

# Metamaterial-Inspired Structures for Microwave and Terahertz Applications

by

**Amir Ebrahimi**

B. Eng. (Electrical and Electronic Engineering, First Class Honours),  
University of Mazandaran, Iran, 2008

M. Eng. (Electronic Engineering, First Class Honours),  
Babol Noshirvani University of Technology, Iran, 2011

Thesis submitted for the degree of

**Doctor of Philosophy**

in

Electrical and Electronic Engineering,  
Faculty of Engineering, Computer and Mathematical Sciences  
The University of Adelaide, Australia

2016

**Supervisors:**

Dr Said Al-Sarawi, School of Electrical & Electronic Engineering

Dr Withawat Withayachumnankul, School of Electrical & Electronic Engineering

Prof Derek Abbott, School of Electrical & Electronic Engineering

© 2016  
Amir Ebrahimi  
All Rights Reserved



THE UNIVERSITY  
*of* ADELAIDE

*To my dearest wife, Aida  
and to my Mum, Dad, and Sister  
with all my love.*



# Contents

<b>Contents</b>	<b>v</b>
<b>Statement of Originality</b>	<b>xi</b>
<b>Acknowledgments</b>	<b>xiii</b>
<b>Thesis Conventions</b>	<b>xvii</b>
<b>Awards and Scholarships</b>	<b>xix</b>
<b>Abstract</b>	<b>xxi</b>
<b>Publications</b>	<b>xxiii</b>
<b>List of Figures</b>	<b>xxvii</b>
<b>List of Tables</b>	<b>xxxiii</b>
<b>Chapter 1. Introduction</b>	<b>1</b>
1.1 Introduction . . . . .	2
1.1.1 Metamaterials definition and background . . . . .	2
1.1.2 Research motivations and thesis objectives . . . . .	3
1.2 Statement of original contributions . . . . .	4
1.2.1 Metamaterial-inspired compact filters . . . . .	5
1.2.2 Metamaterial-inspired sensors . . . . .	5
1.2.3 Frequency selective surfaces (FSSs) . . . . .	6
1.3 Overview of the thesis . . . . .	8
<b>Chapter 2. Fundamentals of metamaterials</b>	<b>11</b>
2.1 Introduction . . . . .	12
2.2 Wave propagation in double negative materials . . . . .	13

2.3	Metamaterial transmission lines . . . . .	16
2.3.1	Purely left-handed transmission lines . . . . .	16
2.3.2	Composite right/left-handed transmission lines . . . . .	20
2.4	Implementation of the CRLH TLs . . . . .	22
2.4.1	LC-loaded lines . . . . .	22
2.4.2	Resonator loaded lines . . . . .	23
2.5	Applications of resonant-type metamaterials in filter and sensor designs	28
2.5.1	Application in microwave filters . . . . .	28
2.5.2	Application in microwave sensors . . . . .	29
2.6	Metamaterial-inspired frequency selective surfaces . . . . .	29
2.6.1	Traditional FSSs with resonant unit cells . . . . .	30
2.6.2	Miniaturised elements frequency selective surfaces (FSSs) . . . . .	32
2.7	Chapter summary . . . . .	34
<b>Chapter 3. Metamaterial-inspired dual-mode filters</b>		<b>37</b>
3.1	Introduction . . . . .	38
3.2	Dual-mode complementary split-ring resonator . . . . .	39
3.2.1	Operation principle of the DMCSRR . . . . .	39
3.2.2	Dual-mode bandpass filter based on microstrip-line-coupled DM-CSRR . . . . .	42
3.2.3	Dual-mode bandstop filter based on microstrip-line-coupled DM-CSRR . . . . .	46
3.3	Dual-mode complementary electric-LC resonators . . . . .	51
3.3.1	Complementary electric-LC resonators . . . . .	52
3.3.2	Microstrip line loaded with CELC2 resonator . . . . .	54
3.3.3	Potential applications of CELC2-coupled microstrip line . . . . .	61
3.3.4	Dual-mode bandpass filter design . . . . .	62
3.4	Conclusion . . . . .	62
<b>Chapter 4. Metamaterial-inspired microfluidic sensors</b>		<b>65</b>
4.1	Introduction . . . . .	66

4.2	Operation principle of SRR-based microfluidic sensor . . . . .	67
4.3	Microfluidic sensor based on complementary split-ring resonator (CSRR)	69
4.3.1	Basics of CSRR-based microfluidic sensor . . . . .	70
4.3.2	Fabrication process . . . . .	72
4.3.3	Calibration of the sensor . . . . .	75
4.3.4	Validation of the sensing concept . . . . .	77
4.4	Microfluidic sensor for determination of glucose content in water solutions	80
4.4.1	Structure of the sensor . . . . .	80
4.4.2	Test setup and experimental verification . . . . .	82
4.5	Conclusion . . . . .	84
<b>Chapter 5. Metamaterial-inspired rotation and displacement sensors</b>		<b>87</b>
5.1	Introduction . . . . .	88
5.2	Fundamentals . . . . .	88
5.3	Wide-dynamic range rotation sensor . . . . .	91
5.3.1	Linearising the sensor response . . . . .	94
5.3.2	Sensitivity analysis . . . . .	96
5.3.3	Detecting the rotating direction . . . . .	97
5.3.4	Experimental results . . . . .	97
5.4	Displacement sensor . . . . .	100
5.4.1	Operation principle of the sensor . . . . .	100
5.4.2	Measurement results . . . . .	101
5.5	Conclusion . . . . .	101
<b>Chapter 6. Microwave tunable and dual-band frequency selective surfaces</b>		<b>105</b>
6.1	Introduction . . . . .	106
6.2	Varactor-based tunable single-pole FSS . . . . .	107
6.2.1	FSS structure and operation principle . . . . .	107
6.2.2	Application in higher-order FSS design . . . . .	111
6.3	Varactor-based second-order tunable FSS with embedded bias network .	113
6.3.1	FSS structure and equivalent circuit model . . . . .	114

6.3.2	Synthesis procedure for the FSS . . . . .	117
6.3.3	Tuning mechanism . . . . .	120
6.3.4	Structure realisation . . . . .	121
6.3.5	Results and discussion . . . . .	123
6.4	Ka-band tunable FSS based on liquid crystals . . . . .	127
6.4.1	Liquid crystal-based tuning mechanism . . . . .	129
6.4.2	Design and modelling of the FSS . . . . .	131
6.4.3	Results and discussions . . . . .	133
6.5	Dual-band FSS based on miniaturised elements . . . . .	135
6.5.1	The FSS design principle . . . . .	136
6.5.2	FSS synthesis based on the circuit model . . . . .	138
6.5.3	Simulation results and discussions . . . . .	139
6.6	Conclusion . . . . .	142
<b>Chapter 7. Terahertz frequency selective surfaces</b>		<b>145</b>
7.1	Introduction . . . . .	146
7.2	Second-order terahertz FSS on quartz substrate . . . . .	147
7.2.1	FSS topology . . . . .	147
7.2.2	Simulation results and discussion . . . . .	148
7.3	Second-order terahertz FSS on PDMS substrate . . . . .	150
7.3.1	FSS structure and equivalent circuit model . . . . .	151
7.3.2	Synthesis procedure of the proposed FSS . . . . .	153
7.3.3	Design of terahertz FSS . . . . .	157
7.3.4	Fabrication process . . . . .	161
7.3.5	Results and discussion . . . . .	163
7.4	Conclusion . . . . .	164
<b>Chapter 8. Conclusion and future work</b>		<b>169</b>
8.1	Part I: Metamaterial-inspired filters . . . . .	170
8.1.1	Metamaterial-inspired dual-mode filters: Chapter 3 . . . . .	170
8.2	Part II: Metamaterial-inspired sensors . . . . .	171



8.2.1	Metamaterial-inspired microfluidic sensors: Chapter 4 . . . . .	171
8.2.2	Metamaterial rotation and displacement sensors: Chapter 5 . . . . .	172
8.3	Part III: Metamaterial-inspired FSSs . . . . .	173
8.3.1	Tunable and dual-band FSSs: Chapter 6 . . . . .	173
8.3.2	Miniaturised elements terahertz FSSs: Chapter 7 . . . . .	174
<b>Bibliography</b>		<b>175</b>
<b>List of Acronyms</b>		<b>191</b>
<b>Index</b>		<b>193</b>
<b>Biography</b>		<b>195</b>



# Statement of Originality

I certify that this work contains no material, which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan, photocopying, and dissemination through the library digital thesis collection subject to the provisions of the Copyright Act 1968.

I also give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search, the Australian Digital Thesis Program (ADTP), and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Signed

06/01/2016

---

Date



# Acknowledgments

First and foremost, I would like to convey my deepest gratitude to my supervisors **Dr Said Al-Sarawi**, **Dr Withawat Withayachumnankul** and **Prof. Derek Abbott** for their guidance and support throughout my candidature. My principal supervisor, Dr Al-Sarawi advised me with his open view and broad knowledge in the field of electronic engineering and circuit design. His critical, and thoughtful comments were always constructive and fruitful to improve the quality of my research. I had also the pleasure to work with Dr Withawat Withayachumnankul. His deep knowledge in the field of electromagnetics, microwave and terahertz engineering have been of great importance toward my research. He always welcomed scientific discussion and has given me critical feedback. I have endured many hard times in thoroughly revising the drafts to satisfy his strict requirements. But eventually it turned out it was worth doing so. He defined the word 'quality' for the research. I would like to gratefully acknowledge his enthusiastic supervision, encouraging attitude, and generously sharing his knowledge. Dear Withawat, you become more of a mentor and friend, than a supervisor. I would also like to thank my other co-supervisor, Prof. Derek Abbott, who has been of great help, support and advice, when it counted most. His enthusiastic supervision, unwavering optimism, constructive suggestions, linguistic finesse, and generous travel financial assistance have been helpful in propelling my research forward.

Another key person whom I am strongly indebted to is **Prof. Christophe Fumeaux**. As a leader of Adelaide Applied Electromagnetic Group, he provided me the opportunity of attending the group meetings. The experiences, discussions and comments in the group meeting were really insightful in my research direction. Christoph never hesitated in giving constructive feedback and discussing electromagnetic issues, whenever I asked.

I wish to express my warm thanks to Prof. Zhongxiang Shen for inviting me to visit his research group at the Nanyang Technological University, Singapore. Prof. Shen's broad theoretical and experimental knowledge in the field of electromagnetic theory and FSS design were of great importance towards my PhD research. I would like to thank my

good friends Jiang Wang, Ali Al-Sheikh, Alex Hu, Zhuozhu Chen, Changzhou Hua, and Yue Cen for making a freindly research environment during my stay in Singapore.

I would like to express my gratitude to Dr Sarath Sriram, Dr Madhu Bhaskaran and Ms Shruti Nirantar at the Functional Materials and Microsystems Research Group, RMIT University, Melbourne for their support and fabrication of the terahertz FSS prototype.

I wish to thank Mr Simon Doe, and Mr Dipankar Chugh at the Ian Wark Research Institute, University of South Australia for their technical assistance in microfabrication of the microfluidic sensors.

There are many people who helped me throughout my PhD candidature. Within the school of Electrical & Electronic Engineering, I am indebted to Dr Thomas Kaufmann and Dr Ali Karami for their kindness, passion in discussing around different research issues and critical suggestions. I would also express my appreciation to my freinds and colleagues in the Applied Electromagnetics Group at the University of Adelaide, Dr Longfang Zou, Dr Zahra Shaterian, Tiaoming (Echo) Niu, Shengjian (Jammy) Chen, Chengjun (Charles) Zou, Nghia Nguyen Trong, Cheng Zhao, Sree Pinapati, Wendy Lee, Andrew Udina, Deshan Govender, and Fengxue Liu, and to the people at the Adelaide T-ray Group, Mr Henry Ho, Dr Gretel M. Png, Dr Alex Dinovitser, Dr Benjamin Ung, Mr Shaoming Zhu, Mr Jining Li, Mr Daniel Headland, and Dr Azhar Iqbal.

My first days in the school were great and happy because of the support and friendliness of Dr Pouria Yaghmaee, Dr Sam Darvishi and Mr Mehdi Kasaei. Indeed, one of the most respected freinds I had in the school, has been Dr Mostafa Rahimi, who was always there for me and I could count on his help and advice. Thank you very much Mostafa.

I also like to thank the office & support staff of the school including Danny Di Giacomo for the logistical supply of required tools and items, IT officers, David Bowler, Mark Innes, and Ryan King, and the administrative staff, Stephen Guest, Greg Pullman, Ivana Rebellato, Rose-Marie Descalzi, Deborah Koch, Lenka Hill, and Jodie Schluter for their kindness and assistance. I would also like to thank the head of school, Associate Prof. Cheng-Chew Lim, for his support regarding my research travels and software required for my PhD research. I am also thankful to my other friends and colleagues within the school. In addition, I sincerely thank my other friends and colleagues Mariam Ebrahimpour, Solmaz Kahourzadeh, Arash Mehdizadeh, Neda Shabi, Muhammad Asraful Hasan, Nicholas P. Lawrence, Mostafa Numan, Vichet Duk, Sarah Immanuel, Robert Moric, Tran Nguyen, and Yansong (Garrison) Gao, for making such

a friendly research environment. Also my wife and I appreciate support of our family friends in Adelaide, Meisam Valizadeh, Reza Salari, Hassan Amirparast, Amin Mahmoudi, Sara Chek, Ryan Darvishi, Hedy Minoofar, Saeid Sedghi, Masoumeh Eyvazi, Ali Gholampour, and Hadis Afshar for their help to make our life in Adelaide so good.

I am also indebted to all my good teachers for planting love of knowledge in my heart, Mr Akbarzadeh, Mr Mashafi, Mr Mohammadpour, Mr Mehdipour, Mr Kheyri, Mr Barari, Mr Hedayat-Zadeh among others. I have learned analog circuit design and microwave engineering from two masters: Prof. Hossein Miar-Naimi (Babol University of Technology) and Dr Withawat Withayachumnankul (The University of Adelaide), and it is appropriate to express my gratitude to them here.

I recognise that this research would not have been possible without the financial support of Australian Government via a generous International Postgraduate Research Scholarship (IPRS) and Australian Postgraduate Award (APA). During my candidature, I was awarded several travel grants, scholarships and awards by other organisations. Here, I would like to deeply appreciate these organisations support including annual travel grants from the School of Electrical & Electronic Engineering (2013-2015), the Australia's Defence Science and Technology Organisation (DSTO) Simon Rockliff Supplementary Scholarship (2015), the University of Adelaide D. R. Stranks Postgraduate Fellowship (2014), and the Australian Nano-Fabrication Facility Start Up Award (2012).

Back to my home country, my endless gratitude goes to my father and mother who always endow me with infinite support, wishes, continuous love, encouragement, and patience. I also thank my best and kindest sister for her love and support. I also wish to express my warm and sincere thanks to my father- and mother-in-law for their kindness, guidance, and earnest wishes. Also, I would like to thank my brothers-in-law for their support, inspiration, and kindness.

Last but not least, my most heartfelt thanks are due to my dearest stunning wife, *Aida*. Words are unable to express my deepest appreciation and love to her. She stood by me in all ups and downs of my PhD and always endowed me with her endless love, and support. Darling, I love you from the bottom of my heart.

Amir Ebrahimi,  
January 2016,  
Adelaide





# Thesis Conventions

The following conventions have been adopted in this Thesis:

## Typesetting

---

This document was compiled using L<sup>A</sup>T<sub>E</sub>X2<sub>ε</sub>. Texmaker and TeXstudio were used as text editor interfaced to L<sup>A</sup>T<sub>E</sub>X2<sub>ε</sub>. Inkscape and Xcircuit were used to produce schematic diagrams and other drawings.

## Referencing

---

The Harvard style has been adopted for referencing.

## System of units

---

The units comply with the international system of units recommended in an Australian Standard: AS ISO 1000–1998 (Standards Australia Committee ME/71, Quantities, Units and Conversions 1998).

## Spelling

---

Australian English spelling conventions have been used, as defined in the Macquarie English Dictionary (A. Delbridge (Ed.), Macquarie Library, North Ryde, NSW, Australia, 2001).



# Awards and Scholarships

## 2015

---

- Yarman-Carlin Best Paper Award, Mediterranean Microwave Symposium
- Simon Rockliff Scholarship, DSTO

## 2014

---

- D. R. Stranks Fellowship, The University of Adelaide

## 2013

---

- Australian National Fabrication Facility (ANFF) Start Up Award

## 2012

---

- International Postgraduate Research Scholarships, The Australian Government
- Australian Postgraduate Award (APA), The Australian Government



# Abstract

Electromagnetic metamaterials are engineered materials that exhibit controllable electromagnetic properties within a desired frequency range. They are usually made of periodic metallic resonant inclusions with dimensions much smaller than the operational wavelength. Since their introduction, they have found many applications from the microwave frequency range up to the terahertz and optical ranges. One key advantage of metamaterial lies in their sub-wavelength resonators making them suitable for miniaturisation of RF circuits and components.

This thesis investigates applications of metamaterial-inspired resonators and structures to design improved devices and components operating at either the microwave or terahertz frequency range. The first part of the dissertation is on the design of miniaturised microwave filters for integrated portable RF systems. Dual-mode metamaterial resonators are proposed as alternatives to conventional resonators for size reduction of the RF filters. In the second part, the focus is on the design of compact metamaterial sensors with improved functionalities. Complementary metamaterial resonators are proposed for designing microfluidic sensors with improved sensitivity and linearity. The designed microfluidic sensors have been tested and verified for dielectric characterisation of chemical and biological solutions. A wide dynamic-range displacement sensor has been designed based on a microstrip-line-coupled complementary electric-LC (ELC) resonator. Furthermore, a rotation sensor is designed with coupled U-shaped resonator with a dynamic range of  $180^\circ$ , where the sensor linearity is improved by asymmetrically tapering the resonators shape. The third part focuses on the design of microwave and terahertz frequency selective surfaces (FSS) based on metamaterial miniaturised elements. Tunable and dual-band FSSs are proposed for reconfigurable and multi-standard microwave communications. Eventually, miniaturised-elements are used to design second-order FSSs at the terahertz frequency range. The simulation and measurement results confirm a harmonic-free and stable frequency response of the designed FSSs under oblique incidence angles.

Overall, the research outcomes in this thesis suggest the efficiency of metamaterial resonators for the design of sensing and communications devices with improved performance over a wide frequency range from the microwave up to terahertz.



# Publications

## Journal Articles

---

- EBRAHIMI-A., NIRANTAR-S., WITHAYACHUMNANKUL-W., BHASKARAN-M., SRIRAM-S., AL-SARAWI-S., AND ABBOTT-D. (2015a). Second-order terahertz bandpass frequency selective surface with miniaturized elements, *IEEE Transactions on Terahertz Science and Technology*, **5**(5), pp. 761–769. \*
- EBRAHIMI-A., WITHAYACHUMNANKUL-W., AL-SARAWI-S., AND ABBOTT-D. (2014f). Dual-mode behavior of the complementary electric-LC resonators loaded on transmission line: Analysis and applications, *Journal of Applied Physics*, **116**, art. no. 083705. \*
- EBRAHIMI-A., WITHAYACHUMNANKUL-W., AL-SARAWI-S., AND ABBOTT-D. (2014d). Metamaterial-inspired rotation sensor with wide dynamic range, *IEEE Sensors Journal*, **14**(8), pp. 2609–2614. \*
- EBRAHIMI-A., WITHAYACHUMNANKUL-W., AL-SARAWI-S., AND ABBOTT-D. (2014c). High-sensitivity metamaterial-inspired sensor for microfluidic dielectric characterization, *IEEE Sensors Journal*, **14**(5), pp. 1345–1351. \*
- EBRAHIMI-A., WITHAYACHUMNANKUL-W., AL-SARAWI-S., AND ABBOTT-D. (2014b). Compact dual-mode wideband filter based on complementary split-ring resonator, *IEEE Microwave and Wireless Components Letters*, **24**(3), pp. 152–154. \*
- EBRAHIMI-A., SHEN-Z., WITHAYACHUMNANKUL-W., AL-SARAWI-S., AND ABBOTT-D. (2015b). Varactor-tunable second-order bandpass frequency selective surface with embedded bias network, *IEEE Transactions on Antennas and Propagation*. Submitted. \*
- EBRAHIMI-A., WITHAYACHUMNANKUL-W., AL-SARAWI-S., AND ABBOTT-D. (2015b). Compact second-order bandstop filter based on dual-mode complementary split-ring resonator, *IEEE Microwave and Wireless Components Letters*. Submitted. \*

EBRAHIMI-A., AND YAGHMAEE-P. (2014). A new enhanced differential CMOS Colpitts oscillator, *Journal of Circuits, Systems, and Computers*, **23**(1). DOI: 10.1142/S0218126614500030.

EBRAHIMI-A., NAIMI-H. M., AND ADRANG-H. (2011). Remarks on transient amplitude analysis of MOS cross-coupled oscillators, *IEICE Transactions on Electronics*, **94**(2), pp. 231–239.

EBRAHIMI-A., AND NAIMI-H. M. (2011). Analytical equations for oscillation amplitude of MOS colpitts oscillator, *International Journal of Electronics*, **98**(7), pp. 883–900.

EBRAHIMI-A., AND NAIMI-H. M. (2010). A 1.2 V high band-width analog multiplier in 0.18  $\mu\text{m}$  CMOS technology, *International Review of Electrical Engineering*, **5**(2), pp. 803–811.

## Conference Articles

---

EBRAHIMI-A., WITHAYACHUMNANKUL-W., AL-SARAWI-S., AND ABBOTT-D. (2015d). Microwave microfluidic sensor for determination of glucose concentration in water, *IEEE 15th Mediterranean Microwave Symposium(MMS)*, pp. 100–102. \*

EBRAHIMI-A., WITHAYACHUMNANKUL-W., AL-SARAWI-S., AND ABBOTT-D. (2015c). Higher-order tunable frequency selective surface with miniaturized elements, *IEEE 15th Mediterranean Microwave Symposium(MMS)*, pp. 140–143. \*

EBRAHIMI-A., NIRANTAR-S., WITHAYACHUMNANKUL-W., BHASKARAN-M., SRIRAM-S., AL-SARAWI-S., AND ABBOTT-D. (2015b). Terahertz bandpass frequency selective surface with improved out-of-band response, *IEEE 40th Int. Conf. on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*. DOI:10.1109/IRMMW-THz.2015.7327920. \*

EBRAHIMI-A., WITHAYACHUMNANKUL-W., AL-SARAWI-S., AND ABBOTT-D. (2014d). Second-order bandpass frequency selective surface for terahertz applications, *IEEE 39th Int. Conf. on Infrared, Millimeter, and Terahertz Waves (IRMMW THz)*. DOI:10.1109/IRMMW-THz.2014.6956237. \*



- EBRAHIMI-A., WITHAYACHUMNANKUL-W., AL-SARAWI-S., AND ABBOTT-D. (2014b). Design of dual-band frequency selective surface with miniaturized elements, *International Workshop on Antenna Technology: "Small Antennas, Novel EM Structures and Materials, and Applications"* (iWAT), pp. 201–204. \*
- EBRAHIMI-A., YAGHMAEE-P., WITHAYACHUMNANKUL-W., FUMEAUX-C., AL-SARAWI-S., AND ABBOTT-D. (2013). Interlayer tuning of X-band frequency-selective surface using liquid crystal, *Proceedings of Asia Pacific Microwave Conference (APMC2013)*, pp. 1118–1120. \*
- YAGHMAEE-P., WITHAYACHUMNANKUL-W., HORESTANI-A. K., EBRAHIMI-A., BATES-B., AND FUMEAUX-C. (2013). Tunable electric-LC resonators using liquid crystal, *IEEE Antennas and Propagation Society International Symposium (APSURSI)*, pp. 382–383.
- EBRAHIMI-A., AND NAIMI-H. M. (2010). An improvement on the analytical methods for amplitude analysis of the MOS Colpitts oscillator, *IEEE XIth International Workshop on Symbolic and Numerical Methods, Modeling and Applications to Circuit Design (SM2ACD)*. DOI:10.1109/SM2ACD.2010.5672336.
- EBRAHIMI-A., NAIMI-H. M., AND GHOLAMI-M. (2010). Compact, low-voltage, low-power and high-bandwidth CMOS four-quadrant analog multiplier, *IEEE XIth International Workshop on Symbolic and Numerical Methods, Modeling and Applications to Circuit Design (SM2ACD)*. DOI: 10.1109/SM2ACD.2010.5672341.
- EBRAHIMI-A., AND NAIMI-H. M. (2010). A 1.2 V single supply and low power, CMOS four-quadrant analog multiplier, *IEEE XIth International Workshop on Symbolic and Numerical Methods, Modeling and Applications to Circuit Design (SM2ACD)*. DOI: 10.1109/SM2ACD.2010.5672334.
- GHOLAMI-M., SHARIFKHANI-M., EBRAHIMI-A., SAEEDI-S., AND ATARODI-M. (2010). Systematic modeling and simulation of DLL-based frequency multiplier, *IEEE XIth International Workshop on Symbolic and Numerical Methods, Modeling and Applications to Circuit Design (SM2ACD)*. DOI: 10.1109/SM2ACD.2010.5672340.

**Note:** Articles with an asterisk (\*) are directly relevant to this thesis.



# List of Figures

1.1	Thesis outline and original contributions . . . . .	9
<hr/>		
2.1	Material categories based on the permittivity and permeability . . . . .	13
2.2	Wavevector and Poynting vector . . . . .	15
2.3	First implementation of double negative medium . . . . .	16
2.4	Unit cells of the purely right-handed and purely left-handed transmission lines . . . . .	17
2.5	Propagation constant and Bloch impedance of a right-handed transmission line . . . . .	18
2.6	Propagation constant and Bloch impedance of a left-handed transmission line . . . . .	18
2.7	Composite left/right-handed transmission line . . . . .	19
2.8	Propagation constant and Bloch impedance of a typical composite right/left-handed transmission line . . . . .	20
2.9	Propagation constant and Bloch impedance of a balanced composite right/left-handed transmission line . . . . .	21
2.10	Implementation of <i>LC</i> -loaded CRLH TLs . . . . .	22
2.11	Split-ring resonator (SRR) . . . . .	24
2.12	Complementary split-ring resonator (SRR) . . . . .	24
2.13	SRR-based transmission line in coplanar technology . . . . .	25
2.14	CRLH TLs in coplanar waveguide technology . . . . .	25
2.15	Artificial transmission line in microstrip technology . . . . .	26
2.16	CRLH TL in microstrip technology . . . . .	26
2.17	Artificial transmission line based on CSRRs . . . . .	27
2.18	CSRR-based CRLH TL in microstrip technology . . . . .	27
2.19	Typical FSS unit cells . . . . .	30
2.20	Frequency selective surfaces made of Jerusalem cross elements . . . . .	31

2.21	The first miniaturised elements FSS . . . . .	32
2.22	Lumped elements modelling of the miniaturised elements FSS . . . . .	33
2.23	Scan angle performance of the miniaturised elements FSS . . . . .	34
<hr/>		
3.1	Conventional complementary split-ring resonator (CSRR) . . . . .	40
3.2	Dual-mode complementary split-ring resonator (DMCSRR) . . . . .	41
3.3	Dual-mode complementary split-ring resonator (DMCSRR) loaded on a microstrip line with a series capacitive gap . . . . .	42
3.4	C-shaped in/output coupling . . . . .	43
3.5	Layout of the Designed Dual-mode Filter . . . . .	43
3.6	Three dimension (3-D) view of the designed dual-mode filter . . . . .	44
3.7	Effects of parameter variations on the filter performance . . . . .	45
3.8	Fabricated prototype of the dual-mode filter . . . . .	45
3.9	Simulated and measured S-parameters of the dual-mode bandpass filter	46
3.10	Circuit model of a notch filter . . . . .	47
3.11	Circuit models of the proposed dual-mode bandstop filter . . . . .	48
3.12	Effect of the impedance inverter on the filter response . . . . .	49
3.13	Microstrip-line-coupled DMCSRR . . . . .	49
3.14	Filter layout . . . . .	50
3.15	The fabricated dual-mode bandstop filter . . . . .	50
3.16	Measured and simulated results of the bandstop filter . . . . .	51
3.17	Complementary electric-LC resonators . . . . .	52
3.18	Lumped element modeling of the CELC2 . . . . .	54
3.19	Microstrip line loaded with CELC2 resonator . . . . .	55
3.20	Lumped element modeling of the CELC2 . . . . .	56
3.21	Simulation response of a CELC2 coupled microstrip line . . . . .	57
3.22	Simulation response of a CELC2-coupled microstrip line with lateral dis- placement . . . . .	58
3.23	Bandpass configuration of the CELC2-loaded microstrip line . . . . .	60
3.24	Even-mode equivalent circuit model . . . . .	60

---

3.25	Simulation results of a bandpass configuration of CELC2-coupled microstrip line . . . . .	61
3.26	Layout of the dual-mode bandpass filter based on CELC2 . . . . .	63
3.27	Fabricated dual-mode bandpass filter based on CELC2 . . . . .	63
3.28	Comparison between the simulated and measures results of the CELC2-based dual-mode bandpass filter . . . . .	64

---

4.1	SRR-coupled microstrip line for microfluidic sensing . . . . .	67
4.2	Simulated response of a SRR-coupled microstrip line section . . . . .	68
4.3	SRR-based microfluidic sensor . . . . .	68
4.4	Measurement results of the SRR-based microwave microfluidic sensor . . . . .	69
4.5	Basic schematic of the CSRR-based microfluidic sensor . . . . .	70
4.6	Simulated transmission response of CSRR-loaded microstrip line . . . . .	72
4.7	Three dimensional view of the designed sensor with microfluidic chamber . . . . .	73
4.8	Fabricated sensor prototype . . . . .	73
4.9	Sensor transmission responses . . . . .	74
4.10	Measurement results for sensor calibration . . . . .	76
4.11	Measurements for validating the sensing concept . . . . .	78
4.12	Measured and actual values of the complex permittivity . . . . .	79
4.13	Type-2 complementary electric-LC (CELC2) resonator . . . . .	80
4.14	Microstrip loaded CELC2 resonator . . . . .	81
4.15	Fabricated microfluidic biosensor . . . . .	83
4.16	Measured transmission response of the sensor for different cases . . . . .	83
4.17	Measured resonance characteristics . . . . .	85
4.18	Verification of the sensing model . . . . .	85
4.19	Comparison between the the retrieved and actual glucose concentrations . . . . .	86

---

5.1	Coplanar waveguide loaded with a single SRR for displacement sensing . . . . .	89
5.2	Basic schematic of the proposed rotation sensor . . . . .	90
5.3	Equivalent circuit models . . . . .	91

---

5.4	Circuit model for analysing the sensor operation . . . . .	93
5.5	Simulated transmission coefficients for different rotation angles . . . . .	94
5.6	Modified rotation sensor for better linearity . . . . .	95
5.7	Simulated transmission responses of the improved sensor . . . . .	95
5.8	Comparison of the sensitivity curve between the two rotation sensors . .	96
5.9	Detection of the rotating direction . . . . .	97
5.10	The fabricated sensor module . . . . .	98
5.11	Measured transmission coefficients for different rotation angles . . . . .	99
5.12	Measured and simulated resonance frequencies . . . . .	99
5.13	Single CELC2 resonator loaded on a microstrip line . . . . .	100
5.14	Fabricated the prototypes of the displacement sensor . . . . .	101
5.15	Transmission responses of the displacement sensor . . . . .	102
5.16	Changes in notch depth . . . . .	102
<hr/>		
6.1	Unit cell of the designed tunable FSS . . . . .	108
6.2	Circuit model . . . . .	109
6.3	Circuit and electromagnetic simulation results of the FSS . . . . .	109
6.4	Tuning performance of the single-pole FSS . . . . .	110
6.5	Second-order FSS design . . . . .	110
6.6	Simulation results of the second-order FSS . . . . .	111
6.7	Tuning of the second-order FSS . . . . .	113
6.8	Scan angle performance of the second-order FSS . . . . .	114
6.9	Proposed second-order tunable FSS . . . . .	115
6.10	Circuit model of the proposed FSS . . . . .	116
6.11	Varactor loaded unit cell with via hole . . . . .	121
6.12	Circuit versus EM simulation results . . . . .	123
6.13	Realised FSS sample . . . . .	124
6.14	FSS test setup . . . . .	124
6.15	Measured versus simulated transmission coefficients of the FSS . . . . .	126
6.16	Varactor characteristics and centre frequency variation . . . . .	127

---

6.17	Scanning angle performance of the proposed FSS . . . . .	128
6.18	Liquid crystal tuning mechanism . . . . .	129
6.19	Unit cells of the designed FSS . . . . .	130
6.20	Structure of the designed FSS . . . . .	131
6.21	Circuit level modelling of the designed FSS . . . . .	133
6.22	Full-wave electromagnetic and circuit model simulation results . . . . .	134
6.23	Lumped-element model of the dual-band FSS . . . . .	137
6.24	Three dimensional view of the designed FSS . . . . .	138
6.25	Simulated transmission and reflection coefficients of the designed FSS . . . . .	139
6.26	Scan angle performance of the designed FSS . . . . .	140
6.27	Effect of $g$ on transmission coefficient . . . . .	141
6.28	Effect of $D_p$ on transmission coefficient . . . . .	142
—————		
7.1	Electromagnetic spectrum . . . . .	146
7.2	Unit cell views of the FSS . . . . .	148
7.3	Lumped-element circuit model of the FSS . . . . .	148
7.4	Circuit versus electromagnetic simulation results . . . . .	149
7.5	Scan angle performance for TE polarisation . . . . .	150
7.6	Scan angle performance for TM polarisation . . . . .	151
7.7	Three dimensional view of the FSS . . . . .	153
7.8	Equivalent circuit model of the THz-FSS . . . . .	154
7.9	Inductive and capacitive FSS arrays . . . . .	157
7.10	Comparison between circuit model and EM simulations before adding the CCSR . . . . .	158
7.11	Comparison between circuit model and EM simulations after adding the CCSR . . . . .	160
7.12	Fabricated second-order terahertz FSS . . . . .	162
7.13	Measurement setup . . . . .	162
7.14	Measured and simulated transmission responses . . . . .	163
7.15	Scanning angle performance under TE polarisation . . . . .	165
7.16	Scanning angle performance under TM polarisation . . . . .	166

---





# List of Tables

3.1	Comparison of various bandstop filters . . . . .	52
3.2	Equivalent circuit parameters . . . . .	58
4.1	Permittivity of water-ethanol mixture . . . . .	75
4.2	Permittivity of water-ethanol mixture . . . . .	79
6.1	Comparison with other structures . . . . .	112
6.2	Tuning performance of different liquid crystals samples . . . . .	133
6.3	Tuning performance of different liquid crystals samples . . . . .	135
7.1	Normalised second-order filter parameters . . . . .	155