Faculty of Electronics and Computer Technology and Engineering

DESIGN AND DEVELOPMENT OF HIGH-EFFICIENCY CMOS ON-CHIP RECTIFIERS FOR RADIO-FREQUENCY ENERGY HARVESTING APPLICATIONS

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DESIGN AND DEVELOPMENT OF HIGH-EFFICIENCY CMOS ON-CHIP RECTIFIERS FOR RADIO-FREQUENCY ENERGY HARVESTING APPLICATIONS

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DECLARATION

I declare that this report entitled "Design and Development of High Efficiency CMOS on-chip Rectifiers for Radio Frequency Energy Harvesting Applications" is the result of my own work except for quotes as cited in the references.

Signature : ....

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Date : .... 30/09/2024..............................

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electronic Engineering.

Signature : ....

Supervisor Name : PM DR. WONG YAN CHIEW…………………

Date : .... 30/09/2024..................................

DEDICATION

I dedicate this thesis to my loving family, my lover, and my beloved friends for their constant support and unconditional love.

ABSTRACT

The on-chip rectifier is major part of the integrated radio frequency energy harvesting system because it converts electromagnetic waves coming to the antenna into usable DC voltage. The diode-connected transistor is the fundamental unit of the on-chip rectifier. Previous studies showed CMOS cross connected rectifier over a wide input range is the most efficient to date and was stated that to design a (<10W rectifier) that can be implemented in medical devices, we use a diode connected transistor on-chip to create the efficient full wave rectifier. CMOS is the preferred technology for building an on-chip rectifier because its circuit is compact, insensitive to noise and consumes less power. The differential cross-connected rectifier architecture is the most efficient rectifier to date and is widely used for passive radio frequency identification tags. The design of the rectifier starts with the specifications of circuit parameters with the use of the Silterra Process Design Kit and the Cadence Virtuoso Platform, schematic capture, layout design as well as simulation and verification. The most important parameters of the CMOS rectifier are sensitivity that measures the minimum power of radio wave required to produce an output of 1 V DC voltage, and the power conversion efficiency that measures the percentage ratio of DC output power to input radio frequency power. The cascade of the rectifier block in series increases the output voltage. The designed differential drive cross connected rectifier schematic circuits with impedance matching network circuits' simulations resulted a power conversion efficiency of 83% and sensitivity of 18 dBm at input power -25 dBm and bandwidth 500 MHz. When the number of the stages of rectifier circuit block were cascaded in the schematic drawing from a single stage to five stages, the output voltage was incremented proportionally. The powercast energy harvesting development kit for wireless sensors was demonstrated at various distances using patch and dipole antennas and was calculated for transmitted 1 W power from powercast transmitter at distance one meter between the transmitter and receiving antennas. The received power conversion efficiency was 55% for both antennas but the received power for patch antenna was 8.1 mW and 3.7 mW for dipole antenna. Applications of the radio frequency energy harvesting system include a wireless sensor network node, radio frequency identification tag, body area network, implantable medical devices and portable sensors.

REKA BENTUK DAN PEMBANGUNAN PENERUS CMOS ATAS-CIP KECEKAPAN TINGGI UNTUK APLIKASI PENUAIAN TENAGA FREKUENSI RADIO

ABSTRAK

Penerus atas-cip adalah bahagian yang paling penting untuk sistem penuaian tenaga frekuensi radio bersepadu kerana ia menukar gelombang elektromagnet dari antena ke voltan DC. Transistor berkait-diod adalah unit asas untuk penerus atas-cip. CMOS adalah teknologi pilihan untuk membina penerus atas-cip kerana litarnya kompak, tidak sensitif kepada hingar dan menggunakan kurang kuasa. Seni bina penerus pembezaan bersambung-silang adalah penerus yang paling cekap sehingga kini dan digunakan secara meluas untuk tag pengenalan frekuensi radio pasif. Reka bentuk penerus ini bermula dengan spesifikasi parameter litar dengan penggunaan Kit Proses Reka Bentuk Silterra dan Platform Cadence Virtuoso, penangkapan skematik, reka bentuk susunatur serta simulasi dan penentusahan. Parameter terpenting bagi penerus CMOS adalah kepekaan untuk mengukur kuasa frekuensi radio minimum yang diperlukan untuk menghasilkan voltan DC 1 V, dan kecekapan penukaran kuasa yang mengukur nisbah peratusan kuasa keluaran DC kepada kuasa masukan radio frekuensi. Lata blok penerus secara sesiri meningkatkan output voltan. Litar skematik penerus penyambung silang pemacu pembezaan yang direka beserta dengan simulasi rangkaian pemadan impedans menghasilkan kecekapan penukaran kuasa sebanyak 86% dan kepekaan sebanyak 18 dBm pada kuasa masukan -25 dBm dan lebar jalur 500 MHz. Apabila bilangan tahap litar penerus meningkat dari tahap satu ke tahap lima, voltan keluaran meningkat secara berkadar. Kit pembangunan penuaian tenaga siaran kuasa untuk sensor tanpa wayar telah ditunjukkan pada pelbagai jarak menggunakan antena tampalan dan dipol dan juga dikira untuk menghantar kuasa 1 W dari pemancar siaran kuasa pada jarak satu meter antara antena pemancar dan penerima. Kecekapan penukaran kuasa penerima adalah 55% untuk kedua-dua antena tetapi kuasa penerima untuk antena tampalan adalah 8.1 mW dan 3.7 mW untuk antena dipol. Aplikasi sistem penuaian tenaga frekuensi radio termasuk nod rangkaian sensor tanpa wayar, tanda pengenalpastian frekuensi radio, rangkaian kawasan badan, alat perubatan yang boleh dilaksanakan dan sensor mudah alih.

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LIST OF ABBREVIATIONS

IC	-	Integrated Circuit
P-MOS	-	P-Type Metal-Oxide Semiconductor
N-MOS	-	N-Type Metal-Oxide Semiconductor
MOSFET	-	Metal-Oxide Semiconductor Field Effect Transistor
LNA	-	Low Noise Amplifier
RF-MOS	-	Radio Frequency Metal Oxide Semiconductor
IMN	-	Impedance Matching Network
DDCCR	-	Differential Drive Cross Connected Rectifier
CAD	-	Computer Aided Design
EDA	-	Electronic Design Automation
CMOS	-	Complementary Metal Oxide Semiconductor
WBAN	-	Wireless Body Area Network
WPT	-	Wireless Power Transfer
SOC	-	System On Chip
LDO	-	Low-Dropout
WSN	-	Wireless Sensor Networks
Iot	-	Internet of things
RFID	-	Radio Frequency Identification
EIRP	-	Effective Isotopically Radiated Power
DCT	-	Diode-Connected Transistor

LIST OF SYMBOLS

dBm	-	Unit power level
Hz	-	Hertz
mm	-	millimeter
MHz	-	Mega Hertz
DC	-	Direct Current
μm	-	Micro Ampere
V	-	Volt
kHz	-	Kilohertz
μm	-	Micrometer
nm	-	Nanometer
$\boldsymbol{\pi}$	-	Phi
Δ	-	Additional offset (Value: 0.01-0.03V)
GHz	-	GigaHertz
λ		Lambda (wavelength)
A_e	-	Antenna Aperture
R		Resistance, Distance or Receiver

LIST OF PUBLICATIONS

A. E. and Wong, Y. C. (2018) ‘Co - design of on - chip 2.5Ghz RF-DC Power Conversion Circuit for Wireless Sensor Network Node Application’, *Proceedings of Symposium on Electrical, Mechatronics and Applied Science 2018 (SEMA’18)*, pp. 81-82, 8 November 2018.

Mohammed Abdul Raheem Esmail Alselwi, Yan Chiew Wong, Zul Atfyi Fauzan Mohammed Napiah, ‘Integrated CMOS Rectifier for RF-Powered Wireless Sensor Network Nodes’ *Bulletin of Electrical Engineering and Informatics (BEEI)*, pp. 1-10, 8(3), 2019.

CHAPTER 1

INTRODUCTION

1.1 Background

On chip rectifier is electronic circuit converts alternating current to discrete voltage at low power electronic systems. CMOS rectifier is major part in radio frequency energy harvesting system. CMOS stands for complementary metal oxide semiconductor. CMOS circuit is immune to noise and low power consumption, therefor it is appropriate technology for designing rectifier for the harvester's power is small. SilTerra's Radio Frequency CMOS (RFCMOS) technologies are customized and developed for wireless related applications such as low power chips for applications in IoT, consumer electronics, next generation sensors and industrial automation. Silterra process design kit (PDK) 0.18 µm CMOS technology is used for simulating differential drive cross connected rectifier. The applications of RF energy harvester are wireless sensor network, implementable medical devices, internet of things, radio frequency identification tag, wireless body area network and wearable sensors.

The on-chip rectifier is a miniaturized device of a few square microns consisting of passive electronic components such as capacitors and active components such as transistors. The integrated rectifier is a crucial element of the radio frequency energy harvesting system. The designed CMOS rectifier circuit of 2.5 GHz frequency band can produce a DC voltage of 1V from a signal of only 13 microwatts. The designed impedance matching network with a reflection coefficient of -17 dBm used to transfer all available power to the DC output voltage and improve the efficiency of the rectifier circuit. The radio frequency energy harvesting is a sustainable and clean energy source in diverse environments as well as a potential replacement of the microsystem battery, such as the wireless sensor network node and the implantable medical devices.

A rectifier circuit converts ambient radio frequency (RF) waves into useful DC power as a major part of a radio frequency energy harvesting system. For example, electromagnetic harvesting refers to converting power from EM wave to DC power, the harvesting or receiving element of the EM power is either photovoltaic module for solar energy harvesting, or an antenna for RF energy harvesting. RF energy harvesting can be Near-field and Far-Field RF energy harvesting, and near field refers to non-radiative energy harvesting at shorter distances such as inductive coupling compared to radiative energy harvesting at longer distance such as ambient RF energy harvesting.

The chip rectifier is an important miniaturized electronic component converts AC energy to a useful DC power that replenishes the energy required for radio frequency energy harvesting (RFEH) applications such as the Internet of Things (IoT) devices. The RFEH is a new technology that addresses the wireless power supply reception for sensor applications, including the wireless body area network sensors, the sensor monitors the environmental weather and the structures. RFEH technology and application simplify life, and it's important to eliminate the use of cables that is complex and the use of many batteries that end up contaminating soil and groundwater. The block diagram of (RFEH) includes an antenna, an impedance matching network, a rectifier, a voltage regulator, and a load. The designed circuit schematic of the CMOS differential drive cross-connected rectifier and the 2.5 GHz impedance matching network using Cadence virtuoso and Silterra Malaysia process design kit achieves an energy conversion efficiency of 83.34%. The design of rectifier is useful for next generation wireless sensor networks and Melaka Smart City (IoT) technologies. The demonstration of wireless power supply for WSN node at different distances using the Powercast P2110 evaluation board, consists of transmitter, the dipole and patch receiving antennas, the wireless sensors, and the 915 MHz measures the receiving power at different distances. In the literature CMOS rectifier were not efficient for lower power RF energy harvesting no sensitivity for detecting ambient low power and their sizes were too big.

1.2 Objective

1- To investigate the main building blocks in RFEH for WSN applications

2- To design and analyse rectifier in RFEH for optimum performance in WSN.

3- To evaluate the performance of wireless sensor network powering by RFEH using PowerCast module.

1.3 Thesis Statement

Periodically replacement and maintenance of batteries of wireless sensor network is not practical. The on-chip rectifier’s low power conversion efficiency for low-power, output power is less than the requirement of the operating voltage of the WSN node. Increasing number of stages of the rectifier increases the size and decreases the efficiency. Lack of feasible study of electrical operations in microelectronics applications devices operations in Malaysia, and limitations of the current designs that are bulky, neither integrated nor fully