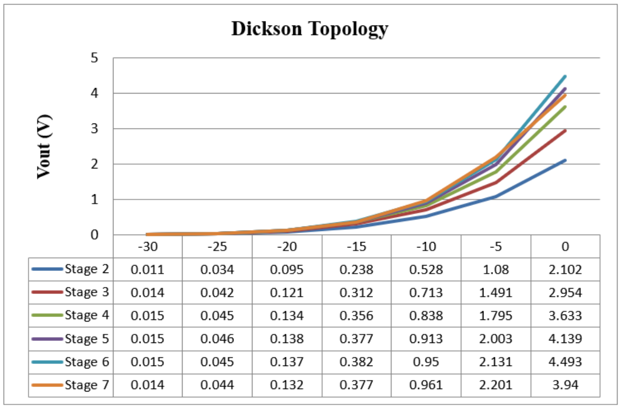
B. Topology and stages

Graph shown in Figure 9 and Figure 10 are the simulated result from the schematic Villard and Dickson topologies with different stages. As can be seen, increasing the number of stages resulted in improvement of the rectified voltage until certain stages. As proved in simulated results, both topologies produced almost identical output, where Villard output is 4.48 V and Dickson was 4.49 V when the circuit are powered with 0 dBm at 6-stages. Based on the analysis, Dickson topology is chosen as it yields slightly higher voltage. In addition, a stage higher than 6, resulted to less output power.



	-30	-25	-20	-15	-10	-5	0
Stage 2	0.011	0.034	0.095	0.238	0.528	1.08	2.101
Stage 3	0.014	0.042	0.121	0.312	0.712	1.49	2.952
Stage 4	0.015	0.045	0.134	0.356	0.837	1.793	3.629
Stage 5	0.015	0.046	0.138	0.377	0.911	1.999	4.133
Stage 6	0.015	0.045	0.136	0.381	0.948	2.127	4.484

Figure 9 Output voltage comparison (villard topology)



	-30	-25	-20	-15	-10	-5	0
Stage 2	0.011	0.034	0.095	0.238	0.528	1.08	2.102
Stage 3	0.014	0.042	0.121	0.312	0.713	1.491	2.954
Stage 4	0.015	0.045	0.134	0.356	0.838	1.795	3.633
Stage 5	0.015	0.046	0.138	0.377	0.913	2.003	4.139
Stage 6	0.015	0.045	0.137	0.382	0.95	2.131	4.493
Stage 7	0.014	0.044	0.132	0.377	0.961	2.201	3.94

Figure 10 Output voltage comparison (dickson topology)

C. Load

Load is used to control the ripple and the output voltage of the rectifier design. The load is consist of a capacitor and resistor which they are parallel to the output of the rectifier circuit. The output voltage from a rectifier can be manipulate by the load. A capacitor help in reducing the ripple in the rectified voltage. Table 3 and Table 4 illustrate the simulation result for variation of load capacitor and resistor. The simulated results is taken from a single stage voltage doubler.

Table 3 Variation in load capacitor analysis

C	Pin (dBm)	Vo Min (V)	Vo Max (V)	Ripple (V)	Pout (mW)
1pF	-30	0.0002	0.004	0.0038	0.0001
	-25	0.003	0.009	0.006	0.0002
	-20	0.014	0.025	0.011	0.001
	-15	0.055	0.078	0.023	0.008
	-10	0.25	0.298	0.048	0.048
	-5	1.206	1.33	0.124	0.553
	0	3.033	3.264	0.231	3.264
47pF	-30	0.0002	0.004	0.0038	0.0001
	-25	0.003	0.01	0.007	0.0002
	-20	0.013	0.026	0.013	0.001
	-15	0.054	0.079	0.025	0.006
	-10	0.248	0.3	0.057	0.052
	-5	1.2	1.331	0.131	0.596
	0	3.04	3.288	0.248	3.288
100 pF	-30	0.0002	0.004	0.0038	0.0001
	-25	0.003	0.01	0.007	0.0002
	-20	0.013	0.026	0.013	0.001
	-15	0.054	0.079	0.025	0.006
	-10	0.248	0.3	0.057	0.052
	-5	1.2	1.331	0.131	0.596
	0	3.04	3.288	0.248	3.288

From the simulated results shown in Table 3, it can be observed that as the input power increases, the ripple will also increases. Analysis were done from 1pF to 1nF, however, capacitor values of greater than 47pF, produced almost identical output to 47pF. Output voltage yields from 47pF is about 0.001 V higher than 1pF, but it generates higher ripple to the output waveform, which make it insignificant. From this analysis, 1pF is used as the load capacitor as it provides a more optimized output voltage with lower ripple compared to 47pF.

Selecting a higher values of resistor, resulting to a higher voltage, however, this will reduce the output current. As tabulated in Table 4, the the output is simulated with variation of resistor values from 200 kOhm to 1 MOhm at -30 dBm input power. Considering the ripple and the output voltage, 820 kOhm resistor is chosen as the output has less ripple and higher output power compare to others. The finalized circuit designed is shown in Figure12.

Table 4 Variation in load resistor analysis

Resistor (kΩ)	Vo Min (V)	Vo Max (V)	Ripple	Vrms (V)	Pout (uW)
200	0.0002	0.005	0.003	0.004	0.1
300	0.003	0.007	0.004	0.005	0.1
510	0.005	0.009	0.004	0.006	0.1
680	0.006	0.01	0.004	0.007	0.1
750	0.007	0.01	0.003	0.007	0.1
820	0.007	0.011	0.003	0.008	0.2
910	0.007	0.011	0.004	0.008	0.2
1000	0.008	0.011	0.003	0.008	0.2

D. Operating frequency

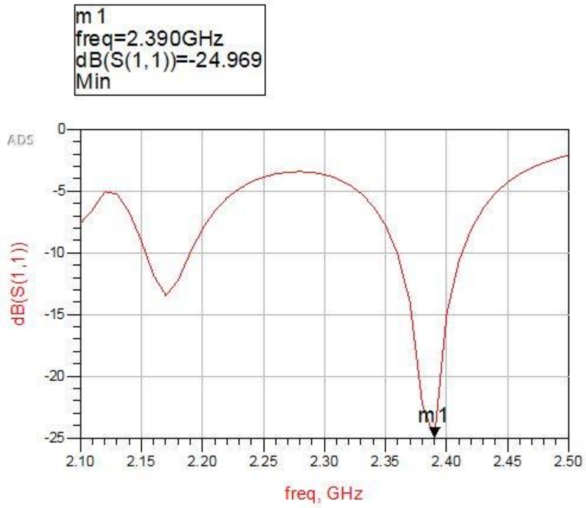


Figure 11 Simulated S_{11} result in ADS

The operating frequency of microwave circuit is monitored from reflection coefficient (S_{11}) result. Graph S_{11} versus frequency is illustrated in Figure 11. It indicates that the rectifier resonates at 2.39 GHz, with 50 MHz bandwidth. In the proposed design, the circuit was matched by using transmission line calculated at the desired frequency as shown in Figure 12. The method used eliminates the needs of matching circuit at the front of rectifier circuit.

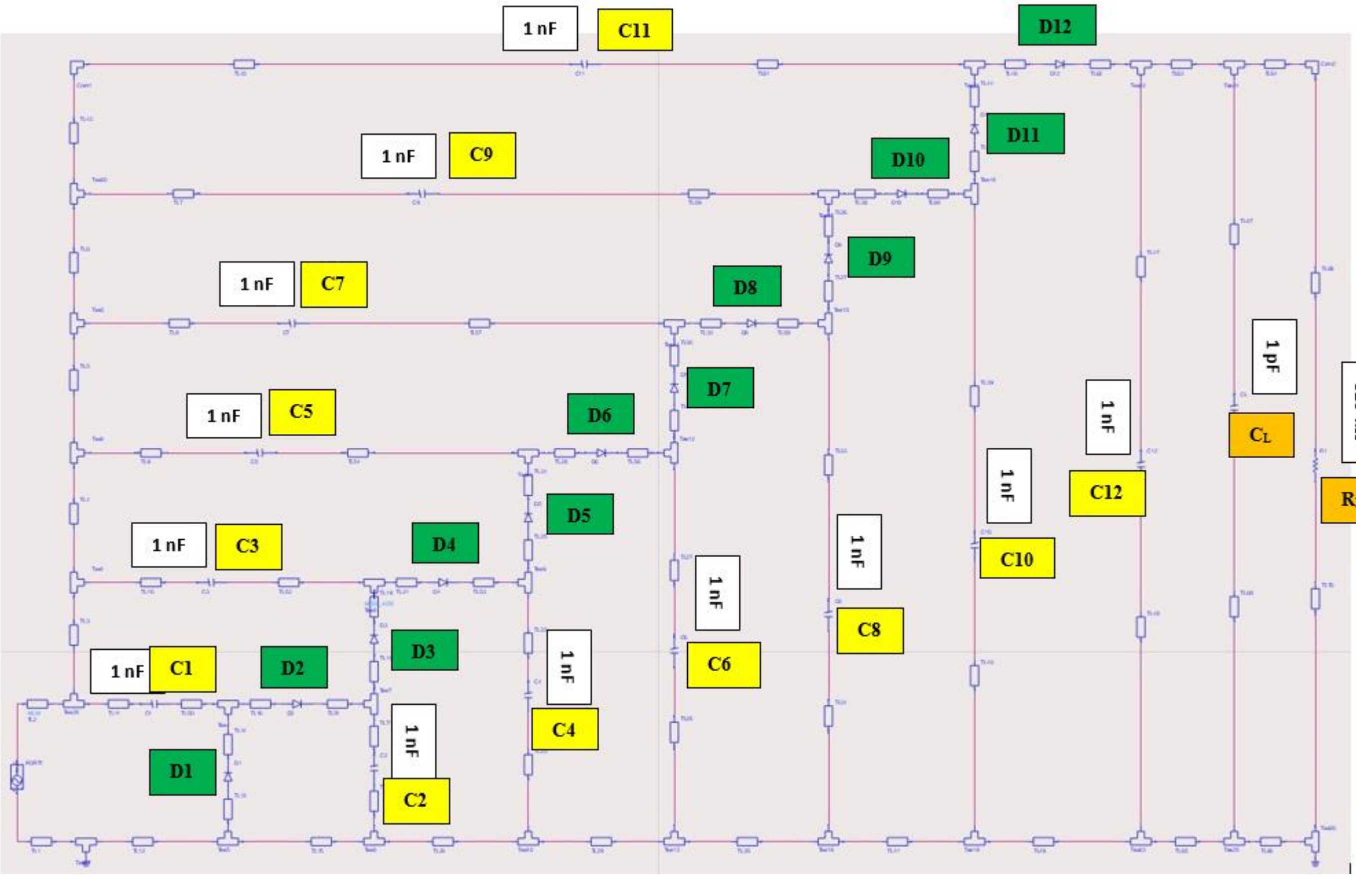


Figure 12 The proposed 6-stages rectifier circuit.

E. Measurement

The fabricated rectifier is shown in Figure 13 using FR-4 with permittivity of 4.7, 1.6-mm and 0.035-mm substrate and conductor thickness. Measurement and simulation result found to be well consistent, which shown in Figure 14. The measured result from VNA showed that the rectifier resonates at 2.4 GHz with a reflection coefficient of -40.3 dB. The measurement operating frequency is from 2.37 GHz to 2.5 GHz, resulted a bandwidth of 230 MHz.

Figure 13 The fabricated of the proposed 6-stages rectifier

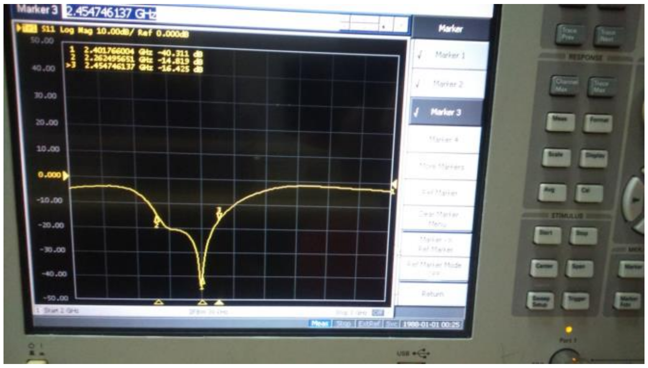


Figure 14 The proposed 6-stages rectifier is tested using VNA

The rectification performance of the design is tested using signal generator as shown in Figure 15, while the output voltage is measured using multi-meter. The comparison between simulation result and the actual measurement result is tabulated in Table 5. The simulation results shown in Table 5 are slightly differ compared to Figure 10 as the results shown in Table 5 are simulated using co-simulation with layout components.

Figure 15 The rectifier is attached to signal generator to test its performance

Table 5 Comparison of simulated and measured output voltage

Pin (dBm)	Simulation Result (V)	Measurement Result (V)
0	4.584	3.400
-5	2.214	1.770
-10	0.907	0.999
-15	0.430	0.455
-20	0.186	0.198
-25	0.073	0.073
-30	0.027	0.025

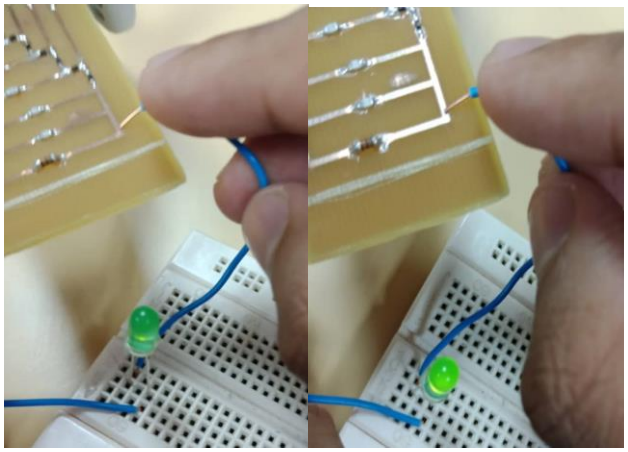


Figure 16 The LED as rectifier load. It lights up at (a) 5dBm and (b) 10 dBm

From the measurement result, it can be observed that at low power, the measured results of -20 dBm to-10 dBm exceeds the simulated results. Conversely, at higher power, the simulated result is higher than the measured result. The rectified voltage is 3.4 V during measurement, while 4.584 V is achieved in ADS simulation. Whereas, at -30 and -25 dBm, both measured and simulated produce almost similar values which are 0.025 V and 0.073 V. The circuit is then tested with LED to identify if the power is sufficient to light up the LED. The LED is a 5mm green lens with typical forward voltage of 2 – 2.4V and a 20mA forward current [21]. With 5dBm, the LED managed to light up as shown in Figure 16 (a), while brighter LED is observed with 10 dBm input power, as shown in Figure 16 (b). Higher voltage needed to light up the LED as the current produces at the output of the voltage doubler is less than the required forward current of the LED.

4.0 CONCLUSION

The steps and parameters for development of RF voltage doubler have been successfully discussed. Based on this rectifier design, it can be concluded that RF energy can be converted into electrical energy and the voltage can be used to power up a small electronic device. However, this process is not easy as the RF energy only supplies small amount of power especially at -30dBm where it only provides only ±0.009 V of AC voltage. Therefore, it is important to design a circuit which can provide a higher gain and efficiency. However, the designed rectifier circuit able to amplify the voltage with gain of 2.78 at -30 dBm where it is more than twice the input. Still, it is not applicable to be used for ambient RF source. The designed rectifier has been successfully fabricated and tested which it is working properly. The measurement result is also promising where the reflection coefficient is low at the 2.4 GHz and the measured output voltage agreed well with the simulation result.

Acknowledgement

This author would like to acknowledge the support from the Fundamental Grant Scheme (FRGS) under a grant number of FRGS/1/2020/TK0/UNIMAP/02/70 from Ministry of Higher Education.

References

[1] C. Shekhar and S. Varma. 2018. An Optimized 2.4GHz RF Energy Harvester for Energizing Low-Power Wireless Sensor Platforms. *J. Circuits, Syst. Comput*. August: 1950104. https://doi.org/10.1142/S0218126619501044.

[2] Y. Huang, N. Shinohara, and H. Toromura. 2016. A Wideband Rectenna for 2.4 GHz-band RF Energy Harvesting. *2016 IEEE Wirel. Power Transf. Conf. WPTC 2016*. 1-3.

[3] P. Xu, S. Member, D. Flandre, S. Member, D. Bol, and S. Member. 2019. Energy Harvester for SWIPT IoT Smart Sensors. 54(10): 2717-2729. https://doi.org/10.1109/JSSC.2019.2914581.

[4] Bhatt, Kapil, Sandeep Kumar, Pramod Kumar, and Chandra Charu Tripathi. 2019. Highly Efficient 2.4 and 5.8 GHz Dual-band Rectenna for Energy Harvesting Applications. *IEEE Antennas and Wireless Propagation Letters*. 18(12): 2637-2641. https://doi.org/10.1109/LAWP.2019.2946911.

[5] Saffari, Parvaneh, Ali Basaligheh, and Kambiz Moez. 2-19.

An RF-to-DC Rectifier with High Efficiency Over Wide Input Power Range for RF Energy Harvesting Applications. IEEE Transactions on Circuits and Systems I: Regular Papers. 66(12): 4862-4875. https://doi.org/10.1109/TCSI.2019.2931485.

[6] Almansouri, Abdullah S., Mahmoud H. Ouda, and Khaled N. Salama. 2018. A CMOS RF-to-DC Power Converter with 86% Efficiency and− 19.2-dBm Sensitivity. IEEE Transactions on Microwave Theory and Techniques. 66(5 (2): 2409-2415. https://doi.org/10.1109/TMTT.2017.2785251.

[7] G. Lin, M. Lee, and Y. Hsu. 2012. An AC-DC Rectifier for RF Energy Harvesting System. *Proc. APMC 2012*. 1052-1054. https://doi.org/10.1109/APMC.2012.6421822.

[8] I. Adam *et al*. 2015. An Efficient Triple Band Microwave Rectifier. *2015 IEEE International Circuits and Systems Symposium (ICSyS)*. 65-70. https://doi.org/10.1109/CircuitsAndSystems.2015.7394066.

[9] I. R. H. Yaldi, S. K. A. Rahim, and M. R. Ramli. 2016. Compact Rectifier Design for RF Energy Harvesting. IEEE Asia-Pasific Conference on Applied Electromagnetics. December: 11-13. https://doi.org/10.1109/APACE.2016.7916437.

[10] U. O. C. C. J. L. Volakis. 2012. Design of an Efficient Ambient WiFi Energy Harvesting System. *IET Microwaves, Antennas Propag. Receiv*. 6(May): 1200-1206. https://doi.org/10.1049/iet-map.2012.0129.

[11] Najeeb, Amena, Mohammed Arifuddin Sohel, and Qudsia Masood. 2019. Design of 8-Stage RF-to-DC Converter for Energy Harvesting Applications. *International Conference on Computers and Devices for Communication*. 421-426. Springer, Singapore, https://doi.org/10.1007/978-981-15-8366-7_62.

[12] Eroglu, Abdullah, Kowshik Dey, Rezwan Hussain, and Tunir Dey. 2019. Design of Dual Band Rectifiers for Energy Harvesting Applications. *Applied Computational Electromagnetics Society Journal*. 34(2).

[13] Adam, Ismahayati, M. Najib M. Yasin, Hasliza A. Rahim, Ping J. Soh, and M. Fareq Abdulmalek. A Compact Dual-band Rectenna for Ambient RF Energy Harvesting. *Microwave and Optical Technology Letters*. 60(11): 2740-2748. https://doi.org/10.1002/mop.31475.

[14] D. Wang and R. Negra. 2012. Design of a Rectifier for 2. 45 GHz Wireless Power Transmission. *2012 8th Conf. Ph.D Res. Microelectron. Electron*. 187-190.

[15] K. Niotaki, S. Kim, S. Jeon, A. Collado, A. Georgiadis, and M. M. Tentzeris. 2013. A Compact Dual-band Rectenna Using Slot-Loaded. *IEEE Antennas Wirel. Propag. Lett*. 12: 1634-1637. https://doi.org/10.1109/LAWP.2013.2294200.

[16] M. ur Rehman, W. Ahmad and W. T. Khan. 2017. Highly Efficient Dual Band 2.45/5.85 GHz Rectifier for RF Energy Harvesting Applications in ISM Band. 2017 IEEE Asia Pacific Microwave Conference (APMC). 150-153. https://doi.org/10.1109/APMC.2017.8251400.

[17] Nazari, M., J. Chen, A. M. Gole, Mi K. Hong, Pritiraj Mohanty, S. Erramilli, and O. Narayan. 2018. Phase Cascade Lattice Rectifier Array: An Exactly Solvable Nonlinear Network Circuit. *New Journal of Physics*. 20(10): 103007. https://doi.org/10.1088/1367-2630/aae3fb.

[18] Skyworks. 2015. Data Sheet @Bullet Sms7630-061 Schottky Diode. 1-7.

[19] AVX. 2010. X7R Dielectric. Options, No. 544606. 14-82, [Online]. Available: http://www.jameco.com/Jameco/Products/ProdDS/740471-DS01.pdf.

[20] Keysight Technologies. 2017. Harmonic Balance Simulator. Keysight Technologies. http://www.keysight.com/main/editorial.jspx?cc=MY&lc=eng&ckey=2061503&nid=-34333.804586&id=2061503.

[21] Multicomp. 2012. Data Sheet LED, 5mm, AC, Yellow/Green MCL056YGW. 1-4.