RESEARCH PROJECTS

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INTRODUCTION

During the fiscal year 1993/1994 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	50%	\$100,303
Project No. 2	30%	\$60,182
Project No. 3	20%	\$40,121

Total claimed for the Investment Tax Credit in respect of Scientific Research and Experimental Development (SR & ED)	\$200,606

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 1993 to November 1994).

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 parameter extraction (in particular GaAs FETs) coupled to sufficiently fast nonlinear circuit simulation and design (including yield-driven design). 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, parameter extraction of microwave active devices based on physics equations, consistent models for all types of circuit simulation and design, and field theory based component analysis, 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 1993 we had already developed, released and marketed three computer programs: (1) HarPE - for nonlinear device parameter extraction, (2) OSA90/hope - a novel, state-of-the-art general purpose CAD software system featuring open architecture achieved through our research on high speed interprocess data communication [11], and (3) Empipe - for direct electromagnetic simulation and optimization. We pioneered the parameter extraction method based on large-signal power spectrum measurements and the harmonic balance simulation technique [6,9]. We laid a foundation for analytical unification of DC, small-signal and large-signal circuit simulations and optimizations [10]. We developed adjoint sensitivity technique for harmonic balance simulations [7,8]. We have developed models for microstrip structures to expand our library of linear elements [13,14], and made a significant progress in connecting external simulators to our software and exploiting them to solve important practical problems [11,15,16]. We have developed a new robust method of optimization using the Huber function for microwave CAD [17,18]. We have developed models and techniques for direct electromagnetic field simulation and optimization [19-21].

Between December 1, 1993 and November 30, 1994 we continued our work on different parts of the project. In particular, we were developing novel and efficient geometry capture and interpolation techniques for direct electromagnetic field optimization of arbitrary planar structures. We were exploiting our novel Space Mapping technique for microwave CAD to achieve the speed of circuit-level optimization and the accuracy of electromagnetic field simulation. We were implementing a number of new device models.

Reports

The papers [27-36], manuals [24-26] and reports [37-47] summarize our new work within the framework of this project. Our new Space Mapping technique for electromagnetic optimization [31] was published in *IEEE Transactions on Microwave Theory and Techniques* which is the most reputable journal in the field. Our Space Mapping method has been considered as a significant breakthrough in microwave CAD. Our earlier work on direct electromagnetic field optimization has been published [32] and new results reported at international symposia [27-30,33]. Three new papers [34-36] were submitted to the 1995 IEEE MTT-S International Microwave Symposium. All of them 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.

The advances in GaAs material development and wafer processing achieved in the past few years have made monolithic microwave integrated circuits (MMICs) practical. The modeling of MMIC devices is recognized as a subject of fundamental importance [1,2,4,5]. Also, the harmonic balance method has become an important tool for the analysis of nonlinear circuits. The excellent paper of Kundert and Sangiovanni-Vincentelli [3] provided systematic insight into that method. Our achievements in the adjoint sensitivity analysis technique [7] and its expedient implementation in general purpose CAD software [8] has made the harmonic balance method attractive for design optimization. These techniques are now being applied in conjunction with the state-of-the-art electromagnetic field level simulation of individual components [12].

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 a new generation comprehensive software system suitable for yield and cost driven design of 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 these features and techniques has been made within the new releases of our software systems HarPE [26], OSA90/hope [24], and in our interface of Empipe [25] to the electromagnetic simulator ***em*** [12] from Sonnet Software.

Our novel and exciting optimization technique Spacing Mapping [31] was published in *IEEE Transactions on Microwave Theory and Techniques*. This new technique provides an efficient way for engineers to solve extremely difficult optimization problems which may be encountered in electromagnetic design due to high sensitivities, long simulation times, etc. Using Space Mapping method circuit design can be carried out at the speed of circuit-level optimization while obtaining 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 [28]. Its advantages have also been demonstrated in a number of circuit designs [28,30,31]. Our new development on Space Mapping by aggressively exploiting every available electromagnetic field analysis can dramatically reduce the computational time [35]. This result will be presented at the 1995 IEEE MTT-S International Microwave Symposium (Orlando, Florida, May 1995).

We have significantly advanced our work on item (1). Four new models for high electron mobility transistors (HEMTs) [41] have been implemented in HarPE [26] and OSA90/hope [25]. A new heterojunction bipolar transistor (HBT) model [47] which takes into account the thermal effects has been added into the device library of HarPE [26] and OSA90/hope [24].

Substantial progress has been achieved on item (9). We have developed a sophisticated technique which we call Geometry Capture for electromagnetic field optimization of arbitrary planar structures [25]. This opens up exciting new applications. Microwave engineers will be able to accurately design circuits consisting of complicated structures and investigate new microstrip components. For the first time, we have integrated electromagnetic field simulations directly with nonlinear harmonic balance simulation and optimization [34] which is critical for the first-pass success in design of nonlinear integrated circuits. We have, also for the first time, developed a parallel optimization technique to handle the massive demand on computer resources due to the large number of designable parameters describing an arbitrary geometry [36]. These two new techniques [34,36] will be presented at the 1995 IEEE MTT-S International Microwave Symposium (Orlando, Florida, May 1995).

Using our efficient harmonic balance simulator of OSA90/hope [24] and Empipe [25] interface to Sonnet's ***em*** [12] we have successfully performed nonlinear analysis and optimization of a class B frequency doubler [38-40]. The frequency doubler was used by Microwave Engineering Europe to challenge the major microwave RF CAD vendors in the whole world [48]. Compared to the actual measurements of the circuit OSA's results were the most accurate [48].

In our future work we will continue to concentrate on further development of automated Space Mapping for electromagnetic field optimization of passive elements and physical optimization of active devices.

Technical Personnel

Dr. J.W. Bandler, Director of Research

Dr. R.M. Biernacki

Dr. S.H. Chen

Dr. Q. Cai

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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 emerging 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 and large-scale optimization techniques 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 prognosis for 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., [2,3]. 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 1993 we successfully demonstrated feasibility of an extremely efficient method [5] 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 [4]. We pioneered yield optimization of nonlinear circuits operating in the steady-state under large-signal excitations [6], and developed a fast gradient based technique for such applications [7]. We developed a quadratic modeling technique based on both simulated responses and their gradients [9]. We researched yield optimization of MMIC circuits in terms of physical and geometrical parameters of active devices and passive components, including correlations [10,15]. We also introduced Monte Carlo analysis into HarPE [20]. We have completed development of yield optimization capabilities for our general purpose CAD software system OSA90/hope [18]. We have devised a new algorithm for yield optimization [14] and investigated the predictability of simulated yield [13]. We have researched yield optimization of microwave circuits with passive components accurately analyzed by an electromagnetic field simulator [12]. We have developed a novel approach for yield-driven electromagnetic optimization using multilevel multidimensional models [16,17].

Between December 1, 1993 and November 30, 1994 we continued our work on this project. We have developed a novel Huber optimization technique for design centering [22]. We have created a CAD environment for yield-driven circuit design employing electromagnetic field simulators [21]. We have utilized Space Mapping technique in electromagnetic field yield optimization [23,24]. We have investigated cost-driven design [25] and heterogeneous parallel yield-driven electromagnetic CAD [26].

Reports

The papers [21-26], manuals [18-20] and reports [27-33] summarize our new work within the framework of this project. Our user-friendly CAD environment for performance and yield driven circuit design [21] and our novel Huber optimization technique for yield optimization [22] were published in the Proceedings of the 1994 IEEE International Symposium on Circuits and Systems. Our electromagnetic field yield optimization using Space Mapping technique was presented at the 1994 IEEE MTT-S International Microwave Symposium [23] and published in *IEEE Transactions on Microwave Theory and Techniques* [24]. Our cost-driven design methodology [25] and heterogeneous parallel yield-driven electromagnetic CAD [26] will be presented at the 1995 IEEE MTT-S International Microwave Symposium.

Description of the Project

Statistical circuit design, or yield optimization has been a subject of extensive research in the last 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 computational effort involved. In this research we concentrate our efforts on algorithms for statistical design of nonlinear circuits operating in the steady state under large-signal periodic excitations.

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 our large paper [15] published in the Special Issue of *IEEE Transactions on Microwave Theory and Techniques* on Process-Oriented Microwave CAD and Modeling. We have implemented a new algorithm for yield optimization, more suitable for gradient based optimizers because of the smoothness of the objective function [14]. We have advanced our previous work on the predictability of simulated yield as compared to yield determined directly from device measurements [13]. We have also developed efficient modeling techniques for yield optimization using electromagnetic field simulators [16,17].

Between December 1, 1993 and November 30, 1994 we devoted great effort to the development of efficient techniques and new methodologies for cost-effective and yield-driven design. In this context we have developed a number of methods such as electromagnetic field yield optimization [21,23,24,27], one-sided Huber centering [22], physics-based cost-driven design [25] and heterogeneous parallel yield-driven design [26].

Our CAD environment for yield-driven circuit design employing electromagnetic field simulators [21] and our novel Huber optimization technique for yield optimization [22] were presented at the 1994 IEEE International Symposium on Circuits and Systems. We explored the Space Mapped yield optimization technique utilizing accurate electromagnetic field simulations which was presented at the 1994 IEEE MTT-S International Microwave Symposium [23] and published in *IEEE Transactions on Microwave Theory and Techniques* [24].

We have investigated cost-driven design to minimize the manufacturing cost while maintaining the required production yield. Using this method the possibility of first-pass success in design of integrated circuits particularly MMICs can be significantly increased. The advantages of this method have been demonstrated by physics-based large-signal simultaneous device and circuit design [25] which will be presented at the 1995 IEEE MTT-S International Microwave Symposium (Orlando, Florida, May 1995).

The integrated parallel optimization framework developed within Research Project 1 was applied to yield-driven design of microstrip circuits of arbitrary geometries [26]. Parallel optimization handles efficiently the massive demand on computer resources due to the large number of simulations involved in yield optimization. This method will be presented at the 1995 IEEE MTT-S International Microwave Symposium (Orlando, Florida, May 1995).

In the future we will concentrate our efforts on further improvements of the algorithms and methods for statistical design of analog and microwave circuits, particularly for direct electromagnetic field yield optimization and physical yield-driven design using the Space Mapping technique.

<u>Technical Personnel</u>

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Dr. S.H. Chen

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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 few years no extra literature search was 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 1993 we had reviewed the state-of-the-art in statistical modeling; we had developed the theory for combined discrete normal statistical modeling [7]; 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 (the current version is 1.8 [15]). We had experimented with the Ladbrooke model [6] and processed wafer measurement data from Plessey Research Caswell Ltd. Encouraging results were obtained [8]. We had also attempted to extend the Khatibzadeh and Trew model [4] to statistical applications. Our experiments indicated that statistical representation of device statistics by the Khatibzadeh and Trew model was not satisfactory. This led us to investigate the possibility of combining the two models into one model exploiting their respective advantages [11]. The combined model (KTL) was implemented in HarPE. We have presented our work on physics based KTL model in our comprehensive paper [10]. We have developed a new optimization technique based on the Huber function for statistical modeling [12,13].

Between December 1, 1993 and November 30, 1994 we continued our work on this project. We enhanced our novel approach of direct statistical modeling by developing a histogram fitting technique [15]. We advanced our research on physics-based statistical modeling of GaAs MESFETs [17]. We extended our approach to statistical modeling utilizing the Huber norm [18].

Reports

The papers [16-18], manual [15] and reports [19-22] summarize our new work within the framework of this project. Our novel approach to statistical modeling using cumulative probability distribution fitting [16] was presented at the 1994 IEEE MTT-S International Microwave Symposium. Our robust physics-oriented statistical GaAs MESFET model [17] was published in the 1994 Proceedings of the European Gallium Arsenide Application Symposium. Our paper on statistical modeling using the Huber function [18] was presented at the 1994 IEEE International Symposium on Circuits and Systems.

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 [1,2]. 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 relatively new to most microwave engineers. The literature on this subject is very sparse, e.g., [3,5,7,8].

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 was one of the leading achievements in this area in the world. This was reflected by our research results presented in a comprehensive paper [10] published in the Special Issue of *IEEE Transactions on Microwave Theory and Techniques* on Process-Oriented Microwave CAD and Modeling.

Between December 1, 1993 and November 30, 1994 we concentrated our efforts on the development and enhancement of our novel approach of direct statistical modeling and the improvement of our statistical models for GaAs MESFETs in the context of robustness and accuracy. We also investigated statistical modeling using external simulators.

Our new approach of direct statistical modeling, based on a solid mathematical foundation [16], was published in the 1994 IEEE MTT-S International Microwave Symposium Digest and proved to be more accurate and reliable. This method was enhanced by introducing statistical histogram matching [15]. The statistical model can be optimized by either cumulative probability distribution fitting or histogram fitting. We have investigated combining indirect and direct methods for statistical modeling to increase the accuracy of the model and the efficiency of the optimization process [15].

Based on our previous work we have improved our physics-based statistical models for GaAs MESFETs by including the statistics of DC measurements in parameter extraction. Our paper in this subject [17] was presented at the 1994 European Gallium Arsenide Application Symposium.

We have advanced our work on the optimization technique for statistical modeling using the Huber norm. Its advantages have been shown on MESFET statistical modeling [18] which was presented at the 1994 IEEE International Symposium on Circuits and Systems.

We have investigated statistical modeling using OSA90/hope [14] driving external simulators. We have demonstrated this concept using the SPICE model [23]. The parameter extraction was driven by OSA90/hope's optimizers with the SPICE MESFET model captured from SPICE [23]. The model responses were compared by OSA90/hope against the measured data. The model statistics including the mean values, standard deviations and the correlation matrix are obtained by statistical postprocessing. Very good results have been obtained [22].

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

Technical Personnel

Dr. J.W. Bandler, Director of Research

Dr. R.M. Biernacki

Dr. S.H. Chen

Dr. Q. Cai

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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 270 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 from the Technical University of Warsaw in 1976. He has more than 20 years of professional experience which includes several academic and research positions.

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

Dr. Biernacki has some 90 publications in IEEE journals and proceedings of IEEE and other conferences. Dr. Biernacki is a Senior Member of the Institute of Electrical and Electronics Engineers.

Research Personnel

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.

Dr. Chen has contributed to some 50 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. 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 joined Optimization Systems Associates Inc. in 1993 as a Research Engineer.

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[39] "OSA90/hope™ User's Manual, Version 3.0," Optimization Systems Associates Inc., Dundas, Ontario, Canada, June 1994.

[40] "HarPE™ User's Manual, Version 1.8," Optimization Systems Associates Inc., Dundas, Ontario, Canada, July 1994.

[41] "Empipe™ User's Manual, Version 2.0," Optimization Systems Associates Inc., Dundas, Ontario, Canada, July 1994.