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Review

MEMS Based RF Energy Harvester for Battery-Less Remote Control: A Review

[1,2]Noor Hidayah Mohd Yunus, [1]Jahariah Sampe, [1]Jumril Yunas and [2]Alipah Pawi

[1]*Institute of Microengineering and Nanoelectronics,*
Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[2]*Communication Technology Section,*
Universiti Kuala Lumpur, British Malaysian Institute, 53100 Gombak, Selangor, Malaysia

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Corresponding Author:
Noor Hidayah Mohd Yunus
and
Jahariah Sampe
Institute of Microengineering and Nanoelectronics,Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
Email: noorhidayahm@unikl.edu.my
jahariah@ukm.edu.my

Abstract: The paper deals with the growing interest of energy harvesting systems due to great development in many new emerging technologies in electronics and telecommunication. The research focuses particularly about rectenna element comprises of antenna, impedance matching and rectifier. The rectenna is applied under Micro-Electromechanical-System (MEMS) technology design use in Radio Frequency (RF) energy harvester. MEMS is a technology of miniaturization that has been mostly adopted from integrated circuit industry together on a chip that are made using micro fabrication technique and applied for not only electrical systems. RF ambient source is considered over other ambient sources because RF can be broadcasted by various wireless systems in unlicensed frequency bands. However, the amount of energy captured from the ambient RF is extremely low which need improvements and more Direct Current (DC) voltage generated from RF energy harvester. For this motivation, a dual band MEMS rectenna is proposed for maximizing the efficiency. Power Management Unit (PMU) is interposed between MEMS rectenna and a load. The system is equipped with temporary energy storage and voltage regulator to produce optimum output voltage. The paper proposes a system that is designed and simulated using PSpice software and modeled in Mentor Graphic. The stated result from RF MEMS energy harvester is to provide functional conversion efficiency and reliable energy harvesting system to reach 1.5-3.0 V output voltage for operating frequency at 1.9 and 2.45 GHz from RF input power at -20 dBm with reveal approximately 100% improvement over other existing designs. The conceptual design can be the platform for innovative developments in recent technologies to achieve wireless transmission powered only by RF MEMS energy harvester.

Keywords: RF MEMS Rectenna, Impedance Matching, Dual Band, Efficiency, Wireless Communication

Introduction

The combination of controlling and wireless communication has led to the development of Remote Control (RC). RC is a convenience device used wirelessly to control a variety of devices such as gates, television, air-conditioning, car unit and even wireless/battery less keyboard and optical mouse in laptops. Normally infrared (IR) technology is implemented for RC systems and with the use of chemical disposable batteries for the controller unit power source. Thus the maintenance cost associated to battery in which sometimes is unpractical, undesirable or even impossible. It should be noticed that ahead of economic cost, there is an environmental cost to pay if improperly treated the toxic waste generated from chemical batteries.

The first wireless RC technology was invented by Polley in year 1955 in which used a light beam specifically to control a television. In the past decades, IR technology became widespread due to low implementation complexity and cost effectiveness. Then due to basic technology limitations, RF technology was not an option. However, when RF/microwave technology has fast enough grown and the components cost have been very much lowered, RF technology turn into a viable option (Boaventura and Carvalho, 2013). Today, RF sources currently can be obtained from billion broadcasted transmitters around the world (Kocher, 2012), including more than a million smart phones activated every day and Wi-Fi communicating signals. In fact the advantages of RF technology were non-line of sight capability and long range two way communication. This was expected that RF technology will be soon replacing IR technology. Thus, many researchers have started to provide some RF based RC solution (Boaventura and Carvalho, 2013) and wireless powered recharges batteries for lots of sensing device applications (Erol-Kantarci and Mouftah, 2012).

In current RF approaches, the most common power supplies used are come from disposable batteries or fixed cable supply voltages that can be both technically and economically challenging. Many researchers are work on the mitigation solution of the battery problem in terms of replaced the need for 9V, 3V, AA or AAA 1.5V batteries toward much smaller battery size, capacity and weight. Very little study and research has deal with the complete removal of batteries used. Replacing or recharging batteries incurs a high cost and can be inconvenient, hazardous or highly undesirable. Despite these challenges, energy harvesting technique is proposed to deal with the battery solution. Energy harvesting technique is a conversion ambient sources from such RF, thermal, solar, mechanical sources etc to electrical energy (Devi *et al*., 2012). The harvested energy can be used more reliably to recharge or directly to power the devices instead of batteries and plug-based connections as well as require little maintenance and do not need battery replacement. This technique has come into sight as an attractive solution for many devices powered by harvested energy (Jalil and Sampe, 2013).

The development of energy harvesting has been motivated by the spread of autonomous wireless electronic systems (Kazmierski and Beeby, 2011). Fortunately, current technological development has improved the efficiency of energy harvesting modules in converting energy from the surroundings into electricity (Frontoni *et al*., 2013). In principle, energy harvesting is not entirely a new concept but has existed for thousands of years. Generally in commercial energy harvesting methods, the harvested energy from ambient environmental sources initially enter into boost converter in which increase the voltage level. Then the energy is stored in the battery management system (Ramesh and Rajan, 2014). The storage section ensures that energy preserve be available continuously even though the ambient resource is not available. This will reduce the operational cost and enable for a battery-less operation. In the system power, the energy is transferred into a regulated form for various different application loads such as a Wireless Sensor Network (WSN), as depicted in Fig. 1.

For commercial operation system, the system should be:

$$P_g > P_c \tag{1}$$

where, P_g and P_c are respectively power generated and power consumed. Generally electric power formula is:

$$P = \frac{E}{t} \tag{2}$$

where, E is electrical energy in joule and t is time in seconds. In long-term period of T, energy storage division is needed due to the unpredictability of ambient energy sources from surrounding to the system. The operation system is approximated as:

$$P_c > P_g \tag{3}$$

From Equation 2 and 3, the energy storage division is given by Equation 4 (Penella and Gasulla, 2007). The energy is accumulated for later use:

$$E_{storage} \geq \max\left\{ \int_T \left(P_c - P_g\right) dt \right\} \tag{4}$$

The energy in commercial operation system is conditioned for direct use, later use or even simultaneously use. When the system operates with the resistance load, R_L, the important parameter is the power conversion efficiency. The efficiency, η is defined as the ratio of the power generated, P_g to the incident power, P_i of the system as given by Equation 5.

$$\eta(\%) = \frac{P_g}{P_i} x100 = \frac{V_o^2 / R_L}{P_i} x100 \tag{5}$$

where, V_o is output voltage of the circuit can be calculated by the subtraction between the incident voltage, V_i of the system and the threshold voltage, V_{th} across the component as in Equation 6:

$$V_O = V_i - V_{th} \tag{6}$$

In current days, solar arrays or waterwheels and even wind farms use the same principle of energy harvesting operation which supplies the generated energy to the main network or grid. This method is considered for large-scale implementation and indeed be referred to macro energy harvesting technique. This is in contrast to micro energy harvesting, on the principle that refers to the task of harvesting small-scale of ambient energy from environmental resources to power electronics systems directly or to store the energy in battery or capacitor (Wahab *et al*., 2014). Although the principle of micro and macro energy harvesting are similar but the scopes and applications are different.

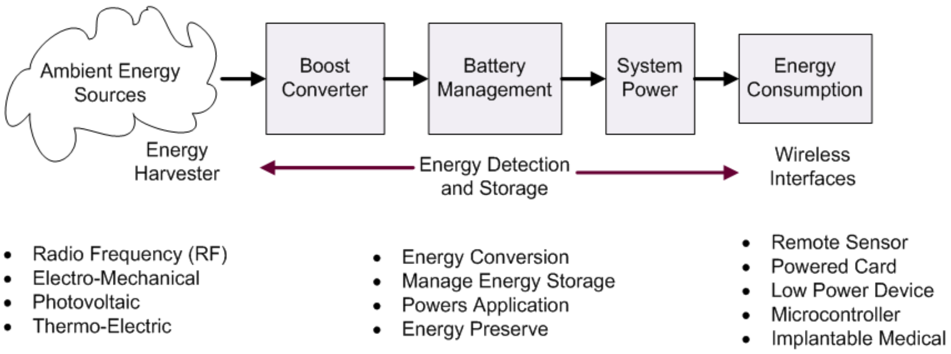

Fig. 1. Commercial energy harvesting system

However, this research work is dealing with micro energy harvesting from RF ambient sources as well as MEMS based energy harvesting techniques. RF MEMS energy harvesting techniques have been an attractive area of research due to its potential applications in numerous modern low-power consumption electronic systems. MEMS technique is leading the way to small and power efficient sensors (Du and Bogue, 2007). Thus the advantages influence RF MEMS energy harvesting mechanisms to achieve higher efficiency and greater scalability compared to conventional technologies (Huang *et al*., 2010). Therefore this topic will be explained in the following literature review.

Related Research

RF energy has greatly presenting as a viable source due to the ubiquitous of electromagnetic wave such as wireless radio network, cell phone tower, Wi-Fi networks, mobile phones signal and television signal. Thus, RF source is constantly available and more reliable than other ambient energy sources. However the amount available for harvesting is very small in the order of microwatts or less ($\leq 0.3\mu W/cm^2$). Thus, normally needs amplification of the received signal for normal radio communication. RF energy sources provides in a relatively low energy density (Visser and Vullers, 2013) of $0.2nW/cm^2$-$1\mu W/cm^2$. The PMU module is used to boost and give maximum energy for battery charging operation (Nadzirin *et al*., 2016). Moreover, voltage amplification is needed to boost up the harvested energy.

Recently, many researchers are focusing on sustainability of RF energy harvesting as a promising alternative for various available energy sources. RF energy harvesting is the process of converting ambient electromagnetic energy, despite its low energy density spectrum into effectively usable charge or electricity energy. The harvested energy can be either temporarily stored or utilized instantly for charging purposes. A typical RF energy harvester system is shown in Fig. 2. Generally, the typical component of RF energy harvesting system is rectenna in which consists of antenna receiver, impedance matching and rectifier. The rectenna is capable to harvest energy from frequency form in free space. The captured RF energy by antenna is rectified and converted into utilizable DC power. A rectifier is a nonlinear circuit formed by a series diode and a resistor-capacitor circuit. The rectenna can be from many types of rectifying circuit, for example a full-wave bridge, single shunt full-wave, or any other types of hybrid circuit (Shrestha *et al*., 2013). In short, a rectenna is a type of microwave antenna radiates at the preferred frequency range with RF diode converts and rectifies incoming RF waves into DC current.

Another aspect to consider in rectenna operation is the method to increase the conversion efficiency, η. The method is important to measure the accuracy of the antenna element and rectifies level of the rectifying circuit in converting RF power received to DC output power. When a system is constantly working off in harvested power, the output power produced and the conversion efficiency are important (Oh and Wentzloff, 2012). In typical rectifying circuit, diode takes important task in changing the microwave signal into DC. RF-DC conversion efficiency is affect by input impedance mismatching and diode losses. However, the diode losses are typically dominant (Bellal *et al*., 2016). A lower built-in voltage for a diode would realize a higher rectifying efficiency.

Brown (1980) was achieved 90.6% conversion efficiency fabricated design of a GaAsPt Schottky diode at 8W microwave power level input, P_{in}. The achieved result also was the greatest conversion efficiency ever recorded. Gao *et al*. (2010) were disclosed a circularly polarized with truncated-corner patch antenna at 5.8 GHz frequency operating with 320 Ohm load resistance, R_L. The authors were achieved 81.4% RF to DC conversion efficiency of P_{in} at 110 mW.

However, among a range unit of rectenna, antenna is the main element or task which responsible for capturing various frequencies of the receiving RF signals (Ramesh and Rajan, 2014). An antenna also can affect the amount of energy harvested. Therefore, numerous research works have been carried on for rectennas by using different types of antennas (Sun *et al*., 2012). A critical requirement in designing antenna deals with the efficiency and to maximize the reception of ambient RF sources.

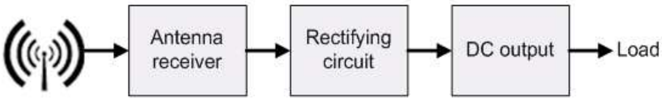

Fig. 2. RF energy harvesting system

The efficiency of an antenna is mostly determined by the antenna impedance and the converter circuit impedance (Zulkifli *et al*., 2015a; Sampe *et al*., 2016).

Previously, numerous research works have been published on ambient RF energy harvesting systems. Vyas *et al*. (2012) presented a unique prototype of energy harvesting which capable in scavenging wireless power source from broadcasts. The prototype capable in powering low power embedded processors and transceivers operating at 3V from such broadcasts at the distance over 6.5 km from source. The authors designed and fabricated an optimized linear dipole antenna using inkjet printing process. This technique is efficiently converted into RF signal from P_{in} at Ultra High Frequency (UHF) bands. Then the RF signal to be supplied to RF-DC impedance matched charge pump which stores for the harnessed energy.

Authors Keyrouz and Visser (2013) have manufactured and tested their research for 50 Ohm rectenna system. Matching network element is designed and interposed between the receiving antenna and rectifier for maximum power transfer. The designed system has reached 0.705 V output voltage at -10 dBm input power level with 868 MHz operating frequency. The authors reached 49.7% RF to DC power conversion efficiency at over 10 k Ohm load resistance.

The authors Haboubi *et al*. (2014) designed a rectenna that allows to harvest RF ambient energy and particularly suitable for remote power supply such as sensor nodes application and low power consumption sensors. The authors investigated a power dual circularly polarized rectenna in the 2.45 GHz band which optimized for -15 dBm per access of the rectifier. The system achieved 215 mV output DC voltage and reached 41.4% global efficiency at 1.49 μW/cm^2 (E_{rms} = 2.37 V/m) very low RF power density.

A new wideband rectenna that able to harvest the RF ambient power is proposed by Zhang *et al*. (2014a). The design consists of a cross-dipole wideban d antenna, low-pass filter of a microwave signals and a rectifying elements. The rectifier consists of doubling rectifying circuit by using Schottky diodes. The rectenna designed has achieved around 57% maximum conversion efficiency at 1.7 GHz as well as over 20% of the overall conversion efficiency at frequency ranges between 1.6 to 2.5 GHz.

Mabrouki *et al*. (2014) presented a design circuit of high efficiency voltage doubler rectifier for RF energy harvesting. Measurement and experimental results show RF to DC conversion efficiencies of 21 and 38% for correspondingly, -20 and -10 dBm low input powers with 10 k Ohm load resistance obtained at 850 MHz.

However, Lakhal *et al*. (2016) designed an efficient rectenna in the 2.45 GHz band for harvesting RF energy applications. They demonstrated the use of the optimization integrated in ADS software simulation for the overall circuit. They discovered the best method to improve the matching impedance between the rectifying circuit and the antenna. The pertinent method is to increase the voltage output and the conversion efficiency from RF to DC forms. The designed system has achieved voltage output at 6V of RF input power at 9.8 dBm and a conversion efficiency of 89%.

Table 1 reviews a few features of energy harvesting by considering antenna used from various RF energy sources proposed in literature. In this research work, a dual-band patch of narrowband antenna is preferred for the RF energy harvesting system which is inspired by Li *et al*. (2013; Bakkali *et al*., 2016). This is due to its capability of achieving higher performance efficiency than single frequency RF harvester, in case conversion losses parameters are taken into account. In this research work, dual-band operating frequencies used are at 1.9 and 2.45 GHz (Wi-Fi band). Since most of the ambient RF energy exists in a small number of narrow bands, a dual-band or multi-band energy harvester architecture should be capable to harvest a lot of the available ambient RF energy (Li *et al*., 2013).

Most of the recent works available in literature reports that RF energy harvesting system just considered for the impedance matching network designed between the particular antenna and the rectifier. The purpose of the method is to maximize the power transfer. However the harvester suffers for uneven energy delivery to the PMU or load. On top of that, recent works available also not study the impact of non-linear frequency and power dependence of the rectifier impedance. In order to work out this challenge, this research work proposes to utilize a tunable narrow band impedance matching network which is inspired by Fouladi *et al*. (2010). The purpose is to produce maximum energy conversion even in case of a slight change of frequency in the matching circuit. In selecting the tunable components, the losses and the linearity have to be considered (Valkonen *et al*., 2010). The changing environment can bring much effect in the antenna impedance that cause a fixed matching network to be ineffective in providing an optimum impedance match network between an antenna and front end circuitry of the mobile device (Brobston *et al*., 2010).

Table 1. Comparisons of previously published RF energy harvesting antenna design

Literature (year)	Type of antenna	Frequency (Hz)	P_{IN} (dBm)	V_{OUT} (V)	R_{LOAD} (Ω)	η (%)	Process method	Application
Sun *et al.* (2012)	Co-design rectenna	2.45 G	-17.2	n/a	1400 2800	83 50	ADS software simulation	Low power RF energy harvesting
Takhedmit *et al.* (2012)	Circularly polarized shorted ring-slot	2.45 G	-10	1.1	2500	69	HFSS and ADS software simulation	Low power sensor
Li *et al.* (2013)	Co-design dual band	900 M 1.9 G	-19.3	1.448 1.12	1.2 M 0.88 M	14 11.4	130 nm CMOS	Charge batteries
Stoopman *et al.* (2014)	Compact square loop with additional short circuited arms	868 M	-17	1.62	0.33 M	40	90nm CMOS	WSN
Mavaddat *et al.* (2015)	4×4 microstrip patch array	35.7 G	8.45	2.18	1k	67	Optical photolithography on RT/Duroid 5880	Wireless power transmission
Bakkali *et al.* (2016)	Dual-band	2.45 G and 5 G	10	1.3	n/a	n/a	RT/Duroid 5870	WSN
This work (2016)	Co-design Dual-band	1.9 G and 2.45 G	-20	1.5 -3.0	1 M	85-90	MEMS and 130 nm CMOS	Battery less remote control

Technology improvement in RF energy harvester in this research work particularly for low power RC sensing device required to be more efficient, easy to maintain, movable and lighter. MEMS technique is a way of miniaturized efficient devices, power efficient sensor and offers a viable option by flexibility in evolving assembly capabilities. Unfortunately, very little literature presented to deals with the implementation and the fabrication for RF energy harvesting by using MEMS technique. This research work is carry on a single chip implementation particularly fabrication of RF MEMS rectenna. Then the PMU system is separately interpose between MEMS rectenna and a single load device. This is believed that the techniques are enabling higher efficiency and greater scalability device than conventional ones. Unsuccessful outcomes occur in case the rectenna is directly connected to the load. In such direct connection, it is either the minimum power or the minimum activation voltage cannot be simultaneously obtainable (Costanzo and Masotti, 2013). RF MEMS rectenna for energy harvester not just a micro-fabrication design technology to provide a promising and convenient energy source solution for various low power electronic devices, but also must work in to obtain functional efficiency.

Problem Statement

In present, everyone prefers to install wireless remote application powered by essentially free natural energy source and the best thing is chemical batteries are not used. In the combination of green technology and growing demand in wireless power most used by everyone, there are high potential markets for RF energy harvester powered batteryless RC in various applications.

RF energy source can be categorized into three common forms which are ambient surrounding sources, on purpose sources and predicted ambient sources (Kim, 2011; Ramesh and Rajan, 2014). At short range, only a little amount of energy can be harvested in the order of microwatts from a normal Wi-Fi router broadcasting at 50-100 mW power level. However, in support of longer range operation, the antenna with higher gain is needed for harvest practically the RF energy from cell phone base stations and radio broadcast towers (Shrestha *et al*., 2013).

RC sensing devices are primarily used in short range operation setting or indoor environment, within the same premises such as offices and homes. On a daily basis, a possible RF energy source for the RC devices are comes from consistently surrounded by RF emitted surrounding sources namely Wi-Fi signal source from nearby towers, devices and smart phones. Even a Wi-Fi signal is capable of put out enough energy to power RC sensor, but the system for powering the device undergoes poor sensitivity and suffers from low efficiency at typical low environment power level of ambient Wi-Fi signals. On the other hand, far-field energy transport particularly for RF energy is known to experience from path loss. Therefore the RF power exist on the rectenna or the rectifying antenna will be usually extremely low (Keyrouz and Visser, 2013).

The main feature of RC is that it requires high speed operation in the operating distance of ≤ 3.0 m. Thus, it is very important that the platform is designed to maximize the received microwave energy and optimize the harvested energy. The receiving antenna must be ideally capable of receiving RF signal across an entire band and the efficiency of a rectifier is important for energy harvester circuit. MEMS technology is widely used and readily implemented for providing RF functionality (Chopra *et al*., 2015).

The goal in MEMS design for this research work is to optimize and fabricate a rectenna that will be able to capture incoming RF signal sources in dual frequency bands wherever the highest RF energy is detected. In order to achieve high efficiency, the research work on designing a circuit with a decreased leakage current, increased forward bias current for the rectifying diodes and threshold voltage will be employed (Kuhn and Gorji, 2016).

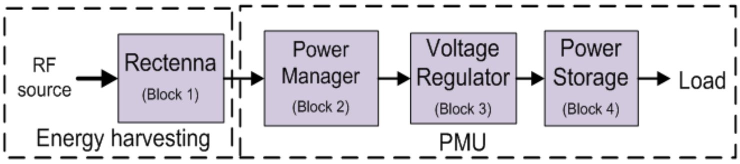

Fig. 3. Proposed RF MEMS energy harvester

The threshold voltage is important in total supply voltage fraction (Faseehuddin *et al*., 2016). In designing a narrowband MEMS rectenna, the tunable matching impedance network between the antenna output and the rectifier input by the diode can be fairly critical in design. The design is investigated and experimented to uphold the narrowband characteristics for this rectenna design.

Proposed Block Diagram

The design of RF MEMS energy harvester begins from receiving antenna and ends in the useable power management for the RC sensing device. The overall system is divided into two parts, MEMS rectenna and PMU as shown in Fig. 3.

The first part in Block-1, the rectenna is considered as front end of energy harvesting system. The rectenna is designed with emphasis on impedance matching between the antenna and the rectifier. In this research, the antenna impedance is 50 Ohm at the desired frequency of operation. The rectenna design is based on the impedance interface of 50 Ohm (Zulkifli *et al*., 2015b) for reducing complexity in the total rectenna design system (Zhang *et al*., 2014b). This system is equipped with a dual band patch receiving antenna, to capture dual frequency band of 1.9 and 2.45 GHz incident RF power radiated by communication and broadcasting systems.

A tunable impedance matching network is utilized to maximize RF power transfer through the system. This tunable impedance matching network also guarantees an optimum current supply of the diode and a rectifier to the PMU. The results measured by Mallik and Kundu (2014) reports that the antenna presents excellent performance in dual frequencies narrow bandwidth (2.45 and 2.84 GHz) with a high gain. The dual-band antenna can be reliably used in short range communications. A high gain and conversion efficiency system for RF to DC conversion can be principally realized by good rectifying diodes (Kim and Lim, 2011).

The second part initiates from energy converter circuit and ends in the useable power load for the RC (Blocks 2-4). The DC supply from Block-1 will be fed to the PMU system and then to the load. In Block-2 the DC voltage is increased to a level required by the load. In Block-3 the activation is needed to fix the value of the supply voltage level at 2-4 V (Semsudin *et al*., 2015). This is an optimal value for the electronic components used in this research work by taking into account the power losses within this system. In Block-4 the optimal energy is stored into temporary storage device for charging process and automatic supply to the load. The storage device can be capacitor or super-capacitor which are the primary types of storage component (Naim Uddin *et al*., 2016; Musa *et al*., 2016). To overcome the power losses, a low leakage super capacitor is applied. Discharging energy stored in temporary storage device, can supply instantaneous power to a particular load in case the RF ambient source from surroundings is insufficient.

Materials and Methods

The research work flow diagram is illustrated in Fig. 4. To develop the system, first of all the literature survey of the existing architecture of energy harvesters particularly those based on harvesting ambient RF input sources are investigated. Then the rectenna circuit and the PMU will be modeled, designed and simulated in PSpice software. Simulation in PSpice software will guarantee and verify that the complete circuit design provide the best result in terms of efficiency, power conditioning and energy transmission before committing to layout and fabrication. When the circuit design is verified which means no error, then optimization particularly for the complete energy harvester circuit is made and the performance is analyzed. As the optimization of the circuit design is not achieved, the redesign processes for the complete energy harvester circuit need to perform as well as the performance analysis. When the optimization of the circuit is achieved, the process of fabrication particularly for rectenna design is made using MEMS technique.

Once a working fabricated rectenna design is completed, the design is merged with the PMU that is implemented using CALIBRE Tools from Mentor Graphics in 130 nm CMOS process technology. Then performance of merged fabricated rectenna with the PMU is analyzed. The merge match with the PMU is carried out and requires careful consideration in terms of complexity, feasibility and reliability. The merging technique will greatly improve the performance of the energy harvester system during power conversion. When the design of the system is accomplished, comparison parameters are carried out to evaluate performance between the PMU with non-fabricated rectenna and the PMU with MEMS rectenna. The measurements and experiments are also carried out to evaluate the coverage band of the design system and its performance capability in terms of power losses, power consumption and sensitivity. Finally the designed RF MEMS energy harvester can be utilized for battery-less RC device and many other signal sensing applications.

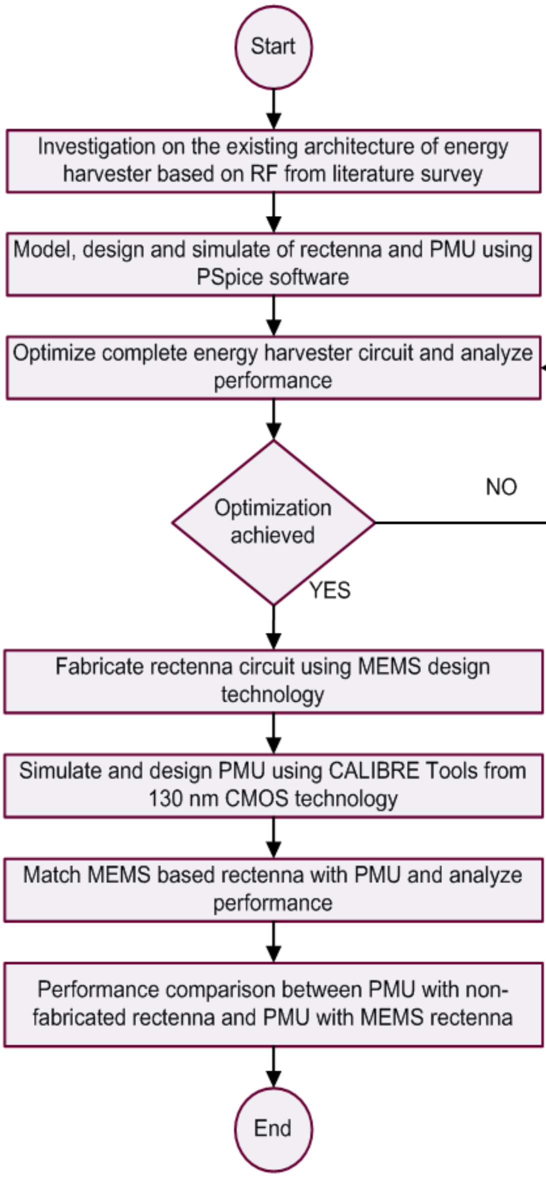

Fig. 4. Flow work process

Conclusion

This work attempt is expected to be helpful in improving RF MEMS rectenna design for most wireless technology applications to achieve better RF MEMS energy harvesting performance. In this proposed system, a receiving rectenna from RF source capable of dual-band operation and indicates a good overall performance in terms of efficiency and reliability. The expected conversion efficiency is to achieve 85-90% at a sensitivity of -20 dBm and 1M Ohm resistance load for 1.9 and 2.45 GHz frequency operating. As the operating distance for low power RC sensing need to be in ≤ 3.0 m, this is estimated that to produce reliably DC output voltage of 1.5-3.0 V for simulation and measurement results that meet the power requirements of the wireless RC. It is expected that this MEMS RF energy harvester model presents a unique prototype which provides a promising solution as green supply for battery-less RC.

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Author's Contributions

Noor Hidayah Mohd Yunus: Involved in review of current research and data investigation, summarizing the information, preparing and writing the manuscript.

Jahariah Sampe: Designed the overall research plan, organizing the study and helping in interpretations of data and reviewing the manuscripts.

Jumril Yunas: Assist with guidance and designed the research plan.

Alipah Pawi: Assist with supervision and guidance.

Ethics

This article is original and has not published elsewhere.

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