RESEARCH PROJECTS

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INTRODUCTION

During the fiscal year 1994/1995 we continued our research work on the following three projects:

(1) Advances in Microwave Computer-Aided Design (CAD),

(2) Yield-Driven Design of Nonlinear Microwave Circuits,

(3) Statistical Modeling of Microwave Integrated Circuits and Devices.

Our overall research effort and net financial contribution were divided between the three projects as follows:

Project No. 1	60%	$124,562
Project No. 2	25%	$51,901
Project No. 3	15%	$31,141

Total claimed for the Investment Tax Credit in respect of Scientific Research and Experimental Development (SR & ED)	$207,604

The Canadian partial funding of our research (not included in the aforementioned figures) during the fiscal year was:

(1) Natural Sciences and Engineering Research Council's contribution to the salary of Industrial Research Fellow Dr. Q. Cai (December 1994 to September 1995).

(2) National Research Council's contribution to the project entitled "A Feasibility Study for Porting OSA's CAD Software from UNIX X-Windows to a PC Environment" funded within NRC's IRAP Technology Enhancement program (included partial support for Dr. Biernacki's salary in the period from May 1995 to August 1995).

RESEARCH PROJECT 1:

ADVANCES IN MICROWAVE COMPUTER-AIDED-DESIGN (CAD)

Objective of the Research

The main objective of the project is to survey the field of microwave CAD and to research and implement advanced features and techniques as either extensions to state-of-the-art existing software systems or as a basis for new software systems. This includes pioneering novel theories and developing new algorithms for parameter extraction, simulation and design optimization of both linear and nonlinear microwave circuits.

Software products exploiting the new features and techniques will be able to meet a strong industrial demand for efficient and reliable tools for nonlinear device modeling, parameter extraction, and automated design optimization coupled to sufficiently fast linear/nonlinear, accurate physical and electromagnetic circuit simulation. Such products should then be more competitive.

Nature of the Research

This research is essentially applied. However, many aspects of basic research are involved. The fields of science involved are mathematics: numerical methods, optimization theory, Fourier transforms; system theory: system identifiability; engineering: electrical circuit theory, electromagnetic field theory; and computer science: software architecture, parsers, data structures, graphics. Engineering applications are found in all aspects of linear and nonlinear analog circuit design.

Reference Material

Many references can be cited. A few important ones are:

V. Rizzoli, A. Lipparini and E. Marazzi, "A general-purpose program for nonlinear microwave circuit design", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, 1983, pp. 762-769.

K.S. Kundert and A. Sangiovanni-Vincentelli, "Simulation of nonlinear circuits in the frequency domain", *IEEE Trans. Computer-Aided Design*, vol. CAD-5, 1986, pp. 521-535.

S.A. Maas, *Nonlinear Microwave Circuits*. Artech House, 1988.

Uncertainty of the Research

The main uncertainty of the project lies in the mathematical robustness and reliability of the methods being developed. We will not be able to implement them if they turn out to be unreliable, or fail to provide satisfactory results.

It is not clear how large the improvement in efficiency will eventually be and whether the methods will be sufficiently cost-effective in their implementation. Many of the features being developed will be buried deeply in new software products, and as such may be appreciated by more advanced users only.

Novelty of the Research

This research represents new work on state-of-the-art software systems. Our group has achieved world recognition in this area. As such our contributions are novel.

Advance in Scientific Knowledge

After this research is successfully completed, the advanced features and techniques developed will constitute a true breakthrough in CAD tools available to microwave circuit design engineers. In particular, design optimization employing electromagnetic simulations of passive structures, as well as physical simulations of microwave active devices, all in a user-friendly CAD environment, are of utmost importance.

Method of Research

Accepted scientific methods are employed. Since the team members have been actively working in this research area for a number of years no extra literature search was necessary except for recent periodicals. Existing CAD software systems are continually studied.

Long-term and short-term goals are carefully defined and milestones are scheduled. Theoretical investigations are conducted and then the new concepts are implemented in computer programs and verified through numerical examples. Promising algorithms are further tested on a number of industrial examples.

Progress to Date

The starting date for this project in its present form was August 1, 1988. However, different components of the project had been carried out since early 1987. By November 1994 we had already developed, released and marketed three computer programs: (1) HarPE [1] - for nonlinear device parameter extraction, (2) OSA90/hope [2] - a novel, state-of-the-art general purpose CAD software system, and (3) Empipe [3] - for direct electromagnetic simulation and optimization. We developed adjoint sensitivity technique for harmonic balance simulations [4]. We pioneered nonlinear device parameter extraction based on large-signal power spectrum measurements and the harmonic balance simulation technique [5]. We laid a foundation for analytical unification of DC, small-signal and large-signal circuit simulations and optimizations [6]. We developed a new robust method of optimization using the Huber function for microwave CAD [7]. We pioneered direct electromagnetic field theory based design optimization [8-10], including a breakthrough Space Mapping optimization technique for microwave CAD to achieve the speed of circuit-level optimization and the accuracy of electromagnetic field simulation [10].

Between December 1, 1994 and November 30, 1995 we continued our work on different parts of the project. In particular, we continued developing our novel Geometry Capture technique for direct electromagnetic field optimization of arbitrary planar structures, including its mathematical foundation. We developed a new aggressive strategy for the Space Mapping technique which promises full automation, as well as faster convergence than our original algorithm. We have advanced parallel computation for electromagnetic design optimization using a network of heterogeneous computers. Electromagnetic simulation of passive structures has been integrated with large-signal simulations of active devices for the most accurate comprehensive design optimization. We have augmented our parameter extraction technique for active devices by incorporating cold measurement data.

Reports

The papers [11-19], manuals [20-22] and reports [23-48] summarize our new work within the framework of this project. Our earlier work on the original Space Mapping technique and new results on Aggressive Space Mapping were published in the *IEEE Transactions on Microwave Theory and Techniques* which is the most reputable journal in the field [10,17]. This technique is considered as a significant breakthrough in microwave CAD. New results were reported at international symposia [12-16]. Two new papers [18-19] were submitted to the 1996 IEEE MTT-S International Microwave Symposium. Both were accepted for presentation.

Description of the Project

Within the framework of this project we make an effort to combine different techniques with the aim of integrating them into versatile, user-friendly and state-of-the-art software systems. It involves developing new methods as well as enhancing some of the existing techniques.

Recent advances in computing technology provide microwave circuit designers with more and more sophisticated simulation technique. Particularly the methods based on numerical solution of the electromagnetic field equations exhibit excellent accuracy. Combined with advances in GaAs material development and wafer processing achieved in the past decade they make the monolithic microwave integrated circuits (MMICs) not only practical but also more affordable. The availability of CAD tools leading to first-pass success in MMIC circuit design is of fundamental importance.

To this end, our research efforts have been concentrated on the following subjects:

(1) development and/or implementation of new nonlinear device models,

(2) investigation of seamlessly integrated, consistent DC/small-signal/large-signal circuit simulations and optimizations,

(3) efficiency and robustness of mathematical algorithms,

(4) open architecture and flexible data structures for CAD tools,

(5) accessing internal variables and processing capabilities of CAD systems,

(6) user-friendliness of CAD tools,

(7) state-of-the-art CAD tools for GaAs FET small-signal, DC and large-signal model simulation, optimization and parameter extraction,

(8) work towards new generation comprehensive software systems suitable for designing microwave circuits in terms of layout/geometrical and process/technological parameters,

(9) direct electromagnetic field simulation and optimization for accurate circuit design taking into account electromagnetic effects such as radiation and coupling.

To date we have made progress in all of these subjects. Implementation of new features and techniques has been made within the new releases of our software systems OSA90/hope [20], Empipe [21] and HarPE [22], as summarized in [43].

Between December 1, 1994 and November 30, 1995 we have made substantial progress on item (9), which was the main focus of our research.

We continued our exciting work on the novel Spacing Mapping optimization technique. The original method developed earlier was published in the December 1994 issue of the *IEEE Transactions on Microwave Theory and Techniques* [10]. The method provides an efficient way for engineers to solve difficult optimization problems which may be encountered in electromagnetic design due to high sensitivities, long simulation times, etc. Using Space Mapping circuit design can be carried out at the speed of circuit-level optimization while retaining the accuracy of electromagnetic field simulation. It has been successfully applied by the engineers in industry to solve practical and difficult problems such as design of high-temperature superconducting microwave filters [11,25,30].

We have proposed a new aggressive Space Mapping strategy [14,26,32]. Instead of waiting for upfront EM analyses at several base points, it exploits every available EM analysis using the classical Broyden update, producing dramatic results right from the first step. A filter design solution emerges after fewer EM analyses than the number of designable parameters! The Space Mapping concept has also been extended to the parameter extraction phase, overcoming severely misaligned starting points induced by inadequate empirical models. This result was presented at the 1995 IEEE MTT-S International Microwave Symposium held in Orlando, Florida, in May 1995. A full journal paper was submitted to the *IEEE Transactions on Microwave Theory and Techniques* [29,34] and was accepted for publication [17]. The Broyden update is more suitable for full automation of Space Mapping than the original algorithm. The generic SM update loop and the model-specific parameter extraction loop can be automated using a two-level Datapipe architecture. This idea was summarized in a paper accepted for presentation at the 1996 IEEE MTT-S International Microwave Symposium to be held in San Francisco, CA, June 1996, [18,48]. The concept and theory of Space Mapping have been presented on several other occasions, including three workshops [49,50,52] (reports [38,41,46]). A full journal paper [45] has been submitted to and accepted for the Proceedings of the Institute of Mathematical Applications on Large-Scale Optimization, a book to be published by Springer Verlag.

We have continued our work on the novel Geometry Capture technique. Our preliminary results were presented at the 1995 IEEE MTT-S International Microwave Symposium [12,24,31]. That paper also includes our pioneering results on integrating electromagnetic simulations of passive structures into the large-signal harmonic balance simulation of the overall circuit containing active devices (in addition to the passive structures). This integration is done in an automatic fashion to allow circuit optimization. Further developments on Geometry Capture were documented in [28,39]. The Geometry Capture technique makes optimization of arbitrary planar structures a reality. For the first time, complicated planar structures can be made fully optimizable. Designable parameters are captured graphically from the layout, and the layout is directly optimized without the need of any schematic translation. Design of a comprehensive class B frequency doubler and a broad-band small-signal amplifier demonstrated our approach. Recently, we started working on the mathematical foundation of the method. Our findings were summarized in a paper accepted for presentation at the 1996 IEEE MTT-S International Microwave Symposium (San Francisco, CA, June 1996) [19,47].

Our work on CAD software architecture has been advanced by experimenting with parallel computation [13,23,42]. Parallel optimization handles the massive demand on computer resources due to a large number of simultaneous simulations involved in optimization or for the purpose of interpolation. It is particularly important for electromagnetic optimization because of long CPU times needed for electromagnetic simulations, and whenever many variables are involved in interpolation. Our parallel strategy can be implemented over local and wide area networks supporting heterogeneous workstations. The approach utilizes the Datapipe technology which we developed a few years ago. It has been modified to control the parallel computations from a master host (one of the networked computers). This includes distributing jobs to the available machines, collecting results (circuit responses) and maintaining a data base of simulated results.

With the goal of direct electromagnetic optimization we have worked on crosstalk analysis of VLSI interconnects [16,40,53]. We employed two different electromagnetic simulators to extract the LC matrices of coupled interconnects to be used in a circuit level simulator. The results were used to investigate the validity of a set of empirical formulas. We have found out that while the empirical formulas are not very accurate, they are an excellent candidate for applying Space Mapping.

We have prepared and presented a comprehensive invited paper [15,27,33,44] at the 25th European Microwave Conference held in Bologna, Italy, in September 1995, the most important annual event in Europe in the field of microwave theory and techniques. We reviewed relevant concepts, formulations and algorithms for microwave circuit optimization. Emphasis was given to recent advances in the state of the art, particularly automated electromagnetic design in an integrated CAD environment.

[6] J.W. Bandler, R.M. Biernacki, S.H. Chen, J. Song, S. Ye and Q.J. Zhang, "Analytically unified DC/small-signal/large-signal circuit design," *IEEE Trans. Microwave Theory Tech.*, vol. 39, 1991, pp. 1076-1082.

[7] J.W. Bandler, S.H. Chen, R.M. Biernacki, L. Gao, K. Madsen and H. Yu, "Huber optimization of circuits: a robust approach," *IEEE Trans. Microwave Theory Tech.*, vol. 41, 1993, pp. 2279-2287.

[8] J.W. Bandler, R.M. Biernacki, S.H. Chen, P.A. Grobelny and S. Ye, "Yield-driven electromagnetic optimization via multilevel multidimensional models," *IEEE Trans. Microwave Theory Tech.*, vol. 41, 1993, pp. 2269-2278.

[9] J.W. Bandler, R.M. Biernacki, S.H. Chen, D.G. Swanson, Jr., and S. Ye, "Microstrip filter design using direct EM field simulation," *IEEE Trans. Microwave Theory Tech.*, vol. 42, 1994, pp. 1353-1359.

[10] J.W. Bandler, R.M. Biernacki, S.H. Chen, P.A. Grobelny and R.H. Hemmers, "Space mapping technique for electromagnetic optimization," *IEEE Trans. Microwave Theory Tech.*, vol. 42, 1994, pp. 2536-2544.

[11] J.W. Bandler, R.M. Biernacki, S.H. Chen, W.J. Getsinger, P.A. Grobelny, C. Moskowitz and S.H. Talisa, "Electromagnetic design of high-temperature superconducting microwave filters," *Int. J. Microwave and Millimeter-Wave Computer-Aided Engineering*, vol. 5, 1995, pp. 331-343.

[12] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Integrated harmonic balance and electromagnetic optimization with Geometry Capture," *IEEE MTT-S Int. Microwave Symp. Digest* (Orlando, FL), 1995, pp. 793-796.

[13] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, P.A. Grobelny and D.G. Swanson, Jr., "Heterogeneous parallel yield-driven electromagnetic CAD," *IEEE MTT-S Int. Microwave Symp. Digest* (Orlando, FL), 1995, pp. 1085-1088.

[14] J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Aggressive space mapping for electromagnetic design," *IEEE MTT-S Int. Microwave Symp. Digest* (Orlando, FL), 1995, pp. 1455-1458.

[15] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization technology for microwave circuit modeling and design," (invited), *Proc. 25th European Microwave Conf.* (Bologna, Italy), 1995, pp. 101-108.

[16] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Toward direct EM optimization of VLSI interconnects: validation of coupled transmission line models," *1995 Canadian Conf. on Electrical and Computer Engineering* (Montreal, PQ), 1995, pp. 377-380.

[17] 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, 1995, pp. 2874-2882.

[18] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Fully automated space mapping optimization of 3D structures," *IEEE MTT-S Int. Microwave Symp.* (San Francisco, CA, June 1996), accepted January 1996.

[19] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Parameterization of arbitrary geometrical structures for automated electromagnetic optimization," *IEEE MTT-S Int. Microwave Symp.* (San Francisco, CA, June 1996), accepted January 1996.

[20] "OSA90/hope™ User's Manual, Version 3.1," Optimization Systems Associates Inc., Dundas, Ontario, Canada, September 1995.

[21] "Empipe™ User's Manual, Version 3.1," Optimization Systems Associates Inc., Dundas, Ontario, Canada, August 1995.

[22] "HarPE™ User's Manual, Version 2.0", Optimization Systems Associates Inc., Dundas, Ontario, Canada, August 1995.

[23] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, P.A. Grobelny and D.G. Swanson, Jr., "Heterogeneous parallel yield-driven electromagnetic CAD," Report OSA-94-OS-29-R, Revised January 6, 1995.

[24] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Integrated harmonic balance and electromagnetic optimization with Geometry Capture," Report OSA-94-OS-27-R, Revised January 18, 1995.

[25] J.W. Bandler, R.M. Biernacki, S.H. Chen, W.J. Getsinger, P.A. Grobelny, C. Moskowitz and S.H. Talisa, "Electromagnetic design of high-temperature superconducting microwave filters," Report OSA-95-OS-1-R, January 23, 1995.

[26] J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Aggressive space mapping for electromagnetic design," Report OSA-94-OS-26-R, Revised January 25, 1995.

[27] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization technology for microwave circuit modeling and design," Report OSA-95-OS-2-R, February 8, 1995.

[28] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Automated EM optimization of linear and nonlinear circuits with geometry capture for arbitrary planar structures," Report OSA-95-OS-4-R, February 28, 1995.

[29] J.W. Bandler, R.M. Biernacki, S.H. Chen, R. H. Hemmers and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping," Report OSA-95-OS-5-R, February 28, 1995.

[30] J.W. Bandler, R.M. Biernacki, S.H. Chen, W.J. Getsinger, P.A. Grobelny, C. Moskowitz and S.H. Talisa, "Electromagnetic design of high-temperature superconducting microwave filters," Report OSA-95-OS-1-R, Revised April 21, 1995.

[31] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Integrated harmonic balance and electromagnetic optimization with geometry capture," Report OSA-95-OS-8-V, May 10, 1995.

[32] J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Aggressive space mapping for electromagnetic design," Report OSA-95-OS-9-V, May 10, 1995.

[33] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization Technology for microwave circuit modeling and design," Report OSA-95-OS-2-R, Revised July 7, 1995.

[34] J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping," Report OSA-95-OS-5-R, Revised July 14, 1995.

[35] "Direct extrinsic parameter extraction from cold measurements," Report OSA-95-OS-12-R, September 6, 1995.

[36] "A feasibility study for porting OSA's CAD software from UNIX X-windows to a PC environment: final report," Report OSA-95-OS-13-R, August 30, 1995.

[37] J.W. Bandler, "Em and mm-wave circuits, detection sources and antennas," Report OSA-95-OS-14-V, January 9, 1995.

[38] S.H. Chen, "Automated EM optimization of linear and nonlinear circuits, with geometry capture for arbitrary planar structures," Report OSA-95-MT-16-V, May 15, 1995.

[39] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "OSA's Empipe drives Sonnet's *em* capturing and optimizing arbitrary structures," Report OSA-95-MJ-18-R, June 7, 1995.

[40] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Toward direct EM optimization of VLSI interconnects: Validation of coupled transmission line models," Report OSA-95-CC-19-R, June 29, 1995.

[41] J.W. Bandler, "Novel electromagnetic optimization techniques, including space mapping," Report OSA-95-IM-20-V, July 17, 1995.

[42] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, P.A. Grobelny and D.G. Swanson, Jr., "Heterogeneous parallel yield-drive electromagnetic CAD," Report OSA-95-OS-21-V, August 16, 1995.

[43] J.W. Bandler, "Performance- and yield-driven design of microwave circuits emphasizing directed em optimization," Report OSA-95-OS-22-V, August 31, 1995.

[44] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization technology for microwave circuit modeling and design," Report OSA-95-EM-23-V, September 4, 1995.

[45] J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Space mapping optimization for engineering design," Report OSA-95-IM-24-R, September 28, 1995.

[46] J.W. Bandler, "Novel space mapping optimization technique for electromagnetic design," Report OSA-95-ES-26-V, November 6, 1995.

[47] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Parameterization of arbitrary geometrical structures for automated electromagnetic optimization," Report OSA-95-MT-27-R, November 30, 1995.

[48] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Fully automated space mapping optimization of 3D structures," Report OSA-95-MT-28-R, November 30, 1995.

[49] S.H. Chen, "Automated EM optimization of linear and nonlinear circuits, with Geometry Capture for arbitrary planar structures," in *Automated Circuit Design using Electromagnetic Simulators*, Workshop WMFE, IEEE MTT-S Int. Microwave Symp., (Orlando, FL), 1995.

[50] J.W. Bandler, "Novel electromagnetic optimization techniques, including space mapping,"(invited), IMA Workshop on Large Scale Optimization (Institute for Mathematics and its Applications, Minneapolis, MN), 1995.

[51] M. Dionigi, R. Sorrentino and J.W. Bandler, "Fullwave design of E plane metal insert band-pass filter by the adjoint network method," Workshop on Advanced CAD for Microwave Filters and Passive Devices (ESA/ESTEC, Noordwijk, The Netherlands), 1995.

[52] J.W. Bandler, "Novel space mapping optimization technique for electromagnetic design," (invited), Workshop on Advanced CAD for Microwave Filters and Passive Devices (ESA/ESTEC, Noordwijk, The Netherlands), 1995.

[53] Q.J. Zhang, M.S. Nakhla, J.W. Bandler and R.M. Biernacki, "Design tools and methodology for high-speed/high frequency circuits and systems," *Micronet 1995 Annual Workshop Proc.*, (Ottawa, ON), Vol. 2: Circuits Coordinated Project, 1995, pp. 2.174-2.187.

[54] J.W. Bandler, Ed., *IEEE Trans. Microwave Theory Tech., Special Issue on Automated Circuit Design Using Electromagnetic Simulators*, vol. 45, 1997.

[55] J.W. Bandler, Ed., *Int. J. Microwave and Millimeter-Wave Computer-Aided Engineering, Special Issue on Optimization-Oriented Microwave CAD*, vol. 7, 1997.

RESEARCH PROJECT 2:

YIELD-DRIVEN DESIGN OF NONLINEAR MICROWAVE CIRCUITS

Objective of the Research

The main objective of the project is to develop new methods and algorithms suitable for statistical design of analog electrical circuits, in particular nonlinear microwave circuits operating in the steady state under large-signal periodic excitations. Our aim is to produce novel results and software relevant to the area of monolithic microwave integrated circuits (MMICs). Software products exploiting such methods should be capable of designing high yield practical nonlinear circuits. These software products will then be competitive commercially.

Nature of the Research

This research is both basic and applied. It is our aim to extend specific techniques and methods by applying them to a larger class of microwave circuits. The fields of science involved are mathematics: optimization theory, statistical analysis; and electrical circuit theory. Engineering applications are specifically found in all aspects of nonlinear analog circuit design including analysis, optimization, parameter extraction, statistical design and modeling.

Reference Material

Many references can be cited. An important contribution is:

J.W. Bandler and S.H. Chen, "Circuit optimization: the state of the art", (invited), *IEEE Trans. Microwave Theory Tech.*, vol. 36, 1988, pp. 424-443.

Uncertainty of the Research

The main uncertainty of the project lies in the feasibility and reliability of the methods being developed since they are computationally intensive and partially heuristic in nature. We will not be able to fully implement them if they turn out to be unreliable, highly sensitive to computational accuracy or fail to provide satisfactory results for a large variety of circuits. Fast workstations, large-scale optimization techniques and parallel computation are likely to be required, which introduces further risk and uncertainty.

The uncertain future of statistical design of microwave integrated circuits, and acceptance of the necessary software tools by microwave engineers also makes this a high risk project. The role of statistical design in the affordable manufacture of monolithic microwave integrated circuits (MMICs) is still uncertain.

Novelty of the Research

This research is a followup of state-of-the-art published works by members of the team, e.g., [1-11]. As such it is novel.

Advance in Scientific Knowledge

If this research is successfully completed, the algorithms may constitute a true breakthrough in the numerical approach to the simulation and statistical analysis and yield optimization of large and nonlinear engineering systems.

Method of Research

Accepted scientific methods are employed. Since the team members have been actively working in this research area for a number of years no extra literature search was necessary except for recent periodicals. According to our expectations, appropriate mathematical manipulations are conducted and then the new concepts are programmed. The algorithms being developed are then tested on a number of circuit examples.

Progress to Date

The starting date for the project was August 1, 1986. By November 1994 we had successfully demonstrated feasibility of an extremely efficient method [2] for quadratic approximation of circuit response functions, including testing, reliability studies and, especially, applying these methods to yield optimization of a large-scale practical microwave circuit, namely a 5-channel multiplexer. We had pioneered yield optimization of nonlinear circuits operating in the steady-state under large-signal excitations, and developed a fast gradient based technique for such applications [3]. We had completed development of yield optimization capabilities for our general purpose CAD software system OSA90/hope [4]. We had developed a quadratic modeling technique based on both simulated responses and their gradients [5]. We had researched yield optimization of MMIC circuits in terms of physical and geometrical parameters of active devices and passive components, including correlations [5]. We had investigated the predictability of simulated yield [6] and devised a new algorithm for yield optimization [7]. We had researched yield optimization of microwave circuits with passive components accurately analyzed by an electromagnetic field simulator and developed a novel approach for yield-driven electromagnetic optimization using multilevel multidimensional models [8]. We had developed a novel Huber optimization technique for design centering [9]. We had created a CAD environment for yield-driven circuit design employing electromagnetic field simulators [10]. We had pioneered Space Mapping based yield optimization [11].

Between December 1, 1994 and November 30, 1995 we continued our work on this project. We focused our work on parallel computation in yield-driven design optimization and on cost-driven design were the manufacturing cost is minimized subject to an acceptable yield. These techniques were specifically oriented to effective utilization of electromagnetic simulations in the design process.

Reports

The papers [12-14], manuals [15-17] and reports [18-30] summarize our new work within the framework of this project. Our approach to yield optimization exploiting parallel computations using a network of heterogeneous workstations and our cost-driven design methodology were presented at the 1995 IEEE MTT-S International Microwave Symposium. Our previous result on exploiting Space Mapping in yield optimization was published in the *IEEE Transactions on Microwave Theory and Techniques* [11]. The use of optimization technology for yield-driven design was reviewed and presented at the 25th European Microwave Conference.

Description of the Project

Statistical circuit design, or yield optimization has been a subject of extensive research for more than two decades, e.g., [1]. It is important to truly reflect the actual statistical spreads during computer simulations. Therefore, the primary physical and geometrical parameters must be available. Unfortunately, component simulation in terms of such parameters is extremely slow. This makes yield optimization of practical nonlinear microwave circuits a challenging task because of complexity and the computational effort involved. In this research we concentrate our efforts on algorithms for statistical (yield- and cost-driven) design of nonlinear circuits operating in the steady state under large-signal periodic excitations, with a particular focus on design of microwave circuits in terms of layout/geometrical and process/technological parameters.

In our previous work we have successfully researched physics-based design and yield optimization of MMICs. Our research results were very well recognized internationally and were described in a comprehensive large paper [5] published in the Special Issue of the *IEEE Transactions on Microwave Theory and Techniques* on Process-Oriented Microwave CAD and Modeling.

Between December 1, 1994 and November 30, 1995 we have continued our work on efficient techniques and new methodologies for yield- and cost-driven design. In this context we have applied the technique, developed within Project 1, for parallel computation using a network of heterogeneous workstations to yield optimization, demonstrating both feasibility and advantages of that approach [12,19,28]. The results were presented at the 1995 IEEE MTT-S International Microwave Symposium. Yield optimization is particularly suitable for parallelization of computation. Many statistically perturbed circuit outcomes need to be simulated to estimate yield by Monte Carlo analysis. Once the perturbed parameter values are determined, these simulations are independent of each other. Therefore they can be carried out simultaneously on a number of computers. Since, throughout the industry, networks of heterogenous computers are typically available to design engineers, this approach is a very natural way of splitting the computational effort and to fully utilize existing computer resources.

We have developed a cost-driven approach to the emerging demand for simultaneous device and circuit design [13,18,23] and presented our results at the 1995 IEEE MTT-S International Microwave Symposium. Here, an analytic physics-based Raytheon model facilitates fast large-signal simulation and optimization. A novel one-sided Huber approach [10] is applied to design centering. The problem of cost-driven design is formulated as the minimization of the cost function while maintaining the required/acceptable yield. The function to be minimized reflects the high cost associated with high precision/narrow tolerance manufacturing. Device parameters are considered as optimization variables in addition to those of the matching circuits. The advantages of that approach have been demonstrated by design of a single-stage power amplifier.

We have investigated [21,22] yield-driven design in a multi-simulator environment where active device models built in the popular circuit simulator SPICE were directly incorporated into OSA90/hope [15]. The built-in FET model was first statistically modeled (work within Project 3) using HarPE [16] and then simulated by SPICE with the parameter values determined by OSA90/hope and passed to SPICE in an automatic fashion. The interface, based on OSA's open architecture technology Datapipe, combines and enhances the features of otherwise disjoint simulators. Time-domain, frequency-domain and electromagnetic simulations were, for the first time, integrated for efficient statistical design with mixed-domain specifications.

We have prepared and presented a comprehensive invited paper [14,20,24,30] at the 25th European Microwave Conference held in Bologna, Italy, in September 1995, the most important annual event in Europe in the field of microwave theory and techniques. That paper includes a review of the use of optimization technology for yield-driven design.

Other activities related to this project included an important workshop presentation [31] (report [26]) at the 1995 IEEE MTT-S International Microwave Symposium (Orlando, Florida, May 1995), and prestigious editorial work (J.W. Bandler, Guest Editor) for two most important journals in the field: *IEEE Transactions on Microwave Theory Techniques* [32], and *International Journal of Microwave and Millimeter-Wave Computer-Aided Engineering* [33].

In the future we will continue research in all of the aforementioned subjects. The parallel computation technique needs to be implemented for commercialization. We feel that the approach can be further generalized and automated. Exploiting Space Mapping in the area of active device simulation and optimization to link physics-based (faster, analytical) and physical (most accurate, numerical) models for faster Monte Carlo yield estimation should also be vigorously investigated.

All our investigations continue to specifically focus on incorporating accurate electromagnetic simulations into the design process [25,27,29]. We use our Empipe [17] to drive the electromagnetic simulator ***em*** from Sonnet Software, Inc.

Technical Personnel

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References

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

[2] R.M. Biernacki, J.W. Bandler, J.Song and Q.J. Zhang, "Efficient quadratic approximation for statistical design", *IEEE Trans. Circuits and Systems*, vol. 36, 1989, pp. 1449-1454.

[3] 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, 1990, pp. 1701-1710.

[4] "OSA90/hope™," Optimization Systems Associates Inc., Dundas, Ontario, Canada, First Release 1991.

[5] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, S. Ye and Q.J. Zhang, "Integrated physics-oriented statistical modeling, simulation and optimization," *IEEE Trans. Microwave Theory Tech.*, Special Issue on Process-Oriented Microwave CAD and Modeling. vol. 40, 1992, pp. 1374-1400.

[6] J.W. Bandler, S. Ye, Q. Cai, R.M. Biernacki and S.H. Chen, "Predictable yield-driven circuit optimization," *IEEE MTT-S Int. Microwave Symp. Digest* (Albuquerque, NM), 1992, pp. 837-840.

[7] J.W. Bandler, R.M. Biernacki and S.H. Chen, "A new formulation for yield optimization," *IEEE MTT-S Int. Microwave Symp. Digest* (Albuquerque, NM), 1992, pp. 1465-1468.

[8] J.W. Bandler, R.M. Biernacki, S.H. Chen, P.A. Grobelny and S. Ye, "Yield-driven electromagnetic optimization via multilevel multidimensional models," *IEEE Trans. Microwave Theory Tech.*, vol. 41, 1993, pp. 2269-2278.

[9] J.W. Bandler, S.H. Chen, R.M. Biernacki and K. Madsen, "The Huber concept in device modeling, circuit diagnosis and design centering," *Proc. IEEE Int. Symp. Circuits Syst.* (London, England), 1994, vol. 1, pp. 129-132.

[10] J.W. Bandler, R.M. Biernacki, S.H. Chen and P.A. Grobelny, "A CAD environment for performance and yield driven circuit design employing electromagnetic field simulators," *Proc. IEEE Int. Symp. Circuits Syst.* (London, England), 1994, vol. 1, pp. 145-148.

[11] J.W. Bandler, R.M. Biernacki, S.H. Chen, P.A. Grobelny and R.H. Hemmers, "Space mapping technique for electromagnetic optimization," *IEEE Trans. Microwave Theory Tech.*, vol. 42, 1994, pp. 2536-2544.

[12] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, P.A. Grobelny and D.G. Swanson, Jr., "Heterogeneous parallel yield-driven electromagnetic CAD," *IEEE MTT-S Int. Microwave Symp. Digest* (Orlando, FL), 1995, pp. 1085-1088.

[13] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "Cost-driven physics-based large-signal simultaneous device and circuit design," *IEEE MTT-S Int. Microwave Symp. Digest* (Orlando, FL), 1995, pp. 1443-1446.

[14] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization technology for microwave circuit modeling and design," (invited), *Proc. 25th European Microwave Conf.* (Bologna, Italy), 1995, pp. 101-108.

[15] "OSA90/hope™ User's Manual, Version 3.1," Optimization Systems Associates Inc., Dundas, Ontario, Canada, September 1995.

[16] "HarPE™ User's Manual, Version 2.0", Optimization Systems Associates Inc., Dundas, Ontario, Canada, August 1995.

[17] "Empipe™ User's Manual, Version 3.1," Optimization Systems Associates Inc., Dundas, Ontario, Canada, August 1995.

[18] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "Cost-driven physics-based large-signal simultaneous device and circuit design," Report OSA-94-OS-25-R, Revised January 5, 1995.

[19] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, P.A. Grobelny and D.G. Swanson, Jr., "Heterogeneous parallel yield-driven electromagnetic CAD," Report OSA-94-OS-29-R, Revised January 6, 1995.

[20] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization technology for microwave circuit modeling and design," Report OSA-95-OS-2-R, February 8, 1995.

[21] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Electromagnetic design of microwave circuits integrated with SPICE device models," Report OSA-95-OS-3-R, February 8, 1995.

[22] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Automated EM optimization of linear and nonlinear circuits with geometry capture for arbitrary planar structures," Report OSA-95-OS-4-R, February 28, 1995.

[23] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "Cost-driven physics-based large-signal simultaneous device and circuit design," Report OSA-95-OS-7-V, May 10, 1995.

[24] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization Technology for microwave circuit modeling and design," Report OSA-95-OS-2-R, Revised July 7, 1995.

[25] J.W. Bandler, "Em and mm-wave circuits, detection sources and antennas," Report OSA-95-OS-14-V, January 9, 1995.

[26] J.W. Bandler, "Statistical modeling, design centering, yield optimization and cost-driven design," Report OSA-95-MT-15-V, May 19, 1995.

[27] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "OSA's Empipe drives Sonnet's *em* capturing and optimizing arbitrary structures," Report OSA-95-MJ-18-R, June 7, 1995.

[28] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, P.A. Grobelny and D.G. Swanson, Jr., "Heterogeneous parallel yield-drive electromagnetic CAD," Report OSA-95-OS-21-V, August 16, 1995.

[29] J.W. Bandler, "Performance- and yield-driven design of microwave circuits emphasizing directed em optimization," Report OSA-95-OS-22-V, August 31, 1995.

[30] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization technology for microwave circuit modeling and design," Report OSA-95-EM-23-V, September 4, 1995.

[31] J.W. Bandler, "Statistical modeling, design centering, yield optimization and cost-driven design," in *CAD for Commercial Applications*, Workshop WFFE, IEEE MTT-S Int. Microwave Symp., (Orlando, FL), 1995.

[32] J.W. Bandler, Ed., *IEEE Trans. Microwave Theory Tech., Special Issue on Automated Circuit Design Using Electromagnetic Simulators*, vol. 45, 1997.

[33] J.W. Bandler, Ed., *Int. J. Microwave and Millimeter-Wave Computer-Aided Engineering, Special Issue on Optimization-Oriented Microwave CAD*, vol. 7, 1997.

RESEARCH PROJECT 3:

STATISTICAL MODELING OF MICROWAVE INTEGRATED CIRCUITS AND DEVICES

Objective of the Research

The main objective of the project is to establish the mathematical theory and algorithms aimed at modeling the statistical behaviour of manufactured microwave integrated devices. Software products implementing such algorithms should provide reliable statistical device models for yield analysis and optimization. These software products will build the bridge between process engineers and circuit designers in a volume production environment.

Nature of the Research

This research is both basic and applied. It is our aim to solve specific practical problems in microwave circuit modeling and design. In that sense it is applied. However, many aspects of basic research are involved. The fields of science involved: numerical methods, electrical circuit theory, microwave theory and techniques, statistical analysis, physics. Engineering applications will be found in all engineering areas involving mathematical modeling and volume production.

Reference Material

Two important papers can be cited:

S. Liu and K. Singhal, "A statistical model for MOSFETs", *IEEE Int. Conf. on Computer-Aided Design* (Santa Clara, CA), 1985, pp. 78-80.

J. Purviance, D. Criss and D. Monteith, "FET model statistics and their effects on design centering and yield prediction for microwave amplifiers", *IEEE Int. Microwave Symp. Digest* (New York, NY), 1988, pp. 315-318.

Uncertainty of the Research

The uncertain future of statistical modeling and design of microwave integrated circuits, and acceptance of the necessary software tools by microwave engineers makes this a high risk project. The prognosis for the affordable manufacture of monolithic microwave integrated circuits (MMICs) is still uncertain. Slow recovery of the high-tech microwave industry from the recession slows down these developments.

Novelty of the Research

Statistical modeling of microwave integrated circuit devices is being pioneered by only a few research groups worldwide, including OSA. This research extends, where possible, statistical modeling techniques used in VLSI digital circuits to microwave circuits. We develop new techniques otherwise. As such, this research is novel.

Advance in Scientific Knowledge

The methods and algorithms developed within this project will help the microwave engineers to investigate, better understand, and, as a consequence, to utilize device statistics in the process of circuit design. This research is aimed at establishing a framework for complete statistical characterization and design of microwave integrated circuits.

Method of Research

Accepted scientific methods are employed. Since the team members have been actively working in this research area for a number years no extra literature search is necessary except for recent periodicals. Long-term and short-term goals are carefully defined and milestones are scheduled. Theoretical investigations are conducted and then the new concepts are implemented in computer programs and verified through numerical examples. Promising algorithms are further tested on a number of industrial examples. The project particularly requires interaction with integrated circuit process and fabrication engineers to determine and obtain relevant measured data. Interaction with industry also provides important feedback.

Progress to Date

The starting date for the project was June 1, 1988. By November 1994 we had reviewed the state-of-the-art in statistical modeling; we had developed the theory for combined discrete normal statistical modeling [1]; and we had developed the theory for optimization based statistical modeling, tested it, and implemented it in our commercial software product HarPE Version 1.4+S [2]. We had focused upon physics-based models, particularly the Ladbrooke model, and processed wafer measurement data from Plessey Research Caswell Ltd. We had tested the Khatibzadeh and Trew model for statistical applications. This led us to combine the Ladbrooke model with the Khatibzadeh and Trew model into one model exploiting their respective advantages [3-5]. The combined model (KTL) was implemented in HarPE. We had developed a new optimization technique based on the Huber function for statistical modeling [6,7]. We had initiated work on a novel approach of direct statistical modeling by developing cumulative distribution function fitting and histogram fitting techniques [8]. More recently, statistical modeling of GaAs MESFETs using the KTL model had been further advanced [9].

Between December 1, 1994 and November 30, 1995 we continued our work on this project. We developed a strategy for effectively combining our novel approach of direct statistical modeling with the indirect approach of multi-circuit parameter extraction and statistical postprocessing, and continued our investigation of utilizing the Huber norm in robust handling of measurement data.

Reports

The papers [10,11] manuals [12,13], and reports [14-20] summarize our new work within the framework of this project. Our approach to statistical modeling combining direct and indirect techniques was published in *Microwave Engineering Europe*. The use of optimization technology for statistical modeling was reviewed and presented at the 25th European Microwave Conference.

Description of the Project

Statistical modeling is a prerequisite to using statistical design techniques. Such a procedure has been successfully used in the design of MOSFET devices, CMOS and other types of VLSI digital circuits. GaAs integrated circuits now play an important role in microwave engineering. How to obtain the statistical models is a vital step towards effective use of yield analysis and optimization. However, such modeling techniques are still relatively new to the majority of microwave engineers.

Generally speaking, statistical modeling is to find a model and the statistical distribution of the model parameters. The available information are measurements of the external behaviour of circuits or devices, and possibly process/geometrical measurements. Different levels of information may be hierarchically classified, from top to bottom, as response level, electrical model parameter level, intermediate parameter level and basic process/geometrical parameter level.

Our work on physics-based statistical modeling has been one of the leading achievements in this area in the world. This was reflected by our research results presented in a comprehensive paper [5] published in the Special Issue of *IEEE Transactions on Microwave Theory and Techniques* on Process-Oriented Microwave CAD and Modeling.

Between December 1, 1994 and November 30, 1995 we concentrated our efforts on further developments and enhancements to our novel approach of direct statistical modeling. By suitably combining it with the indirect approach of multi-circuit parameter extraction and statistical postprocessing we can determine good starting points for direct optimization. This can also provide an estimate of parameter correlations. This approach, described in [10,18], is now fully implemented in HarPE [13].

We have prepared and presented a comprehensive invited paper [11,14,19,20] at the 25th European Microwave Conference held in Bologna, Italy, in September 1995, the most important annual event in Europe in the field of microwave theory and techniques. That paper includes a review of the use of optimization technology for statistical modeling.

We have continued to investigate statistical modeling using built-in active device models in the popular circuit simulator SPICE [15,16]. Using OSA's Datapipe, an open architecture technology, SPICE has been connected to and driven by OSA90/hope [12]. The built-in FET model was simulated by SPICE with the parameter values determined by OSA90/hope and passed to SPICE in an automatic fashion. In this way a "foreign" model can be fully integrated into OSA90/hope for parameter extraction, statistical modelling and, finally, for the overall circuit simulation and optimization.

Other activities related to this project included an important workshop presentation [21] (report [17]) at the 1995 IEEE MTT-S International Microwave Symposium (Orlando, Florida, May 1995), and prestigious editorial work (J.W. Bandler, Guest Editor) for two most important journals in the field: *IEEE Transactions on Microwave Theory Techniques* [22], and *International Journal of Microwave and Millimeter-Wave Computer-Aided Engineering* [23].

In the future we will continue research in all of the aforementioned subjects.

<u>Technical Personnel</u>

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References

[1] J.W. Bandler, R.M. Biernacki, S.H Chen, J.F. Loman, M.L. Renault and Q.J. Zhang, "Combined discrete/normal statistical modeling of microwave devices", *Proc. 19th European Microwave Conference* (London, England), 1989, pp. 205-210.

[2] "HarPE™ User's Manual, Version 1.4+S", Optimization Systems Associates Inc., Dundas, Ontario, Canada, July 15, 1990.

[3] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and S. Ye, "PhorsFET: A new physics-oriented statistical GaAs MESFET model," Report OSA-91-MT-5-R, December 2, 1991.

[4] J.W. Bandler, S. Ye, Q. Cai, R.M. Biernacki and S.H. Chen, "Predictable yield-driven circuit optimization," *IEEE MTT-S Int. Microwave Symp. Digest* (Albuquerque, NM), 1992, pp. 837-840.

[5] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, S. Ye and Q.J. Zhang, "Integrated physics-oriented statistical modeling, simulation and optimization," *IEEE Trans. Microwave Theory Tech.*, Special Issue on Process-Oriented Microwave CAD and Modeling. vol. 40, 1992, pp. 1374-1400.

[6] J.W. Bandler, S.H. Chen, R.M. Biernacki, L. Gao, K. Madsen and H. Yu, "Huber optimization of circuits: a robust approach," *IEEE Trans. Microwave Theory Tech.*, vol. 41, 1993, pp. 2279-2287.

[7] J.W. Bandler, S.H. Chen, R.M. Biernacki and K. Madsen, "The Huber concept in device modeling, circuit diagnosis and design centering," *Proc. IEEE Int. Symp. Circuits Syst.* (London, England), 1994, vol. 1, pp. 129-132.

[8] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "A novel approach to statistical modeling using cumulative probability distribution fitting," *IEEE MTT-S Int. Microwave Symp. Digest* (San Diego, CA), 1994, pp. 385-388.

[9] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "A robust physics-oriented statistical GaAs MESFET model," *Proc. European Gallium Arsenide Application Symp.* (Turin, Italy), 1994, pp. 173-176.

[10] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "Device statistical modelling and verification," *Microwave Engineering Europe*, May 1995, pp. 35-41.

[11] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization technology for microwave circuit modeling and design," (invited), *Proc. 25th European Microwave Conf.* (Bologna, Italy), 1995, pp. 101-108.

[12] "OSA90/hope™ User's Manual, Version 3.1," Optimization Systems Associates Inc., Dundas, Ontario, Canada, September 1995.

[13] "HarPE™ User's Manual, Version 2.0", Optimization Systems Associates Inc., Dundas, Ontario, Canada, August 1995.

[14] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization technology for microwave circuit modeling and design," Report OSA-95-OS-2-R, February 8, 1995.

[15] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Electromagnetic design of microwave circuits integrated with SPICE device models," Report OSA-95-OS-3-R, February 8, 1995.

[16] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Automated EM optimization of linear and nonlinear circuits with geometry capture for arbitrary planar structures," Report OSA-95-OS-4-R, February 28, 1995.

[17] J.W. Bandler, "Statistical modeling, design centering, yield optimization and cost-driven design," Report OSA-95-MT-15-V, May 19, 1995.

[18] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "Device statistical modeling and verification," Report OSA-95-ME-17-R, March 22, 1995.

[19] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization Technology for microwave circuit modeling and design," Report OSA-95-OS-2-R, Revised July 7, 1995.

[20] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization technology for microwave circuit modeling and design," Report OSA-95-EM-23-V, September 4, 1995.

[21] J.W. Bandler, "Statistical modeling, design centering, yield optimization and cost-driven design," in *CAD for Commercial Applications*, Workshop WFFE, IEEE MTT-S Int. Microwave Symp., (Orlando, FL), 1995.

[22] J.W. Bandler, Ed., *IEEE Trans. Microwave Theory Tech., Special Issue on Automated Circuit Design Using Electromagnetic Simulators*, vol. 45, 1997.

[23] J.W. Bandler, Ed., *Int. J. Microwave and Millimeter-Wave Computer-Aided Engineering, Special Issue on Optimization-Oriented Microwave CAD*, vol 6, 1996.

TECHNICAL PERSONNEL

Director of Research

Dr. J.W. Bandler is President of Optimization Systems Associates Inc., established in 1983, and Director of Research.

Dr. Bandler studied at Imperial College of Science and Technology, London, England, from 1960 to 1966. He received the B.Sc. (Eng.), Ph.D and D.Sc. (Eng.) degrees from the University of London, London, England, in 1963, 1967 and 1976, respectively.

Dr. Bandler joined Mullard Research Laboratories, Redhill, Surrey, England in 1966. From 1967 to 1969 he was a Postdoctorate Fellow and Sessional Lecturer at the University of Manitoba, Winnipeg, Canada. He joined McMaster University, Hamilton, Canada, in 1969, where he is currently a Professor of Electrical and Computer Engineering. He has served as Chairman of the Department of Electrical Engineering and Dean of the Faculty of Engineering. He currently directs research in the Simulation Optimization Systems Research Laboratory. He has some 280 research publications. Dr. Bandler is a Fellow of the Royal Society of Canada, a Fellow of the Institute of Electrical and Electronics Engineers and a Fellow of the Institution of Electrical Engineers (Great Britain). He is a member of the Association of Professional Engineers of the Province of Ontario (Canada).

Senior Research Personnel

Dr. R.M. Biernacki received the Ph.D. degree with distinction from the Technical University of Warsaw in 1976. He has more than 25 years of professional experience which includes several academic and research positions.

Dr. Biernacki joined Optimization Systems Associates Inc., in 1986, as Senior Research Engineer. He is now Vice President Research and Development. In 1988 he was appointed Professor of Electrical and Computer Engineering (part-time) at McMaster University, Hamilton, Canada.

Dr. Biernacki has some 100 publications in IEEE journals and proceedings of IEEE and other conferences. Dr. Biernacki is a Fellow of the Institute of Electrical and Electronics Engineers.

Dr. S.H. Chen received the B.S.(Eng.) degree from the South China Institute of Technology, Guangzhou, China, with top class honours, in 1982. Between 1983 and 1987, he pursued his graduate studies in the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada, where he received the Ph.D. degree in 1987.

Dr. Chen joined Optimization Systems Associates Inc. in 1987 as Research Engineer. He is responsible for developing state-of-the-art CAD mathematics, algorithms and software. He is now Consulting Engineer with Optimization Systems Associates Inc.

Dr. Chen has contributed to some 60 technical papers, including an invited paper for the 1988 Special Issue on Computer-Aided Design of the IEEE Transactions on Microwave Theory and Techniques entitled "Circuit optimization: the state of the art". Dr. Chen is a Senior Member of the Institute of Electrical and Electronics Engineers.

Research Personnel

Dr. Q. Cai received the B.Eng. degree from Guangdong Radio and TV University, Guangzhou, China, in 1982, the M.S.(Eng.) degree from the South China Institute of Technology, Guangzhou, China, in 1986 and the Ph.D. degree from McMaster University, Hamilton, ON, Canada, in 1992, all in electrical engineering.

Dr. Cai was with the Department of Electrical Engineering, Guangdong Institute of Technology, Guangzhou, China, from June 1986 to August 1988. He was a graduate student at McMaster University from 1988 to 1992, during which time he was awarded a Chinese Government Graduate Scholarship for the year 1988-1989 and a Clifton W. Sherman Graduate Scholarship for the year 1990-1991. He was a Postdoctoral Fellow in the year 1992-1993 and a Research Associate in 1993, both in the Department of Electrical and Computer Engineering, McMaster University.

Dr. Cai was awarded a Natural Sciences and Engineering Research Council of Canada Industrial Research Fellowship and was with Optimization Systems Associates Inc. from December 1993 to September 1995 as a Research Engineer.

Dr. Cai is a Senior Member of the Institute of Electrical and Electronics Engineers.

Ms. J. Tripp joined Optimization Systems Associates Inc. in September 1995. Her position at OSA is Assistant to the President (Research and Administration). She is responsible for researching and maintaining computer resources, particularly software, and for software comparison and evaluation. She executes technical documentation and presentation material for scientific conferences and journals. She also assists in projecting OSA's hi-tech research profile to potential users and collaborators around the world by means of the Internet. She participated in creating OSA's Internet link and web home page, as well as responding to inquiries. By regularly searching the Internet and gathering relevant technical data, she makes an important contribution to OSA's knowledge base of the latest technical advances and trends.

Ms. Tripp has 18 years of experience in working with DOS and UNIX operating systems, both hardware and software. She has worked as UNIX System Administrator responsible for general maintenance, software upgrades, training and supervising junior personnel. She has also been responsible for hardware installations.

OSA REPORTS FROM DECEMBER 1994 TO NOVEMBER 1995

[1] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "Cost-driven physics-based large-signal simultaneous device and circuit design," Report OSA-94-OS-25-R, Revised January 5, 1995.

[2] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, P.A. Grobelny and D.G. Swanson, Jr., "Heterogeneous parallel yield-driven electromagnetic CAD," Report OSA-94-OS-29-R, Revised January 6, 1995.

[3] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Integrated harmonic balance and electromagnetic optimization with Geometry Capture," Report OSA-94-OS-27-R, Revised January 18, 1995.

[4] J.W. Bandler, R.M. Biernacki, S.H. Chen, W.J. Getsinger, P.A. Grobelny, C. Moskowitz and S.H. Talisa, "Electromagnetic design of high-temperature superconducting microwave filters," Report OSA-95-OS-1-R, January 23, 1995.

[5] J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Aggressive space mapping for electromagnetic design," Report OSA-94-OS-26-R, Revised January 25, 1995.

[6] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization technology for microwave circuit modeling and design," Report OSA-95-OS-2-R, February 8, 1995.

[7] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Electromagnetic design of microwave circuits integrated with SPICE device models," Report OSA-95-OS-3-R, February 8, 1995.

[8] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Automated EM optimization of linear and nonlinear circuits with geometry capture for arbitrary planar structures," Report OSA-95-OS-4-R, February 28, 1995.

[9] J.W. Bandler, R.M. Biernacki, S.H. Chen, R. H. Hemmers and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping," Report OSA-95-OS-5-R, February 28, 1995.

[10] "Research projects: December 1993 - November 1994," Report OSA-95-RC-6-R, April 19, 1995.

[11] J.W. Bandler, R.M. Biernacki, S.H. Chen, W.J. Getsinger, P.A. Grobelny, C. Moskowitz and S.H. Talisa, "Electromagnetic design of high-temperature superconducting microwave filters," Report OSA-95-OS-1-R, Revised April 21, 1995.

[12] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "Cost-driven physics-based large-signal simultaneous device and circuit design," Report OSA-95-OS-7-V, May 10, 1995.

[13] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen and P.A. Grobelny, "Integrated harmonic balance and electromagnetic optimization with geometry capture," Report OSA-95-OS-8-V, May 10, 1995.

[14] J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Aggressive space mapping for electromagnetic design," Report OSA-95-OS-9-V, May 10, 1995.

[15] "HUGHES multiplexer design #5 project report," Report OSA-95-OS-10-R, June 7, 1995.

[16] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization Technology for microwave circuit modeling and design," Report OSA-95-OS-2-R, Revised July 7, 1995.

[17] J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping," Report OSA-95-OS-5-R, Revised July 14, 1995.

[18] "OSA illustrations," Report OSA-95-OS-11-R, August 31, 1995.

[19] "Direct extrinsic parameter extraction from cold measurements," Report OSA-95-OS-12-R, September 6, 1995.

[20] "A feasibility study for porting OSA's CAD software from UNIX X-windows to a PC environment: final report," Report OSA-95-OS-13-R, August 30, 1995.

[21] J.W. Bandler, "Em and mm-wave circuits, detection sources and antennas," Report OSA-95-OS-14-V, January 9, 1995.

[22] J.W. Bandler, "Statistical modeling, design centering, yield optimization and cost-driven design," Report OSA-95-MT-15-V, May 19, 1995.

[23] S.H. Chen, "Automated EM optimization of linear and nonlinear circuits, with geometry capture for arbitrary planar structures," Report OSA-95-MT-16-V, May 15, 1995.

[24] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "Device statistical modeling and verification," Report OSA-95-ME-17-R, March 22, 1995.

[25] J.W. Bandler, R.M. Biernacki, Q. Cai and S.H. Chen, "OSA's Empipe drives Sonnet's *em* capturing and optimizing arbitrary structures," Report OSA-95-MJ-18-R, June 7, 1995.

[26] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Toward direct EM optimization of VLSI interconnects: Validation of coupled transmission line models," Report OSA-95-CC-19-R, June 29, 1995.

[27] J.W. Bandler, "Novel electromagnetic optimization techniques, including space mapping," Report OSA-95-IM-20-V, July 17, 1995.

[28] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, P.A. Grobelny and D.G. Swanson, Jr., "Heterogeneous parallel yield-drive electromagnetic CAD," Report OSA-95-OS-21-V, August 16, 1995.

[29] J.W. Bandler, "Performance- and yield-driven design of microwave circuits emphasizing directed em optimization," Report OSA-95-OS-22-V, August 31, 1995.

[30] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Optimization technology for microwave circuit modeling and design," Report OSA-95-EM-23-V, September 4, 1995.

[31] J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Space mapping optimization for engineering design," Report OSA-95-IM-24-R, September 28, 1995.

[32] J.W. Bandler, "Optimization Systems Associates Inc. case study," Report OSA-95-OS-25-V, October 16, 1995.

[33] J.W. Bandler, "Novel space mapping optimization technique for electromagnetic design," Report OSA-95-ES-26-V, November 6, 1995.

[34] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Parameterization of arbitrary geometrical structures for automated electromagnetic optimization," Report OSA-95-MT-27-R, November 30, 1995.

[35] J.W. Bandler, R.M. Biernacki and S.H. Chen, "Fully automated space mapping optimization of 3D structures," Report OSA-95-MT-28-R, November 30, 1995.