CMOS RECTIFIER DESIGN WITH POWER MANAGEMENT FOR INDOOR LIGHT AND RF ENERGY HARVESTING WIRELESS SENSOR NODES

by

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for the degree of

DOCTOR OF PHILOSOPHY

Under the supervision of

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Certificate of Original Authorship

I, Jefferson A. Hora declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Electrical and Data Engineering, Faculty of Engineering and IT at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Dedicated to My Beloved Family

Wife Kate and Son Xian

List of Publications

<u>IEEE Journal (for resubmission)</u>

- **Jefferson A. Hora**, Xi Zhu, Lang Chen, and Eryk Dutkiewicz, "Design Analysis of Indoor Light and 2.4-GHz RF CMOS Rectifier with High Voltage Conversion in Energy Harvesting for Internet-of-Things."

<u>IEEE Conference Proceedings</u>

- **Jefferson A. Hora**, Xi Zhu, and Eryk Dutkiewicz, "Design of High Voltage Output for CMOS Voltage Rectifier for Energy Harvesting Design," in *Proc. IEEE 2nd Wireless Power Transfer Conference,* June 2019. (Corresponding to Chapter 4)
- **Jefferson A. Hora**, Xi Zhu, and Eryk Dutkiewicz, "2.4-GHz CMOS Design RF-to-DC Energy Harvesting with Charge Control System for WSN Application," in *Proc. 2nd IEEE Wireless Power Transfer Conference,* June 2019. (Corresponding to Chapter 4)
- **Jefferson A. Hora**, Xi Zhu, and Eryk Dutkiewicz, "Simplified Over-Temperature Protection Circuit Structure for WSN/IoT Device Power Management," in *Proc. IEEE 13th International Conference on Sensing Technology,* December 2019. (Corresponding to Chapter 6)
- **Jefferson A. Hora**, Meilyssa Mayormita, John Raul Rebollos, Xi Zhu, and Eryk Dutkiewicz, "On-chip Inductor-less Indoor Light Energy Harvester with Improved Efficiency for WSN/IoT Device Design," in *Proc. IEEE 13th International Conference on Sensing Technology,* December 2019. (Corresponding to Chapter 5)
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- **Jefferson A. Hora**, Jim Darell Ang, Xi Zhu, and Eryk Dutkiewicz, "A Highly Linear OTA with 759 µS gm for RF Transceiver Application," in *Proc. IEEE 19th International Symposium on Communications and Information Technologies,* September 2019. (Corresponding to Chapter 6)
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Others

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- Lang Chen, Hang Liu, **Jefferson Hora**, J. Andrew Zhang, Kiat Seng Yeo, and Xi Zhu, "A Monolithically Integrated Single-Input LoadModulated Balanced Amplifier With Enhanced Efficiency at Power Back-Off," *IEEE Journal of Solid-State Circuit, vol. 56, no. 5, pp. 1553-1564*, Jan. 2021.
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- **Jefferson A. Hora**, Dessa Piandong, Paul Emmanuel Empas, Olga Joy Gerasta, Xi Zhu, and Eryk Dutkiewicz, "A CMOS implemented transimpedance amplifier design for optical communications*," in Proc. IEEE 10th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management,* December 2018.
- Meriam Gay Bautista, **Jefferson A. Hora**, and Eryk Dutkiewicz, "Design methodology of a miniaturized millimeter wave integrated passice resonator using (Bi)-CMOS Technology," *in Proc. 18th IEEE International Symposium on Communications and Information Technologies, pp. 275-277,* September 2018.

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Symbol	Description
V_j	voltage across both diode
V_T	thermal voltage at 25°C
q	electron charge (1.6x10^{-19} Coulombs)
I_0	dark/reverse saturation current of the P-N diodes (1×10^{-9} A)
k	Boltzmann's constant (1.38x10^{-23}J/K)
T_c	absolute temperature (K).
J_{sc}	short-circuit density in mA/cm^2
n	diode ideality factor (1 for an ideal diode)
R_{sh}	shunt resistance
I_{PV}	Photovoltaic output current
I_D	diode current
I_L	photogenerated current or load current
I_{sh}	current lost due to the shunt resistance
V_{PV}	photovoltaic output voltage
R_s	equivalent small series resistance
V_{oc}	maximum voltage difference across the cell in a forward-bias sweep in the power quadrant
λ	photon excitation or wavelength
I_{sc}	short-circuit current
A	surface area
G	irradiance of the incident light
η	Photovoltaic efficiency
P_{PV}	Power of the photovoltaic cell
E	illuminance expressed in lux
I	candlepower with a cd unit
D	measured distance of the point from the light source in meter
G_{RX}	RF harvester's receiving antenna gain
α_p	*p*-type–Seebeck coefficient value of the thermocouple
α_n	*n*-type–Seebeck coefficient value of the thermocouple
ΔT_{TEG}	temperature difference of the two distinct materials in a TEG [K]
K_{in}	thermocouple's internal thermal conductivity

Abstract

There is a vast potential for using wireless sensor networks and IoT devices to improve the efficiency and quality of manufacturing operations. It will also enable energy efficiency, increase demand for responsive building, interconnected and full-operational smart grid systems, and other futuristic next-level energy and infrastructure systems. These promising devices are expected to work autonomously for years with no recharging, no human intervention, and no updates.

There are two possible solutions to address the energy needs of these power-hungry devices. One is the reduction of the power consumption of the device's internal circuitry, and the other is the continuous-intermittent charging of the device battery through ambient energy harvesting to extend longevity. Henceforth, this work focused on the integrated circuits design and implementation of the energy harvesting and power management component blocks for its future integration on the system-on-chip IoT device.

The harvesting performance relies on the circuit design integrity of the rectifier circuit block, which is the essential building block of all sources of energy harvesting systems. Thus, this thesis presents novel circuit design techniques for CMOS-based rectifiers with an enhanced voltage-conversion ratio and power conversion efficiency. Two rectifiers are designed in 65-nm CMOS technology to develop indoor light and 2.4-GHz RF energy harvesting using the split-capacitor and auxiliary path techniques in the cross-coupled differential drive structure. Moreover, the unconventional DC-DC boosting technique for processing the voltage required by the load from a single unit of 0.5-V rating PV cell is also highlighted in this thesis. Utilizing a rectifier circuit block instead of the conventional charge-pump circuit after signal pre-processing from the oscillator and buffer driver circuit block offers an alternate technique for the system energy harvesting design that requires dual or multiple energy sources, like RF+PV harvesters.

This thesis also proposes a power-management circuit design implementation in 65 nm CMOS technology to possibly reduce the power consumption of the internal circuitry of the sensor node device. The study explored using a power-down control mechanism implementation to a particular circuit block of the power management and energy harvesting unit with the preliminary performance of the DC-DC boost and LDO block.