OSA's INNOVATIONS
IN MICROWAVE CAE

OSA-89-OS-3-P

January 11, 1989

INDEX

SUMMARY

This document introduces Optimization Systems Associates Inc. (OSA). Technical plans for the immediate future are outlined.

Challenges faced by CAE software architects arising from microwave industrial demand for more efficient, more robust and powerful software systems capable of designing circuits in current technologies are addressed. In particular, we discuss nonlinear circuit simulation, efficient yield-and cost-driven design, including sensitivity analysis for fast optimization, parameter extraction for both small-signal and large-signal applications, and statistical modeling of microwave devices.

OSA's position in the creation of the next generation software tools for the microwave industry is established. In this context the company, its achievements and potential for future development are described. A list of recent OSA publications is appended.

OSA's EXPERIENCE

Optimization Systems Associates (OSA) was established in 1983. OSA's innovations are driven by the microwave industry's growing demand for user-friendly, state-of-the-art software design tools. OSA features:

Microwave circuit analysis, design and optimization

Statistical estimation of production yield

Robust active and passive device modeling

Harmonic balance simulation of nonlinear circuits

Automated processing of DC, RF and harmonic measurement data

Statistical modeling of devices

Powerful performance and yield driven optimizers

Manufacturing tolerance assignment and cost minimization

Customized gradient and minimax optimizers

Computer optimization of matching networks, filters and multiplexers

Algorithms for automated production alignment and tuning

OSA is applying and extending pioneering research originated by Bandler and his colleagues.

OSA's software and services are dramatically impacting the CAE of microwave integrated circuits, and will continue to do so into the next decade. OSA has originated features never previously offered by commercial microwave software houses.

OSA specializes in implementation of advanced theory and techniques and new software architectures in commercial software on a large variety of platforms and using several programming languages.

OSA has reshaped Touchstone by developing state-of-the-art optimizers, originally featured in Version 1.5, including minimax, quasi-Newton and generalized least pth optimizers.

OSA continues to play a key role in future releases of popular microwave CAE products such as Super-Compact, Microwave Harmonica, Super-Compact PC and Microwave Harmonica PC.

Since 1985 OSA has supported Raytheon Company's initiatives towards the U.S. DoD's MIMIC (Microwave/Millimeter-Wave Monolithic Integrated Circuits) Program. Currently, OSA is a subcontractor on the Raytheon/Texas Instruments/Compact Software MIMIC team under a Phase 1 Subcontract.

INNOVATIONS BY OSA

Introduction

Advances in GaAs material development and wafer processing achieved in the past few years have made monolithic microwave integrated circuits (MMICs) practical. With successful applications to microwave power amplifiers, mixers, oscillators, etc., the need for the next generation CAE software has become more and more pressing.

Design of nonlinear circuits is one of the most challenging tasks in the microwave CAE area. The pseudo-linear behaviour commonly existing in analog and microwave circuits and the intentional use of nonlinearities in circuits such as mixers are typical examples requiring nonlinear circuit CAE techniques.

Adequate CAE techniques are increasingly crucial for the microwave and millimeter-wave IC chips that are essential for the coming generation of radar systems, space technology and radio-frequency communications. The recognized number one task for such systems is to make them affordable. Efficient yield-driven design methodology is, consequently, an essential feature of the next generation of microwave software systems.

Yield Optimization

Our work is directed at a hardware/software system for design of analog microwave circuits that takes into account manufacturing tolerances, model uncertainties, variations of the process parameters, environmental uncertainties, etc. (Bandler and Chen 1988). It is particularly important for large volume production of MMICs.

Statistical design (yield optimization, design centering) involves simultaneous optimization of a large number of statistically related outcomes. Each outcome circuit has to be simulated in order to check its performance against design specifications. This, in turn, has to be repeated at each optimization step. Repeated analyses at many frequencies and for many sets of circuit parameters require both efficient algorithms and high computing speed. This is particularly important for nonlinear circuits.

Nonlinear Circuit Simulation

Traditional circuit simulators, such as SPICE, operate in the time domain. To use such an approach to analyze the steady-state behaviour of nonlinear circuits is excessively computer time intensive because the circuit needs to be simulated until the transient vanishes.

Recent years have witnessed a resurgence of interest in harmonic balance simulation methods by the microwave industry. A growing number of microwave engineers are using such simulators to design nonlinear circuits. Extensive number crunching currently required by available harmonic balance simulators have inhibited fast optimization of nonlinear circuits and its extension to yield driven design. Another significant drawback of current implementations is due to inaccurate or inefficient sensitivity and gradient calculations.

Commercial software using the harmonic balance method for analyzing nonlinear circuits has become recently available, e.g., Compact Software's Microwave Harmonica and EEsof's Libra. The Microwave Harmonica program, although considered as the world's most advanced of its kind today, suffers from heavy memory requirements and a limited variety of circuit elements available to the user. The program can perform nominal design with only linear elements as variables. It does not perform yield analysis and optimization, a difficult but nonetheless essential task for microwave CAE.

Efficient Sensitivity Analysis

The hierarchical decomposition of circuits is an extremely convenient approach to handle large circuits. It fits in well with the syntax-oriented description of the circuits (Jansen 1983). It also has great potential for parallel processing and elimination of unnecessary calculations.

The efficient adjoint circuit technique for sensitivity analysis has been established for linear circuits (Director and Rohrer 1969). However, it has not been implemented in commercial microwave packages. Instead, a simple but computationally expensive perturbation method has to be used in conjunction with gradient optimization (e.g., in Super-Compact, Touchstone, Microwave Harmonica).

OSA has pioneered a unified theory for frequency domain simulation and sensitivity analysis of linear and nonlinear circuits. A theoretical breakthrough was presented at the 1988 IEEE International Microwave Symposium and published in the *IEEE Trans. Microwave Theory and Techniques* (Bandler, Zhang and Biernacki 1988). An elegant derivation expands the harmonic balance technique from nonlinear simulation to nonlinear adjoint sensitivity analysis. In our approach, the linear part of the circuit can be large and can be hierarchically decomposed. Analysis of the nonlinear part is performed in the time domain and the large signal steady-state periodic analysis of the overall circuit is carried out by means of the harmonic balance method. The solution of a single adjoint system is sufficient for the computation of sensitivities w.r.t. all parameters in both the linear and nonlinear subnetworks, in the bias circuit, driving sources and terminations. No parameter perturbation or iterative simulations are required. Significant CPU time savings can be achieved over the perturbation method. Recently an expedient implementation of this adjoint technique has been demonstrated (Bandler, Zhang and Biernacki 1988).

Device Modeling

In the area of device modeling or parameter extraction, the traditional small-signal model alone does not provide satisfactory solutions in the design and analysis of nonlinear circuits. A nonlinear or large-signal model is needed to model the device operating under large-signal conditions.

There are difficulties in modeling of such devices with present techniques used by industry. The large signal model extracted from DC measurements does not agree well with RF measurements. There are parasitic circuit elements. There are too many variables and inaccessible nodes to create a unique solution based only upon one set of broadband scattering parameter measurements.

OSA has evolved a robust model parameter extraction approach simultaneously processing DC and RF measurements (Bandler, Chen, Ye and Zhang 1988). The DC characteristics are used to constrain bias-dependent parameters, thus improving the uniqueness and reliability of small-signal modeling. This feature has been implemented into OSA's RoMPE™.

OSA has developed a novel approach to large-signal nonlinear parameter extraction of GaAs FET devices measured under harmonic conditions (Bandler, Zhang, Ye and Chen 1988). Powerful nonlinear adjoint based optimization simultaneously process multi-bias, multi-power-input, multi-frequency excitations and multi-harmonic measurements to uniquely reveal the parameters of the intrinsic FET. Our results demonstrate excellent match between computed and measured powers over the entire frequency spectrum including all harmonics. This feature is being implemented into OSA's new product line.

Statistical Device Modeling

Yield optimization requires effective statistical representation of devices. The model statistics originate from simple random variations of basic process/physical/geometrical parameters. They are reflected in complicated distributions and correlations of device responses or equivalent model parameters. Statistical modeling has been seriously studied for MOS and CMOS circuits for more than 10 years (e.g., Dutton et al. 1977). The subject recently gained attention by MMIC microwave engineers.

The equivalent circuit based (Purviance et al. 1987) and the process/geometry based approaches (Liu and Singhal 1985) are two important ones for statistical modeling. The first approach typically results in a large number of statistical variables with complicated correlations. Consequently, the yield optimization problem will deal with a large number of variables and functions. The second approach requires physical/empirical formulas to express the device model in terms of basic process/geometrical parameters. Such formulas may be highly nonlinear and extremely complicated (Brazil et al. 1988). These nonlinear formulas have to be computed or solved for each outcome of the device during each iteration of optimization.

Other approaches to statistical modeling are also possible. Since all approaches deal with statistics which originate from basic process/geometrical variations, they all have to deal with the multi-outcome, multi-frequency concept. An intensive number crunching procedure is necessary to generate reliable statistical models.

OSA's Role in Microwave CAE

We are addressing the challenging yield- and cost-driven design of microwave integrated circuits for the early 1990's to optimally accommodate manufacturing tolerances and device statistics. We will provide features for the designer for enhancing wafer/chip yields in a CAE workstation environment which will include statistics, measurement uncertainties, efficient optimization and design centering, in particular for nonlinear circuits.

A comprehensive software system suitable for yield- and cost-driven design of microwave circuits in terms of layout/geometrical and process/technological parameters is planned. The system will be capable of handling microwave hybrid integrated and MMIC circuits, including design of GaAs MESFET mixers, amplifiers, power amplifiers, phase shifters, filters, oscillators, etc. It will be layout-oriented, process independent, and based on combined field/circuit theoretical approach.

Our ambitions go far beyond any contemplated improvements to existing software products that we are aware of. We will remain technically ahead of the capabilities of any existing commercial software. We are directing efforts at dual software systems: (1) specialized modules for device parameter extraction and modeling, including statistics, and (2) a system for general microwave circuit simulation and design including statistics. To this end OSA's plans include:

- new releases of RoMPE™, OSA's FET parameter extractor
- nonlinear parameter extraction within a harmonic balance simulation environment,
- statistical modeling of linear devices for small-signal applications,
- statistical modeling of nonlinear devices for large-signal applications within a harmonic balance environment,
- high performance software engine for the next generation microwave CAE systems.

Our demonstrated expertise in CAE of microwave circuits, and deep understanding of the existing software tools and their limitations support our expectations of success.

Cooperation with Canadian Industry

There is a significant Canadian thrust at this time in the design and manufacture of microwave integrated circuits. Organizations taking initiatives in this area include ComDev Ltd. of Cambridge, Ontario, MA Electronics Canada Ltd. of Mississauga, Ontario, Spar Aerospace Ltd. of Montreal, Bell-Northern Research of Ottawa, Gennum Corporation of Burlington, Ontario, the Communications Research Centre (Ottawa), and Microtel Pacific Research Ltd. of Burnaby, BC.

It is our plan to cooperate as fully as feasible with such Canadian industrial and government laboratories, to explore ways of including their device models and fabrication statistics into our software and to ensure compatibility with their own hardware/software.

RECENT PUBLICATIONS BY OSA

[1] J.W. Bandler, S. Daijavad and Q.J. Zhang, "Exact simulation and sensitivity analysis of multiplexing networks," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, 1986, pp. 93-102.

[2] J.W. Bandler, S.H. Chen and S. Daijavad, "Microwave device modeling using efficient ℓ_1 optimization: a novel approach", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, 1986, pp. 1282-1293.

[3] J.W. Bandler, S.H. Chen, S. Daijavad, W. Kellermann, M. Renault and Q.J. Zhang, "Large scale minimax optimization of microwave multiplexers", *Proc. European Microwave Conf.* (Dublin, Ireland), 1986, pp. 435-440.

[4] J.W. Bandler and Q.J. Zhang, "An automatic decomposition approach to optimization of large microwave systems", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, 1987, pp. 1231-1239.

[5] J.W. Bandler, W. Kellermann and K. Madsen, "A nonlinear ℓ_1 optimization algorithm for design, modeling and diagnosis of networks", *IEEE Trans. Circuits and Systems*, vol. CAS-34, 1987, pp. 174-181.

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

[7] J.W. Bandler, S.H. Chen and K. Madsen, "An algorithm for one-sided ℓ_1 optimization with application to circuit design centering", *Proc. IEEE Int. Symp. Circuits and Systems* (Espoo, Finland), 1988, pp. 1795-1798.

[8] J.W. Bandler, R.M. Biernacki, S.H. Chen, M.L. Renault, J. Song and Q.J. Zhang, "Yield optimization of large scale microwave circuits" *Proc. 18th European Microwave Conference* (Stockholm, Sweden), 1988, pp. 255-260.

[9] J.W. Bandler, S.H. Chen, S. Ye and Q.J. Zhang, "Integrated model parameter extraction using large-scale optimization concepts", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-36, 1988, pp. 1629-1638.

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

[11] J.W. Bandler, S.H. Chen, S. Daijavad and K. Madsen, "Efficient optimization with integrated gradient approximations", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-36, 1988, pp. 444-454.

[12] R.M. Biernacki, J.W. Bandler, J. Song and Q.J. Zhang, "Efficient quadratic approximation for statistical design", Optimization Systems Associates Inc., Dundas, Ontario, Canada, Report OSA-88-IS-7-R, 1988.

[13] J.W. Bandler, Q.J. Zhang, S. Ye and S.H. Chen, "Efficient large-signal FET parameter extraction using harmonics", Optimization Systems Associates Inc., Dundas, Ontario, Canada, Report OSA-88-MT-28-R, December 1988.

[14] J.W. Bandler, Q.J. Zhang, J. Song and R.M. Biernacki, "Yield optimization of nonlinear circuits with statistically characterized devices", Optimization Systems Associates Inc., Dundas, Ontario, Canada, Report OSA-88-MT-29-R, December 1988.

[15] J.W. Bandler, Q.J. Zhang and R.M. Biernacki, "Practical, high speed gradient computation for harmonic balance simulators", Optimization Systems Associates Inc., Dundas, Ontario, Canada, Report OSA-88-MT-30-R, December 1988.

OSA's TECHNICAL PERSONNEL

John W. Bandler, Ph.D., D.Sc.(Eng.), P.Eng., C.Eng., FIEEE, FIEE, Fellow of the Royal Society of Canada

OSA Founder, President and Research Director; Professor of Electrical and Computer Engineering and Director of the Simulation Optimization Systems Research Laboratory, McMaster University, Hamilton, Ontario; 25 years of professional experience; expert in optimization methods and their applications to computer-aided network design, sensitivity analysis of electrical circuits, least pth and minimax optimization, fault location of analog circuits, optimal load flow in power systems, microwave filter and multiplexer design; recognized for his pioneering work in optimal design centering, tolerancing, tuning and yield optimization; author of more than 220 publications, listed in Who's Who in Engineering, American Men and Women of Science, Who's Who in America and in Canadian Who's Who; consultant to several major companies.

Radek M. Biernacki, Ph.D., SMIEEE

Senior Research Engineer; Part-time Professor in the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario; 20 years of professional experience; expert in electronic circuits, computer-aided design, circuit theory, fault diagnosis of analog circuits, statistical analysis and in robust control; author of more than 50 publications.

Shaohua Chen, Ph.D., MIEEE

Research Engineer; 5 years of professional experience in optimization theory and algorithms, computer-aided circuit design, device modeling, statistical analysis and optimization, computer graphics, and control systems; expert in programming languages; author of 16 publications.

John Loman, B.Sc.

Software Engineer; 1.5 years of professional experience in computer-aided design of digital circuits, microwave device modeling, small-signal parameter extraction techniques.

Monique Renault, M.Eng., MIEEE

Research Engineer; 6 years of professional experience in optimization theory and algorithms, computer-aided circuit design, device modeling, statistical analysis and optimization, software quality control, and documentation; author of 3 publications.

Qi-Jun Zhang, Ph.D., MIEEE

Research Engineer; 5 years of professional experience in analysis and optimal design of linear/nonlinear microwave circuits, large-scale simulation and optimization, small- and large-signal parameter extraction of FET devices, sensitivity analysis, statistical modeling, diagnosis and tuning of analog circuits; author of 13 publications.