AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
CAIRO-EGYPT

# Design and Implementation of Compact and Reconfigurable Planar Filters

A Thesis
Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in the Electrical Engineering

**Submitted by**
Eng. Hesham Abd Elhady Mohammed Abd Elhady
M.Sc. of Electrical Engineering

**Supervised by**
Prof. Esmat Abdel-Fattah Abdallah
Prof. Hadia Mohamed Said El Hennawy
Dr. Heba Badr El-Din El-Shaarawy

**Cairo, Egypt**

**2014**

AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
CAIRO-EGYPT

## Examiners Committee

**Name:** Hesham Abd Elhady Mohammed Abd Elhady
**Thesis:** Design and Implementation of Compact and Reconfigurable Planar Filters
**Degree:** Doctor of Philosophy in Department of Electronics and Communication Engineering.

| | Name, Title and Affiliation | Signature |
|---|---|---|
| 1 | **Prof. Abdel Razik Abdelmgeed Sebak**<br>Professor in Electrical and Computer Engineering, Concordia University. | ……………………… |
| 2 | **Prof. Dr. Abdelhalim A. Zekry**<br>Professor in Electrical and Communication Engineering, Ain Shams University. | ……………………… |
| 3 | **Prof. Esmat Abdel-Fattah Abdallah**<br>Former President of Electronics Research Institute and Professor in Microstrip Dep. | ……………………… |
| 4 | **Prof. Hadia Mohamed Said El Hennawy**<br>Former Dean of Faculty of Engineering, Ain Shams University and Professor in Electronics and Communication Dep. | ……………………… |

Date: / / 2014

# ACKNOWLEDGEMENTS

All gratitude is due to " *ALLAH* " who guides me to bring forth to light this thesis.

Pursuing Ph.D in Design and implementation of compact and reconfigurable planar filters is one of the most valuable and exciting experiences in my education. The knowledge I learned and confidence I gained during the studying years will be beneficial to my whole life.

I owe my deepest gratitude to my supervisor, Prof. Dr. Esmat A. Abdallah, *Former President of Electronics Research Institute*, whose encouragement, guidance and support from the initial to the final level enabled me to develop an understanding of the subject. Prof. Dr. Esmat teaches me how to be a researcher, how to be patient and how to deal with research problems quietly. Prof. Dr. Esmat exerts extreme efforts in revising thesis and papers, never forgetting any details. As a matter of fact, this thesis would not have been possible without her deeply insight, opinions and her widely knowledge (God bless her).

I also want to thank Prof. Dr. Hadia M. S. Elhennawy, Former Dean of Ain Shams University, Egypt for her interest in microwave components and her guidance in Ph.D qualification courses.

Also my deepest gratitude and sincerest thanks to Dr. Heba Badr El-Din El-Shaarawy for her supervision, fruitful guidance through the course of the work, encouragement, endless help and many illuminating discussions.

Thanks for my colleagues and friends in Microstrip Department and the Electronics Research Institute staff for being around me helping and caring.

Also, I would like to thank Prof. Ashraf S. Mohra, Chairmen of Microstrip Department of ERI for assisting me in soldering and measurement process, many thanks for the staff of Microstrip Department.

Also, I would like to thank my family. I am very grateful to my mother, brothers who encouraged and supported me. I owe all my achievement to my wife Dr. Nagwa Ibrahim, who always encourages me for further progress, and my two kids, Raghd and Abd Allah, who shares all my joy and bitterness every day and night. I also, would like to thank my father.

# Curriculum Vitae

| | |
|---|---|
| Name of the Researcher | Hesham Abd Elhady Mohammed Abd Elhady |
| Date of Birth | 1st of October 1979 |
| Place of Birth | Sharkia, Egypt |
| Last University Degree | M.Sc in Electrical Engineering, Electronics and Communication Department, Ain-Shams University |
| Date of Degree | April, 2009. |

# STATEMENT

This Thesis is submitted for the degree of Doctor of Philosophy to the Department of Electronics and Communication Engineering, Faculty of Engineering of Ain Shams University, 2014.

The work included in this thesis was carried out by the author in the Department of Electronics and Communication Engineering, Ain Shams University and Electronics Research Institute, Microstrip Department.

No part of this Thesis has been submitted for a degree or a qualification at any other university or institute.

Name: Hesham Abd Elhady Mohammed Abd Elhady

Signature:

Date:

## Published Papers

1. Hesham A. Mohamed, H. B. El-Shaarawy, E. Abdallah and H. S. El-Hennawy, "Design of miniaturized reconfigurable UWB–BPF" IEEE Asia Pacific Microwave Conference (APMC 2012), Kaohsiung, Taiwan, pp. 741-743, Dec. 4-7, 2012.
2. Hesham A. Mohamed, H. B. El-Shaarawy, E. Abdallah and H. S. El-Hennawy, " Design of reconfigurable miniaturized UWB-BPF with tuned notched band" Progress In Electromagnetics Research B, Vol. 51, pp. 347-365, 2013.
3. Hesham A. Mohamed, H. B. El-Shaarawy, E. Abdallah and H. S. El-Hennawy, "Miniaturized and reconfigurable 2U-shaped DGS based UWB-BPF with notched band" Proceedings of IEEE International Symposium of Antennas and Propagation Society (APSURSI), Florida, USA, July 2013.
4. Hesham A. Mohamed, H. B. El-Shaarawy, E. Abdallah and H. S. El-Hennawy. " Reconfigurable BPF using dual mode resonator and RF PIN diodes" PIERS 2013 in Stockholm, Sweden, 12-15 August, 2013.
5. Hesham A. Mohamed, H. B. El-Shaarawy, E. Abdallah and H. S. El-Hennawy, "Compact dual mode switchable BPF – BSF using RF PIN diodes and DGS" IEEE Asia Pacific Microwave Conference (APMC 2009), APMC, Coex in Seoul, Korea, pp. 651-653, Nov. 5-8, 2013.
6. Hesham A. Mohamed, H. B. El-Shaarawy, E. Abdallah and H. S. El-Hennawy, "Reconfigurable compact dual mode resonators UWB-BPF using DGS and RF PIN diodes" International Journal of Engineering & Technology IJET-IJENS Vol.14, No.1, pp.19-23, 2014.
7. Hesham A. Mohamed, H. B. El-Shaarawy, E. Abdallah and H. S. El-Hennawy, "A very compact novel multi-band BPF for recent mobile/satellite communication systems "Progress In Electromagnetics Research C, Vol. 50, pp.47-56, 2014.

8 Hesham A. Mohamed, H. B. El-Shaarawy, E. Abdallah and H. S. El-Hennawy, “Frequency-reconfigurable microstrip filter with dual mode resonators using RF PIN diodes and DGS" International Journal of Microwave and Wireless Technologies, Cambridge University Press and the European Microwave Association. Received 23 February 2014; Revised 25 June 2014; Accepted 2 July 2014.

AIN SHAMS UNIVERSITY
FACULTY OF ENGINEERING
CAIRO-EGYPT

Electronics and Communication Department

**Supervised by**

Prof. Dr. Esmat A. Abdallah, Prof. Dr. Hadia M. Elhennawy, and Dr. Heba Badr El-Din El-Shaarawy

# SUMMARY

The increasing development of wireless applications turns out to new requirements for transceiver architectures that have to feature excellent microwave performances (linearity, spurious rejection, noise figure and bandwidth) and enhanced integration density that are achieved through the miniaturization of the modules as well as the introduction of multi standard functionalities. All these requirements translate to the need of filter circuits as miniaturized as possible and featuring the highest performances in term of insertion loss and rejection. Microwave filters possessing various forms are essential components in radar, satellite and mobile communication systems. Increased demands for low-loss, miniature filters that can be mass produced at low cost have provided a significant challenge reinforcing the need for improving or even replacing the conventional microwave filters.

This thesis introduces the investigation and development of design methodologies for the creation of multi-functional bandpass filters and lowpass filters at microwave frequencies. These filters are capable of tuning to different frequency bands as well as varying their fractional bandwidth.

The work presented here relates to the evolving multifunction philosophy of RF systems.

This thesis presents a comprehensive study of RF reconfigurable planar microwave filters, which generate reliable and scalable filter topologies with tunable properties. The study includes

the analysis of single, dual -mode filters together with an investigation of the coupling behavior of synchronously and asynchronously tuned resonators. This study identified the main properties responsible for frequency and bandwidth control in a filter, and consequently systematically created innovative design techniques.

The research also proposes novel planar microstrip filters employing DGS structures in the form of slots etched on the ground plane. Such filters are not only miniaturized, but also have improved RF performance in both the passband and the stopband. This proposed concept is further extended to implement low-loss tunable bandpass filters, by integrating switching elements directly into the slots. Transmission line circuit models are developed to design the proposed microstrip filters and switchable filters. To verify the concept and the validity of the developed circuit models, theoretical and experimental results are presented and carefully compared. The main goal of this effort is the creation of planar reconfigurable filters with arbitrary assigned transmission zeros. These advanced realizations require meeting complex design specifications of advanced systems in both commercial and military applications.

Over the work introduced, tremendous progress has been made to reduce the size, and enhance the in-band and out-of-band performance of microstrip filters. The experimental measurement results confirm the validity of the theoretical designs of the new filters, which makes this concept very attractive for further applications in both wireless and satellite communication. This work has produced several first time demonstrations of reconfigurable filter techniques, dual-mode, multi-band filters, and miniaturized low pass filter with advanced responses, and several design of filters to obtain the recent technologies with lumped element capacitors, and RF PIN diodes switches. Filters with tunable center frequency, dual-mode resonators were designed with reconfigurable passband width, and center frequency. Moreover, reconfigurable with RF PIN diodes techniques were used as powerful tools for the creation of filters capable of manipulating the location of their transmission zeros. Dual-mode filters that are tunable in frequency provide advantages in the reduction of size and number of tuning elements when compared to single-mode tunable filters today.

A triple-band bandpass filter was designed using spiral lines approach for the first time. The filter topology consists of a meander stub resonant pattern located inside a spiral square loop resonator. A filter prototype was fabricated and measured producing a fully canonical filtering function with three resonant frequencies and three transmission zeros. The final prototype approaches the performance of good filters in terms of loss, while keeping a compact size profile comparable to standard planar filters. The final part of this work is that new high performance filter is miniaturized, reconfigurable and can be easily packaged in microwave components and antenna arrays. A comparison has been made using a single defected ground structure and then using two defects. The simulation firmly establishes the fact that when a single defect is introduced, a reduction of 20 dB in the power level is obtained at 3.5 GHz, the spurious frequency is eliminated in the stop band up to 14 GHz.

Finally, for future work, the implementation of these structures on silicon substrates using MEMS switches and ferroelectric materials is proposed to achieve overall better performance and easy tuning.

# Table of Contents


| Content | Pages |
|---|---|
| Cover page………………………………………………………………. | i |
| Examiners Committee………………………………………………… | ii |
| Acknowledgements …………………………………………………… | iii |
| Curriculum Vitae……………………………………………………... | iv |
| Statement ……………………………………………………………... | v |
| Published Papers ……………………………………………………... | vi |
| Summary………………………………………………………………... | vii |
| Table of Contents……………………………………………………… | x |
| List of Abbreviations…………………………………………………. | xv |
| List of Symbols………………………………………………………. | xvi |
| List of Figures………………………………………………………… | xvii |
| List of Tables…………………………………………………………. | xxviii |
| Chapter 1<br>Introduction | 1 |
| 1.1 Motivation of the thesis ………………………………….... | 1 |
| 1.2 Thesis objectives………………………………….……….… | 1 |
| 1.3 Filter applications in modern commercial systems………..… | 2 |
| 1.4 Software packages used …………………………………….. | 5 |
| 1.5 Achievements and organization of the thesis……………….. | 6 |
| Chapter 2<br>Microwave Filter Synthesis and Design | 8 |
| 2.1 Introduction…………………………………………………… | 8 |
| 2.2 Filter theory………………………………... | 9 |
| 2.2.1 Filter fundamentals and definitions…………... | 9 |
| 2.2.2 Periodic structures ………………………….….. | 13 |
| 2.2.3 Insertion loss method …………………………… | 13 |
| 2.3 RF filter applications ………………………………… | 16 |
| 2.3.1 Evolution of mobile wireless communication networks. | 16 |
| 2.3.2 RF stage of wireless transmitters and receivers | 18 |
| 2.3.3 Flexible frequency discrimination subsystems for reconfigurable radio front ends | 19 |
| 2.3.4 Tunable filter in RFID………………………………….. | 20 |
| 2.3.5 Modern communication and reconfiguration radar systems | 21 |
| Chapter 3 | 25 |
| RF Switches tools and Reconfigurable Planar Filters | 25 |
| 3.1 Introduction………………………………………………. | 25 |
| 3.2 Tools of electronically reconfigurable microstrip circuits | 25 |
| 3.3 RF switches review……………………………….………… | 26 |

| | | |
|---|---|---|
| 3.4 | Important parameters of RF switches | 27 |
| | 3.4.1 Insertion loss | 27 |
| | 3.4.2 Isolation | 27 |
| | 3.4.3 Power handling | 27 |
| | 3.4.4 Operating bandwidth | 27 |
| | 3.4.5 Switching speed | 27 |
| 3.5 | Survey on types of RF switches | 28 |
| | 3.5.1 Electromechanical (MEMS) switches | 28 |
| | 3.5.2 Solid-state switches | 28 |
| 3.6 | PIN diode switches | 28 |
| | 3.6.1 HPND-4005 RF PIN diode | 29 |
| 3.7 | Biasing accessories | 30 |
| | 3.7.1 Bias Tee | 30 |
| | 3.7.2 PIC Microcontroller DC biasing circuit for PIN diode switches | 31 |
| 3.8 | Wideband BPF with reconfigurable bandwidth for BPF | 32 |
| 3.9 | Miniaturized reconfigurable and switchable filter from UWB to 2.4 GHz WLAN using PIN diodes | 37 |
| 3.10 | Wideband reconfigurable bandstop filter | 38 |
| 3.11 | Tunable and reconfigurable DGSs | 40 |
| 3.12 | Reconfigurable microstrip dual-band filter using varactor-tuned stub-loaded stepped-impedance resonators | 43 |
| 3.13 | Conclusion | 45 |
| Chapter 4 | | 46 |
| | Design of Reconfigurable Miniaturized UWB-BPF with Tuned Notched Band | 46 |
| 4.1 | Introduction………………………………………………………. | 46 |
| 4.2 | Previous work………………………….. | 48 |
| | 4.2.1 Ultra-wideband bandpass filters using a multiple-mode resonator (MMR)……………………………… | 48 |
| | 4.2.2 Ultra-wideband bandpass filter using three pairs of impedance-stepped stubs……………………………… | 49 |
| | 4.2.3 Ultra-wideband bandpass filter using broadside-coupled microstrip-coplanar waveguide structure ………………. | 49 |
| | 4.2.4 Ultra-wideband microstrip/coplanar waveguide bandpass filter | 50 |
| | 4.2.5 Design of the UWB bandpass filter by coupled microstrip lines with U-defected ground structure | 51 |
| | 4.2.6 Design of the UWB bandpass filter by coupled double step impedance resonator U-defected ground structure | 52 |
| | 4.2.7 A compact dual-band UWB filter based on the parallel line structure with the slot-line | 53 |
| 4.3 | New U-DGS UWB filter | 54 |
| | 4.3.1 Structure description….. | 55 |
| | 4.3.2 Frequency characteristics of U-DGS | 56 |

4.3.3 Influence of the D-arm length ($D_1$) 56
4.3.4 Influence of the U-arm length ($L_1$) 57
4.3.5 Influence of the U-width ($S_1$) 58
4.3.6 Equivalent lumped circuit model of UWB filter with U-DGS 59
4.3.7 Fabrication and measurements 60
4.4 Design of UWB BPF with notch band 62
4.5 Reconfigurable filter with capacitors in inner U-DGS 65
4.6 Reconfigurable filter with capacitors in outer U-DGS 70
4.7 Reconfigurable filter with RF PIN diode in outer U-DGS 72
4.8 Results and discussion 75
4.9 Conclusion 76
Chapter 5 77
Design of a Compact Dual Mode Resonators with Reconfigurable Frequency 77
5.1 Introduction 77
5.2 The Structure of stepped impedance resonator (SIR) 78
5.3 Operational principle of stepped impedance coupled resonators 78
5.4 Dual-mode resonator. 80
5.4.1 Analysis of the odd mode equivalent circuit 81
5.4.2 Analysis of the even mode equivalent circuit 82
5.5 Design of bandpass filter using symmetrical step-impedance resonator 88
5.6 Two-poles filter parametric analysis 90
5.6.1 Effect of the internal coupled lines length ($L_2$) 90
5.6.2 Influence of the coupled line width ($W_2$) 91
5.6.3 Influence of the admittance $Y_3$ ($W_3$) 92
5.6.4 Influence of the coupled line separation ($t_o$) 93
5.6.5 Influence of the feed coupled line length ($L_1$) 94
5.6.6 Effect of the slot in open stub 95
5.7 Design of the reconfigurable filter 97
5.7.1 Reconfigurable dual mode BPF using two RF PIN diode switches 97
5.7.2 Reconfigurable asymmetric responses filter of transmission-zero 100
5.7.3 Reconfigurable dual mode BPF using varactor diodes 102
5.8 Reconfigurable dual-mode coupled line resonator matched bandstop filter 103
5.8.1 Reconfigurable dual-mode coupled line resonator to match dual bandstop filter 108
5.9 UWB BPF design using DGS 110
5.9.1 Compact defected ground structure in microstrip technology 112
5.9.2 Design of UWB dual mode resonators with DGS 113
5.9.3 Sharpness factor by DGS 115
5.10 Reconfigurable UWB filter structures 117
5.11 Results and discussions 121
5.12 Conclusions 122

Chapter 6 124

Tunable Multi-Band Bandpass Filter with Very Compact Size

6.1 Introduction………………………………………………………. 124

6.2 Basic structure and characteristics of SLR…………… 126

6.3 Analysis of the proposed stub-loaded resonator 127

6.4 The stub loaded resonator characteristics 130

6.5 Feed structures design of dual-band filter …………. 132

6.5.1 Analysis of different feed structures 132

6.5.2 $0^0$ -Feed structure 133

6.5.3 Non $0^0$ Feed structure 136

6.5.4 Switchable microstrip bandpass filters with reconfigurable frequency responses 138

6.6 Design of single BPF for $L_1$ band LTE mobile communications 140

6.7 Centrally loaded resonators to suppressed the $2^{nd}$ harmonic of bandpass filters 141

6.7.1 Characteristics of centrally loaded resonators 141

6.7.2 Design of a harmonic-suppressed bandpass filter 144

6.8 Design of the dual-band bandpass filter with open stub structure 145

6.9 Design of dual-band bandpass filter using compact spiral-shaped microstrip resonators 147

6.10 Reconfigurable single/double band BPF using RF PIN diodes 152

6.11 Design of dual-band microstrip bandpass filters with good in-between isolation 154

6.12 Design of tri-band BPF 156

6.13 Tunable BPF using RF PIN diodes 159

6.14 Results and Discussion 165

6.15 Conclusion 166

Chapter 7 167

Design of Miniaturized Elliptic Low Pass Filter 167

7.1 Introduction 167

7.2 Proposed elliptic function LPF 168

7.3 Elliptic function filter 169

7.4 Design procedure 169

7.4.1 Traditional LPF implementation 171

7.5 The modified microstrip elliptic function LPF 173

7.6 Defected ground structure (DGS) 175

7.6.1 Basic structure and transmission characteristics 177

7.6.2 DGS Unit 177

7.7 Equivalent circuits of DGS 178

7.7.1 LC and RLC equivalent circuits 179

7.7.2 π Shaped equivalent circuits 181

7.7.3 Quasi-static equivalent circuit 182

7.8 Structure description of the proposed DGS 182

| | | |
|---|---|---|
| 7.9 | Spurious suppression in elliptic functions microstrip LPF using two different techniques | 186 |
| 7.10 | Microstrip LPF using proposed asymmetric modified DGS | 189 |
| 7.11 | Microstrip LPF using proposed meander thin slots of DGS | 190 |
| 7.12 | Reconfigurable lowpass filter with three states | 192 |
| 7.13 | Miniaturized LPF using lumped shunt capacitors | 194 |
| 7.14 | Miniaturized LPF using lumped shunt capacitors with ultra-stop band | 196 |
| 7.15 | UWB bandpass filter with wide stopband using lumped coupling capacitors | 197 |
| | 7.15.1 Effect of capacitance on LPF response | 198 |
| | 7.15.2 Simulation and measurement results | 200 |
| 7.16 | Results and discussions | 201 |
| 7.17 | Conclusion | 203 |
| Chapter 8 | | 205 |
| Conclusions and Suggestions of Future Work | | 205 |
| 8.1 | Conclusions | 205 |
| 8.2 | Suggestions of future work | 205 |
| | Appendix data sheet of PIN diode | 207 |
| | References | 209 |

## List of Abbreviations

| | |
|---|---|
| ADS | Advanced Design System |
| BPF | Band Pass Filter |
| BSF | Band Stop Filter |
| CPW | Coplanar Waveguide |
| CST | Computer Simulation Technology |
| DGS | Defected Ground Structure |
| EBG | Electromagnetic Bandgap Structure |
| EM | Electromagnetic |
| FIM | Finite Integral Method |
| GPS | Global Positioning System |
| GSM | Global System for Mobile |
| GUI | Graphical User Interface |
| IC | Integrated Circuits |
| LMDS | Local Multipoint Distribution Systems |
| LPF | Low Pass Filter |
| LTE | Long Term Evolutions |
| MEMS | Micro Electro Mechanical Systems |
| MLS | Microwave Landing System |
| MMDS | Multipoint Multichannel Distribution Systems |
| MMIC | Monolithic Microwave Integrated Circuits |
| MoM | Method-Of-Moments |
| NFC | Near Field Communication |
| PBG | Photonic Band Gap |
| PCB | Printed Circuit Board |
| PCS | Personal Communication System |
| PIN | P Junction Isolator N Junction |
| RF | Radio Frequency |
| RFIC | Radio Frequency Integrated Circuits |
| TV | Television |
| UMTS | Universal Mobile Telecommunications System |
| USB | Universal Serial Bus |
| UWB | Ultra-Wide-Bandwidth |
| VNA | Vector Network Analyzer |
| VSWR | Voltage Standing Wave Ratio |
| Wi-Fi | Wireless Fidelity |
| Wi-MAX | Worldwide Interoperability For Microwave Access |
| WLAN | Wireless Local Area Network |