NEXT GENERATION NONLINEAR/LINEAR MICROWAVE CIRCUIT SIMULATOR

NSERC Strategic Grant No. STR0040923 FINAL REPORT

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Fiscal Year	1988/89	1989/90	1990/91
Requested in 1988	$89,680	$89,580	$90,080
Amounts Awarded	$89,680	$89,580	$90,080
Amount Spent			$269,340

OBJECTIVES

The research was to contribute to the next generation of CAD software for microwave integrated circuit design. It was to address simulation and optimization of large linear and nonlinear (monolithic) microwave integrated circuits: (M)MICs. We were to incorporate and expand the unified, syntax-oriented hierarchical circuit decomposition methodology. We were to take advantage of state-of-the-art sparse matrix solvers, the most advanced optimization techniques as well as to experiment with supercomputers. We were to conduct frontier level research on the harmonic balance simulation technique and sensitivity analysis of nonlinear circuits. We were to work on efficient modeling of circuit responses at various levels of computational hierarchy. This was to facilitate construction of implementable, accurate and robust algorithms for yield-driven optimization of (M)MICs. We were to include important nonlinear device models for GaAs MESFETs.

Long term goals were to contribute to Canadian competitiveness in high technology, advancement of knowledge and national expertise in simulation, design and testing of microwave devices and circuits.

ACHIEVEMENTS OF THE OBJECTIVES

All the objectives of the research under this grant have been achieved. We have developed a software framework for the next generation of nonlinear/linear microwave circuit simulators. We have significantly contributed to the advancement of knowledge in and creation of efficient algorithms for design optimization and yield-driven design of nonlinear circuits based on the harmonic balance simulation and sensitivity analysis techniques. Some of our achievements are, in fact, extensions to the original objectives, and have laid foundation for future research.

<u>Software Integration</u> New research results and most of the software modules developed under this grant have been integrated into a research system called McCAE [33,34,35,38]. The system also utilizes some public domain and proprietary modules.

General Harmonic Balance Simulation We have vigorously researched simulation methodologies for nonlinear circuits with a general topology and multiple devices [2-5,9,11-15,20,21,23,24, 26-37,47-49]. We have unified DC, small-signal and large-signal circuit simulations within the harmonic balance environment and evolved a new avenue in circuit design methodology [13,15, 26,30]. It extends the traditional frequency domain design concept into a multidimensional space. For example, small-signal amplifiers can be optimized over different biasing conditions while accommodating undesirable nonlinear effects. We have devised an efficient linear multiport subcircuit analysis for harmonic balance simulations [29]. We developed an optimization based method for generating optimal time domain samples for multitone harmonic balance simulations [37]. It was combined with a new algorithm by Ngoya *et al.* (*IEEE Trans. Circuits and Systems*, 1990) to provide for effective and robust multi-excitation, multitone harmonic balance simulations.

Sensitivity Analysis of Nonlinear Circuits Significant theoretical results have been obtained. A breakthrough (Bandler, Zhang and Biernacki), applicable to both linear and nonlinear circuits, is the feasible adjoint sensitivity technique called FAST [4,12,36] which combines the power of the exact adjoint approach [2] with the simplicity of perturbation. It can speed up gradient calculations by more than 20 times compared with traditional perturbation.

Sparse Matrix Technique and Hierarchical Circuit Description We have experimented with different sparse solvers (SPARSE 1.2 of UC Berkeley, MA28A(D)/ME28A(D) of the Harwell Library, SPICE) and investigated their features and efficiency, in particular in solving modified nodal equations. We have found SPARSE 1.2 to be the most suitable one. We have improved its reliability and expanded its capabilities by incorporating the partial elimination technique. We have developed the syntax-oriented hierarchical circuit description in which both linear and nonlinear subcircuit can be defined. The subcircuits can accommodate individualized or common parameter values while placed at a higher level of hierarchy. This multi-level circuit description is internally expanded to a single-level representation needed for harmonic balance equation formulation and for full utilization of the advantages of sparse calculations.

Device Models Our intensive investigations into large-signal MESFET models [1,3,9,11,16,20, 23,27,28,31,32,34,44,46] culminated in our preference for and enhancements of: the Materka and Kacprzak model, the Curtice and Ettenberg model, the Statz model, the Ladbrooke model. To keep pace with to-day's challenges in (M)MIC design we have expanded our work to handle physics based models. We have investigated the large-signal analytical physics based Trew and Khatibzadeh model (developed from the Madjar and Rosenbaum model and published after the submission of our proposal for this grant) and enhanced it by dynamically integrating it into the harmonic balance equations. Additional improvements include making the velocity-electric field curve optimizable [11,27,31,32] and development of a new transition function for the doping profile [20,46] making certain intermediate integrations greatly simplified. We have implemented and tested a recent research model by Plessey with improved DC characteristics [20,46]. We have also initiated work on a full 2D field theory based model [20,40,46], primarily as a reference for more efficient analytical models.

Linear Component Library We have developed modules to handle commonly used components including RLC elements, all types of controlled sources both ideal and non-ideal, transmission lines both ideal and lossy and dispersive, microstrip lines, junctions, bends, stubs, and some microstrip discontinuities. Extremely efficient modules for handling complex parasitic subcircuits for active devices have also been developed as "supercomponents".

Yield Optimization of Nonlinear Circuits We have pioneered yield optimization of nonlinear microwave circuits operating in the steady-state under large-signal operating conditions [5,8,10, 12,14,19,20,24,36,42,46]. Formulated as a one-sided ℓ_1 optimization problem, high-speed gradient calculation links state-of-the-art optimizers with harmonic balance simulation making yield optimization of nonlinear circuits feasible. Our approach [12] was applied to a frequency doubler with 6 design/toleranced variables, 6 toleranced linear parameters and a large-signal FET model with 22 toleranced and correlated parameters. Full design involves 100 error functions and takes approximately 8 minutes on the Multiflow Trace 14/300. To achieve maximum efficiency we have developed suitable built-in mechanisms for skipping unnecessary calculations during repeated analyses in optimization and statistical analysis. We have initiated [11,19,20,27, 42,46] and are advocating both performance driven design and yield optimization with physical and geometrical FET parameters as design variables. The objective is to create a methodology for prefabrication design of microwave circuits including active devices. Our approach [20] was applied to a three stage X-band MMIC amplifier where the FETs as well as spiral inductors and MIM capacitors are described by physics-based models. The number of turns of 10 spiral inductors, the metal plate area of 4 MIM capacitors and channel thickness and doping density of the MESFETs were optimized. There were 37 statistical (correlated) variables.

<u>Modeling of Circuit Responses</u> We worked on efficient approximation and numerical techniques to make yield optimization with physics based models tractable. Our previous work [7,22] has been implemented into McCAE and tested on linear circuits. We have extended this approach [17,20,43,46] to handle not only the circuit responses but also their gradients w.r.t. optimizable parameters. To this end we have exploited the FAST sensitivities. Quadratic models are built for the statistical variables only, so the dimensionality of the model becomes conveniently reduced. A predefined pattern of the base points used for model building leads to an extremely efficient algorithm. Once the model is built, a great number of statistical outcomes can be approximately analyzed using the model, and cost of such analyses becomes marginal.

<u>Vector Processing and Hardware</u> Although most of the new code is structured to exploit the existing potential for vector processing we have abandoned our original objective of developing the simulator on the Cray X-MP. Recent advances re-directed our attention to UNIX-based workstations in preference to the originally planned "micro-computer - super-computer" interaction. We shifted from super-computing to the workstation environment as it became more cost effective. Nevertheless, we have continued experimenting with supercomputing on the Cray X-MP for remote number crunching, with vectorized codes, for time consuming 2D field theory based device simulations. We have also used McMaster's FPS-264 and the Multiflow Trace 14/300 (BUB - "Big Unix Box") for remote number crunching.

<u>Software Utilities</u> We have developed a measurement data file transfer system from HP BASIC machines to UNIX workstations, an inexpensive solution to importing such data into CAD systems. HP BASIC workstations are widely used to control measurement equipment. We have also developed graphics screen printing ("screen dump") utility modules, a desirable CAD feature, for Hewlett-Packard 9000/300 series workstations, Sun workstations, and for Apollo workstations. The HP Starbase (HP), Pixrect (Sun) and Graphics Primitive Resource (Apollo) graphics libraries are used to capture the screen. Two main lines of printers are supported, namely HP PCL (such as the HP LaserJet) and Postscript printers.

<u>Software Development Milestones</u> C has been selected for new developments, both mathematical modules and user-interface, graphics, etc. Existing time-tested and proven Fortran routines were utilized to the maximum possible extent. ANSI standard was conformed to for portability. We have acquired a proprietary software architecture from Optimization Systems Associates Inc. (OSA). This has provided us with a user-friendly software development environment. As proposed, we have acquired public domain software from UCB, Harwell and Argonne National Laboratory. Many new C modules have been written implementing mathematical and circuit-theory techniques, taking advantage of specific C language capabilities, our own experience and new developments. Personal contacts with key industrial and government individuals has instilled us with leading-edge knowledge of user-oriented features and expectations for (M)MIC/CAD software.

Spinoff Research Several new research topics have emerged from our work on this projects. Although they were not included in our original application for this grant we have initiated relevant research, as we feel that the importance of those subjects is pressing. The most important area is physically unified statistical modeling/yield optimization of microwave circuits. Our initial research into statistical modeling is covered by [6,16,25,44] and yield optimization in terms of physical parameters by [19,42]. Our new software architecture solutions are proposed in [18, 39,41] and research on multiconductor coupled transmission lines reported in [45].

ACCESSIBILITY OF RESULTS TO THE INTENDED USER COMMUNITY

Dissemination of Results Our group has a well-established system of dissemination of results through publication, consulting, education and software demonstration. Through personal discussion, seminars, consulting and contracts, we transfer our knowledge and expertise to industry. Modules developed under this grant are available to supporting Canadian organizations. Further promotion of our results will be through direct interaction with potential Canadian industrial users.

In addition to SOS reports [22-46], published journal papers, conference and workshop presentations [1-21] and three Ph.D. theses [47-49] we have delivered talks at: Department of Regional Industrial Expansion, Ottawa (January 1989); AT&T Laboratories, Allentown, PA (February 1989); TRW Electronic Systems Group, Space Park, Redondo Beach, CA, (March 1990); Carleton University, Ottawa (April 1990); Texas A&M University, College Station, Texas (May 1990); TRIO Meeting, Ottawa (October 1990); Bell-Northern Research, Ottawa (October 1990), IBM Watson Research Center, Yorktown Heights, NY (April 1991); Canadian Microelectronics Corporation, Queen's University, Kingston, Ontario (May 1991); Siemens, Munich, Germany (June 1991); University of Bologna, Alenia, Elettronica and University of Rome, Italy (July 1991); Lucas Aerospace, Mississauga, Ontario (July 1991); ComDev, Cambridge, Ontario (October 1991), George Washington University, Washington DC (November 1991).

A Special Issue of the *IEEE Transactions on Microwave Theory and Techniques* on Process-Oriented Microwave CAD and Modeling, July 1992 [50], is currently jointly edited by Bandler and Jansen. This confirms international recognition of our research contributions and gives us additional opportunity to expose and disseminate our results.

Live demonstrations of our software have been made in Europe, Canada and in the US, both at international microwave symposia and in industry.

Industrial Interactions Close interaction with Optimization Systems Associates Inc. (OSA) was particularly beneficial. First, a number of OSA's proprietary software modules were made available to our group and let us more quickly develop and test new ideas. In return, it has served as a vehicle for transfer of technology from university to industry.

The grantee and co-investigator have been involved in related R&D sponsored by OSA and IRAP. Through this and the NSERC Strategic Grant we have gained significant input in know-how, state-of-the-art technology, device models, measurement considerations, etc. Canadian interactions include Bell-Northern Research, BEL-Tronics, ComDev, the Communications Research Centre, Lucas Aerospace, Optotek, Quantic Laboratories and Spar Aerospace. International interactions have included Argumens, AT&T, Avantek, British Telecom, Cascade Microtech, Compact Software, EEsof, General Electric, Hughes, IBM, Jansen Microwave, JPL, Martin Marietta, Plessey Research Caswell, Raytheon, Sandia Laboratories, Siemens, Tektronix, Texas Instruments, Thorn-EMI, TriQuint and TRW. Close association with OSA permitted significant national and international industrial interaction regarding software needs, requirements and user-oriented features.

Scientific Interactions Our research achievements and funding provided by this grant have enabled us to attract some of the finest researchers in the CAD field to McMaster University. We arranged seminars of Drs. R. Jansen (Germany), A. Konczykowska (CNET, France), R. Trew (North Carolina State University), W. Curtice (W.R. Curtice Consulting), W. Zuberek (Memorial University) and M. Styblinski (Texas A&M University).

We co-chaired a session on Microwave Measurement for Gigabit Devices at the 1990 Asia-Pacific Microwave Conference in Tokyo, Japan, 1990 [51], and participated in panel discussions at the workshop of the West German IEEE MTT/AP Joint Chapter on Integrated Nonlinear Microwave and Millimeterwave Circuits, Duisburg, Germany, October 1990 [52], at the Productivity Improvement Seminar on CAE Applications for High-Yield Microwave Circuit Design, RF Technology Expo, Anaheim, CA, March, 1990 [53], and at the 1991 Canadian Microelectronics Corporation Workshop, "Mixed Signal ASIC Testing", Kingston, Ontario, May 1991 [54].

TRAINING OF RESEARCH PERSONNEL

Doctoral students, all of whom have been awarded the Provincial Differential Fee Waiver Award and some of whom have held the Ontario Graduate or McMaster University Scholarship (S. Ye, J. Song and Q. Cai) and three engineering professionals (Dr. S.H. Chen, Dr. Q.J. Zhang and Mr. G. Simpson) have contributed. One of our outstanding contributors, Dr. Q.J. Zhang has accepted an offer of a faculty position at Carleton University (BNR/NSERC Junior Chair in CAD). Another contributor, Dr. Ye, has been awarded a two year Industrial Research Fellowship by NSERC.

We take advantage of software resulting from this work (graphics, user-friendly features) to attract new undergraduate and graduate students during events such as university open houses or meetings on graduate studies for undergraduate students, etc. Many graduate students have used our software for their courses and as vehicle to advance their research.

Development of a new graduate course is under way, and a number of topics resulting from this research has already been incorporated into the existing graduate courses. One undergraduate course is currently being reshaped with the aid of our software.

POTENTIAL SOCIO-ECONOMIC BENEFITS

Our work has contributed to Canadian competitiveness in high technology through advancement of knowledge and national expertise in simulation, design and testing of microwave devices and circuits.

The field of CAE software is still dominated by the US companies. The commercial software market related to this research is covered by TOUCHSTONE, LIBRA, Microwave SPICE, SUPER-COMPACT, MICROWAVE HARMONICA and MDS. All these products have to be purchased from the United States.

With this project, we have made a significant contribution to improving Canadian presence and competitiveness in CAE. Our work has led to the development of new capabilities that go far beyond the features of those commercial products. In our research we remain technically ahead of the capabilities of commercial software.

The techniques and software will have an impact on increased automation in the electrical manufacturing industries. The work will help Canada maintain its position in relevant areas, such as in the aerospace and related electronics and communications industries. Availability of enhancing production yield will make a substantial contribution to the viability of Canadian high-technology products. It will also have an immeasurable impact on the development of export-oriented high technology products, including software.

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