RECTIFIER DESIGN FOR RADIO FREQUENCY ENERGY HARVESTING SYSTEM

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ABSTRACT

This thesis presents the development of rectifying circuits suitable for Radio Frequency (RF) energy harvesting application with dual-band capabilities. The main contribution of this thesis is the development of compact dual-band two-stage rectifier with high efficiency. Firstly, a voltage doubler rectifying circuit is designed to get a compact size. A source-pull simulation of matching circuit is used to find the optimal load impedance and enhance the conversion efficiency over the frequency range. The accuracy of the design has been justified by the simulation and measurement results. Secondly, a dual-band impedance matching network based on transmission line is developed. A short stub and general impedance transformer are designed to match different complex impedance at the two operating frequencies. Measurement results have fully demonstrated. Thirdly, a new rectifier circuit is proposed. It employs a dual-band multi resonant matching network and a high efficiency modified quadruplor rectifier for harvesting the ambient RF power at both 2.45 GHz Global System for Mobile Communications (GSM) and 5.8 GHz Wireless Local Area Network (WLAN). An attempt was made for matching network with a series of combination of a capacitor and inductor with a parallel LC tank. For rectifier circuit part, low power harvested from the RF is boosted up using two-stage of voltage multiplier and the input capacitor is rearranged to be in parallel connection to get smaller size and uniform pressure on diode. The prototypes are developed, and simulation results are obtained. The proposed rectifier is proven to exhibit greatly higher output voltage and efficiency compared to the conventional circuit. The rectifier is designed on the FR-4 board. Its capability of working within two frequency bands at 2.45 GHz and 5.8 GHz is verified by measurement. The proposed rectifier has met the requirement of high conversion efficiency (79.1% and 78.4% at the respective 2.45 GHz and 5.8 GHz), and able to boost up to the maximum voltage level of 14V at 20 dBm input power. Hence, the aims of this research have been achieved and are practically suitable for the use in wireless sensor networks and low power devices.

ABSTRAK

Tesis ini membentangkan reka bentuk litar penerus yang sesuai untuk aplikasi pengutipan tenaga Radio Frekuensi (RF) dengan keupayaan dwi-jalur. Sumbangan utama tesis ini adalah pembangunan penerus dwi-jalur dua-peringkat yang bersaiz kompak serta kecekapan yang tinggi. Pertama, litar penerus voltan berganda direka untuk mendapatkan saiz yang kompak. Satu simulasi litar *source-pull* digunakan untuk mencari galangan beban yang optimum dan meningkatkan kecekapan penukaran di keseluruhan julat frekuensi. Ketepatan model telah disahkan oleh persetujuan yang baik antara keputusan simulasi dan pengukuran. Kedua, rangkaian padanan galangan dwi-jalur berdasarkan talian penghantaran telah dibangunkan. Puntung pemintas dan pengubah galangan yang umum telah direka untuk dipadankan dengan galangan kompleks yang berbeza pada dua frekuensi operasi. Hasil pengukuran telah didemonstrasikan sepenuhnya. Ketiga, litar penerus baru telah diusulkan. Ia menggunakan rangkaian padanan berganda pada dwi-jalur dan penerus berkecekapan tinggi yang diubah suai untuk mengutip kuasa ambien RF di kedua-dua sistem global untuk Komunikasi Frekuensi Mudah Alih (GSM) 2.45 GHz dan Rangkaian Kawasan Setempat Wayarles (WLAN) 5.8 GHz. Percubaan telah dibuat dengan kombinasi siri kapasitor dan induktor dengan tangki LC yang sejajar. Untuk bahagian litar penerus, kuasa rendah yang dituai dari RF didorong dengan menggunakan dua-peringkat pengganda voltan dan input kapasitor telah disusun semula secara selari bagi mendapatkan saiz yang lebih kecil dan tekanan yang seragam pada diod. Prototaip dibangunkan dan hasil simulasi diperolehi. Penerus yang diusulkan telah terbukti mempunyai output voltan dan kecekapan yang lebih tinggi berbanding dengan penerus tradisional. Penerus tersebut telah direka pada FR-4. Keupayaannya bekerja dalam dua jalur frekuensi pada 2.45 dan 5.8 GHz disahkan oleh keputusan pengukuran. Penerus yang diusulkan telah memenuhi keperluan kecekapan penukaran yang tinggi (79.1% dan 78.4% pada masing-masing 2.45 GHz dan 5.8 GHz), dan mampu meningkatkan tahap voltan maksimum hingga 14V pada daya input 20 dBm. Oleh itu, matlamat penyelidikan ini telah dicapai dan secara praktikal sesuai untuk penggunaan dalam rangkaian sensor wayarles dan peranti berkuasa rendah.

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LIST OF ABBREVIATIONS

BW	-	Bandwidth
C	-	Capacitance
CST	-	Computer Simulation Technology
DC		Direct Current
dB	-	Decibel
dBm	-	Decibel to 1 miliwatt
EH	-	Energy Harvesting
EHF	-	Extremely High Frequency
EM	-	Electromagnetic
FOM	-	Figure of Merit
FF	-	Far Field
FR-4	-	Flame Retardant-4
GSM	-	Global System Mobile
L	-	Inductance
ISM	-	Industrial Sciences Medical
IoT	-	Internet of Thing
MLIN	-	Microstrip Line
MN	-	Matching Network
MPA	-	Microstrip Patch Antenna
PCB	-	Printed Circuit Board
Q-factor	-	Quality factor
R	-	Resistance
RF	-	Radio Frequency
RFID	-	Radio Frequency Identification
RL	-	Return Loss
SMA	-	Sub Miniature Version A
UHF	-	Ultra High Frequency
VSWR	-	Voltage Standing Wave Ratio

WLAN	-	Wireless Local Area Network
WPT	-	Wireless Power Transfer
WSN	-	Wireless Sensor Network

LIST OF SYMBOLS

λ	-	Wavelength
λ_g	-	Guided wavelength
c	-	Speed of light
ε_r	-	permittivity
ε_e	-	Effective permittivity
e_0	-	Total efficiency
e_r	-	Reflection (mismatch)
e_c	-	Conduction efficiency
e_d	-	Dielectric efficiency
λ_0	-	Free Space wavelength
λ_c	-	wavelength at center frequency
λ_g	-	guided wavelength
f_c	-	Center frequency
f_H	-	High frequency
f_L	-	Low frequency
h	-	Height of substrate
L	-	Length of patch
W	-	Width of patch
L_{eff}	-	Effective length
ΔL	-	Delta Length
ω	-	Omega
Z	-	Impedance
Z_L	-	Load impedance
Z_0	-	Characteristic impedance

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CHAPTER 1

INTRODUCTION

1.1 Research Background

In recent few years, a lot of researches and efforts on energy harvesting have been conducted in order to find safer and greener energy resources. Many such sources of ambient energy are available for use by the mentioned consumer devices: solar energy, wind energy, kinetic energy conversion and recycled ambient electromagnetic (EM) or Radio Frequency (RF) energy, to name a few. Besides energy in earth, energy from space also can be harvested and transmitted through laser or microwave beams. The beam delivered by the laser has an advantage of having small beam divergence. The disadvantages of laser beam include low efficiencies in generating and converting the laser beam back into electrical energy compared with microwave [1], [2]. Also, it is difficult to use the solar directly on earth because of the irregular weather condition and low density. Therefore, the microwave beam power transmission is more appealing to researcher. Since it is unpractical for transmitting power from one place to another by traditional distribution and transmission system, the concept of beamed microwave power transmission is important. Microwave is the general term used to describe RF waves which cover all frequency that start from UHF to EHF (300 MHz-300 GHz).

Ambient RF energy harvesting has become an attractive opportunity as a source node in Wireless Sensor Network (WSN). The idea of energy harvesting from inexhaustible and abundant RF, such as nearby mobile phones, wireless LANs, broadcast television signals and FM/AM radio signals has taken the interest of public for its advantage of availability in harsh environments which it is hard to deliver other power supplies. Recent work showed that in a typical office environment, ambient levels of power down to -20 dBm (at the cable feedpoint of an 8 dBi patch antenna) are abundant in the 2.45 GHz ISM band in which Wi-Fi and Bluetooth devices operate. Meanwhile, the input power level to WPT front-end is typically between 1µW and 1 mW (-30 dBm to 0 dBm) [3]. The reliability and cost are the key elements that differentiate RF energy harvesting from other sources. As the reliability for continuous operation of sensors is of paramount importance for any sensor networks, it is essentials to make sure that enough energy can be harvested for each sensor at any location and any time within the operating range of the system. Use of dedicated RF sources in addition to the other RF energy sources available in most indoor and outdoor environments such as television, radio, cellular network, Wi-Fi, and Bluetooth signals among others can supplement the harvested energy therefore increases the likelihood of available of ambient energy. Furthermore, the ever-growing spread of commercial and personal wireless installations enable on the collection of ambient RF energy emanating from cellular base stations, Wi-Fi access points and dozens of other such sources.

While in WPT the electromagnetic beams are clearly directed in the direction of the device to power up, in Electromagnetic Energy Harvesting, the main concept is to gather electromagnetic waves from the air and convert them into DC energy. It is mainly a question of harvesting it from the ambient as the energy is already there, while in WPT there is the need to generate RF power as explained above. The RF energy harvesting schemes has started to become viable as technology is moving towards battery-less paradigm. RF energy can benefit wireless sensor networks and low power devices such as watch, earphone, hearing aid and alarm sensor despite of the small amount of harvested power. So, the RF energy harvesting can be widely employed in various applications such as home and building automation, security and energy management. The number of consumer-oriented compact electronic devices also has been growing at exponential rates for several years. These can be realized by RF energy harvesting systems, which can be easily integrated to the existing antenna and also the rest of wireless sensor on a single chip.

Furthermore, the application of energy harvesting offers a promising decrease of the ominous consequences of climate change and global warming. In Malaysia, the government has taken the issue in hand through the launching of National Green Technology Policy[4]. Malaysia has massive amount of electromagnetic energy radiated in our environment and the number of this electromagnetic is keep growing with time to time. For example, Internet source from the city can be transmitted to rural area using 5.8 GHz point-to-point data transmission. Either it benefits for data transmission for wireless communication; it also can be used for energy harvesting application. Because of this, Malaysia is a potential place to be a rectenna site.

The key element of wireless power transmission is rectenna, which consists of a rectifier and antenna to receive Radio Frequency (RF) energy in free space and transform it into Direct Current (DC) power. The RF energy is harvested by an antenna and the received RF power is converted into DC power by the rectifying diodes as shown in Fig. 1.1. The impedance of the antenna must be matched with the rectifier impedance. Without this matching network, higher harmonics will re-radiate from the antenna back to the free space and decrease the conversion efficiency. The conversion efficiency can be defined as a ratio of the output DC power to the incident wave collected by the antenna. It is an important performance parameter to evaluate rectenna efficiency. Therefore, all components have their applications to enhance efficiency. Low-power device is represented at the load because of small amount of energy available at the harvesting output port [5].

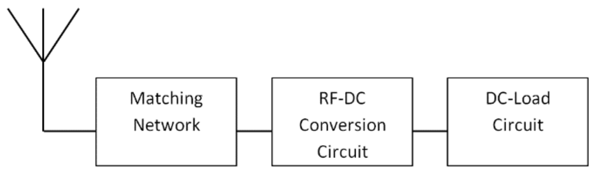

Figure 1.1 Block Diagram of rectenna

The important parameter of this development is the output voltage and efficiency of the RF front-ends. This is important as the minimum turn on voltage for low power devices is 3.3 Volts. Harvesting single frequency band however possess low dc output voltage. As the multiple RF energy sources of different frequency bands are available, thus from an ambient RF harvesting perspective, the output dc voltage could be increased when multiple frequency bands circuit is designed rather than a single band. A wide-band energy harvester can also promise a high output voltage by accumulating the number of RF signals at a time. However, harvesting wide-band circuit could exhibits nonlinearity due to nonlinear behavior of the diode. For example, the input impedance may vary with the received RF power. Thus, it is quite difficult to retain the impedance match and high conversion efficiency over a wide frequency range [6]. On the other hand, it is necessary to achieve decent rectifier performance, even while attaining the size and weight reduction.

As a summary, RF energy-harvesting technology is still progressing, which may explain the lack of solutions available to consumers at the time of this work's authoring. Reviewing recent literature on the subject, one might classify the incremental improvements into five major areas: novel antennas, impedance matching, different rectifying circuits and circuit miniaturization requirements.

1.2 Problem Statement

The most significant problem found in conventional rectifier design is plenty of rectifiers has only one specific frequency band which limits the power available for harvesting. A small number of multiband frequencies in single rectifier have been invented and its optimal rectifying strategies need further exploration. Nevertheless, total size of the dual band rectifier design is increased which lead to the high assembly cost.

The nonlinearity of elements such as diode in the rectifier resulted in challenging work in the impedance matching, particularly for broadband and multiband device. This is because the impedance will change as a function of frequency, input power, and load impedance.

Besides, it is challenging to preserve high energy efficiency while reducing the rectifier size. The components should be small enough to be embedded in low power devices. A compact rectifier is needed to correlate with smaller device and low cost fabrications. Additionally, it requires very high impedance loads to provide enough voltage output.

1.3 Objectives

The foremost purpose of the research work is to design a rectifier which can be used for energy harvesting application with dual band capabilities. The specific objectives embark on the following:

1. To design a dual band matching circuit at Industrial Scientific Medical (ISM) band (2.45 GHz and 5.8 GHz).
2. To design a compact multiplier rectifier with high efficiency
3. To evaluate and validate the performance and efficiency of the proposed rectifier. The simulated and fabricated results are stated in tabular form and represented in graph to easily evaluate the outcome of different designs.

1.4 Scope of Works

The research begins with an extensive study on the basics of rectifier system, components, frequencies, and impedance matching. It is important to build a basic knowledge on designing the proposed rectifier and to identify the expected result in designing rectifier.

The rectifier is designed at 2.45 GHz and 5.8 GHz unlicensed ISM band for WLAN and WPT. Both frequencies have comparably low atmospheric loss, cheap components availability, and reported high conversion efficiency. The scope of the research will be limited to the design, simulate and development of simple and compact rectifier as a front-end system to provide a platform for low-power wireless charging and harvesting energy from the ambient. The proposed system is required to provide high RF-DC conversion efficiency (>60%) from the transmitting antenna as a source for low-power wireless charging and energy harvesting[7]. The high efficiency can be achieved by multiplication of the doubler which can boost up the DC output voltage. So far, the reviewed compact rectifiers were all based on classical approach, not concerning the compactness limit [8].

Computer software employed in this study include Advanced Design System(ADS) for harmonic balance and numeral computations, and the CST studio suite for return loss simulation of matching network and Matlab for complex numeral computations. The rectifier models are implemented on low cost Flame Resistant 4(FR4) board with thickness of 1.6mm, relative permittivity 4.7 and loss tangent 0.019. The rectifier will be given input power from signal generator, tested by using the network analyser and multimeter. The output power level of signal generator is programmed from –25 to 25 dBm in 5-dBm steps. Network analyser is used to determine the return loss and bandwidth of the rectifier as well as its operating frequency, while multimeter is used to measure the output DC voltage. All rectifier performance such as return loss, output voltage and efficiency were carefully compared and discussed.

1.5 Thesis Outline

This thesis is organized with five chapters. Chapter 1 introduces the research work which includes the background, objective, scope, contribution of the research and problem statement.

Chapter 2 cover the basic theory of the energy harvesting system, matching network, the voltage multiplier used and rectifier. Literature review from previous research related to dual band rectifier is also presented to ensure the proposed rectifier has some contribution to fill in the gap of other rectifier design.

Chapter 3 discusses the steps taken to complete the design. This chapter will focus on the design stage using appropriate software. Then, the fabrication stage is explained, which involves software part, printing and hardware part. The final stage of this chapter will include the measurement setup. This final stage can be used to determine either the fabricated rectifier is working at proposed frequency band.

In Chapter 4, the design of the matching circuit and voltage doubler rectifier is discussed. Initially, one schottky diode rectifier without matching circuit is designed. Then, single stub matching circuit is added to the rectifier operated at 2.45 GHz. One stage doubler was also presented. Simulation results were presented and discussed. Next, dual band matching circuit and two stage multiplier is proposed with enhancement in term of compactness and efficiency was presented. The experimental testing of the designed matching circuit and rectifier were presented.

Lastly, Chapter 5 concludes this thesis and present the future works to be done.

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