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Jordi Naqui

Symmetry Properties in Transmission Lines Loaded with Electrically Small Resonators

Circuit Modeling and Applications

Doctoral Thesis accepted by
Universitat Autònoma de Barcelona, Spain

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J. Naqui and F. Martín, "Mechanically reconfigurable microstrip lines loaded with stepped impedance resonators and potential applications," *Int. J. Antennas Propag.*, vol. 2014, Article ID 346838, 8 pages, Feb. 2014.

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J. Naqui, M. Durán-Sindreu, F. Martín, "Selective mode suppression in microstrip differential lines by means of electric-LC (ELC) and magnetic-LC (MLC) resonators," *Appl. Phys. A*, vol. 115, no. 2, pp. 637–643, May 2014.

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Conferences

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Workshops

J. Naqui, A. K Horestani, C. Fumeaux, and F. Martín, "Microwave sensors based on symmetry properties of resonator-loaded lines," in workshop "Using symmetry-related electromagnetic properties for microwave device design: application to half-mode circuits, balanced lines and circuits, and microwave sensors," *Europ. Microw. Week*, Paris, France, Sept. 2015.

J. Naqui, J. Bonache and F. Martín, "Revisiting equivalent circuit models for emerging technologies: from microwaves to THz," in workshop "Equivalent circuit models for metamaterial-inspired planar circuits based on split rings and related resonators," *IEEE MTT-S Int. Microw. Symp.*, Tampa, FL, USA, Jun. 2014.

J. Naqui, M. Durán-Sindreu and F. Martín, "On the symmetry properties of transmission lines loaded with metamaterial resonators: theory and applications," in workshop "Microwave Metamaterial Concepts, Circuits and Applications," *Europ. Microw. Conf.*, Nurember, Germany, Oct. 2013.

F. Martín, J. Naqui, P. Vélez, M. Durán-Sindreu and J. Bonache, "Split ring resonator (SRR) and stepped impedance resonator (SIR) based metamaterial transmsission lines: application to microwave components and novel sensing strategies," in workshop "Metamaterials in communications and sensing: reality or fiction?," *IEEE Radio Wireless Week*, Austin, TX, USA, Jan. 2013.

Supervisor's Foreword

It is a great pleasure to introduce Dr. Jordi Naqui's thesis work, accepted for publication within Springer Theses and awarded with a prize for outstanding original work. Dr. Naqui joined my Research Group and CIMITEC (the Technology Transfer Centre I head at the Universitat Autonoma de Barcelona) in September 2009. He has had a national predoctoral fellowship, granted by the Spanish Ministry of Education, Culture, and Sports (ref. AP2010-0431), for the development of his research activities during these years that have concluded with the oral presentation and defense of the Ph.D. thesis on October 17, 2014.

Dr. Naqui's thesis includes significant original scientific contributions, representing considerable advance in the field of Microwave Engineering, specifically on the topics of wireless communications, sensing, and radiofrequency identification (RFID). Such contributions have been published or will be shortly published in top journals, international well-recognized conferences, and book chapters. I would like to emphasize that the work carried out by Dr. Naqui, reported in this book, is very extensive and complete. It covers the research cycle in the area of experimental sciences and engineering, including fundamentals/theory, design/simulation, and fabrication/characterization, and a wide variety of proof-of-concept demonstrators of the novel ideas generated in the thesis are reported.

In the thesis, a new design principle, based on the symmetry-related electromagnetic properties of transmission lines loaded with electrically small and symmetric resonators (mostly inspired by metamaterials), is introduced for the first time and is transversely applied to the different types of devices considered. This design principle is the most important contribution of the thesis. It is described in detail in the thesis and the potentiality of this novel design approach is demonstrated through the development of a wide variety of proof-of-concept devices, including common-mode suppressed differential lines and balanced filters, microwave sensors (for linear/angular displacement and rotation speed measurements, for alignment purposes and for dielectric characterization), and spectral signature barcodes. Thus the thesis clearly identifies different scenarios where the proposed design principle can be applied. I would like to highlight the novel sensing concept reported in the

thesis, based on symmetry disruption, hence resulting in microwave sensors robust against changes in environmental conditions (the reported contactless angular displacement and velocity sensors are good examples of such sensors).

It is also remarkable that the different structures considered in this work, based on resonator-loaded lines, have been modeled by means of lumped element equivalent circuits, very useful for design purposes. These models have been validated through parameter extraction methods and comparison to electromagnetic simulations and experimental results. Moreover, the thesis includes the modeling of two important effects in resonator-loaded lines not considered so far: (*i*) the arbitrary orientation of split rings in lines loaded with such elements, where mixed (magnetoelectric) coupling between the line and the rings arises and (*ii*) the modeling of transmission lines with inter-resonator coupling, where stopband bandwidth enhancement is explained by the appearance of complex modes.

Some parts of the research activity reported in this book have been carried out in collaboration with other Groups, particularly, with the Group of Prof. Francisco Medina (University of Seville) on the topic of common-mode suppressed balanced lines and filters, with the Group of Prof. Christophe Fumeaux (University of Adelaide) in the field of spatial sensors, and with the Group of Prof. Rolf Jakoby (Darmstadt University of Technology) on the topic of sensors for dielectric characterization (Dr. Naqui made a fruitful three-month stay in Darmstadt before the Ph.D. defense). Such collaborations have opened new research horizons in the near future, and Dr. Naqui's thesis constitutes the seed for new research lines within my Group, which will represent novel Ph.D.'s in a few years.

And last but not least, it is remarkable that thanks to the research activity carried out in this thesis, a contract with the European Space Agency in collaboration with the company *EMXYS Embedded Instruments*, focused on the development of angular velocity sensors for reaction wheels, has been achieved. Within the topic of RFID, printed radiofrequency barcodes (i.e., chipless RFID tags operating in the frequency domain) will be developed in the framework of a collaborative project with the company *Scytl*, for electronic voting and tracking of election processes. These are two examples of the potential of the ideas generated in this thesis. Dr. Naqui is a key researcher in these projects, and a large part of his time is now dedicated to them. Nevertheless, after the Ph.D. presentation he has given continuity to the research activities, trying to bring beyond the state-of-the-art ideas and concepts of interest for the academia and useful to the industry. Being aware of the passion and enthusiasm of Dr. Naqui for Research, I hope to see him involved in the university for many years.

Bellaterra, Barcelona Prof. Ferran Martín
April 2015

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I would like to express my most sincere gratitude to those who have contributed to the present thesis.

First of all, many thanks to my supervisor Ferran Martín, who gave me the opportunity to begin the Ph.D. His knowledge, motivation, and continuous help during these past years have played a key role in this thesis. I would also like to thank the people from the research center CIMITEC, the Department of Electronics Engineering, and the Engineering School at the Universitat Autònoma de Barcelona. Among them, I am particularly very grateful to Gerard Sisó and Javier Hellín. Although they are not formally coauthors of the publications within the context of this thesis, they are of course part of them. Almost all experimental results in this thesis are merits of their outstanding and patient work on fabrication-related tasks.

I am also very grateful to my colleagues from national and international universities with whom I have collaborated. Many thanks to Francisco Medina, Francisco Mesa, and Armando Fernández from University of Seville for our continuous collaboration. Many thanks to Rolf Jakoby and Christian Damm to let me carry out a great stay in Darmstadt University of Technology.

Many thanks to my friends, especially to Marín, Novo, Dani, and Núria. Thanks also to my pet Dana, my Boxer dog, for receiving me with so much enthusiasm every weekday. Lastly, special gratitude to those who have really suffered my difficult and stressful moments, my family. Especially, my wife Amalia and my little daughter Martina, my mother Mercè, my grandmother Mercè, and my parents-in-law Antonio and Amalia. Thank you for your patience.

Jordi Naqui

Contents

About the Author

Jordi Naqui was born in Granollers, Spain, in 1984. He received the Telecommunication Technical Engineering diploma (specialty in Electronic Systems), the Telecommunication Engineering degree, the Master's degree in Microelectronics and Nanoelectronics Engineering, and the Ph.D. degree in Electronics Engineering from the Universitat Autònoma de Barcelona (UAB), Bellaterra (Barcelona), Spain, in 2006, 2010, 2011, and 2014, respectively. From 2007 to 2009, he conducted internships in Mier Comunicaciones and Ficosa International (Advanced Communications), and he worked as a telecommunication engineering consultant in Sayós & Carrera. He carried out a three-month predoctoral research stay at the Institute for Microwave Engineering and Photonics (IMP) from Darmstadt University of Technology (TUD). He was a recipient of a national predoctoral teaching and research fellowship by the Spanish Government (2012–2014). He received the first prize of Yarman-Carlin Best Student Paper Contest at 14th Mediterranean Microwave Symposium in 2014 and the Young Scientist Award at XXX International Union of Radio Science (URSI) Spanish National Symposium in 2015. He was the co-recipient of IX Comerma Engineer Research Award of Industrial Engineering awarded by the Local Government of Ferrol and University of A Coruña, Spain, in 2015. He has been teaching at the UAB in the Department of Electronics Engineering since 2010. Currently, he is a postdoctoral researcher of CIMITEC at the UAB. His research activities are focused mainly on modeling and design of passive RF/microwave resonant structures, applied to filters, sensors, and chipless Radio-Frequency Identification (RFID) tags. Dr. Naqui is member of the Institute of Electrical and Electronics Engineers (IEEE), and he serves as a reviewer in many international journals.

Acronyms

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AM	Amplitude modulation
ASM	Aggressive space mapping
BW	Backward wave
CB-CPW	Conductor-backed coplanar waveguide
CMRR	Common-mode rejection ratio
CPS	Coplanar strips
CPW	Coplanar waveguide
CRLH	Composite right/left-handed
CSRR	Complementary split-ring resonator
CSSRR	Complementary split squared ring resonator
DGS	Defected ground structure
DNG	Double-negative
DPS	Double-positive
DS-CSRR	Double-slit complementary split-ring resonator
DS-SRR	Double-slit split-ring resonator
EBG	Electromagnetic bandgap
EIW	Electro-inductive wave
ELC	Electric inductive-capacitive
EM	Electromagnetic
EMI	Electromagnetic interference
ENG	Epsilon-negative
FBW	Fractional bandwidth
FSIR	Folded stepped-impedance resonator
IC	Integrated circuit
LH	Left-handed
LTCC	Low temperature co-fired ceramic
MIW	Magneto-inductive wave
MLC	Magnetic inductive-capacitive
MNG	Mu-negative

NB-CSRR	Non-bianisotropic complementary split-ring resonator
NB-SRR	Non-bianisotropic split-ring resonator
NRI	Negative-refractive index
OCSRR	Open complementary split-ring resonator
OSRR	Open split-ring resonator
PCB	Printed circuit board
PGS	Patterned ground structure
PLH	Purely left-handed
PRH	Purely right-handed
RF	Radio frequency
RFID	Radio-frequency identification
RH	Right-handed
SIR	Stepped-impedance resonator
SISS	Stepped-impedance shunt-stub
SNG	Single-negative
SRR	Split-ring resonator
SSRR	Split squared ring resonator
TEM	Transverse electromagnetic
VNA	Vector network analyzer