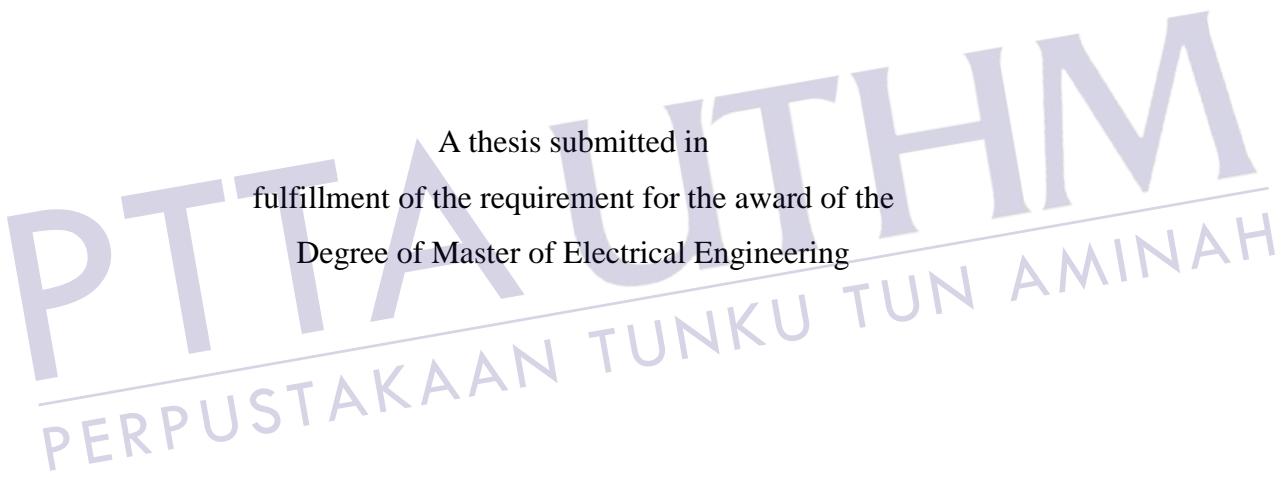


MICROSTRIP PATCH ARRAY RECTENNA WITH HARMONIC SUPPRESSION
CAPABILITY FOR ENERGY HARVESTING APPLICATION

NUR `AISYAH BINTI AMIR

A thesis submitted in
fulfillment of the requirement for the award of the
Degree of Master of Electrical Engineering



Faculty of Electrical and Electronic Engineering

Universiti Tun Hussein Onn Malaysia

MARCH 2018

To my beloved parents, siblings and friends for their endless love, support and
tolerance



ACKNOWLEDGEMENT

In the name of Allah, Most Gracious and Most Merciful, Praise is to Allah, the guidance that brought this study to a completion.

I would like to take this opportunity to thank Dr Shipun Anuar bin Hamzah as my supervisor for his support, encouragement, guidance and motivation through the years. My special thanks to my parents, En. Amir bin Musa and Pn Aaizat binti Ismail as well as my siblings for the love and their continuous support and willing to share with me all my joy and pain in completing this study.

My heartfelt thanks go to my co supervisor, Dr Khairun Nidzam bin Ramli in providing necessary guidance and help. So does the entire technician involved in this study for their help and advice throughout the project.

I also highly appreciate the cooperation, guidance and unconditional support from my fellows, Hisyamuddin, Rashid, Nik, Farah, Hidayah and Umol.

Last but not least, I would like to thanks those who have directly or indirectly contributed towards the accomplishment of this study.



ABSTRACT

This research proposes a microstrip patch array rectenna for Radio Frequency (RF) energy harvesting at 2.45 GHz. Energy harvesting is a process where energy is derived from external sources which is captured and converted into power supply. External source being used in this research is RF energy. Rectenna is a combination of rectifier circuit and antenna. There are three stages in designing a rectenna system. The first stage is receiving antenna which is designed to have high gain and able to capture the 2.45 GHz signal. In order to yield high gain and suppress the harmonic frequency, microstrip patch array antenna is integrated with electromagnetic bandgap (EBG) and filter. The microstrip patch array antenna is etched on FR-4 substrate with thickness of 1.6 mm and the dielectric constant of 4.4. The antenna is designed and simulated using the Computer Simulation Technology (CST) Microwave Studio software. The effectiveness of the EBG and filter structure for harmonic suppression and gain improvement has been tested. The simulation and measurement results verified that the combination of the array antenna with EBG and filter is efficient in eliminating unwanted frequencies and increase the gain from 3.665 dB to 9.112 dB. In the second stage, seven stages Villard voltage multiplier circuit has been used as a rectifier circuit which converts the RF signal into direct current (DC) power supply. The rectifier is designed and simulated using Advanced Design System (ADS) software. Rectifier circuit prototype is measured and the result indicated that it can convert signal into 0.5V DC power supply. The third stage is the integration of the receiving array antenna and rectifier circuit which successfully produced 0.3V power supply. The tested result in anechoic chamber verified that the rectenna design is able to capture and convert the 2.45 GHZ signal into DC power supply.

ABSTRAK

Kajian ini mencadangkan kaedah penuaian tenaga frekuensi radio (RF) dengan menggunakan *rectenna* susunan tampil mikrojalur yang beroperasi pada frekuensi 2.45 GHz. Penuaian tenaga adalah proses tenaga daripada sumber luaran yang diserap dan diubah menjadi bekalan kuasa. RF adalah sumber tenaga luaran yang digunakan dalam kajian ini. *Rectenna* adalah gabungan litar penerus dan antena penerima. Terdapat tiga peringkat yang terlibat dalam merekabentuk sistem *rectenna*. Peringkat pertama adalah antena penerima. Antena penerima direkabentuk untuk memiliki nilai gandaan yang tinggi, keupayaan menyingkirkan harmonik dan berupaya untuk menyerap gelombang 2.45 GHz. Antena susunan tampil mikrojalur disepadukan dengan jurang jalur elektromagnet (EBG) dan penapis untuk meningkatkan prestasi gandaan dan menyingkirkan frekuensi harmonik. Antena dicetak pada substrat FR-4 dengan ketebalan 1.6 mm dan pemalar dielektrik 4.4. Semua rekaan dan simulasi dijalankan dengan menggunakan perisian *Computer Simulation Technology* (CST). Keberkesanan struktur EBG dan penapis untuk menyingkirkan harmonik dan penambahbaikan telah diuji. Hasil simulasi dan pengujian mengesahkan bahawa gabungan antena susunan dengan EBG dan penapis adalah berkesan dalam menyingkirkan frekuensi yang tidak diingini dan meningkatkan gandaan iaitu dari 3.665 dB kepada 9.112 dB. Dalam peringkat kedua, litar pengganda voltan Villard tujuh peringkat direkabentuk dan digunakan sebagai litar penerus dimana ia dapat menukar gelombang RF kepada bekalan kuasa arus terus (AT). Reka bentuk dan simulasi litar, dilakukan dengan menggunakan perisian *Advanced Design System* (ADS). Setelah diuji, prototaip litar penerus didapati mampu menukar gelombang RF kepada 0.5V bekalan kuasa AT. Peringkat ketiga dan terakhir adalah gabungan antena susunan tampil mikrojalur dan litar penerus. Gabungan antara keduanya berjaya menghasilkan bekalan kuasa 0.3V. Ujian yang dijalankan di ruang *anechoic* telah mengesahkan bahawa reka bentuk *rectenna* dapat menangkap dan menukar isyarat 2.45 GHz kepada bekalan kuasa.

TABLE OF CONTENTS

DECLARATION	ii
DEDICATION	iii
ACKNOWLEDGEMENT	iv
ABSTRACT	v
ABSTRAK	vi
TABLE OF CONTENTS	vii
LIST OF TABLES	x
LIST OF FIGURES	xii
LIST OF SYMBOLS AND ABBREVIATIONS	xvii
LIST OF APPENDICES	xx
CHAPTER 1 INTRODUCTION	1
1.1 Problem statement	3
1.2 Objective	4
1.3 Scopes of the study	5
1.4 Research contribution	6
1.5 Outline of the thesis	7



CHAPTER 2 LITERATURE REVIEW	9
2.1 Review of microstrip patch rectenna	10
2.2 Review of harmonic suppression antenna	13
2.3 Review of high gain antenna	24
2.4 Review of rectifier circuit	30
2.5 Summary	32
CHAPTER 3 METHODOLOGY	34
3.1 Design methodology	35
3.2 Simulation and optimization set up	36
3.3 Measurement set up	39
3.3.1 Antenna measurement	39
3.3.1.1 S-Parameter	39
3.3.1.2 Gain	40
3.3.1.3 Radiation pattern	42
3.3.2 Measurement technique for rectifier circuit	43
3.3.3 Performance measurement for rectenna design	44
3.4 Summary	45
CHAPTER 4 DEVELOPMENT OF RECTENNA	47
4.1 Propose antenna design	48
4.1.1 Rectangular inset feed antenna	48
4.1.2 Rectangular inset feed antenna with EBG	51
Structure	
4.1.2.1 Performances study of square holes EBG	52
4.1.2.2 Performances study of circular holes EBG	56
4.1.2.3 Performances study of hexagon holes EBG	59
4.1.2.4 Study of surface current on EBG structure	65
4.1.3 Rectangular inset feed antenna with EBG	70
Structure and filter	
4.1.4 2x1 array antenna with EBG structure and filter	79
4.1.5 4x1 array antenna with EBG structure and filter	84
4.2 Rectifier circuit design	89

4.2.1 Effect of load impedance	89
4.2.2 Number of stages	93
4.2.3 Grainacher voltage doubler circuit	96
4.2.4 Villard voltage multiplier circuit	97
4.2.5 Rectifier circuit measurement	99
4.3 Rectenna measurement and analysis	101
4.4 Conclusion	103
CHAPTER 5 CONCLUSION AND FUTURE RECOMMENDATIONS	105
5.1 Future recommendations	107
REFERENCES	108
APPENDICES	114



PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF TABLES

2.1	Comparison of the previous studies in microstrip patch rectenna for rectenna system	13
2.2	Comparison of the previous studies in harmonic suppression antenna	23
2.3	Comparison of the previous studied in high gain antenna	29
2.4	Comparison of the previous studies in rectifier circuit	32
4.1	Dimension of rectangular inset feed antenna	49
4.2	S-Parameter of different radius square holes EBG	53
4.3	S-Parameter of different gap square holes EBG	55
4.4	S-Parameter of different radius circular holes EBG	56
4.5	S-Parameter of different gap circular holes EBG	58
4.6	S-Parameter of different radius hexagon holes EBG	59
4.7	S-Parameter of different gap hexagon holes EBG	61
4.8	Comparison result under different radius with static gap (5.5 mm)	62
4.9	Comparison result under different gap with static radius (7 mm)	63
4.10	Surface current at each frequency	67
4.11	Gain comparison between conventional antenna and EBG antenna	68
4.12	S-Parameter for filter in different length of Z	71
4.13	S-Parameter for filter in different length of Y	72

4.14	Surface current at each harmonic frequency	73
4.15	Comparison between previous design dimension and new design (unit: mm)	77
4.16	Comparison between simulation and measurement of antenna's gain based on structure added at 2.45 GHz	78
4.17	Dimension of 2x1 rectangular inset feed array antenna with EBG structure filter (unit: mm)	81
4.18	Comparison between simulation and measurement of antenna's gain based on structure added at 2.45 GHz	83
4.19	Dimension on 4x1 array antenna (unit: mm)	85
4.20	Comparison of antenna's gain between single antenna, 2x1 array antenna and 4x1 array antenna based on structure added at 2.45 GHz	88



PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF FIGURES

1.1	A chart from Texas Instrument (TI) showing the available power from different energy harvesting chips and what is needed to power selected devices [3]	2
1.2	Block diagram of the RF energy harvesting system [6]	2
2.1	3D view of rectangular patch antenna [18]	10
2.2	Square aperture coupled patch antenna with a cross shaped slot [19]	11
2.3	Prototype of 2nd iteration Koch fractal patch antenna with two stage Dickson charge pump voltage-doubler rectifier circuit [20]	11
2.4	Rectangular inset feed antenna [21]	12
2.5	Microstrip patch with photonic bandgap in the ground plane [22]	14
2.6	Measured return loss for the PBG antenna and the normal antenna [22]	14
2.7	Microstrip patch antenna array with circular PBG on the ground plane (a) front view and (b) back view [23]	15
2.8	Return loss of microstrip patch antenna array with circular PBG on the ground plane [23]	15
2.9	S-parameter of microstrip circular PBG on the ground plane [23]	16
2.10	Configuration of the proposed antenna with its optimal parameters [24]	17
2.11	Return losses of the RDGS type slot antenna [24]	17
2.12	The circularly polarized harmonic suppression elliptical shape patch antenna (a) front view (b) back view [25]	18
2.13	Return loss of the antenna [25]	18
2.14	(a) Structure of DGS (b) Structure of PBG [26]	19
2.15	Return loss comparison for the microstrip patch antenna [26]	19

2.16	Structure of the slot coupled dipole antenna.[Dimensions: La=140, Wa=12, L1=27, W1=1, G1=2 (units=mm)] [27]	20
2.17	Simulated S-parameter characteristics of LPF [27]	20
2.18	Integrated layout of pentagonal patch antenna and the stepped impedance low pass filter [28]	20
2.19	Comparison of return loss between with and without LPF [28]	21
2.20	Configuration of the antenna design [29]	22
2.21	Simulated frequency response of the antenna and the filter structure [29]	22
2.22	(a) Two element rectenna array (b) Three element rectenna array [30]	24
2.23	Transparent array antenna [31]	24
2.24	Measured result for (a) single rectenna (b) two element array (c) three element array [31]	25
2.25	The proposed antenna design (a) top view (b) side view [32]	26
2.26	Simulated gain of proposed antenna at different frequencies [32]	26
2.27	Antenna design (a) side view (b) dimension of antenna [33]	27
2.28	Measured gain of the proposed antenna [33]	28
2.29	Geometry of the proposed compact antenna with circular polarization [34]	28
2.30	Measured peak gain of the proposed compact antenna optimized in frequency range from 2.1 GHz to 2.7 GHz [34]	29
2.31	Schematic of 7 stage voltage multiplier [36]	31
2.32	Schematic of grainacher Voltage-doubler circuit [41]	31
2.33	Schematic of Dickson charge pump voltage doubler rectifier [42]	31
3.1	Flow chart of the study	35
3.2	Input setup for rectifier circuit	37
3.3	Harmonic balance setup for input power range	38
3.4	A part of rectifier circuit design	38
3.5	Vector network analyzer	39
3.6	Setup for normalization to a reference antenna [43]	41
3.7	setup after replace reference antenna with AUT for relative gain measurement [43]	41
3.8	Gain measurement setup in anechoic chamber EMC Lab UTHM	42

3.9	Radiation pattern measurement setup in full anechoic chamber	43
3.10	Input and output port for rectifier circuit	44
3.11	Spectrum network analyzer that use to measure rectifier circuit	44
3.12	Output port is connected to the multimeter	44
3.13	Rectenna measurement setup in anechoic chamber	45
3.14	Measurement setup for rectenna	45
4.1	Rectangular inset feed antenna (a) front view (b) back view	49
4.2	Prototype of Rectangular inset feed antenna (a) front view (b) back view	50
4.3	Return loss of rectangular inset feed antenna	50
4.4	E-plane of rectangular inset feed antenna at 2.45 GHz	50
4.5	H-plane of rectangular inset feed antenna at 2.45 GHz	51
4.6	EBG structure at ground plane	52
4.7	Square holes EBG	53
4.8	Circular holes EBG	56
4.9	Hexagon holes EBG	59
4.10	EBG structure on ground plane (a) simulation design (b) prototype	63
4.11	S_{11} of rectangular inset feed antenna with EBG	64
4.12	Effect of EBG structure	64
4.13	Fringing field of the microstrip patch antenna	65
4.14	Surface current of the antenna (a) plain ground (b) EBG structure	66
4.15	Surface current at 2.45 GHz (a) 4 x 3 element (b) 6 x 4 element (c) 11x 6 element	66
4.16	S_{11} comparison between rectangular inset feed antenna and rectangular inset feed antenna with EBG structure	67
4.17	E-plane of rectangular inset feed antenna with EBG structure at 2.45 GHz	69
4.18	H-plane of rectangular inset feed antenna with EBG structure at 2.45 GHz	69
4.19	Dimension of low pass filter	70
4.20	Effect of LPF rejection band on antenna with EBG structure and filter antenna with EBG structure only	73

4.21	Comparison between rectangular inset feed antenna, rectangular inset feed antenna with filter only and rectangular inset feed antenna with combination of EBG structure and filter	75
4.22	The prototype of new propose antenna (a) front view (b) back view	76
4.23	The comparison of return loss between previous antenna and new propose antenna	76
4.24	(a) Previous antenna design (b) new propose antenna design	77
4.25	Comparison of return loss between simulation and measurement result	77
4.26	E-plane of rectangular inset feed antenna with EBG structure and filter at 2.45 GHz	78
4.27	H-plane of rectangular inset feed antenna with EBG structure and filter at 2.45 GHz	79
4.28	Dimension of filter	80
4.29	2x1 rectangular inset feed array antenna with EBG structure and stub (a) front view (b) back view	80
4.30	Prototype of 2x1 rectangular inset feed array antenna with EBG structure and filter (a) front view (b) back view	82
4.31	Comparison of return loss between simulation and measurement	82
4.32	E-plane of 2x1 rectangular inset feed array antenna with EBG structure and filter at 2.45 GHz	83
4.33	H-plane of 2x1 rectangular inset feed array antenna with EBG structure and filter at 2.45 GHz	83
4.34	4x1 rectangular inset feed array antenna with EBG structure and filter (a) front view (b) back view	84
4.35	Prototype of 4x1 rectangular inset feed array antenna with EBG structure and filter (a) front view (b) back view	86
4.36	Return loss of 4x1 array antenna	86
4.37	Comparison return loss between antenna with and without EBG structure and filter	87
4.38	Number of array elements vs gain (dB)	87
4.39	E-plane of 4x1 rectangular inset feed array antenna with EBG structure and filter at 2.45 GHz	88
4.40	H-plane of 2x1 rectangular inset feed array antenna with EBG structure and filter at 2.45 GHz	88
4.41	Effect of load impedance for Grainacher Voltage Doubler Circuit at 20 dBm input power	90

4.42	Effect of load impedance for Villard Voltage Multiplier Circuit at 20 dBm input power	90
4.43	Effect of load impedance for Grainacher Voltage Doubler Circuit for single stage	91
4.44	Effect of load impedance for Grainacher Voltage Doubler Circuit for 3 stages	91
4.45	Effect of load impedance for Villard Voltage Multiplier Circuit for single stage	92
4.46	Effect of load impedance for Villard Voltage Multiplier Circuit for 7 stages	92
4.47	Effect of number of stages on the output voltage of Grainacher Voltage Doubler Circuit for $10k\Omega$ load impedance	93
4.48	Effect of number of stages on the output voltage of Grainacher Voltage Doubler Circuit for $100k\Omega$ load impedance	94
4.49	Comparison of number of stages on the output voltage of Grainacher Voltage Doubler Circuit between $10k\Omega$ and $100k\Omega$ load impedance	94
4.50	Effect of number of stages on the output voltage Villard Voltage Multiplier Circuit for $10k\Omega$ load impedance	95
4.51	Effect of number of stages on the output voltage Villard Voltage Multiplier Circuit for $100k\Omega$ load impedance	95
4.52	Comparison of number of stages on the output voltage of Villard Voltage Multiplier Circuit between $10k\Omega$ and $100k\Omega$ load impedance	96
4.53	First stage Grainacher voltage doubler circuit	96
4.54	Three stage Grainacher voltage doubler circuit	97
4.55	First stage Villard voltage Multiplier circuit	97
4.56	Seven stage Villard voltage Multiplier circuit	98
4.57	Prototype of Villard Voltage Multiplier Circuit (a) single stage (b) seven stages	99
4.58	Rectifier measurement setup	100
4.59	Result for single and 7 stages Villard Voltage Multiplier Circuit	101
4.60	Rectenna measurement setup	101

4.61	Comparison 2x1 rectenna output voltage power between 60cm and 100 cm	102
4.62	Comparison 4x1 rectenna output voltage power between 60cm and 100 cm	103



PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF SYMBOLS AND ABBREVIATIONS

μ	-	micron
mm	-	millimetre
k	-	kilo
M	-	mega
pF	-	Pico farad
nH	-	nano henry
Ω	-	ohm
%	-	percent
η	-	Efficiency
λ	-	lambda
c	-	speed of light
f_o	-	operating frequency
ϵ_r	-	dielectric constant
dB	-	decibel
dB _i	-	decibels relative to isotropic
dB _m	-	decibel milliwatts
I	-	Current
V	-	Voltage
W	-	Watt
RF	-	Radio frequency
DC	-	Direct current
Wi-Max	-	Worldwide Interoperability for Microwave Access
Wi-Fi	-	Wireless fidelity
PBG	-	Photonic band gap
EBG	-	Electromagnetic band gap
DGS	-	Defected ground structure

MHz	- Megahertz
GHz	- Gigahertz
FR-4	- Fire resistant
SMD	- Surface-mount device
CST	- Computer Simulation Technology
ADS	- Advanced Design Simulation
RFID	- Radio Frequency Identification
2-D	- Two dimensional
HSA	- Harmonic Suppression Antenna
LPF	- Low pass filter
S11	- Return loss
S21	- Insertion loss
SMA	- SubMiniature version A
AUT	- Antenna under test
IEEE	- Institute of Electrical and Electronics Engineers



PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Published paper	115
B	Book chapter	132
C	Fabrication setup	147
D	Calculation of antenna dimension	150
E	Calculation of near and far fields	153
F	HSMS 2850 Schottky diode datasheet	155
G	Antenna factor for gain measurement	161



PERPUSTAKAAN PUNKU TUN AMINAH
UTHM

CHAPTER 1

INTRODUCTION

Energy harvesting is a process where energy derived from external sources is captured and converted into power supply. For many eras, people have discovered ways to store the energy from wind and sun. The first wind turbine to generate electricity was developed by Professor James Blyth of Anderson's College [1] in Glasgow. The configuration consisted of cloth sails resembling windmill blades. The generated energy was stored in accumulators and used to power the lights of his vacation cottage in Marykirk [2]. Their success has inspired great thinkers to scale down energy harvesting to the micro level. As a result, the girth of energy harvesting has expanded beyond just wind and sun to include movement, heat, mechanical vibration, RF, and others. Figure 1.1 shows the harvested power that can be obtained from different sources and the selected devices with value to power up the devices.



Power available from energy sources

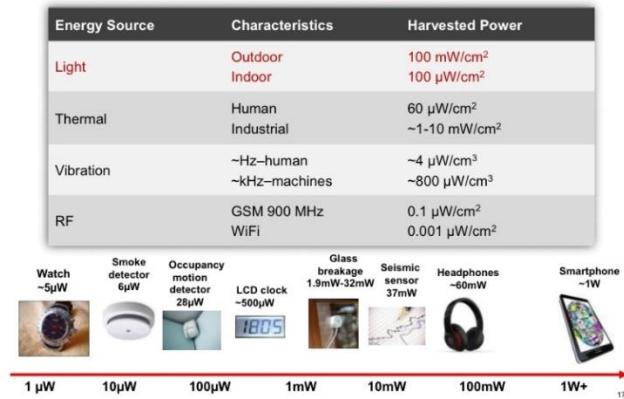


Figure 1.1: A chart from Texas Instrument (TI) showing the available power from different energy harvesting chips and what is needed to power the selected devices [3]

Among all the available sources for energy harvesting, RF energy has recently captured significant interest because of the increased availability of free RF energy. This is because RF energy is a renewable energy where it can be collected from public services. There are large number of RF energy sources such as, broadcasting radio and TV stations, mobile telephony base stations and wireless networks in cities and very populated areas. For example, ambient RF energy is collected and converted into alternating current (AC) by antenna and then rectified to direct current (DC) for charging system batteries. The rectenna which is integration of rectifier circuit and antenna is one of the most important components for above-mentioned systems. A basic RF energy harvesting system is shown in Figure 1.2. The typical rectenna [4-5] system basically consists of receiving antenna for receiving RF power, a low-pass filter (LPF) or band-pass filter (BPF) as an input filter for selecting or suppressing unwanted signal and a diode as the rectifier device for RF-to-DC power conversion.

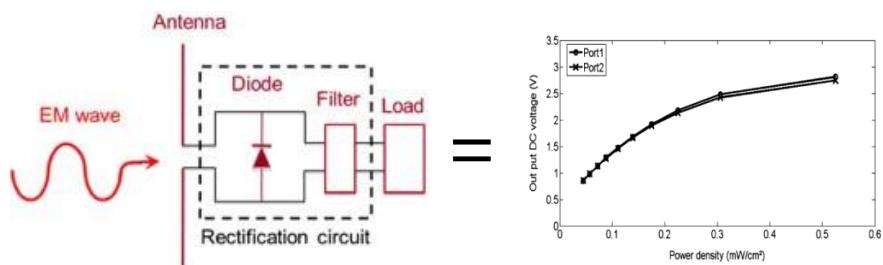


Figure 1.2: Block diagram of the RF energy harvesting system [6]

Rectenna in the wireless energy harvesting faces numerous challenges such as compact size, low cost, and high integration in the system. In this research, the focus is on design and development of microstrip patch rectenna operating at 2.45 GHz. From the design's point of view, the selection of antenna has a great effect on the size and the order of the system's complexity.

1.1 Problem statement

One of the most common types of antenna used for rectenna applications is the microstrip patch antenna. Some of the advantages of using this type of antenna are low profile, low cost, light-weight and suitability of integration with RF devices. However, it also exhibits some disadvantages such as the excitation of surface waves that exist in the substrate layer. Surface waves are exceptionable because when a patch antenna radiates, a part of the total available radiated power becomes trapped along the surface of the substrate. It diminishes the total available power for radiation to space wave and produces unwanted harmonic frequencies. In addition, for array antennas, surface waves have a significant impact on the mutual coupling between array elements [7]. Besides that, in rectifying circuit, diode used to convert the RF signal to DC power supply also generates the unwanted radiation of harmonic frequencies. Hence, the rectenna cannot perform well and will degrade the system performance. Therefore, several design methods have been proposed in the past in order to overcome these unwanted generated harmonic problem. One of the most popular methods is called the photonic band gap (PBG) or electromagnetic band gap (EBG) [8] and defected ground structure (DGS) [9], [10]. Several other techniques, for instance antenna with slit and stub structure [11], circular sector patch antenna [12], slot antenna and notch antenna [13], [14] also have been proposed as a the methods to suppress the harmonic frequencies.

Besides, another challenge faced in RF energy harvesting is to extract power from the air at very low power density since RF energy drops off rapidly with the increased distance from the transmitter. In free space, the electric field and propagation power density diminishes with the square of distance according to Friis Transmission Formula [15]:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \quad (1.1)$$

Where,

- P_r = Power at the receiving antenna
- P_t = Power at transmitting antenna
- G_r = Antenna gain of the receiving antenna
- G_t = Antenna gain of the transmitting antenna
- R = Distance between the transmitting and receiving antennas
- λ = Electromagnetic wavelength in the transmission medium

However, as the distance increases, the available power and rate of charge decrease [16]. Moreover, for multipath situations with environmental reflections and losses, the power density drops off at a much faster rate. It is therefore critical for the system to operate at low receive power with high conversion efficiency. One of the solutions to increase the received power is by increasing the gain of the receiving antenna, G_r . However, it is a known fact that microstrip patch antenna generally has low gain as compared to high gain antenna such as yagi-uda antenna, helical antenna, parabolic antenna and many more. Therefore, in this work, a microstrip patch rectenna with harmonic suppression capability and high gain is designed and developed in order to improve the system performance.

1.2 Objectives

The aim of this project is to design a microstrip patch antenna with high gain performance that can cooperate with rectifier circuit in order to convert the captured signal into DC power supply. In order to achieve the aim, the main objectives formulated for this work are:

1. To investigate the most optimum microstrip patch array antenna for rectenna system that operates at 2.45 GHz with harmonic suppression capability.
2. To design a rectifier circuit that can convert 2.45 GHz signal to DC power supply.

3. To integrate a microstrip patch array antenna with rectifier to form a rectenna that can wirelessly gather energy from antenna and convert it into DC power supply.

1.3 Scopes of the study

1. The receiving antenna is designed to operate at 2.45 GHz and has the characteristics of high gain and harmonic frequencies suppression capability.
2. This antenna is fabricated on 1.6 mm thick FR-4 substrate with dielectric constant of 4.4. This is because, the criterion for selection of suitable substrate are its price, efficiency and size. Hence, FR-4 substrate is an optimal choice compared to others substrate such as Roger 4350.
3. An EBG structure and a filter that match with the antenna are designed to block any harmonic generated by diode and antenna itself.
4. The topology used for the rectifier is Villard voltage multiplier. This because voltage multiplier circuit allows higher voltages to be created from a low voltage power source without a need for an expensive high voltage transformer. By using combinations of rectifier diodes and capacitors, the input peak voltage is effectively multiplied to give a DC output equal to some odd or even multiple of the peak voltage value of the AC input voltage.
5. The combination of receiving antenna and rectifier circuit produces a perfect rectenna system which can operate at 2.45 GHz and convert the RF energy to the DC power supply.
6. The commercial Schottky diode model HSMS-2850 from Avago Technologies has been chosen for rectifier circuit. There are various types of diodes that can be used based on the applications. For rectenna system, since the energy harvesting circuit is operating at high frequencies, diodes with a very fast switching time are needed. When sufficient forward voltage is applied, a current flow in the forward direction. A silicon diode has a typical forward voltage of 600–700 mV, while the Schottky's forward voltage is 150 – 450 mV. This lower forward voltage requirement allows higher switching speeds and better system efficiency [17]. The special features of

REFERENCES

- [1] T. J. Price, "James Blyth—Britain's first modern wind power pioneer," Wind engineering, 29(3), 191-200, 2005
- [2] "Making low-voltage energy harvesting practical: Part1-The history of energy harvesting,"[Online].Available:http://www.electronicproducts.com/Power_Products/Invertors/Making_low_voltage_energy_harvesting_practical_Part_1_The_history_of_energy_harvesting.aspx [Accessed May 31, 2015]
- [3] "Energy harvesting chips: The next big thing for a connected world," [Online]. Available:<https://gigaom.com/2013/11/21/energy-harvesting-chips-the-next-big-thing-for-a-connected-world/> [Accesed May 31,2015]
- [4] J. S. Sun, R. H. Chen, S. K. Liu and C. F. Yang, "Wireless power transmission with circularly polarized rectenna,". Microw. J. Tech. Library, 2011
- [5] S. Keyrouz and H. Visser, "Efficient direct-matching rectenna design for RF power transfer applications," In Journal of Physics: Conference Series, Vol. 476, No. 1, p. 012093, IOP Publishing. 2013
- [6] Z. Harouni, L. Cirio, L. Osman, A. Gharsallah, and O. Picon, "A dual circularly polarized 2.45-GHz rectenna for wireless power transmission,"Antennas and Wireless Propagation Letters, IEEE, 10, 306-309, 2011.
- [7] D. M. Nashaat Elsheakh, M. F. Iskander, E. A.-F. Abdallah, H. A. Elsadek, and H. Elhenawy, "Microstrip Array Antenna With New 2D-Electromagnetic Band Gap Structure Shapes To Reduce Harmonics and Mutual Coupling," Prog. Electromagn. Res. C, vol. 12, pp. 203–213, 2010.
- [8] M. N. Aktar, M. S. Uddin, M. R. Amin, and M. A. Ali, "Enhanced gain and bandwidth of patch antenna using ebg substrates," Int. J. Wirel. Mob. Networks, vol. 3, 2011.

- [9] V. S. Kushwah and G. S. Tomar, "Size reduction of microstrip patch antenna using Defected Microstrip Structures," Proc. - 2011 Int. Conf. Commun. Syst. Netw. Technol. CSNT 2011, pp. 203–207, 2011.
- [10] R. L. Dua, H. Singh, and N. Gambhir, "2.45 ghz microstrip patch antenna with defected ground structure for bluetooth," International Journal of Soft Computing and Engineering (IJSCE), 1(6), 262-265, 2012.
- [11] R. A. Rahim, F. Malek, S. F. W. Anwar, S. L. S. Hassan, M. N. Junita, and H. F. Hassan, "A harmonic suppression circularly polarized patch antenna for an RF ambient energy harvesting system," CEAT 2013 - 2013 IEEE Conf. Clean Energy Technol., pp. 33–37, 2013.
- [12] F. J. Huang, T. C. Yo, C. M. Lee, and C. H. Luo, "Design of circular polarization antenna with harmonic suppression for rectenna application," IEEE Antennas Wirel. Propag. Lett., vol. 11, pp. 592–595, 2012.
- [13] R. A. Rahim, M. N. Junita, S. I. S. Hassan, and H. F. Hassan, "Harmonics suppression circular polarization elliptical shape microstrip patch antenna," Proc. 2014 2nd Int. Conf. Technol. Informatics, Manag. Eng. Environ. TIME-E 2014, pp. 147–150, 2015
- [14] N. Ghasemi and S. Jamali, "International Journal of Research in Computer Applications and Robotics ISSN 2320-7345," vol. 3, no. 4, pp. 168–176, 2013.
- [15] F. Lassabe, P. Canalda, P. Chatonnay, F. Spies and O. Baala, "A Friis-based calibrated model for WiFi terminals positioning" In World of Wireless Mobile and Multimedia Networks, 2005. WoWMoM 2005. Sixth IEEE International Symposium on a (pp. 382-387). IEEE, 2005
- [16] H. Ostaffe, "RF-based wireless charging and energy harvesting enables new applications and improves product design," 2012 [Online]. Available: http://www.mouser.com/applications/rf_energy_harvesting/, [Accessed June 10, 2015]
- [17] Y. H. Suh and K. Chang, "A high-efficiency dual-frequency rectenna for 2.45- and 5.8-GHz wireless power transmission," IEEE Transactions on Microwave Theory and Techniques, 50(7), 1784-1789, 2001.
- [18] S. Shrestha, S. K. Noh, and D. Y. Choi. "Comparative study of antenna designs for RF energy harvesting," International Journal of Antennas and Propagation, 2013.

- [19] G. A. Vera, A. Georgiadis, A. Collado, and S. Via, "Design of a 2.45 GHz rectenna for electromagnetic (EM) energy scavenging," Radio and Wireless Symposium (RWS), 2010 IEEE (pp. 61-64). IEEE, 2010.
- [20] U. Olgun, C. C. Chen and J. L. Volakis, "Wireless power harvesting with planar rectennas for 2.45 GHz RFIDs," Electromagnetic Theory (EMTS), 2010 URSI International Symposium on (pp. 329-331). IEEE, 2010.
- [21] H. Takhedmit, B. Merabet, L. Cirio, B. Allard, F. Costa, C. Vollaire and O. Picon, "A 2.45-GHz low cost and efficient rectenna," Antennas and Propagation (EuCAP), 2010 Proceedings of the Fourth European Conference on (pp. 1-5). IEEE, 2010.
- [22] Y. Horii and M. Tsutsumi, "Harmonic control by photonic bandgap on microstrip patch antenna," Microwave and Guided Wave Letters, IEEE, 9(1), 13-15, 1999.
- [23] W. Zhang, J. Mao, X. Sun, R. Qian, and D. Zhang, "Microstrip patch antenna array on ground with circular PBG," Microwave and optical technology letters, 41(2), 127-130, 2004.
- [24] M. S. Ghaffarian, G. Moradi, and R. Zaker, "Harmonic suppression slot antenna using rectangular defected ground structure," Electrical Engineering (ICEE), 2011 19th Iranian Conference on (pp. 1-4). IEEE, 2011.
- [25] R. A. Rahim, M. N. Junita, S. I. S. Hassan and H. F. Hassan, "Harmonics suppression circular polarization elliptical shape microstrip patch antenna," Technology, Informatics, Management, Engineering, and Environment (TIME-E), 2014 2nd International Conference on (pp. 147-150). IEEE, 2014.
- [26] H. Liu, Z. Li, X. Sun, and J. Mao, "Harmonic suppression with photonic bandgap and defected ground structure for a microstrip patch antenna," IEEE microwave and wireless components letters, 15(2), 55-56, 2005.
- [27] M. Han, S. Jung and H. Sohn, "High efficient rectenna using a harmonic rejection low pass filter for RF based wireless power transmission," Wireless Communications Systems (ISWCS), 2014 11th International Symposium on (pp. 423-426). IEEE, 2014.
- [28] D. Gangwar and R. L. Yadava, "Design and analysis of a pentagonal rectenna," Signal Processing and Integrated Networks (SPIN), 2014 International Conference on (pp. 654-658). IEEE, 2014.

- [29] J. Zhang, Y. Huang and P. Cao, "A wideband cross dipole rectenna for RF wireless harvesting," *Antennas and Propagation (EuCAP), 2013 7th European Conference on* (pp. 3063-3067). IEEE, 2013.
- [30] J. Zhang, Y. Huang and P. Cao, "Harvesting RF energy with rectenna arrays," *Antennas and Propagation (EUCAP), 2012 6th European Conference on* (pp. 365-367). IEEE, 2012.
- [31] H. Takhedmit, L. Cirio, F. Costa and O. Picon, "Transparent rectenna and rectenna array for RF energy harvesting at 2.45 GHz," *Antennas and Propagation (EuCAP), 2014 8th European Conference on* (pp. 2970-2972). IEEE, 2014.
- [32] M. T. Islam, M. N. Shakib, and N. Misran, "High gain microstrip patch antenna". *European journal of scientific research*, 32(2), 187-193. 2009
- [33] A. T. Mobashsher, M. T. Islam and N. Misran, "A novel high-gain dual-band antenna for RFID reader applications", *IEEE Antennas and Wireless Propagation Letters*, 9, 653-656. 2010
- [34] T. Wu, H. Su, L. Gan, H. Chen, J. Huang, and H. Zhang, "A compact and broadband microstrip stacked patch antenna with circular polarization for 2.45-GHz mobile RFID reader", *IEEE Antennas and Wireless Propagation Letters*, 12, 623-626. 2013
- [35] K. K. A. Devi, M. D. Norashidah, C. K. Chakrabarty and S. Sadasivam, "Design of an RF-DC conversion circuit for energy harvesting." *Electronics Design, Systems and Applications (ICEDSA)*, 2012 IEEE International Conference on (pp. 156-161). IEEE, 2012.
- [36] K. K. A. Devi, N. M. Din and C. K. Chakrabarty, "Optimization of the voltage doubler stages in an RF-DC convertor module for energy harvesting," 2012.
- [37] R. Yuwono, I. Mujahidin and A. Mustofa, "Rectifier using UFO microstrip antenna as electromagnetic energy harvester." *Advanced Science Letters*, 21(11), pp.3439-3443, 2015.
- [38] A. Mabrouki, M. Latrach and Z. Sayegh, "Design and experiment of RF rectifiers for wireless power transmission." *Microwave Symposium (MMS), 2013 13th Mediterranean* (pp. 1-4). IEEE, 2013.
- [39] H. Jabbar, Y.S. Song and T. T. Jeong, "RF energy harvesting system and circuits for charging of mobile devices." *IEEE Transactions on Consumer Electronics*, 56(1), 2010.

- [40] G. A. Vera, A. Georgiadis, A. Collado and S. Via, "Design of a 2.45 GHz rectenna for electromagnetic (EM) energy scavenging." Radio and Wireless Symposium (RWS), 2010 IEEE (pp. 61-64). IEEE, 2010.
- [41] S. B. Alam, M.S. Ullah and S. Moury, "Design of a low power 2.45 GHz RF energy harvesting circuit for rectenna." Informatics, Electronics & Vision (ICIEV), 2013 International Conference on (pp. 1-4). IEEE, 2013.
- [42] U. Olgun, C. C. Chen and J. L. Volakis, "Wireless power harvesting with planar rectennas for 2.45 GHz RFIDs." Electromagnetic Theory (EMTS), 2010 URSI International Symposium on (pp. 329-331). IEEE, 2010
- [43] "How To Measure Antenna Gain (Part 1) - Gain Transfer Method," [Online]. Available: http://www.measurementtest.com/2010/09/how-to-measure-antenna-gain-part-1-gain_08.html [Accessed July 2, 2016]
- [44] "Rectenna serves 2.45 GHz wireless power transmission," 2014 [Online]. Available: <http://mwrf.com/systems/rectenna-serves-245-ghz-wireless-power-transmission>, [Accessed Jan 10, 2015]
- [45] M. S. Joshua, M. Mayank and S. Prafull, "Design and Optimization of Microstrip Patch Antenna," International Jurnal of Emerging Trends & Technology in Computer Science (IJETTCS), 2013.
- [46] C. H. Lin, G. Y. Chen, J. S. Sun, K. K. Tiong, and Y. D. Chen, "The PBG filter design". Progress in Electromagnetics Research Symp. Proc., HangZhou, China. 2008
- [47] I. Garde, M. J. Yábar and C. del Río, "Simple modelling of DGS to design 1D-PBG low-pass filters," Microwave and Optical Technology Letters, 37(3), 228-232, 2003.
- [48] "Simulation and Measurement: Complementary Design Tools," [Online]. Available: <https://www.cst.com/Applications/Article/Simulation-Measurement-Design-Tools> [Accessed November 22, 2016]
- [49] S. H. Yahya, "Design of 4 elements rectangular microstrip patch antenna with high gain for 2.4 GHz applications," Modern applied science, 6(1), 68, 2011.
- [50] K. K. A. Devi, N. M. Din and C. K. Chakrabarty, "Optimization of the voltage doubler stages in an RF-DC convertor module for energy harvesting," 2012.

- [51] K. K. A. Devi, M. D. Norashidah, C. K. Chakrabarty and S. Sadasivam, "Design of an RF-DC conversion circuit for energy harvesting," Electronics Design, Systems and Applications (ICEDSA), 2012 IEEE International Conference on (pp. 156-161). IEEE, 2012.
- [52] "Schottky diode," [Online]. Available: https://en.wikipedia.org/wiki/Schottky_diode, [Accessed June 18, 2016]
- [53] Y. H. Suh and K. Chang, "A high-efficiency dual-frequency rectenna for 2.45- and 5.8-GHz wireless power transmission," IEEE Transactions on Microwave Theory and Techniques, 50(7), 1784-1789, 2001.
- [54] J. Heikkinen and M. Kivikoski, "A novel dual-frequency circularly polarized rectenna," IEEE Antennas and Wireless Propagation Letters, 2(1), 330-333, 2003.

