PERFORMANCE OF MOSFET RECTIFIER FOR ULTRA-LOW POWER RF ENERGY HARVESTING SYSTEM

[1]NOOR HIDAYAH MOHD YUNUS, [2]JAHARIAH SAMPE, [3]JUMRIL YUNAS, [4]ALIPAH PAWI

[1,2,3]Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia.
[1,4]Communication Technology Section, Universiti Kuala Lumpur British Malaysian Institute, Batu 8 Jalan Sungai Pusu, 53100 Gombak, Selangor, Malaysia.
E-mail: [1]noorhidayahm@unikl.edu.my, [2]jahariah@ukm.edu.my, [3]jumrilyunas@ukm.edu.my, [4]alipah@unikl.edu.my

Abstract - This paper presents an analysis simulation of the performance on the MOSFET rectifier circuit designed to operate at ultra-low power levels by utilizing of RF energy harvesting source for a wireless microsensor network applications. Research on energy harvesting proposes that microsensors could utilize the harvested energy from the surroundings. This research aims to propose an architecture of ultra-low power operation and energy efficiency enhancement in RF energy harvester from RF energy sources captured by surface-micromachined patch antenna. The MOSFET rectifying circuit is simulated and analyzed using PSPICE software. Three different transistors are studied for rectifying an AC signal at 5 GHz operating frequency. A comparison between CMOS technology and normal transistor conditions in which identifying one transistor in 0.13-µm CMOS technology implementation and two different commercial Philips transistors, respectively, has been investigated. The input power levels of focus are ranging from -30 to 10 dBm. The simulated results indicate the maximum DC output voltage of 2.15 V from low input power source of -20 dBm at high resistance load of 1 MΩ on the transistor-based implementation. Characterization of efficiency plots reveals approximately 99.47% improvement compared to other commercial transistor-based with commercial capacitance-based system. Thus, it is demonstrated that the proposed architectural design deals a promising solution for an efficient functionality at ultra-low power of RF energy harvesting system.

Keywords - Energy Harvesting, Integrated Circuit, Microsensor Nodes, Radio Frequency.

I. INTRODUCTION

With the increasing applications and popularity of sensor-based wireless nodes such as Internet of Things (IoT), battery-less remote control, structural health monitoring, wearable devices and so on, green technology approaches are of paramount importance. In recent times, chemical batteries are used to power up the node devices. Battery usage is infeasible for continuous power supply and have to be replaced as the battery lifetime is limited. Battery replacement may economically impractical and take along significant risks to human life and environment impact owing to chemical leakage. Thus, it is a strong motivation on enabling self-powered system with energy harvesting capability in, which would substitute the dependency of the batteries. The concept of energy harvesting is a promising approach to demonstrate the technology comprising continuous self-powered nodes and sustained the sensor nodes operation. Energy harvesting is a technique deployed for extracting 'green' sources of energy, and converts them into utilizable direct current (DC) voltage [1-2].

There are several energy sources that can be used for energy harvesting such as tide, thermal, solar, motion, wind, radio frequency (RF), vibration etc. [1-6]. Among them, RF energy harvesting is one of the best practices for extracting energy from surrounding as the RF energy sources are extensively available at any time and present everywhere. The general RF energy harvesting component is shown in

Figure1 In this system, RF energy sources from the environment are captured by antenna and rectified into DC voltage by a voltage multiplier or rectifying circuit to power the node devices. It has energy storage using super capacitor to guarantee smooth power delivery to load or/and as a backup for intervals when external energy is insufficient. The proposed RF energy harvesting system is based on the development of the rectenna in which consists of an antenna with matching network for capturing RF signal and rectifier metal-oxide semiconductor field-effect transistor (MOSFET) model–based for rectifying alternating current (AC) into DC voltage. Here, these components have been specifically matched operating in the narrow-band of Industrial Scientific Medical (ISM) at 5 GHz. However, they are only a little amount of RF energy sources employed for energizing the node device application. Thus, the energy harvested from these resources is impractical to be capitalized on power hungry devices. It is only limited to the ultra-low power applications. Here, a narrow-band surface-micromachined patch antenna with 50-Ω impedance matched is proposed to increase the amount of RF energy captured. The major challenges of this RF energy harvesting system are the design of a highly

efficient operability and sensitive rectenna circuit in ultra-low power operations. Thus, this paper focuses on MOSFET models used as a power driven switch of the voltage multiplier in Complementary Metal-Oxide Semiconductor (CMOS) circuit design process as well as evaluation and comparison of commercial MOSFET models in the standard circuit design process. Conventional model methods, which use diode components intensively, are less manufacturing costs, low breakdown voltage, fast switching and robust design [7]. However, diodes are less efficient in low voltage operation, but rather to handle much higher voltages than the MOSFET models. Thus, in low voltage operation, MOSFET is chosen in which is aimed for enhancing the sensitivity and efficiency parameters, increasing maximum output voltage and its diode connected MOSFET contributes low ratio of threshold voltage to forward current (V_{th}:I_f) in ultra-low power operation [8].

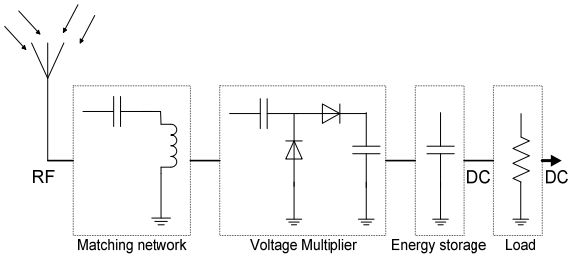


Fig1. RF energy harvesting components

In this paper, the performance of MOSFET rectifier by three different transistor-based concepts in the same architecture appropriate for RF energy harvesting is compared. One of the rectifier circuit is implemented W/L parameter in standard 0.13-µm CMOS technology and two rectifier circuits are designed by commercial Philips transistor model-based on standard printed circuit board (PCB) fabrication process in which to compare on both CMOS technology and normal transistor state of the arts, respectively. The rectifier characteristics as well as the surface-micromachined antenna used to capture RF signals in the RF energy harvesting system are presented in Section II. Performance results attained are discussed and presented in Section III, where comparisons of simulation outcomes are detailed. Finally, the key point remarks and a summary of the energy harvesting system are presented in Section IV.

II. RF ENERGY HARVESTING

A.Micromachined Patch Antenna

Micromachined antenna is a signal conception of the radiation features which is realized using a micromachining process [9]. A patch antenna is preferred owing to its capability of decreasing the harmonics radiation and design compactness that could be integrated into electronic circuitry while improving optimum performance of the system [10]. The proposed micromachined patch antenna is modelled, optimized and simulated by Computer Simulation Technology-Microwave Studio (CST-MWS) software based on a 50-Ω impedance line feed operating at 5 GHz. It is then fabricated and measured for the validation purposes. The measurement is conducted in an anechoic chamber environment. The antenna patch is fabricated on glass substrates with dielectric constant ε_r = 4.7, dissipation factor tan δ = 0.0037, substrate thickness = 2000 µm and conducting metal thickness = 1 µm. This glass-based micromachined antenna is fabricated by a surface micromachining process. Here, the patch and ground plane of the antenna is patterned on top and bottom of the substrate surface, respectively. The geometric patch antenna pattern of the top substrate surface in which is metallized with Aluminium (Al) is shown in Figure . While, the ground surface is completely metallized with the Al, where the L x W area is similar as the glass substrate size, 19 x 19 mm. The optimized dimensions of surface-micromachined antenna pattern is shown in Table .

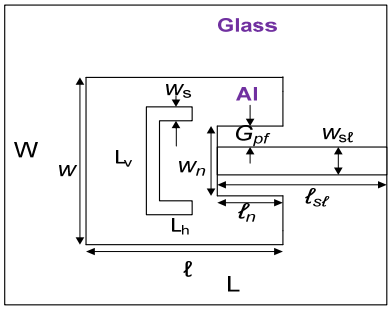


Figure 2 Optimized geometry layout

Specifications	Unit (mm)
Length of the rectangular patch (ℓ)	10
Width of the rectangular patch (w)	15.5
Patch thickness (h_p)	0.001
Substrate thickness (h_s)	2
Ground thickness (h_g)	0.001
Length of the horizontal slot cut (L_h)	5.6
Length of the vertical slot cut (L_v)	8
Width of the slot cut (w_s)	0.9
Length of the notch (ℓ_n)	6.48
Width of the notch (w_n)	3.85
Length of the strip line (ℓ_{sl})	14.3
Width of the strip line (w_{sl})	1.93
Gap of the patch feed (G_{pf})	0.96

Table 1 CST optimized dimension

B. Rectification by Diode Connected MOSFET

Here, a voltage multiplier-based on RF-DC conversion by diode connected MOSFET for driving low voltage in order to convert the wireless energy from the captured RF energy sources into DC voltage. Three different transistor components with similar scheme of RF-DC converters are implemented and compared. The rectifier is tuned operate from the input power level ranging from -30 to 10 dBm using 50-Ω matched antenna as input.

The schematic of the rectifying circuit operating at 5 GHz in which analysed by PSPICE is shown in Figure 3. The circuit consists of input terminal that simulating the RF input coming from the antenna, with the input voltage applied to the rectifier circuit is purely sinusoidal, imitating the incoming signal from the antenna. Moreover, power matching or impedance matching circuit and six stage voltage multiplier topology are developed to cope the input voltage. Each of the rectifier stage is cascaded in the topologies, in order to increase the amplitude voltage [11]. By increasing the stage number of multiplier, high voltage value is obtained at the load. However, the current reduces at the final load node. Thus, undesirable charging delays is happening in the energy storage component. By decreasing the number of multiplier stages, fast charging of the energy storage component is desirable, conversely, the voltage produced is insufficient for the load node [7].

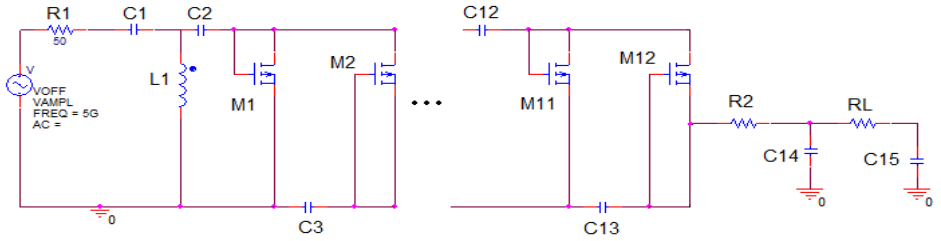


Figure 1 Schematic design of rectifying circuit

III. RESULT AND DISCUSSION

The measured and simulated results of the glass-based micromachined antenna at 5 GHz is plotted in the S_{11} return losses graph as in Figure 4. It is observed that the return loss parameter is less than -10 dB for both results. However, the measured resonant frequency is shifted nearly 50 MHz to the left as of the targeted 5 GHz. Meanwhile, the -10 dB bandwidth parameter is presented significantly dissimilar by 65.59% difference of both measured and simulated results. Those differences are possibly owing to the slightly inaccurate glass substrate dimension cut and imprecise degree pattern developed during the fabrication process. Also insufficient soldering contacts between the transmission strip line of the patch antenna and coaxial SubMiniature version A (SMA) connector during the measurement.

The peak antenna gain parameter at top 0 degrees is considered good of more than 5 dB value obtained for both measured and simulated results as illustrated in Figure 5. The voltage standing wave ration (VSWR) of fabricated antenna is within the ration range of 1 to 2 with only 4.76% different compared to the simulated results. It is indicated that the antenna is slightly well matched in the impedance line connection to the SMA connector. Performances of the antenna are summarized in Table 2.

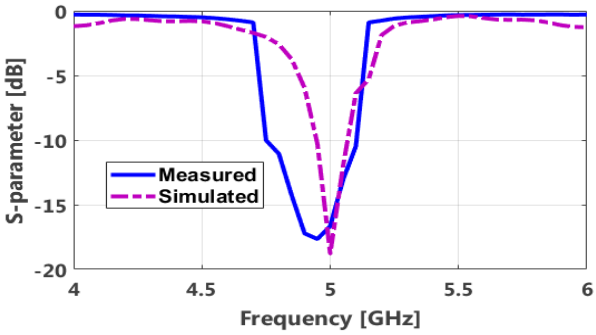
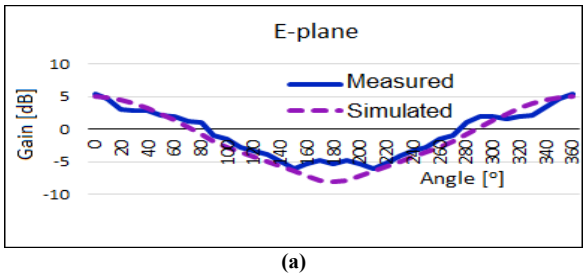
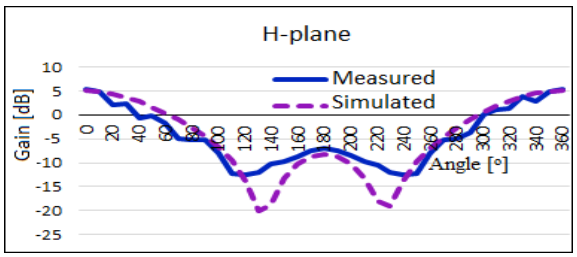


Figure 4 S_{11} parameter of micromachined antenna



(a)



(b)

Figure 5 Measured and simulated of peak gain at 5 GHz (a) E-plane and (b) H-plane

Antenna	S_{11} [dB]	Gain [dB]	Bandwidth [MHz]	VSWR
Measured	-17.66	5.38	340	1.26
Simulated	-18.8	5.02	117	1.2

Table 2 Summary of antenna performances

Generally, to operate in ultra-low input energy harvesting system, the V_{th} of the MOSFET is much larger than the RF input signal. Here, the RF signal captured by approximately at 5 dB antenna gain obtained means an amplitude of 32 mV or -20 dBm RF input signal power to the rectifying circuit. MOSFETs with lowest possible turn on voltage are desirable for the received voltage as well as MOSFETs with fast switching time are needed for this harvesting circuit is operating at high frequency.

PMOS transistor-based on CMOS technology is suitable in ultra-low power operation [12-17], while the commercial transistor-based is preferred in high power operation modes as shown in Figure 6. The DC output voltage of PMOS transistor-based is remaining constant at 3.2 V when the input power is increased, whereas the DC output voltage of the commercial transistor-based is increased when the input power is increased. However, practical constraints on the commercial capacitor components also force a limit only for 1 pF capacitance value, and cause, the peak voltage of the AC signal obtained at the matching network circuit and the DC voltage obtained at every voltage multiplier stage are much smaller than the incoming RF input signal. Thus, it indicates that the commercial transistor-based for the system might suffer from parasitic capacitance because of the unmatched capacitor value used.

Since the energy harvesting system is capturing by the micromachined antenna at an amplitude of 32 mV or -20 dBm, the peak of the efficiency curve is a corresponding major at the amplitude level as shown in Figure 7. A 1 MΩ resistance load is implemented in the harvesting system. Characteristics and performances of the three rectifiers are summarized in Table 3.

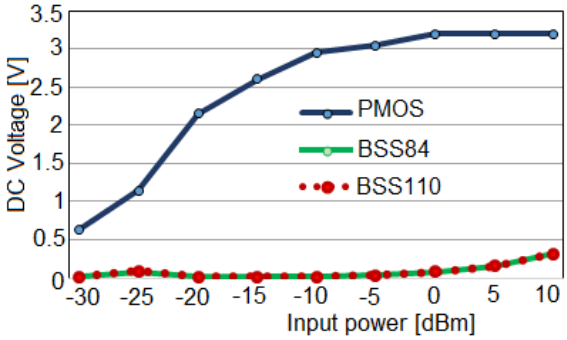


Figure 6 Maximum DC output voltage of the rectifier

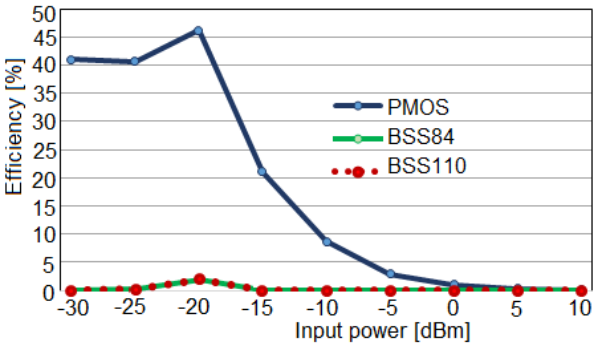


Figure 7 Conversion efficiency

Transistor	W/L parameter	Capacitor per stage	Output voltage at -20 dBm input power	Conversion efficiency at 1M Ω load
CMOS technology	37.5 µm / 0.13 µm	0.004 pF	2.15 V	46.23%
BSS84/PLP	n/a	pF	0.16 V	0.26%
BSS110/PLP	n/a	1 pF	0.15 V	0.23%

Table 3 Summary of rectifier characteristics and performances

IV. CONCLUSION

This paper presents an architectural design of RF energy harvesting systems. Initially, surface-micromachined patch antenna is designed and optimized based on 50-Ω impedance matched operating at 5 GHz by CST-MWS software. It is fabricated by micromachining process and measured in an anechoic chamber. The experimental results are in good agreement with the simulated results. In terms of rectifying circuit, three different MOSFET-based that implemented in a same voltage multiplier topology arranged in cascade are investigated and compared. They are operated through different V_{th} of the transistors and capacitance variation in which for identifying on both CMOS technology and normal transistor conditions. It is presented big hindrance to rectify the maximum DC output voltage when both commercial transistor-based and capacitor-based are implemented. This RF energy harvesting system has achieved a maximum sensitivity of -25 dBm at 1.14 V DC output with 40.71% conversion efficiency in 1M-Ω resistive load for the transistor in 0.13-µm CMOS technology. Finally, it is demonstrated that the proposed architectural design deals a promising functionality on both CMOS technology and normal transistor conditions at ultra-low power operation.

In future work, System on Chip (SoC) implementation is an idea for performance enhancement and reducing the parasitic effect hindered.

ACKNOWLEDGEMENT

This work is funded by Minister of Education Malaysia under grant FRGS/1/2018/TK04/UKM/02/1 and UKM internal grant KRA-2018-058. The authors also would like to acknowledge Universiti Kuala Lumpur-Malaysian France Institute (UniKL-MFI), and Pusat Angkasa Negara, Malaysia for their kind support of the facilities and measurement.

REFERENCES

[1] Sampe J, Yunus NH, Yunas J, Pawi A, Rhazali ZA. Design and fabrication of a dual band 1.8/2.5 GHz antenna for RF energy harvester. International Journal of Engineering & Technology. 2018;7(4):3574-8.

[2] Yunus NH, Sampe J, Yunas J, Pawi A. MEMS based RF energy harvester for battery-less remote control: A review. American Journal of Applied Sciences. 2017.

[3] Ahn, D., & Choi, K. (2018). Performance Evaluation of Thermoelectric Energy Harvesting System on Operating Rolling Stock. Micromachines, 9(7), 359.

[4] Sampe J, Yunus NH, Yunas J, Pawi A. Ultra-low power RF energy harvesting of 1.9 GHz & 2.45 GHz narrow-band rectenna for battery-less remote control. Int. J. Information and Electronics Engineering. 2017 May 1;7(3):118-22.

[5] Yunus NH, Sampe J, Yunas J, Pawi A. Parameter design of microstrip patch antenna operating at dual microwave-band for RF energy harvester application. In Micro and Nanoelectronics (RSM), 2017 IEEE Regional Symposium on 2017 Aug 23 (pp. 92-95). IEEE.

[6] Mohd Yunus, N.H.; Yunas, J.; Pawi, A.; Rhazali, Z.A.; Sampe, J. Investigation of Micromachined Antenna Substrates Operating at 5 GHz for RF Energy Harvesting Applications. Micromachines 2019, 10(2), 146.

[7] Nintanavongsa, Prusayon, Ufuk Muncuk, David Richard Lewis, and Kaushik Roy Chowdhury. "Design optimization and implementation for RF energy harvesting circuits." IEEE Journal on emerging and selected topics in circuits and systems 2, no. 1 (2012): 24-33.

[8] Calhoun, B. H., Daly, D. C., Verma, N., Finchelstein, D. F., Wentzloff, D. D., Wang, A., ... & Chandrakasan, A. P. (2005). Design considerations for ultra-low energy wireless microsensor nodes. IEEE Transactions on Computers, 54(6), 727-740.

[9] Yunus, N. H. M., Sampe, J., Yunas, J., & Pawi, A. (2018, August). Comparative Study of Si Based Micromachined Patch Antenna Operating at 5 GHz for RF Energy Harvester. In 2018 IEEE International Conference on Semiconductor Electronics (ICSE) (pp. 238-241). IEEE.

[10] K. F. L. and K. M. Luk, Microstrip Patch Antennas. Imperial College Press: London, 2011.

[11] Gonçalves, H., Fernandes, J., & Martins, M. (2013, May). A study on MOSFET rectifiers maximum output voltage for RF power harvesting circuits. In Circuits and Systems (ISCAS), 2013 IEEE International Symposium on (pp. 2964-2967). IEEE.

[12] F. F. Zulkifli, J. Sampe, M. S. Islam, and M. A. Mohamed, "Architecture of ultra low power micro energy harvester using RF signal for health care monitoring system: A review," American Journal of Applied Sciences, vol. 12, p. 335, 2015.

[13] J. Sampe, F. F. Zulkifli, N. Semsudin, M. Islam, and B. Y. Majlis, "Ultra low power hybrid micro energy harvester using RF, thermal and vibration for biomedical devices," International Journal of Pharmacy and Pharmaceutical Sciences, vol. 8, pp. 18-21, 2016.

[14] T. N. T. Mohamad, J. Sampe, and D. D. Berhanuddin, “Architecture of micro energy harvesting using hybrid input of RF, thermal and vibration for semi-active RFID tag,” Engineering Journal, vol. 21, no. 2, pp. 183–197, 2017

[15] Tengku Norliza Tengku Mohamad, Jahariah Sampe, Dilla Duryha Berhanuddin, “RF and Thermal Hybrid Input for Ultra-Low Power Semi-Active UHF RFID Tags”, 2018 IEEE 14th International Colloquium on Signal Processing & its Applications (CSPA 2018), 9 -10 March 2018, Penang, Malaysia.

[16] Musa, A.A., S. Jahariah, I. Md Shabiul and B.Y. Majlis. (2016). Ultra low power energy harvester using hybrid input for wireless communication devices-a review. J. Theoretical Applied Inform. Technology, 86(3).

[17] Nadzirin, H.M.; Sampe, J.; Islam, M.S.; Kamal, N. Architecture of Low Power Energy Harvester Using Hybrid Input of Solar and Thermal for Laptop or Notebook: A Review. Am. J. Appl. Sci. 2016, 13, 953–961.

★★★