Computer-Aided Design of RF and Microwave Circuits and Systems

Michael B. Steer, *Fellow, IEEE*, John W. Bandler, *Fellow, IEEE*, and Christopher M. Snowden, *Fellow, IEEE*

Invited Paper

***Abstract*—The history of RF and microwave computer-aided engineering is documented in the annals of the IEEE Microwave Theory and Techniques Society. The era began with elaborate analytically based models of microwave components and simple computer-aided techniques to cascade, cascode, and otherwise connect linear component models to obtain the responses of linear microwave circuits. Development has become rapid with today's computer-oriented microwave practices addressing complex geometries and with the ability to globally model and optimize large circuits. The pursuit of accurate models of active devices and of passive components continues to be a key activity.**

***Index Terms*—Circuit theory, computer-aided design, device modeling, EM modeling, global modeling, microwave circuits, nonlinear analysis, optimization.**

I. INTRODUCTION

THE development of computer-aided engineering (CAE) for RF and microwave circuits coincided with the formation of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) in 1953—roughly corresponding to the birth of the computer era. Design by computer was once regarded by some with serious misgivings. Almost every engineer, as an essential component of the art and science of engineering practice, now embraces it. Real hands-on engineering design now includes computer hardware, computer software, and information processing in various relevant forms.

The greatest inspiration for CAE as we know it today was the 1967 Special Issue of the PROCEEDINGS OF THE IEEE [1] with such diverse topics as Chebyshev filter optimization through to nonlinear electronic network analysis [2]. Branin's paper in this issue, "Computer methods of network analysis," [3] explains the development of a matrix formulation involving an underlying topological structure with a superimposed algebraic structure. It is regarded as the origin of the circuit models and equations we commonly use today in CAE. The activity in circuit modeling and CAE has resulted in more additional special issues [4]–[21] of this TRANSACTIONS than any other area of microwave theory and technology. This activity began in 1968 with this TRANSACTIONS' "Special Issue on Microwave Integrated Circuits" [4], which included early papers on using computer-aided techniques to design complex microwave circuits. This first special issue was followed by special issues specifically devoted to computer-oriented microwave practices [5], [8], [14]–[18], [20]. Getsinger was one of the earliest proponents of "Computer-Oriented Microwave Practices," which culminated in the 1969 special issue of this TRANSACTIONS, for which he was guest editor [5]. Getsinger was also the driving force behind the formation of the Technical Committee on Computer-Oriented Microwave Practices, now technical committee MTT-1 (Computer-Aided Design).

This paper points out the major developments in CAE of RF, microwave, and millimeter-wave circuits. It is not possible to cite the large number of individual contributors. Readers are referred to numerous special issues and review papers on this topic. With a few exceptions, the rise of RF and microwave CAE has been exclusively documented in IEEE MTT-S publications.

II. ORIGINS OF RF AND MICROWAVE CIRCUIT MODELING

Many of the important early developments in microwave engineering were made possible when the electromagnetic (EM) environment was transformed into a circuit abstraction, thus capturing the relevant, perhaps complex, physical behavior in a form that could lend itself to linear solution. Four particular developments exemplify the modeling procedure of transforming a distributed structure into a lumped circuit. The first of these is the modeling work undertaken for radar development at the Massachusetts Institute of Technology (MIT) Radiation Laboratory in the 1940s. Marcuvitz's book, in the Radiation Laboratory Series, documented the results of part of this effort and showed how discontinuities in waveguide could be modeled by lumped-element equivalents [22]. Barrett [23] documented a similar treatment for planar transmission-line circuits. The development of microwave network analysis continued at the Microwave Research Institute organized at the Brooklyn Polytechnic Institute, Brooklyn, NY, in 1942 (e.g., see [24]). The pioneers here included Oliner, Weber, Felsen, Marcuvitz, and Hessel. The second development that had a tremendous effect on a generation of microwave engineers was

---

Manuscript received October 31, 2001. This material is based upon work supported in part by the Space and Naval Warfare Systems Center San Diego under Grant N66001-01-1-8921 as part of the Defense Advanced Research Projects Agency NeoCAD Program.

M. B. Steer is with the Electrical and Computer Engineering Department, North Carolina State University, Raleigh, NC 27695-7914 USA (e-mail: m.b.steer@ieee.org).

J. W. Bandler is with the Bandler Corporation, Dundas, ON, Canada L9H 5E7 and also with the Department of Electrical Engineering, McMaster University, Hamilton, ON Canada L8S 4K1 (e-mail: j.bandler@ieee.org).

C. M. Snowden is with the Department of Microwave Engineering, The University of Leeds, Leeds LS2 9JT, U.K. and also with Filtronic plc, Shipley BD18 3TT, U.K. (e-mail: csnowden@filct.com).

Publisher Item Identifier S 0018-9480(02)01953-1.

Collin's *Foundation of Microwave Engineering*, which presented a formalism for treating distributed structures as circuit elements [25]. The third significant development was the work of Eisenhart and Khan [26] that presented an approach to modeling waveguide-based structures as circuit elements. In that paper, it was shown that quite sophisticated and accurate models could be developed for a three-dimensional waveguide system. The ramification of that paper extends beyond waveguide circuits. The key concept introduced is that a structure that can support multiple EM modes can be described by a circuit with defined coupling between the modes, and with each mode represented by its own equivalent circuit. Thus, a system that is generally considered as supporting incoherent components (a multimode system) can be modeled as a deterministic structure, as required in the circuit-modeling paradigm. The final development in linear circuit modeling technology is the segmentation approach most recently reviewed by Gupta [27]. In this segmentation (or diakoptic) approach, a structure is partitioned into smaller parts and each part is characterized electromagnetically. These characterizations are then combined using concepts based on network theory to yield the overall response of the circuit. One result of the segmentation approach is that the computational burden becomes manageable and the structure can be partially redefined and earlier characterizations of the unchanged parts reused.

From the early days, commercial microwave circuit simulators supported a technique based on the incorporation of any device or simple circuit model that could be described by port-based network parameters. Generally, these device and circuit models were linear models specified by measured or derived scattering parameters at a number of discrete frequencies. The microwave circuit simulators were port based, without the capability of specifying a reference node. At the same time, major advances were made in nodal-based electrical circuit modeling principally for digital circuits. This provided the capability of handling very large complex circuits and modeling transient effects in circuits consisting of nonlinear devices.

III. MICROWAVE CIRCUIT SIMULATION

There are three important reasons to simulate RF and microwave circuits and systems: to understand the physics of a complex system of interacting elements; to test new concepts; and to optimize designs. Also, as the frequency of RF circuits extends beyond a gigahertz to tens and hundreds of gigahertz, wavelengths become large with respect to device and circuit dimensions and the three-dimensional EM environment becomes more significant. If reliable high-yielding optimized designs of microwave and millimeter-wave circuits are to be achieved, the interrelated effects of the EM field and the linear and nonlinear circuit elements must be self-consistently modeled (e.g., see this TRANSACTIONS' "Special Issue on Global Modeling" [20], in which the global modeling of distributed microwave circuits, integrating EM, electrical circuit, and thermal modeling, are discussed (e.g., [28]).

The nonlinear simulation of microwave circuits has seen considerable development over the last decade. By assuming that only a finite number of sinusoids is present in a nonlinear circuit, the computational burden of computing the transient response of the circuit is avoided and only the steady-state response, given by the amplitudes and phases of the sinusoids, is required.

A. Nonlinear Microwave Simulation: Frequency Domain

Frequency-domain nonlinear circuit analysis methods represent logical developments from frequency-domain linear circuit analysis. Initially they were restricted to weakly nonlinear systems, but today, can be used with strongly nonlinear systems with large-signal excitation. The roots of frequency-domain nonlinear analysis techniques are contained in Volterra's theory of functionals (see [29]). The common underlying principle is that the spectrum of the output of a broad class of nonlinear circuits and systems can be calculated directly given the spectrum input to the nonlinear system. Some techniques determine an output frequency component by summing calculations of individual intermodulation products. For example, the product of two tones is, in the time-domain, the product of two sinusoids. The trigonometric expansion of this yields two intermodulation products that have frequencies that are the sum and difference, respectively, of the frequencies of the tones. Power series techniques use trigonometric identities to expand the power series and calculate each intermodulation product individually. Algorithms sum these by frequency to yield the output spectrum. At the coarse end of the scale are Volterra series-based techniques that evaluate groups of intermodulation products at a single frequency. Some frequency-domain nonlinear analysis techniques are noniterative, although these are restricted to unilateral systems. Others, known as frequency-domain spectral balance techniques, are iterative being the frequency-domain equivalent of the HB techniques discussed in Section III-B. Intermediate between these extremes are techniques that operate by converting a nonlinear element into a linear element shunted by a number of controlled current sources. This process is iterative and, at each iteration, a residual nonlinear element is left, which reduces from one iteration to another.

B. Nonlinear Microwave Simulation: Steady-State

The roots of the HB procedure, the term used for nonlinear steady-state simulation, are in Galerkin's method in which a solution is assumed, in our case, a set of phasors, with unknown coefficients. Guesses of these coefficients are adjusted to minimize the error in the governing equations, usually the Kirchoff's current laws for nonlinear circuits. The method was applied to nonlinear circuits by Baily in 1960. In 1975, Nakhla and Vlach [30] introduced partitioning of a circuit into linear and nonlinear subcircuits (see Fig. 1) so that linear circuit reduction could be used to drastically simplify treatment of the linear circuit. The variables, often current phasors, describing the state of the nonlinear subcircuit are determined as the Fourier transform of the time-domain response of the nonlinear subcircuit. These are compared to the frequency-domain response of the linear circuit. This mixed time-domain/frequency-domain analysis, identified by the use of Fourier transforms, has become known as the HB method.

The first significant use of HB in the analysis of microwave circuits was by Egami, as described in this TRANSACTIONS' "Special Issue on Computer-Oriented Microwave Practices"

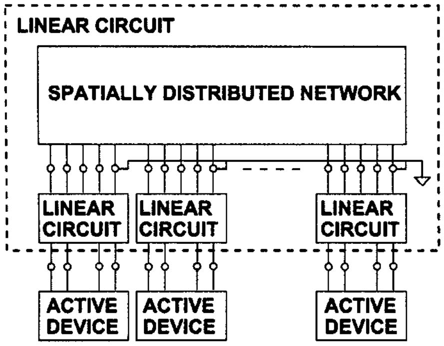

Fig. 1. HB partitioning into linear circuit and nonlinear active devices with the spatially distributed network modeled using EM techniques.

[8]. Egami used a Newton iteration procedure to minimize the HB error determining the local-oscillator waveform in a diode mixer. One of the first practical applications of HB to multitone analysis was in 1983 by Rizzoli *et al.*, who also introduced a state-variable approach to maintain conservation of charge among other attributes in using arbitrary models of nonlinear elements. The developments in HB analysis are reviewed by Rizzoli and Neri [31] and Gilmore and Steer [32]. More recent developments enable the technique to be used to model large circuits excited by digitally modulated signals using, for example, matrix-free Krylov techniques [33] and extensions to time-marching transient and HB analyses [34].

C. Adjoint Sensitivity Technique

The adjoint network method developed by Director and Rohrer [35] is usually cited as the starting point for the adjoint circuit approach to sensitivity evaluation based on Tellegen's theorem. The essential features are the simple relation between the original circuit and an auxiliary or "adjoint" circuit (e.g., transpose of the nodal admittance matrix [36]) and the need to derive simple element level sensitivity expressions. As a result, the computational effort to evaluate the first-order derivatives of any response with respect to all design parameters corresponds essentially to two circuit analyses [37].

The microwave literature abounds with techniques and applications in the 1970s and 1980s using generalized scattering parameters, voltage–current variables, and branched cascaded topologies (for waveguide multiplexers). Exact sensitivities can be developed for nonlinear HB analyses [38], as well as implementable approximations such as the feasible adjoint sensitivity technique [39]. In the 1990s, Alessandri *et al.* spurred the application of the adjoint network method to full-wave modeling of a microwave structure, using a mode-matching orientation [40]. These sensitivity techniques significantly facilitate powerful gradient-based optimizers, making the optimal design of nonlinear circuits in the frequency domain tractable.

IV. DESIGN CENTERING AND TOLERANCE OPTIMIZATION

A. Design With Tolerances

Uncertainties, which deteriorate performance, may be due to physical (manufacturing, operating) tolerances, as well as to parasitic effects such as EM coupling between elements, dissipation, and dispersion. In the design of substantially untunable circuits, these phenomena lead to two important classes of problems: worst-case design and statistical design. Following Karafin's original formulation (*Bell System Technical Journal*, 1971), the main objective is the reduction of cost. Worst-case design requires that all units meet the design specifications under all circumstances with or without tuning. In statistical design, it is recognized that a yield of less than 100% is likely; therefore, with respect to an assumed probability distribution function, yield is estimated and enhanced by optimization. We either attempt to center the design with fixed assumed tolerances or we attempt to optimally assign tolerances and/or design tunable elements to reduce production cost [41].

B. Algorithms for Design Centering

A number of algorithms for yield optimization were developed in the late 1970s and 1980s. They include Director and Hachtel (simplicial approximation), Soin and Spence (the center of gravity method), Bandler and Abdel-Malek (updated approximations and cuts), Styblinski and Ruszczynski (stochastic approximation), Polak and Sangiovanni-Vincentelli (outer approximation), Singhal and Pinel (parametric sampling), Bandler and Chen (generalized LP centering), and Biernacki *et al.* (efficient quadratic approximation). Yield optimization of nonlinear microwave circuits within the HB simulation environment has been treated by Bandler *et al.* in 1990 [39].

C. Process-Oriented Yield Optimization Paradigm

A process-ready computer-aided design (CAD) module may refer to a computer program that facilitates a path for technologically oriented information from a process-, physically, or geometrically based description of a device or circuit to readily interface with a yield-driven optimization-oriented man–machine design environment [42]. The classical approach of employing equivalent circuit models with independent parameters hinders the effective representation of and optimal design with statistical effects and spreads in integrated circuits. It is an obstacle to yield-driven design.

V. EM MODELING OF RF AND MICROWAVE CIRCUITS

A. Brief History of EM Modeling

The ubiquitous finite-difference time-domain (FDTD) approach is traceable to Yee [43]. The finite-element method (FEM) can be traced back to Silvester [44]. Wexler, known for his novel mode-matching contribution [45], makes the case for numerical solutions of field equations and reviews solution techniques based on finite differences [46]. Foundations of the method of moments (MoM) for EM can be attributed to Harrington [47] and, for implementation in planar simulators, to Rautio and Harrington [48]. The "rooftop" expansion functions for current densities over rectangular patches widely used in MoM for planar structures, and expansion over triangular patches, very flexible geometrically in the sense that they can approximate curved surfaces as well, are attributed to Rao *et* *al.* [49]. An overview of the transmission-line matrix (TLM) method, pioneered in the microwave arena by Johns in the 1970s, is presented by Hoefer [50].

B. Commercial EM Simulators

EM field analysts have been preoccupied with analysis so they are now the last major computationally oriented group in the microwave community to adopt formal optimization techniques for automated EM design. We can single out the High Frequency Structure Simulator (HFSS) from Ansoft and HP (Agilent) as the flagship FEM solver and the MoM product ***em*** from Sonnet Software as the benchmark planar solver. They emerged in the late 1980s.

C. Fundamental Issues for EM-Oriented Design

As an indication of the complexity of optimization-oriented physically and EM-based CAD, we list the following 21 imperatives:

1) design with tolerances and yield-driven design using EM simulators;
2) implementable adjoint parameter-sensitivity computations;
3) automatic layout optimization with EM validation;
4) techniques for capturing and automating parameterization of two-dimensional (2-D) and three-dimensional (3-D) geometries;
5) parameterized geometrical model primitives;
6) scalable models for optimization;
7) space-mapping (SM) optimization;
8) quasi-global modeling of EM simulated subcircuits and devices;
9) parameter-extraction methodologies for companion modeling;
10) techniques for numerical, geometrical, and EM decomposition;
11) optimization strategies for complex and irregular shapes;
12) active-device physical/EM simulation and optimization;
13) use of supercomputers, massively parallel, and heterogeneous workstations;
14) software architectures for EM optimization environments;
15) use of databases and automated table lookup for EM simulations;
16) multidimensional response surface approximation and effective interpolation techniques;
17) exploitation of meshing, simulation accuracy, and simulation speed;
18) techniques for "inverse" EM problems;
19) visualization for automated EM design;
20) merging of linear/nonlinear circuit theoretic and field-theoretic simulations;
21) simultaneous optimization in the frequency, time, thermal, and mixed domains.

VI. MODELING ACTIVE DEVICES

Numerous special issues of this TRANSACTIONS addressed the modeling of active devices [6], [7], [9]–[12], [19]. Ever since the early days of active devices, it has been necessary to represent the dc and ac characteristics of these circuit elements by models suitable for use in association with established circuit-design methodologies. Over the past 50 years, there has been progressive improvement in both the active devices and their associated models. Most traditional microwave and RF design techniques for active circuits are based on equivalent-circuit models or parametric characterization (black-box models), requiring extensive dc and RF characterization, although there is an increasing trend toward using physical models as part of the designers' library of tools. The reader is encouraged to consult Curtice's excellent review of active device modeling in [51].

A. Equivalent-Circuit Models

Early models of diodes and transistors consisted of a few ideal circuit elements to represent the dc, transient, and high-frequency performance of these active devices. As the frequency of operation increased, so did the complexity of the models and parasitic (extrinsic) elements were added to improve accuracy. Considerable effort has been devoted to the modeling of microwave transistors, although there still remains today interest in modeling the nonlinear behavior of microwave and millimeter-wave Schottky, p-i-n, and resonant tunneling diodes. Equivalent circuit models are particularly attractive for established device designs and well-characterized fabrication processes.

Perhaps the most significant work on microwave transistor equivalent-circuit modeling for MESFETs and high electron-mobility transistors (HEMTs) occurred from 1975 to 1990, when the foundations were laid for all the models used in today's CAD. One of the first large-signal equivalent-circuit FET models was proposed by Van Tuyl and Liechti in 1974, which was later simplified by Curtice in 1980, who introduced a "quadratic model," using a square law dependency for the "ohmic" region and a $\tanh$ function to model saturation in the drain–source current (see [52]). It was well suited to dc and small-signal characterization, although it had shortcoming at low values of V_{DS} and for negative values of V_{DS}. Several enhancements to this model followed, notably the popular cubic model developed with Ettenburg in 1985. Tajima's models of 1981 and 1984 achieved a very good fit to dc characteristics and were used in large-signal analysis. Materka and Kacprzak introduced a more tractable model in their 1983 and 1985 papers (see [53]) based on Taki's 1978 model, with fewer parameters, which again provided good fits to measured dc data. Statz *et al.*'s 1987 model [54] (also known as the Raytheon model) also demonstrated good accuracy, overcoming some of the limitations of the early Curtice model, although it still omitted some effects such as pinchoff voltage dependency on V_{DS}. Statz's model, like that of Larson's 1987 model, used a polynomial fit for the current saturation regime. A modified form of the Statz model was developed by Triquint, designated the Triquint's Own Model (TOM), which improved the accuracy. Jastrzebski's model from the same era followed the more common $\tanh$ formulation. The Root model, which was developed explicitly for CAD, is an excellent example of the later type of microwave FET model [55]. Most of these models are empirical in nature, requiring extensive dc and RF data to obtain good fits to measured results. Many of these models have been used in SPICE and its derivatives (notably HSPICE). Golio's books provide a very good review of many of these models [51], [56].

Many of the original MESFET models have been modified for use with HEMTs, by changing the transconductance and capacitance formulations. Notable examples are the Curtice, Materka-Kacprzak [53], and Angelov [57] models. The HEMT is generally a little more difficult to model, although excellent agreement between modeled and measured data is frequently obtained, as in Brazil's more recent models [58].

Fukui proposed the extremely well-known noise model for MESFETs in 1979. Although this model is empirically based, requiring $F_{\min}$, R_n, and $I_{\rm opt}$ at one frequency and set of bias conditions, it predicts the noise characteristics of microwave MESFETs accurately over a range of frequencies. Podell described an efficient means of obtaining a noise figure in 1981 and M. Gupta *et al.* proposed an even more efficient model in 1987. This model, in common with most of the empirical models, is also suitable for modeling an HEMT noise figure. Pucel developed a simplified physics-based equivalent-circuit model with noise sources represented by additional voltage and current sources. This model has also been adapted to model HEMT noise mechanisms.

Microwave bipolar junction transistors and heterojunction bipolar transistors (HBTs) have been extensively studied using equivalent-circuit models [59]. In the case of bipolar transistors and especially HBTs, the junction interface plays a crucial role in determining the absolute characteristics of the device. In view of the extreme sensitivity of the junction diode parameters to material growth and fabrication processes, it is usually found necessary to characterize the junction diode properties using Gummel plots obtained from measured data (as a function of temperature). Notable HBT models include those of Grossman *et al.* [83] and Snowden [60], both of which address large-signal modeling in a comprehensive fashion. Snowden's model [61] was one of the first physics-based HBT models to use a fully coupled electrothermal solution for multicell devices. In bipolar devices, many of the model elements (notably the diode currents) are strong functions of temperature, which is especially significant for power devices, which experience significant self-heating. HBT, models must account for current collapse, which can be an important limiting process for this type of transistor.

B. Physical Models

Early physical models were developed principally to provide insight into the intrinsic physical operation of devices and as an aid in the design and optimization of these semiconductor devices. Over the past 30 years, there has been an increasing application of physical models in microwave CAD and, in particular, in the study of large-signal nonlinear operation. Indeed, one of the most important developments in semiconductor device modeling, the well-known Scharfetter-Gummel numerical algorithm, first reported in 1969, emerged from the need to simulate the nonlinear behavior of Read (avalanche) diodes. As in the case of equivalent-circuit models, most types of device have been studied, from Schottky diodes through to complex quantum transistor structures. The operation of the transferred electron device (Gunn diode) has been extensively studied using one-dimensional numerical simulations, where equivalent-circuit models fail to provide a suitable vehicle for studying this type of device.

There are two principal types of physical models that are applied to device design and characterization. The most straightforward of these is based on a derivative of equivalent-circuit models, where the circuit element values are quantitatively related to the device geometry, material structure, and physical processes. The second approach is more fundamental in nature and is based on the rigorous solution of the carrier transport equations over a representative geometrical domain of the device. These models use numerical solution schemes to solve the carrier transport equations in semiconductors often accounting for hot electrons, quantum mechanics (HEMTs), EM, and thermal interaction. In particular, a key advantage is that physical models allow the performance of the device to be closely related to the fabrication process, material properties, and device geometry. This allows performance, yield, and parameter spreads to be evaluated prior to fabrication, resulting in a significant reduction in the design cycle (and cost). Furthermore, since physical models can be embedded in circuit simulations, the impact of device–circuit interaction can be fully evaluated. A further advantage of physical models is that they are generally intrinsically capable of large-signal simulation.

Physical models have been implemented using either analytical expressions or numerical algorithms. Snowden's text [62] provides a useful summary. Analytical models clearly have the advantage of rapid solution, requiring only modest computation (possible on a modern programmable calculator), whereas numerical models require a greater amount of computational power and effort. The speed of many numerical models is no longer prohibitive for CAD and models can be fully evaluated in seconds on the more powerful desktop computers. The tradeoff between analytical models and numerical models is usually considered in terms of speed and accuracy—many of the analytical models lack the detail and fidelity of their numerical counterparts.

Early analytical models of microwave FETs were based on derivatives of proven JFET models, such as that of the Lehovec and Zuleeg's model published in 1970 [63]. In 1974, Pucel *et al.* introduced a physical analytical model for MESFETs based on a two-region (ohmic and saturation) description of device operation. Equivalent-circuit element values for the intrinsic device were predicted from the model. Ladbrooke [64] described comprehensive physics-based equivalent-circuit models for MESFETs and HEMTs, taking into account surface effects and dispersive trapping phenomena [64] (see also [65]). Many of the analytical transistor models derive from charge-control analysis, originally proposed by Johnson and Rose in 1959. Ando and Itoh's 1990 paper presented a more recent model for HEMTs. Shur proposed an easily implemented analytical model for GaAs MESFETs in 1978. Delagebeaudeuf and Linh described an analytical treatment for early studies on

HEMTs in 1982. Trew *et al.* [66], [67] reported a model that is particularly suited to large-signal characterization of FETs.

The most common approach to physical modeling relies on 2-D simulations, solving the drift-diffusion or energy-transport approximations for cross sections of the semiconductor devices. This type of model, which has been applied to silicon bipolar transistors, MOSFETs, MESFETs, HBTs, and HEMTs, is now highly developed and several commercial simulators exist. However, even with the advent of powerful workstations and advanced numerical techniques, this class of model remains relatively slow, requiring many thousands of CPU seconds to simulate even a small number of bias points. Recent work has focused on EM interaction with the device, such as in Megahed and El-Ghazaly's work (see [67]).

Fast numerical algorithms and models developed over the past ten years have led to the introduction of commercial microwave CAD software that is orders of magnitude faster than earlier physical models. An important example of this class of simulator uses algorithms based on a quasi-two-dimensional (Q2D) descriptions, pioneered by Carnez and Cappy *et al.*, Snowden and Pantoja [68], Sandborn *et al.*, and Cook and Frey [69], have already been shown to be an effective and accurate method of representing short-gatelength MESFETs. More recently, HEMT models, such as those of Morton and Drury [70], incorporating a quantum mechanical charge-control model, have been shown to provide excellent agreement between measured and simulated data up to at least 100 GHz. Cappy's group extended the Q2D model to include noise analysis in their HELENA program. Snowden's team focused on the application of these models to microwave and millimeter-wave CAD and especially large-signal analysis and, in 1997, their Leeds physical model was integrated into the Hewlett-Packard Microwave Design System. The Q2D FET models are based on the efficient numerical solution of a coupled set of transport equations, which describe conservation of carrier density, momentum, and energy.

Recent work has lead to the incorporation of electrothermal effects into FET and HBT models, which requires the coupled solution of the transport equations and heat generation/flow equations. The challenge of electrothermal modeling requires that the temperature within the active device to be related not only to the self-heating of the device in question, but also to that of adjacent elements and is also a strong function of the die dimensions, mounting surface, and ambient temperatures. Other temperature-dependent phenomena, which are known to be important in limiting the performance of microwave transistors, include trapping effects and breakdown, can be addressed in this type of simulation. It should be noted that it is generally necessary to consider a 3-D domain to achieve accurate electrothermal modeling, and this increases the computational burden.

VII. KNOWLEDGE-BASED CAD OF MICROWAVE CIRCUITS

In our approach to microwave CAD and modeling, the terms "analysis and synthesis" should yield to the terminology "simulation and optimization." Numerical analysis is highly mature in both field theory and circuit theory. The term "inverse" as used in the context "inverse problems," i.e., optimization [71], in field-theoretic studies is a contemporary manifestation of analysis fixation [72]. To a microwave circuit design engineer schooled in the exploitation of optimizers, there seems nothing inverse about optimization. The term "synthesis," for many years associated with the orthodox approach to design by analytically oriented circuit theorists, shielded its adherents from facing the reality of competitive optimal design by iterative techniques.

A. Progress in Microwave CAD

The 1974 "Special Issue on Computer-Oriented Microwave Practices" of this TRANSACTIONS [8] contains an enormously influential set of contributions. They include Silvester and Cendes (EM modeling), Johns (TLM method), Della Torre (finite elements), Ruehli, Wexler, Charalambous (optimization), Penfield, Jr. (deembedding and unterminating), and Monaco and Tiberio (circuit simulation and adjoint sensitivity analysis).

Many papers in this TRANSACTIONS' 1988 "Special Issue on Microwave Computer-Aided Design" [15] are as fresh and relevant now as they appeared then, others even more so. The editorial by Gupta and Itoh is relevant to this day. They affirm that, to increase yield and to reduce cost, it is desirable to pack circuits into as small an area as possible. This creates increased proximity coupling between parts of the circuit. Adequate ways of modeling the effects of these couplings have to be incorporated into CAD software. The treatment of couplings due to the substrate and packaging are further complications. The review of the state-of-the-art in optimization technology by Bandler and Chen [73] includes a detailed survey of design with tolerances, tuning, and yield driven design.

This TRANSACTIONS' 1992 special issue was focused on process-oriented microwave CAD and modeling [17]. The incredible list of contributors includes Arndt, Atia, Bandler, Biernacki, Bornemann, Chen, Filicori, Ghione, Hoefer, Monaco, Mongiardo, Nahkla, Rizzoli, Ruehli, Snowden, Sorrentino, Trew, White, Zaki, and Zhang.

This TRANSACTIONS' 1997 special issue [21] particularly emphasizes the use of EM simulations as effective tools in an automated design environment. This emerging design technology is expected to be a cornerstone of future integrated CAE systems. One paper deals with the application of neural network modeling to EM-based CAD and optimization (Veluswami *et al.*). Jain and Onno document their expertise in state-of-the-art industrial applications of commercial EM simulators. Arndt presents a very comprehensive survey of the design of waveguide components using EM building blocks, offering high speed and high accuracy. Other papers deal with decomposition, SM, adjoint sensitivity computations, neural networks, and a variety of relevant numerical, geometrical, and computational techniques for improving the effectiveness of EM field solvers in design automation. The year 1997 saw a second relevant special issue of this TRANSACTIONS with significant optimization oriented contributions [74].

B. Automated Circuit Design Using EM Simulators

EM simulators offer excellent accuracy if critical areas are meshed with a sufficiently small grid. A major disadvantage is their heavy demand on computer resources. In the 1980s, the concept of automated circuit design directly exploiting EM simulators in the optimization loop was widely considered ludicrous. Practical utilization of EM simulators was limited to design validation. The 1990s saw serious advances in microwave CAD technology, the availability of powerful PCs, workstations, and massively parallel systems. This suggested the feasibility of interfacing EM simulations into optimization systems or CAD frameworks for direct application of powerful optimizers. This was clearly demonstrated in a seminal 1995 IEEE MTT-S International Microwave Symposium (IMS) workshop. The participating pioneers were Arndt, Chen, Hoefer, Jain, Jansen, Pavio, Pucel, Sorrentino, and Swanson, Jr. From this date on it became clear to the community that EM simulators were cornerstones both of performance- and yield-driven circuit optimization, to combine the advantages of yield-driven design with the accuracy of EM simulation for first-pass success. The push was to go beyond traditional uses of EM simulators for validation, for generation of equivalent circuits or lookup tables. It was to integrate EM simulations directly into the linear/nonlinear circuit design process in a manner transparent to the designer so that their full potential to the designer could be realized.

C. Role of Artificial Neural Networks (ANNs)

Significant advances have been made in the exploitation of ANNs as an unconventional alternative to modeling and design tasks in RF and microwave CAD [75], [76]. ANN computation is very fast and ANNs can learn and generalize from data, allowing model development even when component formulas are unavailable. State-of-the-art developments include knowledge-based ANN modeling and neural SM optimization. Initiatives in integration of ANN capabilities into circuit optimization, statistical design, and EM and global modeling are being made.

D. Microwave Component Design Using SM Technology

SM optimization intelligently links companion “coarse” and “fine” models of different complexities (different resolutions or fidelities), e.g., full-wave EM simulations and empirical circuit-theory based simulations, to accelerate iterative design optimization of engineering structures. It is a simple CAD methodology, which closely follows the traditional experience and intuition of microwave designers, yet can be treated rigorously. SM models promise effective tools for design, tuning, and alignment, including yield optimization, exploiting accurate physically based device and component models.

As depicted in Fig. 2, an accurate, but computationally intensive fine-resolution EM model is used sparingly only to calibrate a less accurate, but computationally much more efficient coarse model. A mapping is established between two spaces, namely, between the coarse and fine models. The aggressive SM algorithm [77] incorporates a quasi-Newton iteration with first-order derivative updates using the classic Broyden formula. A rapidly improved design is expected to be obtained after each fine-model simulation, while the bulk of the computation involved in optimization is carried out in the coarse-model space. This is far more effective than a “brute-force” optimization directly driving fine-model EM simulations.

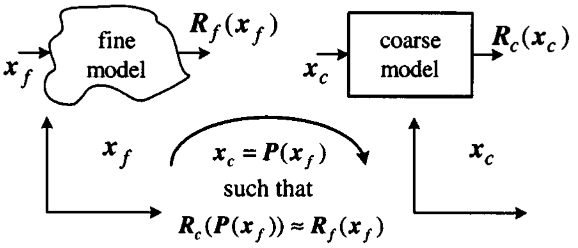

Fig. 2. Illustration of fundamentals of SM.

Circuit decomposition, used for the coarse model, can partition a complex structure into a few smaller substructures. Each is analyzed separately and the results are combined to obtain the response of the overall structure. More efficiently, 2-D analytical methods or even empirical formulas can be used for the calculation of some noncritical regions, while full-wave 3-D models may be adopted for the analysis of the key substructures. Couplings between the decomposed substructures are neglected, hence, a loss of accuracy in this coarse model.

VIII. FUTURE OF RF AND MICROWAVE CAE

A. CAE Environment

RF and microwave CAE will benefit from advances in computing power and memory, the migration to new computer architectures such as highly parallel computers, and algorithmic advances [78]. Current analysis schemes are limited to portions of circuits and not able to handle real-world excitations such as digitally modulated signals without significant simplification. In the future, we must be able to model accurately real-world signals and whole RF front-ends with the full dynamic resolution significantly exceeding the performance expected of the actual circuit. New approaches to CAE development and to the integration of dissimilar simulation and computation techniques will be developed. We have progressed from spaghetti programming to structured programming to object-oriented programming. At the same time, non-CAE specific numerical algorithms have been developed and are being incorporated in evolving CAE environments. Our views of what a circuit is (and, thus, how it is to be modeled) have changed, thus, we can utilize the off-the-shelf numerics without customizing numerical algorithms to our specific requirements. Object-oriented programming is a significant paradigm shift enabling new CAE concepts to be implemented with much less effort than in the past. The future promises a design environment enabling geographically dispersed engineers to work on large mixed-signal systems with the utilization of the Internet to incorporate manufacturing process requirements into the design environment and to flow design through to manufacture.

B. EM Modeling and Optimization

Madsen has long been associated with powerful minimax, $L1$, and Huber optimizers featured in commercial microwave CAD programs. In 2000, he organized a workshop on surrogate modeling and SM for the engineering community at large and for the mathematical optimization arena. In the future, we believe that flexible macromodeling of devices and components will be created through space-mapped super models to replace CPU intensive EM models, as exemplified by Snel [79]. Furthermore, optimization software engines will appear for wireless and microwave circuit design, which exploit both full-wave EM simulators and fast, empirical, coarse or surrogate device models.[1] Their potential benefits have been demonstrated by Swanson and Wenzel [80]. They achieved optimal mechanical adjustments by iterating between and FEM and circuit simulators. Links between SM technology and ANN technology for device modeling and circuit optimization will continue to be developed.

Fast frequency sweep methodologies have already found their way into commercial EM solvers. We can expect commercial implementations of optimization ready EM simulators incorporating exact or adjoint sensitivities [40], [81], [82] in the next decade, as well as robust algorithms for EM optimization fully exploiting SM and surrogate models.[2] Knowledge-based ANN techniques are expected to play a significant role in future CAD.

C. Device Modeling

The significant improvements in computer power in recent years and the increased use of monolithic microwave integrated circuits (MMICs) are leading to the use of more detailed models, especially physics-based equivalent-circuit and physical models, to achieve improved large-signal designs and to relate the yield and performance of the designs to the fabrication process. There is also increasing interest in new types of heterostructure and quantum device, requiring more sophisticated models. Very recently, there has been a significant amount of interest in exploring the potential of ANN models.[3] Modern CAD optimization techniques can now utilize most types of model, including multidimensional physical models. SM offers a particularly powerful means of linking relatively slow multidimensional numerical simulations (both device and EM simulations) to CAD applications. Furthermore, there is a desire to encompass global modeling of the circuit, with the device electrical, EM, thermal, topological, and mechanical aspects in the same simulation, enhancing the accuracy and scope of CAD. This ultimate goal for the modeler is close to becoming a reality, and will no doubt stimulate a broader appreciation of the requirements for modeling, as well as satisfying the needs of the designer.

High-performance systems, such as those used in modern mobile communications, place demanding specifications on designers. There will continue to be demand for design aids and models, which are valid over a very wide dynamic range capable of accurately accounting for nonlinear effects such as intermodulation. Additionally, the increased utilization of higher millimeter-wave frequencies, ultimately into the terahertz regime, will require new models for active devices to aid in the development of new and improved circuits and devices, enhancing the role of technology computer-aided design (TCAD).

IX. CONCLUSION

The heritage and capability of device models for microwave and millimeter wave has been briefly explored, defining the background for equivalent-circuit and physics-based modeling of active devices. Models for dc, small-signal, large-signal, and noise analysis exist. Recent improvements include electrothermal coupling, global modeling, and improved yield prediction and optimization. Contemporary models can now facilitate process-oriented design and provide spread and yield prediction, as well as basic CAD. The future demand for highly accurate and flexible models will continue to drive research in this area

The future will see hierarchically structured simulation, optimization, and tuning of nonlinear RF and microwave systems with accurately represented mixed signals integrating nonlinear circuit analysis with physically based electrothermal device models. In a global modeling strategy, we will see integrated thermal, noise, and electromechanical-acoustic-optical analyses with optimization of complicated geometry captured using 2-D and 3-D EM simulation. Knowledge-based schemes will aid in design dramatically reducing the RF design bottleneck.

ACKNOWLEDGMENT

The authors acknowledge their collaborators, fellow researchers, and others too numerous to name, who have contributed to the CAE of RF and microwave circuits. These people have taken us from electrical and magnetic fields confined in a waveguiding structure to design centered and optimized designs using what must be the greatest abstraction in electrical engineering: the rendering of EM effects as circuit elements.

REFERENCES

[1] *Proc. IEEE (Special Issue)*, vol. 55, 1967.
[2] G. C. Temes and D. A. Calahan, "Computer-aided network optimization the state-of-the-art," *Proc. IEEE*, vol. 55, pp. 1832–63, Nov. 1967.
[3] F. H. Branin, Jr., "Computer methods of network analysis," *Proc. IEEE*, vol. 55, pp. 1787–809, Nov. 1967.
[4] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. MTT-16, July 1968.
[5] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. MTT-17, Aug. 1969.
[6] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. MTT-18, Nov. 1970.
[7] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. MTT-21, Nov. 1973.
[8] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. MTT-22, Mar. 1974.
[9] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. MTT-24, June 1976.
[10] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. MTT-30, July 1982.
[11] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. MTT-31, Jan. 1983.
[12] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. MTT-32, Mar. 1984.
[13] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. MTT-32, Sept. 1984.
[14] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. MTT-33, Oct. 1985.
[15] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. 36, Oct. 1988.
[16] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. 37, Sept. 1989.
[17] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. 40, July 1992.

---

[1] Various paper published from 1998 to 2001 by Bakr, Bandler, Ismail, Madsen, Rayas-Sánchez, Sondergaard, and Zhang concern this subject.

[2] Various papers by Amari, Harscher, Vahldieck, and Bornemann, which appeared in the 1999–2001 *IEEE MTT-S Int. Microwave Symp. Dig.*

[3] Various papers published from 1998 to 2001, by Bakr, Bandler, Ismail, Madsen, Rayas-Sánchez, Sondergaard, and Zhang concern this subject.

[18] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. 40, July 1992.

[19] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. 45, Oct. 1997.

[20] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. 47, June 1999.

[21] *IEEE Trans. Microwave Theory Tech. (Special Issue)*, vol. 45, May 1997.

[22] N. Marcuvitz, *Waveguide Handbook*, ser. Radiation Lab. 10. New York: McGraw-Hill, 1951.

[23] R. M. Barrett, "Microwave printed circuits—A historical survey," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-3, pp. 1–9, Mar. 1955.

[24] A. A. Oliner, "Equivalent circuits for discontinuities in balanced strip transmission line," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-3, pp. 134–142, Mar. 1955.

[25] R. E. Collin, *Foundations for Microwave Engineering*. New York: McGraw-Hill, 1966.

[26] R. L. Eisenhart and P. J. Khan, "Theoretical and experimental analysis of a waveguide mounting structure," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 706–19, Aug. 1971.

[27] K. C. Gupta, "Emerging trends in millimeter-wave CAD," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 475–483, Apr. 1998.

[28] M. Steer, J. Harvey, J. Mink, M. N. Abdulla, C. E. Christoffersen, H. M. Gutierrez, P. L. Heron, C. W. Hicks, A. I. Khalil, U. A. Mughal, S. Nakazawa, T. W. Nuteson, J. Patwardhan, S. G. Skaggs, M. A. Summers, S. Wang, and A. B. Yakovlev, "Global modeling of spatially distributed microwave and millimeter-wave systems," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 830–839, June 1999.

[29] M. B. Steer, C. R. Chang, and G. W. Rhyne, "Computer aided analysis of nonlinear microwave circuits using frequency domain spectral balance *techniques*: The state of the art," *Int. J. Microwave Millimeter-Wave Computer-Aided Eng.*, vol. 1, pp. 181–200, Apr. 1991.

[30] M. Nakhla and J. Vlach, "A piecewise harmonic balance technique for determination of periodic response of nonlinear systems," *IEEE Trans. Circuits Syst.*, vol. CAS-23, pp. 85–91, Feb. 1976.

[31] V. Rizzoli and A. Neri, "State of the art and present trends in nonlinear microwave CAD techniques," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 343–365, Feb. 1988.

[32] R. Gilmore and M. B. Steer, "Nonlinear circuit analysis using the method of harmonic balance—A review of the art," *Int. J. Microwave Millimeter-Wave Computer-Aided Eng.*, vol. 1, pp. 22–37/159–180, Jan./Apr. 1991.

[33] R. Melville, P. Feldmann, and J. Roychowdhury, "Efficient multi-tone distortion analysis of analog integrated circuits," in *Proc. IEEE Custom Integrated Circuits Conf.*, May 1995, pp. 241–244.

[34] K. S. Kundert, "Introduction to RF simulation and its applications," *IEEE J. Solid-State Circuits*, vol. 34, pp. 1298–319, Sept. 1999.

[35] S. W. Director and R. A. Rohrer, "Automated network design the frequency-domain case," *IEEE Trans. Circuit Theory*, vol. CT-16, pp. 330–337, Aug. 1969.

[36] F. H. Branin, Jr., "Network sensitivity and noise analysis simplified," *IEEE Trans. Circuit Theory*, vol. CT-20, pp. 285–288, Feb. 1973.

[37] J. W. Bandler and R. E. Seviora, "Current trends in network optimization," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 1159–1170, Dec. 1970.

[38] J. W. Bandler, Q. J. Zhang, and R. M. Biernacki, "A unified theory for frequency-domain simulation and sensitivity analysis of linear and nonlinear circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 1661–1669, Dec. 1988.

[39] J. W. Bandler, Q. J. Zhang, J. Song, and R. M. Biernacki, "FAST gradient based yield optimization of nonlinear circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 1701–1710, Nov. 1990.

[40] F. Alessandri, M. Mongiardo, and R. Sorrentino, "New efficient full wave optimization of microwave circuits by the adjoint network method," *IEEE Microwave Guided Wave Lett.*, vol. 3, pp. 414–416, Nov. 1993.

[41] J. W. Bandler, P. C. Liu, and H. Tromp, "Integrated approach to microwave design," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 584–591, Sept. 1976.

[42] R. H. Jansen, R. G. Arnold, and I. G. Eddison, "A comprehensive CAD approach to the design of MMIC's up to mm-wave frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 208–219, Oct. 1988.

[43] K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Trans. Antennas Propagat.*, vol. AP-14, pp. 302–307, May 1966.

[44] P. Silvester, "A general high-order finite-element waveguide analysis program," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 204–210, Apr. 1969.

[45] A. Wexler, "Solution of waveguide discontinuities by modal analysis," *IEEE Trans. Microwave Theory Tech*, vol. MTT-15, pp. 508–517, Aug. 1967.

[46] ——, "Computation of electromagnetic fields," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 416–439, Aug. 1969.

[47] R. F. Harrington, "Matrix methods for field problems," *Proc. IEEE*, vol. 55, pp. 136–149, Feb. 1967.

[48] J. C. Rautio and R. F. Harrington, "An electromagnetic time-harmonic analysis of shielded microstrip circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 726–730, Aug. 1987.

[49] S. M. Rao, D. R. Wilton, and A. W. Glisson, "Electromagnetic scattering by surfaces of arbitrary shape," *IEEE Trans. Antennas Propagat.*, vol. AP-30, pp. 409–418, May 1982.

[50] W. J. R. Hoefer, "The transmission-line matrix method—Theory and applications," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 882–893, Oct. 1985.

[51] J. M. Golio, Ed., *The RF and Microwave Handbook*. Boca Raton, FL: CRC Press, 2001.

[52] W. R. Curtice, "A MESFET model for use in the design of GaAs integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 448–456, May 1980.

[53] T. Kacprzak and A. Materka, "Compact DC model of GaAs FETs for large-signal computer calculation," *IEEE J. Solid-State Circuits*, vol. Scull, pp. 211–213, Apr. 1983.

[54] H. Statz, R. Newman, I. W. Smith, R. A. Pucel, and H. A. Haus, "GaAs FET device and circuit simulation in SPICE," *IEEE Trans. Electron Devices*, vol. ED-34, pp. 160–169, Feb. 1987.

[55] D. E. Root, S. Fan, and J. Meyer, "Technology independent large-signal non quasistatic FET models by direct construction from automatically characterized device data," in *Proc. 21st Eur. Microwave Conf.*, 1991, pp. 927–932.

[56] J. M. Golio, Ed., *Microwave MESFET's & HEMT's*. Norwood, MA: Artech House, 1991.

[57] L. Angelov, H. Zirath, and N. Rorsman, "New empirical nonlinear model for HEMT and MESFET and devices," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 2258–2266, Dec. 1992.

[58] V. I. Cojocaru and T. J. Brazil, "A scalable general-purpose model for microwave FET's including the DC/Ac dispersion effects," *IEEE Trans. Microwave Theory Tech.*, vol. 12, pp. 2248–2255, Dec. 1997.

[59] H. K. Gummel and Poon, "An integral charge-control model of bipolar transistors," *Bell Syst. Tech. J.*, vol. 49, pp. 827–852, May 1970.

[60] C. M. Snowden, "Nonlinear modeling of power FET's and HBT's," *Int. J. Microwave and Millimeter-Wave Computer-Aided Eng.*, vol. 6, pp. 219–33, July 1996.

[61] ——, "Large-signal microwave characterization of AlGaAs/GaAs HBT's based on a physics-based electrothermal model," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 58–71, Jan. 1997.

[62] ——, *Semiconductor Device Modeling*. Stevenage, U.K.: Peregrinus, 1988.

[63] K. Lehovec and R. Zuleeg, "Voltage–current characteristics of GaAs JFET's in the hot electron range," *Solid State Electron.*, vol. 13, pp. 1415–1426, Oct. 1970.

[64] P. H. Ladbrooke, *MMIC Design: GaAs FET's and HEMT's*. Norwood, MA: Artech House, 1989.

[65] Q. Li and R. W. Dutton, "Numerical small-signal AC modeling of deep-level-trap related frequency dependent output conductance and capacitance for GaAs MESFET's on semi-insulating substrates," *IEEE Trans. Electron Devices*, vol. 38, pp. 1285–1288, June 1991.

[66] M. A. Khatibzadeh and R. J. Trew, "A large-signal analytical model for the GaAs MESFET," *IEEE Trans Microwave Theory Tech.*, vol. 36, pp. 231–238, Feb. 1988.

[67] R. J. Trew, "MESFET models for microwave CAD applications," *Int. J. Microwave Millimeter-Wave Computer-Aided Eng.*, vol. 1, pp. 143–58, Apr. 1991.

[68] C. M. Snowden and R. R. Pantoja, "Quasitwo-dimensional MESFET simulation for CAD," *IEEE Trans. Electron Devices*, vol. 36, pp. 1564–1574, Sept. 1989.

[69] T. R. Cook and J. Frey, "An efficient technique for two-dimensional simulation of velocity overshoot effects in Si and GaAs devices," *COMPEL—Int. J. Comput. Math. Electr. Electron. Eng.*, vol. 1, no. 2, p. 65, 1982.

[70] C. G. Morton, J. S. Atherton, C. M. Snowden, R. D. Pollard, and M. J. Howes, "A large-signal physical HEMT model," in *IEEE MTT-S Int. Microwave Symp. Dig.*, June 1996, pp. 1759–1762.

[71] *IEEE Trans. Magn.*, vol. 28, Mar. 1992.

[72] R. A. Rohrer, "Panel discussion on computer-aided design," *Proc. IEEE*, vol. 55, p. 1784, Nov. 1967.

[73] J. W. Bandler and S. H. Chen, "Circuit optimization: The state of the art," *IEEE Trans. Microwave Theory Tech.*, vol. 36, pp. 424–443, Oct. 1988.

[74] *Int. J. Microwave Millimeter-Wave Computer-Aided Engineering (Special Issue)*, vol. 7, 1997.

[75] Q. J. Zhang and K. C. Gupta, *Neural Networks for RF and Microwave Design*. Norwood, MA: Artech House, 2000.

[76] P. Burrascano, S. Fiori, and M. Mongiardo, "A review of artificial neural networks applications in microwave computer-aided design," *Int. J. Microwave and Millimeter-Wave Computer-Aided Eng.*, vol. 9, pp. 158–174, May 1999.

[77] J. W. Bandler, R. M. Biernacki, S. H. Chen, R. H. Hemmers, and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2874–2882, Dec. 1995.

[78] *IEEE Trans. Computer-Aided Design (Special Issue)*, vol. 19, Dec. 2000.

[79] J. Snel, "Space mapping models for RF components," presented at the IEEE MTT-S Statistical Design Modeling Tech. for Microwave CAD Workshop, 2001.

[80] D. G. Swanson, Jr. and R. J. Wenzel, "Fast analysis and optimization of combline filters using FEM," in *IEEE MTT-S Int. Microwave Symp. Dig.*, May 2001, pp. 1159–1162.

[81] J. Ureel and D. De Zutter, "A new method for obtaining the shape sensitivities of planar microstrip structures by a full-wave analysis," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 249–260, Feb. 1996.

[82] Y.-S. Chung, C. Cheon, I. Park, and S. Hahn, "Optimal shape design of microwave device using FDTD and design sensitivity analysis," *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 2289–2296, Dec. 2000.

[83] P. C. Grossman and J. Chroma, Jr, "Large-signal modeling of HBT's including self-heating and transit time effects," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 449–464, Mar. 1992.

Michael B. Steer (S'76–M'78–SM'90–F'99) received the B.E. and Ph.D. degrees in electrical engineering from the University of Queensland, Brisbane, Australia, in 1978 and 1983, respectively.

He is currently he Professor of Electrical and Computer Engineering at North Carolina State University, Raleigh. In 1999 and 2000, he was a Professor in the School of Electronic and Electrical Engineering, The University of Leeds, where he held the Chair in Microwave and Millimeterwave Electronics. He was also Director of the Institute of Microwaves and Photonics, The University of Leeds. He has taught many short courses on signal integrity, wireless, and RF design. He has authored over 200 refereed papers and book chapters on topics related to RF and microwave design methodology. He co-authored *Foundations of Interconnect and Microstrip Design* (New York: Wiley, 2000). His current research projects include global modeling integrating the EM, circuit, thermal, and mechanical analyses of large electronic systems; the integrated modeling and design of RF transmitter systems by optimizing coding, modulation format, RF circuitry, filters, amplifiers and antennas to achieve significantly longer battery life and multifunctional adaptive RF systems; and the modeling and fundamental understanding of high-power millimeter-wave and terahertz spatially distributed systems.

Dr. Steer is active in the IEEE Microwave Theory and Techniques Society (IEEE MTT-S). In 1997, he was secretary of the IEEE MTT-S and was an elected member of the IEEE MTT-S Administrative Committee from 1998 to 2001. He has organized many workshops. He was a 1987 Presidential Young Investigator (U.S.). He was also the recipient of the 1994 and 1996 Bronze Medallion presented by U.S. Army Research for "Outstanding Scientific Accomplishment."

John W. Bandler (S'66–M'66–SM'74–F'78) was born in Jerusalem, on November 9, 1941. He studied at Imperial College of Science and Technology, London, U.K., from 1960 to 1966. He received the B.Sc. (Eng.), Ph.D., and D.Sc. (Eng.) degrees from the University of London, London, U.K., in 1963, 1967, and 1976, respectively.

In 1966, he joined Mullard Research Laboratories, Redhill, Surrey, U.K. From 1967 to 1969, he was a Post-Doctorate Fellow and Sessional Lecturer at the University of Manitoba, Winnipeg, MB, Canada. In 1969, he joined McMaster University, Hamilton, ON, Canada, where he has served as Chairman of the Department of Electrical Engineering and Dean of the Faculty of Engineering. He is currently Professor Emeritus in Electrical and Computer Engineering, and directs research in the Simulation Optimization Systems Research Laboratory. He was President of Optimization Systems Associates Inc. (OSA), which he founded in 1983, until November 20, 1997, the date of acquisition of OSA by the Hewlett-Packard Company (HP). OSA implemented a first-generation yield-driven microwave CAD capability for Raytheon in 1985, followed by further innovations in linear and nonlinear microwave CAD technology for the Raytheon/Texas Instruments Incorporated Joint Venture MIMIC Program. OSA introduced the CAE systems RoMPE in 1988, HarPE in 1989, OSA90 and OSA90/hope in 1991, Empipe in 1992, and Empipe3D and EmpipeExpress in 1996. OSA created ***empath*** in 1996, marketed by Sonnet Software Inc. He is currently the President of the Bandler Corporation, Dundas, ON, Canada, which he founded in 1997. He has authored or co-authored over 335 papers. He joined the Editorial Boards of the *International Journal of Numerical Modeling* in 1987, the *International Journal of Microwave and Millimeterwave Computer-Aided Engineering* in 1989, and *Optimization and Engineering* in 1998.

Dr. Bandler is a Fellow of the Royal Society of Canada, the Institution of Electrical Engineers (IEE), U.K., and the Engineering Institute of Canada. He is a member of the Association of Professional Engineers of the Province of Ontario, Canada, and a member of the Massachusetts Institute of Technology (MIT) Electromagnetics Academy. He was an Associate Editor of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES (1969–1974), and has continued serving as a member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) Editorial Board. He is currently the co-chair of the IEEE MTT-1 Technical Committee on Computer-Aided Design. He was the recipient of the 1994 Automatic Radio Frequency Techniques Group (ARFTG) Automated Measurements Career Award.

Christopher M. Snowden (S'82–M'82–SM'91–F'96) received the B.Sc. (with honors), M.Sc., and Ph.D. degrees from The University of Leeds, Leeds, U.K.

Following graduating in 1977, he was an Applications Engineer for Mullard (near London), U.K. (now part of Philips). His Ph.D. studies were later conducted in association with Racal-MESL, and were concerned with the large-signal characterization and design of MESFET microwave oscillators. He has held the Personal Chair of Microwave Engineering at The University of Leeds since 1992. From 1995 to 1998, he was Head of the Microwave Engineering Department and subsequently Head of the School of Electronic and Electrical Engineering, The University of Leeds. He was the first Director of the Institute of Microwaves and Photonics, which is within the university. From 1989 to 1998, he was a consultant to M/A-COM Inc. In 1998, he joined Filtronic ptl, Shipley, U.K., as Director of Technology and became the Joint Chief Executive Officer (CEO) a year later. He has authored eight books and authored or co-authored over 250 refereed journal and conference papers, and many other papers. His main personal research interests include semiconductor device and circuit modeling and design (CAD), together with microwave, millimeter-wave and optoelectronic circuit technology. He is a member of the Editorial Board of the *International Journal of Microwave and Millimeter-Wave Computer-Aided Engineering* and the *Journal of Numerical Modeling* He is a member of the Editorial Review Board of *Microwave Engineering Europe*. He was the Editor for the Wiley Electronic and Electrical Engineering Text Book Series. He has been the Guest Editor of several special issues, including the *International Journal of Numerical Modeling Numerical* "Modeling of Semiconductor Devices" (December 1991) and in the *International Journal of Microwave and Millimeter-Wave Computer-Aided Design* "CAD of MESFET's and HEMTs" (January 1992).

Dr. Snowden is a Fellow of the Royal Academy of Engineering and the Institution of Electrical Engineers (IEE), U.K. He is a Chartered Engineer and a member of the Massachusetts Institute of Technology (MIT) Electromagnetics Academy. He is a Distinguished Lecturer for the IEEE (the IEEE Electron Devices Society). He chaired several international conferences, including the 1993 International Conference on Computational Electronics, the 1995 International Microwaves and RF Conference, and the 1998 6th IEEE Conference on Terahertz Electronics. He is a member of the U.K. National Advisory Panel on Electronic Materials. He was co-chair of the IEEE MTT-1 Committee on Computer-Aided Design from 1997 to 2001. He is currently a member of the European Microwave Conference Steering Committee. He is a member of the Editorial Board of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES. He recently presented the 2001 Blumlein Lecture for the IEE. He was the recipient of the 1999 IEEE Microwave Theory and Techniques Society (IEEE MTT-S) Microwave Prize.