Faculty of Electronic and Computer Engineering

IMPROVEMENT ON RECTIFICATION AND REGULATION OF POWER CONDITIONING CIRCUIT FOR RF ENERGY HARVESTING

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DECLARATION

I declare that this thesis entitled "Improvement on Rectification and Regulation of Power Conditioning Circuit for RF Energy Harvesting" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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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	:	....
Date	:	....

DEDICATION

To my father, brothers and two lovely cats for whose love and supports have made this journey possible, and the enduring memory of my mother

ABSTRACT

Power management is one of critical issues in most of integrated circuit (IC) applications as it determines the ability of a device to maintain its operating time. Power management system can be divided into two parts, energy harvesting and low dropout (LDO) voltage regulator circuits. Due to the increase of radio frequency (RF) sources around the globe, RF energy harvesting system which mainly composes of a rectifier becomes promising solution to power the low-powered electronic devices as it offers low power density and smaller size of energy converter make it easily to be integrated into a chip. The sensitivity, efficiency, and output voltage play an important role in the design of rectifier for energy harvesting. High efficiency conventional rectifiers typically provide either high sensitivity or high output voltage characteristics. Due to the limitation in rectifier architectures and the physical structure of transistor that causing large voltage drop across the rectifier over a wide range of sensitivity and output voltage, improving one of the characteristics trades off the other. The objective of this research is to design a high efficiency rectifier that operates at high sensitivity, targeting urban and rural areas and producing large output voltage that is sufficient to supply low-power electronic devices. The proposed rectifier comprises bulk-to-source BTMOS differential-drive based rectifier to produce a high efficiency RF energy harvesting system. Low-pass upward matching network is applied at the rectifier input to minimize the power loss between antenna and the rectifier hence increasing the sensitivity and output voltage. Dual-oxide-thickness transistors are used in the rectifier circuit to optimize the power efficiency at each of the rectifier’s stage over a wide range of output voltage and sensitivity. The system is designed using 0.18µm Silterra RF in deep n-well process technology and produces 3.997V output at -15dBm sensitivity without the need of complex auxiliary control circuit and DC – DC charge-pump circuit. Meanwhile, technology scaling in modern IC industries causing the ripple noise from power supply become dominant for analogue and RF circuits. RF circuit demands for voltage regulator that has high power supply rejection ratio (PSRR) and low temperature coefficient as this circuit is very sensitive to noise. Small changes in its supply voltage may cause the circuit not functioning properly. Conventional regulators provide high PSRR, but it typically focuses on low frequency application. Due to this reason, LDO with high PSRR at high frequency and low temperature coefficient over a wide range of temperature is proposed. The proposed LDO uses rail-to-rail folded cascode amplifier to achieve high PSRR while obtaining good open-loop gain and stability. Large 1µF off-chip load capacitor is used to further increase the PSRR. The LDO uses transistors operating in weak and strong inversions at the voltage reference circuit to achieve 2nd order voltage-temperature characteristic hence reducing the temperature coefficient. The LDO is designed using 0.18µm Silterra thick-oxide technology and produces a constant 1.8V output voltage for input voltage between 3.2V to 5V and load current up to a 128mA at temperature between -40°C to 125°C. The LDO achieves more than 100dB PSRR for frequency greater than 900MHz and obtained temperature coefficient of lower than 5ppm/°C within the desired temperature range.

ABSTRAK

Pengurusan kuasa adalah salah satu masalah kritikal dalam aplikasi litar bersepadu (IC) kerana ia menentukan keupayaan peranti untuk mengekalkan hayat operasi. Pengurusan kuasa terbahagi kepada dua, iaitu penuaian tenaga dan pengawal selia voltan rendah (LDO). Peningkatan sumber frekuensi radio (RF) di seluruh dunia menjadikan penuaian tenaga RF dimana komponen utamanya adalah litar penerus sebagai penyelesaian terbaik untuk digunakan oleh peranti berkuasa rendah kerana mempunyai rendah ketumpatan kuasa dan bersaiz kecil, menjadikannya sesuai untuk disepadukan ke dalam cip. Sensitiviti, kecekapan dan voltan keluaran memainkan peranan penting dalam reka bentuk penerus. Penerus konvensional berkecekapan tinggi menghasilkan litar bersensitiviti atau voltan keluaran yang tinggi. Akan tetapi, batasan daripada reka bentuk penerus dan struktur fisikal transistor menyebabkan hanya salah satu daripada ciri-ciri ini mampu dicapai. Objektif kajian ini adalah untuk menghasilkan penerus yang mempunyai tinggi kecekapan dan sensitiviti, menyasarkan kawasan bandar dan kampung serta menghasilkan DC voltan yang besar dan mencukupi untuk membekalkan kuasa kepada peranti berkuasa rendah. Cadangan penuaian tenaga terdiri daripada substrat-ke-sumber BTMOS penerus berlainan pemacu untuk menghasilkan penuaian tenaga RF berkecekapan tinggi. Penaik pemadan impedans laluan-rendah diterapkan pada input penerus untuk meminimumkan kehilangan kuasa antara antena dan input penerus sekaligus meningkatkan kepekaan dan voltan keluaran. Transistor duo-ketebalan-oksida digunakan untuk mengoptimumkan kecekapan kuasa pada kadar voltan keluaran dan sensitiviti yang luas. Sistem ini direka menggunakan teknologi Silterra RF 0.18μm proses n-well mendalam dan menghasilkan 3.997V DC voltan pada kepekaan -15dBm tanpa menggunakan litar tambahan kompleks dan pengepam DC – DC. Sementara itu, penskalaan teknologi dalam industri IC menyebabkan hingar daripada voltan bekalan menjadi dominan untuk litar analog dan RF. Litar RF memerlukan LDO yang mempunyai nisbah penolakan bekalan kuasa (PSRR) yang tinggi serta rendah pekali suhu kerana sifatnya yang sensitif terhadap hingar. LDO konvensional menawarkan PSRR tinggi tetapi hanya fokus pada frekuensi rendah. Projek ini mencadangkan reka bentuk LDO yang mempunyai PSRR yang tinggi pada frekuensi tinggi serta pekali suhu yang rendah pada kadar suhu yang luas. Penguat rel-ke-rel kaskod lipat digunakan untuk mencapai PSRR dan gandaan gelung-terbuka yang tinggi serta kestabilan yang baik. 1μF luar cip kapasitor digunakan untuk meningkatkan PSRR. Transistor penyongsangan lemah dan kuat digunakan pada litar voltan rujukan untuk menghasilkan voltan rujukan bersifat lengkungan peringkat kedua sekaligus mengurangkan pekali suhu. LDO ini direka menggunakan teknologi Silterra 0.18μm oksida-tebal dan menghasilkan 1.8V voltan keluaran yang malar pada input 3.2V ke 5V dan bebanan sehingga 128mA pada suhu antara 40℃ hingga 125℃. PSRR lebih daripada 100dB dihasilkan pada frekuensi melebihi 900MHz dan mencapai pekali suhu kurang daripada 5ppm/℃ dalam julat suhu yang dikehendaki.

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AC	-	Alternating current
BJT	-	Bipolar junction transistor
BTMOS	-	Bulk/body threshold MOSFET
CMOS	-	Complementary MOSFET
CMRR	-	Common mode rejection ratio
DC	-	Direct current
DDR	-	Differential-drive rectifier
DTMOS	-	Dynamic threshold MOSFET
ESD	-	Electrostatic discharge
ESR	-	Equivalent series resistance
IC	-	Integrated circuit
ICMR	-	Input common-mode ratio
I_{CTAT}	-	Current complementary-to-temperature
I_{PTAT}	-	Current proportional-to-temperature
I_q	-	Quiescent current
I/O	-	Input/Output
LDO	-	Low dropout
MOSFET	-	Metal-oxide-semiconductor field effect transistor
OTA	-	Operational transconductance amplifier
OVP	-	Over-voltage protection
PCE	-	Power conversion efficiency

PMU	-	Power management unit
ppm	-	Parts per million
PSRR	-	Power supply rejection ratio
$Q_{-factor}$	-	Quality factor
RF	-	Radio frequency
RFEH	-	Radio frequency energy harvesting
r_{on}	-	Channel resistance
S11	-	Reflection coefficient
SoC	-	System-on-chip
STI	-	Shallow tranch isolation
UVLO	-	Under voltage lock-out
V_{BE}	-	BJT base-emitter turn-on voltage
V_{bs}	-	Body-to-source voltage
V_{CTAT}	-	Voltage complementary-to-absolute-temperature
V_D	-	Diode voltage
V_{ds}	-	Drain-to-source voltage
V_F	-	Feedback voltage
V_{gs}	-	Gate-to-source voltage
V_{out}	-	Output voltage
V_{PTAT}	-	Voltage proportional-to-absolute-temperature
V_{REF}	-	Reference voltage
V_{REG}	-	Regulated voltage
V_T	-	Thermal voltage
V_{RF}		Radio frequency input AC signal
V_{th}	-	Threshold voltage
Z11	-	Real and Imaginary

LIST OF PUBLICATIONS

Asli, A.N.F., and Wong, Y.C., 2019. 3.3V DC Output at -16dBm Sensitivity and 77% PCE Rectifier for RF Energy Harvesting, *International Journal of Power Electronics and Drive System (IJPEDS)*, 10(3), pp. 1398–1409.

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CHAPTER 1

INTRODUCTION

1.1 Research background

In recent years, much attention has been placed on the Internet of Things (IoT) technology. IoT refers to the vast network of physical devices that are connected to the internet via built-in sensors, software and necessary electronic circuits allowing the devices to send, receive and exchange data. The 'Things', for example home appliances are put into home network and can be controlled by using voice, remote control or smartphone via the internet. In large-scale deployment area such as Smart Cities, billions of sensors are needed to control the 'Things'. These wireless sensor nodes are normally powered by batteries which are known for its limited lifetime and the use of batteries in a large network area is not practical as it involves the cost of purchase, maintain and disposal of large amount of batteries.

There are also few cases where the application of batteries is not feasible such as implantable medical devices, habitat monitoring devices or devices that is used to monitor the change in environment (volcano or earth surface) due to the limited battery's lifetime and the need of replacing the battery. As the alternative solution to this problem, energy harvesting system is used. Energy harvesting system harnesses energy from ambient environment and converts the energy into electricity to power electronic or electrical devices. This provides a long operating life to the electronic devices and eliminates the need to replace the batteries.