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Research Article

An Integrated CMOS Voltage Multiplier and Shunt Voltage Regulator of RF Energy Harvester for Health Care Monitoring System

[1]Farah Fatin Zulkifli, [1]Jahariah Sampe, [1]Md. Shabiul Islam and [2]Z.A. Rhazali

[1]Institute of Microengineering and Nanoelectronics (IMEN), National University of Malaysia, 43600 Bangi, Selangor, Malaysia
[2]University Tenaga Nasional, Jalan Serdang, Seksyen 11, 43650 Bandar Baru Bangi, Selangor, Malaysia

Abstract

Background: The increasing demand of energy harvester implementation in low power electronic devices has encouraged most of the researchers to put more effort to improve the efficiency and sensitivity of RF energy harvester system. **Materials and Methods:** In this study, these three blocks; voltage boosting and matching network, voltage multiplier and voltage regulator have been combined to harvest RF input as low as -20 dBm at operating frequency 915 MHz. By designing a network at the beginning of the circuit which called as voltage boosting network, the low input signal is boosted to sufficient voltage that can switch on the active component of voltage multiplier such as MOSFET. This network is designed based on LC resonant circuit which is consists of inductor and capacitor. Meanwhile, voltage multiplier is designed based on Dickson's voltage multiplier concept which utilizing NMOS diode with bulk modulation technique. The purpose of this technique is to lower down the threshold voltage (V_{th}) of the MOSFET. By using this four stages voltage multiplier, the input AC voltage has been rectified and boosted up efficiently. This circuit is designed based on 0.13 µm CMOS technology. **Results:** This system managed to achieve approximately 2 V at -10 dBm input power for 1 MΩ load resistance. However, to avoid over voltage to the load, a voltage regulator based on zener diode that is applied to limit and regulate the output voltage of rectifier. The key finding of this study is the system able to produce 2.72 V for -8 dBm input power at resistance load 1 MΩ and the efficiency about 30.95% which is much better compared to previous study. **Conclusion:** The proposed combination blocks of LC circuit, voltage multiplier and voltage regulator is able to produce suitable voltage for helath care monitoring system applications.

Key words: Radio frequency, energy harvester, resonant circuit, bulk modulation, voltage regulator, threshold voltage

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Corresponding Authors: Farah Fatin Zulkifli and Jahariah Sampe, Institute of Microengineering and Nanoelectronics (IMEN), National University of Malaysia, 43600 Bangi, Selangor, Malaysia

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Recently, the demand of self-powered devices is increasing due to the low cost and easy maintenance. This is because the sources of this kind of system are basically from surrounding such as thermal gradient, vibration, electromagnetic wave and solar. The selection of suitable sources depends on the requirements of the particular applications[1]. By using these ambient sources and the usage of battery could be eliminated. This technology prevents regular replacement of battery especially at rural area which sometimes is quite risky. The development of energy harvester gives a huge contribution towards biomedical field. For example, now-a-day there is a growing demand on implanted devices that will monitor the condition of the body. Typically, energy harvester able to supply 10-100 μW output power[2]. Implanted devices is one of the technologies that employs this harvester system in order to operate. They are passively powered with radio frequency signal to extend the lifetime of the battery[3]. At the same time, it can reduce the chemical instability and possibility of infection caused by batteries usage[4]. The advantage of Radio Frequency (RF) energy source compared to other sources is the availability, it can be captured at anytime either day or night and it is present everywhere. The RF energy harvester can be defined as a process of absorbing energy from propagating wave and converting it into useful electrical energy without requiring any internal power sources[5]. Figure 1 shows the basic block diagram of RF energy harvester system.

In this study, the system is based on ultra high frequency which is 915 MHz because the RF power is effectively propagated for longer distances at this condition. The propagational losses also is lower than the losses at higher frequency bands[4]. The output voltage, efficiency and minimum input power required for the system to operate will determine its performance. However, the major constraint is to produce sufficient voltage to trigger the active device for rectification. It can only be solved by these two techniques: Reducing threshold voltage or input voltage boosting.

These methods have been proposed to reduce the threshold voltage:gate pre-biasing, V_{th} cancellation schemes or zero V_{th} transistor. However, these modification will need a special process to create the schottky diodes or native low V_{th} transistor. This additional process will increase the cost of fabrication while reverse leakage current or calibration phase are too expensive and impractical[6]. Meanwhile, the idea of LC resonant circuit is utilized for input voltage boosting to produce a sufficient voltage to overcome the threshold voltage. At the same time, matching impedance is important to make sure maximum power is transferred[4]. When the impedances of the receiving antenna and the rectifier circuit is matching and passive amplification of voltage is done. Previous researchers used different techniques of matching to increase the input voltages[7].

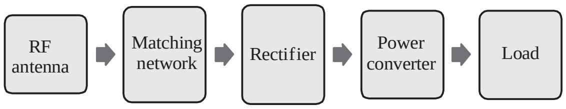

Fig. 1: Block diagram of RF energy harvester

The proposed system comprises a receiving antenna, a voltage boosting based on LC resonant circuit, voltage multiplier and voltage regulator. Basically, the Power Conversion Efficiency (PCE) is defined as in Eq. 1:

$$\text{PCE} = \frac{P_L}{P_S} \tag{1}$$

where, P_L is the load power and:

$$P_S = \frac{V_A^2}{Z_A}$$

is represents the maximum power that can be delivered at the rectifier.

The PCE of the rectifier circuit is determined by circuit topology, MOSFET parameter, RF signal frequency, amplitude and condition of load[8].

In this study, some of the previous study on voltage boosting mechanism, rectifier and power matching techniques are modified. Instead of using Schottky diode, this study focuses on the development of the circuit using regular MOSFETs in a standard CMOS process.

MATERIALS AND METHODS

Proposed RF energy harvester system: The threshold voltage of the system has been reduced to achive high PCE so that it will be highly sensitive. With the maximum transmit power allowed by Federal Communications Commision (FCC) is 36 dBm EIRP and the system is designed to operate in 915 MHz.

Voltage boosting/power matching: Power matching is necessary to make sure impedance of rectifier circuit is the complex conjugate of antenna impedance. The proposed impedance matching with basic concept of LC resonant is utilized to passively amplify low ambient voltage to a sufficient level that can turn on the active element of the rectifier. This network is combining inductive and capacitive element. In this study, the threshold voltage for the diode connected MOSFET is 378 mV. For a typical 50 antenna, the -20 dBm received RF signal power equivalent with 32 mV input voltage. This voltage is much lower than the threshold voltage.

Four stage voltage multiplier: For this system, four stages Dickson's voltage multiplier is designed to rectify the AC input and boost it to a higher level simultaneously. Conventionally, Schottky diode has been used to avoid large voltage drop[9]. However, it has been replaced with diode connected MOSFET since that model is not ready to implement on the current CMOS technology.The MOSFET acts as a diode when the drain and gate are short or tied together[10]. An enhancement mode n-channel MOSFET is chosen for this circuit design. However, there is still a limitation as the threshold voltage of this type of MOSFET still too large compared to the amplitude of the input signal. Since, this circuit is simulated using PSPICE software, the MOSFET spice model have been program according to Predictive Tecnology Model (PTM) 0.13 µm technology MOSFET. Hence, bulk modulation technique is utilised to improve efficiency and performance. This technique is the process where the bulk terminal of NMOS diode or PMOS diode is connected to drain, respectively[11].

The advantage of diode connected transistor is its low "Threshold voltage to forward current ratio" (V_{th}/I_f) and low leakage current. The voltage doubler rectifier structure is considered for the design of RF-DC power conversion system because it rectifies both positive and negative wave of the input signal. Another advantage is it can be arranged in cascade to produce high output. The number of voltage multiplier stages is important because if too many rectifier stages will increase accumulated parasitic effect while too few stages will produce insufficient voltage[12]. Therefore, the number of stages is optimized to get the best performance.

Shunt voltage regulator: The voltage regulator used in this design is based on zener diode. Under various load current conditions, zener diode is an important element to stabilise the output voltage. This regulator circuit consists of an NPN transistor (Q2N3055) and a zener diode (D1N750) together with a series resistor R_{series} that is connected with the input supply. The zener diode is connected across the base and the collector of transistor which is connected across the output.

RESULTS

Simulation performance of RF energy harvester system: Since, the voltage of AC waveform at the input of the voltage multiplier is less compared to the turn on voltage of the NMOS diode, LC boosting network has been designed to boost up the input power as low as -20 dBm. The Q of the inductor is the important parameter which decides how much of the voltage can be boosted. For the calculation of the LC values the basic formulae for resonance has been used, where $X_L = X_C$:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

Voltage at the output of the LC network is given by:

$$V_{out} = \frac{1}{R_S}\sqrt{\frac{L}{C}}V_S \tag{3}$$

Where:

R_s = Series resistance of the inductor
V_s = Input voltage to the LC network
V_{out} = Output voltage of the LC network and the input voltage to the voltage multiplier

Figure 2a shows the LC resonant circuit proposed to boost the input voltage. The value of inductor and capacitor are set based on the value calculated. Figure 2b shows that the amplitude of input signal 32 mV has been boosted to 144 mV. This voltage will then be the input of voltage multiplier.

In order to choose the best rectifier topology for this application, three different configuration of rectifier as in Fig. 3 have been compared. By fixing the number of

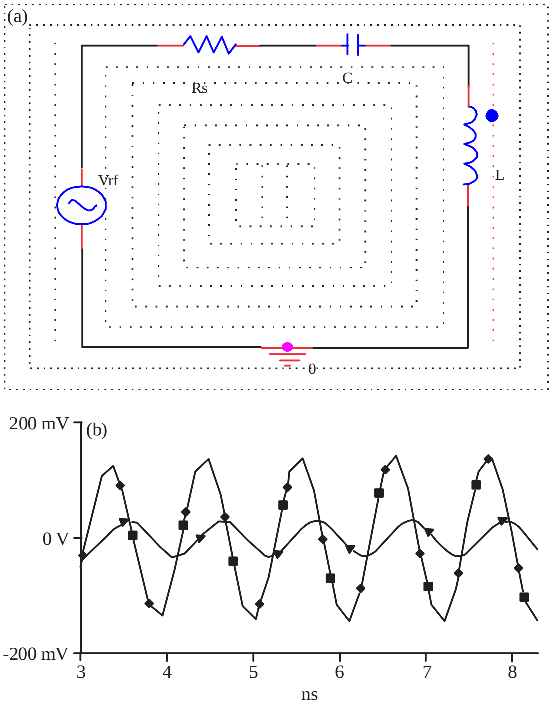

Fig. 2(a-b): LC resonant circuit and waveform of input voltage boosted from 32-144 mV

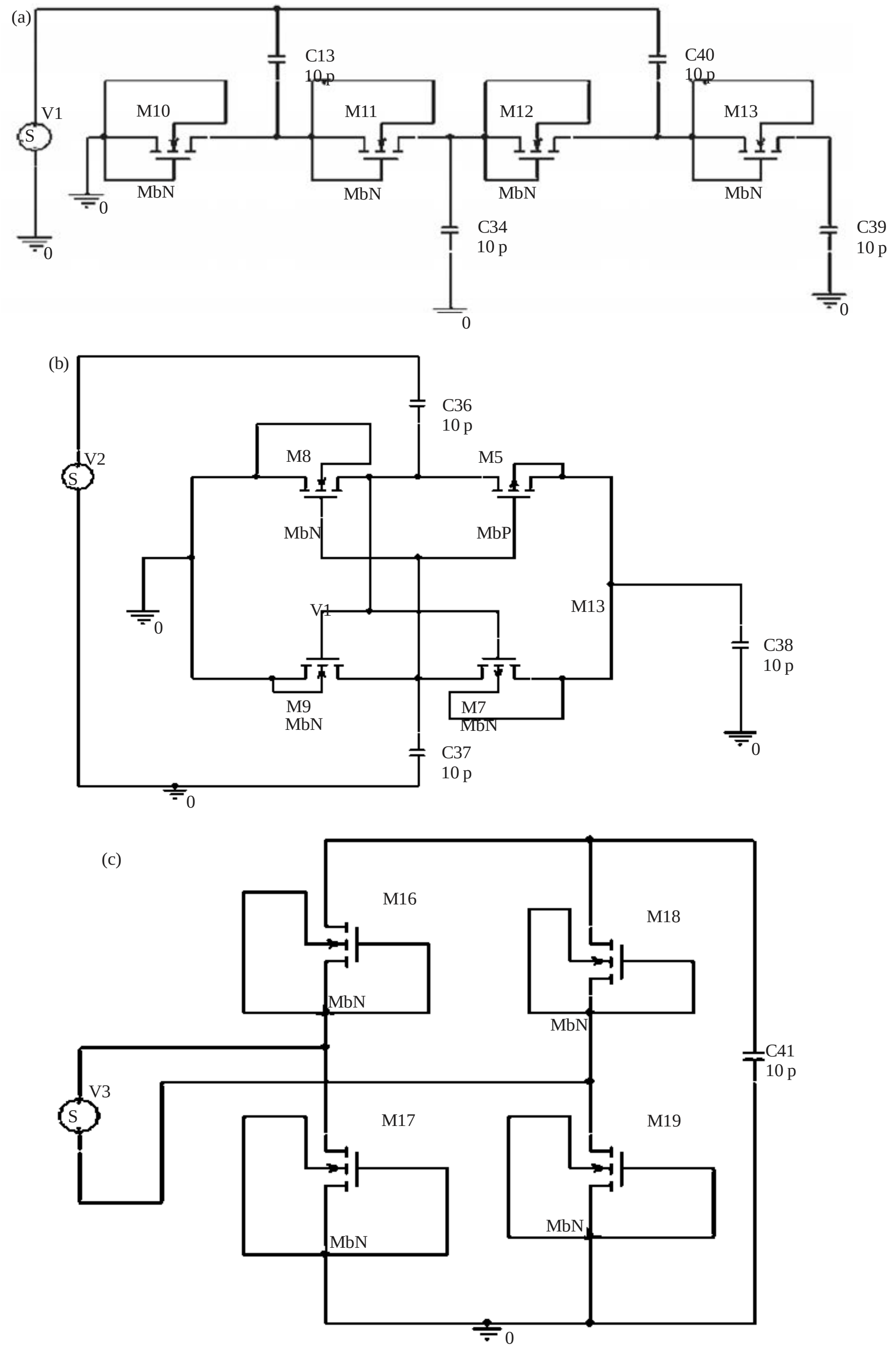

Fig. 3(a-c): Three different topologies of rectifier that have been compared, (a) Voltage multiplier, (b) Full wave bridge rectifier and (c) Differential drive CMOS rectifier

MOSFET, capacitor load value and input voltage and the performance of each one of them are simulated. The result shows that voltage multiplier achieved the highest output voltage followed by full wave and differential drive CMOS rectifier as in Fig. 4. Therefore, voltage multiplier has been chosen as the rectifying circuit for this system since it is able to rectify and boost the input AC signal simultaneously. This choice also has overcome the issue of integrating basic rectifier and DC-DC boost due to different frequency setting. Without any external sources like battery or DC generator required, this circuit able to boost up small value of input voltage efficiently.

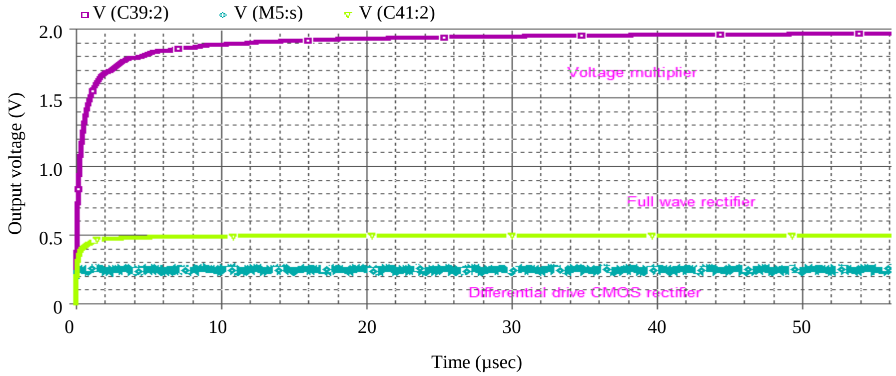

Fig. 4: Output voltage for different topologies of rectifier

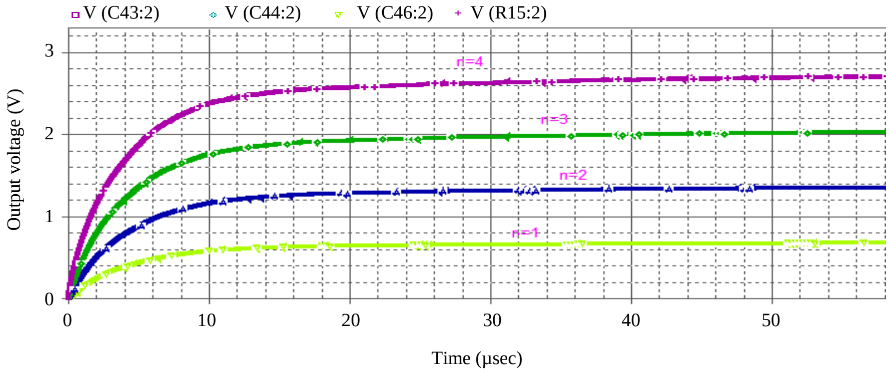

Fig. 5: Output voltage for varies No. of stages

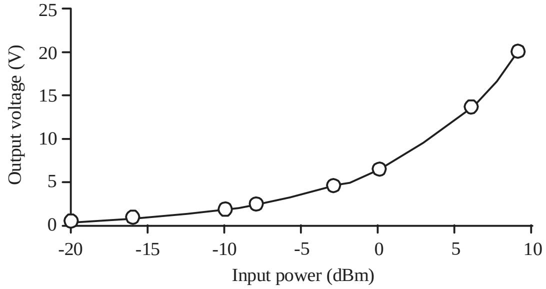

Fig. 6: Output voltage of voltage multiplier for varies No. of input power

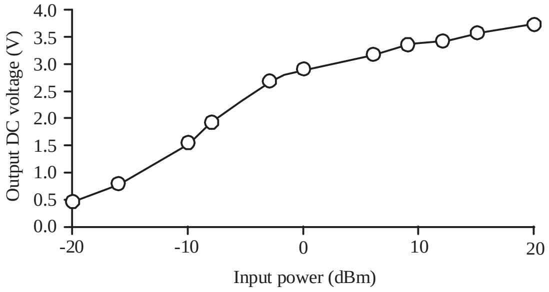

Fig. 7: Output voltage of regulator for varies No. of input power

Four stage voltage multiplier has been designed with each stage using two NMOS connected diode and two capacitors values 10 pF. The width and length of the NMOS diodeare set as 37.5 and 130 nm, respectively. About 1 MΩ resistive load is used at the output for the measurement of the output power. Figure 5 shows the output across 1 MΩ resistance load when input power equals -8 dBm. The output voltage is increasing by increasing number of stages and n from n = 1 to n = 4.

The output of voltage multiplier could reach till 20 V at input power equals 10 dBm as shown in Fig. 6. At input as low as -20 dBm which is equivalent to 32 mV and the output voltage is around 500 mV. Graph in Fig. 7 shows the output of the whole system for input varies from -20 to 20 dBm when the voltage regulated is integrated. The output voltage has been limited by voltage regulator so that the chip would not damage. After integrated with voltage regulator, output voltage at input power equals to 10 dBm, 20 V is limited to

3.5 V. These voltage is sufficient for supplying small electronic devices or for any energy storage purpose. Meanwhile, Fig. 8 shows the graph of efficiency versus input power for voltage multiplier. There is an increment of efficiency when the input power getting higher.

DISCUSSIONS

This RF energy harvester system is highly demand nowadays due to the capability to harvest ambient energy from the surrounding and convert it into useful energy. Therefore, this system is proposed to improve the existing system in term of the efficiency and sensitivity. As the input is too small, LC resonant circuit has been used to passively amplify the input voltage. As shown in the result as in Fig. 2b, the amplitude of the input voltage is amplified due to maximum current that flow across the inductor during resonance. During this situation, total impedance is at its minimum value, therefore $I = V_{in}/R$. This boosting network is important to improve the sensitivity of the system on low ambient input. Li *et al.*[6] and Mansano *et al.*[13] also presented their study that employs voltage boosting transform by forming a resonator.

Meanwhile, after the input already amplified, it is still in AC form. Therefore, voltage multiplier has been used to rectify the input voltage to DC. With each stage has a gain of 2 and the overall gain of the proposed voltage multiplier as shown in Fig. 9 is 8. During the negative half cycle of V_{in}, the MOSFET MN_1, MN_3, MN_5 and MN_7 are on and MN_2, MN_4, MN_6 and MN_8 are off. This voltage multiplier can be regarded as a convenient alternative to the full wave topology according Reddy[10] since, it will reduce area of silicon and the series losses. Implementation of bulk modulation technique in this circuit really contribute to low power energy harvesting application because it manage to reduce the threshold voltage. The NMOS transistors with isolated bodies which called as deep n well has been used in this design. Compared to the previous studies that utilized Schottky diode[14] or floating gate device[4], this technique does not require any additional procedure or special fabrication process. The number of stages in the system has the greatest effect on the DC output voltage as shown from Eq. 4 below. The output voltage is directly proportional to the number of stages as shown in Fig. 5. However, too many stages will increase the accumulated parasitic capacitance. Therefore, the optimized number of stages need to be verified. In this study, the DC output voltage of voltage multiplier obtained at 0 dBm is 7.11 V which is comparatively much better than in Devi *et al.*[14] where in 0 dBm, they achieved 2.12 V:

$$V_{out} = \frac{nV_0}{nR_0 + R_L} = V_0 = \frac{1}{\frac{R_0}{R_L} + \frac{1}{n}} \qquad (4)$$

Hence, the proposed voltage regulator manage to limit the output voltage of the voltage multiplier to sufficient voltage for small electronic devices applications. The value of

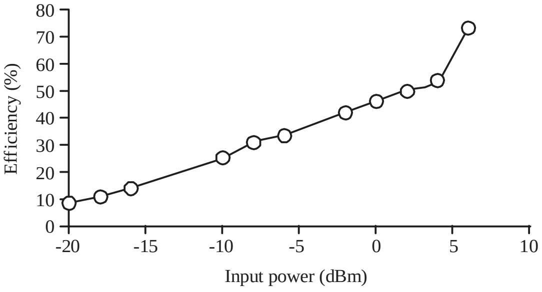

Fig. 8: Graph of efficiency versus input power

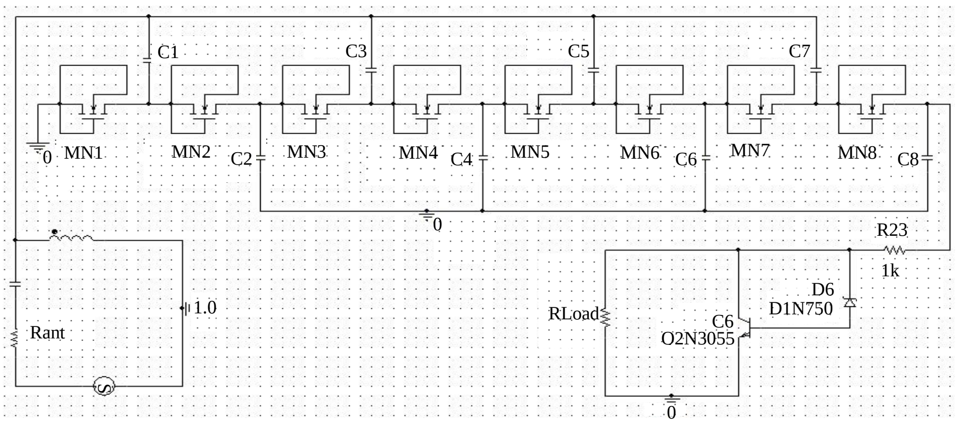

Fig. 9: Proposed RF energy harvester system

Table 1: Comparison between this study and previous study[15,16]

	Maximum efficiency approach		
No. of stages	4	5	10
Shokrani *et al.*[15] and Yi *et al.*[16]			
Transistor W/L	37.5 μm/0.13 μm	30 μm/0.18 μm	30.2 μm/0.5 μm
Output voltage	1.77 V at -8 dBm 50Ω input power	1.15 V at -8 dBm 50Ω input power	1.05 V at -8 dBm 50Ω input power
Capacitor per stage	10 pF/stage	32 pF/stage	5.6 pF/stage

the voltage across the load has been determined by the zener diode and the transistor base emitter voltage V_{be}. A small current that passing through the diode from output of the voltage multiplier and a suitable current limiting resistor (R_s) will control the voltage drop of V_{out}.

The relationship can be written as in Eq. 5:

$$V_{out}=V_{zener}+V_{be}= V_{in}-I.R_{series} \tag{5}$$

The output for the overall system showing that this system able to harvest the voltage as low as 32 mv (-20 dBm) to 20 dBm and produce between 0.5-3.8 V voltage range as shown in Fig. 7.

Table 1 shows the comparison between this study and previous studies which are using technology 0.18 μm bulk modulation MOSFET[15] and zero-threshold MOSFET[16].

CONCLUSION

A comparison between three types of rectifier configuration have been carried out. There are full wave bridge rectifier, differential drive CMOS rectifier and half wave voltage multiplier (known as Dickson's voltage multiplier). Result shows that voltage multiplier is the best configuration that able to rectify and boost up low AC voltage to a desired DC output when the system is operating at ultra high frequency 915 MHz. Voltage multiplier is proposed to overcome the problem that occur when integrating rectifier with the DC-DC boost converter since they are operated at different frequency. The usage of NMOS connected diode with bulk modulation technique able to improve the system performance by reducing the threshold voltage and leakage current. The rectifier is designed in 0.13 μm CMOS process. This proposed design also able to eliminate the usage of any other internal sources such as battery. By using only ambient input which is radio frequency signal, this energy harvester system able to produce sufficient voltage for biomedical application. By combining a proper voltage boosting and matching network system, four stages voltage multiplier and voltage regulator and this systemis able to achieve the target output.

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REFERENCES

1. Semsudin, N.A.A., J. Sampe, M.S. Islam and A.R.M. Zain, 2015. Architecture of ultra-low-power micro energy harvester using hybrid input for biomedical devices. Asian J. Sci. Res., 8: 212-224.
2. Albrni, M.A., J. Sampe, M.S. Islam and B.Y. Majlis, 2016. Ultra low power energy harvester using hybrid input for wireless communication devices-a review. J. Theoret. Applied Inform. Technol., 86: 365-376.
3. Papotto, G., F. Carrara and G. Palmisano, 2011. A 90-nm CMOS threshold-compensated RF energy harvester. IEEE J. Solid-State Circ., 46: 1985-1997.
4. Le, T., K. Mayaram and T. Fiez, 2008. Efficient far-field radio frequency energy harvesting for passively powered sensor networks. IEEE J. Solid-State Circ., 43: 1287-1302.
5. Zulkifli, F.F., J. Sampe, M.S. Islam and M.A. Mohamed, 2015. Architecture of ultra low power micro energy harvester using RF signal for health care monitoring system: A review. Am. J. Applied Sci., 12: 335-344.
6. Li, B., X. Shao, N. Shahshahan, N. Goldsman, T.S. Salter and G.M. Metze, 2011. Antenna-coupled dual band RF energy harvester design. Proceedings of the International Semiconductor Device Research Symposium, December 7-9, 2011, College Park, MD., USA.
7. Li, B., X. Shao, N. Shahshahan, N. Goldsman, T. Salter and G.M. Metze, 2013. An antenna co-design dual band RF energy harvester. IEEE Trans. Circ. Syst. I: Regular Pap., 60: 3256-3266.
8. Kotani, K., A. Sasaki and T. Ito, 2009. High-efficiency differential-drive CMOS rectifier for UHF RFIDs. IEEE J. Solid-State Circ., 44: 3011-3018.
9. Semsudin, N.A.A., J. Sampe, M.S. Islam, A.R.M. Zain and D.D. Berhanuddin, 2015. Designing a boost converter of micro energy harvester using thermal and vibration input for biomedical devices. Proceedings of the IEEE Regional Symposium on Micro and Nanoelectronics, August 19-21, 2015, Kuala Terengganu, Malaysia, pp: 1-4.

10. Reddy, D., 2011. New architecture development for energy harvesting. M.Sc. Thesis, Texas Tech University, Texas, USA.
11. Shrivastava, R.D., D. Deshpande, C. Li and R. Gale, 2013. An energy harvesting system using 3-stage voltage multiplier and MPVD charge pump for wireless sensor networks. Proceedings of the IEEE Topical Conference on Wireless Sensors and Sensor Networks, January 20-23, 2013, Arizona, pp: 40-42.
12. Zulkifli, F.F., J. Sampe, M.S. Islam, M.A. Mohamed and S.A. Wahab, 2015. Optimization of RF-DC converter in micro energy harvester using voltage boosting network and bulk modulation technique for biomedical devices. Proceedings of the IEEE Regional Symposium on Micro and Nanoelectronics, August 19-21, 2015, Kuala Terengganu, Malaysia.
13. Mansano, A., S. Bagga and W. Serdijn, 2013. A high efficiency orthogonally switching passive charge pump rectifier for energy harvesters. IEEE Trans. Circ. Syst. I: Regular Pap., 60: 1959-1966.
14. Devi, K.K.A., N.M. Din and C.K. Chakrabarty, 2012. Optimization of the voltage doubler stages in an RF-DC convertor module for energy harvesting. Circ. Syst., 3: 216-222.
15. Shokrani, M.R., M. Khoddam, M.N.B. Hamidon, N.A. Kamsani, F.Z. Rokhani and S.B. Shafie, 2014. An RF energy harvester system using UHF micropower CMOS rectifier based on a diode connected CMOS transistor. Scient. World J. 10.1155/2014/963709.
16. Yi, J., W.H. Ki and C.Y. Tsui, 2007. Analysis and design strategy of UHF micro-power CMOS rectifiers for micro-sensor and RFID applications. IEEE Trans. Circ. Syst. I: Regular Pap., 54: 153-166.