



بسم الله الرحمن الرحيم

∞∞∞∞

تم رفع هذه الرسالة بواسطة / هناء محمد علي

بقسم التوثيق الإلكتروني بمركز الشبكات وتكنولوجيا المعلومات دون أدنى

مسئولية عن محتوى هذه الرسالة.

ملاحظات:

.....
.....
.....
.....
.....
.....



**AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
CAIRO - EGYPT**

Electronics and Communications Engineering Department

Investigations on RF Wireless Power Transfer System

A thesis submitted in partial fulfillment of the requirements of the degree of
Doctor of Philosophy in Electrical Engineering

Submitted by

Eng. Dalia Hussein Sadek Kamal

Supervised by

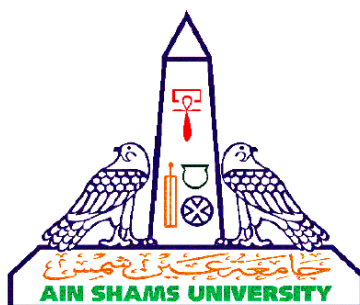
Prof. Dr. Abdelhalim Abdelnabi Zekry

Ain Shams University

Prof. Dr. Heba A. Shawkey

Electronics Research Institute (ERI)

Cairo 2022



AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING
CAIRO - EGYPT

Examiners Committee

Name: Dalia Hussein Sadek Kamal

Thesis: Investigations on RF Wireless Power Transfer System.

Degree: Doctor of Philosophy in Electrical Engineering (Electronics and Communications Engineering).

Title, Name and Affiliation

Signature

1. Prof. El-Sayed Mahmoud Abdelhamid El-Rabaie

.....

Electronics and Communications Eng. Dept.

Faculty of Engineering – Menouf- Menofia University.

2. Prof. Wagdy Refat Anis

.....

Electronics and Communications Eng. Dept.

Faculty of Engineering - Ain Shams University.

3. Prof. Abdelhalim Abdelnaby Zekry

.....

Electronics and Communications Eng. Dept.

Faculty of Engineering - Ain Shams University.

Date: / /2022

Statement of Original Authorship

This thesis is submitted as partial fulfillment of Doctor of Philosophy degree in Electrical Engineering, Faculty of Engineering, Ain shams University.

The author carried out the work included in this thesis, and no part of it has been submitted for a degree or a qualification at any other scientific entity.

Name: Dalia Hussein Sadek Kamal

Signature: Dalia Sadek

Date: // 2022

Researcher Data

Name : Dalia Hussein Sadek Kamal

Date of Birth : 15th of January.

Place of Birth : Cairo, Egypt.

Last University Degree : Master of Science in Electrical Engineering
“Electronics & communications”.

Field of specialization : Electronics and Communications Engineering.

University issued the degree: Ain Shams University.

Date of issued degree : November 2015.

ACKNOWLEDGEMENTS

I start by thanking ALLAH for guiding me to accomplish this work and writing this thesis.

I express my deepest gratitude and thanks to **Prof. Abdelhalim Zekry**, Ain Shams University, for his continuous supervision support. Prof. Zekry is behind all analytical, technical, and even spiritual actions throughout this work.

Special thanks to **Prof. Heba A. Shawkey** for her continuous supervision, support, and their technical support along the way of my work.

I would also like to thank my examination committee members: **Prof. El- Sayed El-Rabaie** and. **Prof. Wagdy Refat Anis**, and thanks to you for serving as my committee members.

A great appreciation for my parents and my brothers for always encouraging and supporting me in whatever I do. I especially wish to thank my husband and my children for their patience and care during my long working hours.

Dalia Sadek

Published Papers

1. Dalia Sadek, Abdelhalim Zekry and Heba A. Shawkey," Multiband Triple L-Arms Patch Antenna with Diamond Slot Ground for 5G applications “, The Applied Computational Electromagnetics Society Journal. ACES JOURNAL, Vol. 36, No. 3, March 2021, p302-307. DOI: 10.47037/2020.ACES. J.360310.
2. Dalia Sadek, Abdelhalim Zekry and Heba A. Shawkey, " Compact and High Efficiency Rectenna for Wireless Power Harvesting Applications ", International Journal of Antennas and Propagation., 15 December 2021, Volume 2021. DOI:10.1155/2021/1109850.
3. Dalia Sadek, Abdelhalim Zekry and Heba A. Shawkey, "10 GHz Compact Shunt-Diode Rectifier Circuit Using Thin-film Ag/AZO Schottky Barrier Diode for Energy Harvesting Applications”, International Conference on Human-Computer Interaction, Accepted.

Abstract

Due to the increased usage of portable electronics such as laptops, mobile phones, wearable/implantable sensors, etc., wireless power transmission systems have grown in popularity in recent years. Previously, these devices were powered by a rechargeable battery. Wireless power transmission offers the potential to enable a variety of portable electronic usage devices when the battery cannot be used (due to its size or weight) or where recharging the battery with a wired charger is impractical. Energy harvesting systems are becoming increasingly popular. The antenna is connected to a rectifying unit, which is the system's most important component (rectenna). This thesis focuses on the analysis, design, and measurement of two designs of tiny RF wireless power transfer antenna; a rectifier circuit (rectenna), and matching circuit are the three primary blocks that make up the system. Operating in 5G band. The complete rectenna is implemented in three stages:

The first stage was the design and fabrication of a microstrip patch antenna with a multiband response. A diamond-shaped ground slot is added to control and increase the bandwidth of the resonant frequency. Microwave Studio by Computer Simulation Technology is used to test the antenna (CST). The recommended circuit is built on a ROGERS (RO4003c) substrate. The overall dimensions of the antenna are 16.5mm x16.5mm x 0.81 mm. The antenna is designed to resonate at 10,13,17 and 26 GHz with 10 dB impedance bandwidths of 0.67,0.8,2.45 and 4.3 GHz respectively. The multiband antenna has sufficient realized gain of 4.95, 5.72, 4.94, and 7.077 dB respectively.

The second stage of this thesis is that two rectifier designs with matching circuits have been fabricated, a half-wave rectifier with a shunted Schottky diode and a voltage doubler rectifier. The circuits of both rectifiers are set to 10 GHz center frequency and implemented using a 0.81mm Rogers (RO4003c) substrate. The overall size of the shunted rectifier is only 13.3 mm X 8.2 mm X 0.81 mm and 19.7 mm X 7.4 mm X 0.81 mm for the voltage doubler rectifier. Then the antenna with the rectifier and matching circuit are combined to obtain a complete system for wireless power transfer, then measurements for the whole system. The ROHDE&SCHWARZ ZVA6 Vector Network Analyzer (VNA) is used to measure scattering parameters. The RF/microwave signal generators Anritsu MG3697C are used to transmit a microwave signal to a horn. The DC output voltage for both systems is then measured and compared for high voltage output acquired through

RF to DC conversion using a voltmeter attached to the wireless power transmission system under test. With 300 Ω load resistance and 0.51 V output voltage, the highest conversion efficiency of the rectenna with a shunted diode half-wave rectifier is 41%, compared to 50% for the rectenna using a voltage doubler rectifier with 650 Ω load resistance and 1.1 V output voltage. It is important to notice that the voltage doubler rectifier circuit has a higher efficiency than the shunted rectifier circuit. The suggested WPT system's measured performance is compared to that of existing systems to demonstrate its suitability for wireless power harvesting applications.

The third stage is to design a thin-film Ag/AZO Schottky Barrier Diode device consisting of 3 layers: a commercial copper tape as the flexible substrate, a thin-film of p-type semiconductor nanoparticle-ink AZO and a silver measuring electrode. The device area is 1 mm² and implemented in 280nm thickness for the AZO. The proposed thin-film Schottky diode (TFSD) is implemented with 280nm thickness in the complete shunt rectifier circuit on 0.81mm Rogers (RO4003c) substrate. To provide the microwave signal that is input to the rectifier, an Anritsu MG3697C RF/Microwave signal generator is used at the intended frequency of 10 GHz. The DC output voltage for the rectifier is then measured using a voltmeter connected to the rectifier under test (RUT). With 300 load resistance and 0.3 V output voltage, the rectifier's maximum conversion efficiency is 35 percent.

Table of Contents

CHAPTER(1) : INTRODUCTION	2
1.1 Overview.....	2
1.2 Wireless Power Transfer History	4
1.3 Thesis Objective and Achievements	5
1.4 Thesis Organization	6
CHAPTER(2) : LITERATURE REVIEW	8
2.1 Introduction.....	8
2.2 Single-band Millimeter Waves WPT Rectennas.....	9
2.3 Multi-band Millimeter Wave WPT Rectennas.....	17
2.4 Conclusions	22
CHAPTER (3) : MULTIBAND TRIPLE L-ARMS PATCH ANTENNA WITH DIAMOND SLOT GROUND FOR 5G WPT	24
3.1 Introduction.....	24
3.2 Microstrip Patch Antenna	24
3.3 The Proposed Multiband Triple L-Arms Patch Antenna with Diamond Slot Ground for 5G WPT	28
3.3.1 Antenna Design and Layout	28
3.3.2 Antenna Implementation and Measurement	31
3.3.3 Designed Antenna S-parameters.....	32
3.3.4 Equivalent Circuit of The TLA Antenna (Modeling of Patch Antenna)	33
3.3.5 Surface Current Distribution.....	35
3.3.6 2D-Polar Radiation Patterns	36
3.4 Conclusions	39
CHAPTER(4) : COMPACT AND HIGH EFFICIENCY RECTIFIER FOR WIRELESS POWER TRANSFER RECTENNA.....	40
4.1 Introduction.....	40
4.2 Rectifier Design Parameters	40

4.3	Diode Characterization	41
4.3.1	Operation Concept	41
4.3.2	Diode Selection	42
4.4	Diode-Based Rectifier Topologies	43
4.4.1	Half-wave Rectifier	43
4.4.2	Full-wave Rectifier	43
4.4.3	Voltage Doubler Rectifier	43
4.4.4	Multistage Rectifier	45
4.5	The Proposed Rectifier Designs and Simulation Results	46
4.5.1	Input Impedance Matching Network	47
4.5.2	Shunt Diode Rectifier Design and Optimization	48
4.5.3	Doubler Rectifier Design and Optimization	51
4.6	Complete Rectenna Measurements	52
4.6.1	Measurement for Shunt Rectenna	54
4.6.2	Measurement for Voltage Doubler Rectenna	55
4.7	Conclusions	58
CHAPTER (5) : THIN FILM SCHOTTKY DIODE AG/AZO FOR RECTENNA DEVICE		
.....		59
5.1	Introduction.....	59
5.2	Ag/AZO/Cu Thin-film Schottky Diode.....	59
5.2.1	TFSD Device Fabrication.....	60
5.2.2	Rectifier Circuit Architecture Using Thin-film Schottky.....	60
5.2.3	TFSD DC Current-Voltage (I-V) Measurement.....	61
5.3	Rectifier Circuit Measurements	62
5.3.1	Measurement Results for Rectifier with TFSD	62
5.4	Conclusions.....	64
CHAPTER (6) : CONCLUSIONS AND FUTURE WORK.....		65
6.1	Conclusions.....	65
6.2	Future Work.....	66
REFERENCES.....		67

Table of Figures

Fig 1.1: Summary of different wireless power transfer technologies	5
Fig 1.2: Far-field Wireless power transfer block diagram working principle	5
Fig 2.1: Circuit layout of the designed rectenna	9
Fig 2.2: Fabricated Rectenna on commercial photo paper substrate	10
Fig 2.3: (a)Optimal rectenna efficiency versus power input for fixed frequency 24.125 GHz. The load was fixed at 280 Ohm. (b) Optimal rectenna efficiency versus frequency for fixed power input at 15 dBm and optimal load 280 Ohm.	10
Fig 2.4: Configuration of proposed antenna	11
Fig 2.5: Layout of the designed rectifier (unit: mm)	11
Fig 2.6: MW-DC efficiency changes with the length of short ended line	12
Fig 2.7: Prototype of the designed rectenna array.....	12
Fig 2.8: Conformal MPA array a). Simulation layout b). Fabricated prototype.....	13
Fig 2.9: Simulated and measured S-Parameter	13
Fig 2.10: (a) Antenna configuration for a CP patch array. (b) Photograph of the fabricated prototype.....	14
Fig 2.11: Simulation and measurement results of the CP array impedance matching from 22 GHz to 28 GHz.....	14
Fig 2.12: (a) The SIW cavity-backed CP array in 3D.. (b) The constructed prototype's front side (c) The constructed prototype's backside.....	15
Fig 2.13: Simulation and test results for SIW cavity-backed CP array impedance matching from 22 to 28 GHz	16
Fig 2.14: (a)Layout of the designed rectifier (b)Fabricated prototype	16
Fig 2.15: (a) The constructed rectenna's front side. (b) The constructed rectenna's backside	17
Fig 2.16: At 24 GHz, DC output voltage and efficiency were measured vs incoming power density of the rectenna at a distance of 1 m..	17
Fig 2.17: (a) Top view (not to scale) of the layout of the 4CDAA rectenna and (b) photos of the top and bottom sides of the manufactured rectenna.	18

Fig 2.18: (a) S11 vs frequency at the diode's input port (b) input impedance vs frequency at the diode's input port.	19
Fig 2.19: Voltage doubler based RF energy harvester.....	20
Fig 2.20: the specified rectifier (a) An impedance matching network. (b) A rectifier that has been constructed on a standard cm scale (7 by 3).	21
Fig 2.21: The designed rectifier's S11 (a) $R_L = 15\text{ k}\Omega$ for multiple power levels. (b) For $P_{in} = -15\text{ dBm}$ simulation for several loads.....	21
Fig 2.22: The designed rectifier's RF to DC conversion efficiency.	22
Fig 3.1: Structure of A Microstrip Patch Antenna	24
Fig 3.2: Variety of Shapes for Microstrips Patch Elements	25
Fig 3.3: Structure geometry of the antenna.....	28
Fig 3.4: Configuration of the proposed antenna (a) Top view (b) Bottom view.	29
Fig 3.5: The reflection coefficient of the design steps for the proposed antenna.....	30
Fig 3.6: Antenna bandwidth adjustment for different ground slot values.	30
Fig 3.7: Photograph of the fabricated patch antenna (a) bottom layer (b) top layer	31
Fig 3.8: Microwave test feature to connect the antenna with Vector Network Analyzer.	31
Fig 3.9: The measurement of the S11 parameter using the VNA ROHDE&SCHWARZ ZVA6.	32
Fig 3.10: Simulation and measured reflection coefficient vs. frequency.	33
Fig 3.11: (a) Equivalenlumped-elemets circuit for antenna in ADS (b) Comparison of the reflection coefficient responses of CST, ADSnt, and measurement.	35
Fig 3.12: Current distribution of 5G antenna at the resonant frequencies (a) 10 GHz (b) 13 GHz (c) 17 GHz (d) 26GHz.	36
Fig 3.13: The radiation pattern of the proposed antenna in E-plane and H- plane . (a) 10 GHz measured and simulated, (b) 13 GHz measured and simulated, (c) 17 GHz simulate,d and (d) 26 GHz simulated.....	37
Fig 3.14: Gain versus frequency	37
Fig 4.1: Rectifier structure illustrating the concept of efficiency.	40
Fig 4.2: RF Half-wave rectifier	43
Fig 4.3: full Half-wave rectifier.....	43
Fig 4.4: Voltage doubler rectifier	44
Fig 4.5: Rectifier RF signal (a) positive cycle (b) negative cycle	45

Fig 4.6: N-stage multistage rectifier	45
Fig 4.7: SC-79 Package Dimension Drawing	48
Fig 4.8: General rectifier block diagram	48
Fig 4.9: The shunt rectifier layout and photograph of the fabricated shunt rectifier.	49
Fig 4.10: The measurement of the S11 parameter using the VNA ROHDE&SCHWARZ ZVA6.	50
Fig 4.11: Comparison between Simulation and measured S11 versus frequency.....	51
Fig 4.12: The layout of the voltage doubler rectifier and photograph of the fabricated voltage doubler rectifier.	52
Fig 4.13: Rectenna measurement setup.	53
Fig 4.14: Photo of the rectenna measurement setup.	53
Fig 4.15: Measured and simulated DC voltage and conversion efficiency of the rectenna with voltage shunt rectifier versus continuous wave input power at 10 GHz.	55
Fig 4.16: Measured and simulated DC voltage and conversion efficiency of the rectenna with voltage doubler rectifier versus continuous wave input power at 10 GHz.	56
Fig 4.17: Conversion efficiency versus input power concerning load resistances.....	57
Fig 5.1: Proposed Thin Film Schottky Diode Device structure.....	60
Fig 5.2: (a) Image of the fabricated rectifier (b) Measured reflection coefficient versus frequency.	60
Fig 5.3: I-V characteristics of the AZO Schottky diode.	61
Fig 5.4: Rectifier measurement setup.....	62
Fig 5.5: Photo of the measurement setup.	62
Fig 5.6: Measured performance of the proposed rectifier with thin-film diode versus continuous wave input power at 10 GHz, (a) DC voltage, and (b) conversion efficiency.	63

List of Tables

Table 2.1: The impedance matching network parameters.....	21
Table 3.1: Advantages and Disadvantages of Microstrip Patch Antenna	26
Table 3.2: Elements values of the equivalent circuit model.....	34
Table 3.3: Comparison of the proposed antenna with other antennas.....	38
Table 4.1: Schottky diode parameters	46
Table 4.2: Dimensions of the shunt rectifying circuit.	50
Table 4.3: RF-to-dc conversion efficiency vs power input & frequency.....	57