Faculty of Electronic and Computer Engineering

MINIATURIZED ON-BOARD AND ON-CHIP ANTENNA DESIGN FOR INTEGRATED RF ENERGY HARVESTING SYSTEM

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Master of Science in Electronic Engineering

2019

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A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
in Electronic Engineering

Faculty of Electronic and Computer Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

DECLARATION

I declare that this thesis entitled "Miniaturized On-board and On-chip Antenna Design for Integrated RF Energy Harvesting System" 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.

Signature	:	……………………………………….
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Date	:	……………………………………….

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 all those that have been in my life during the completion of this thesis, this one's for you

ABSTRACT

Radio Frequency (RF) energy harvesting refers to the concept of harvesting and recycling the RF energy in the surroundings that is widely broadcasted by many wireless systems. It is a promising technique that can be used to replace batteries or prolong their lifespan. Nowadays, mobility and low power consumption has led to small electronic circuitry, thus RF Energy Harvesting System (RFEHS) is desired to be miniature so that it can be integrated with other small systems as well. However, this will be a challenge as antenna is often the largest single component in the system. Furthermore, there are emerging demands on building RFEHS on a single silicon chip known as System on Chip (SoC) using Complementary Metal-Oxide-Semiconductor (CMOS) technology, but there is currently no extensive research that has been published regarding CMOS antenna design for lower sub 10-GHz frequency. Hence, this work presents the study on miniature antenna for RFEHS which is further divided into on-board design and on-chip design to consider both Printed Circuit Board (PCB) and CMOS technologies. In the on-board design, a high gain and miniature size are the main objectives, and the design process is conducted through mathematical approximation, followed by modelling and simulations in Computer Simulation Technology (CST) and verification through antenna's fabrication and measurement. As a result, two on-board topologies have been evaluated which are the staircase shaped Co-Planar Waveguide (CPW) monopole antenna and Dielectric Resonator Antenna (DRA). The staircase shaped CPW monopole antenna is shown to have up to 32.19% improvement in term of received power compared to previous work. To assess the improvement of DRA against previous work, a way to find the Figure of Merit (FOM) is identified and it is found that the DRA have up to 90% higher FOM than others. The FOM takes into account the gain and volume to emphasize high gain and miniature size. Meanwhile, the on-chip design is based on 0.13 µm and 0.18 µm CMOS process technologies and two antenna topologies have been evaluated which are the spiral-slot design and spiral design. Studies involving the thicknesses of metals and substrate in CMOS technology have been performed and the results show that thicker metal and substrate contribute to an improved gain and bandwidth. The rate of bandwidth increment has a mean of 0.65 GHz per 8.25 µm increment of substrate thickness, while gain improvement is up to 18.45%. This work has also proposed a technique to transfer antenna design between different CMOS process technologies without having major effect on its gain and bandwidth through manipulation on the ground planes. The work has been fabricated considering the required standard thickness of the CMOS technology defined by the selected foundry. The on-chip antenna proposed has an area of less than 4 mm^2 and thickness of less than 1 mm. Overall, miniature antenna design has been presented for on-chip and on-board topologies for RFEHS. It is hopeful that the contribution from this work can be used to achieve further advancement in miniature and integrated antenna and RFEHS development, thus providing a solution for energy issue.

ABSTRAK

Penuaian tenaga Frekuensi Radio (RF) merujuk kepada konsep penuaian tenaga RF daripada persekitaran yang disiarkan secara meluas oleh sistem tanpa wayar. Ia adalah teknik yang menjanjikan dan boleh digunakan untuk menggantikan bateri atau memanjangkan jangka hayatnya. Pada masa kini, mobiliti dan penggunaan kuasa rendah telah membawa kepada litar elektronik bersaiz kecil, oleh itu Sistem Penuaian Tenaga RF (RFEHS) dikehendaki menjadi kecil supaya ia boleh diintegrasikan dengan sistem kecil lain juga. Namun, ini akan menjadi cabaran kerana antena sering merupakan komponen tunggal terbesar dalam sistem. Tambahan pula, terdapat permintaan dalam membina RFEHS pada satu cip silikon yang dikenali sebagai Sistem pada Cip (SoC) dengan menggunakan teknologi Semikonduktor-Oksida-Logam Pelengkap (CMOS), tetapi pada masa ini tidak ada penyelidikan luas yang telah diterbitkan mengenai reka bentuk antena CMOS untuk sub frekuensi 10-GHz. Oleh itu, kerja ini membentangkan kajian mengenai antena miniatur untuk RFEHS yang selanjutnya dibahagikan kepada reka bentuk pada-papan dan reka bentuk pada-cip untuk mempertimbangkan kedua-dua Papan Litar Bercetak (PCB) dan teknologi CMOS. Dalam reka bentuk pada-papan, gandaan yang tinggi dan saiz kecil adalah matlamat utama, dan proses reka bentuk dijalankan melalui perkiraan matematik, diikuti dengan pemodelan dan simulasi menggunakan Teknologi Simulasi Komputer (CST) dan pengesahan melalui fabrikasi dan pengukuran antena. Hasilnya, dua topologi pada-papan telah dinilai yang merupakan monopole antena berbentuk tangga Co-Planar Panduan-gelombang (CPW) dan Antena Resonator Dielektrik (DRA). Monopole antenna berbentuk tangga CPW menunjukkan peningkatan sehingga 32.19% dari segi penerimaan tenaga berbanding kerja sebelumnya. Untuk menilai DRA berbanding kerja sebelumnya, satu cara untuk mencari Angka Merit (FOM) dikenalpasti dan didapati bahawa DRA mempunyai FOM yang 90% lebih tinggi berbanding yang lain. FOM mengambil kira gandaan dan saiz untuk menekankan gandaan tinggi dan saiz kecil. Sementara itu, reka bentuk pada-cip adalah berdasarkan pada teknologi proses CMOS 0.13 μm dan 0.18 μm dan dua topologi antena telah dinilai iaitu reka bentuk lingkaran-berlubang dan reka bentuk lingkaran. Pengajian yang melibatkan ketebalan logam dan substrat dalam teknologi CMOS telah dilakukan dan hasilnya menunjukkan bahawa logam dan substrat tebal menyumbang kepada peningkatan gandaan dan lebar jalur. Kadar kenaikan lebar jalur mempunyai purata 0.65 GHz bagi setiap pertambahan ketebalan substrat sebanyak 8.25 μm, sementara kenaikan gandaan adalah sehingga 18.45%. Kerja ini juga telah mencadangkan teknik untuk memindahkan reka bentuk antena antara teknologi proses CMOS yang berbeza tanpa memberi kesan besar ke atas gandaan dan lebar jalurnya melalui manipulasi dataran tanah. Antena CMOS telah difabrikasi menurut piawai yang ditetapkan oleh kilang terpilih. Antena CMOS yang dicadangkan mempunyai keluasan kurang daripada 4 mm^2 dan ketebalan kurang dari 1 mm. Secara keseluruhannya, reka bentuk antena miniatur telah dibentangkan untuk topologi pada-cip dan pada-papan bagi RFEHS. Diharapkan sumbangan dari kerja ini dapat digunakan untuk mencapai kemajuan selanjutnya dalam pembangunan sistem antena kecil dan terintegrasi serta pembangunan RFEHS, dengan itu menyediakan penyelesaian untuk masalah tenaga.

ACKNOWLEDGEMENTS

In the name of Allah, the most Merciful, the most Gracious. All praise is due to Allah, may blessings and peace be upon the Messenger of Allah, and upon his family, his companions, and those who follow him. As for what follows:

It is to my utmost gratitude to take this opportunity to thank everyone that has been helping me and contribute to the completion of this thesis. Special thanks go to my supervisor, Associate Professor Dr. Wong Yan Chiew for her guidance, patience, advices, ideas and encouragements throughout this study.

My gratitude also extends to all staff and fellow students of the Faculty of Electronic Engineering and Computer Engineering for their assistance and readiness to share their knowledge and skills to help me in completing this study. Not forgotten, my appreciation also goes to the Ministry of Energy, Science, Technology, Environment and Climate Change (MESTECC, formerly known as MOSTI) for the financial support and opportunity granted through Science Fund.

To my parents, Masius Julit and Sainah binti Rimpun; there are no words to express how grateful I am for your endless support, patience and understanding for my decision to further my study and all the burden that comes with it, and this also goes to my brothers and sister; Rozer, Roland and Celestina. It is from the deepest of my heart that I hope for the gift of Hidayah to reach to all of you by Allah’s will. To my beloved friend, Mohamad Khairul bin Mohd Kamel which has been in the same ship in the journey for Master of Science, and his family; thank you for your companionship, patience and love. Let it be known, that all of you that has been mentioned in this paragraph are very dear to me; and life, especially this journey, has been much more meaningful and enjoyable because of you.

Finally, to any and all individuals involved in this project which names were not mentioned, along with all mentioned above; without all of you, this thesis will not be possible.

Thank you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AgHT-4	-	Silver coated polyester-4
AgHT-8	-	Silver coated polyester-8
CAD	-	Computer aided design
CMOS	-	Complementary metal-oxide-semiconductor
CPW	-	Co-planar waveguide
CST	-	Computer simulation system
CSTMWS	-	Computer simulation technology microwave studio
DC	-	Direct current
DRA	-	Dielectric resonator antenna
DRC	-	Design rule check
ECAD	-	Electronic computer-aided design
ESA	-	Electrically small antenna
FOM	-	Figure of merit
FR-4	-	Flame retardant-4
FTO	-	Fluorine-doped tin oxide
GSM	-	Global system for mobile communications
HFSS	-	High frequency structure simulator
IoT	-	Internet of things
ISM	-	International, scientific and medical
ITO	-	Indium tin oxide

LTE	-	Long term evolution
MIM	-	Metal-insulated-metal
MMIC	-	Monolithic microwave integrated circuit
PIFA	-	Planar inverted-F antenna
RF	-	Radio frequency
RFIC	-	Radio frequency integrated circuits
SiO_2	-	Silicon dioxide
SoC	-	System on chip
TCO	-	Transparent conductive oxide
VSWR	-	Voltage standing wave ratio
WPH	-	Wireless power harvesting
WPT	-	Wireless power transfer
WSN	-	Wireless sensor network

LIST OF PUBLICATIONS

In the course of this study, the following journals and conference papers have been published:

1) Masius, A. A., and Wong, Y. C., 2018. Multiband Antenna Design for Radio-Frequency Energy Harvesting, in *Proceedings of Mechanical Engineering Research Day 2018*. Centre for Advanced Research on Energy, pp. 125–126.

2) Masius, A. A., Wong, Y. C., and Lau, K. T., 2018. Miniature High Gain Slot-Fed Rectangular Dielectric Resonator Antenna for IoT RF Energy Harvesting, *AEU - International Journal of Electronics and Communications*, 85, pp. 39–46. doi: 10.1016/j.aeue.2017.12.023.

3) Masius, A. A., and Wong, Y. C., 2017. Parameter Optimization of Staircase Shaped Co- Planar Waveguide Monopole Antenna with Modified Ground Plane for Radio-Frequency Energy Harvesting Application, *Journal of Telecommunication Electronic and Computer Engineering*, 9(4), pp. 103–107.

4) Masius, A. A., and Wong, Y., 2017. Design of High Gain Co-Planar Waveguide Fed Staircase Shaped Monopole Antenna With Modified Ground Plane for RF Energy Harvesting Application, in *Proceedings of Mechanical Engineering Research Day 2017*, pp. 118–119.

CHAPTER 1

INTRODUCTION

1.1 Motivation for an RF energy harvesting system

It is well known from the first law of thermodynamics which states that energy can neither be created nor destroyed in a closed system (Bett, Rowlinson and Saville, 2003). The universe itself is a closed system, thus the total amount of energy is constant. However, the forms of energy are constantly changing. Over the centuries, researchers have gained better understanding on the forms of energy thus new ways for energy to convert from one form to another is revealed. This enables vast development in industrial and technology that leads to modern lifestyles nowadays. However, in every industrial process and everyday technology, a small amount of energy is being unintendedly loss into the environment in the form of heat, light, sound, vibration, or electromagnetic waves. The energy leaked into the environment is referred to as ambient energy. The ambient energy is usually very low and in a form that is not readily available for use. It needs to be harvested, collected, and stored into a form that can be readily used for an intended application through a specialized method referred to as energy harvesting (Bogue, 2015).

Energy harvesting generally refers to the collection, conversion, and storage of ambient energy into electrical energy. In this study, the focus is on the harvesting of electromagnetic energy, also known as radio frequency (RF) energy. RF energy originates from the RF signals emitted in wireless communication systems, as radio waves can simultaneously carry information and energy. RF energy harvesting can be classified into two categories as follows:

a) Ambient RF source: Ambient RF source are not actually dedicated RF energy transfer, and this RF energy is freely available. The frequency range of ambient RF transmission is 0.2 to 5.8 GHz, and this includes most of the radiations from domestic appliances such as television, Bluetooth, mobile telecommunication services and Wi-Fi.

b) Dedicated RF source: This on-demand supply generally has a relatively higher power density due to directional transmission, and it is used to recharge nodes that requires predictable and high amounts of energy. The energy transfer is done in the license-free industrial, scientific, and medical (ISM) frequency bands.

RF energy harvesting is a type of wireless power harvesting (WPH) method. Other sources for WPH includes solar power, wind energy, thermal energy, kinetic energy, and so on. Nowadays, wireless communication system has become so essential that it is no longer possible to separate it from our daily life. In accordance to Industrial Revolution 4.0, massive ranges of electronic devices are being interconnected through wireless communication system which give rise to the Internet of Things which we are experiencing today. The main advantage of RF energy harvesting is that the RF source is continuously available throughout the day, unlike the other sources (sun, wind, movement, etc.) that are only available at a certain time and condition for a limited period. However, the main constrains in ambient RF energy harvesting is the very low power level which was caused by various losses, including path loss, energy dissipation, shadowing, and fading. Along with this problem, several other factors such as the low energy reception sensitivity, restriction of maximum RF energy radiation due to human health hazards, and sharply decreasing RF-to-DC conversion efficiency at low received power is making it more challenging for the development of ambient RF harvesting system (Mishra et al., 2015).

A basic RF power harvesting system consists of four main modules; the antenna, impedance matching network, voltage multiplier and energy storage, as shown in Figure 1.1. Each of the individual module needs to be optimized in order to improve the system (Tran, Cha and Park, 2017). Since the antenna is the first module of the system, it can be considered as the foremost element as it can determine the sensitivity of the whole system. Thus, this thesis focuses on the antenna design for RF energy harvesting system. The antenna design is further divided into two categories which are on-board and on-chip. On-board design is currently the typical way antenna are being deployed, however other approach is needed when miniaturization and highly integration are the main requirements, and on-board design can only achieve so much in this term. Therefore, on-chip design is proposed as an alternative due to the possibility to design antenna in micrometer-scale using CMOS technology. A further elaboration on the research problem, objectives, scopes and contribution, as well as the organization of this thesis is presented in the following sections of this chapter.

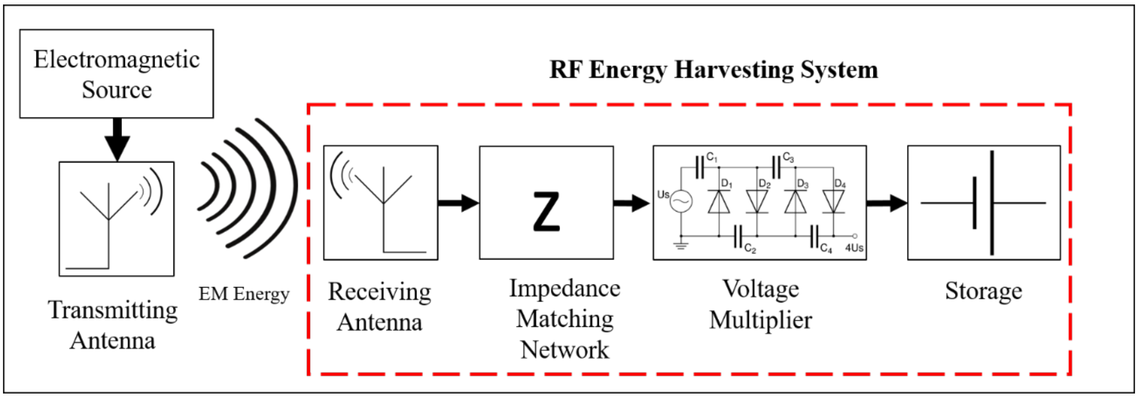

Figure 1.1: Block diagram of an RF energy harvesting system