RESEARCH PROJECTS

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INDEX

INTRODUCTION

This report describes OSA's research projects in the four month period starting August 1, 1990 and ending November 30, 1990.

During this fiscal period we continued our research work within the scope of the following three on-going 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 was divided between the three projects as follows:

Project No. 1	40%
Project No. 2	40%
Project No. 3	20%

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; electrical circuit 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:

Libra, EEsof Inc., Westlake Village, CA 91362.

A. Materka and T. Kacprzak, "Computer calculation of large-signal GaAs FET amplifier characteristics", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, 1985, pp. 129-135.

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.

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, highly sensitive to computational accuracy or the starting point of the iterative numerical solution process, 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 within the framework of other projects since early 1987. By July 1990 we had already developed, released and started marketing a computer program called HarPE for nonlinear device parameter extraction. We demonstrated the feasibility of the parameter extraction method based on large-signal power spectrum measurements and the harmonic balance simulation technique. We investigated analytical unification of DC, small-signal and large-signal circuit simulations and optimizations. We developed adjoint sensitivity technique for harmonic balance simulations. We also introduced advanced features including a statistical design of linear circuits option for general CAD systems.

Between August 1, 1990 and November 30, 1990 we continued work on different components of the project. We continued enhancing efficiency and robustness of mathematical algorithms. We have made progress in designing open architecture, and user-friendly software.

Reports

The papers [21-24] summarize our achievements within the framework of this project. Reference [21] was presented at the 3rd Asia-Pacific Microwave Conference held in Tokyo, Japan, in September 1990. We worked on an extended version of that paper. It is now accepted for publication in *IEEE Transactions on Microwave Theory and Techniques* [22], the most reputable journal in the field. New papers [23] and [24] have been submitted to the 1991 European Microwave Conference.

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 one versatile, user-friendly and state-of-the-art software system. It involves developing new methods as well as enhancing some of the existing techniques. In addition to the mathematical aspect of the algorithms considerable effort is devoted to the computer science aspects arising from the requirements for the new generation of CAD systems.

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 [1-4,7-14,17].

The harmonic balance method has become an important tool for the analysis of nonlinear circuits. The work of Rizzoli et al. [1], Gilmore and Rosenbaum [2], Curtice and Ettenberg [4], Gilmore [6], Curtice [12] stimulated work on harmonic balance in the microwave CAD community. The excellent paper of Kundert and Sangiovanni-Vincentelli [5] provided systematic insight into the harmonic balance method. Our achievements in the adjoint sensitivity analysis technique [15] and its expedient implementation in general purpose CAD software [16] has made the harmonic balance method attractive for design optimization.

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.

To date we have made progress in all of these subjects. Implementation of these features and techniques has been made within the software system HarPE [18] as well as within a new software system OSA90™ which we plan to release soon.

Our previous work on consistency of the harmonic balance simulations under small-signal excitations with the traditional DC/small-signal simulation technique based on local linearizations at the operating points [21] was presented at the 1990 Asia-Pacific Microwave Conference held in Tokyo, Japan, in September 1990. Our results open a new avenue in design optimization and parameter extraction, where both small-signal and large-signal performance can be simultaneously and seamlessly taken into account. We worked on an extended version of [21] which is now accepted for publication in *IEEE Transactions on Microwave Theory and Techniques* [22].

We have continued our work on different computer scientific solutions needed for the new generation CAD tools for design of MMICs in the 1990s. We have investigated and developed an inter-program pipe communication technique for high speed numerical interactions between independent programs. This provides architectural foundation for a new generation of large-scale CAD software systems. Reference [23] has been submitted to the 1991 European Microwave Conference to be held in Stuttgart, Germany, in September 1991.

We have also initiated research on multi-conductor coupled transmission lines. A literature search has been conducted and a first implementation has been experimented with. Reference [24] has been submitted to the 1991 European Microwave Conference to be held in Stuttgart, Germany, in September 1991.

In our future work we will continue to concentrate on (1) further theoretical developments, including mathematical algorithms for simulation and optimization, (2) researching and implementing nonlinear device models and linear library elements, (3) extensive testing.

Technical Personnel

Dr. J.W. Bandler, Director of Research

Dr. R.M. Biernacki

Dr. S.H. Chen

Dr. Q.J. Zhang

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[24] Q.J. Zhang and J.W. Bandler, "Optimization of the time responses of multiconductor transmission lines", submitted to the *1991 European Microwave Conference* (Stuttgart, Germany), 1991.

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. Supercomputers 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 particularly uncertain.

Novelty of the Research

This research is a followup of state-of-the-art published works by members of the team, e.g., [1,2,5,7-11]. 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 July 1990 feasibility of an extremely efficient method for quadratic approximation of circuit response functions had been successfully demonstrated, including testing, reliability studies and, especially, applying the methods to the yield optimization of a large-scale practical microwave circuit, namely a 5-channel multiplexer. We developed a fast gradient based technique for yield optimization of nonlinear circuits operating in the steady-state under large-signal excitations. Two techniques for gradient approximation were exploited: Integrated Gradient Approximation Technique and Feasible Adjoint Sensitivity Technique. We also introduced Monte Carlo analysis into HarPE [12].

Between August 1, 1990 and November 30, 1990 we continued our work on this project. We have investigated yield optimization of nonlinear circuits in terms of physical and geometrical parameters of active devices and passive components. We have also made progress in quadratic modeling of circuit behaviour based on both simulated responses and their gradients.

Reports

The references [13-17] summarize our achievements within the framework of this project. An extended version of our earlier work has been published in *IEEE Transactions on Microwave Theory and Techniques* [13], the most reputable journal in the field. An invited paper [14] was presented in Duisburg, Germany, in October 1990. New papers [16] and [17] have been submitted to the 1991 IEEE MTT-S International Microwave Symposium and to the 1991 European Microwave Conference, respectively.

Description of the Project

Statistical circuit design, or yield optimization has been a subject of extensive research in the last decade, e.g., [1-11]. High production costs of present MMICs due to fluctuations in the manufacturing process demand yield-driven design CAD [6]. It is important to truly reflect the actual statistical spreads during computer simulations. Therefore, the primary physical and geometrical parameters must be available. Unfortunately, device 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. The following is a brief description of our results.

We finalized our previous work on efficient yield-driven optimization of nonlinear microwave circuits with statistically characterized devices exploiting Integrated Gradient Approximation Technique and Feasible Adjoint Sensitivity Technique. A scientific paper [13] has been published in the *IEEE Transactions on Microwave Theory and Techniques*. An invited paper [14] and related report [15] provide an up-to-date comprehensive review of the techniques and algorithms for yield-driven design of nonlinear circuits.

We have developed, implemented and tested a new approach to modeling of circuit responses and their gradients. We exploit multidimensional quadratic approximation and take full advantage of available gradient information in order to replace expensive repeated actual circuit simulations and gradient calculations by approximate model evaluations. This may significantly speed up the simulation process. Efficiency and accuracy of the new technique have been tested by gradient-based yield optimization of a filter and an MMIC amplifier. A research paper [16] has been submitted to the 1991 IEEE MTT-S International Microwave Symposium, to be held in Boston, MA, in June 1991.

We have initiated research on physics-based design and yield optimization of MMICs. Multidimensional statistical models are considered for the physical, geometrical and process-related parameters of active devices and passive components. We concentrate our efforts on feasibility studies of this extremely complex and computationally involved problem. We are experimenting with efficient gradient-based yield optimization technique. Our preliminary results have been reported in [17], a paper submitted to the 1991 European Microwave Conference to be held in Stuttgart, Germany, in September 1991.

In the future we plan to incorporate the yield optimization features into our new software system OSA90. In general, we will concentrate on new methods and algorithms aimed at improving efficiency of statistical design of analog and microwave circuits.

Technical Personnel

Dr. J.W. Bandler, Director of Research

Dr. R.M. Biernacki

Dr. S.H. Chen

Dr. Q.J. Zhang

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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 particularly uncertain. Recent cuts throughout the high-tech microwave industry may slow 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 July 31, 1990 we had reviewed the state-of-the-art in statistical modeling; we had developed the theory for combined discrete/normal statistical modeling; and we had developed the theory for optimization based statistical modeling, tested it, and implemented it in a new commercial software product HarPE Version 1.4+S. The latter was carried out with a partial support by the National Research Council of Canada through its IRAP-M grant "Linear/Nonlinear Statistical Modeling for Computer-Aided Engineering of Microwave Integrated Circuits" [8-10]. Between August 1990 and November 1990 we focused our research on physics based statistical modeling. We have experimented with the Ladbrooke model and processed wafer measurement data from Plessey Research Caswell Limited. Encouraging results have been obtained.

Reports

Two feature articles [9,10] appeared in the August issues of two trade journals, namely, *Microwave Engineering Europe* and *Microwave Journal*. A new scientific paper [11] has been submitted to the 1991 IEEE MTT-S International Microwave Symposium.

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 in the microwave community is very sparse, e.g., [3-7].

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 concentrates on the following on-going activities:

(1) investigate direct use of data bases of both measured and extracted parameters,

(2) investigate an interpolation technique for correlated statistical parameters,

(3) investigate physics based model statistical properties,

(4) continue to interact with process and fabrication engineers for measurement data and process information,

(5) continue to test statistical modeling using real measurement data.

During the reported period we have made progress in the last three subjects. We continued interaction with a few leading companies, in particular Plessey Research Caswell Ltd., England. We have processed real S-parameter measurement data from a sample of devices from two wafers manufactured by Plessey. We have studied and implemented a first, experimental version of the Ladbrooke physics based model. A new scientific paper [11] which summarizes our achievements within the framework of this project has been submitted to the 1991 IEEE MTT-S International Microwave Symposium to be held in Boston, MA, in June 1991. The paper contrasts the statistical extraction of GaAs MESFET equivalent circuit model parameters and physical model parameters. We have observed that the Materka and Kacprzak model based on equivalent circuit parameters provides a better match for individual devices, but the Ladbrooke model based on physical parameters provides a better estimate of device statistics.

In 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.J. Zhang

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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 more than 230 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's research interests include system theory, optimization and numerical methods, computer-aided design of integrated circuits and control systems. He has more than 60 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's professional interests include optimization theory and algorithms, computer-aided microwave circuit design, statistical analysis and yield optimization, robust device modeling, and user-friendly computer graphics. He has contributed to 15 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". During his stay in McMaster University he contributed to 20 technical reports.

Dr. Qi-jun Zhang received the B.Eng. degree from the East China Engineering Institute, Nanjing, China in 1982. 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. Zhang was a research assistant in Tianjin University, Tianjin, China in 1982 and 1983. He was a Postdoctoral Fellow in the Department of Electrical and Computer Engineering, McMaster University from September 1987 to March 1988. He joined Optimization Systems Associates Inc. in 1988 as Research Engineer. In 1989 he became Assistant Professor of Electrical and Computer Engineering (part-time) at McMaster University, Hamilton, Canada.

Dr. Zhang's professional interests include large-scale optimization techniques for design and modeling of microwave circuits, analysis and optimization of nonlinear microwave circuits, sensitivity analysis, diagnosis and tuning of analog circuits. He has published more than 20 technical papers.

Dr. Zhang has accepted an offer of a faculty position at Carleton University, Ottawa, Ontario, starting in December 1990.

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