DESIGN AND DEVELOPMENT OF AN RF POWER HARVESTER OPERATING IN SUBTHRESHOLD FOR BODY AREA NETWORKS

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This Report Is Submitted in Partial Fulfilment of Requirements for The Bachelor Degree of Electronic Engineering (Telecommunication Electronics)

Faculty of Electronics and Computer Engineering

Universiti Teknikal Malaysia Melaka

June 2016

UNIVERSTI TEKNIKAL MALAYSIA MELAKA

FAKULTI KEJURUTERAAN ELEKTRONIK DAN KEJURUTERAAN KOMPUTER

BORANG PENGESAHAN STATUS LAPORAN

PROJEK SARJANA MUDA II

Tajuk Projek : Design and Development of an RF Power Harvester Operating in Subthreshold for Body Area Networks

Sesi Pengajian : 1 5 / 1 6

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ACKNOWLEDGEMENT

At the end of my thesis, I would like to thank all those people who made this thesis possible and an unforgettable experience for me. This final year project report could not be realized without the sincere help and support from many people. I am very appreciating their help and support.

Firstly, I would like to express my deepest sense of gratitude to my supervisor, Dr. Wong Yan Chiew who offered her continuous advice and encouragement throughout this project. She is a nice lecturer who always giving her students enough space to perform and develop. I thank her for the excellent guidance and great effort she put into training me in the analog IC design field.

Next, I thankful to my friends especially BENT colleagues who give the motivation and encouragement along the way to make this thesis successful. Special thanks to my friends, Lee YouHui and Ang Wei Pin for their helping, sharing of knowledge and guidance throughout the project. I am much appreciated with the friendships as well as good advice and collaboration has been built up.

Finally, I take this opportunity to express the profound gratitude from my deep heart to my beloved parents, grandparents, and my siblings for their love and continuous support – both spiritually and materially. I am very grateful to all the people I met along the way and have contributed to the development of my project.

ABSTRACT

High power consumption and small battery size severely limit the operating time of devices in Body Area Network (BAN). Radio Frequency (RF) harvesting system can be one of the ways to solve this constraint. The function of the rectifier is to converts the ambient RF into direct current (DC) voltage. The Fully Gate Cross Couple (FGCC) rectifier, Self-Vth Cancellation (SVC) rectifier and Dynamic Threshold Voltage MOSFET (DTMOS) rectifier have been investigated in term of rising time and output voltage. On the other hand, Schottky diode has been considered as an attractive candidate in conventional rectifier circuit due to their low forward voltage drop and fast switching speed. However, it requires high cost due to the complex fabrication process. Thus, an efficient model of Schottky diode in an integrated circuit (IC) domain is needed. In this project, Ultra-Low Power (ULP) diode has been proposed to be implemented in IC rectifier designs. The performance of ULP diode has been compared with diode-connected MOSFET based on Dickson charge pump and Villard voltage multiplier in 130nm Silterra process technology. Then, a layout of high sensitivity RF rectifier design with the size of 313mm X 214mm which applied in BAN has been developed. Besides, a modeling and prototyping of a simple RF harvesting system have been presented. An antenna and impedance matching has been investigated. Lastly, 8 stages Dickson charge pump rectifier using diode IN5819 has been simulated, fabricated and analyzed.

ABSTRAK

Penggunaan kuasa yang tinggi dan saiz bateri kecil teruk menghadkan masa operasi peranti dalam *Body Area Network (BAN).* Sistem penuaian frekuensi radio boleh menjadi salah satu cara untuk menyelesaikan kekangan ini. Fungsi penerus adalah untuk menukarkan frekuensi radio sekeliling kepada voltan terus (DC). *Fully Gate Cross Couple (FGCC)* penerus, *Self-Vth* Cancellation (SVC) penerus dan *Dynamic Threshold-voltage MOSFET (DTMOS)* penerus telah disiasat dalam jangka masa naik dan voltan keluaran. Sebaliknya, *Schottky Diode* telah dianggap sebagai calon yang menarik di litar penerus konvensional akibat kejatuhan voltan hadapan rendah dan kelajuan pensuisan pantas. Walau bagaimanapun, ia memerlukan kos yang tinggi kerana proses fabrikasi kompleks. Oleh itu, model yang cekap *Schottky Diode* dalam litar bersepadu diperlukan. Dalam projek ini, kuasa yang sangat rendah *(ULP) diode* telah dicadangkan untuk dilaksanakan dalam reka bentuk penerus. Prestasi *ULP diod*e telah dibandingkan dengan *Diode-connected MOSFET* berdasarkan *Dickson charge pump* penerus dan *Villard* voltan pengganda dalam *130nm* teknologi proses *Silterra.* Kemudian, susun atur reka bentuk penerus frekuensi radio yang kepekaan tinggi dengan saiz 313mm X 214mm yang digunakan dalam *BAN* telah dibangunkan. Selain itu, sebuah model dan prototaip sistem penuaian frekuensi radio yang mudah telah dibentangkan. Antena dan padanan impedans telah disiasat. Akhir sekali, 8 peringkat *Dickson charge pump* penerus menggunakan *diode IN5819* telah simulasi, direka dan dianalisis.

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LIST OF ABBREVIATIONS

EEG	-	Electroencephalography
BAN	-	Body Area Network
RF	-	Radio Frequency
DC	-	Direct Current
PCE	-	Power Conversion Efficiency
CMOS	-	Complementary Metal Oxide Semiconductor
DRC	-	Design Rule Checking
LVS	-	Layout Versus Schematic
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
FGCC	-	Fully Gate Cross Coupler
SVC	-	Self Vth Cancellation
DTMOS	-	Dynamic Threshold-voltage MOSFET
IC	-	Integrated Circuit
ULP	-	Ultra Low Power
PCB	-	Printed Circuit Board
LIP	-	Low Input Power
BCU	-	Body Central Unit
BSU	-	Body Sensor Unit
AC	-	Alternate Current
NMOS	-	N-type MOSFET
PMOS	-	P-type MOSFET

CHAPTER 1

INTRODUCTION

1.1 Project Overview

Body Area Network (BAN) network is a wireless network of wearable computing devices. It has tremendous potential in health monitoring systems as it eliminates the inconvenience of having wires around the patient's body, offering more freedom of movement and comfort, enhanced monitoring, and the administration of at-home treatment [1]. By using this BAN network, patient's health can be monitored anywhere in real time without the need of wired devices. However, high power consumption and small battery size restrict the operating time of the devices in BAN. Hence, the sensors are severely energy constrained. Thus, the demand of battery-free applications raises the interest in Radio Frequency (RF) energy harvesting. RF energy harvesting can be one of the ways to solve this energy constraint. The rectifier which function to convert the RF signal into a Direct Current (DC) voltage in the power harvester has been focused. However, the ambient RF signal is usually too low and caused the traditional rectifier unable to operate. The threshold voltage of transistor also will affect the performance of rectifiers such as output voltage, current and power consumption. In order for rectifier to work with very low input power, all the transistors of rectifier should operate in the sub-threshold region. Therefore, an improved high power conversion efficiency (PCE) and low voltage operation capability RF rectifier design will be presented. Synopsys simulator will be used in designing the Complementary Metal-Oxide Semiconductor (CMOS) rectifier. A high sensitivity RF rectifier design which applied in BAN is expected to be developed.

1.2 Problem Statement

RF energy is a widely available energy source due to continuous broadcasting from radio sources like mobile phones, television broadcast stations, and others. However, the ambient RF power signal is usually too weak [2] and it is not able to turn on the traditional rectifiers to operate. It is usually lower than the threshold voltage of the transistor. But it should not being wasted and can be used to power up the low power consumption BAN devices. Besides, the threshold voltage of the transistors also affects the performance of PCE. More stages used will also degrade the PCE. Not only that, the high power consumption and small battery size also severely limit the operating time of sensor devices in BAN [1]. Therefore, there is a need for high sensitivity RF rectifier design. The RF rectifier should have the ability for harvesting efficiently energy from RF sources to enable the wireless charging of low power devices in BAN. Thus, the cost for purchasing the battery can be saved since the battery replacement can be eliminated through wireless charging devices.

1.3 Objectives

The main objectives of this project are:

- To investigate the topologies of RF rectifier
- To design RF rectifier with high sensitivity
- To enhance the PCE of RF rectifier
- To develop the proposed design into a layout

1.4 Score of Project

In RF energy harvesting system could have many functional blocks. However, this project will only focus on RF rectifier. The investigation on the topologies of RF rectifiers has been performed. Besides, Synopsys simulator will be used in designing CMOS rectifier. The RF rectifier which is able to operate at low input power has to be designed and developed. The RF rectifier should be able to function at 900MHz and produce a stable DC output voltage for remote application in BAN. Lastly, the high efficiency of rectifier design is desired to produce the higher output power.

1.5 Project Development

The RF rectifier design involves a few stages where the first stage is to study and understand the operation of existing topologies and compare its simulated result by using Synopsys simulator. The second stage is to set the specifications. Then, the circuit will be designed in schematic and simulated to verify whether the design match with the specifications mentioned. If the design meets the specifications set, then proceed to the layout design, Design Rule Checking (DRC) checking, Layout Versus Schematic (LVS) checking and parasitic extraction. Next, the last verification will do to ensure the design is match with the specifications set. Lastly, the RF rectifier design was completed once the last verification meets the specifications set.

1.6 Report Outline

This thesis consists of five chapters. It explains and discusses each description and detail for each chapter.

Chapter I – Introduction

The important parts of the project have been introduced. Section 1.5 presents the project development. The scope of the project is focused on the RF rectifier.

Chapter II - Literature Review

The important terms such as BAN, RF harvesting system, rectifier, operating region of Metal Oxide Semiconductor Field Effect Transistor (MOSFET) transistor and design consideration of high-quality rectifier have been described. Section 2.7 presents the RF rectifier topologies based on MOSFET which are Fully Gate Cross Coupler (FGCC) rectifier, Self Vth Cancellation (SVC) rectifier and Dynamic Threshold-voltage MOSFET (DTMOS) rectifier. Their specifications, advantages, disadvantages, circuit design and operation have been reviewed. Charge transfer switches in Integrated Circuit (IC) domain have been studied in Section 2.8. It includes Schottky diode, diode-connected diode and Ultra-Low Power (ULP) diode.

Chapter III – Methodology

The methodology shows the process of circuit design has been developed in Section 3.1. The Synopsys software used in design the CMOS rectifier. The specifications have been set in Section 3.2. Section 3.3 mentions that the schematic designs have been simulated in order to achieve the specification set. Lastly, the layout design included DRC checking, LVS checking, and parasitic extraction were discussed in Section 3.4.

Chapter IV – Comparison on RF Rectifier Based on MOSFET

The overview of this chapter has been presented in Section 4.1. Section 4.3 shows the schematic design of FGCC, SVC, and DTMOS rectifier while Section 4.3 shows the parameter setting at 90nm and 130nm technology for RF rectifier topologies. The optimization on the width of transistors has been carried out. The simulation result and analysis in term of rise time and the output voltage of RF rectifiers have been reviewed in Section 4.4.

Chapter V – Comparison on Charge Transfer Switches in IC Domain

The voltage multiplier rectifier topologies include Villard voltage multiplier and Dickson charge pump rectifier have been reviewed in Section 5.2. Section 5.3 shows the schematic design of Villard voltage multiplier and Dickson charge pump rectifier applied with the charge transfer switches. Their simulation result in term of leakage current and output voltage have been presented in Section 5.3.1 and 5.3.2 respectively. Section 5.4 presents the parameters optimization in the Dickson charge pump using ULP diode. The high sensitivity rectifier shows in Section 5.5 and proceeds to a layout designed in Section 5.6.

Chapter VI – Modeling and Prototyping of A Simple RF Harvesting System

A block diagram of RF energy harvesting has been reviewed in Section 6.1. Section 6.2 shows a dual-band planar antenna design which operates in 900MHz and 1900MHz. Then, microstrip single stub matching network has been investigated in Section 6.3. Lastly, 8 stages of Dickson Charge Pump using diode IN5819 has been simulated and then fabricated in a Printed Circuit Board (PCB) as shown in Section 6.4. The simulated and measured results obtained have been analyzed and discussed.

Chapter VII – Conclusion and Recommendation

A high sensitivity RF rectifier design which applied in BAN is presented. The result and analysis for the whole project were concluded in Section 7.1. The future works have been discussed and suggested in Section 7.2.

Next, the thesis has contributed some technical papers which to be published as shown in the Appendix part.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In this chapter, it includes the reviews on BAN, RF harvesting system, rectifier, operating region of MOSFET transistor, characteristics of the high-quality rectifier. Besides, the topologies such as Fully Gate Cross Coupler (FGCC) rectifier, Self Vth Cancellation (SVC) rectifier and Dynamic Threshold-voltage MOSFET (DTMOS) rectifier have been reviewed. The charge transfer switches in IC domain such as Schottky diode, diode-connected MOSFET, and ULP diode have been studied.

2.2 Body Area Network (BAN)

BAN is a wireless communication between multiple Body Sensor Units (BSUs) and a single Body Central Unit (BCU) around body [3]. The BCU can be a cell phone while BSUs can be a pedometer, pacemaker, pulse oximeter and etc. The BSUs work as health monitoring sensor to collect the biological information of patient continuously. These data will be collected and saved in a local BSU memory then only send to the BCU through an RF communication channel. Then, BCU will process these data and communicate with a doctor via cell phone or Wi-Fi network [1]. In this way, patient's health can be monitored anywhere in real time without the need of wired devices. However, the high power consumption and small battery size severely restricts the operating time of the BSUs and cause the sensors severely energy constrained. Thus, the demand for battery-free applications raises the interest in RF energy harvesting since energy harvesting from an external source from RF is one of the ways to solve this energy constraint.

2.3 RF Energy Harvesting

RF energy harvest is one of the popular types of power harvesting. The goal of an RF energy harvester is to convert the ambient RF energy sources into a stable DC power. A block diagram of RF harvesting system shown in Figure 2.1 [4]. It consists of the power source, impedance matching, rectifier, regulator circuit, and load. The power source is generally an antenna were used to capture the ambient RF signal while the impedance matching circuit is required to ensure the maximum RF energy is transferred from the source to load. In another word, it is used to match the impedance of antenna and rectifier in order to reduce the loss in the system. Next, the rectifier circuits convert the received RF signal voltage into a stable output DC voltage. When the output voltage of rectifier is not stable, a regulator circuit is a function to provide a smooth, stable and ripple free DC voltage. Lastly, the load is where the produced power is delivered to related applications or devices.

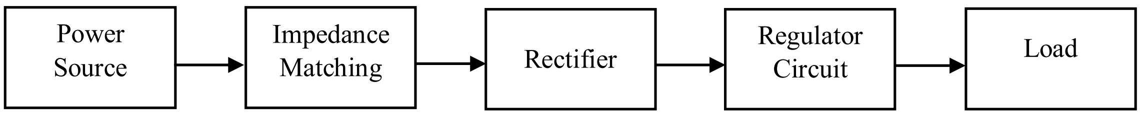

Figure 2.1: Block diagram of RF harvesting system

The rapid expansion of sensor network requires a reliable power supply to replace the battery. However, the battery technology still in the slow progress to catch up with the latest electronic devices especially in nanometer (nm) technology where existing batteries are not fixed for such miniaturization[4]. With the RF harvesting system, the battery could be replaced by RF power harvesting devices to provide an independent energy source. Therefore, the need of battery could be eliminated and it is able to save on the operation and maintenance cost. Thus, this alternative source of energy has brought lots of attention for development.

2.4 Rectifier

A rectifier is also known as RF to DC converter which necessary to provide a stable power supply with the required voltage level [5]. The rectification occurs in both half-wave and full wave rectifier as shown in Figure 2.2 and Figure 2.3. The half-wave rectification allows either the positive or negative half of the alternating current (AC) signal to pass through and block the other half. While the full-wave rectification converts both polarities of the alternate current (AC) input waveform to pulsating DC. Thus, a higher average output voltage is able to produce. However, more ripple will be produced in half-wave rectifier compared to full-wave rectifiers. Therefore, much more filtering is needed to eliminate harmonics of the AC frequency from the output in half-wave rectification process.

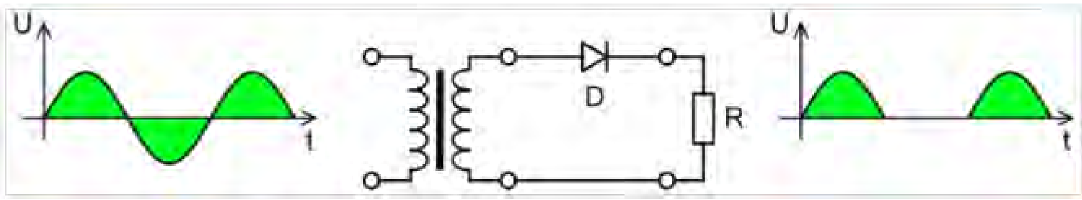

Figure 2.2 : Half-wave rectification

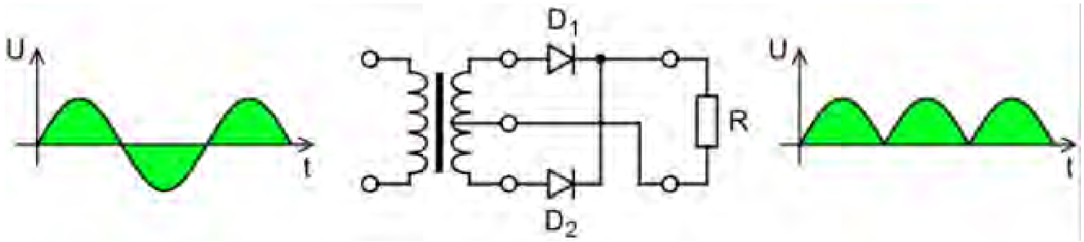

Figure 2.3 : Full-wave rectification

In conventional rectifier circuit, Schottky diodes were considered as an attractive candidate to perform the charge transfer task due to their low forward voltage drop and fast switching speed [6]. However, Schottky diodes are not properly modeled in all CMOS technologies which restrict their usefulness in low-cost applications where high integration levels are desired [7]. Therefore, recently most researchers have been working towards finding solutions to the forward voltage drop and leakage current mentioned in CMOS technology. Besides, the previous rectifier focused on maximizing the PCE and output power rather than sensitivity [8]. Since the available power supplies to the rectifier block is too low for traditional rectifiers to operate. Therefore, plenty of new and improved high sensitivity rectifier topologies for low input power (LIP) used were researched. Besides, the efficient model of Schottky diode in an integrated circuit (IC) domain also been investigated. In order for rectifier to work with very low input power, all the transistors in rectifier should operate in the sub-threshold region.