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

THE UNIVERSITY
of ADELAIDE

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

Contents

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.

06/01/2016

Signed

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 throughly revising the drafts to satisfy his strict requirements. But eventually in 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 genereously sharing his knowledge. Dear Withawat, you become more of a mentor and freind, 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 genereous 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 LATEX2e. Texmaker and TeXstudio were used as text editor interfaced to LATEX2e. 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°, 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. 0 83705. *

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 μm 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

List of Tables