COMPACT CIRCULAR POLARIZATION FILTENNA FOR WIRELESS POWER TRANSFER APPLICATIONS

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ABSTRACT

Nowadays, Internet of Things (IoT) electronic devices are needed to realize the fifth generation (5G) device-to-device communication. Obviously, current developments tend to focus more towards structure compactness for mobility purposes. However, the main weakness for mobile devices is its power supply. This can be improved by increasing the individual battery capacity or having external batteries. These proposed solutions will increase the weight of the devices, hence making them heavier to carry around. Most total IoT devices are also required to be multi-functional depending on different radio frequencies (RF). Commonly, the RF signal radiated is solely used for data communication. This useful RF signal can also be converted into small energy, instead of being left to disperse into the environment. This relates to wireless energy harvesting called as rectifying antenna (rectenna) which converts RF signal to direct current (DC). A generic rectenna consists of the combination of several components such as antenna, filter, diode and resistive load. The aim of this research is to develop a compact or miniaturized RF front-end component for the rectenna. Compactness can be achieved by embedding the filter into the antenna to form a filtenna. Non-contacted electromagnetic coupling technique with the circular patch antenna operated at 2.45 GHz is selected as the basic design and the simulation work was done using the Computer Simulation Technology (CST) software. To enhance the quality of propagation and the multi-functional properties, the proposed design optimized for circular polarization (CP) and wider bandwidth. Therefore, the modification of the basic design change to proximity coupled feeding technique with double layered configuration is presented. Analysis of the slot line resonator near to the transmission line on several locations is discussed to realize a filtenna. In this research, several different designs of antennas and filters are presented with different compactness, CP, and higher resonant rejection properties. All proposed designs are fabricated and validated through measurement studies. Good agreement is shown between simulation and measurement results. By having approximately 45-50 % of size reduction as compared to the conventional 2.45 GHz microstrip patch antenna, the developed antennas are compact in size with higher resonant rejection up to third harmonic and exhibit 5.2 dB gain.

ABSTRAK

Pada masa kini, *Internet of Things* (IoT) diperlukan bagi merealisasikan generasi kelima (5G) komunikasi peranti ke peranti. Jelas, perkembangan masa kini cenderung memberi lebih tumpuan pada kepadatan struktur untuk tujuan mobiliti. Walau bagaimanapun, kelemahan utama peranti mobiliti ini adalah bekalan kuasa yang terhad. Ia boleh ditingkatkan dengan menambah kapasiti bateri atau mempunyai bateri luaran. Kaedah yang dicadangkan ini akan menambah jumlah berat peranti elektronik menyebabkan ianya bertambah berat untuk dibawa ke mana-mana. Kebanyakan peranti IoT ini mempunyai pelbagai fungsi bergantung kepada frekuensi radio (RF) yang berbeza. Kebiasaannya, isyarat RF yang dipancarkan hanya digunakan untuk komunikasi data. Isyarat RF yang berguna ini juga boleh ditukar menjadi tenaga kecil, dari dibiarkan terpancar begitu sahaja ke persekitaran. Ini berkaitan dengan penuaian tenaga tanpa wayar menggunakan *rectifying antenna* (*rectenna*) yang menukarkan isyarat RF ke arus terus. Umumnya, *rectenna* merupakan gabungan beberapa komponen seperti antena, penapis, diod, dan beban rintangan. Tujuan utama penyelidikan ini adalah membangunkan komponen RF bahagian hadapan yang padat dan bersaiz kecil untuk *rectenna*. Kepadatan boleh dicapai dengan membenamkan penapis ke dalam antena bagi membentuk *filtenna*. Kaedah gandingan elektromagnet tidak sentuh bersama antena tampalan berbentuk bulat berfungsi pada 2.45 GHz dipilih sebagai reka bentuk asas dan ia disimulasikan menggunakan perisian *Computer Simulation Technology* (CST). Untuk meningkatkan kualiti perambatan dan kepelbagaian fungsi, reka bentuk yang dicadangkan telah dioptimum untuk polarisasi bulat (CP) dan lebih jalur lebar. Oleh itu, pengubahsuaian kaedah reka bentuk asas diubah kepada kaedah penyambungan jarak dekat dengan konfigurasi dua lapis dibentangkan. Analisis penyalun garis slot berhampiran dengan talian penghantaran dengan beberapa lokasi telah dibincangkan untuk merealisasikan *filtenna*. Dalam kajian ini, beberapa reka bentuk antena dan penapis yang dibentangkan dengan mempunyai beza kepadatan, CP, dan penolakan harmonik yang lebih tinggi. Semua reka bentuk yang dicadangkan dihasilkan dan disahkan dengan pengukuran. Ia menunjukkan persetujuan yang baik antara simulasi dan pengukuran. Dengan memiliki anggaran 45-50% pengurangan saiz jika dibandingkan dengan 2.45 GHz antena tampalan lazim, antena yang dibangunkan ini mempunyai saiz yang padat dan penolakan harmonik yang lebih tinggi sehingga harmonik ketiga dan menampakkan gandaan sebanyak 5.2 dB.

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LIST OF ABBREVIATIONS

5G		Fifth generation
AC	-	Alternating Current
AR	-	Axial Ratio
BW	-	Bandwidth
C	-	Capacitance
CP	-	Circular Polarization
CST	-	Computer Simulation Technology
DC		Direct Current
DGS		Defected Ground Structure
dB	-	Decibel
EM	-	Electromagnetic
FGS	-	Full Ground Structure
FR-4	-	Flame Retardant-4
GSM	-	Global System Mobile
GPS	-	Global Positioning System
L	-	Inductance
LHCP	-	Left Hand Circular Polarization
LP	-	Linear Polarization
LPF	-	Low Pass Filter
MPT	-	Microwave Power Transmission
ISM	-	Industrial Sciences Medical
IoT	-	Internet of Thing
MPA	-	Microstrip Patch Antenna
PCB	-	Printed Circuit Board
Q-factor	-	Quality factor
R	-	Resistance
RF	-	Radio Frequency
RFID	-	Radio Frequency Identification

RHCP	-	Right Hand Circular Polarization
RL	-	Return Loss
SMA	-	Sub Miniature Version A
SGS	-	Slotted Ground Structure
UV	-	Ultra Violet
VSWR	-	Voltage Standing Wave Ratio
WLAN	-	Wireless Local Area Network
WPT	-	Wireless Power Transfer
WSN	-	Wireless Sensor Network

LIST OF SYMBOLS

λ	-	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

Nowadays, wireless mobile gadgets such as smartphones, tablets, and laptops have become an integral part of daily living. All these gadgets are called Internet of Thing (IoT) devices and are interconnected with each other. These IoT devices can support multiple applications such as the Bluetooth, Global System Mobile (GSM) and Global Positioning System (GPS), as well as the more traditional voice calls and text messaging. These applications have placed a greater demand on electrical power. It is a typical scenario for users to run out of battery charge at critical moments, necessitating the immediate location of the nearest Alternating Current, (AC) power outlet. Presently, it is common for people in Malaysia to carry an extra bag, which houses their mobile gadgets, as well as handy battery chargers. It is also common for users to take along a power bank as a handy accessory. Thus, ensuring that one's mobile gadgets always have enough battery power is rather inconvenient and could be expensive. Battery lifetime for these mobile gadgets continues to be a challenge faced by users.

The concept of wireless energy or power transfer is one whose origins go as far back as the late nineteenth century, with early formal descriptions presented at the dawn of the twentieth century. This concept has been developed to solve the global energy problem [1]. Although subsequently there seem to have been a relative lull in further research and development, an upsurge in the use of autonomous electronic devices has evoked rapidly increasing interest in wireless energy transmission. The development of wireless charging mechanisms that should be rid of tether-devices from their typically wired battery-charging mechanisms, and thereby making them truly mobile, became to be of interest. In this sense, wireless charging is believed to be the appropriate response to the increasing gap between device power consumption and battery capacity.

There are broadly two energy transfer scenarios encountered in literature, namely far-field and near-field energy transfer [2]. Near-field wireless energy transfer requires both the power source and recipient to be in proximity, enabling magnetic coupling of both terminals. Energy is then transferred either by mutual induction or by resonance field effects. The inductive transfer has been successfully implemented in electric toothbrushes, and more recently in mobile phones, to enable them to be charged wirelessly by placing them in charging docks or on charging pads.

In the far-field scenario, Radio Frequency (RF) is a promising feature for generating a small amount of electrical power to drive partial circuits in electronic devices. It can be called the wireless power transfer (WPT) technology and receives attention in the field of solar energy transmission research as a part of renewables. This idea was derived by the famous researcher, Tesla [3][4]. WPT can be accomplished by having a rectenna which is a combination of the rectifier and the antenna. This will collect the RF energy carried by electromagnetic (EM) waves from an ambient environment or specific source and be converted into direct current (DC) and voltage. This conversion 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 WPT efficiency.

Conventionally, the rectenna consists of four primary components: the antenna, a low-pass filter (LPF) for fundamental frequency, microwave schottky detector diodes or rectifying diode, LPF for DC, and load resistances[5]. Key element of this technology is diode where it will convert the received wireless energy into DC power. It is also recognized as the nonlinear element which generates harmonics of the fundamental frequency. Therefore, the LPF between the antenna and the rectifying diode is used to block the higher frequency and harmonics created by the diode. Without this LPF, higher harmonics will re-radiate from the antenna and decrease the conversion efficiency. By combining the filter and antenna as filtenna structure, it can make rectenna a compact structure where it allows the lower frequency to radiate and eliminate higher resonant up to specific harmonics. Therefore, area between antenna and filter can be compressed as a single structure. All components are capable of enhancing WPT performance even under compact circumstances.

Circular polarization (CP) characteristic is crucial to boost EM propagation transmission between transmitter and receiver for WPT application. The necessity of changing voltage output due to the rotation of transmitter and receiver is avoided with the implementation of CP behaviour in antenna as the same voltage output values are obtained regardless of orientation position. In addition, CP is able to create constant output at random polarization angles. Hence, using CP with harmonic rejection antenna for rectenna application is advantageous since it is not significantly affected by rotation and alignment of transmitting and receiving antenna.

These two important points namely CP and higher resonant rejection can be realized when the compact antenna is multi-functional, either for data transmission or wireless power transfer. However, the hardware design trends for wireless technology have a tendency towards compactness. A key aspect of this development concerns the miniaturization of the RF front-ends, and by implication, the antennas. On the other hand, it is necessary to achieve decent antenna performance, even while attaining the size and weight reduction. As a summary, performance of the wireless devices can be improved when they can sustain the power source to allow the sensor to remain working and having an efficient antenna to collect the RF signal.

1.2 Problem Statement

Nowadays, the loT devices are needed to realize the fifth-generation wireless system (5G) communication between devices. The 5G communication is capable of turning an end user's life into a more organized one by interconnecting each wireless device, commonly owned by the same end user. IoT devices are developed towards compact structures that can minimize the cost of production, and wider bandwidth (BW) for multi-functionality. But, most significant problem coming from battery lifetime of the devices for the sustenance of 5G communication. Battery draining is rapid when the devices have multiple functions running concurrently. Since RF energy is radiated through the surrounding air for data communication only, it can also be harvested as small energy named as WPT technology instead of wasting the RF energy. Therefore, this technology can assist to enhance the battery lifetime of the devices. Conventionally, a WPT consists of an antenna, pre-filter, rectifying diode, post-filter, and the resistive load. It is usually easier to design WPT components separately before combining them, but the drawback of such design is the bulkiness and massiveness in structure. Thus, the RF front-end as a receiver is a main component of IoT devices and it should be concomitant with current demand coincided for WPT application. Proper design is necessary in ensuring effective signal received from the transceiver of EM propagation as well as in enhancing RF to DC conversion. This effectiveness will be reduced when the RF front-end components are installed in the wrong position aside from the difficulty in predicting EM signal if common antenna has linear polarization.

1.3 Objectives

The foremost purpose of the research work is to design a compact RF front-end component which can be used for WPT application. Three specifications are required to be met in securing efficient RF-DC conversion for this application namely circular polarization (CP) to improve EM propagation and maximize received output signal; wider bandwidth in collecting energy from ambient or specific transmitter at different frequency to maximize the output power.; and higher resonant rejection as a filter to eliminate higher harmonic created by diode which cause the reduction of RF-DC conversion efficiency. To this end, the research objectives are specified as below:

I. To design a compact circular polarization (CP) antenna operating at 2.4 GHz unlicensed Industrial, Scientific and Medical (ISM) band.

II. To enhance the operating BW from ISM band; (2.4 - 2.5) GHz to (2.3 - 2.7) GHz while attaining the compact structure

III. To integrate and analyze the harmonic rejection up to third harmonic including other higher resonant to the proposed antenna design while remaining compact structure.

1.4 Scope of Works

The research focuses on the design of a compact and miniature RF front-end structure operating within 2.45 GHz unlicensed ISM band for WPT applications. WPT components are comprising five essential elements: antenna, pre-filter, rectifier, post-filter and load. Emphasis will be given only on designing antenna and filter towards compactness feature for WPT application. Several selected design methods are used to achieve the compactness with acceptable performances. The chosen approaches are studied to occupy the compact antenna and filter structures. The proposed antennas and filters are simulated and optimized using the Computer Simulation Technology (CST) based on the required performances. The optimum design is fabricated and measured in terms of the reflection coefficient (S_{11}), radiation pattern, gain and axial ratio.

1.5 Novelty of Contributions

One of the goals of future wireless communication is extreme energy efficiency, which can be realized through this technology. Therefore, Wireless Power Transfer (WPT) or a RF energy harvesting is very useful application to produce small DC energy to recharge and improve battery lifetime. In the other case, this application can be integrated with the small power sensor which is receive RF signal then convert it to small energy to recharge sensor battery[6]. Thus, this research work will consist of three major contributions to the antenna and filter designs with the several different prototypes with compact and CP:

I. Design and analysis of a new compact single layer microstrip antenna with non-contacted EM coupled feeding method and different shaped slots: Investigation on the shaped slot is carried out to control the circularly polarized performance without altering the S_{11}. Implementation of the groove inside the radiating element contributes to the compact and miniaturized structure.

II. The design of a compact dual layer harmonic rejection antenna with BW enhancement: The compact and miniature radiating element is achieved by implementing the slot ring on the ground plane parallel to the patch element. It also improves the S-parameter and antenna efficiency with acceptable gain. Defected Ground Structure (DGS) methods have also been applied near the transmission line to filter and reduce the higher resonant frequency.

III. The design of a compact circularly polarized harmonic rejection antenna: The CP antenna is achieved by the modification of the square slot ring on the ground plane. Direct stub and slot have been applied and attached to the transmission line to reject and reduce higher resonant frequency.

1.6 Thesis Outline

This thesis is organized into seven chapters; wherein each chapter will describe the different aspects and design of the work. The outline of the dissertation in seven chapters is organized as follows:

Chapter one presents an introduction to the wireless communication and WPT application. Both applications have proper interrelations to improve the communication between devices. Then, related problem statement has been justified with valid objectives to overwhelm that problem. However, there are some restrictions and limitations on undertaking research project and this is discussed within the scope of work subtopic.

Chapter two describes the history of wireless power transfer until the current research and significance of front-end design including the antenna and filter for this application. A major discussion is about the theories regarding the microstrip antenna, antenna properties, and performances. Some numbers of related literature are reviewed from previous researches regarding the compact antenna, the CP antenna, and the harmonic rejection antenna. These parameters are used for this application, promising a better conversion energy performance that is suitable for rectenna components.

Chapter three clarifies the procedure of the research work. Flow chart of the project consisting of the design consideration, simulation tools, fabrication, and measurement process is details described . Each process will be explained clearly to ensure that perfect research work can be done.

Chapter four provides detailed discussions of the basic circular polarized microstrip patch antenna (MPA). It starts with an explanation of the compact single layer with the electromagnetically coupled feeding technique. Analysis of the suitable slot on the radiating element for compactness and CP behavior is also discussed in this chapter as a major contribution to the compact RF front end component design. The critical part of this design is to know how the parameter of the antenna affects the resonant and CP. A detailed examination of the slot that influences the performance has been studied.

Chapter five explains the BW enhancement performance of the previous antenna design with the annular slot ring on the ground plane. Two layered sandwich configurations with proximity coupled fed is used to improve the BW. Annular ring slot at the back of radiating element is implemented for compactness. The size of the radiating element becomes smaller compared to its fundamental lambda. Since this antenna is proposed for wireless power transfer, a filter design has been added directly to that of the antenna to block higher resonant frequency up to the third higher harmonic. A unique arrangement of the U-slot has been installed on the ground plane to reject higher harmonics.

Chapter six describes the CP enhancement performance of the previous antenna with a truncated square slot ring at the ground plane. By having this configuration, it offers miniaturization of the radiating element and produces the CP antenna. Two modified U-shaped slot and stub near the transmission line are used to eliminate the higher resonance. A specific analysis regarding the filter design based on current distribution on the transmission line has been investigated and presented.

Chapter seven concludes this project and indicates some possible future work.

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