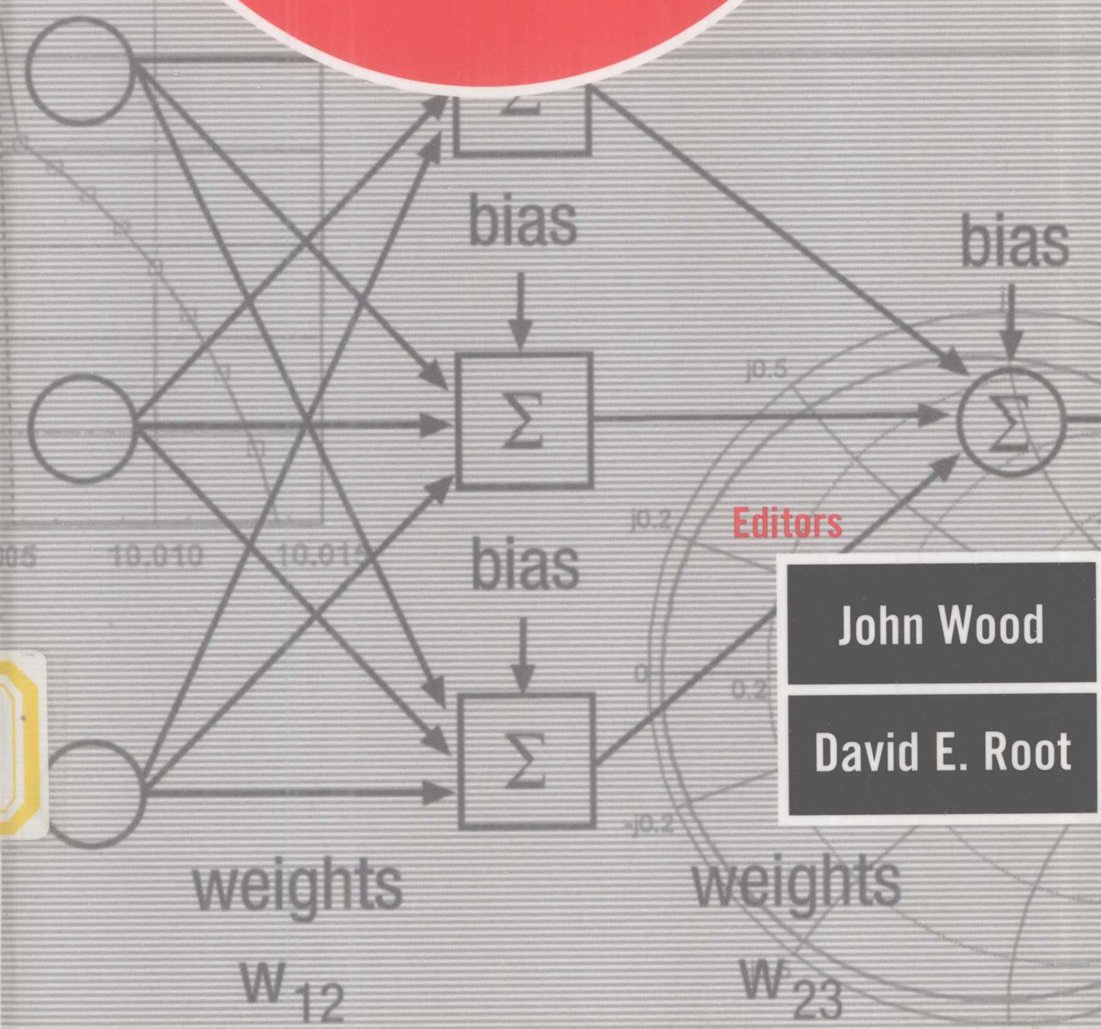
Fundamentals of Nonlinear Behavioral Modeling for RF and Microwave Design



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Preface

Good, accurate models are in demand in almost every form of business. In the electronics industry, models for transistors and other circuit components have been the cornerstone of circuit design for many years. Integrated circuit designers rely upon models at many levels — from compact models of transistors, to higher-level and more abstract forms of gate-level models and timing models for the validated design of large digital systems. And with great success: witness the successful design of multimillion transistor microprocessor and DSP ICs that simply could not be designed at the transistor level of circuit description. The "higher-level" models constitute the behavioral descriptions of the circuits used in the overall designs.

In the analog-mixed signal design arena it is more difficult, especially at high frequencies — the RF and microwave end of the spectrum — to obtain validated designs. Often the circuits or modules are "tweaked" and tuned to obtain optimal results, a process that can generate several design turns and hence cost time and money. The wireless communications market is very important commercially, and so there is a big interest in finding suitable models to use in the RF system design process.

Behavioral models are often used to describe phenomena where the underlying physical processes may not be known fully, or else are too difficult to capture completely. These models are often built from observed data, and relate the outcomes of a process to its stimuli through a purely mathematical relationship. "Behavioral modeling" is therefore often thought to be merely a form of multidimensional curve fitting. The scientific foundations, mathematical methods, and practical implications of behavioral modeling are much broader than this.

It is from this perspective that we organized a successful workshop on behavioral modeling at the International Microwave Symposium in

Philadelphia in June 2003. Our aims with this workshop were to introduce to RF and microwave engineers some of the fundamental ideas and techniques of behavioral modeling, so that these methods could be adopted and adapted in their own design methods and processes. At this workshop, we were privileged to have several speakers with great experience and expertise in behavioral modeling, characterization, and design at RF and microwave frequencies. To disseminate these ideas and techniques to a broader audience, we chose to publish the workshop materials in the form of a book. Many of the workshop speakers volunteered to expand their workshop presentations into formal texts, which now appear as chapters of this book. We would like to thank them for their professionalism and dedication in this task; it has been a pleasure to work with them.

We hope that you derive as much benefit from this book in reading it as we have in putting it all together.

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Chapter 1

Introduction to Fundamentals of Nonlinear Behavioral Modeling for RF and Microwave Design

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1.1 INTRODUCTION

Modern microwave and wireless communications systems are often too complex to permit their complete simulation at the transistor level of description. The very large number of nonlinear equations to be solved is prohibitive, in terms of simulation time and memory, for circuit simulators running on typical computer workstations available to most designers. This remains a problem even when using modern simulation algorithms such as harmonic balance [1, 2] and transient envelope analysis [3, 4] that enable, for certain classes of stimuli, much more efficient solution of the circuit equations than traditional time-domain integration methods used by such simulators as SPICE. The lack of complete and accurate system simulation capability presents a severe hindrance to efficient system design, often leading to costly and time-consuming design iterations and expensive build-test prototype cycles.

One solution to this design challenge is to replace entire circuits and nonlinear functional blocks of complicated systems with simplified, but sufficiently accurate, behavioral models. Behavioral models enable complete simulation at a higher level of abstraction while still representing, accurately, the effect of the nonlinear blocks on the overall system performance. A wide variety of behavioral modeling methods and techniques are presented in this book.

Behavioral models can be derived from measurements and simulations. Measurements can capture the detailed dynamical response of the component, whether or not a model of the IC or functional block is available or even exists. Simple measurement-based models can be generated from relatively straightforward measurements, such as single-frequency swept power measurements, which yield AM-to-AM compression. Adding vector error correction to such measurements enables the AM-to-PM characteristics to be extracted. The more sophisticated models described herein often require more advanced measurement instruments. The envelope models can be generated from data obtained by exciting the device-under-test with modulated signals, and measuring with a vector signal analyzer, or phase-corrected oscilloscope at RF. The frequency-domain and time series behavioral models rely upon the phase-corrected port qualities: the a and b waves or the instantaneous voltages and currents. These can presently only be measured over broad bandwidths using the nonlinear vector network analyzer, for example. At the present time, such instruments are not widely available, and they may not have the required dynamic range or operate to high enough frequencies.

There are two distinct ways of generating a simulation-based behavioral model. The first makes use of the specific internal information encapsulated in the detailed model of the circuit or functional block. This information is in the form of knowledge of all the nonlinear equations, parameter values, and topological connections among the constituent component (e.g., transistor) models. Methods of order reduction can then be applied to reduce the number of equations, resulting in a simplified behavioral model. This is not the type of approach presented in this book. The interested reader is referred to [5].

In the second simulation-based approach, the circuit simulator is used as a virtual instrument, to excite the detailed model with relevant stimuli, and the results used as if they were real data to generate the behavioral model.

All of the behavioral modeling approaches presented in this book can be applied at the device external terminals. Therefore, these techniques are generally applicable to both simulation-based and measurement-based cases.

The frequency range of simulations is virtually unlimited, and the dynamic range is limited only by the tolerances of the convergence conditions and the numerical finite precision used in the code. However, the accuracy of simulation-based behavioral models can be limited by the accumulation of approximations from its lower-level constituent models (e.g., transistor models) and the neglect of certain intercomponent couplings (e.g., electromagnetic interactions between passive elements).

Behavioral models provide a key way of protecting intellectual property (IP) associated with a circuit or functional block, while still encapsulating its performance. For all of the techniques presented here, it is rigorously impossible to reverse engineer the component from its behavioral model. This is much higher security than merely encrypting (hiding the details) of the circuit-level model. Sensitive intellectual property can be freely shared and combined for mutual benefit, without risk of compromise.

A system designer may not have all the actual hardware components necessary to prototype a complete design. Behavioral models can provide the ability to design the system before the components are available. Conversely, a behavioral model representing an IC can be used to determine whether or not the IC is a good candidate for use in a system design. In fact, a good behavioral model is perhaps the best specification of the IC performance.

Behavioral models can be a key competitive advantage for both circuit design houses and system design houses. A behavioral model of a circuit can be sent to a system design house for evaluation, in lieu of the actual component. Circuit design houses providing good behavioral models make it easier for their product to be designed into systems, giving them an advantage over other design houses with comparable hardware technology. Conversely, a system design house with the capability of creating their own behavioral models can much more easily design systems than those who must wait for hardware and build costly and time-consuming prototypes.

For linear circuits, broadband *S*-parameters provide an essentially complete behavioral model of the component. The circuit can be replaced by an *S*-parameter simulation block and simulated at the higher level of abstraction. (Of course there are practical difficulties including limited frequency range of the data, interpolation issues, noise, causality constraints, and so forth.)

Nonlinear problems are much harder. Insight and methods of linear analysis do not generally apply. Superposition doesn't hold in general, Green functions don't exist, the Fourier domain is less useful, and there is no single, overarching theory that is complete and also useful. Nevertheless, a great deal of progress has been made both at the foundational level and also at the practical application level. This book is a sampling of both these categories.

Some of the methods presented in this book constitute extensions of linear theory. Other approaches are based on fundamentally nonlinear concepts. Techniques are presented in the time domain, frequency domain, and also in mixed time-frequency domains. Simulator algorithms and techniques are discussed.

Nonlinear methods are highly interdisciplinary. Contributions have come from device physics, the mathematics of functional analysis and nonlinear dynamics, and engineering disciplines of control theory, system identification, nonlinear microwave measurements, neural networks, and nonlinear circuit simulation, just to name a few. The recent *Special Issue of the Proceedings of the IEEE on Applications of Nonlinear Dynamics to Electronic and Information Engineering* [6] is indicative of the timeliness and value such interdisciplinary approaches can bring to the rapidly developing area of microwave and RF nonlinear behavioral modeling.

From the conceptual perspective, similar problems to those discussed in this book are encountered in many fields. This fact makes the approaches presented here suitable for applications far beyond the field of microwaves and even electronics.

1.2 BOOK ORIGINS, CONTENTS, AND OBJECTIVES

This book has evolved from the highly successful behavioral modeling workshop, *Fundamentals of Nonlinear Behavioral Modeling: Foundations and Applications*, that was organized by the editors, and presented at the International Microwave Symposium in Philadelphia, Pennsylvania, on June 8, 2003. The workshop was cosponsored by MTT-1 (CAD) and MTT-11 (Microwave Measurements) committees.

Each chapter of the book is an expanded and self-contained version of the respective workshop presentation.

Chapter 2 presents an introduction to the theory of Volterra analysis and shows how it can be used for modeling RF and microwave systems. Volterra theory has its roots in the mathematics of functional analysis, and provides a rigorous foundation for theoretical developments and practical applications. It is well suited for modeling the weakly nonlinear individual blocks of RF and microwave systems in the frequency domain. It also provides a link to other techniques (see Chapters 3 and 4), not all of which are restricted to weak nonlinearities.

Chapter 3 presents a treatment of several envelope-domain behavioral models and their identification using a modified Volterra series methodology. This type of modeling approach takes into account the critical multiple time-scale coupled dynamics generated by RF and microwave blocks stimulated by complex signals, such as those used in modern communication systems. The treatment includes techniques to excite the system dynamics and generate the respective models from measurements and simulations. The discussion includes efficient implementation into the simulator and measurement environments.

Chapter 4 presents mixed time-frequency domain methods for modeling and simulating long-term memory effects in RF and microwave nonlinear circuits and systems. The physical origins and macroscopic effects of these dynamics are discussed. An application to an S-band amplifier with and without bias-circuitry dynamics is presented, demonstrating that long-term memory effects can determine a circuit's nonlinear distortion characteristics when its excitation signal bandwidth is varied. A hybrid technique of envelope simulation at the system level and RF simulation at the circuit level is emphasized for evaluating the performance of wideband nonlinear systems.

Chapter 5 presents the "scattering functions" black-box frequency domain behavioral modeling technique. Scattering functions are a rigorous nonlinear generalization of (linear) *S*-parameters under the assumption of superposition for the harmonic components of the signal. The scattering function model and its identification from nonlinear vector network analyzer measurements are presented. It is demonstrated that the scattering functions are capable of describing many nonlinear component characteristics including fundamental gain compression, AM-PM, "hot S_{22}," and harmonic distortion.

Chapter 6 presents artificial neural networks (ANNs) as a new tool for nonlinear behavioral modeling. The fundamentals of ANN structures are presented, including feed-forward, recurrent, and dynamic neural networks. Neural network training concepts and issues are introduced. The relationship among different categories of neural networks and different modeling requirements is summarized, with illustrative examples for amplifiers, mixers, and their joint use in a system. Issues of efficiently incorporating ANN models into circuit simulators are also discussed.

Chapter 7 presents behavioral modeling from the perspective of nonlinear dynamics, which provides a theoretical foundation for a fundamentally nonlinear theory of black box modeling in the time domain. An introduction to state equations and phase space is presented, followed by a description of the methods used for the reconstruction of model dynamics from time series data. This "nonlinear time series" technique is used to construct models from large-signal microwave measurements or simulations. It is illustrated by the generation of a transportable and cascadable model of a microwave IC amplifier that predicts accurately the DC, small-signal, and large-signal behavior, including the harmonic and intermodulation distortion behavior.

This book has the following objectives. The first goal is to present foundational material to the IMS (MTT) community from renowned experts in their own disciplines to catalyze and cross-fertilize present behavioral modeling research in the RF and microwave arena. The second goal is to present recent state-of-the-art applications of behavioral modeling to RF and microwave circuit and system design.

The level is appropriate for workers in the field who want exposure to cross-disciplinary approaches, and to circuit/system designers who want to know the practical state of these techniques for immediate or near term application.

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