UNIVERSITI PUTRA MALAYSIA

SINGLE-BAND AND DUAL-BAND MICROSTRIP FILTER-ANTENNA FOR WIRELESS APPLICATIONS

MOHAMMED KADHIM KHUDHAIER

FK 2018 9

SINGLE-BAND AND DUAL-BAND MICROSTRIP FILTER-ANTENNA FOR WIRELESS APPLICATIONS

By

MOHAMMED KADHIM KHUDHAIER

Thesis is Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilllment of the Requirements for the Degree of Doctor of Philosophy

December 2017

© COPYRIGHT UPM

COPYRIGHT

All material contained within the thesis, including without limitation text, logos, icons, photographs, and all other artwork, is copyright material of Universiti Putra Malaysia unless otherwise stated. Use may be made of any material contained within the thesis for non-commercial purposes from the copyright holder. Commercial use of material may only be made with the express, prior, written permission of Universiti Putra Malaysia.

Copyright © Universiti Putra Malaysia

DEDICATION

To my ever-beloved mother and the memories of my father…
To my supportive mother in law and the memories of my father in law…
To my dearest and altruistic wife…
To my beloved siblings…

To every person has supported me and made an effort to provide scientific advice…
To everyone looking for freedom and peace in this world…

© COPYRIGHT UPM

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

SINGLE-BAND AND DUAL-BAND MICROSTRIP FILTER-ANTENNA FOR WIRELESS APPLICATIONS

By

MOHAMMED KADHIM KHUDHAIER

December 2017

Chairman : Ratna Kalos Zakiah Sahbudin, PhD
Faculty : Engineering

In conventional narrow band radio frequency (RF) systems, all RF components are designed separately and all the input/output ports are matched to a standardized value typically 50 Ω. For simplicity and miniaturization, it is preferable to integrate the filter and the antenna into a single module that achieves filtering and radiating functions at the same time, known as filter-antenna. Integration of microstrip filter and microstrip antenna represents a challenge for many researchers. The filter-antenna circuit suffers from some design problems that affect its performance. These problems were the main reasons for the variation between the simulation and experimental results.

This study presents two different types of microstrip filter-antenna structures. It is the effort to improve the performance characteristics of the single-band filter-antenna and the dual-band filter-antenna. A single-band, dual-mode filter-antenna was designed using a Chebyshev lowpass prototype with passband ripple of 0.1 dB and fractional bandwidth (FBW) of 10.5 %, which operates at a centre frequency of 5.794 GHz. The measured S_{11} of the filter-antenna is better than -21 dB. This microstrip filter-antenna is designed by using the modified shaped dual-mode square open-loop resonator structure. These types of resonators behave as a double tuned circuit. This new design not only reduces the circuit size of about 50 % as compared with the single-mode resonators, but also got the crucially less insertion loss. The single-band, dual-mode filter-antenna design is then modified by using U-shaped slot etched on the patch antenna to improve its performance. This filter-antenna is suitable for portable communication applications; because of its compact size of 22 x 22 x 1.6 mm^3. The folded Stepped Impedance Resonator (SIR) dual-band filter-antenna was designed using Butterworth lowpass prototype. The measured fractional bandwidth for the first frequency band is 24.37 % and the measured fractional bandwidth for the second frequency band is 17.24 %. The measured first frequency passband of the filter-

© COPYRIGHT UPM

antenna operates at a centre frequency of $f_o^I = 5.75$ GHz, and the measured second frequency passband operates at a centre frequency of $f_o^{II} = 8.35$ GHz. The measured S_{11}^I of the first frequency passband is better than -24 dB, and S_{11}^{II} of the second frequency passband is better than -15 dB. The folded SIR dual-band filter-antenna is designed by using four-folded SIR, where any two-folded SIR is connected together. These folded SIR are used instead of the conventional SIR to miniaturize the overall circuit size. The folded SIR dual-band filter-antenna is designed, and then modified by using the dumbbell-shaped Defected Ground Structure (DGS) to improve the filter-antenna performance and for further reduce the size of the circuit. The dual-band filter-antenna is suitable for mobile communication because of it is compact size of $41.4 \times 30 \times 1.6$ mm^3. The comparison of the simulated and measured S_{11}-parameters of the folded SIR dual-band filter-antenna shows an acceptable matching between the simulation results and experimental results. The centre frequency of the first frequency passband is moves down from 5.8 GHz to 5.75 GHz and the centre frequency of the second frequency passband is shifted from 8.184 GHz to 8.35 GHz. This frequency shifting is due to the difference in the design component values of the theoretical and the practical design.

Some comparisons have been made between the proposed designs and other literature works, also among some literature works for both single-band and dual-band filter-antennas. The aim of these comparisons is to investigate the achievement of the research objectives.

Single-band, dual-mode filter-antenna is compared with other filter-antennas literature works such as Ref. [85] and Ref. [109]. The specification and design comparison show that the proposed filter-antenna has a good design performance such as insertion loss, return loss, gain, and band edge selectivity. The proposed single-band, dual-mode filter-antenna has a circuit size reduction as compared with the circuit of Ref. [85] of about 50 %, and 70 % as compared with the circuit of the Ref. [109]. The design comparison of the proposed dual-band, folded SIR filter-antenna and other literature works such as Ref. [110], Ref. [89], and Ref. [111] shows that the proposed filter-antenna has good design performance and good band edge selectivity. The proposed dual-band, folded SIR filter-antenna has a circuit size reduction as compared with the circuit of Ref. [110] more than 85 %, and 43 % as compared with the circuit of the Ref. [89].

The single-band, dual-mode filter-antenna is designed and fabricated to cover the Worldwide Interoperability for Microwave Access (WiMAX) application. Based on IEEE 802.16-2005 (802.16e), this technology supports mobility networking between the fixed base station and mobile devices. In addition, enables high signal speed required for communications with users moving by vehicles to have speed which is below 100 km/h. This technology provides symmetric bit rates of 70 Mbps and operates in the frequency range 2-6 GHz. The folded SIR dual-band filter-antenna is designed and fabricated to cover a Wireless Local Area Network (WLAN) application (5.75 GHz) for the first frequency passband and X-band (8-12GHz) applications for

© COPYRIGHT UPM

the second frequency passband. Satellite communication operates in part of the X-band or Super High Frequency (SHF) spectrum which is specified by (ITU). Satellite communication has the frequencies in the range 7.25 GHz to 7.75 GHz (space to earth) and 7.9 GHz to 8.4 GHz (earth to space).

The main contributions of this study represented by the design and fabrication of a new structure single-band, dual-mode filter-antenna which used a novel shaped of the dual-mode resonator. The dual-mode resonator has highly contributed to the overall circuit size reduction and improved its band edge selectivity. In addition, the design of a new dual-band filter-antenna structure which used folded SIR and defected Ground Structure (DGS) are for more size reduction and band edge selectivity improvement. Single-band and dual-band microstrip filter-antennas are developed and analyzed using 3-D Computer Simulation Technology electromagnetic simulator software (CST). In order to verify the simulation results, the single-band filter-antenna and the dual-band filter-antenna are fabricated on FR-4 epoxy glass substrate material with a dielectric constant of 4.3 and loss tangent $tan\delta =$ 0.02. The experimental measurements are carried out by using a Vector Network Analyzer (VNA Anritsu 37347D). The design of the filter-antenna models are fabricated and tested. A good agreement was found between simulated and measured results. The results were also compared to previous work to show the uniqueness of the design process implemented in the present work. All the objectives of the study have been achieved with a significant improvement in the performances of the proposed filter-antennas compared with previous works.

© COPYRIGHT UPM

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENAPIS-ANTENA MIKROJALUR DWI-JALUR DAN JALUR TUNGGAL UNTUK APLIKASI WAYARLES

Oleh

MOHAMMED KADHIM KHUDHAIER

Disember 2017

Pengerusi : Ratna Kalos Zakiah Sahbudin, PhD
Fakulti : Kejuruteraan

Dalam sistem frekuensi radio (RF) jalur sempit konvensional, semua komponen RF telah direka bentuk secara berasingan dan semua pangkalan masukan / keluaran telah dipadankan dengan nilai yang seragam iaitu biasanya 50 Ω. Untuk mendapatkan keringkasan dan pengecilan, adalah menjadi pilihan untuk mengintegrasikan penapis dan antena ke dalam modul tunggal yang mencapai fungsi penapisan dan pancaran pada masa yang sama, ia dikenali sebagai penapis-antena. Integrasi penapis mikrojalur dan antena mikrojalur merupakan satu cabaran bagi kebanyakan penyelidik. Litar penapis-antena menghadapi beberapa masalah dari segi reka bentuk dan menjejaskan prestasinya. Masalah ini menjadi sebab utama perbezaan antara keputusan teori dan praktikal.

Kajian ini membentangkan dua jenis struktur penapis-antena mikrojalur. Ia adalah usaha untuk meningkatkan ciri-ciri prestasi penapis- antena jalur-tunggal dan penapis-antena dwi-jalur. Penapis-antena jalur tunggal dwi-mod direka bentuk menggunakan prototaip lulus rendah Chebyshev dengan riak jalur lulus sebanyak 0.1 dB dan lebar jalur pecahan (*FBW*) sebanyak 10.5%, yang beroperasi pada frekuensi pusat 5.794 GHz. Nilai S_{11} penapis- antena yang diukur lebih baik daripada -21 dB. Penapis-antena mikrojalur ini direka bentuk dengan menggunakan struktur resonator gelung terbuka dua dimensi persegi yang diubah suai. Resonator jenis ini bertindak sebagai litar tertala dua kali. Reka bentuk baru ini bukan sahaja mengurangkan saiz litar sebanyak kira-kira 50% berbanding dengan resonator mod-tunggal, tetapi juga yang penting kehilangan penyisipan yang kurang. Reka bentuk penapis-antenna jalur tunggal, dwi-mod kemudian diubahsuai dengan menggunakan slot berbentuk U diikatkan pada antena tampal untuk meningkatkan prestasinya. Penapis-antena ini sesuai untuk aplikasi komunikasi mudah alih; kerana ia bersaiz padat 22 x 22 x 1.6 mm^3. Penapis-antena dwi-jalur Resonator Impedans Bertangga (SIR) terlipat telah direka bentuk

© COPYRIGHT UPM

menggunakan prototaip lulus rendah Butterworth. Jalur lebar pecahan untuk jalur frekuensi pertama ialah 24.37 % dan untuk jalur frekuensi kedua ialah 17.24 %. Jalur frekuensi pertama penapis-antena beroperasi pada frekuensi pusat f_o^I = 5.75 GHz, dan jalur frekuensi kedua beroperasi pada frekuensi pusat f_o^{II} = 8.35 GHz. Nilai S_{11}^I jalur pertama yang diukur adalah lebih baik daripada -24 dB, dan S_{11}^{II} jalur kedua adalah lebih baik daripada -15 dB. Penapis-antena dwi-jalur SIR terlipat direka bentuk dengan menggunakan SIR terlipat empat, di mana SIR terlipat dua disambungkan bersama-sama. SIR terlipat ini digunakan, dan bukannya SIR konvensional untuk mengecilkan saiz litar keseluruhannya. Penapis-antena dwi-jalur SIR yang direka bentuk, dan kemudian diubah suai dengan menggunakan Struktur Bumi Tersingkir (DGS) berbentuk dumbel untuk meningkatkan prestasi penapis- antena dan untuk mengurangkan lagi saiz litar. Penapis-antena dwi-jalur sesuai untuk komunikasi mudah alih kerana saiznya yang kompak 41.4 x 30 x 1.6 mm^3. Perbandingan antara parameter S_{11} yang disimulasikan dan diukur untuk penapis- antena SIR dwi-jalur terlipat menunjukkan satu persamaan yang boleh diterima antara keputusan simulasi dan keputusan eksperimen. Frekuensi pusat untuk jalur frekuensi pertama berkurangan dari 5.8 GHz ke 5.75 GHz dan frekuensi pusat untuk jalur frekuensi kedua beralih daripada 8.184 GHz kepada 8.35 GHz. Peralihan frekuensi ini disebabkan oleh perbezaan dalam nilai komponen untuk reka bentuk teori dan reka bentuk praktikal.

Beberapa perbandingan telah dilakukan antara reka bentuk yang dicadangkan dan kerja-kerja penyelidik yang lain, juga antara beberapa kerja-kerja penyelidik untuk penapis-antena jalur tunggal dan dwi-jalur. Tujuan perbandingan ini adalah untuk menyiasat pencapaian objektif penyelidikan.

Penapis-antena jalur-tunggal, dwi-mod dibandingkan dengan kerja-kerja saringan penapis-antena lain seperti Ref. [85] dan Ref. [109]. Spesifikasi perbandingan dan reka bentuk menunjukkan bahawa penapis-antena yang dicadangkan mempunyai prestasi reka bentuk yang baik, seperti kehilangan sisipan, kehilangan pulangan, gandaan, dan selektiviti jalur pinggir. Penapis-antena jalur-tunggal, dwi-mod yang dicadangkan mempunyai pengurangan ukuran litar berbanding dengan litar Ref. [85] kira-kira 50 %, dan 70 % berbanding dengan litar Ref. [109]. Perbandingan reka bentuk dwi-jalur yang dicadangkan, penapis-antena SIR terlipat dan kajian semula penyelidikan yang lain seperti Ref. [110], Ref. [89], dan Ref. [111] menunjukkan bahawa penapis-antena yang dicadangkan mempunyai prestasi reka bentuk yang baik dan selektiviti jalur pinggir yang baik. Dwi-jalur yang dicadangkan, penapis-antena SIR terlipat mempunyai pengurangan ukuran litar berbanding dengan litar Ref. [110] lebih daripada 85%, dan 43% berbanding dengan litar Ref. [89].

Penapis-antena jalur-tunggal, dwi-mod direka bentuk dan difabrikasi untuk menampung penggunaan Kebolehgacaraan Seluruh Dunia untuk Akses Microwave (WiMAX). Berasaskan kepada IEEE 802.16-2005 (802.16e), teknologi ini menyokong mobiliti rangkaian antara peranti mudah alih dan stesen pangkalan yang tetap. Di samping itu, membolehkan kelajuan isyarat tinggi yang diperlukan untuk

© COPYRIGHT UPM

komunikasi dengan pengguna bergerak dengan kenderaan yang mempunyai kelajuan di bawah 100 km/j. Teknologi ini memberikan kadar bit yang simetri pada 70 Mbps, dan beroperasi dalam julat frekuensi 2-6 GHz. Penapis-antena SIR dwi-jalur terlipat direka bentuk dan difabrikasi untuk menampung penggunaan Rangkaian Kawasan Setempat Tanpa Wayar (WLAN) untuk (5.75 GHz) jalur lulus frekuensi pertama dan jalur-X (8-12 GHz) untuk jalur lulus frekuensi pertama kedua. Komunikasi satelit beroperasi dalam bahagian spektrum jalur-X atau frekuensi tinggi super (SHF) yang ditetapkan oleh (ITU). Komunikasi satelit mempunyai julat frekuensi dalam 7.25 GHz ke 7.75 GHz (angkasa ke bumi) dan 7.9 GHz ke 8.4 GHz (bumi ke ruang).

Sumbangan utama kajian ini adalah reka bentuk dan fabrikasi struktur baru penapis-antena jalur-tunggal, dwi-mod yang menggunakan bentuk resonator dwi-mod yang laru. Resonator dwi-mod telah menyumbang dalam mengurangkan saiz keseluruhan litar dan mempertingkatkan selektiviti jalur pinggir. Di samping itu, reka bentuk struktur penapis-antena dwi-jalur yang baru dengan SIR terlipat dan DGS digunakan untuk lebih mengurangkan saiz dan menambahbaik selektiviti jalur pinggir.

Penapis-antena mikrojalur jalur tunggal dan dwi-jalur dibangunkan dan dianalisis dengan menggunakan perisian Simulator Elektromagnetik Teknologi Simulasi 3-D (CST). Untuk mengesahkan hasil simulasi, penapis-antena jalur tunggal dan penapis-antena dwi-jalur dibina di atas bahan substrat kaca epoksi FR-4 dengan pemalar dielektrik sebanyak 4.3 dan kehilangan tangent $\tan\delta = 0.02$. Pengukuran eksperimen dilakukan dengan menggunakan Vector Analyzer Network (VNA Anritsu 37347D). Reka bentuk model penapis-antena dibina dan diuji. Kesepakatan yang baik telah ditemui di antara keputusan simulasi dan pengukuran. Hasilnya juga dibandingkan dengan kerja sebelumnya untuk menunjukkan keunikan proses reka bentuk yang dilaksanakan dalam kerja sekarang. Semua objektif kajian telah dicapai dengan peningkatan yang signifikan dalam prestasi penapis-antena yang dicadangkan berbanding dengan kerja sebelumnya.

© COPYRIGHT UPM

ACKNOWLEDGEMENTS

I am deeply grateful for Allah S.W.T. who blessed me with the greatest strength, patience and good health and supportive supervisors, family and friends to accomplish my work. I am also thankful to my supervisors Dr. Ratna Kalos Zakiah Sahbudin for her expert supervision, endless guidance and assistance she provided throughout the course of this research work. In addition, I would like to express my appreciation to the members of my committee, Assoc. Prof. Dr. Alyani Ismail and Assoc. Prof Dr. Shaiful Jahari Hashim for offering their valuable comments. I owe my loving thanks to my family for their unlimited support and love. For my country and for those who sacrificed their lives trying to protect our homeland, it would be impossible for me to finish without their Sacrifices.

My sincere appreciation goes to the University Putra Malaysia for the endless cooperation that I have to finish my work. I acknowledge the Department of Computer and Communication Systems of the University Putra Malaysia for unlimited access to the research facilities and library throughout my work. Finally, my hearty appreciation goes to lecturers, classmates, friends, and staff of the University Putra Malaysia for all their support.

Finally, I would like to thank the Ministry of Higher Education and Scientific Research of Iraq / Scholarships & The Cultural Relations Directorate and the Foundation of Technical Education / Southern Technical University for providing me with this opportunity to complete my studies.

© COPYRIGHT UPM

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of Supervisory Committee were as follows:

Ratna Kalos Zakiah Sahbudin, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Alyani Ismail, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Shaiful Jahari Hashim, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

© COPYRIGHT UPM

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software

Signature: ________________________ Date: ___________________

Name and Matric No: Mohammed Kadhim Khudhaier, GS39897

© COPYRIGHT UPM

Declaration by Members of Supervisory Committee

This is to confirm that:
- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signature: ______________________
Name of Chairman
of Supervisory
Committee: Dr. Ratna Kalos Zakiah Sahbudin

Signature: ______________________
Name of Member
of Supervisory
Committee: Associate Professor Dr. Alyani Ismail

Signature: ______________________
Name of Member
of Supervisory
Committee: Associate Professor Dr. Shaiful Jahari Hashim,

© COPYRIGHT UPM

TABLE OF CONTENTS

			Page
ABSTRACT			i
ABSTRAK			iv
ACKNOWLEDGEMENTS			vii
APPROVAL			viii
DECLARATION			x
LIST OF TABLES			xvi
LIST OF FIGURES			xviii
LIST OF ABBREVIATIONS			xxv
LIST OF SYMBOLS			xxvii

CHAPTER

1	**INTRODUCTION**		1
	1.1	Background	1
	1.2	Problem Statement	2
	1.3	Motivation of Study	2
	1.4	Aim and Objectives	3
	1.5	Scope of Research	4
	1.6	Thesis Organization	5
2	**LITERATURE REVIEW**		7
	2.1	Background	7
		2.1.1 Filter Network Theory	7
		2.1.2 Scattering Parameters	10
	2.2	Filter Classifications	13
		2.2.1 Lowpass Filter	13
		2.2.2 Highpass Filter	14
		2.2.3 Bandpass Filter	15
		2.2.4 Bandstop (Band-Reject) Filter	16
	2.3	Filters Based on Butterworth (Maximally Flat) Function Response	17
	2.4	Filters Based on Chebyshev Function Response	18
	2.5	Frequency Transformation	20
		2.5.1 Lowpass to Highpass Transformation	20
		2.5.2 Lowpass to Bandpass Transformation	21
		2.5.3 Lowpass to Bandstop (Band-Reject) Transformation	23
	2.6	Microstrip Antennas	24
	2.7	Fundamental Specifications of Microstrip Antennas	25
		2.7.1 Radiation Pattern	25
		2.7.2 Radiation Efficiency	26
		2.7.3 Gain and Directivity	27
		2.7.4 Input Impedance	27
		2.7.5 Return Loss	27
		2.7.6 Bandwidth	28

© COPYRIGHT UPM

2.7.7 Beamwidth and Side Lobes 28
2.7.8 Polarization 28
2.7.8.1 Polarization Mismatch 29
2.8 Microstrip Patch Antenna 30
2.8.1 Microstrip Patch Antenna Design 30
2.8.2 Advantage and Disadvantage of Microstrip Patch Antenna 31
2.8.3 Monopole Patch Antennas 32
2.8.4 Characteristics of Microstrip Patch Antenna 32
2.9 Feeding Techniques 33
2.9.1 Microstrip Line Feed 33
2.9.2 Coaxial Feed Technique 34
2.9.3 Aperture Coupled Feed Technique 34
2.9.4 Proximity Coupled Feed Technique 35
2.10 Comparison of Different Feeding Techniques of the Patch Antenna 37
2.11 Microstrip Antenna Bandwidth Enhancement Techniques 37
2.12 Microstrip Filter – Antenna 38
2.12.1 Integrated Filter Antenna 38
2.12.2 Microstrip Filter – Antenna Design Topologies 40
2.13 Comparison of Filter-Antenna Designs 41
2.13.1 Comparison of Different types of the Single-Band Filter-Antenna Designs 41
2.13.2 Comparison of Different Types of the Dual-band Filter-Antenna Designs 44
2.14 Summary 45

3 **METHODOLOGY** 46
3.1 Synthesis and Design Methodology of Single-Band Dual-Mode Filter-Antenna 46
3.1.1 An Overview of Computer Simulation Technology (CST) Software 46
3.1.2 Microwave Resonators 46
3.1.3 Transmission Line Resonators 48
3.1.4 Microstrip Coupled Resonators 51
3.2 Computer-Aided Design (CAD) Procedures for Filter-Antenna Design 54
3.3 Synthesis and Design Procedures of Filter-Antenna 55
3.3.1 Chebyshev LPF Prototype 59
3.3.2 Lowpass to Bandpass Filter Transformation 61
3.4 Parameter Calculations of the Single-Band Dual-Mode Filter-Antenna 63
3.5 Realization of the Single-Band Dual-Mode Microstrip Filter-Antenna in a Microstrip Transmission Line 68
3.6 Synthesis and Design Methodology of Dual-Band Folded Stepped Impedance Resonator (SIR) Filter-Antenna 75
3.6.1 Stepped Impedance Resonators 75
3.6.2 The Basic Structure of Stepped Impedance Resonator (SIR) 76

© COPYRIGHT UPM

	3.7	Synthesis Procedures of the Dual-Band Folded SIR Filter-Antenna	79
		3.7.1 Maximally Flat Lowpass Filter Prototype	80
		3.7.2 Lowpass Filter to Bandpass Prototype Transformation	81
	3.8	Parameter Calculations of the Dual-band Folded SIR Filter-Antenna	82
	3.9	Realization of a Dual-Band Filter-Antenna	88
	3.10	Summary	89
4	**RESULTS AND DISCUSSION**		91
	4.1	Simulation Results of the Single-Band, Dual-Mode Filter-Antenna	91
		4.1.1 The Impact of the Gap (s) between the Resonators on the Quality Factor and Insertion Loss	92
		4.1.2 The Influence of Slot Loaded Etched on a Patch Antenna of the Filter-Antenna Performance	97
	4.2	Experimental Results of the Single-Band, Dual-Mode Filter-Antenna	100
	4.3	Comparison of Simulated and Measured Results of the Single-Band, Dual-Mode Filter-Antenna	104
	4.4	Comparison of Single-Band, Dual-Mode Filter-Antenna and the Filter-Antenna Using Dual-Mode Square Open-Loop Resonator with Perturbation at the Corner	111
	4.5	Comparison of the proposed single-band filter-antenna and Other Single-Band Filter-Antenna Literature works	115
		4.5.1 Three-Order Equal-Ripple Band-Pass Filtering Antenna Design Using Capacitive-Gap Coupled Asymmetrical-CPW Resonator	116
		4.5.2 A Simple Filtering Antenna with Compact Size for WLAN Applications	117
	4.6	Simulation Results of the Folded SIR Dual-Band Filter-Antenna	120
		4.6.1 The Influence of the DGS on the Dual-Band Filter-Antenna Performance	122
		4.6.2 The Effect of the Gap between the Resonators on the Performance of Dual-Band Filter-Antenna	122
	4.7	Experimental Results of the Folded SIR Dual-Band Filter-Antenna	126
	4.8	Comparison of the Simulated and Measured Results of the Dual-Band Filter-Antenna	130
	4.9	Comparison of the Folded SIR Dual-Band Filter-Antenna and a Dual-Band Filter-Antenna Using Square Open Loop Resonators	133
	4.10	Comparison of the proposed Dual-Band Filter-Antenna and other Literature Works	137
	4.11	Summary	139

© COPYRIGHT UPM

5	**CONCLUSION AND FUTURE WORK**	141
	5.1 Conclusion	141
	5.1 Contribution to Research Field	142
	5.2 Future Work	142
REFERENCES		144
APPENDICES		153
BIODATA OF STUDENT		163
LIST OF PUBLICATIONS		164

© COPYRIGHT UPM

LIST OF TABLES

Table		Page
2.1	The effects of misalignment angle on the polarization mismatch loss	29
2.2	Advantages and disadvantages of microstrip patch antenna	32
2.3	Comparison of different feeding techniques of the path antenna	37
2.4	Comparison of different types of the single-band filter-antenna, literature works from 2 – 2.5 GHz	42
2.5	Comparison of different types of the single-band filter-antenna, literature works from 5 –5.8 GHz	43
2.6	Comparison of different types of the dual-band filter-antenna literature works	44
3.1	Two-pole Chebyshev LPF prototype element values	61
3.2	Scaling impedance values of the two-pole Chebyshev LPF prototype	61
3.3	Two-pole BPF element values after frequency transformation.	62
3.4	Quality factor values of the single-band, dual-mode filter-antenna	63
3.5	Admittance inverter (J-inverter) values with respect to characteristic admittance and the coupling coefficient value	68
3.6	Optimized physical dimensions of the single-band, dual-mode filter-antenna	74
3.7	Element values of the fourth order maximally flat LPF prototype	81
3.8	Element values of the four-pole maximally flat BPF for the first and second frequency passbands	82
3.9	Coupling coefficients and quality factor values of the four-pole BPF for the first and second frequency passbands	83
3.10	Admittance inverter and susceptance values of the dual-band filter-antenna microwave model	85

© COPYRIGHT UPM

3.11	Optimized physical dimensions of the top view of the dual-band filter-antenna	88
3.12	Optimized physical dimensions of the bottom view of the dual-band filter-antenna	88
4.1	Comparison of the single-band, dual-mode filter-antenna design results with and without slot loaded	100
4.2	Comparison of simulated and measured results of the single-band, dual-mode filter-antenna	107
4.3	Comparison results of the traditional patch antenna and the single-band, dual-mode filter-antenna	111
4.4	Comparison results of the single-band, dual-mode filter-antenna, and the single-band, dual-mode SOLR filter-antenna	115
4.5	Comparison of the proposed filter-antenna and other literature works	120
4.6	Comparison of simulated and measured results of the dual-band filter-antenna	132
4.7	Comparison results of the proposed dual-band filter-antenna and the modified square open loop dual-band filter-antenna	137
4.8	Comparison of the proposed dual-band filter-antenna and other literature works	138
4.9	Comparison results of the proposed filter-antenna and other literature work at 5.9 GHz and 8.8 GHz	139

© COPYRIGHT UPM

LIST OF FIGURES

Figure		Page
1.1	Thesis scope	5
2.1	Input/output of the linear system	7
2.2	Convention defining of S-parameters	10
2.3	LPF frequency response	14
2.4	HPF frequency response	15
2.5	BPF frequency response	16
2.6	BSF frequency response	17
2.7	Attenuation characteristics of the Butterworth LPF	18
2.8	Realization of a filter using LC components	18
2.9	Attenuation characteristics of LPF based on Chebyshev approach	19
2.10	Typical radiation pattern of a microstrip antenna (a) polar form (b) Rectangular form	26
2.11	Rectangular microstrip patch antenna structure	30
2.12	Microstrip feed-line technique	33
2.13	Coaxial feed technique	34
2.14	Aperture coupled feed technique	35
2.15	Proximity coupled feed technique	36
2.16	The diagram of the BPF integrated with the antenna	39
3.1	The equivalent circuits of microwave resonators (a) Series resonant lossless circuit. (b) Parallel resonant lossless circuit. (c) Series resonant lossy circuit. (d) Parallel resonant lossy circuit	47
3.2	Some typical microstrip resonators (a) λ_go⁄4 line resonator (shunt series resonance) (b) λ_go⁄4 line resonator (shunt parallel resonance)	49
3.3	Half wavelength $\lambda_{go}/2$ line resonator	49

© COPYRIGHT UPM

3.4	Closed ring resonators (a) Circular (b) square	50
3.5	Half-wavelength $\lambda_{go}/2$ open-loop resonators (a) Circular (b) Square	50
3.6	Split Ring Resonator (SRR) (a) Circular (b) Square	51
3.7	Equivalent circuit of *n*th-coupled lossy resonator filter (a) Magnetic coupling (b) Electric coupling	52
3.8	General Computer-Aided Design flow chart for the filter-antenna design procedures	55
3.9	Filter-antenna synthesis procedures	56
3.10	Filter-antenna design procedures	56
3.11	3-D view of the basic single-band, dual-mode filter-antenna circuit design	57
3.12	Two-pole Chebyshev LPF prototype	60
3.13	Two-pole Chebyshev BPF prototype	62
3.14	The external quality factor and the loaded quality factor of the filter-antenna with respect to the gap between the resonators	64
3.15	The relation between *VSWR* and both of reflection coefficient and ripple constant	64
3.16	The relation between *VSWR* and the return loss (dB)	65
3.17	The two square dual-mode open-loop resonators (a) resonator structures (b) Equivalent circuit	65
3.18	Coupling coefficient between the resonators as a function of a coupling gap (s)	67
3.19	(a) The admittance inverter diagram. (b) The filter-antenna microwave circuit model using admittance inverters (J-inverters)	67
3.20	The relation between the effective dielectric constant of the FR-4 dielectric substrate and *W/h* ratio	70
3.21	The relation between characteristic impedance and *W/h* ratio	70
3.22	Characteristic impedance of a microstrip for different types of dielectric substrates with respect to W/h ratio	71

© COPYRIGHT UPM

3.23	a) Characteristic impedance and the electrical length of the resonator (b) physical dimensions of the resonator	71
3.24	(a) Microstrip line calculator software. (b) Patch antenna calculator software	73
3.25	Single-band, dual-mode microstrip filter-antenna circuit design	74
3.26	Basic unit structure of SIR (a) $R_z < 1$ (b) $R_z > 1$	76
3.27	The basic unit of conventional folded SIR (a) Resonator structure (b) Equivalent circuit of the resonator.	77
3.28	Equivalent circuit of resonator (a) J-inverter (b) Open stub	78
3.29	Dual-band folded SIR filter-antenna layout	80
3.30	Ladder circuit of maximally flat LPF prototype	80
3.31	Four-pole maximally flat BPF prototype	81
3.32	The four resonators of the dual-band filter-antenna (a) Resonator structures (b) Equivalent circuit	82
3.33	Coupling coefficient of the dual-band filter-antenna as a function of the coupling gap (s)	83
3.34	External quality factor of the dual-band filter-antenna as a function of the gap (s).	84
3.35	The relationship between the coupling coefficient and the reflection-parameter for the first and second frequency bands	84
3.36	Microwave model of the dual-band filter-antenna using J-inverters	85
3.37	(a) Configuration of the BPF with DGS on the ground plane (b) Equivalent circuit of the DGS	87
3.38	Dual-band folded SIR filter-antenna layout (a) Top view (b) Bottom view	89
4.1	3-D view of the single-band, dual-mode filter-antenna design (a) The single-band, dual-mode filter-antenna structure (b) Bottom view-ground plane	91
4.2	Simulated S11-parameter of the Single-band, dual-mode filter-antenna	92

© COPYRIGHT UPM

4.3 S_{11}-parameter of the filter-antenna for different values of the gap (s) between the two resonators 93

4.4 Simulated VSWR of the single-band, dual-mode filter-antenna 94

4.5 Simulated S_{11}-parameter and gain of the single-band, dual-mode filter-antenna 95

4.6 The simulated radiation and total power efficiencies of the single-band, dual-mode filter-antenna 96

4.7 3-D view of the single-band, dual-mode filter-antenna radiation pattern 96

4.8 The simulated far-field of the filter-antenna (a) Directivity (b) Gain (c) H-field (d) E-field 97

4.9 Surface current distribution of the filter-antenna (a) With slot (b) Without slot. 98

4.10 Comparison of S_{11}- parameter for the single-band, dual-mode filter-antenna with and without a slot loaded 98

4.11 Comparison of gain for the single-band, dual-mode filter-antenna with and without slot loaded 99

4.12 Comparison of *VSWR* for the single-band, dual-mode filter antenna with and without slot loaded 99

4.13 Comparison of the power radiation efficiencies for the single-band, dual-mode filter-antenna 100

4.14 The photograph of the Vector Network Analyzer (VNA) model Anritsu 37347D 101

4.15 The photograph of the filter-antenna under test 101

4.16 Measured S_{11}-parameter of the single-band, dual-mode filter-antenna by using VNA instrument 102

4.17 Measured *VSWR* of the single-band, dual-mode fitter-antenna 102

4.18 Measured gain of the single-band, dual-mode filter-antenna 103

4.19 The photograph of the fabricated single-band, dual-mode filter-antenna (a) Top view (b) Bottom view 104

© COPYRIGHT UPM

4.20 Comparison of simulated and measured S11-parameter of the single-band, dual-mode filter-antenna 105

4.21 Comparison of simulated and measured *VSWR* of the single-band, dual-mode filter-antenna 106

4.22 Simulated and measured gain of the single-band, dual-mode filter-antenna 107

4.23 (a) Traditional rectangular patch antenna design. (b) S11-parameter of the patch antenna 108

4.24 Comparison of S-parameters for the traditional patch antenna and the filter-antenna 109

4.25 Comparison of the gain for the rectangular patch antenna and the single-band, dual-mode filter-antenna 109

4.26 Comparison of the power radiation efficiency for the rectangular patch antenna and the single-band, dual-mode filter-antenna 110

4.27 3-D view of the rectangular patch antenna radiation pattern 110

4.28 (a) The layout of the dual-mode SOLR filter-antenna (b) S_{11}-parameter and gain of the dual-mode SOLR filter-antenna 112

4.29 The layout of a single-band, dual-mode filter-antenna 113

4.30 (a) The modified shaped dual-mode resonator (b) The dual-mode SOLR with perturbation at the corner 113

4.31 Comparison of the S_{11}-parameters for single-band, dual-mode filter-antenna, and dual-mode SOLR filter-antenna. 114

4.32 Comparison of the gain for single-band, dual-mode filter-antenna, and dual-mode SOLR filter-antenna 114

4.33 (a) The structural schematic of the capacitive-gap coupled Asymmetrical-CPW resonator (b) The 50-Ω dimension of the asymmetrical CPW 116

4.34 S_{11}-parameter and gain of the filtering antenna [85] 117

4.35 Design evolution of the filter-antenna [109] 118

4.36 S_{11}-parameter and gain of the filter-antenna 118

© COPYRIGHT UPM

4.37 Comparison of the S_{11}-parameter for the proposed filter-antenna and other literature works 119

4.38 Comparison of the gain for the proposed filter-antenna and other literature works 119

4.39 3-D view of the folded SIR dual-band filter-antenna (a) Top view (b) Bottom view 121

4.40 Simulated S_{11}-Parameter of the dual-band filter-antenna 121

4.41 S_{11}-parameter of the dual-band filter-antenna with and without DGS 122

4.42 S_{11}-parameter for the different values of the gap, s between the resonators 123

4.43 *VSWR* of the dual-band filter-antenna with and without DGS 123

4.44 Simulated S_{11}-parameter and gain of the dual-band filter-antenna 124

4.45 3-D view of the folded SIR dual-band filter-antenna radiation pattern (a) First frequency passband. (b) Second frequency passband. 124

4.46 Simulated far-field, gain, directivity, E-field, and H-field (a) First band f_o=5.8 GHz (b) Second band f_o= 8.184 GHz 126

4.47 The photographs of the experimental measurements of the dual-band filter-antenna 127

4.48 The photograph of the fabricated dual-band filter-antenna circuit (a) Top view (b) Bottom view 128

4.49 Measured S_{11}-parameter of the dual-band filter-antenna 128

4.50 Measured *VSWR* of the dual-band filter-antenna 129

4.51 Measured gain and S_{11}-parameter of the dual-band filter-antenna 129

4.52 Simulated power radiation and total input power efficiencies of the dual-band filter-antenna 130

4.53 Comparison of the simulated and measured S_{11}-parameters for the dual-band filter-antenna 130

4.54 Comparison of the simulated and measured *VSWR* for the dual-band filter-antenna 131

© COPYRIGHT UPM

4.55	Comparison of simulated and measured gain for the dual-band filter-antenna	132
4.56	Dual-band filter-antenna layout (a) Top view (b) Bottom view (c) Folded SIR Resonator (d) modified square open-loop resonator	134
4.57	S_{11}-parameter and gain of the modified square open-loop resonator dual-band filter-antenna	135
4.58	Comparison of the reflection coefficient for the folded SIR dual-band filter-antenna and the modified square open-loop resonator dual-band filter-antenna	135
4.59	Comparison of the simulated gain for the folded SIR dual-band filter-antenna and the modified square open-loop dual-band filter-antenna	136

© COPYRIGHT UPM

LIST OF ABBREVIATIONS

BPF	Bandpass Filter
BSF	Bandstop Filter
CPW	Coplanar Waveguide
dBm	A logarithmic unit to measure power in milli Watt
DGS	Defected Ground Structure
FCC	United State, Federal Communication Commission
FR-4	Epoxy glass dielectric material
FBW	The fractional bandwidth
GPS	Global Positioning System
HPF	Highpass Filter
IMT 2000	International Mobile Telecommunication for the year 2000
LPF	Lowpass Filter
MPA	Microstrip Patch Antenna
MMIC	Monolithic Microwave Integrated Circuits
OCS	Open Circuited Stubs
OLR	Open-Loop Resonator
PCB	Printed Circuit Boards
PCS 1900	Personal Communications Service 1900
RF	Radio frequency
RLC	Resistance, Inductance, capacitance
SIR	Stepped Impedance Resonator
TEM	Transverse Electromagnetic wave

© COPYRIGHT UPM

UWB	Ultra-Wideband
VSWR	Voltage Standing Wave Ratio
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

© COPYRIGHT UPM

LIST OF SYMBOLS

$A_v(\Omega)$	The network (filter) attenuation
BW	Bandwidth
$D(s)$	The denominator of the transfer function *H(s)*
$E(s)$	The numerator of the characteristic function *K(s)*
$H(s)$	Rational function of a complex frequency variable (**s**)
$K(s)$	The characteristic function
$N(s)$	The numerator of the transfer function *H(s)*
$t(j\Omega)$	The inverted of the transfer function $H(j\Omega)$
W	A metal strip (conducting-strip) width
t	A metal strip (conducting-strip) thickness
s	Complex frequency variable
S_{11}	Forward Reflection Coefficient
S_{12}	Reverse Transmission Coefficient
S_{21}	Forward Transmission Coefficient
S_{22}	Reverse Reflection Coefficient
Q_e	External quality factor
$M_{i,i+1}$	Coupling coefficient between i and $i+1$ resonators
h	Height of the dielectric material
H	Magnetic field
G	Conductance
E	Electric field
D	Antenna directivity

$\boldsymbol{C}$	The light speed (i.e., $3 \times 10^8\ m/s$)
ΔL	The patch antenna extended the length
φ_{21}	The phase response
λ_o	The free space wavelength
β	The propagation constant
λ_g	The guided wavelength
θ	An electrical length of the microstrip line
ε_{reff}	The effective dielectric constant
ε_r	Substrate dielectric constant
$v_o(t)$	Output voltage in the time domain
v_p	Phase velocity
α_c	Attenuation conductor loss
$\tau_d(\Omega)$	The group delay
a_n	The definition of the incident voltage signal
b_n	The normalized reflected voltage signal
f_c	Cutoff frequency
f_o	Centre frequency
f_{pass}	Passband frequency
f_{stop}	Stopband frequency
g_i	Chebyshev lowpass filter prototype components
t_{pd}	Microstrip propagation delay
$v_i(t)$	Input voltage in the time domain
A_{stop}	Stopband gain
$I_L(\Omega)$	The transmission loss (dB)

© COPYRIGHT UPM

$R_L(\Omega)$	The reflection loss (return loss) (dB)
$P_{inc.}$	Incident power
$P_{radiated}$	Radiated power of the antenna
$P_{ref.}$	Reflected power
P_s	Supplied power to the antenna
Q_{BP}	Bandpass quality factor
Q_u	The unloaded quality factor
R_L	The loss resistance
R_r	The radiation resistance
R_s	Surface resistance in ohms per unit area
$T_N^2(\frac{\omega}{\omega_p})$	The square magnitude of a Chebyshev approach transfer function
$V_i(s)$	Input voltage in the frequency domain
$V_{inc.}$	The incident wave amplitude, voltage
V_{max}	The maximum amplitude voltage
V_{min}	The minimum amplitude voltage
$V_o(s)$	Output voltage in the frequency domain
$V_{ref.}$	The reflected wave amplitude, voltage
Ω	Angular frequency
μ_o	Free space permeability
α_d	The microstrip attenuation due to the dielectric loss
ε	Material permittivity
μ	Material permeability
ε	The passband ripple parameter

© COPYRIGHT UPM

$\boldsymbol{N}$	The filter order
ω_p	The upper-frequency passband edge
η	Antenna radiation efficiency
ρ	Reflection coefficient
σ	The real part of (s) and is called Neper frequency (neper/second)
$tan\delta$	The loss tangent of the dielectric substrate
Z_o	Characteristic impedance

© COPYRIGHT UPM

CHAPTER 1

INTRODUCTION

1.1 Background

The filter and the antenna are the major parts of wireless communication systems. It is known that the antenna transmits and receives electromagnetic waves and the filter, especially Band Pass Filters (BPF) selects signals in the specific band and rejects the spurious (out-of-band) signals [1]. This caused many inventions in wireless services and products such as Global Positioning System (GPS), Wireless Local Area Network (WLAN), Bluetooth, and mobile phone [2]. In order to obtain the requirements of compactness, low cost, and low profile passive component, many researchers attempts to design filters and antennas simultaneously on a small single module [3]. The integration of filters and antennas in one module achieves filtering and radiating functions at the same time, called filter-antenna [4]. Filter-antenna improves the system performance, such as insertion loss, return loss, Voltage Standing Wave Ratio (*VSWR*), gain and reduces the pre-filtering requests. Several topologies of filter-antenna are designed using filter synthesis approach. Filter synthesis approach consideration that the antenna acts as the last resonator within the filter. Filter-antenna has performed in several forms as well as rectangular patch antenna [5], circular patch antenna [6], patch array antenna [7], Γ-shaped antenna [8], inverted L-antenna [9], slot dipole antenna [10], monopole antenna [11], conductor slot antenna [12], and stuff resonator antenna [13]. Different studies in the literature applied for integration of filter and antenna in a single microwave module [1, 4]. A predesigned BPF with appropriate configurations is directly inserted into the feed position of the patch antenna [1]. For the particular system of measurement, the BPF is often integrated properly with the antenna [2, 4] by exploitation, an additional impedance transformation structure sandwiched the filter and the antenna. The transition structure needs for additional size; therefore, the design did not have a good filter response among the frequency ranges. The design of the filter-antenna following the bandpass filter synthesis method is assigned in [5, 8]. In these designs, an antenna is treated as a series or parallel Resistance, Inductance, and Capacitance (*RLC*) equivalent circuit substituted the last resonator and the load resistance of the BPF. The co-design approach of the filter-antenna did not have a good band-edge selectivity and stopband rejection [2]. This is often due to deficiency of the extraction of the antenna equivalent circuit over a suitable bandwidth, especially at the centre frequency, which has extracted and utilized in the filter synthesis. Furthermore, the antenna gain versus frequency, which is a vital characteristic of the filter-antenna, has been considered in this study. Integration of a compact dual-band microstrip filter with dual-band antenna leads to the formation of a dual-band filter-antenna. The WLAN is usually used in commercial and residential complex networks providing wireless access to their customers. Almost all WLAN's modems are based on IEEE 802.11 standards. The bandwidths of IEEE 802.11b/g and 802.11a/j are 2.4 - 2.483 GHz and 4.905 – 5.845 GHz, respectively. For this reason, it requires a dual-band with broadband for higher data rates to allow for the greatest number of devices to share the available space [14].

© COPYRIGHT UPM

Various designs of patch antennas for WLAN applications have been done to improve the patch antenna performance [15]. Furthermore, the patch antenna typically has a narrow bandwidth and second-harmonic radiation characteristics of the radiation patterns of the high band. Ultra-Wideband (UWB) technology has a big possibility in the development of different modern transmission systems. In February 2002, the U.S Federal communications commission (FCC) licensed the unlicensed use of UWB devices for a spread of applications. Now UWB approach is another way to make high data rate links between devices. This standard depends on a very low power level over very large bandwidth (3.1-10.6 GHz). This requires introducing filtering after or inside the antenna [16]. Many researchers have raised the development of the UWB filters and UWB antennas [17].

1.2 Problem Statement

In this study, integration of microstrip filter and microstrip antenna represents a challenge for many researchers. The filter-antenna circuit has several problem sources, which of course affect the performance of the circuit. These problems are the main reasons for the difference between the simulation and experimental results. Some of these problems can be solved or at least minimizing the adverse effects on the overall circuit performance. The important problem sources are:

- The filter-antenna did not show a good filter performance, especially the band-edge selectivity and stopband suppression [18].
- Filter-antenna generally consists of two separate circuits, therefore; the mismatch problem may exist.
- Size and cost are also the problems faced by the designers, especially in the modern mobile communication systems, such as Wireless Local Area Network (WLAN), Worldwide Interoperability for Microwave Access (WiMAX), satellite communication, and so on which required a small circuit size. Some single-band filter-antenna literature works having a relatively big size such as the design includes in Ref. [19], which has a size of 42.6×42.6 mm^2. In addition, some dual-band filter-antenna literature works having a bigger size such as the design includes in Ref. [20], which has a size of 140×140 mm^2.
- Most microstrip antennas, especially patch antennas have narrow bandwidths of about (2 – 5 %) of the operating frequency that does not cover the requirements of WLAN, WiMAX, and other wireless applications [21].

1.3 Motivation of Study

The microstrip transmission line has become the best known and most widely used planar transmission line for RF/microwave circuits. The microstrip transmission line has some of the favourite specifications such as it is planar nature, ease of fabrication, easily integrated with other RF/microwave circuits and solid-state devices, and good heat sinking. The significance of this study comes from the importance of this topic (filter-antenna). The filter-antenna plays an important role in the overall circuit size

© COPYRIGHT UPM

reduction and improvement of the system noise reduction. In addition, this study focuses directly on the problem sources experienced by the filter-antenna and find the suitable solutions to remove, or at least reduce their effects on the overall circuit performance. Design and fabrication of a compact, low cost, and highly selective single-band and dual-band filter-antennas have been done by using the Computer Simulation Technology software (CST) Microwave Studio Suite. The motivation behind the design of single-band, dual-mode filter-antenna at a center frequency f_o = 5.794 GHz is to cover the WiMAX applications. This frequency band is included in the Industrial, Scientific, and Medical radio band (ISM band). Generally ISM bands are open frequency bands, which are different based on regions and permits. The motivation behind the design of folded SIR dual-band filter-antenna at a first center frequency band f_o = 5.75 GHz is to cover the WLAN requirements based on IEEE 802.11 standards. The bandwidths of IEEE 802.11b/g and 802.11a/j are 2.4 - 2.483 GHz and 4.905 – 5.845 GHz. The second frequency passband is designed at f_o = 8.35 GHz to cover the X-band requirements (8-12GHz). Satellite communication operates in part of the X-band or Super High Frequency (SHF) spectrum which is specified by (ITU). Satellite communication has the frequencies in the range 7.25 GHz to 7.75 GHz (space to earth) and 7.9 GHz to 8.4 GHz (Earth to Space). On the other hand, the designers and researchers should search other frequency bands because many researchers have covered the frequency bands of 2.4GHz, 3.3GHz, 5.2GHz, and 5.8GHz.

Comparison of the proposed filter-antenna design theoretically and experimentally and also a comparison with other research works are important. This is to investigate and validate the performance of the proposed filter-antenna design.

1.4 Aim and Objectives

The aim of this study is to design and develop microwave filter-antennas and investigate the performance by comparing with other kinds of filter-antenna structures. Although the filter-antenna designs are small and compact in size, the application in wireless communication requires much smaller size. Thus new filter-antenna design with low loss and high selective single-band and dual-band is introduced.

© COPYRIGHT UPM

To achieve the aim, the main objectives of the study are as follows:

1. To design a compact, low loss and high selective single-band, dual-mode filter-antenna suitable for WiMAX applications for first frequency passband and dual-band filter-antenna suitable for WLAN applications and satellite communication wireless applications in a second frequency passband, respectively.
2. To simulate, fabricate, and investigate the performance of the single-band and dual-band filter-antennas by comparing with other literature works.
3. To compare the simulated and measured results such as insertion loss, return loss, *VSWR*, gain and circuit size against other filter-antennas at the specific frequency band to achieve the uniqueness of the design process performed in the proposed works.

1.5 Scope of Research

The scope of this thesis is to design and fabricate a new compact microstrip single-band, dual-mode filter-antenna and a new compact folded SIR dual-band filter-antenna for wireless applications. The main reason for the work done in this study is to achieve new compact microstrip filter-antenna designs have filtering and radiating simultaneously on a small single module. The integration of filters and antennas will reduce the overall size of the resulting circuit and highly improve its performance. The design of a single-band filter-antenna is performed by using a new efficient kind of dual-mode resonators to enhance the performance of the filter-antenna. The design of a dual-band filter-antenna is performed by using folded SIR resonators to give a further reduction in the circuit size. The flow chart of this study is shown in Figure 1.1. The yellow colour blocks represent the direction followed in this study to achieve the objectives, while the blue colour blocks are referred to other research areas which are out of the scope of this study.

© COPYRIGHT UPM

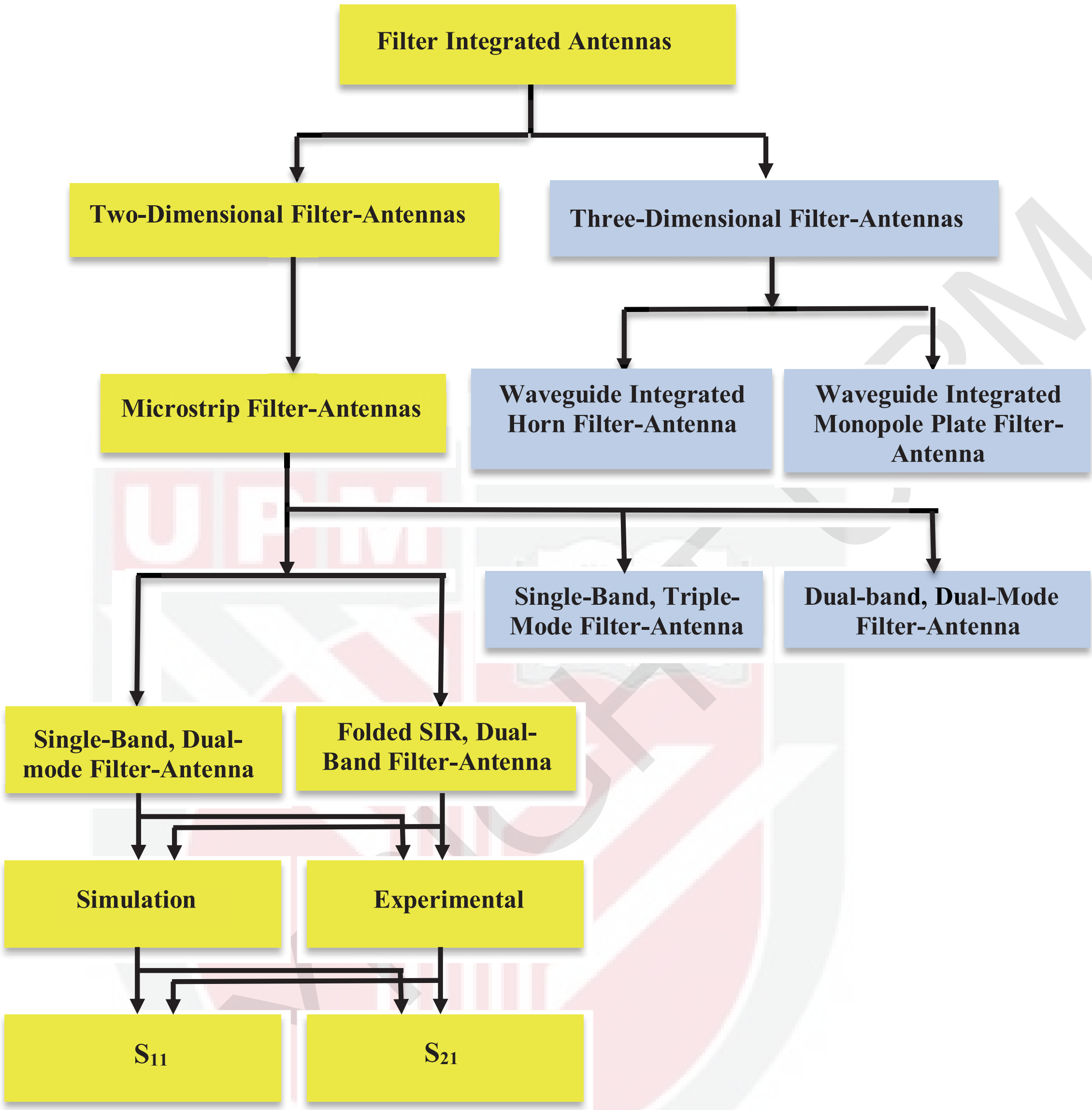

Figure 1.1 : Thesis scope

1.6 Thesis Organization

This thesis is arranged into five chapters, each one is summarized as follows Chapter 1 covers a general introduction to the research study and distinguishes the existing problems in designing the filter-antennas. It also presents the problem statement and motivation of the study, the aim, and objectives, scope of research as well as the organization of the thesis.

Chapter 2 is the literature review. It first gives a background of the filter network theory, which includes the transfer function of the linear system, scattering parameters of the two-port network, filter classifications. It also focuses on the filters, which are based on maximally flat function response and Chebyshev function response. It introduces the frequency transformation and a realization of filters in a microstrip transmission line with some of the design examples. This chapter includes a review and background of a microstrip patch antenna and presents some design examples for different types of patch antennas. Finally, chapter 2 introduces a background and review of microstrip filters integrated microstrip antennas and some of the techniques, for designing filter-antenna. In addition, it presents some of the design examples for different types of filter-antennas for various frequency band applications.

Chapter 3 contains the research methodology and materials that have been performed in the synthesis and design of microstrip single-band and dual-band filter-antennas. It includes the main contribution of this research, which is the design methodology for two new compact microstrip filter-antennas using a new structure of dual-mode resonators and folded SIR resonators. The design procedure steps include choosing the substrate, calculation of some typical parameters and optimized dimensions of the single-band and dual-band filter-antennas.

Chapter 4 is devoted to the results and discussion. All simulated and measured many results of the single-band; dual-mode filter-antenna and the dual-band filter-antenna are stated and compared to prove the validity of the method. It includes the research outcomes and the achievements of the research objectives.

Chapter 5 is the conclusion of the entire thesis that can be acquired from the results of this study. It is followed by the discussion of the main contribution of this study. Finally, possible ideas for future work are proposed.

© COPYRIGHT UPM

REFERENCES

[1] G. Mansour, M. J. Lancaster, P. S. Hall, P. Gardner, and E. Nugoolcharoenlap, "Design of filtering microstrip antenna using filter synthesis approach," *Progress In Electromagnetics Research,* vol. 145, pp. 59-67, 2014.

[2] W.-J. Wu, Y.-Z. Yin, S.-L. Zuo, Z.-Y. Zhang, and J.-J. Xie, "A new compact filter-antenna for modern wireless communication systems," *IEEE Antennas and Wireless Propagation Letters,* vol. 10, pp. 1131-1134, 2011.

[3] C.-T. Chuang and S.-J. Chung, "New printed filtering antenna with selectivity enhancement," in *Microwave Conference, 2009. EuMC 2009. European*, 2009, pp. 747-750.

[4] Z. Zakaria, W. Y. Sam, M. A. Aziz, and M. M. Said, "Microwave filter and antenna for wireless communication systems," in *Wireless Technology and Applications (ISWTA), 2012 IEEE Symposium on*, 2012, pp. 75-80.

[5] M. N. Srifi, M. Meloui, and M. Essaaidi, "Rectangular slotted patch antenna for 5-6GHz applications," *International Journal of microwave and optical technology,* vol. 5, pp. 52-57, 2010.

[6] B. Kwaha, O. Inyang, and P. Amalu, "The circular microstrip patch antenna–design and implementation," *Journal of IJRRAS,* vol. 8, pp. 86-95, 2011.

[7] S. Yahya, "Design of 4 elements rectangular microstrip patch antenna with high gain for 2.4 GHz applications," *Modern applied science,* vol. 6, p. 68, 2011.

[8] M. A. Dorostkar, R. Azim, and M. Islam, "A novel Γ-shape fractal antenna for wideband communications," *Procedia Technology,* vol. 11, pp. 1285-1291, 2013.

[9] A. Andujar, J. Anguera, C. Puente, and A. Pérez, "On the radiation pattern of the L-shaped wire antenna," *Progress In Electromagnetics Research M,* vol. 6, pp. 91-105, 2009.

[10] D. Deepa and C. Poongodi, "Design and Analysis of Printed Dipole Slot Antenna for WLAN and RFID Applications," Adv. Studies Theor. Phys., vol. 8, 2014, no. 14, 635 - 641, 2014.

[11] M. Villegas, J.-L. Polleux, X. Begaud, J. Kaur, R. Khanna, and M. Kartikeyan, "Novel dual-band multistrip monopole antenna with defected ground structure for WLAN/IMT/BLUETOOTH/WIMAX applications," *International Journal of Microwave and Wireless Technologies,* vol. 6, pp. 93-100, 2014.

[12] A. Ghosh and S. Das, "Gain Enhancement of Slot Antenna Using Laminated Conductor Layers," in *Devices, Circuits and Communications (ICDCCom), 2014 International Conference on*, 2014, pp. 1-4.

© COPYRIGHT UPM

[13] A. Sharma and R. Gangwar, "Circularly Polarized Hybrid Z-Shaped Cylindrical Dielectric Resonator Antenna for Multiband Applications," IET Microwaves, Antennas & Propagation, vol. 10, pp. 1259 – 1267, 2016.

[14] I. Yeom, J. M. Kim, and C. W. Jung, "Dual-band slot-coupled patch antenna with broad bandwidth and high directivity for WLAN access point," *Electronics Letters,* vol. 50, pp. 726-728, 2014.

[15] C. won Jung and F. De Flaviis, "A dual-band antenna for WLAN applications by double rectangular patch with 4-bridges," in *Antennas and Propagation Society International Symposium, 2004. IEEE*, 2004, pp. 4280-4283.

[16] J.-F. Pintos, P. Chambelin, A. Louzir, and D. Rialet, "Low cost UWB printed dipole antenna with filtering feature," in *2008 IEEE Antennas and Propagation Society International Symposium*, 2008, pp. 1-4.

[17] S. W. Wong, T. G. Huang, C. X. Mao, Z. N. Chen, and Q. X. Chu, "Planar filtering ultra-wideband (UWB) antenna with shorting pins," *IEEE Transactions on Antennas and Propagation,* vol. 61, pp. 948-953, 2013.

[18] C.-T. Chuang and S.-J. Chung, "A new compact filtering antenna using defected ground resonator," in *Microwave Conference Proceedings (APMC), 2010 Asia-Pacific*, 2010, pp. 1003-1006.

[19] B. Ding, X. Wei, C. Wang, M. Zhang, Z. He, and Y. Shi, "A compact printed filtering antenna with flat gain using annular slot and UIR," in *Electronic Packaging Technology (ICEPT), 2014 15th International Conference on*, 2014, pp. 1252-1255.

[20] C.-K. Lin and S.-J. Chung, "A filtering microstrip antenna array," *IEEE Transactions on Microwave Theory and Techniques,* vol. 59, pp. 2856-2863, 2011.

[21] M. Abbaspour and H. R. Hassani, "Wideband star-shaped microstrip patch antenna," *Progress In Electromagnetics Research Letters,* vol. 1, pp. 61-68, 2008.

[22] H. Sandberg and E. Mollerstedt, "Frequency-domain analysis of linear time-periodic systems," *IEEE Transactions on Automatic Control,* vol. 50, pp. 1971-1983, 2005.

[23] J. S. Lee, "Microwave resonator filters for advanced wireless systems," The University of Michigan, Thesis, 2009.

[24] V. V. Pillai, "Design Of Microwave Non-redundant Band-pass Filter Using Microstrip And Edge Coupled Sections," University of Texas, Thesis, 2010.

[25] I. Hunter, *Theory and design of microwave filters*: Institute of Engineering and technology, UK, 2001.

© COPYRIGHT UPM

[26] J. S. Hong, "Basic Concepts and Theories of Filters," *Microstrip Filters for RF/Microwave Applications, Second Edition,* pp. 28-74, 2001.

[27] L. D. Thede, *Practical analog and digital filter design*: Artech House New Jersey, 2005.

[28] T. C. Edwards, T. Edwards, and M. Steer, *Foundations for microstrip circuit design*: John Wiley & Sons, 2016.

[29] Z. Ye and H. Mohamadian, "Application of modern control theory on performance analysis of generalized notch filters," in *Modern Circuits and Systems Technologies (MOCAST), 2016 5th International Conference on*, 2016, pp. 1-4.

[30] S. Saeedi, J. Lee, and H. H. Sigmarsson, "A New Property of Maximally-Flat Lowpass Filter Prototype Coefficients with Application in Dissipative Loss Calculations," *Progress In Electromagnetics Research C,* vol. 63, pp. 1-11, 2016.

[31] J.-S. G. Hong and M. J. Lancaster, *Microstrip filters for RF/microwave applications* vol. 167: John Wiley & Sons, 2004.

[32] K. L. Su, *Analog filters*: Springer Science & Business Media, 2012.

[33] T. A. Milligan, *Modern antenna design*: John Wiley & Sons, 2005.

[34] C. A. Balanis, *Antenna theory: analysis and design*: John Wiley & Sons, 2016.

[35] N. Parmar, M. Saxena, and K. Nayak, "Review of Microstrip Patch Antenna for WLAN and WiMAX Application," *International Journal of Engineering Research And Applications,* vol. 4, pp. 168-171, 2014.

[36] H. Kobayashi, "Radiation pattern of rectangular patch antenna with curved surface," in *Electromagnetic Theory (EMTS), 2016 URSI International Symposium on*, 2016, pp. 721-724.

[37] D. Moernaut and D. Orban, "The Basics of Patch Antennas," Globalnet's RF & Microwave Solutions Update, Orban Microwave Products, 2006.

[38] R. Elliott and E. Gillespie, "IEEE Standard definitions of terms for antennas," *IEEE Transactions on Antennas and Propagation,* vol. 31, pp. 1-29, 1983.

[39] C. Fung, "Basic Antenna Theory and Application," WORCESTER POLYTECHNIC INSTITUTE, Thesis, 2011.

[40] I. Purdie, "Antenna basics" www. *Electronic-Tutorials. com,* 2008.

[41] W. L. Stutzman and G. A. Thiele, *Antenna theory and design*: John Wiley & Sons, 2012.

© COPYRIGHT UPM

[42] K. M. Singh, *Design of Square Patch Microstrip Antenna for Circular Polarization*: LAP LAMBERT Academic Publishing, Thesis, 2012.

[43] I. Singh and D. V. Tripathi, "Micro strip patch antenna and its applications: a survey," *Int. J. Comp. Tech. Appl,* vol. 2, pp. 1595-1599, 2011.

[44] N. Ahuja, R. Khanna, and J. Kaur, "Design of Single Band Rectangular Patch Antenna for WLAN Application," in *IJCA Proceedings on International Conference on Recent Advances and Future Trends in Information Technology (iRAFIT 2012)*, 2012, pp. 29-31.

[45] S. Song and B. Issac, "Analysis of WiFi and WiMAX and Wireless Network Coexistence," International Journal of Computer Networks & Communications (IJCNC), vol. 6, pp. 63-78, 2014.

[46] N. Ahuja, R. Khanna, and J. Kaur, "Design of Single Band Rectangular Patch Antenna for WLAN Application," *Department of Electronics&Comunication Engineering Thapar University, Patiala, Punjab, (iRAFIT 2012), pp. 29-31,* 2012.

[47] D. Guha and Y. M. Antar, *Microstrip and printed antennas: new trends, techniques and applications*: John Wiley & Sons, 2011.

[48] J. R. Panda and R. S. Kshetrimayum, "Parametric study of printed rectangular monopole antennas," *International Journal of Recent Trends in Engineering,* vol. 1, pp. 42-46, 2009.

[49] Y. Li, Z. Zhang, J. Zheng, and Z. Feng, "Design of dual-polarized monopole-slot antenna with small volume and high isolation," *IEEE Transactions on Antennas and Propagation,* vol. 60, pp. 2511-2514, 2012.

[50] D. Orban and G. Moernaut, "The basics of patch antennas, updated," *RF Globalnet (www. rfglobalnet. com) newsletter,* 2009.

[51] A. Arora, A. Khemchandani, Y. Rawat, S. Singhai, and G. Chaitanya, "Comparative study of different feeding techniques for rectangular microstrip patch antenna," *IJIREEICE,* vol. 3, pp. 32-5, 2015.

[52] D. M. Elsheakh and E. A. Abdallah, "Different feeding techniques of microstrip patch antennas with spiral defected ground structure for size reduction and ultra-wide band operation," *Journal of Electromagnetic Analysis and Applications,* vol. 4, p. 410, 2012.

[53] A. Arora, A. Khemchandani, Y. Rawat, S. Singhai, and G. Chaitanya, "Comparative study of different feeding techniques for rectangular microstrip patch antenna," *International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering,* vol. 3, pp. 32-35, 2015.

[54] K. F. Leea and K.-F. Tongb, "Microstrip patch antennas," Imperial College Press, UK, 2015.

© COPYRIGHT UPM

[55] M. D. Sharma, A. Katariya, and R. Meena, "Broad Band Aperture Coupled Microstrip Antenna with Dual Feed and Three Feed Technique," in *Communication Systems and Network Technologies (CSNT), 2012 International Conference on*, 2012, pp. 62-65.

[56] A. Kumar, J. Kaur, and R. Singh, "Performance analysis of different feeding techniques," *International Journal of Emerging Technology and Advanced Engineering,* vol. 3, pp. 884-890, 2013.

[57] P. Singh and R. Tomar, "The use of defected ground structures in designing microstrip filters with enhanced performance characteristics," *Procedia Technology,* vol. 17, pp. 58-64, 2014.

[58] A. Thatere, P. Zade, and D. Arya, "Bandwidth enhancement of microstrip patch antenna using 'U'slot with modified ground plane," in *Microwave, Optical and Communication Engineering (ICMOCE), 2015 International Conference on*, 2015, pp. 408-411.

[59] K. A. Hamad, "Design and Enhancement Bandwidth of Rectangular Patch Antenna Using Single Trapezoidal Slot Technique," *ARPN-JEAC, ISSN,* vol. 7, pp. 292-297, 2012.

[60] A. Singh, K. Kamakshi, M. Aneesh, and J. Ansari, "Slots and notches loaded microstrip patch antenna for wireless communication," *Indonesian Journal of Electrical Engineering and Computer Science,* vol. 13, pp. 584-594, 2015.

[61] J. B. Jadhav and P. J. Deore, "Filtering antenna with radiation and filtering functions for wireless applications," *Journal of Electrical Systems and Information Technology,* vol. 4, pp. 125–134, 2017.

[62] C. Xinwei, Z. Fengxian, Y. Liyun, and Z. Wenmei, "A Compact Filtering Antenna With Flat Gain Response Within the Passband," *Antennas and Wireless Propagation Letters, IEEE,* vol. 12, pp. 857-860, 2013.

[63] J.-H. Lee, N. Kidera, S. Pinel, J. Laskar, and M. M. Tentzeris, "Fully integrated passive front-end solutions for a V-band LTCC wireless system," *IEEE Antennas and Wireless Propagation Letters,* vol. 6, pp. 285-288, 2007.

[64] N. Yang, C. Caloz, and K. Wu, "Co-designed CPS UWB filter-antenna system," in *2007 IEEE Antennas and Propagation Society International Symposium*, 2007, pp. 1433-1436.

[65] K.-W. Li, W.-B. Tsai, and C.-J. Wang, "Enhancement of impedance bandwidth for the microstrip monopole slot antenna," in *Progress in Electromagnetic Research Symposium (PIERS)*, 2016, pp. 105-105.

[66] T. Le Nadan, J. Coupez, S. Toutain, and C. Person, "Integration of an antenna/filter device, using a multi-layer, multi-technology process," in *Microwave Conference, 1998. 28th European*, 1998, pp. 672-677.

© COPYRIGHT UPM

[67] A. Abbaspour-Tamijani, J. Rizk, and G. Rebeiz, "Integration of filters and microstrip antennas," in *Antennas and Propagation Society International Symposium, 2002. IEEE*, 2002, pp. 874-877.

[68] F. Queudet, I. Pele, B. Froppier, Y. Mahe, and S. Toutain, "Integration of pass-band filters in patch antennas," in *2002 32nd European Microwave Conference*, 2002, pp. 685-688.

[69] W.-J. Wu, R. Fan, C. Wang, and J. Wang, "A compact and anti-interference filter-antenna for modern wireless communication systems," in *Microwave, Antenna, Propagation, and EMC Technologies (MAPE), 2015 IEEE 6th International Symposium on*, 2015, pp. 60-62.

[70] E. Nugoolcharoenlap, "New design approach of antennas with integrated coupled resonator filters," University of Birmingham, Thesis, 2015.

[71] J. N. Lee, J. H. Yoo, J. H. Kim, J. K. Park, and J. S. Kim, "The Design of UWB Bandpass Filter-Combined Ultra-Wide Band Antenna," in *Vehicular Technology Conference, 2008. VTC 2008-Fall. IEEE 68th*, 2008, pp. 1-5.

[72] Y. Chen and Y. Zhou, "Design of a filter-antenna subsystem for UWB communications," in *Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications, 2009 3rd IEEE International Symposium on*, 2009, pp. 593-595.

[73] D. Zayniyev and D. Budimir, "An integrated antenna-filter with harmonic rejection," *EuCAP 2009,* pp. 393-394, 2009.

[74] J. Zuo, X. Chen, G. Han, L. Li, and W. Zhang, "An integrated approach to RF antenna-filter co-design," *IEEE Antennas and Wireless Propagation Letters,* vol. 8, pp. 141-144, 2009.

[75] D. Zayniyev and D. Budimir, "Dual-band microstrip antenna filter for wireless communications," in *2010 IEEE Antennas and Propagation Society International Symposium*, 2010, pp. 1-4.

[76] C.-T. Chuang and S.-J. Chung, "Synthesis and design of a new printed filtering antenna," *IEEE Transactions on Antennas and Propagation,* vol. 59, pp. 1036-1042, 2011.

[77] N. S. Bhuvana and S. K. Menon, "OLR-filtenna for Wi-Fi applications," in *Progress in Electromagnetic Research Symposium (PIERS)*, 2016, pp. 1968-1971.

[78] A. I. Abunjaileh, I. C. Hunter, and A. H. Kemp, "A circuit-theoretic approach to the design of quadruple-mode broadband microstrip patch antennas," *IEEE transactions on microwave theory and techniques,* vol. 56, pp. 896-900, 2008.

© COPYRIGHT UPM

[79] S. Oda, S. Sakaguchi, H. Kanaya, R. Pokharel, and K. Yoshida, "Electrically small superconducting antennas with bandpass filters," *IEEE Transactions on Applied Superconductivity,* vol. 17, pp. 878-881, 2007.

[80] Z. Wang, P. Hall, and P. Gardner, "Yagi antenna with frequency domain filtering performance," in *Proceedings of the 2012 IEEE International Symposium on Antennas and Propagation*, 2012, pp. 1-2.

[81] Y. Yang and M. Lancaster, "Waveguide slot antenna with integrated filters," in *32 European Space Agency Workshop*, pp. 412-416, 2010.

[82] E. H. Lim and K. W. Leung, "Use of the dielectric resonator antenna as a filter element," *IEEE Transactions on Antennas and Propagation,* vol. 56, pp. 5-10, 2008.

[83] C.-T. Chuang and S.-J. Chung, "A new compact filtering antenna using defected ground resonator," in *2010 Asia-Pacific Microwave Conference*, 2010, pp. 1003-1006.

[84] X. Chen, F. Zhao, L. Yan, and W. Zhang, "A compact filtering antenna with flat gain response within the passband," *Antennas and Wireless Propagation Letters, IEEE,* vol. 12, pp. 857-860, 2013.

[85] C.-S. Yang, P.-H. Chen, J.-H. Lu, and C. F. Jou, "A three-order equal-ripple band-pass filtering antenna design using capacitive-gap coupled asymmetrical-CPW resonator," in *Antenna Technology:" Small Antennas, Novel EM Structures and Materials, and Applications"(iWAT), 2014 International Workshop on*, 2014, pp. 389-391.

[86] L. Chen and Y.-L. Luo, "Compact filtering antenna using CRLH resonator and defected ground structure," *Electronics Letters,* vol. 50, pp. 1496-1498, 2014.

[87] C.-K. Lin and S.-J. Chung, "A filtering microstrip antenna array," *Microwave Theory and Techniques, IEEE Transactions on,* vol. 59, pp. 2856-2863, 2011.

[88] Y.-J. Lee, G.-W. Cao, and S.-J. Chung, "A compact dual-band filtering microstrip antenna with the same polarization planes," in *2012 Asia Pacific Microwave Conference Proceedings*, 2012, pp. 1178-1180.

[89] C.-Y. Hsieh, C.-H. Wu, and T.-G. Ma, "A compact dual-band filtering patch antenna using step impedance resonators," *IEEE Antennas and wireless propagation letters,* vol. 14, pp. 1056-1059, 2015.

[90] W.-J. Wu, Q.-F. Liu, Q. Zhang, and J.-Y. Deng, "Co-Design of a Compact dual-band filter-antenna for WLAN application," *Progress In Electromagnetics Research Letters,* vol. 40, pp. 129-139, 2013.

[91] W. Z. Shareef, "Miniaturization of microstrip and CPW-fed UWB printed antennas with band rejection characteristics," Universiti Putra Malaysia, Thesis, 2010.

© COPYRIGHT UPM

[92] K.-W. Yeom, *Microwave Circuit Design: A Practical Approach Using ADS*: Prentice Hall Press, 2015.

[93] B. Jitha and C. Aanandan, "Development of compact microwave filters using microstrip loop resonators," Cochin University of Science and Technology, Thesis, 2010.

[94] M. Meng, "Design and synthesis of lossy microwave filters," University of Leeds, Thesis, 2014.

[95] I. C. Hunter, L. Billonet, B. Jarry, and P. Guillon, "Microwave filters-applications and technology," *IEEE Transactions on microwave theory and techniques,* vol. 50, pp. 794-805, 2002.

[96] D. G. Swanson, "Narrow-band microwave filter design," *IEEE Microwave magazine,* vol. 8, pp. 105-114, 2007.

[97] M. T. Nguyen, B. Kim, H. Choo, and I. Park, "Effects of ground plane size on a square microstrip patch antenna designed on a low-permittivity substrate with an air gap," in *Antenna Technology (iWAT), 2010 International Workshop on*, 2010, pp. 1-4.

[98] M. A. Afridi, "Microstrip Patch Antenna− Designing at 2.4 GHz Frequency," *Biological and Chemical Research,* vol. 128, p. 132, 2015.

[99] V. Ahumada, M. del Castillo, F. L. Mesa Ledesma, J. Martel Villagrán, and F. Medina Mena, "Design of a band-pass filter using stepped impedance resonators with floating conductors," *Progress In Electromagnetics Research,* vol. 105, pp. 31-48, 2010.

[100] T. Yang, M. Tamura, and T. Itoh, "Compact hybrid resonator with series and shunt resonances used in miniaturized filters and balun filters," *IEEE Transactions on microwave Theory and Techniques,* vol. 58, pp. 390-402, 2010.

[101] K. Yoon, H. Lee, J. Lee, J. Park, T. Kim, T. Jung, *et al.*, "Open Stub Band-pass Filter Using Stepped Impedance Resonator for Size Reduction," Session 2PK, pp. 1168-1171, 2013.

[102] J. Lee, K.-C. Yoon, H. Lee, T.-S. Jung, T.-Y. Kim, and J.-C. Lee, "Short stub band-pass filter using stepped impedance resonator for size reduction," in Microwave Conference Proceedings (APMC), 2013 Asia-Pacific, 2013, pp. 875-877.

[103] J.-T. Kuo and E. Shih, "Microstrip stepped impedance resonator bandpass filter with an extended optimal rejection bandwidth," *IEEE Transactions on microwave theory and techniques,* vol. 51, pp. 1554-1559, 2003.

© COPYRIGHT UPM

[104] X. Chen, G. Han, R. Ma, J. Gao, and W. Zhang, "Design of balanced dual-band bandpass filter with self-feedback structure," *ETRI journal,* vol. 31, pp. 475-477, 2009.

[105] H. Liu, X. Sun, and Z. Li, "A new parameter-extraction method for DGS and its application to the low-pass filter," *Active and passive electronic components,* vol. 27, pp. 119-123, 2004.

[106] R. Rodrigo, "Fundamental Parameters of Antennas," Lecture Notes, Arizona State University, 2010.

[107] R. Hopkins, "The Microstrip Ring Resonator for Characterising Microwave Materials," *Advanced Technology Institute, School of Electronics and Physical Science, University of Surrey,* Thesis, 2006.

[108] L. E. Larson, *RF and microwave circuit design for wireless communications*: Artech House, Inc., 1996.

[109] S. Zuo, W.-J. Wu, and Z.-Y. Zhang, "A simple filtering-antenna with compact size for WLAN application," *Progress In Electromagnetics Research Letters,* vol. 39, pp. 17-26, 2013.

[110] Y.-J. Lee, G.-W. Cao, and S.-J. Chung, "A compact dual-band filtering microstrip antenna with the same polarization planes," in *Microwave Conference Proceedings (APMC), 2012 Asia-Pacific*, 2012, pp. 1178-1180.

[111] S. Gupta, S. S. Dhillon, P. Khera, and A. Marwaha, "Dual band U-slotted microstrip patch antenna for C band and X band radar applications," in *Computational Intelligence and Communication Networks (CICN), IEEE, 2013 5th International Conference on*, 2013, pp. 41-45.

© COPYRIGHT UPM