# Metamaterial-Inspired Structures and Their Applications in Microwave, Millimeter-wave and Terahertz Planar Circuits

by

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*To my Mom and Dad*
*and also to my wife, Zahra*
*with all my love.*

# Contents

# Abstract

Metamaterials are generally defined as periodic composite structures that are engineered to modify the electromagnetic properties of materials, especially in order to achieve new physically realizable responses that may not be readily available in nature. The key to the application of metamaterial resonators for the synthesis of such effective media is their small electrical size. This feature can be also exploited for the miniaturization of planar circuits.

Motivated by the need for miniaturized planar structures in mobile wireless systems, metamaterial-inspired structures are proposed throughout this thesis for the design of compact microwave, millimeter-wave and terahertz planar structures with improved performance. The thesis firstly proposes slow-wave and SRR-loaded coplanar strips resonators for the design of compact high quality factor balanced resonators for 60 GHz VCOs in CMOS technology. Next, the thesis is focused on the miniaturization of microwave filters either by proposing resonators with dual-band functionality or through modifying the shape of metamaterial resonators. Shape modifications of metamaterial resonators are also used for the design of high-dynamic-range one- and two-dimensional displacement sensors as well as of a rotation sensor with improved dynamic range. It is further shown that high level of miniaturization can be achieved in a single-layer S-shaped SRR (S-SRR), if the loops of the S-SRR are excited by contra-directional magnetic fluxes, which makes the S-SRR very well suited for application in coplanar waveguide (CPW) technology. The thesis also proposes the dual counterpart of the S-shaped SRR, i.e., S-shaped complementary split ring resonator (S-CSRR) for application in the design of compact differential bandpass filters with inherent common-mode suppression. Finally, the application of SRRs to the design of compact bandpass filters for terahertz surface waves on single wire waveguides—the so-called planar Goubau lines (PGLs)—is studied numerically and experimentally. The results of this research show the versatility and potential of metamaterial-inspired resonators for the realization of miniaturized structures in planar technologies in different frequency bands.

# 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. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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# 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 was 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

American English spelling is adopted in this thesis.

# Publications

## Journal Articles

**Horestani-A. K.**, Fumeaux-C., Al-Sarawi-S., and Abbott-D. (2012b). Split ring resonators with tapered strip width for wider bandwidth and enhanced resonance, *IEEE Microwave and Wireless Components Letters*, **22**(9), pp. 450–452.

**Horestani-A. K.**, Fumeaux-C., Al-Sarawi-S., and Abbott-D. (2013a). Displacement sensor based on diamond-shaped tapered split ring resonator, *IEEE Sensors Journal*, **13**(4), pp. 1153–1160.

**Horestani-A. K.**, Abbott-D., and Fumeaux-C. (2013b). Rotation sensor based on horn-shaped split ring resonator, *IEEE Sensors Journal*, **13**(8), pp. 3014–3015.

**Horestani-A. K.**, Withayachumnankul-W., Chahadih-A., Ghaddar-A., Zehar-M., Abbott-D., Fumeaux-C., and Akalin-T. (2013c). Metamaterial-inspired bandpass filters for terahertz surface waves on Goubau lines, *IEEE Transactions on Terahertz Science and Technology*, **3**(6), pp. 851–858 (**Invited**).

**Horestani-A. K.**, Naqui-J., Shaterian-Z., Abbott-D., Fumeaux-C., and Martín-F. (2014). Two-dimensional alignment and displacement sensor based on movable broadside-coupled split ring resonators, *Journal of Sensors and Actuators A: Physical*, **210**, pp. 18–24.

**Horestani-A. K.**, Durán-Sindreu-M., Naqui-J., Fumeaux-C., and Martín-F. (2014). S-shaped complementary split ring resonators and their application to compact differential bandpass filters with common-mode suppression, *IEEE Microwave and Wireless Components Letters*, **24**(3), pp. 150–152.

**Horestani-A. K.**, Naqui-J., Abbott-D., Fumeaux-C., and Martín-F. (2014). Two-dimensional displacement and alignment sensor based on reflection coefficients of open microstrip lines loaded with split ring resonators, *Electronics Letters*, **50**(8), pp. 620–622.

**Horestani-A. K.**, Durán-Sindreu-M., Naqui-J., Fumeaux-C., and Martín-F. (n.d.a). Coplanar Waveguides Loaded with S-Shaped Split Ring Resonators:

Modeling and Application to Compact Microwave Filters, *IEEE Antennas Wireless Propagation Letters,* submitted.

## Conference Articles

**Horestani-A. K.**, Al-Sarawi-S., and Abbott-D. (2010). Designing of high-Q slow-wave coplanar strips for CMOS MMICs, *Proc. 35th International Conference on Infrared, Millimeter, and Terahertz Waves*, Rome, Italy, DOI: 10.1109/ICIMW.2010.5612952.

**Horestani-A. K.**, Shaterian-Z., Withayachumnankul-W., Fumeaux-C., Al-Sarawi-S., and Abbott-D. (2011c). Compact wideband filter element based on complementary split-ring resonators, *Proc. SPIE Smart Nano-Micro Materials and Devices*, Melbourne, Australia, art. no. 820431.

**Horestani-A. K.**, Shaterian-Z., Al-Sarawi-S., and Abbott-D. (2011b). High quality factor mm-wave coplanar strip resonator based on split ring resonators, *Proc. 36th International Conference on Infrared, Millimeter and Terahertz Waves, (IRMMW-THz)*, Houston, TX, DOI: 10.1109/irmmw-THz.2011.6105225.

**Horestani-A. K.**, Mehdizadeh-A., Al-Sarawi-S., Fumeaux-C., and Abbott-D. (2011a). Quality factor optimization process of a tapered slow-wave coplanar strips resonator in CMOS technology, *Proc. Asia-Pacific Microwave Conference (APMC)*, Melbourne, Australia, pp. 45–48.

Mehdizadeh-A., **Horestani-A. K.**, Al-Sarawi-S., and Abbott-D. (2011). An efficient 60 GHz resonator using Harmony Search, *2011 IEEE Recent Advances in Intelligent Computational Systems,*Trivandrum, India, pp. 369–372.

**Horestani-A. K.**, Fumeaux-C., Al-Sarawi-S., and Abbott-D. (2012a). Characterization of the complex permittivity of thin films using a slow-wave coplanar strips resonator, *Proc. 37th International Conference on Infrared, Millimeter, and Terahertz Waves*, DOI: 10.1109/IRMMW-THz.2012.6379510.

**Horestani-A. K.**, Shaterian-Z., Al-Sarawi-S., Abbott-D., and Fumeaux-C. (2012c). Miniaturized bandpass filter with wide stopband using complementary spiral resonator, *Proc. Asia-Pacific Microwave Conference (APMC)*, Kaohsiung, Taiwan, pp. 550–552.

YAGHMAEE-P., **HORESTANI-A. K.**, BATES-B., AND FUMEAUX-C. (2012). A multi-layered tunable stepped-impedance resonator for liquid crystal characterization, *Asia-Pacific Microwave Conference Proceedings (APMC)*, Kaohsiung, Taiwan, pp. 776–778.

SHATERIAN-Z., **HORESTANI-A. K.**, AND FUMEAUX-C. (2013). Metamaterial-Inspired Displacement Sensor with High Dynamic Range, *Proc. 4th International Conference on Metamaterials, Photonic Crystals and Plasmonics, META'13*, Vol. 1, Sharjah, United Arab Emirates, pp. 9–11.

YAGHMAEE-P., WITHAYACHUMNANKUL-W., **HORESTANI-A. K.**, AMIR EBRAHIMI, BATES-B., AND FUMEAUX-C. (2013). Tunable electric-LC resonators using liquid crystal, *IEEE Antennas and Propagation Society International Symposium (APSURSI)*, pp. 382–383.

**HORESTANI-A. K.**, WITHAYACHUMNANKUL-W., FUMEAUX-C., ABBOTT-D., AND AKALIN-T. (2013c). Metamaterial-inspired bandpass filter for the terahertz Goubau line, *Proc. 4th International Conference on Metamaterials, Photonic Crystals and Plasmonics, META'13*, Sharjah, United Arab Emirates, pp. 117–118.

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