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Cite as: AIP Conference Proceedings **1883**, 020015 (2017); https://doi.org/10.1063/1.5002033
Published Online: 14 September 2017

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Fast Switching Wideband Rectifying Circuit for Future RF Energy Harvesting

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Abstract. This paper presents the design and simulation of fast switching microwave rectifying circuit for ultra wideband patch antenna over a dual-frequency band (1.8 GHz for GSM and 2.4 GHz for ISM band). This band was chosen due to its high signal availability in the surrounding environment. New rectifying circuit topology with pair-matching trunks is designed using Advanced Design System (ADS) software. These trunks are interfaced with power divider to achieve good bandwidth, fast switching and high efficiency. The power divider acts as a good isolator between the trunks and its straightforward design structure makes it a good choice for a single feed UWB antenna. The simulated results demonstrate that the maximum output voltage is 2.13 V with an input power of -5 dBm. Moreover, the rectifier offers maximum efficiency of 86% for the input power of −5 dBm at given band, which could easily power up wireless sensor networks (WSN) and other small devices sufficiently.

INTRODUCTION

The radio frequency (RF) energy harvesting technology has received a most attention in the last several years. This might be due to the increasing capacity of wireless broadcasting systems in urban areas such as mobile communication systems, Wi-Fi base stations, wireless sensor networks and wireless portable devices. Consequently, this makes RF resources far more available into the environment. As reported in [1], since the ambient RF energy resources are usually at a low input power level, rectifiers with high efficiency for low input power are in great demand. Therefore, (UWB) ultra wideband patch antenna could be exploited in order to capture more than one operational frequency. This type of antenna is normally connected to rectifying circuit within matching circuit network to perform a complete wireless energy harvesting system receiver (rectenna).

A number of rectifying circuits for wireless energy harvesting system have appeared in many published literatures. A dual-band frequency rectifying circuit, which consists of single stub impedance matching, a multi-stage Wilkinson power combiner and a voltage doubler, has been proposed in [2]. In [3], another dual-band rectifier for RF energy harvesting systems was designed to operate at 2.1 GHz and 2.45 GHz. The results showed that with input power of 10 dBm, the maximum efficiency obtained through this work is only 18% with the output voltages of 1.9 V and 1.7 V at 2.1 GHz and 2.4 GHz, respectively. Meanwhile, in [4], two rectifier circuit configurations for microwave power transmission system operating at ISM band are investigated. In the first configuration, a series of half wave diode rectifier is used, whereas in the second configuration a voltage doubler rectifier is used. The

Advances in Electrical and Electronic Engineering: From Theory to Applications
AIP Conf. Proc. 1883, 020015-1–020015-8; doi: 10.1063/1.5002033
Published by AIP Publishing. 978-0-7354-1563-8/$30.00

maximum conversion efficiency of rectifier using a series of half wave diode rectifier is 40.17 % with 220 Ω load resistance and 70.06 % with 330 Ω load resistance for the voltage doubler rectifier.

In general, wideband RF energy harvesting system introduces a rectifying circuit which contains a shunt single diode of HSMS2850. It exhibits a high efficiency of approximately 63% within the bandwidth of 2.41-2.47 GHz with a power level as low as 0 dBm [5]. The researchers in [6] investigated a prototype of 7-stage Cockroft-Walton voltage multiplier integrated with band pass filter and low pass for rectenna model. The model was successful to power LED over a 10 cm distance. As expected, the researchers found that a single narrow-band design is useful to achieve a high efficiency but the amount of the DC output power is limited. A wideband or a multiband design can collect more power from the weak ambient sources and produce more output power than that from a narrow-band, but the trade-offs might decrease the overall DC output voltage due to impedance matching at low load resistance.

This paper aims to propose a wideband, fast and efficient microwave rectifier circuit for the RF energy harvester at an operating frequency of 1.8 GHz and 2.4 GHz. By using a combination of high performance diode and a pair of matching trunk along with the introduction of a new design methodology, a new microwave rectifier circuit was created and analyzed.

RESEARCH METHODOLOGY

Rectifier Initial Design

The first step in rectifying circuit design is to create a single stage voltage multiplier circuit. In order to select the best diode performance, primarily this circuit was redesigned to simulate three different diode models (SMS286B, SMS7630 and SMS8202). Figure 1 illustrates a single stage voltage multiplier circuit [4] which consists of two rectifying elements (diode) to perform the RF-to-dc conversion, a dc-pass filter for smoothing the ripple of output dc (shunt capacitor) and a load (resistor).

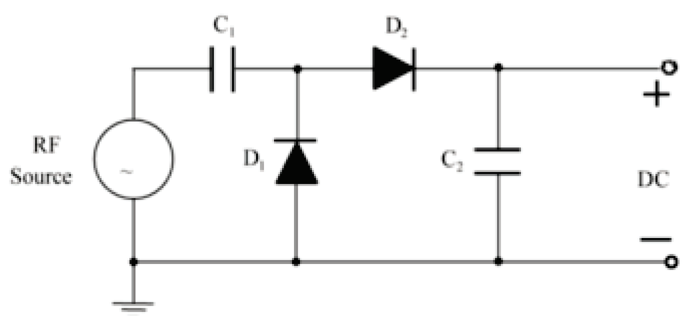

FIGURE 1. Single stage voltage multiplier circuit [4]

Figure 2 shows the block diagram of the proposed rectifying circuit which consists of UWB antenna, AC single stage Wilkinson divider, a pair matching trunk, a three-stage voltage multiplier and a load resistive. The single feed UWB antenna is connected to the single stage Wilkinson divider which in turns divides the single feed into a pair-matching trunk.

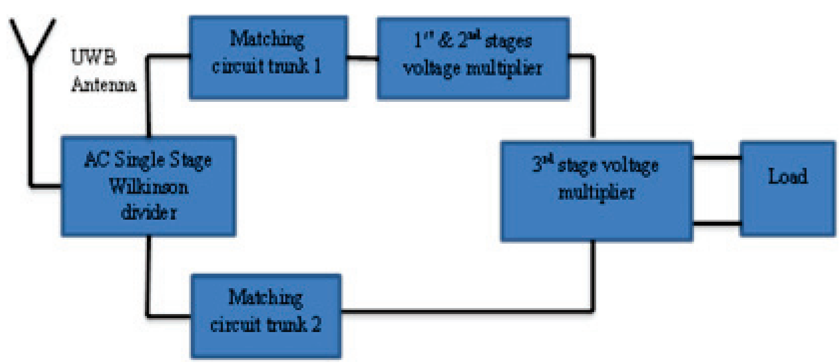

FIGURE 2. Block diagram of the rectifying circuit with UWB antenna

The upper trunk consists of an 8-nH chip inductor and a bent open stub and is intended to get the circuit matched around 1.8 GHz. The lower trunk consists of a 12-nH chip inductor and open stub and is intended to get the circuit matched around 2.4 GHz. In addition, those trunks block the higher order harmonics generated by the nonlinear device (diodes) and prevent higher frequencies re-radiation by UWB antenna thus enabling the circuit to function properly.

According to [7], the Friis formula can be used to express the RF energy transmission:

$$P_R = \frac{G_t G_R \lambda^2}{(4\pi R)^2} P_T \tag{1}$$

In this equation, P_R is the power received, G_t is the gain of the transmitter antenna, G_R is the gain of the receiver antenna, λ is the wavelength of the radiation, R is the distance, and P_T is the power transmitted. The wavelength is given by:

$$\lambda = \frac{c}{f} \tag{2}$$

where c the speed of light and f is is the frequency of the single-tone signal.

Furthermore, the efficiency conversion of the rectifier can be determined by the following equation [10]:

$$\eta_{rec}(\%) = \frac{P_{dc}}{P_{RF}} = \frac{V_{dc}}{P_{RF} R_L} \times 100 \tag{3}$$

In this expression, P_{dc} is the output power in dc, P_{RF} is the input RF power to the rectifier, V_{dc} is the output voltage, and R_L is the load resistance.

Rectifier Design

The simulated schematic diagram as shown in Fig. 3 consists of 50 Ω of input termination, a pair-matching trunk, 3-stage voltage multiplier circuit, a DC-filter capacitor and a load resistance. The rectifying circuit simulation is employed on a 1.6 mm thick FR-4 substrate with a dielectric constant, ε_r = 4.6, and loss tangent of 0.025. The copper thickness is 0.035 mm. Based on single stage voltage multiplier circuit simulation, the Schottky diode SMS7630 is chosen due to its rapid switching time at low power input. The initial design was produced for 0 dBm input power with input impedance of 30.9–207.6j at 1.8 GHz and 20.4–156.6j at 2.4 GHz. LC-matching network was used to match both trucks. Then, the shunt grounded capacitor was transformed to micro-strip transmission line using ads tools in order to reduce the cost and the signal loss that may occur due to soldering in the manufacturing process. Table 1 tabulates all the components used in the rectifier circuit.

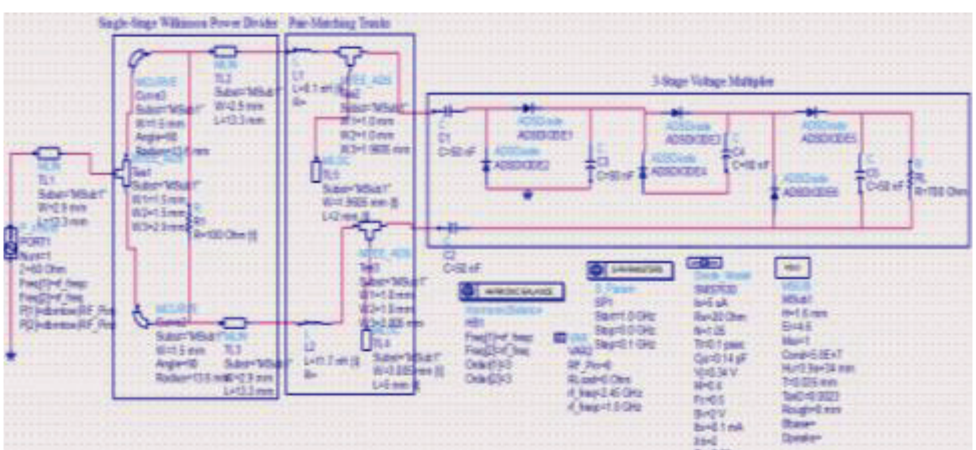

FIGURE 3. ADS schematic diagram of the proposed rectifier circuit

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

Name of the component	Symbol	Value
Diodes	D_1-D_6	SMS7630
capacitors	$C_1 – C_5$	50 nF
upper inductor	L_1	8 nH
Lower inductor	L_2	12 nH
Load resistance	R_L	700 Ohm
divider resistance	R_D	100 Ohm

Since the SMS7630 diode model is created in the schematic workspace based on manufacture properties which is shown in Table 2, the EM simulation is unable to simulate discrete components directly; the layout is generated for each of the power divider and the pair matching trunks in order to place it back into the schematic again. The accurate co-simulation can then be performed either for the discrete components or the transmission line layout. Figure 4 demonstrates the entire co-simulation rectifying circuit integration.

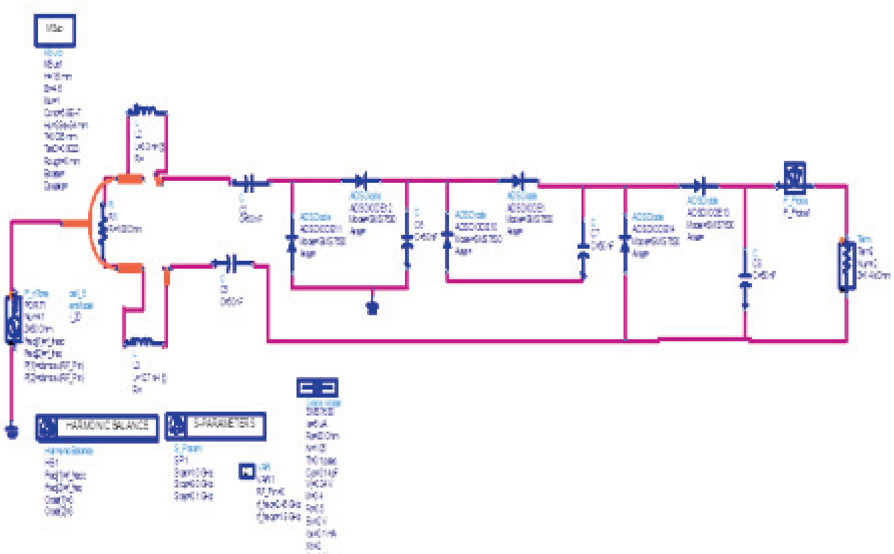

FIGURE 4. ADS co-simulation schematic of the proposed rectifier circuit

TABLE 2. SMS7630 Schottky diode model parameters [11]

Parameters	Is	R_S	N	TT	Cj0	M	E_G	XTI	Fc	B_V	I_{BV}	V_J
Units	A	Ω	-	Sec	pF	-	eV	-	-	V	A	V
SMS7630	5E-6	20	1.05	1E-11	0.14	0.40	0.69	2	0.5	2	1E-4	0.34

RESULTS AND ANALYSIS

Figure 5 shows the simulation performance of three different Schottky diodes which are SMS8202, SMS286B and SMS7630. Although the simulation graphs of SMS8202 and SMS286B exhibit higher output voltage at high input power, their poor output voltage at low input power results in slower time switching. However, the SMS7630 Schottky diode gives higher output voltage at low power input in a way which makes it a suitable fast time switching candidate for microwave rectifying circuit.

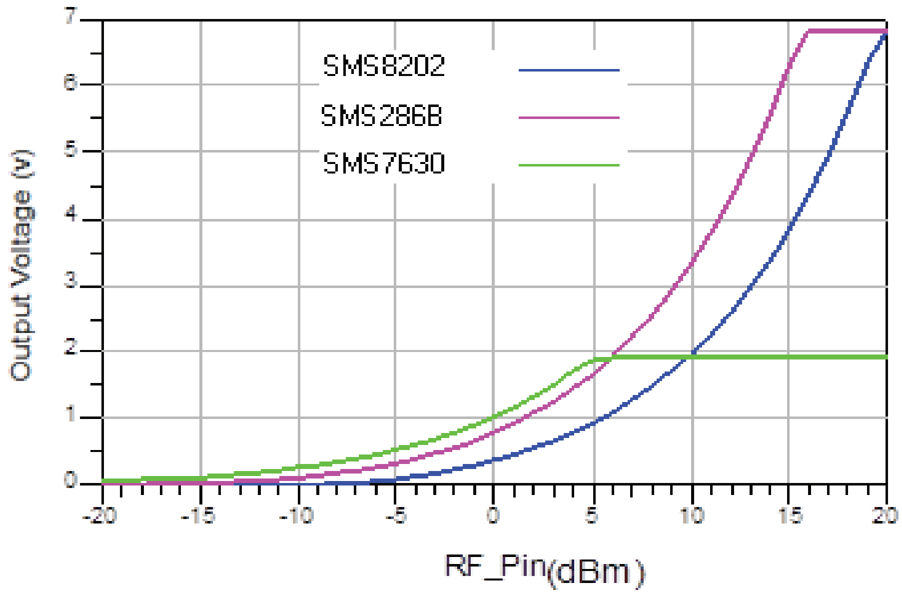

FIGURE 5. Output voltage of difference SMS diodes for single voltage multiplier

The simulated value of output DC voltage as a function of the input power in (dBm) with various frequency bands is shown in Fig. 6. It is clear that when selecting a single frequency band, the output DC voltage displays low value at low input power. However, the output DC voltage of the rectifier circuit significantly improves when opting for dual band frequencies.

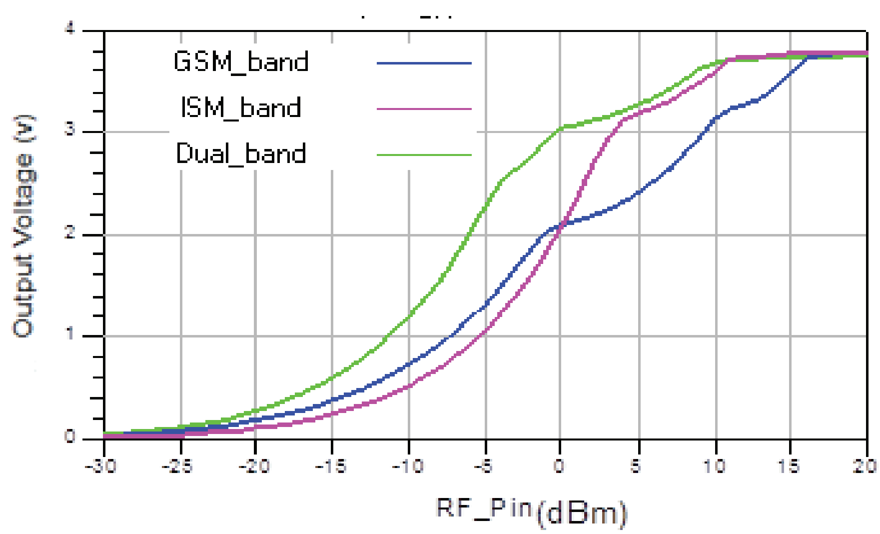

FIGURE 6. The output DC voltage as a function of the input power

The simulated result in Fig. 7 demonstrates that the reflection coefficient is achieved with less than -10 dB within a frequency ranging from 1.65 to 2.6 GHz. It is clear that the pair matching trunks block both the nonlinear harmonic reflection and the antenna re-radiation frequency which would enable an increase in the efficiency conversion of the rectifier circuit.

In Fig. 8, both the efficiency conversion on the left axis and the output DC voltage on the right-axis, are shown as functions of the load resistance with a constant -5 dBm input power. There is a clear connection between the increase of the conversion efficiency and the decrease of the load resistance, but the trade-off causes a drop in the output DC voltage at low load resistance. This may be because of the matching over wideband.

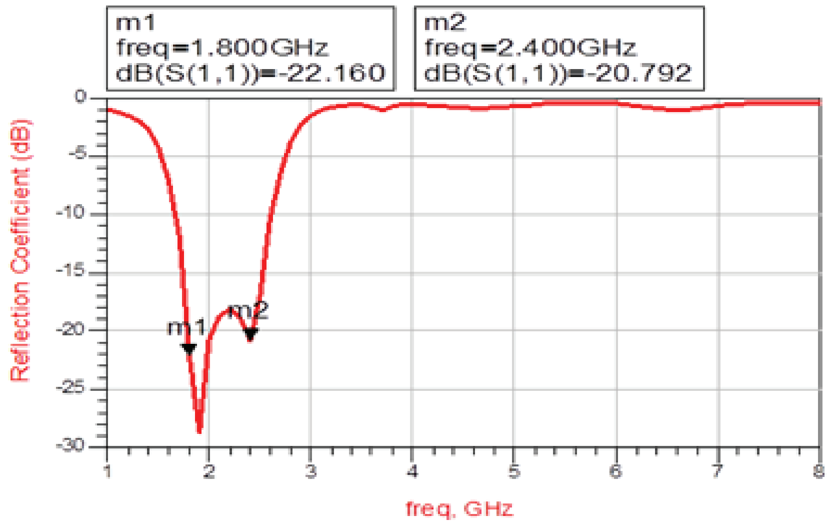

FIGURE 7. The simulated S11 for the proposed rectifier with pair matching trunks

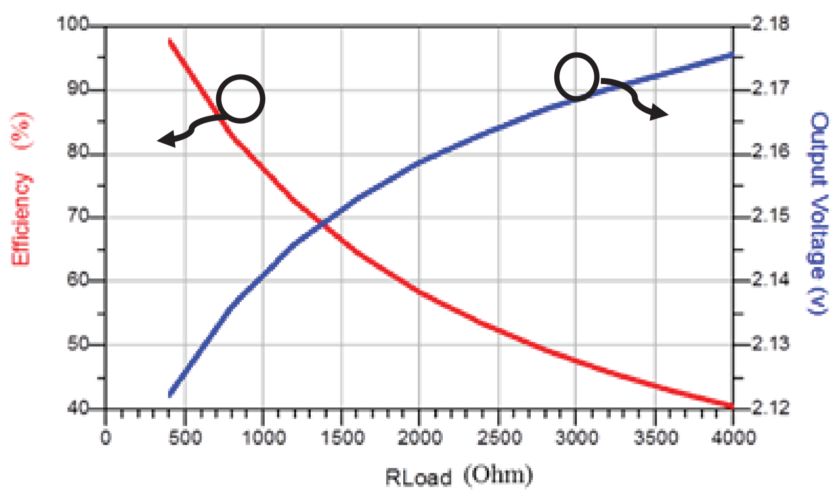

FIGURE 8. The output DC voltage and efficiency as functions in swept load resistance

Figure 9 presents the variation of the simulated efficiency and DC output voltage simultaneously with respect to the input power for a 700 Ohm load resistance. It can be seen from this figure that the conversion efficiency is low at small values of source power. The value of conversion efficiency rises with the increase of input power, reaching a peak value of 86% at -5dBm input power before dropping down to almost 10% at 20dBm input power. This might be due to the input voltage being higher than the diode breakdown voltage [8]. The output voltages at −5 dBm and 20 dBm input power levels are 2.13 V and 3.7 V respectively for load resistance at 700 ohm load.

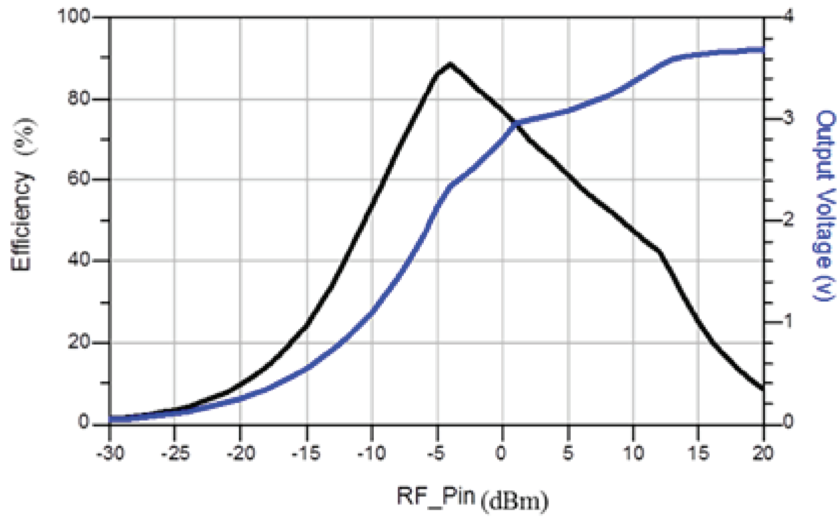

FIGURE 9. Efficiency and DC output voltage versus input power for the rectifier circuit

TABLE 3. A comparison of the proposed circuit with other related simulated works

Reference	Frequency operation (GHz)	Maximum conversion efficiency (%)	Input power level (dBm)	Voltage range (v)
[2]	1.8 - 2.45	78	-20 to 20	0.058 - 6.75
[9]	1.7 - 3	75	-3 to 8.8	2 - 5
[10]	1.8 - 2.5	70	-35 to -10	-
This work	1. 8 - 2.4	86	-30 to 20	0.125- 3.75

A comparison on the performance metrics between the proposed rectifying circuit and other related circuit designs are shown in Table 3. It can be seen that the proposed work offers the highest conversion efficiency at a lower input power level in comparison to all the other works. For example, designs [2] and [9] produced a higher range of voltage but for the RF ambient energy harvesting systems to function properly it requires a lower input power. As in [2], the system needs +15 dBm input power to achieve a higher voltage range. It is unclear what the results would be for the work in [10] as the simulated voltage range is not given. However, even though the input power level is lower than the proposed work, the maximum conversion efficiency remains at 70% in comparison to 86% for the proposed design.

CONCLUSION

In this paper, a 3-stage voltage multiplier rectifier associated with a single stage Wilkinson power divider and pair matching trunks has been designed using ADS software. The simulated results have shown that the microwave rectifying circuit has a maximum conversion efficiency of around 86% for a −5 dBm input power over a frequency range of 1.8 to 2.4 GHz. In addition, the output DC voltage with the same input power level is 2.13V. The circuit provides a much wider bandwidth compared to any available structures in literature. As a suggestion, the circuit can be optimized by connecting to a DC-DC converter in order to boost the DC output voltage.

ACKNOWLEDGMENT

The author would like to thank the Universiti Tun Hussein Onn Malaysia for the generous financial support.

REFERENCES

[1] Zhang J, Wu ZP, Liu CG, Zhang BH, Zhang B. A double-sided rectenna design for RF energy harvesting. In Wireless Symposium (IWS), 2015 IEEE International 2015 Mar 30 (pp. 1-4). IEEE.

[2] Nurasyidah, Mohd Salleh. Dual Band Rectifying Circuit for RF Energy Scavenging. *ARPN Journal of Engineering and Applied Sciences 2*. VOL. 11, NO. 5, 2015; pp. 3286-3290.

[3] Khansalee E, Zhao Y, Leelarasmee E, Nuanyai K. A dual-band rectifier for RF energy harvesting systems. In Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2014 11th International Conference on 2014 May 14 (pp. 1-4). IEEE.

[4] Doan CH, Bach DG. Investigation of Rectifier Circuit Configurations for Microwave Power Transmission System Operating at S Band. International Journal of Electrical and Computer Engineering. 2015 Oct 1; 5(5).

[5] Huang Y, Shinohara N, Toromura H. A wideband rectenna for 2.4 GHz-band RF energy harvesting. In Wireless Power Transfer Conference (WPTC), 2016 IEEE 2016 May 5 (pp. 1-3). IEEE.

[6] Ibrahim RB, Mohd SH, Khir HB, Zakariya MA, Daud H. Powering LED from Wi-Fi: A qualitative assessment for rectenna design. InSciences and Techniques of Automatic Control and Computer Engineering (STA), 2014 15th International Conference on 2014 Dec 21 (pp. 793-796). IEEE.

[7] Mascarenas DL, Flynn EB, Todd MD, Overly TG, Farinholt KM, Park G, Farrar CR. Experimental studies of using wireless energy transmission for powering embedded sensor nodes. Journal of Sound and Vibration. 2010 Jun 7; 329(12):2421-33.

[8] Arunadevi V, Mithya V. Study and analysis of rectifying antenna for wireless transmission. In Green Engineering and Technologies (IC-GET), 2015 Online International Conference on 2015 Nov 27 (pp. 1-3). IEEE.

[9] Zhang J, Huang Y, Cao P. A wideband cross dipole rectenna for RF wireless harvesting. In Antennas and Propagation (EuCAP), 2013 7th European Conference on 2013 Apr 8 (pp. 3063-3067). IEEE.

[10] Song C, Huang Y, Zhou J, Zhang J, Yuan S, Carter P. A high-efficiency broadband rectenna for ambient wireless energy harvesting. IEEE Transactions on Antennas and Propagation. 2015 Aug; 63(8):3486-95.

[11] Skyworks Solutions, Inc., Surface mount mixer and detector Schottky diodes, http://www.mouser.com/ds/2/472/Surface_Mount_Schottky_Diodes_200041AC-708941.pdf, (2016).