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MICROWAVE DE-EMBEDDING

FROM THEORY TO APPLICATIONS

Microwave De-embedding

From Theory to Applications

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Microwave De-embedding

La Clairvoyance

The painting "La Clairvoyance" of the Belgian artist Rene Magritte can be viewed as an intriguing, captivating, and eye-catching picture symbolizing the book's purpose: to provide the reader with all the ingredients required for extracting the full potential of the microwave de-embedding concept from its theoretical background (i.e., the egg) to recent applications (i.e., the bird) like waveform engineering. The de-embedding concept allows accessing the behavior of the actual device and then predicting (i.e., La Clairvoyance) its performance to design amplifiers.

Foreword

The very title of this book, *Microwave De-Embedding: From Theory to Applications* brings to me some memories from my early research career. When I started working at Politecnico di Torino on active microwave device physics-based modeling (that was, alas, more than 30 years ago), on-wafer measurements were hardly available and the measured scattering parameters were in package or with coaxial text fixtures. At that time, I was doing physics-based 2D simulations of gallium arsenide metal–semiconductor field effect transistors (GaAs MESFETs), and the simulated scattering parameters I was deriving from the frequency-domain solution of the linearized continuity and Poisson equations were no match at all with the measured ones. This was causing me considerable puzzlement and distress: Why did the simulated S_{11} look so regular, while the measured one had sudden wiggles when plotted on the Smith chart? Not to speak of the vagaries of (however small) S_{12}, one of the keys to transistor stability. For my senior, and now happily retired, colleague in charge of the measurements, the explanation was simple enough: What I was simulating was (more or less) the intrinsic device, the unobservable core of transistor operation; to obtain a fair comparison, I should shift the reference planes and de-embed the test fixtures.

I went on to apply this wise recipe by embedding the simulated *S* parameters into a network of intrinsic parasitics; then I added pad capacitances, and after this I added low-pass sections simulating the test fixtures and some transmission lines for plane shift.... Finally, I tried to optimize the resulting network in order to get back the measured *S* parameters. The FORTRAN code implementing gradient optimization was slow, there were too many parameters to optimize, and the program was running on a PDP-11 DEC computer with a hard disk as large as 500 Mbytes (or so, I recollect)—all those factors made the optimization painful, but, in the end, I got, after (too) many false starts, an embedding network that gave me back, starting from the simulated data, the measured ones. Was that the right one? Nobody knows, but it looked reasonable. A few years later, with the advent of on-wafer probes and cold-FET parasitic characterization techniques, the situation improved dramatically—finally, measurements matched simulations (and not, mind you, the other way round…).

This is to say that reading through the table of contents of *Microwave De-Embedding: From Theory to Applications* had a sort of Proustian madeleine effect on me—although I never had to do measurements myself; modeling and simulation was my field. To quote from Chapter 1, "To de-embed properly…is a work of art that requires knowledge and experience"—a sentence that I can fully endorse. The concept of embedding and de-embedding is indeed shown, through a series of interesting and informative chapters, to be far richer than the simple "mathematical shift of reference planes" (see Chapter 1, *A Clear-Cut Introduction to the De-embedding Concept: Less is More* by G. Crupi, D. Schreurs, and A. Caddemi), that is, transmission line embedding or de-embedding. De-embedding concerns the removal of linear parasitics that can be directly measured not only through cold-transistor techniques but also (and more conveniently, in technologies, with lossy or complex substrates) by characterizing dummy text structures developed ad hoc, not to mention the possibility of deriving their parameters through accurate EM solvers, ultimately obtaining integrated transistor models that can be effectively scaled (see Chapter 4, *High-Frequency and Microwave Electromagnetic Analysis Calibration and De-embedding* by J. C. Rautio and Chapter 8, *Electromagnetic-Analysis-Based Transistor De-embedding and Related Radio-Frequency Amplifier Design* by M. Yarlequé, D. Schreurs, B. Nauwelaers, D. Resca, and G. Vannini). However, de-embedding can be extended to the inclusion or exclusion of nonlinear parasitics within the framework of waveform-based measurements, see Chapter 5, *Large-Signal Time-Domain Waveform Based Transistor Modeling* by I. Angelov, G. Avolio, and D. Schreurs, and Chapter 6, *Measuring and Characterizing Nonlinear Radio-Frequency systems* by W. Van Moer, L. Lauwers, and K. Barbé), ultimately becoming a circuit design tool (see Chapter 9, *Nonlinear Embedding and De-embedding: Theory and Applications* by A. Raffo, V. Vadalà, and G. Vannini). Embedding and de-embedding also enter noise characterization, as discussed in Chapter 2, *Millimeter-Wave Characterization of Silicon Devices Under Small-Signal Regime: Instruments and Measurement Methodologies* by G. Dambrine (a chapter that is a really nice and self-contained introduction to microwave measurements) and Chapter 3, *Characterization and Modeling of High-Frequency Active Devices Oriented to High-Sensitivity Subsystems Design* by E. Limiti, W. Ciccognani, and S. Colangeli. Embedding and de-embedding pervasively enters not only gray-box or equivalent circuit modeling but also black-box or behavioral modeling, as discussed in Chapter 7, *Behavioral Models for Microwave Circuit Design* by J. C. Pedro and T. R. Cunha, again an excellent and self-contained introduction to black-box modeling at large.

Devoting a book to a very specific subject like microwave de-embedding is like visiting a historical city (Turin, for instance...) in search of a particular architectural item (say, baroque churches). There are lots of baroque churches in Turin, so the visitor is not to be disappointed, but going through the streets and the piazzas the visitor will see a lot of other artistic items and also will stop here and there to rest and to eat some local delicacy, or will go through the same quarters again and again seeing monuments he or she is already familiar with, maybe each time from a different angle. But let us go back to the real subject, microwaves; a book on de-embedding is ultimately bound to include a wealth of important topics in microwave modeling and design, but all of them see from a certain perspective and are endowed with a certain distinctive flavor. In this respect, the editors (Giovanni Crupi and Dominique Schreurs) and all the authors have done an excellent job in assembling this book, which has the quality of being, so to speak, both specific and inclusive (shall I say *broadband*?). I would recommend it to all researchers working in the evergreen and fascinating field of active microwave and millimeter wave device modeling.

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July 2013

Foreword

The problem of measurement calibration has always been with us. Before the days of computer-controlled instrumentation, it was inevitably a manual process: measure the input and output losses and correct the measurements manually. For a vector measurement, the best one could usually do was to insert a short circuit at some convenient point, adjust the reflectometer to indicate a short circuit, and correct the measurements to put the reference plane where it was really needed. This process simply was not good enough to obtain, for example, scattering parameters of transistors for use in circuit design. The accuracy fell short of what was required, and the laborious process made the cost of characterizing a device or component far too great.

With the advent of small computers in the late 1970s and early 1980s, and the standardization of the IEEE 488 instrument-control bus in 1975, computer-controlled measurements became a practical reality. The IEEE 488 bus was intended primarily for the control of instruments and data collection, but once those data were safely stored in the computer's memory, that computer could easily be used for the calibration and de-embedding of the test system.

De-embedding is the process of removing the effects of undesired circuit elements from measurements so that the measurement describes the device of interest alone. That device is invariably embedded in some type of test fixture, often with wire bonds, ribbons, or other types of connection. By replacing the device with a set of well-defined standards, measuring them, and applying post-measurement computation, it is possible to remove the parasitic effects virtually completely. An early technique, for example called *through-short-delay* (TSD), had three types of standards used in the process: a direct connection, a short, and a length of transmission line. Today, those early methods are largely obsolete, as subsequent methods are more versatile and accurate. It is no longer necessary, for example, to have highly precise test standards; it is possible to determine their imperfections by analysis and include them in the de-embedding process. As a result, modern microwave measurements, even at millimeter wavelengths, are impressive. They are well beyond the capabilities many of us would have thought possible 30 years ago.

Progress in this area has provided more than simply improved accuracy and versatility; it has given us a more sophisticated view of the problem. De-embedding has been extended in concept from use exclusively in measurements to being an integral part of the design process. Modern electromagnetic simulation, for example, would not be very useful without the ability to remove port parasitics and interconnections from the results of an analysis. Even in circuit simulation, the ability to remove an element mathematically from an analysis is often essential.

Most remarkably, the technology of de-embedding has moved from the exclusively linear domain into the nonlinear. As such, the idea has necessarily become broader, including techniques necessary for large-signal network analysis and new technologies, such as X parameter and waveform engineering approaches. These involve kinds of measurement that were inconceivable in the early days of automated measurement technology.

In view of the recent history of this technology, I am enthusiastic about its growth in the coming years. It seems inevitable that the more advanced methods described in this book will become everyday technology, and that new methods going well beyond these will be developed. It's an exciting time to be working in this field.

Stephen Maas
AWR Corporation
July, 2013

About the Editors

Giovanni Crupi is an assistant professor at the University of Messina, Italy, where he teaches microwave electronics and optoelectronics. Since 2005, he has been a visiting scientist with KU Leuven and IMEC, Leuven, Belgium. Giovanni's main research interests include small and large signal modeling of advanced microwave devices. He is the chair of the IEEE Microwave Theory and Techniques Society (MTT-S) Fellowship program and serves as an associate editor of *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*.

Dominique Schreurs is a full professor at KU Leuven, Leuven, Belgium. Previously, she had been a visiting scientist at Agilent Technologies (USA), Eidgenössische Technische Hochschule Zürich (Switzerland), and the National Institute of Standards and Technology (USA). Dominique's main research interests concern linear and nonlinear characterization and modeling of microwave devices and circuits, as well as linear and nonlinear hybrid and integrated circuit design for telecommunications and biomedical applications. She is the technical chair of ARFTG and serves as the editor of the *IEEE Transactions on Microwave Theory and Techniques*.

Authors' Biographies

Iltcho Angelov

Chapter 5. Large-Signal Time-Domain Waveform-Based Transistor Modeling

Iltcho Angelov was born in Bulgaria. He received his MSc in electronics (honors) and PhD in mathematics and physics from Moscow State University. From 1969 to 1991, he was with the Institute of Electronics, Bulgarian Academy of Sciences (IE BAS) as a researcher and research professor, and head of the Department of Microwave Solid State Devices from 1982. Since 1992 he has been with Chalmers University of Technology, Göteborg, Sweden as a research professor. As a researcher he worked on various microwave devices: Impatt, Gunn, BJT, FET, low-noise & power amplifiers, oscillators, synchronization & phase modulators, frequency dividers, multipliers, and low-noise receivers up to 220 GHz. In recent years his main activity has been related to FET and HBT modeling. Together with CAD companies FET GaAs, and later GaN, a HEMT model was implemented associated with various CAD tools.

Gustavo Avolio

Chapter 5. Large-Signal Time-Domain Waveform-Based Transistor Modeling

Gustavo Avolio was born in Cosenza, Italy, in 1982. In 2006 he received the MSc degree in electronic engineering from the University of Calabria (UniCAL), Italy. In 2008 he joined the TELEMIC Division of the KU Leuven, Leuven, Belgium, where he obtained the PhD degree in electronic engineering in 2012. His research work focuses on large-signal measurements and nonlinear characterization and modeling techniques for microwave active devices. His research is supported by Fonds Wetenschappelijk Onderzoek – Vlaanderen (FWO).

Kurt Barbé

Chapter 6. Measuring and Characterizing Nonlinear Radio-Frequency Systems

Kurt Barbé received her Masters in electrical engineering in 2005 from the Vrije Universiteit Brussel (VUB), Brussels, Belgium. In 2011, she obtained her PhD at the Fundamental Electricity and Instrumentation (ELEC) department of the VUB. Her PhD work was focused on nonlinear block-oriented modeling. Currently, she is working as a postdoctoral researcher of the Flemish Research Foundation (FWO-Vlaanderen). Her main research interests are in the field of nonlinear modeling and non-Gaussian signal analysis for biomedical applications. She holds strong expertise in parameter estimation of nonlinear models and the statistical postprocessing of fMRI signals.

Alina Caddemi

Chapter 1. A Clear-Cut Introduction to the De-embedding Concept: Less is More

Alina Caddemi has been an assistant professor in the field of Microwave Electronics from 1990 to 1998 at the University of Palermo, Italy. In 1998, she joined the University of Messina, as an associate professor of Electronics. Her current research interests are: temperature-dependent and noise characterization techniques for solid-state devices, cryogenic measurements and modelling of HEMT's for radio-astronomy applications, noisy circuit modelling of field-effect transistors, neural network modelling of devices, CAD and realization of hybrid low-noise circuits. Prof. Caddemi serves as an associate editor of the *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields and Microwave Review*, as well as a reviewer of many international journals.

Walter Ciccognani

Chapter 3. Characterization and Modeling of High-Frequency Active Devices Oriented to High-Sensitivity Subsystems Design

Walter Ciccognani received the MS degree in electronic engineering from the University of Roma "Tor Vergata" in 2002 and a PhD in telecommunications and microelectronics therefrom in 2007. From 2007 to date, he has collaborated with the same university, where he has been a researcher since 2012. His research interests include linear microwave circuit-design methodologies, linear and noise analysis/measurement techniques, and small-signal and noise modeling of microwave active devices.

Sergio Colangeli

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Sergio Colangeli received the MS degree in electronic engineering in 2008 from the University of Roma "Tor Vergata" where he has recently received a PhD degree in telecommunications and microelectronics. His research interests include low-noise design methodologies for microwave applications, and small-signal and noise measurement and modeling of microwave active devices. He was a recipient of the EuMIC Young Engineer Prize in 2012.

Telmo Reis Cunha

Chapter 7. Behavioral Models for Microwave Circuit Design

Telmo Reis Cunha was born in Porto, Portugal, in 1973. He received the diploma and doctorate degrees in electronics and computer engineering from the University of Porto, Portugal, in 1996 and 2003, respectively. Before 2004 he was first involved with the Astronomical Observatory of the University of Porto and, afterward, he was a technical director and research engineer with Geonav Lda., a private company near Porto. Since 2004 he has been an assistant professor with the Department of Electronics, Telecommunications and Informatics, University of Aveiro, Portugal, and also a research engineer with the Institute of Telecommunications of Aveiro. He has been lecturing in the areas of control theory and electronics, and has been involved in several national and international research projects. His current research interests include behavioral modeling and linearization applied to radio frequency and microwave devices, and also integrated-circuit signal integrity analysis.

Gilles Dambrine

Chapter 2. Millimeter-Wave Characterization of Silicon Devices under Small-Signal Regime: Instruments and Measurement Methodologies

Gilles Dambrine is currently the deputy director of the Institute of Electronics, Microelectronics and Nanotechnology (IEMN-University of Lille-CNRS). He is a full professor of electronics at Lille 1 University and specialist in the characterization of active devices under high-frequency regimes. Over the years, his research interests have been oriented to the study of the microwave and millimeter-wave properties and applications of nanodevices such as CNTs, graphene, and semiconducting nanowires. He is also an IEEE senior member, the author and coauthor of about 120 papers and communications and four book chapters in the field of microwave devices, and also the scientific coordinator of Nanoscience-Characterization-Center ExCELSiOR (www.excelsior-ncc.eu).

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Ernesto Limiti

Chapter 3. Characterization and Modeling of High-Frequency Active Devices Oriented to High-Sensitivity Subsystems Design

Ernesto Limiti has been a full professor of electronics in the EE Department of the University of Roma "Tor Vergata" since 2002. His research activities are focused on three lines, all in microwave and millimeter-wave electronics. The first concerns active devices oriented to small-signal, noise, and large-signal modeling. Novel methodologies are developed for noise characterization and modeling; equivalent-circuit modeling strategies are implemented both for small- and large-signal operating regimes for GaAs, GaN, SiC, Si, InP MESFET/HEMT devices. The second line is related to design methodologies and characterization methods for low-noise devices and circuits. His main focus is on extremely low-noise cryogenic amplifiers. His collaborations run with major radio-astronomy institutes in Europe (FP6 and FP7 projects). The third line is analysis and design methodologies for linear and nonlinear microwave circuits. He is a referee of several international microwave and millimeter-wave electronics journals and is a member of several international conference and workshop steering committees.

Bart Nauwelaers

Chapter 8. Electromagnetic-Analysis-Based Transistor De-embedding and Related Radio-Frequency Amplifier Design

Bart Nauwelaers is a full professor at the KU Leuven, where he currently heads the Department of Electrical Engineering (ESAT). Since 1981 he has been with the TELEMIC division of the same department, being involved in research on microwave antennas, passive components, interconnects, microwave integrated circuits and MMICs, linear and nonlinear device modeling, MEMS, ultrasonics, and phononics. He is a former chair of IEEE AP/MTT-Benelux and past chair of URSI-Benelux. Bart Nauwelaers teaches courses on microwave engineering, information theory and transmission, digital and analogue communications, and design in electronics and telecommunications. For the last 20 years he has served education in several functions, the last being the program director for the Bachelor and Masters programs in electrical engineering.

José Carlos Pedro

Chapter 7. Behavioral Models for Microwave Circuit Design

José Carlos Pedro received the diploma in 1985, doctorate in 1993, and habilitation degree in 2002 in electronics and telecommunications engineering, from University of Aveiro, Portugal, where he is now a full professor. His research interests include modeling, design, and testing of various nonlinear microwave circuits. He is the leading author of *Intermodulation Distortion in Microwave and Wireless Circuits* (Artech House, 2003) and has authored more than 250 technical papers and served as an associate editor for the *IEEE MTT Transactions* and reviewer for major international microwave journals and symposia. He served his university department as the coordinator of the scientific council and as the department head. He received the Marconi Young Scientist Award in 1993 and the 2000 IEE Measurement Prize. In 2007 he was elected as a fellow of the IEEE for his contributions to the nonlinear distortion analysis of microwave devices and circuits.

Antonio Raffo

Chapter 9. Nonlinear Embedding and De-embedding: Theory and Applications

Antonio Raffo was born in Taranto, Italy, in 1976. He received an MS degree (honors) in electronic engineering and a PhD in information engineering from the University of Ferrara, Ferrara, Italy, in 2002 and 2006, respectively. From 2006 to 2010 he was with the Engineering Department, University of Ferrara, as a post-doctoral researcher. He is currently a research associate at the Engineering Department, University of Ferrara, where he teaches the courses in semi-conductor devices and electronic instrumentation and measurement. He has coauthored over 90 papers in international scientific journals and conferences and serves as reviewer for many international journals. His research activity is mainly oriented to nonlinear electron-device characterization and modeling and circuit-design techniques for nonlinear microwave and millimeter-wave applications. Antonio Raffo is a member of the IEEE MTT-11 Technical Committee (Microwave Measurements).

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James C. Rautio is CEO, president, and founder of Sonnet Software, which has been developing, selling, and supporting the world's highest accuracy planar EM software for over 30 years. He received his BSEE from Cornell University, an MS from the University of Pennsylvania, and his PhD from Syracuse University, advised by Professor Roger Harrington. He has published numerous papers on the topics of EM analysis, error, and calibration. In a related area, he has published and presented many times on the life of James Clerk Maxwell as well as taking an active role in preserving Maxwell's home, Glenlair.

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Davide Resca is currently a senior microwave design engineer at MEC srl, Bologna (Italy). He joined MEC in January 2009, as an MMIC designer after his PhD and postdoctoral studies with the Department of Electronics, Computer Science and Systems (DEIS) of the University of Bologna. He is responsible for MMIC design, hybrid module design, passive and active device characterization, and modeling. His current research interests are advanced CAD techniques for microwave integrated-circuit design, EM subcircuit advanced modeling, and planar filter design synthesis and analysis.

Valeria Vadalà

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Wendy Van Moer was born in Belgium in 1974 and received Master of Engineering and PhD degrees in engineering from the Vrije Universiteit Brussel (VUB), Brussels, Belgium, in 1997 and 2001, respectively. She is currently an associate professor with the Department of Electrical Measurement (ELEC), VUB, and a visiting professor at the Department of Electronics, Mathematics and Natural Sciences, University of Gävle, Sweden. Her main research interests are nonlinear measurement and modeling techniques for medical and high-frequency applications. She has published over 100 related conference/peer reviewed journal articles. She was the recipient of the 2006 Outstanding Young Engineer Award from the IEEE Instrumentation and Measurement Society. Since 2007, she has been an associate editor for the *IEEE Transactions on Instrumentation and Measurement*. From 2010 till 2012, she was an associate editor for the *IEEE Transactions on Microwave Theory and Techniques*. In 2012, she was elected as a member of the administrative committee of the IEEE Instrumentation and Measurement Society for a 4-year term.

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Giorgio Vannini is a full professor of electronics and currently the head of the Engineering Department of the University of Ferrara, Italy. He joined the University of Ferrara in 1998 after being a research associate at the University of Bologna and the National Research Council. He holds a PhD degree in electronics and computer science engineering. During his academic career he has been a teacher of applied electronics, electronics for communications, and industrial electronics as well as advanced courses on microwave circuit design. He has coauthored over 200 papers devoted to electron-device modeling, computer-aided design techniques for MMICs, and nonlinear circuit analysis and design. He is a co-founder of the academic spin-off MEC (Microwave Electronics for Communications).

Manuel Yarlequé

Chapter 8. Electromagnetic-Analysis-Based Transistor De-embedding and Related Radio-Frequency Amplifier Design

Manuel Yarlequé is an associate professor at Pontificia Universidad Católica del Perú. He teaches graduate and undergraduate courses on electromagnetics, microwaves, and antennas. He is a member of the IEEE MTT-S and ComSoc. In 2001, he joined KULeuven ESAT-Telemic research, focusing on the design of highly efficient and linear RF amplifiers, obtaining a doctorate degree in 2008. During that period, he performed research on RF transistor modeling and de-embedding. His current research interests are electromagnetics, surface plasmon resonance applications, RF/microwave circuit design, microwave imaging, and phase array antennas.