

SLOTTED LOG PERIODIC FRACTAL KOCH ANTENNA FOR ULTRA HIGH  
FREQUENCY DIGITAL TELEVISION APPLICATION

NUR SYAHIRAH BINTI MOHD YAZIZ

UNIVERSITI TEKNOLOGI MALAYSIA

SLOTTED LOG PERIODIC FRACTAL KOCH ANTENNA FOR ULTRA HIGH  
FREQUENCY DIGITAL TELEVISION APPLICATION

NUR SYAHIRAH BINTI MOHD YAZIZ

A thesis submitted in fulfilment of the  
requirements for the award of degree of  
Master of Philosophy

Faculty of Electrical Engineering  
Universiti Teknologi Malaysia

MAY 2018

*Specially dedicated to my beloved parent, Radziah Long and Mohd Yaziz Ahmad  
my supportive husband, Muhammad Ridduan Ramli  
my siblings, Syazwan, Syuhada and Syazana  
with love for their prays and encouragement.*

## ACKNOWLEDGEMENT

In the name of Allah, the Most Gracious and the Most Merciful. Alhamdulillah, all praise to Allah for all strength and His blessing in completing in this study.

Special appreciation goes to my supervisor, Prof Dr. Mohamad Kamal A. Rahim for his supervision and constant support. His invaluable help of constructive comments and suggestion have contributed to the success of this study. Not forgotten, appreciation to my Co-supervisor, Dr. Farid Zubir for his support and knowledge regarding this research.

To my colleagues at P18 members, Saidah, Afifah, Izni, Nazirah, Hafizah, Jannah, Arrauzah, Fatin, Raimi, Ezwan, Amerul, Azfar, Syazwan and Murtala for their sharing knowledge and ideas which helping me a lot. Without their help and support this study will be much harder.

My special thanks to my dearest parents, my lovely family members and my close friends who give their unconditional support, love and prayers throughout my entire journey. My deepest appreciation to my husband, Muhammad Ridduan Ramli for his understanding, moral support and endless love that are the key of my strength to complete the study.

My sincere appreciation also goes to everyone whom I may not have mentioned above who have helped directly or indirectly in the completion my project. Thank you for all your kindness and generosity.

## ABSTRACT

The Ultra High Frequency (UHF) band has long been used for voice, data and video communications. For the terrestrial television broadcasting, the lower frequency band of the UHF is used which ranges between 470 to 890 MHz. The conventional UHF antennas for receiving TV signals are quite large. One method that can be utilized is by using a compact and directional antenna that can be easily fabricated. The geometry used in this antenna design is Koch curve fractal structure. The advantage of using fractals in designing the antenna is to minimize the antenna size. The Log Periodic Antenna (LPA) is chosen because it had a wide bandwidth. This thesis describes the design of the planar fractal Koch antenna with slots for the UHF band. Four different iterations which is 0<sup>th</sup> iteration, 1<sup>st</sup> iteration, 2<sup>nd</sup> iteration and series iteration have been designed and simulated. The simulation process was done using Computer Simulation Technology (CST). The antenna has been fabricated on the Flame Retardant 4 (FR4) laminate microstrip board with dielectric constant of 5.4 and thickness of 1.6 mm. The simulation results show that the Koch curve technique can be used to minimize the length of the arm LPA, but the lower frequency tends to shift to the higher frequency as the number of iterations increases. Thus, a slot is introduced at each of the element of the Log Periodic Antenna in order to avoid the lower designed frequencies from shifting to higher band. A 28.7% reduction of the antenna size has been achieved by using slotted fractal Koch technique at the 2<sup>nd</sup> iteration. All antennas have been tested and measured in terms of reflection coefficient, radiation pattern and its realized gain. The simulation and measurement results have been compared and analyzed. A good agreement was achieved with reflection coefficient,  $S_{11} < -10$  dB for the entire UHF digital television band frequency design, directional radiation patterns with beamwidth of 75°, wide bandwidth up to 95% and an average gain of 6 dBi along the frequency range. This proposed antenna suitable for the intended application.

## ABSTRAK

Jalur Frekuensi Ultra Tinggi (UHF) telah lama digunakan untuk komunikasi suara, data dan video. Untuk penyiaran televisyen terrestrial, jalur frekuensi rendah UHF yang digunakan adalah antara 470 hingga 890 MHz. Kebanyakan antenna konvensional UHF yang telah digunakan untuk menerima isyarat televisyen agak besar saiznya. Salah satu dari kaedah untuk memenuhi permintaan ini adalah dengan menggunakan antenna kompak dan berarah. Geometri yang digunakan dalam reka bentuk antenna ini adalah struktur fraktal lengkung Koch. Salah satu kelebihan menggunakan fraktal dalam reka bentuk antenna adalah untuk mengecilkan saiz antenna. Antena log berkala (LPA) dipilih kerana ia boleh menghasilkan jalur lebar yang lebih luas. Tesis ini menerangkan reka bentuk fraktal Koch dengan gabungan slot untuk antenna frekuensi UHF. Empat rekabentuk yang berbeza seperti iterasi 0, 1, 2 dan sesiri telah direka dan disimulasi. Proses simulasi telah dilakukan dengan menggunakan perisian Teknologi Simulasi Komputer (CST). Rekabentuk yang diperolehi dari simulasi telah difabrikasikan dengan substrat bahan rencat nyala 4 (FR4) dengan pemalar dielektrik 5.4 dan ketebalan 1.6 mm. Hasil simulasi menunjukkan bahawa teknik geometri Koch boleh digunakan untuk mengurangkan panjang elemen LPA, tetapi frekuensi yang lebih rendah cenderung untuk beralih ke frekuensi yang lebih tinggi apabila bilangan iterasi bertambah. Frekuensi yang teranjak telah dipulih dengan memperkenalkan slot di setiap elemen LPA. Dengan menggunakan teknik slot fraktal Koch pada leleran ke-2, didapati saiz antenna berkurang sebanyak 28.7 %. Kesemua antenna telah diuji dan diukur dari segi pekali pantulan, corak radiasi dan gandaan. Keputusan simulasi dan pengukuran telah dibandingkan dan dianalisa. Kesemua antenna menunjukkan keputusan yang baik dengan nilai pemalar pantulan  $S_{11} < -10$  dB pada frekuensi jalur UHF televisyen digital, corak sinaran terarah dengan lebaralur  $75^\circ$ , lebar jalur yang besar iaitu melebihi 95% serta gandaan purata 6 dBi sepanjang julat frekuensi. Antena yang dicadangkan adalah sesuai digunakan untuk aplikasi ini.

## TABLE OF CONTENTS

<b>CHAPTER</b>	<b>TITLE</b>	<b>PAGE</b>
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGEMENTS</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENTS</b>	vii
	<b>LIST OF TABLES</b>	xi
	<b>LIST OF FIGURES</b>	xiii
	<b>LIST OF ABBREVIATION</b>	xix
	<b>LIST OF SYMBOLS</b>	xx
	<b>LIST OF APPENDICES</b>	xxi
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Research Background	1
	1.2 Problem Statement	3
	1.3 Objectives	3
	1.4 Scope of Works	4
	1.5 Thesis Outline	4
<b>2</b>	<b>LITURATURE REVIEW</b>	<b>6</b>
	2.1 Introduction	6
	2.2 History of Log Periodic Dipole Antenna	6
	2.3 Previous Research Work	8
	2.3.1 UHF Antenna Design	8
	2.3.2 Log Periodic Antenna Design	12

2.3.3	Fractal Antenna Design	20
2.3.4	Slotted Antenna Design	24
2.4	Chapter Summary	29
<b>3</b>	<b>RESEARCH METHODOLOGY</b>	<b>30</b>
3.1	Introduction	30
3.2	Methodology of the Project	30
3.3	Design and Simulation	33
3.3.1	Antenna Design Specification	33
3.3.2	The Design of Planar Straight Dipole	34
3.3.3	The Design of Log Periodic Dipole Antenna	35
3.3.4	The Design of Fractal Koch Log Periodic Antenna	36
3.3.5	Method to Create Fractal Koch in CST	37
3.4	Fabrication and Measurement	42
3.5	Chapter Summary	45
<b>4</b>	<b>FRactal Koch Log Periodic Antenna</b>	<b>47</b>
4.1	Introduction	47
4.2	0 <sup>th</sup> Iteration Fractal Koch Log Periodic Antenna	47
4.2.1	Antenna Design and Configuration	47
4.2.2	Simulation, Measurement and Validation	49
4.3	1 <sup>st</sup> Iteration Fractal Koch Log Periodic Antenna	54
4.3.1	Antenna Design and Configuration	54
4.3.2	Variation of Flare Angle of the Fractal Koch Log Periodic Antenna	55
4.3.3	Simulation, Measurement and Validation	57
4.4	2 <sup>nd</sup> Iteration Fractal Koch Log Periodic Antenna	61
4.4.1	Antenna Design and Configuration	61
4.4.2	Simulation, Measurement and Validation	62
4.5	Series Iteration Fractal Koch Log Periodic Antenna	65
4.5.1	Antenna Design and Configuration	66
4.5.2	Simulation, Measurement and Validation	68



4.6	Comparison on the Fractal Koch Log Periodic Antenna Performance	72
4.6.1	Antenna Size	72
4.6.2	Bandwidth	72
4.6.3	Realized Gain	73
4.7	Chapter Summary	74
<b>5</b>	<b>SLOTTED FRACTAL KOCH LOG PERIODIC ANTENNA</b>	<b>75</b>
5.1	Introduction	75
5.2	Slotted 0 <sup>th</sup> Iteration Fractal Koch Log Periodic Antenna Design	75
5.2.1	Variation of Slot Width ( $w_s$ ) and Slot Length ( $l_s$ ) of the Fractal Koch Log Periodic Antenna Design	76
5.2.2	Design Configuration	79
5.2.3	Simulation and Measurement Results	80
5.3	Slotted 1 <sup>st</sup> Iteration Fractal Koch Log Periodic Antenna Design	84
5.3.1	Design Configuration	84
5.3.2	Simulation and Measurement Results	86
5.4	Slotted 2 <sup>nd</sup> Iteration Fractal Koch Log Periodic Antenna Design	90
5.4.1	Design Configuration	90
5.4.2	Simulation and Measurement Results	92
5.5	Slotted Series Iteration Fractal Koch Log Periodic Antenna Design	96
5.5.1	Design Configuration	96
5.5.2	Simulation and Measurement Results	98
5.6	Comparison on the Antenna Performance of the Slotted Fractal Koch Log Periodic Antenna Design	102
5.6.1	Antenna Size	102
5.6.2	Bandwidth	103

5.6.3	Realized Gain	104
5.7	Chapter Summary	105
<b>6</b>	<b>CONCLUSION AND FUTURE WORK</b>	<b>106</b>
6.1	Overall Conclusion	106
6.2	Key Contributions	107
6.3	Future Work	107
	<b>REFERENCES</b>	<b>109</b>
	Appendices A-B	115-116

## LIST OF TABLES

<b>TABLE NO.</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	Previous research on UHF antenna design	11
2.2	Previous research on log periodic antenna design	18
2.3	Previous research on fractal antenna design	23
2.4	Previous research on slotted antenna design	28
3.1	Design specification of Fractal Koch Log Periodic antenna	33
3.2	The equation used to generate the Koch fractal	38
4.1	Dimension of 0 <sup>th</sup> Iteration Fractal Koch Log Periodic Antenna	48
4.2	Realized gain of the 0 <sup>th</sup> iteration fractal Koch log periodic antenna	53
4.3	Dimension of 1 <sup>st</sup> Iteration Fractal Koch Log Periodic Antenna	55
4.4	Realized gain of the 1 <sup>st</sup> iteration fractal Koch log periodic antenna	60
4.5	Dimension of 2 <sup>nd</sup> Iteration Fractal Koch Log Periodic Antenna	62
4.6	Realized gain of the 2 <sup>nd</sup> iteration fractal Koch log periodic antenna	66
4.7	Dimension of Series Iteration Fractal Koch Log Periodic Antenna	67
4.8	Realized gain of the series iteration fractal Koch log periodic antenna	71
4.9	Percentage of the size reduction on the fractal Koch log periodic antenna design	72
4.10	Summary of measured results for all antenna type of antenna FKLPA configurations	73
4.11	Comparison of the simulated and measured realized gain for the FKLPA	73
5.1	Dimension of the proposed antenna on slotted 0 <sup>th</sup> iteration Fractal Koch antenna	80

5.2	Realized gain of the sotted 0 <sup>th</sup> iteration fractal Koch log periodic antenna	84
5.3	Dimension of the proposed antenna on slotted 1 <sup>st</sup> iteration Fractal Koch antenna	85
5.4	Realized gain of the slotted 1 <sup>st</sup> iteration fractal Koch log periodic antenna	90
5.5	Dimension of the proposed antenna on slotted 2 <sup>nd</sup> iteration Fractal Koch antenna	91
5.6	Realized gain of the slotted 2 <sup>nd</sup> iteration fractal Koch log periodic antenna	96
5.7	Dimension of the proposed antenna on slotted series iteration Fractal Koch antenna	97
5.8	Realized gain of the slotted series iteration fractal Koch log periodic antenna	102
5.9	Percentage of the size reduction on the slotted fractal Koch log periodic antenna design	103
5.10	Summary of measured results for all antenna type of antenna FKLPA configurations	103
5.11	Comparison of the simulated and measured realized gain for the slotted FKLPA	104

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Fractal classification	7
2.2	Proposed antenna geometry [1]	8
2.3	$S_{11}$ of the proposed antenna [1]	9
2.4	Fabricated antenna; (a) Front view, (b) Back view [2]	9
2.5	Simulated and measured VSWR and gain of the proposed antenna [2]	9
2.6	Proposed antenna [3]	10
2.7	$S_{11}$ of the proposed antenna [3]	10
2.8	Fabricated antenna [4]	11
2.9	$S_{11}$ of the compact dipole antenna [4]	11
2.10	LPDA with cylindrical-hat cover [5]	13
2.11	The $S_{11}$ and gain of the proposed antenna[5]	13
2.12	The dimension and fabricated bow-tie LPDA [6]	14
2.13	Radiation pattern of the proposed design [6]	14
2.14	Geometry of the proposed log-periodic dumb-bell slot antenna array [7]	14
2.15	Measured radiation pattern; (a) 1.8 GHz, (b) 5.4 GHz [7]	15
2.16	Arrangement of the PLPDA above the ground plane; (a) Overview, (b) Front view, (c) Side view [8]	15
2.17	Gain of the PLPDA [8]	16
2.18	Antenna layout; (a) top layer, (b) coplanar waveguide transverse section at the input port, (c) coplanar waveguide view at the via-hole section, (d) top view of the coplanar waveguide [9]	16
2.19	The proposed log periodic microstrip antenna [10]	17
2.20	Fabricated sub sectional tapered fed printed LPDA [11]	17
2.21	(a) Fabricated fractal bow-tie design, (b) antenna dimension [12]	20

2.22	Geometry of the proposed cross-element LPFKA [13]	21
2.23	Proposed antenna design; (a) fabricated antenna, (b) antenna dimension [14]	21
2.24	2 <sup>nd</sup> iteration Koch antenna [15]	22
2.25	Fabricated flower-shaped antenna; (a) front, (b) back [16]	22
2.26	Geometry of the CPW-fed log-periodic slot antennas (a) without band-notched, (b) with band-notched [17]	25
2.27	Measured input return losses of the prototype antennas [17]	25
2.28	Fabricated compact Koch fractal patch antenna;(a) without slot, (b) with slot (stage 2), (c) with slot (stage 3) [18]	26
2.29	Fabricated slotted-fractal Koch log-periodic antenna [19]	26
2.30	Geometry of the proposed antenna (a) front view and (b) side view [20]	27
2.31	Return loss of the proposed antenna [20]	27
3.1	Flow chart of the log periodic fractal Koch antenna process	31
3.2	Flow Chart of the slotted log periodic fractal Koch antenna process	32
3.3	Illustration of dipole antenna design	34
3.4	Carrel's table [21]	35
3.5	Segments that form the basis of the Koch fractal antenna	37
3.6	0 <sup>th</sup> iteration log periodic antenna set up	37
3.7	The steps set-up for the 1 <sup>st</sup> iteration of fractal Koch	38
3.8	2 <sup>nd</sup> iteration of fractal Koch set-up	39
3.9	Steps to design 2 <sup>nd</sup> iteration fractal Koch	40
3.10	Series iteration steps of the fractal Koch	40
3.11	Slot implementation of the fractal Koch antenna design; (a) 0 <sup>th</sup> iteration, (b) 1 <sup>st</sup> iteration, (c) 2 <sup>nd</sup> iteration and (d) series iteration	42
3.12	Antenna fabrication flowchart	43
3.13	Rohde & Schwartz ZVL VNA	44
3.14	Radiation pattern and gain measurement layout	45
3.15	Radiation pattern measurement in the anechoic chamber	45
4.1	Log Periodic Dipole Antenna design. (a) front view (b) side view	48
4.2	Fabricated 0 <sup>th</sup> iteration fractal Koch log periodic antenna	49

4.3	Measured and simulated reflection coefficient of 0 <sup>th</sup> iteration fractal Koch log periodic antenna	50
4.4	3D radiation pattern of the 0 <sup>th</sup> iteration FKLPA.	50
4.5	Efficiency and gain of the 0 <sup>th</sup> iteration log periodic fractal Koch antenna	51
4.6	Current distribution of 0 <sup>th</sup> iteration FKLPA; (a) 0.5 GHz, (b) 0.7 GHz and (c) 0.9 GHz	52
4.7	Simulated and measured radiation patterns for 0 <sup>th</sup> iteration fractal Koch log periodic antenna at; 0.5 GHz (a) E-plane (b) H-plane, 0.7 GHz (c) E-plane (d) H-plane, 0.9 GHz (e) E-plane (f) H-plane	53
4.8	1 <sup>st</sup> iteration Fractal Koch Log Periodic Antenna design. (a) front view (b) side view	54
4.9	Fabricated 1 <sup>st</sup> iteration fractal Koch log periodic antenna	55
4.10	The flare angle of the fractal Koch antenna design; (a) 30°, (b) 45°, (c) 60°, (d) 75°	56
4.11	Performance of S <sub>11</sub> with different flare angle	57
4.12	Measured and simulated reflection coefficient of 1 <sup>st</sup> iteration FKLPA	57
4.13	Efficiency and gain of the 1 <sup>st</sup> iteration log periodic fractal Koch antenna	58
4.14	3D radiation pattern of the 1 <sup>st</sup> iteration FKLPA.	58
4.15	Current distribution of 0 <sup>th</sup> iteration FKLPA; (a) 0.5 GHz, (b) 0.7 GHz and (c) 0.9 GHz	59
4.16	Simulated and measured radiation patterns for 1 <sup>st</sup> iteration fractal Koch log periodic antenna at; 0.5 GHz (a) E-plane (b) H-plane, 0.7 GHz (c) E-plane (d) H-plane, 0.9 GHz (e) E-plane (f) H-plane	60
4.17	2 <sup>nd</sup> iteration Fractal Koch Log Periodic Antenna design. (a) front view (b) side view	61
4.18	Fabricated 2 <sup>nd</sup> iteration fractal Koch log periodic antenna	62
4.19	Measured and simulated reflection coefficient of 2 <sup>nd</sup> iteration fractal Koch log periodic antenna	63
4.20	Efficiency and gain of the 2 <sup>nd</sup> iteration log periodic fractal Koch antenna	63
4.21	3D radiation pattern of the 2 <sup>nd</sup> iteration FKLPA.	64
4.22	Current distribution of 2 <sup>nd</sup> iteration FKLPA; (a) 0.5 GHz, (b) 0.7 GHz and (c) 0.9 GHz	64

4.23	Simulated and measured radiation patterns for 2 <sup>nd</sup> iteration fractal Koch log periodic antenna at; 0.5 GHz (a) <i>E</i> -plane (b) <i>H</i> -plane, 0.7 GHz (c) <i>E</i> -plane (d) <i>H</i> -plane, 0.9 GHz (e) <i>E</i> -plane (f) <i>H</i> -plane	65
4.24	Series iteration Fractal Koch Log Periodic Antenna design. (a) front view (b) side view	67
4.25	Fabricated series iteration fractal Koch log periodic antenna	68
4.26	Measured and simulated reflection coefficient of series iteration fractal Koch log periodic antenna	68
4.27	Efficiency and gain of the series iteration log periodic fractal Koch antenna	69
4.28	3D radiation pattern of the series iteration FKLPA	69
4.29	Current distribution of series iteration FKLPA;(a) 0.5 GHz, (b) 0.7 GHz and (c) 0.9 GHz	70
4.30	Simulated and measured radiation patterns for series iteration fractal Koch log periodic antenna at; 0.5 GHz (a) <i>E</i> -plane (b) <i>H</i> -plane, 0.7 GHz (c) <i>E</i> -plane (d) <i>H</i> -plane, 0.9 GHz (e) <i>E</i> -plane (f) <i>H</i> -plane	71
5.1	Dimension of the varying width slot, $w_n$	76
5.2	Simulated performance of $S_{11}$ with varying width slot, $w_s$	77
5.3	Dimension of the varying length slot, $l_n$	78
5.4	Simulated performance of $S_{11}$ with varying length slot, $l_s$	78
5.5	Geometry of the slotted 0 <sup>th</sup> iteration Fractal Koch antenna. (a) front view (b) side view, (c) slotted dimension	79
5.6	Fabricated slotted 0 <sup>th</sup> iteration fractal Koch log periodic antenna	80
5.7	Measured and simulated reflection coefficient of slotted 0 <sup>th</sup> iteration fractal Koch log periodic antenna	81
5.8	Efficiency and realized gain of the slotted 0 <sup>th</sup> iteration FKLPA	81
5.9	3D radiation pattern of the slotted 0 <sup>th</sup> iteration FKLPA.	82
5.10	Current distribution of slotted 0 <sup>th</sup> iteration FKLPA; (a) 0.45 GHz, (b) 0.7 GHz and (c) 0.9 GHz	82
5.11	Simulated and measured radiation patterns for slotted 0 <sup>th</sup> iteration fractal Koch log periodic antenna at; 0.5 GHz (a) <i>E</i> -plane (b) <i>H</i> -plane, 0.7 GHz (c) <i>E</i> -plane (d) <i>H</i> -plane, 0.9 GHz (e) <i>E</i> -plane (f) <i>H</i> -plane	83
5.12	Geometry of the slotted 1 <sup>st</sup> iteration Fractal Koch antenna. (a) front view (b) side view, (c) slotted dimension	85



5.13	Fabricated slotted 1 <sup>st</sup> iteration fractal Koch log periodic antenna	86
5.14	Measured and simulated reflection coefficient of slotted 1 <sup>st</sup> iteration fractal Koch log periodic antenna	87
5.15	Efficiency and realized gain of the slotted 1 <sup>st</sup> iteration log periodic fractal Koch antenna	87
5.16	3D radiation pattern of the slotted 1 <sup>st</sup> iteration FKLPA.	88
5.17	Current distribution of slotted 1 <sup>st</sup> iteration FKLPA; (a) 0.45 GHz, (b) 0.7 GHz and (c) 0.9 GHz	88
5.18	Simulated and measured radiation patterns for slotted 1 <sup>st</sup> iteration fractal Koch log periodic antenna at; 0.5 GHz (a) <i>E</i> -plane (b) <i>H</i> -plane, 0.7 GHz (c) <i>E</i> -plane d) <i>H</i> -plane, 0.9 GHz (e) <i>E</i> -plane (f) <i>H</i> -plane	89
5.19	Geometry of the slotted 2 <sup>nd</sup> iteration Fractal Koch antenna. (a) front view (b) side view, (c) slotted dimension	91
5.20	Fabricated slotted 2 <sup>nd</sup> iteration fractal Koch log periodic antenna	92
5.21	Measured and simulated reflection coefficient of slotted 2 <sup>nd</sup> iteration fractal Koch log periodic antenna	93
5.22	Efficiency and realized gain of the slotted 2 <sup>nd</sup> iteration log periodic fractal Koch antenna	93
5.23	3D radiation pattern of the slotted 2 <sup>nd</sup> iteration FKLPA.	94
5.24	Current distribution of slotted 2 <sup>nd</sup> series iteration FKLPA; (a) 0.45 GHz, (b) 0.7 GHz and (c) 0.9 GHz	94
5.25	Simulated and measured radiation patterns for slotted 2 <sup>nd</sup> iteration fractal Koch log periodic antenna at; 0.5 GHz (a) <i>E</i> -plane (b) <i>H</i> -plane, 0.7 GHz (c) <i>E</i> -plane d) <i>H</i> -plane, 0.9 GHz (e) <i>E</i> -plane (f) <i>H</i> -plane	95
5.26	Geometry of the slotted series iteration Fractal Koch antenna. (a) front view (b) side view, (c) slotted dimension	97
5.27	Fabricated slotted series iteration fractal Koch log periodic antenna	98
5.28	Measured and simulated reflection coefficient of slotted series iteration fractal Koch log periodic antenna	99
5.29	Efficiency and realized gain of the slotted series iteration log periodic fractal Koch antenna	99
5.30	3D radiation pattern of the slotted series iteration FKLPA.	100
5.31	Current distribution of slotted series iteration FKLPA; (a) 0.45 GHz, (b) 0.7 GHz and (c) 0.9 GHz	100

5.32	Simulated and measured radiation patterns for slotted series iteration fractal Koch log periodic antenna at; 0.5 GHz (a) E-plane (b) H-plane, 0.7 GHz (c) E-plane d) H-plane, 0.9 GHz (e) E-plane (f) H-plane	101
------	---	-----

**LIST OF ABBREVIATIONS**

BW	-	Bandwidth
CPW	-	Co-Planar Waveguide
CST	-	Computer Simulation Technology
dB	-	Decibel
dB <sub>i</sub>	-	Decibel Isotropic
DCS	-	Digital Code Squelch
DTV	-	Digital Terrestrial Video
FR-4	-	Flame Retardant-4
FKLPA	-	Fractal Koch Log Periodic Antenna
GSM	-	Global System Mobile
LPA	-	Log Periodic Antenna
LPDA	-	Log Periodic Dipole Antenna
ISM	-	Industrial Sciences Medical
PCS	-	Personal Communications Service
RF	-	Radio Frequency
RFID	-	Radio Frequency Identification
SMA	-	Sub Miniature Version A
TV	-	Television
TVWS	-	Television White Spectrum
UHF	-	Ultra High Frequency
UWB	-	Ultra Wide Band
VSWR	-	Voltage Standing Wave Ratio
WiMAX	-	Worldwide Interoperability for Microwave Access
WLAN	-	Wireless Local Area Network

**LIST OF SYMBOLS**

$\lambda$	-	Wavelength
$c$	-	Speed of light
$\epsilon_r$	-	permittivity
$\lambda_0$	-	Free Space wavelength
$\lambda_c$	-	wavelength at center frequency
$\lambda_g$	-	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

**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	List of Publications	115
B	FR-4 Datasheet	116

## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Research Background**

Antenna design has grown to be one of the most active fields in the wireless communication [22]. In the early years, whilst radio frequency became determined, simple antenna design was the main tool used to transmit electrical energy or radio wave via the air in all paths [23]. The wireless technology has improved swiftly not only simply for commercial use, but also for navigation [24], [25].

In modern-day telecommunication systems, the requirement for antennas with wider bandwidth [26] and smaller dimensions [27] than conventional ones are desired. This has initiated studies of the antenna in numerous directions, one among those via the usage of fractal shaped antenna elements. In current years [28], numerous fractal geometries [29] have been brought for antenna applications with varying degrees of achievement in enhancing antenna characteristics [30]. Some of these geometries were especially beneficial in decreasing the dimensions of the antenna [31], [32] whilst other designs intended to be incorporating multi-band [33], [34], [35] behaviors. Several researches were made in designing the fractal shape properties for the antennas.

The deployment of digital terrestrial broadcasting (DTV) has stretched all over the world and Malaysia has announced their involvement since 2005 [36]. The Malaysian conventional analog TV will be replaced with DTV by 2018 [36]. DTV standard allows contents provider to transmit programs in high definition video and six channel-surround audios. The bandwidth allocation of DTV is rather extensive and

imposes the need for a broadband [9] reception antenna. In order to support the DTV front end device, a compact yet broadband [37] reception antenna which covers from 460 MHz to 870 MHz [36] [38] will be designed for the DTV receiver.

Many studies have been carried on frequency independent antennas since the late 1950s and experiments with several geometries such as spiral, biconical and fractal have been developed. Log periodic dipole array (LPDA) was firstly introduced by DuHamel and Isbell in 1957 [39] as one of the frequency independent antenna. Printed log-periodic dipole antenna has been given a great deal of interest and is becoming an attractive candidate in this area due to its merits such as a light weight, low cost, and easy to integrate [40]. Directional antenna has an advantage of higher gain [41] than omni-directional antenna because it can radiate in a specific direction. Besides, log-periodic dipole array (LPDA) antennas are extensively used in different applications due to their broadband characteristics [42], high gain [43], and low cross-polarization ratio [44]. This type of antenna was recommended at the beginning of the 1960s. In [45], Carrel demonstrated on how to design an LPDA per specifications in terms of bandwidth and directivity [46], [47].

Several antenna configurations which are totally based on fractal geometries [48], [49] had been pronounced in recent years. These were low profile antennas with slight benefits [50] and can be made operative at many frequency bands [51] and as a result, they become multifunctional [52]. In this study, the antennas with a reduced size had been obtained by using Koch curve fractal geometry with a combination of slot curve [53]. Furthermore, design equations for the antennas are acquired in phrases of its geometrical parameters such as fractal size. Antenna properties have also been linked to the fractal dimension of the geometry. In an effort to lay the principles for the understanding of the behavior of such antennas, the nature of fractal geometries is explained first, before providing the reputation of literature on antennas using such geometries.

## 1.2 Problem Statement

As the demands for UHF communication system have increased, a low-profile system has been drawn and brought much interest to researchers. The size of the antenna is important for making it to be a low-profile communication system. Hence, numerous methods such as using dielectric substrate, multiple layers and by optimizing the shape of the antennas have been proposed and applied to the microstrip and planar antennas.

Most televisions, whether analog or digital, need antennas to receive signals. Generally, former antenna used for television broadcasting is bulky in size and is usually placed outdoor. Therefore, this research aims to design and develop a compact log periodic dipole antenna for UHF digital TV application. The proposed antenna design will be compact in size and can be incorporated with the digital box. A new approach inspired by the fractal geometry with slot will be employed in order to design the compact antenna. Furthermore, it will provide a stable radiation pattern and gain throughout the DTV band.

## 1.3 Objectives

The primary objectives of this project are as follows:

- i. To design and develop a new technique of size reduction in a log periodic dipole antenna for UHF/DVB TV application.
- ii. To reduce the size and improve the shifting frequency of the antenna using fractal Koch technique and slotted insertion for first, second and series iterations LPA.



- iii. To compare and analyze the antenna performance between simulation and measurement results in terms of reflection coefficient, radiation pattern, gain and current distributions of the antenna.

## **1.4 Scope of Works**

The scope of this research begins with the understanding the concept and characteristics of the log periodic dipole antenna (LPDA), fractal geometries and slot techniques. The literature and the advantages of fractal antenna and slot techniques have been studied.

Four different iteration have been designed which were on 0<sup>th</sup> iteration, 1<sup>st</sup> iteration, 2<sup>nd</sup> iteration and series iteration fractal Koch log periodic antenna. Then follow by slotted 0<sup>th</sup> iteration, slotted 1<sup>st</sup> iteration, slotted 2<sup>nd</sup> iteration and slotted series iteration which improves more on the bandwidth performance.

The simulation process has been carried out using Computer Simulation Technology (CST) software to analyse the performance of the antennas. After the optimal design is confirmed, the designed structures are fabricated on Flame Retardant 4 (FR4) board using wet etching technique.

The antenna performances were then investigated and compared in terms of reflection coefficient, gain and radiation pattern. Lastly, all data were compiled for thesis documentation.

## **1.5 Thesis Outline**

This thesis is organized into six chapters whereas in each chapter will describe the several aspects and design of the work. The outline of the study in six chapters is organized as follows:

A brief introduction to the UHF antenna, the principle motivation, scope of research and objectives are presented in Chapter 1.

In chapter two, the background of the log periodic antenna, UHF fractal antenna and microstrip slot antenna are discussed. Previous works on UHF antenna design which include log periodic antenna, fractal Koch antenna and slot technique are reported and summarized.

As for chapter three, it discusses the methodology of the research. The flow of work is presented, where two main work stages are described. The first stage of work which is the design and simulation are explained in detail. For the second stage of work, the fabrication and measurement of the antennas are thoroughly discussed.

Chapter four provides detailed discussions of the basic log periodic fractal Koch antenna. It starts with an explanation of the design for 0<sup>th</sup>, 1<sup>st</sup>, 2<sup>nd</sup> and series iteration. Analysis of the suitable flare angle on the radiating element for compactness is also discussed in this chapter as a contribution to the compact design using fractal Koch geometry. The critical part of this design is to know how the parameter of the antenna affects the bandwidth of the antenna. A detailed examination of the different iteration of fractal Koch that influences the performance has been studied.

Chapter five explains the bandwidth enhancement performance of the previous antenna design with the slotted design on each of the elements. Slotted ring at the element is implemented for compactness. The size of the radiating element becomes smaller compared to its fundamental lambda.

Chapter six concludes the overall research work and discusses some potential future work. It highlights the significance of this study in this field and how it can be developed further in the future.

## REFERENCES

- [1] C. Yang, H. Kim, and C. Jung, "Compact broad dual-band antenna using inverted-L and loop for DVB-H applications," *Electron. Lett.*, vol. 46, no. 21, p. 1418, 2010.
- [2] J. Lee, J. Yeo, and Y.-K. Cho, "Broadband Compact Quasi-Yagi Antenna for Indoor Digital TV," *Microw. Opt. Technol. Lett.*, vol. 55, pp. 2781–2784, 2013.
- [3] M. H. Jamaluddin, T. A. Rahman, H. Mohamad, N. Ramli, and M. T. Islam, "Wideband Planar U-shaped Monopole Antenna with Meandering Technique for TV White Space Application," *Radioengineering*, vol. 22, pp. 708–713, 2013.
- [4] A. R. Raslan and A. M. E. Safwat, "N-internal port design for wide band electrically small antennas with application for UHF band," *IEEE Trans. Antennas Propag.*, vol. 61, pp. 4431–4437, 2013.
- [5] H. Jardon-Aguilar, J. A. Tirado-Mandez, R. Flores-Leal, and R. Linares-Miranda, "Reduced Log-Periodic Dipole Antenna Using a Cylindrical-Hat Cover," *IET Microwaves, Antennas Propag.*, vol. 5, pp. 1697–1702, 2011.
- [6] J. Yeo and J. Lee, "Planar Log-Periodic Bow-Tie Dipole Array Antenna with Reduced Size and Enhanced Front-Back Ratio," *Microw. Opt. Technol. Lett.*, vol. 57, pp. 1435–1441, 2012.
- [7] S. H. Kim, J. H. Choi, J. W. Baik, and Y. S. Kim, "CPW-Fed Log Periodic Dumb-Bell Slot Antenna Array," *Electron. Lett.*, vol. 42, pp. 8–9, 2006.
- [8] A. Chauloux, F. Colombel, M. Himdi, J. Lasserre, and P. Pouliguen, "Low-Return-Loss Printed Log-Periodic Dipole Antenna," *IEEE Antennas Wirel. Propag. Lett.*, vol. 13, pp. 503–506, 2014.
- [9] G. A. Casula, P. Maxia, G. Montisci, G. Mazzarella, and F. Gaudiomonte, "A Printed LPDA Fed By A Coplanar Waveguide for Broadband Applications," *IEEE Antennas Wirel. Propag. Lett.*, vol. 12, pp. 1232–1235, 2013.
- [10] Q. Wu, R. Jin, and J. Geng, "A Single-Layer Ultrawideband Microstrip Antenna," *IEEE Trans. Antennas Propag.*, vol. 58, pp. 211–214, 2010.
- [11] G. Bozdag and A. Kustepeli, "Subsectional Tapered Fed Printed LPDA Antenna With a Feeding Point Patch," *IEEE Antennas Wirel. Propag. Lett.*, vol. 15, pp. 437–440, 2016.
- [12] D. Li and J. F. Mao, "A Koch-Like Sided Fractal Bow-Tie Dipole Antenna," *IEEE Trans. Antennas Propag.*, vol. 60, pp. 2242–2251, 2012.
- [13] G. Liu, L. Xu, and Z. Wu, "Miniaturised Wideband Circularly-polarised Log-periodic Koch Fractal Antenna," *Electron. Lett.*, vol. 49, pp. 1315–1316, 2013.
- [14] D. Elsheakh and E. Abdallah, "Compact Printed Log-periodic Dipole Antenna for Terrestrial Digital Video Broadcast Application," *Microw. Opt. Technol. Lett.*, vol. 56, pp. 1002–1007, 2014.
- [15] M. K. A. Rahim, M. N. A. Karim, F. Zubir, O. Ayop, and N. A. Samsuri, "Second Iteration Fractal Koch Planar Log Periodic Antenna Design," *Microw. Opt. Technol. Lett.*, vol. 53, pp. 1869–1875, 2011.

- [16] S. R. Patre and S. P. Singh, "Study of Microstrip Line-fed Flower-shaped Patch Antenna Providing Enhanced Bandwidth and Radiation Efficiency," *Microw. Opt. Technol. Lett.*, vol. 58, pp. 2041–2046, 2016.
- [17] S. Chen, P. Wang, P. Hsu, S. Member, and A. Abstract, "Uniplanar Log-Periodic Slot Antenna Fed by a CPW for UWB Applications," *IEEE Antennas Wirel. Propag. Lett.*, vol. 5, pp. 256–259, 2006.
- [18] S. E. Muthumani, R. Vallikannu, and H. R. Patnam, "Compact slot loaded Koch fractal microstrip patch antenna," in *2013 IEEE Applied Electromagnetics Conference, AEMC 2013*, 2014, pp. 2–3.
- [19] N. A. A. Rahman, M. F. Jamlos, H. Lago, M. A. Jamlos, P. J. Soh, and A. A. Al-Hadi, "Reduced Size of Slotted-Fractal Koch Log-Periodic Antenna for 802.11af TVWS Application," *Microw. Opt. Technol. Lett.*, vol. 57, pp. 2781–2784, 2015.
- [20] D. D. Krishna, M. Gopikrishna, C. K. Aanandan, P. Mohanan, and K. Vasudevan, "Compact Wideband Koch Fractal Printed Slot Antenna," *IET Microwaves, Antennas Propag.*, vol. 3, no. October 2008, p. 782, 2009.
- [21] C. A. Balanis, *Antenna Theory Analysis and Design Third Edition*. 2005.
- [22] L. X. Truong and N. C. Tien, "Design a Log Periodic Fractal Koch Microstrip Antenna for S Band and C Band Applications," in *International Conference on Advanced Technologies for Communications (ATC)*, 2015, vol. 7, pp. 556–560.
- [23] G. Falciasecca, "Marconi's early experiments in wireless telegraphy, 1895," *IEEE Antennas Propag. Mag.*, vol. 52, pp. 220–221, 2010.
- [24] J. B. L. Rao, R. Mital, D. P. Patel, M. G. Parent, and G. Tavik, "Low-Cost Multibeam Phased Array Antenna for Communications with GEO Satellites," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 28, pp. 32–37, 2013.
- [25] M. Jusoh, M. Jamlos, M. R. Kamarudin, and F. Malek, "Progress In Electromagnetics Research B, Vol. 36, 357–371, 2012," *Prog. Electromagn. Res. B*, vol. 36, pp. 357–371, 2012.
- [26] L. Zhou, Y. Jiao, C. Zhang, Y. Qi, and T. Ni, "Wide Bandwidth Horizontally-Polarized Omnidirectional Antennas for Indoor Distributed Antenna System Applications," *Prog. Electromagn. Res. C*, vol. 61, pp. 47–54, 2016.
- [27] C. P. Baliarda, J. Romeu, and A. Cardama, "The Koch Monopole: A Small Fractal Antenna," *IEEE Trans. Antennas Propag.*, vol. 48, pp. 1773–1781, 2000.
- [28] W. C. Weng and C. L. Hung, "An H-fractal antenna for multiband applications," *IEEE Antennas Wirel. Propag. Lett.*, vol. 13, pp. 1705–1708, 2014.
- [29] S. Singhal and A. K. Singh, "CPW-fed hexagonal Sierpinski super wideband fractal antenna," *IET Microwaves, Antennas Propag.*, vol. 10, pp. 1701–1707, 2016.
- [30] Y. B. Thakare and Rajkumar, "Design of Fractal Patch Antenna for Size and Radar Cross-Section Reduction," *IET Microwaves, Antennas Propag.*, vol. 4, pp. 175–181, 2010.
- [31] R. Sammeta and D. S. Filipovic, "Reduced Size Planar Dual-Polarized Log-Periodic Antenna for Bidirectional High Power Transmit and Receive Applications," *IEEE Trans. Antennas Propag.*, vol. 62, pp. 5453–5461, 2014.
- [32] H. Oraizi and S. Hedayati, "Miniaturized UWB Monopole Microstrip Antenna Design by the Combination of Giuseppe Peano and Sierpinski Carpet Fractals," *IEEE Antennas Wirel. Propag. Lett.*, vol. 10, pp. 67–70, 2011.
- [33] O. M. Khan, Z. U. Islam, I. Rashid, F. I. Bhatti, and Q. U. Islam, "Novel Miniaturized Koch Pentagonal Fractal Antenna for Multiband Wireless

- Applications,” *Prog. Electromagn. Res.*, vol. 141, pp. 693–710, 2013.
- [34] M. Ihamji, E. Abdelmounim, H. Bennis, M. Hefnawi, and M. Latrach, “Design of Compact Tri-Band Fractal Antenna for RFID Readers,” *Int. J. Electr. Comput. Eng.*, vol. 7, p. 2036, 2017.
- [35] S. Singh, P. K. Singhal, and V. V. Thakare, “Design and Analysis of Tripple Band Koch Fractal Yagi Uda Antenna,” *Int. J. Electr. Comput. Eng.*, vol. 3, pp. 456–460, 2013.
- [36] Malaysian Communications and Multimedia Commission (MCMC), “Requirements for Digital Terrestrial Television (including digital terrestrial sound) (DTT) Service Operating In The Frequency Bands 174 MHz to 230 MHz and 470 MHz to 742 MHz,” 2007.
- [37] R. Wang and J. Yang, “A New Compact Antenna for Digital Television Reception Based on the Eleven Antenna,” *Microw. Opt. Technol. Lett.*, vol. 53, pp. 824–827, 2011.
- [38] W. Webb, “On Using White Space Spectrum,” *IEEE Communications Magazine*, pp. 145–151, 2012.
- [39] R. H. DuHamel and D. E. Isbell, “Broadband Logarithmically Periodic Antenna Structure,” *1958 IRE Int. Conv. Rec.*, pp. 119–128, 1957.
- [40] A. Hakimi and M. Movahhedi, “UWB Active Integrated Antenna Design and Simulation,” in *2014 First International Conference on Systems Informatics, Modelling and Simulation*, 2014, pp. 168–172.
- [41] M. Van Rooyen, J. W. Odendaal, S. Member, J. Joubert, and S. Member, “High-Gain Directional Antenna for WLAN and WiMAX Applications,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 16, pp. 286–289, 2017.
- [42] J. O. Yang, S. Bo, J. Zhang, and F. Yang, “A Low-Profile Unidirectional Cavity-Backed Log-Periodic Slot Antenna,” *Prog. Electromagn. Res.*, vol. 119, pp. 423–433, 2011.
- [43] S. R. Agrawal, K. A. Lele, and A. A. Deshmukh, “Review on Printed Log Periodic and Yagi MSA,” *Int. J. Comput. Appl.*, vol. 126, pp. 38–44, 2015.
- [44] S. M. Hashemi, V. Nayyeri, M. Soleimani, and A. Mallahzadeh, “Designing a Compact-Optimized Planar Dipole Array Antenna,” *IEEE Antennas Propag. Lett.*, vol. 10, pp. 243–246, 2011.
- [45] R. Carrel, “The Design of Log Periodic Dipole Antennas,” *1958 IRE Int. Conv. Rec.*, pp. 61–75, 1961.
- [46] S. S. Pawar, M. Shandilya, and V. Chaurasia, “Parametric evaluation of microstrip log periodic dipole array antenna using transmission line equivalent circuit,” *Eng. Sci. Technol. an Int. J.*, vol. 20, no. 4, pp. 1260–1274, 2017.
- [47] R. S. Pavlov, A. G. Curto, and N. F. Van Hulst, “Log-periodic optical antennas with broadband directivity,” *Opt. Commun.*, vol. 285, no. 16, pp. 3334–3340, 2012.
- [48] Y. Wang, Z. Wang, and J. Li, “UHF Moore Fractal Antennas for Online GIS PD Detection,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 16, pp. 852–855, 2017.
- [49] F. Wang, F. Bin, Q. Sun, J. Fan, and H. Ye, “A Compact UHF Antenna Based on Complementary Fractal Technique,” *IEEE Access*, vol. 5, pp. 21118–21125, 2017.
- [50] S. R. Emadian, C. Ghobadi, J. Nourinia, M. H. Mirmozafari, and J. Pourahmadazar, “Bandwidth Enhancement of CPW-Fed Circle-Like Slot Antenna With Dual Band-Notched Characteristic,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 11, pp. 543–546, 2012.

- [51] A. Azari, "A New Super Wideband Fractal Microstrip Antenna," *IEEE Trans. Antennas Propag.*, vol. 59, pp. 1724–1727, 2011.
- [52] Y. K. Choukiker and S. K. Behera, "Wideband Frequency Reconfigurable Koch Snowflake Fractal Antenna," *IET Microwaves, Antennas Propag.*, vol. 11, pp. 203–208, 2017.
- [53] Y. Sung, "Bandwidth Enhancement of a Microstrip Line-Fed Printed Wide-Slot Antenna With a Parasitic Center Patch," *IEEE Trans. Antennas Propag.*, vol. 60, pp. 1712–1716, 2012.
- [54] T. O. L. Y. Alxtevxas, "Log Periodic Dipole Arrays \*," *IRE Trans. ANTENNAS Propag.*, pp. 260–267, 1960.
- [55] R. DuHamel and F. Ore, "Logarithmically Periodic Antenna Designs," *IRE Int. Conv. Rec.*, vol. 6, 1958.
- [56] M. N. A. Karim, M. K. A. Rahim, H. A. Majid, O. Ayop, M. Abu, and F. Zubir, "Log Periodic Fractal Koch Antenna for UHF Band Applications," *Prog. Electromagn. Res.*, vol. 100, pp. 201–218, 2010.
- [57] A. Gheethan and D. Anagnostou, "The Design and Optimization of Planar LPDAs," *PIERS Online*, vol. 4, pp. 811–814, 2008.
- [58] T. Tauqeer, M. U. Afzal, H. T. Butt, M. Islam, M. A. Tarar, and B. A. Khawaja, "Analytical Comparison Of Wideband Microstrip Log-Periodic and Coplanar Waveguide Antennas," *Microw. Opt. Technol. Lett.*, vol. 56, no. 8, pp. 79–81, 2014.
- [59] L. Gurel and O. Ergul, "Design and Simulation of Circular Arrays of Trapezoidal-Tooth Log-Periodic Antennas Via Genetic Optimization," *Prog. Electromagn. Res.*, vol. 85, pp. 243–260, 2008.
- [60] J. I. Kim and A. Safaai-Jazi, "Log-Periodic Loop Antennas with High Gain and Linear Polarization," *Microw. Opt. Technol. Lett.*, vol. 27, pp. 66–68, 2000.
- [61] R. L. Carrel, "Analysis and Design of the Log-Periodic Dipole Antenna," *Antenna Lab. Univ. Illinois, Urbana, Illinois USA*, vol. Technical, 1961.
- [62] H. Oraizi, A. Amini, and M. K. Mehr, "Design of Miniaturised UWB Log-Periodic End-Fire Antenna Using Several Fractals With WLAN Band-Rejection," *IET Microwaves, Antennas Propag.*, vol. 11, pp. 193–202, 2017.
- [63] J. Hettenhausen, A. Lewis, D. Thiel, and M. Shahpari, "An investigation of the performance limits of small, planar antennas using optimisation," *Procedia Comput. Sci.*, vol. 51, pp. 2307–2316, 2015.
- [64] Y. Lee and J. Sun, "Compact Printed Slot Antennas for Wireless Dual and Multi-Band Operations," *Prog. Electromagn. Res.*, vol. 88, pp. 289–305, 2008.
- [65] A. M. Abbosh and S. Member, "Miniaturized Microstrip-Fed Tapered-Slot Antenna With Ultrawideband Performance," *IEEE Antennas Wirel. Propag. Lett.*, vol. 8, pp. 690–692, 2009.
- [66] J. Mazloum, "Reconfigurable Active Integrated Antenna with Log-periodic Matching Network Structures and Reduced Pin Diodes for WLAN/WIMAX Applications," *Microw. Opt. Technol. Lett.*, vol. 58, pp. 787–791, 2016.
- [67] M. N. A. Karim, M. K. A. Rahim, and T. Masri, "Fractal Koch Dipole Antenna for UHF Band Application," *Microw. Opt. Technol. Lett.*, vol. 51, pp. 2612–2614, 2009.
- [68] B. B. Mandelbrot, *The Fractal Geometry of Nature*, vol. 51. 1983.
- [69] S. Tripathi, A. Mohan, and S. Yadav, "Ultra-Wideband Antenna using Minkoski-Like Fractal Geometry," *Microw. Opt. Technol. Lett.*, vol. 59, no. 1, pp. 2273–2279, 2014.
- [70] A. Barcellos, "The Fractal Geometry of Mandelbrot," *Coll. Math. J.*, vol. 15,

- pp. 98–114, 1984.
- [71] Anuradha, “Design and Simulation of Koch Fractal Antenna Array for Mobile Communications,” Mater Thesis, Deemed University, 2006.
  - [72] D. H. Werner, R. L. Haupt, and P. L. Werner, “Fractal Antenna Engineering: The Theory and Design of Fractal Antenna Arrays,” *IEEE Antennas Propag. Mag.*, vol. 41, pp. 37–59, 1999.
  - [73] A. Chatterjee, T. Mondal, D. G. Patanvariya, and R. P. K. Jagannath, “Fractal-based design and fabrication of low-sidelobe antenna array,” *AEU - Int. J. Electron. Commun.*, vol. 83, no. November 2017, pp. 549–557, 2018.
  - [74] S. Singhal, T. Goel, and A. K. Singh, “Inner Tapered Tree-Shaped Fractal Antenna for UWB Application,” *Microw. Opt. Technol. Lett.*, vol. 57, pp. 559–567, 2015.
  - [75] N. Wideband, P. Fractal, and M. Antenna, “Novel Wideband Planar Fractal Monopole Antenna,” *IEEE Trans. Antennas Propag.*, vol. 56, pp. 3844–3849, 2008.
  - [76] P. N. Rao and N. V. S. N. Sarma, “The Effect of Indentation Angle of Koch Fractal Boundary on the Performance of Microstrip Antenna,” *Int. J. Antennas Propag.*, vol. 2008, pp. 1–5, 2008.
  - [77] H. Rajabloo, V. Amiri Kooshki, and H. Oraizi, “Compact microstrip fractal Koch slot antenna with ELC coupling load for triple band application,” *AEU - Int. J. Electron. Commun.*, vol. 73, pp. 144–149, 2017.
  - [78] R. S. Brar, S. Singhal, and A. K. Singh, “Fractal Dipole Antenna for UWB Application,” *Microw. Opt. Technol. Lett.*, vol. 58, pp. 39–47, 2016.
  - [79] D. B. Oliveira and E. J. Silva, “Design of the compact UHF RFID meander-line antenna loaded with CPW elements,” *AEU - Int. J. Electron. Commun.*, vol. 77, pp. 57–60, 2017.
  - [80] J. Yang, F. Kong, K. Li, and S. Sheng, “Analysis of a log periodic nano-antenna for multi-resonant broadband field enhancement and the Purcell factor,” *Opt. Commun.*, vol. 342, pp. 230–237, 2015.
  - [81] M. Gupta and V. Mathur, “Sierpinski fractal antenna for internet of things applications,” *Mater. Today Proc.*, vol. 4, pp. 10298–10303, 2017.
  - [82] M. Gupta and V. Mathur, “Wheel shaped modified fractal antenna realization for wireless communications,” *AEU - Int. J. Electron. Commun.*, vol. 79, pp. 257–266, 2017.
  - [83] T. Ali, A. W. Mohammad Saadh, R. C. Biradar, J. Anguera, and A. Andújar, “A miniaturized metamaterial slot antenna for wireless applications,” *AEU - Int. J. Electron. Commun.*, vol. 82, pp. 368–382, 2017.
  - [84] T. Ali, M. M. Khaleeq, and R. C. Biradar, “A multiband reconfigurable slot antenna for wireless applications,” *Int. J. Electron. Commun.*, vol. 84, pp. 273–280, 2018.
  - [85] G. Varamini, A. Keshtkar, N. Daryasafar, and M. Naser -Moghadasi, “Microstrip Sierpinski fractal carpet for slot antenna with metamaterial loads for dual-band wireless application,” *AEU - Int. J. Electron. Commun.*, vol. 84, pp. 93–99, 2018.
  - [86] A. Farswan, A. K. Gautam, B. K. Kanaujia, and K. Rambabu, “Design of Koch Fractal Circularly Polarized Antenna for Handheld UHF RFID Reader Applications,” *IEEE Trans. Antennas Propag.*, vol. 64, pp. 771–775, 2016.
  - [87] K. Kamardin, “Artificial Magnetic Conductor Waveguide Sheet for Transmission Enhancement Between Antennas for Body Centric Communication,” Phd Thesis, Universiti Teknologi Malaysia, 2014.

- [88] R. Janaswamy and D. H. Schaubert, "Characteristic Impedance of a Wide Slotline on Low-Permittivity Substrates," *IEEE Trans. Microw. Theory Tech.*, vol. 34, pp. 900–902, 1986.
- [89] Y. M. Madany, A. I. Almahallawy, and H. M. Elkamchouchi, "Methodology of band rejection / addition for microstrip antennas design using slot line theory and current distribution analysis," *2014 Loughbrgh. Antennas Propag. Conf. LAPC 2014*, pp. 602–606, 2014.
- [90] R. Dewan, S. K. A. Rahim, S. F. Ausordin, and T. Purnamirza, "The Improvement of Array Antenna Performance with the Implementation of an Artificial Magnetic Conductor (Amc) Ground Plane and in-Phase Superstrate," *Prog. Electromagn. Res.*, vol. 140, pp. 147–167, 2013.