



**DESIGN OF A MULTI-BAND RF ENERGY HARVESTING
RECTENNA WITH HARMONICS SUPPRESSION
CAPABILITY**

FAZA SYAHIRAH BINTI MOHD NOOR

MASTER OF SCIENCE IN ELECTRONIC ENGINEERING

2020



Faculty of Electronic and Computer Engineering

**DESIGN OF A MULTI-BAND RF ENERGY HARVESTING
RECTENNA WITH HARMONICS SUPPRESSION
CAPABILITY**

Faza Syahirah binti Mohd Noor

Master of Science in Electronic Engineering

2020

**DESIGN OF A MULTI-BAND RF ENERGY HARVESTING RECTENNA WITH
HARMONICS SUPPRESSION CAPABILITY**

FAZA SYAHIRAH BINTI MOHD NOOR

**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

2020

DECLARATION

I declare that this thesis entitled “Design of A Multi-band RF Energy Harvesting Rectenna with Harmonics Suppression Capability” 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 :

Name : FAZA SYAHIRAH BINTI MOHD NOOR

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 : **PROFESSOR DR. ZHRILADHA BIN ZAKARIA**

Date :

DEDICATION

The name of ALLAH Almighty creator,

My beloved father, Mohd Noor Radiman and mother, Zalinawati Kosnan,

My supportive family members for your encouragement and undying supports.

And to everyone.

ABSTRACT

In recent years, rectenna with the ability of energy harvesting has been gaining tremendous interests by researchers. Constant availability of radio frequency (RF) signals at which it is being deployed both at indoor and outdoor environment favors these types of signals as the optimum choice of energy to be harvested considering its continuous operation. The design and development of RF energy harvesting is fit to describe the transmission of power wirelessly. RF signals which is in form of alternating current (AC) is being radiated through electromagnetic (EM) waves into the environment and rectenna structure will capture the RF signals and therefore converts it into direct current (DC) signals. Rectenna which constructed upon the integration of antenna and rectifier structure within the same physical structure explains the ability of rectenna in harvesting and rectifying AC signals into DC signals. The antenna is to receive or capture the RF signals at which it is then being rectified into DC signals by the rectifier. The integration of both antenna and rectifier structures contribute to the creation of harmonics due to the non-linear behavior of active elements such as Schottky diode and capacitor at the rectifier circuit. Hence, harmonics suppression filter design is proposed to suppress the harmonics generated. This thesis presents a design of rectenna structure with multi-band characteristics and harmonics suppression capability. Multi-band characteristics of operating frequency at 2.45GHz and 5.80GHz are achieved using inverted π -shaped coupling slot while the ability of harmonics suppression is achieved through the introduction of embedded U-slot and asymmetrical right-and-left-handed stubs at the antenna transmission feedline. The addition of slot and stubs at the transmission feedline has replaced the conventional filter structure which is larger in size. In order to enhance the gain of antenna, aperture-coupled antenna is constructed with air gap through the simulation using Computer Simulation Technology (CST) software. Meanwhile, the rectifier of double-diode configuration circuit of the rectenna is designed and simulated using Advanced Design System (ADS) with rectifying element HSMS286B Schottky diodes and interdigital capacitor. The structure interdigital capacitor in the form of transmission line is applied to replicate the series-configuration active capacitor component. The development of the rectenna prototype is executed using FR-4 substrate material with dielectric constant of 4.3 and thickness of 1.6mm. The antenna is able to suppress third and higher-order harmonics ranging from 6.12GHz up to 10.00GHz and achieve the gain of 7.05dBi and 0.94dBi at the operating frequency 2.45GHz and 5.80GHz, respectively. The double-diode rectifier prototype can be operated at both 2.45GHz and 5.80GHz hence, maximum RF-to-DC conversion efficiency of 92.26% for frequency 2.45GHz and 30.14% for frequency 5.80GHz is achieved, each with the RF input power of 20dBm and 25dBm respectively. The rectenna design proposed does not only possessed the characteristic of a multi-band, but also the has the harmonics suppression ability for the purpose of improving the RF-to-DC conversion efficiency thus makes it appropriate for the application of wireless power transmission.

ABSTRAK

Kebelakangan ini, rektena berkebolehan penuaian tenaga telah menarik perhatian para penyelidik. Kebolehdapatan isyarat frekuensi radio (RF) di mana ianya diguna pakai untuk persekitaran dalam dan luar memberi kelebihan pada isyarat-isyarat ini sebagai pilihan yang optimum untuk proses penuaian berikutan sistem operasi yang berterusan. Rekabentuk dan pembangunan penuaian tenaga RF ini sesuai bagi menerangkan penghantaran tenaga secara wayarles. Isyarat RF dalam bentuk arus ulang-alik (AC) dipancarkan ke persekitaran melalui gelombang elektromagnetik (EM) dan struktur rektena akan menangkap dan seterusnya menukar isyarat tersebut ke dalam bentuk isyarat arus terus (DC). Rektena berdasarkan integrasi struktur antena dan penerus pada struktur fizikal yang sama menggambarkan kebolehan rektena dalam penuaian dan penukaran isyarat AC kepada isyarat DC. Antena berfungsi untuk menerima atau menangkap isyarat RF di mana ianya ditukarkan kepada isyarat berbentuk DC oleh penerus. Integrasi struktur antena dan penerus menyumbang kepada penciptaan harmonik berikutan perilaku ketaklelurusan elemen-elemen aktif seperti diod Schottky dan kapasitor pada litar penerus. Berikutan itu, rekabentuk penapis penindasan harmonik telah dicadangkan untuk menindas harmonik yang terhasil. Tesis ini membentangkan rekabentuk struktur rektena bersama ciri jalur pelbagai dan kebolehan penindasan harmonik. Ciri jalur pelbagai pada operasi frekuensi 2.45GHz dan 5.80GHz dicapai menggunakan bentuk songsang “ π ” sebagai gandingan lubang alur manakala kebolehan penindasan harmonik dicapai melalui pelaksanaan lubang alur berbentuk “U” dan puntung tangan kanan dan kiri tidak simetri pada talian suapan transmisi antena. Penambahan lubang alur dan puntung pada talian suapan antena telah menggantikan struktur lazim penapis yang lebih besar. Bagi meningkatkan gandaan antena, struktur “aperture-coupled” dibina bersama jurang udara melalui simulasi perisian Computer Simulation Technology (CST). Litar penerus berkonfigurasi dual-diod pada rektena pula dibina dan disimulasi menggunakan perisian Advanced Design System (ADS) bersama elemen penerus diod Schottky HSMS286B dan kapasitor interdigital dalam bentuk garis penghantaran diaplikasi bagi menghasilkan replika konfigurasi siri komponen aktif kapasitor. Pembangunan prototaip rektena dilaksana menggunakan bahan substratum FR-4 di mana pemalar dielektrik adalah 4.3 dan berketebalan 1.6mm. Antena ini berkebolehan menindas harmonik ketiga dan harmonik tertib lebih tinggi pada julat frekuensi 6.12GHz sehingga 10.00GHz dan juga mencapai gandaan antena 7.05dBi dan 0.94 dBi setiap satu pada operasi frekuensi 2.45GHz dan 5.80GHz. Prototaip penerus dual-diod boleh beroperasi pada operasi frekuensi 2.45GHz dan 5.80GHz seterusnya kecekapan penukaran tenaga RF kepada tenaga DC mencapai bacaan maksimum 92.26% bagi frekuensi 2.45GHz dan 30.14% bagi frekuensi 5.80GHz setiap satu berdasarkan paras kuasa masukan isyarat RF pada 20dBm dan 25dBm. Rekabentuk rektena yang dicadangkan bukan sahaja mempunyai ciri-ciri jalur pelbagai malah turut mempunyai kebolehan penindasan harmonik bagi meningkatkan kecekapan penukaran tenaga RF kepada tenaga DC, justeru membuatkan rekabentuk ini bersesuaian bagi aplikasi penghantaran tenaga wayarles.

ACKNOWLEDGEMENTS

First and foremost, I would like to take this opportunity to express my deepest gratitude to my main supervisor, Professor Dr. Zahriladha bin Zakaria from Faculty of Electronic and Computer Engineering (FKEKK), Universiti Teknikal Malaysia Melaka (UTeM) and my co-supervisor Dr. Herwansyah bin Lago from the Faculty of Engineering, Universiti Malaysia Sabah (UMS) for their undying support and essential research guidance throughout the project execution and encouragement towards the completion of this research work and thesis.

Special acknowledgement to the postgraduate students, staffs and friends from Faculty of Electronic and Computer Engineering (FKEKK) which are Dr. Sam Weng Yik, Nurhasniza, Ameer Farhan, Associate Professor Dr. Mohamad Zoinol Abidin, Dr. Nornikman, Mohd Khairy, Sulaiman Ali Mohammad, Seah Boon York, Muhammad Haziq, Dinesh Periannan, Nurul Shafnie, Husna 'Izzati, Siti Allyna and Syazwani for their knowledge contribution, technical and spiritual support.

I would also like to take this opportunity to thank my parents, Mohd Noor bin Radiman and Zalinawati binti Kosnan and family members, Faza Syazwina, Faza Arif Putra and Faza Ammar Putra for their continuous support, encouragement and prosperous prayers all of these years through the course of my master journey. The journey is made possible with them continuously cheering by my side.

I am thankful to laboratory assistance, Imran and Muhd Sufian together with technician Research Lab I Khairul Zaman for their assistance throughout the fabrication and measurement procedures.

Finally, I would like to acknowledge Ministry of Education, Malaysia government and Universiti Teknikal Malaysia Melaka (UTeM) for the research funds. Deepest gratitude to everyone who had contributed either directly or indirectly to this research work.

TABLE OF CONTENTS

	PAGE
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vii
LIST OF FIGURES	x
LIST OF APPENDICES	xix
LIST OF ABBREVIATIONS	xx
LIST OF SYMBOLS	xxi
LIST OF PUBLICATIONS	xxii
AWARD	xxiii
CHAPTER	
1. INTRODUCTION	1
1.1 Research background	1
1.2 Problem statement	3
1.3 Objectives	4
1.4 Scope of research	5
1.5 Contribution of research work	6
1.6 Thesis organization	6
2. LITERATURE REVIEW	9
2.1 Introduction	9
2.2 Rectenna concept	9
2.2.1 Design of antenna	11
2.2.1.1 Return loss performance and harmonics suppression capability	12
2.2.1.2 Gain of antenna	16
2.2.1.3 Radiation pattern of antenna	16
2.2.1.4 Antenna polarization	17
2.2.2 Design of rectifier	19
2.2.3 Matching network	22
2.3 Conversion efficiency of RF-to-DC signals	23
2.4 History of rectenna design	25
2.5 Previous studies of rectenna	28
2.6 Summary	42
3. METHODOLOGY	43
3.1 Introduction	43
3.2 Flow chart of the research work	44
3.3 Antenna design	48
3.3.1 Aperture-coupled antenna design structure	49
3.3.2 Fabrication and measurement of antenna prototype	58

3.4	RF-to-DC rectifier design	59
3.4.1	Diode selection	59
3.4.2	Impedance matching	60
3.4.2.1	Input impedance of single-diode rectifier	61
3.4.2.2	Input impedance of double-diode rectifier	62
3.4.3	Matching network design	62
3.4.4	Simulation of RF-to-DC rectifier	63
3.4.4.1	Single-diode rectifier design	65
3.4.4.2	Double-diode rectifier design	68
3.4.5	Measurement of rectifier prototype	74
3.5	Rectenna design	75
3.5.1	Simulation of rectenna design	75
3.5.2	Fabrication and measurement of rectenna prototype	76
3.6	Summary	77
4.	RESULT AND DISCUSSION	78
4.1	Introduction	78
4.2	Results of antenna design	78
4.2.1	Simulation results of antenna design	79
4.2.1.1	Return loss response and harmonics suppression capability	80
4.2.1.2	Gain of antenna	92
4.2.1.3	Radiation pattern of antenna	95
4.2.2	Measurement results of antenna prototype	98
4.2.2.1	Antenna prototype of design A	98
4.2.2.2	Antenna prototype of design E	101
4.3	Results of rectifier design	106
4.3.1	Single-diode rectifier for operating frequency 2.45GHz	106
4.3.2	Single-diode rectifier for operating frequency 5.80GHz	108
4.3.3	Double-diode rectifier for operating frequency 2.45GHz	111
4.3.4	Double-diode rectifier for operating frequency 5.80GHz	114
4.3.5	Double-diode rectifier for operating frequency 2.45GHz and 5.80GHz	117
4.4	Results of rectenna design	120
4.4.1	Rectenna A	120
4.4.1.1	Rotation of rectenna at 0° xz-plane	121
4.4.1.2	Rotation of rectenna at 30° xz-plane	125
4.4.1.3	Rotation of rectenna at 60° xz-plane	129
4.4.2	Rectenna B	133
4.4.2.1	Rotation of rectenna at 0° xz-plane	134
4.4.2.2	Rotation of rectenna at 30° xz-plane	137
4.4.2.3	Rotation of rectenna at 60° xz-plane	141
4.4.3	Rectenna C	145
4.4.3.1	Rotation of rectenna at 0° xz-plane	146
4.4.3.2	Rotation of rectenna at 30° xz-plane	149
4.4.3.3	Rotation of rectenna at 60° xz-plane	153
4.4.4	RF-to-DC conversion efficiency performance of rectenna	156
4.4.4.1	Rectenna A	156
4.4.4.2	Rectenna B	158

4.4.4.3	Rectenna C	160
4.4.4.4	Overall rectenna performance comparison	162
4.5	Comparison of proposed rectenna with previous researchers designs	164
4.6	Summary	166
5.	CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORKS	167
5.1	Conclusion	167
5.2	Recommendations for future work research	168
	REFERENCES	170
	APPENDICES	205

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Summary of past research studies	37
2.2	Proposed rectenna design specifications	41
3.1	Performance specification of antenna	46
3.2	Performance specification of rectifier	46
3.3	The initial design parameter dimension of the aperture-coupled antenna	53
3.4	Optimized antenna design parameters of the antenna Design E	57
3.5	Detailed specification of interdigital capacitor	64
4.1	Summary of antenna design structures	79
4.2	Return loss response comparison	92
4.3	Simulated antenna realized gain and directivity at 2.45GHz	93
4.4	Simulated antenna realized gain and directivity at 5.80GHz	94
4.5	Antenna directivity at 2.45GHz	96
4.6	Antenna directivity at 5.80GHz	97
4.7	Gain of antenna at 2.45GHz	105
4.8	Gain of antenna at 5.80GHz	105
4.9	Measured output DC voltage and RF-to-DC conversion efficiency at 0° rectenna rotation for 2.45GHz (Rectenna A)	122

4.10	Measured output DC voltage and RF-to-DC conversion efficiency at 0° rectenna rotation for 5.80GHz (Rectenna A)	123
4.11	Measured output DC voltage and RF-to-DC conversion efficiency at 30° rectenna rotation for 2.45GHz (Rectenna A)	125
4.12	Measured output DC voltage and RF-to-DC conversion efficiency at 30° rectenna rotation for 5.80GHz (Rectenna A)	127
4.13	Measured output DC voltage and RF-to-DC conversion efficiency at 60° rectenna rotation for 2.45GHz (Rectenna A)	129
4.14	Measured output DC voltage and RF-to-DC conversion efficiency at 60° rectenna rotation for 5.80GHz (Rectenna A)	131
4.15	Measured output DC voltage and RF-to-DC conversion efficiency at 0° rectenna rotation for 2.45GHz (Rectenna B)	134
4.16	Measured output DC voltage and RF-to-DC conversion efficiency at 0° rectenna rotation for 5.80GHz (Rectenna B)	136
4.17	Measured output DC voltage and RF-to-DC conversion efficiency at 30° rectenna rotation for 2.45GHz (Rectenna B)	137
4.18	Measured output DC voltage and RF-to-DC conversion efficiency at 30° rectenna rotation for 5.80GHz (Rectenna B)	139
4.19	Measured output DC voltage and RF-to-DC conversion efficiency at 60° rectenna rotation for 2.45GHz (Rectenna B)	141
4.20	Measured output DC voltage and RF-to-DC conversion efficiency at 60° rectenna rotation for 5.80GHz (Rectenna B)	143
4.21	Measured output DC voltage and RF-to-DC conversion efficiency at 0° rectenna rotation for 2.45GHz (Rectenna C)	146

4.22	Measured output DC voltage and RF-to-DC conversion efficiency at 0° rectenna rotation for 5.80GHz (Rectenna C)	148
4.23	Measured output DC voltage and RF-to-DC conversion efficiency at 30° rectenna rotation for 2.45GHz (Rectenna C)	149
4.24	Measured output DC voltage and RF-to-DC conversion efficiency at 30° rectenna rotation for 5.80GHz (Rectenna C)	151
4.25	Measured output DC voltage and RF-to-DC conversion efficiency at 60° rectenna rotation for 2.45GHz (Rectenna C)	153
4.26	Measured output DC voltage and RF-to-DC conversion efficiency at 60° rectenna rotation for 5.80GHz (Rectenna C)	155
4.27	Rectenna design performance comparison	163
4.28	Performance comparison of proposed rectenna design with previous researchers works	164

LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Types of wireless power transmission	1
2.1	General rectenna structure in block diagram (Liu, 2011)	10
2.2	Antenna with harmonics suppression capability with embedded U-slot and symmetrical right-left-handed stubs (Zainol et al., 2016)	13
2.3	Defected ground structure and fractal iterations method for physical miniaturization; (a) Plus-shaped patch of 3rd iteration and (b) H-shaped defected ground structure on ground plane (Prajapati, 2015)	14
2.4	Proposed circular patch for harmonics suppression purpose; (a) Top view and (b) Ground from the bottom view (Rahim et al., 2012)	14
2.5	Harmonics suppression capability using spur-line design technique; (a) Reference antenna, (b) Proposed antenna design with spur-line, and (c) Geometry of the spur-line design (Su et al., 2009)	15
2.6	Return loss response comparison with and without the introduction of spur-line design (Su et al., 2009)	15
2.7	Radiation pattern of an antenna (Hyperphysics, 2016)	17
2.8	Polarization of an elliptical (Balanis, 2005)	18
2.9	Polarization of a circular (Hyperphysics, 2016)	18
2.10	Voltage multiplier of seven stages Dickson topology (Ali et al., 2019)	20

2.11	DC output voltages against the number of stage (Ali et al., 2019)	21
2.12	The position of a matching network in the general rectenna structure	23
2.13	Experimental setup to verify the property of microwave beam (Brown, 1969)	26
2.14	Integration of antenna and rectifier with the additional band-stop filter design of a dipole rectenna (Young-Ho Suh and Kai Chang, 2002)	29
2.15	Proposed rectenna design performance; (a) Return loss response comparison before and after the inclusion of band-stop filter and (b) Simulated and measured conversion efficiency against power density (Young-Ho Suh and Kai Chang, 2002)	30
2.16	Novel dual-frequency with circular polarization; (a) Circular patch antenna with dual rectifier output and (b) Simulated and measured return loss response of the low and high band rectifier circuit (Heikkinen and Kivikoski, 2003)	31
2.17	Geometry of proposed antenna design with seven points for optimized position of SMA connector (Falkenstein et al., 2012)	32
2.18	Integrated dual-polarized patch rectenna (Falkenstein et al., 2012)	33
2.19	Measured RF-to-DC conversion efficiency with varying power when different frequency tone is applied to the rectenna (Niotaki et al., 2013)	34
2.20	Antenna design with characteristics of six-band dual circular polarization (Song et al., 2016)	35
2.21	Simulated and measured output voltage against input power (Adam et al., 2018)	36
3.1	Flow chart of multi-band RF energy harvesting rectenna	45

3.2	Rectenna experimental setup	48
3.3	Detailed material layers of π -shaped aperture-coupled antenna structure	49
3.4	The cross-sectional view of the π -shaped aperture-coupled antenna	50
3.5	Antenna layout with design parameters; (a) View from Side A and (b) View from Side B	51
3.6	Antenna layout with design parameters; (a) View from Side C and (b) Side view	51
3.7	Transmission feedline initial design (Design A)	54
3.8	Transmission feedline with U-slot design (Design B)	55
3.9	Transmission feedline with U-slot and right-handed stub (Design C)	56
3.10	Transmission feedline with U-slot and symmetrical right-and-left-handed stubs (Design D)	56
3.11	Transmission feedline with U-slot and asymmetrical right-and-left-handed stubs (Design E)	57
3.12	Schematic design of single-diode rectifier	61
3.13	Schematic design of double-diode rectifier	62
3.14	Design geometry of an interdigital capacitor	64
3.15	Schematic design of single-diode rectifier in the microstrip transmission line form for frequency 2.45GHz	66
3.16	Schematic design of single-diode rectifier in the microstrip transmission line form for frequency 5.80GHz	67
3.17	Layout design of single-diode rectifier in the microstrip transmission line form for frequency 2.45GHz	68

3.18	Layout design of single-diode rectifier in the microstrip transmission line form for frequency 5.80GHz	68
3.19	Schematic design of double-diode rectifier in the microstrip transmission line form for frequency 2.45GHz	70
3.20	Schematic design of double-diode rectifier in the microstrip transmission line form for frequency 5.80GHz	71
3.21	Layout design of double-diode rectifier in the microstrip transmission line form for frequency 2.45GHz	72
3.22	Layout design of double-diode rectifier in the microstrip transmission line form for frequency 5.80GHz	72
3.23	Schematic design of double-diode rectifier in the microstrip transmission line form for frequency 2.45GHz and 5.80GHz	73
3.24	Layout design of double-diode rectifier in the microstrip transmission line form for frequency 2.45GHz and 5.80GHz	74
3.25	Integration of the antenna structure with the rectifier circuit	75
3.26	Block diagram of rectenna measurement equipment setup	76
4.1	Simulated return loss response (Antenna A)	80
4.2	Current distribution at the antenna transmission feedline (Design A); (a) 2.44GHz, (b) 5.24GHz, and (c) 8.96GHz	81
4.3	Parametric studies on the width and length of the radiator patch	82
4.4	Parametric studies on the length of transmission feedline	83
4.5	Simulated return loss response (Design B)	84
4.6	Current distribution at the antenna transmission feedline (Design B); (a) 2.45GHz, (b) 5.00GHz, (c) 8.69GHz, and (d) 9.45GHz	85

4.7	Simulated return loss response (Design C)	86
4.8	Current distribution at the antenna transmission feedline (Design C); (a) 2.45GHz, (b) 5.00GHz, (c) 7.51GHz, and (d) 9.82GHz	87
4.9	Simulated return loss response (Design D)	88
4.10	Simulated return loss response (Design E)	89
4.11	Parametric studies on position of asymmetrical stubs	90
4.12	Simulated return loss response by different antenna design structure	91
4.13	The simulated antenna realized gain at 2.45GHz; (a) Design A, (b) Design B, (c) Design C, (d) Design D, and (e) Design E	93
4.14	The simulated antenna realized gain at 5.80GHz; (a) Design A, (b) Design B, (c) Design C, (d) Design D, and (e) Design E	94
4.15	Radiation pattern of antenna at 2.45GHz; (a) Design A, (b) Design B, (c) Design C, (d) Design D, and (e) Design E	96
4.16	Radiation pattern of antenna at 5.80GHz; (a) Design A, (b) Design B, (c) Design C, (d) Design D, and (e) Design E	97
4.17	Return loss response of the fabricated antenna (Design A)	99
4.18	Simulated and measured return loss response of antenna (Design A)	100
4.19	Simulated and measured radiation pattern of antenna Design A; (a) 2.45GHz and (b) 5.00GHz	101
4.20	Return loss response of the fabricated antenna (Design E)	102
4.21	Simulated and measured return loss response of antenna (Design E)	103
4.22	Fabricated antenna prototype (Design E); (a) Top view, (b) Bottom view, and (c) Embedded U-slot and asymmetrical right-and-left-handed stubs at the transmission feedline	104

4.23	Simulated and measured radiation pattern of antenna Design E; (a) 2.45GHz and (b) 5.80GHz	105
4.24	Single-diode rectifier prototype for operating frequency 2.45GHz	106
4.25	Simulated and measured return loss response of single-diode rectifier for the operating frequency 2.45GHz	107
4.26	Simulated and measured output DC voltage of single-diode rectifier for the operating frequency 2.45GHz	108
4.27	Single-diode rectifier prototype for operating frequency 5.80GHz	109
4.28	Simulated and measured return loss response of single-diode rectifier for the operating frequency 5.80GHz	110
4.29	Simulated and measured output DC voltage of single-diode rectifier for the operating frequency 5.80GHz	111
4.30	Double-diode rectifier prototype for operating frequency 2.45GHz	112
4.31	Simulated and measured return loss response of double-diode rectifier for the operating frequency 2.45GHz	113
4.32	Simulated and measured output DC voltage of double-diode rectifier for the operating frequency 2.45GHz	114
4.33	Double-diode rectifier prototype for operating frequency 5.80GHz	115
4.34	Simulated and measured return loss response of double-diode rectifier for the operating frequency 5.80GHz	115
4.35	Simulated and measured output DC voltage of double-diode rectifier for the operating frequency 5.80GHz	116
4.36	Double-diode rectifier prototype for operating frequency 2.45GHz and 5.80GHz	117

4.37	Simulated and measured return loss response of dual-band double-diode rectifier	118
4.38	Simulated and measured output DC voltage of dual-band double-diode rectifier at 2.45GHz	119
4.39	Simulated and measured output DC voltage of dual-band double-diode rectifier at 5.80GHz	119
4.40	Fabricated rectenna prototype (Rectenna A)	121
4.41	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 0 $^\circ$ rectenna rotation for 2.45GHz (Rectenna A)	123
4.42	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 0 $^\circ$ rectenna rotation for 5.80GHz (Rectenna A)	125
4.43	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 30 $^\circ$ rectenna rotation for 2.45GHz (Rectenna A)	127
4.44	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 30 $^\circ$ rectenna rotation for 5.80GHz (Rectenna A)	129
4.45	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 60 $^\circ$ rectenna rotation for 2.45GHz (Rectenna A)	131
4.46	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 60 $^\circ$ rectenna rotation for 5.80GHz (Rectenna A)	132
4.47	Fabricated rectenna prototype (Rectenna B)	133
4.48	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 0 $^\circ$ rectenna rotation for 2.45GHz (Rectenna B)	135
4.49	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 0 $^\circ$ rectenna rotation for 5.80GHz (Rectenna B)	137

4.50	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 30° rectenna rotation for 2.45GHz (Rectenna B)	139
4.51	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 30° rectenna rotation for 5.80GHz (Rectenna B)	141
4.52	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 60° rectenna rotation for 2.45GHz (Rectenna B)	143
4.53	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 60° rectenna rotation for 5.80GHz (Rectenna B)	144
4.54	Fabricated rectenna prototype (Rectenna C)	145
4.55	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 0° rectenna rotation for 2.45GHz (Rectenna C)	147
4.56	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 0° rectenna rotation for 5.80GHz (Rectenna C)	149
4.57	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 30° rectenna rotation for 2.45GHz (Rectenna C)	151
4.58	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 30° rectenna rotation for 5.80GHz (Rectenna C)	152
4.59	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 60° rectenna rotation for 2.45GHz (Rectenna C)	154
4.60	DC voltage output with 1.50k Ω load resistor and RF-to-DC conversion efficiency at 60° rectenna rotation for 5.80GHz (Rectenna C)	156
4.61	RF-to-DC conversion efficiency at 2.45GHz (Rectenna A)	157
4.62	RF-to-DC conversion efficiency at 5.80GHz (Rectenna A)	158
4.63	RF-to-DC conversion efficiency at 2.45GHz (Rectenna B)	159

4.64	RF-to-DC conversion efficiency at 5.80GHz (Rectenna B)	160
4.65	RF-to-DC conversion efficiency at 2.45GHz (Rectenna C)	161
4.66	RF-to-DC conversion efficiency at 5.80GHz (Rectenna C)	162