RESEARCH PROJECTS
NOVEMBER 2001 - OCTOBER 2002

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INTRODUCTION

Commercial CAE systems for high-speed, wireless and microwave circuits and systems are no longer regarded as complete without a variety of design automation capabilities. Computer-integrated manufacturing, including CAD, CAM, information management and decision support systems will be a reality facing the design engineer in the next century.

Developments in wireless telecommunications push frequencies to higher and higher bands. Advanced research is already under way for developing hardware for wireless telecommunication services at frequencies as high as 20-30 GHz. Here, novel types of transmission lines are used, such as multilayer printed coplanar and slot lines. These require the development of a whole new generation of passive and active devices, such as coplanar/slot junctions, bends, power dividers, couplers, radiating elements, etc. The development of sufficiently accurate models for reliable analysis and design is of great importance to the telecommunications industry in the years ahead.

CAE practices such as active and passive device, circuit and system design are expected to be physically and electromagnetically based, to include electrical, mechanical and thermal effects. Future developments in integrated CAE tools will concurrently link geometry, layout, physical, electromagnetic and process simulations, with performance, yield, cost, system specifications, manufacturability and testability in a manner transparent to the designer.

In our research we focus upon exciting concepts, which we believe will play important roles in future optimization methodologies including device modeling through artificial neural network technology and Space Mapping optimization and modeling technologies. These technologies are targeted at the design of high-speed VLSI interconnects, large-scale mixed frequency/time domain simulation, chip design, package design, design of multichip modules, printed circuit boards and backplanes, as well as low cost, high-performance RF, microwave and millimeter wave components for system applications.

During the fiscal year 2001/2002 we conducted scientific research work on the research project "Next Generation Methodologies for RF, Wireless and Microwave Computer-aided Engineering (CAE)".

Our overall research effort and cost of specified employees are as follows:

Project No. 1	100%	$30,000
Total allowable expenditures claimed for Scientific Research and Experimental Development (SR & ED)		$30,000

RESEARCH PROJECT:

NEXT GENERATION METHODOLOGIES FOR RF, WIRELESS AND MICROWAVE COMPUTER-AIDED ENGINEERING (CAE)

Starting Date

The starting date for this project was November 20, 1997.

Objective of the Research

The main objective of the project is to conduct research in the field of microwave CAE 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 such new features and techniques will be able to meet a continually strong industrial demand for efficient and reliable tools for nonlinear device modeling, device parameter extraction, and automated design optimization coupled to sufficiently fast linear/nonlinear, accurate physical and electromagnetic circuit simulation. Such products should then be more competitive.

Our work opens up new opportunities for significant advances. It addresses the long-term goal of a fully integrated CAD system, enabling virtual prototyping and concurrent design. Advances in wireless technologies are placing demands on the CAD environment and simulation tools to handle increased circuit miniaturization and complexity. Further innovative designs may be achieved using powerful 3D full-wave electromagnetic simulators in conjunction with sophisticated optimizers. This requires robustizing and expanding our novel Space Mapping technology and seamless integration of a variety of simulators with optimization software.

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, microwave theory, antenna theory, electromagnetic field theory; and computer science: software architecture, parsers, data structures, graphics. Applications are in all aspects of linear and nonlinear analog electrical circuit design. Many concepts are strongly rooted in engineering practice and find application in other branches of engineering.

Reference Material

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

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Uncertainty of the Research

The main uncertainty of the project lies in the feasibility of implementation, mathematical robustness and reliability of the methods being developed. 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 PCs and workstations, large-scale optimization techniques and parallel computation may be required, which introduces further risk and uncertainty.

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. Uncertain future developments in statistical design of microwave integrated circuits, and acceptance of the necessary software tools by wireless, RF and microwave engineers also makes this a high-risk project.

Novelty of the Research

Our work is highly regarded by other engineering researchers, in areas of engineering as diverse as civil and automotive, and promises a significant impact on the state of the art in automated CAE of RF, wireless and microwave circuits and systems. Workshop contributions [33-41] include: J.W. Bandler, Organizer and Chairman, Full-Day Workshop on Workshop on Microwave Component Design Using Space Mapping Methodologies, *IEEE MTT-S Int. Microwave Symp.*, Seattle, WA, June 3, 2002, which featured Bandler as lecturer [34], the Micronet Annual Workshop 2002 [15], and the international workshop contribution "Space Mapping: A Sensible Concept for Engineering Optimization Exploring Surrogates," an invited presentation at the Second International Workshop on Nonlinear Optimization: Theoretical Aspects of Surrogate Optimization, Coimbra, Portugal, May 17, 2003 [33]. Several international workshops are already planned for 2003 [26, 39-40].

This research represents new work directed at state-of-the-art software systems. Our group has achieved world recognition and has an excellent track record in this area. J.W. Bandler was inducted into the Canadian Academy of Engineering in 2003 (an elite group of some 300 engineers in all disciplines, Canada wide). He continues to serve on Canadian research initiatives, for example, he is Thrust Leader for "Optimization and Computer-aided Design" on McMaster University's successful multimillion dollar Canada Foundation for Innovation Infrastructure Project "Communication Technology Research Centre." Most of our publications are peer-reviewed: as such our contributions are novel.

Advance in Scientific Knowledge

After the research on Space Mapping is successfully completed, the advanced features and techniques developed will constitute a true breakthrough in CAE tools available to wireless, RF and microwave circuit and system design engineers. In particular, design optimization employing electromagnetic simulations of passive structures, as well as physical simulations of high speed/high frequency active devices, all in a user-friendly CAE environment, are of utmost importance.

Method of Research

Accepted scientific methods are employed. Since the team members and their collaborators in academic and industrial institutions have been actively working in relevant research areas for a number of years no additional literature search was necessary except for recent periodicals. Existing state-of-the art CAE 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. The project particularly requires interaction with integrated circuit process and fabrication engineers to determine and obtain relevant measured data. Interaction with industry and sharing of results, both in Canada, the US and in Europe, also provides important feedback.

We visited and made presentations at ComDev, Nortel, CRC and Carleton University. We held a one-day workshop on June 20, 2002 at Carleton University, Ottawa, ON, on "Optimization Engines for Wireless and Microwave Computer-Aided Engineering, organized by J.W. Bandler, N.K. Georgieva and Q.J. Zhang. Dr. Kaj Madsen and his group (Technical University, Lyngby, Denmark) continue to actively collaborate on Space Mapping optimization and we visit and collaborate with his graduate students.

Software, Hardware and Documentation Facilities

Our research has led us to the conclusion that a dedicated "Space Mapping optimization software engine" needs to be developed in its own right. Our work in the fiscal year has strongly focused on the development of prototype software written in C++ and Java which implement our latest theoretical contributions. We expect Bandler Corporation to be a key niche player in this unique field.

There continues to be reorganization and regular maintenance and upgrading of the computing and software facilities at Bandler Corporation in order to facilitate continued work in the chosen area of research. There also continue to be changes in the primary documentation preparation software, requiring the re-working of many existing documents. Such change is necessary to ensure a smooth progression to the future, as old software fails to meet expectations.

Reports

Published papers [1-32], as well as many seminars, workshops and panels [33-] contain results of our work within the framework of this project. Much of our work is published in the *IEEE Transactions on Microwave Theory and Techniques*, which is the most reputable journal in the field, and the *IEEE MTT-S International Microwave Symposium*, which is the most reputable conference in the field.

Selected Highlights of Progress to Date

We worked on ways of incorporating accurate electromagnetic simulations into the yield-driven circuit design process, and on techniques for exploiting our Space Mapping technology for statistical circuit design (design centering). The results appeared in publications listed in the previous section ("Reports").

Our work involves developing theoretically justifiable methods and algorithms, as well as enhancing existing techniques. To this end, our research efforts have been concentrated on efficiency and robustness of mathematical algorithms, as well as direct electromagnetic field simulation and optimization for accurate circuit design taking into account electromagnetic effects such as radiation and parasitic coupling between components.

We continued our unique work on the novel Space Mapping optimization technology, which we have pioneered. This technology addresses an efficient way for engineers to solve design optimization problems when the simulation time of the underlining simulator (such as an electromagnetic field solver) may be prohibitively long. Using Space Mapping methodologies, device modeling and circuit design can be carried out at the speed of circuit-level optimization while retaining the accuracy of CPU intensive electromagnetic simulations. New developments in the aggressive strategy for Space Mapping were applied to novel electromagnetic design problems, results of which have been published.

Important collaborators in this work are Dr. N. Nikolova (Georgieva) of McMaster University, Dr. M.H. Bakr, A.S. Mohamed and Q. Cheng of McMaster University, Dr. Q.J. Zhang of Carleton University, Dr. M.A. Ismail of ComDev in Cambridge, ON, Dr. J.E. Rayas-Sánchez of ITESO in Mexico and Dr. K. Madsen, Dr. J. Søndergaard and F. Pedersen of the Technical University of Denmark in Lyngby, Denmark.

The concept and theory of Space Mapping continue to be presented on many occasions, including invited review papers, workshops and numerous seminars. The significance of the area and our contribution to it is also evidenced by our organization and contributions to various special issues of prestigious technical journals. The first is *Optimization and Engineering* [10, 11], edited by J.W. Bandler and K. Madsen, published in 2001. A new special issue of the *IEEE Transactions on Microwave Theory and Techniques* on "Electromagnetics-Based Optimization of Microwave Components and Circuits," edited by J.W. Bandler and M. Mongiardo will be published in 2004.

At the time of writing researchers in the following countries have reported studying or implementing our research in Space Mapping: Turkey, Korea, Cyprus, Australia, France, UK, Denmark, Sweden, Netherlands, Canada, USA, Mexico, Spain, South Africa, Switzerland, Portugal, France and Italy, covering many disciplines, including mathematical optimization and several branches of engineering. Philips Semiconductors of the Netherlands has adopted Space Mapping as a key methodology for design of RF components used in hand held mobile telephones. Several corporations in the US, including Motorola, have similarly adopted Space Mapping for RF component design.

Space Mapping has been adopted by ComDev, Cambridge, ON, for design and tuning of microwave filters and multiplexers. Other Canadian groups which have adopted Space Mapping for CAD include the University of Waterloo (the research groups of Dr. R. Mansour and Dr. S. Safavi-Naeini).

Highlights of Space Mapping Technology for Engineering Design Optimization

Space Mapping involves the interplay between two representations of a circuit or device. The aim is to align two different simulation models: the so-called "coarse" model or surrogate, typically an empirical circuit simulation and a "fine" model, typically a full-wave electromagnetic simulation. The coarse model is also called the "optimization" model and the fine model is identified as the "validation" model.

The technique combines the accuracy of the fine (validation) model with the speed of the coarse (optimization) model during the circuit optimization process. Parameter extraction is a crucial part of the technique. During this step the parameters of the coarse model whose response matches the fine model response are obtained through an optimization process. The extracted parameters may not be unique, causing the technique to fail to converge to the optimal design.

New, more robust algorithms for Aggressive Space Mapping electromagnetic optimization have been introduced. They have been applied to a number of design examples exploiting full-wave electromagnetic simulators. The Sonnet method-of-moments electromagnetic solver ***em*** as well as Agilent Technologies' ADS and method-of-moments solver Momentum have been used to optimize various filters, including the design of a high temperature superconducting filter. The finite element solver Agilent HFSS (from Agilent Technologies, formerly Hewlett-Packard) has been used to design various 3D structures such as waveguide transformers and filters. Coarse models for these examples exploited coarse grid electromagnetic models or circuit-theoretic/analytical models. Coarse models, decomposed into subnetworks, have even consisted of a mixture of electromagnetics based subnetworks and empirical elements connected through circuit theory (co-simulation and co-optimization).

A novel design framework for microwave circuits has been formulated [22]. We expanded the original Space Mapping technique by allowing preassigned parameters (which are not used in optimization) to change in some components of the coarse model (surrogate). The coarse model (surrogtae) is (re)calibrated to align with the fine model. Our algorithm establishes a mapping from some of the optimizable parameters to the preassigned parameters of the relevant components. This mapping is updated iteratively until we reach the optimal solution. This proposed approach has been tested through various microstrip design examples. This work has evolved into exciting new interpretations of Space Mapping in engineering design and consequent simplification of the iterative process. We called the new approach Implicit Space Mapping [18, 20, 26, 28, 30].

A new Neural Inverse Space Mapping (NISM) optimization for EM-based design of microwave structures has been developed [4, 25]. The inverse of the mapping from the fine to the coarse model parameter spaces is exploited for the first time in a Space Mapping algorithm. This NISM optimization is formulated such that it does not require: up-front EM simulations, multipoint parameter extraction or frequency mapping. A neural network whose generalization performance is controlled through a network growing strategy approximates the inverse of the mapping. The new algorithm has been tested and contrasted with Neural Space Mapping (NSM) optimization for circuit design.

A key development in Space Mapping optimization is the Surrogate Model-based Space Mapping algorithm. It formulates the design procedure as a general optimization problem of a surrogate model [10, 28, 33]. The surrogate is a convex combination of a mapped coarse model and a linearized fine model. The step taken in each iteration is confined to a region in which the surrogate model is trusted. We have thus strongly progressed towards the creation of an automated Space Mapping Optimization Engine. Our research version is called SMX. It is an object oriented prototype research system written in C and C++. It can be linked with OSA90 and Agilent Momentum. A user-friendly interface allows the user to set the coarse and fine models, the simulation frequencies, etc. SMX utilizes the multithread capability of Windows operating system. The program interacts with the user during the optimization steps showing the improvement in the objective function. Alternative prototype software for the surrogate approach written both in C++ and Java is being developed in collaboration with Dr. Madsen's group at the Technical University of Denmark.

Research on Artificial Neural Network Technology for Device Modeling

This work is conducted in collaboration with Dr. Q.J. Zhang of Carleton University, Ottawa.

The need for statistical analysis and yield optimization coupled with the desire to use accurate models such as physics-based and electromagnetics-based models leads to tasks that are computationally intensive using conventional approaches. Exploitation of microelectronics CAE models that are both accurate and fast has been a contradictory requirement until neural based models for active and passive elements were introduced (see section on "Reference Material" above).

Neural networks can learn from and generalize patterns in data, and model nonlinear relationships. Neural models can be much faster than the original models, more accurate than polynomial and empirical models, allow more dimensions than table lookup models and are easier to develop for a new device/new technology.

Theoretically, a multilayer perceptron neural network can model any arbitrary nonlinear relationship. At the model development stage training data is generated from electromagnetic simulation or measurement. The neural model is trained to learn relevant mathematical relationships from the data. Specifically, training is to determine neural model parameters, i.e., neural network internal weights, such that the neural model predicted output best matches that of the training data. In the model testing stage, a new set of input-output samples, called the testing data, is used to test the accuracy of the neural model.

A trained and tested neural model can be used online during the design stage, providing fast model evaluation replacing original slow electromagnetic/device simulators. The benefits of the neural model approach are especially significant when the model is repetitively used such as in circuit optimization, statistical analysis and yield maximization.

Neural networks have been used to develop models for passive components, e.g., coupled transmission lines, and active components, e.g., physics-based MESFETs, in high-speed/high-frequency circuits and systems. Electromagnetic simulation of coupled transmission lines is slow especially if carried out repetitively in the analysis of high speed VLSI interconnects. Neural networks can relate physical parameters, such as conductor width, conductor thickness, directly to electrical parameters, such as cross-sectional RLCG parameters. In addition to modeling a component, neural networks can model the entire circuit with the circuit responses as outputs of the models, e.g., a high-speed VLSI interconnect network. A neural model can predict the signal integrity responses such as signal propagation delays at the terminations.

Research into novel neural based modeling techniques for high-speed/high-frequency circuits and systems has been carried out during the fiscal year. We investigated approaches that combine engineering empirical knowledge with the learning power of neural networks. With the ultra fast recalling speed of neural models, this promises to have significant impact on the development of interactive CAE tools. As a result, a new collaborative project (2003) is built on advances in artificial neural network based modeling (Dr. Q.J. Zhang), and Space Mapping for electromagnetic optimization (Dr. J.W. Bandler). The goal is to develop the next generation modeling and optimization engines that will dramatically increase the productivity of high-speed/high-frequency circuit and system design.

Electromagnetic Optimization

This work is conducted in collaboration with Dr. Natalia Nikolova (Georgieva) and Dr. Mohamed Bakr of McMaster University, Hamilton.

Advances in computational electromagnetics and optimization technology allow direct exploitation of electromagnetic simulation techniques in circuit design optimization. We have researched recent advances in electromagnetic optimization of microwave components, circuits and antenna structures. Increasingly, more complex structures need to be accurately simulated in their entirety for design purposes. Decomposition into substructures should be considered only if no significant couplings are neglected.

We solved many industrially relevant examples exploiting Agilent EEsof HFSS, Agilent EEsof ADS (including the field solver Momentum), Sonnet's ***em***, MATLAB, OSA90, NeuroModeler, Datapipe, interpolation and database techniques and Geometry Capture.

In consultation with industry we selected microwave or RF structures, both planar and 3D, to test new theories and algorithms: a six-section H-plane waveguide passband filter, a microstrip double-folded stub (DFS) stopband filter (Sonnet), a microstrip-fed rectangular patch antenna, H-plane waveguide filters (Hughes), a high-temperature superconducting (HTS) four pole quarter-wave parallel coupled-line microstrip filter (Westinghouse), standard waveguide transformers, various microstrip bends and T-junctions, and a library of microstrip and stripline models. We research models (fast empirical or equivalent circuit models) of waveguide filters and impedance transformers, microstrip filters and transformers, T-junctions, bends, and microstrip antennas, etc. We construct coarse models by utilising a full-wave electromagnetic simulation on a coarse space-time discretization grid, or by circuit decomposition.

Adjoint Sensitivity Techniques in Electromagnetics Based Design

This work is conducted in collaboration with Dr. Natalia Nikolova (Georgieva) and Dr. Mohamed Bakr of McMaster University, Hamilton.

The adjoint variable method for design sensitivity analysis of linear systems is investigated for implementation computational methods in electromagnetics which reduce the problem to a system of linear equations. We are currently exploiting the property that the solution to the adjoint problem can be obtained with very little overhead once the original problem is solved. We are deriving general design sensitivity formulas, which produce the gradient of the objective function using the solution of the original system and that of the adjoint system at the current design. From this formula the gradient of the objective function is computed through a single analysis regardless of the number of the design parameters. Certain overhead computations are always necessary; however, they should not significantly exceed the computational requirements of one system analysis. The concept currently focuses on the Method of Moments (MoM) [13, 17, 23, 27, 31]. Important issues related to implementation with numerical algorithms are being resolved. Applications to design of wire and printed circuit antennas are in progress. As a result of our research a major technical paper has been accepted for publication [31]: "Adjoint techniques for sensitivity analysis in high-frequency structure CAD."

TECHNICAL PERSONNEL

Director of Research

Dr. J.W. Bandler is President of Bandler Corporation, established in 1997, 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.

He 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. Dr. Bandler joined McMaster University, Hamilton, Canada, in 1969. He has served as Chairman of the Department of Electrical Engineering and Dean of the Faculty of Engineering. In 2000 he became Professor Emeritus in the Department of Electrical and Computer Engineering, where he directs research in the Simulation Optimization Systems Research Laboratory. He is a member of the Micronet Network of Centres of Excellence.

Dr. Bandler was President of Optimization Systems Associates Inc. (OSA), which he founded in 1983, until November 20, 1997, the date of acquisition of OSA by Hewlett-Packard Company (HP). OSA implemented a first-generation yield-driven microwave CAD capability for Raytheon in 1985, followed by further innovations in linear and nonlinear microwave CAD technology for the Raytheon/Texas Instruments Joint Venture MIMIC Program. OSA introduced the CAE systems RoMPE™ in 1988, HarPE™ in 1989, OSA90™ and OSA90/hope™ in 1991, Empipe™ in 1992, Empipe3D™ and EmpipeExpress™ in 1996. OSA created the product ***empath***™ in 1996 which was marketed by Sonnet Software, Inc., USA. Dr. Bandler is President of Bandler Corporation, which he founded in 1997.

Dr. Bandler was an Associate Editor of the IEEE Transactions on Microwave Theory and Techniques (1969-1974), and has continued serving as a member of the Editorial Board. He was Guest Editor of the Special Issue of the IEEE Transactions on Microwave Theory and Techniques on Computer-Oriented Microwave Practices (1974) and Guest Co-Editor with Rolf H. Jansen of the Special Issue of the IEEE Transactions on Microwave Theory and Techniques on Process-Oriented Microwave CAD and Modeling (1992). He joined the Editorial Boards of the International Journal of Numerical Modelling in 1987, the International Journal of Microwave and Millimeterwave Computer-Aided Engineering in 1989 and Optimization and Engineering in 1998. He was Guest Editor, International Journal of Microwave and Millimeter-Wave Computer-Aided Engineering, Special Issue on Optimization-Oriented Microwave CAD (1997), and Guest Editor, IEEE Transactions on Microwave Theory and Techniques, Special Issue on Automated Circuit Design Using Electromagnetic Simulators (1997). He is Guest Co-Editor, Optimization and Engineering Special Issue on Surrogate Modelling and Space Mapping for Engineering Optimization (2001). He is Guest Co-Editor, IEEE Transactions on Microwave Theory and Techniques, Special Issue on Electromagnetics-Based Optimization of Microwave Components and Circuits (2004). He has served as Chair of the MTT-1 Technical Committee on Computer-Aided Design.

Dr. Bandler has published more than 355 papers. He contributed to Modern Filter Theory and Design, Wiley-Interscience, 1973 and to Analog Methods for Computer-aided Analysis and Diagnosis, Marcel Dekker, Inc., 1988. Four of his papers have been reprinted in Computer-Aided Filter Design, IEEE Press, 1973, one in each of Microwave Integrated Circuits, Artech House, 1975, Low-Noise Microwave Transistors and Amplifiers, IEEE Press, 1981, Microwave Integrated Circuits, 2nd ed., Artech House, 1985, Statistical Design of Integrated Circuits, IEEE Press, 1987 and Analog Fault Diagnosis, IEEE Press, 1987.

Dr. Bandler is a Fellow of the Canadian Academy of Engineering, a Fellow of the Royal Society of Canada, a Fellow of the Institute of Electrical and Electronics Engineers, a Fellow of the Institution of Electrical Engineers (Great Britain), a Fellow of the Engineering Institute of Canada, a Member of the Association of Professional Engineers of the Province of Ontario (Canada) and a Member of the MIT Electromagnetics Academy. He received the Automatic Radio Frequency Techniques Group (ARFTG) Automated Measurements Career Award in 1994.

Senior Research Personnel

Dr. Natalia Nikolova (Georgieva) received the Diploma in Engineering (Electronics) from the Technical University of Varna, Bulgaria, in 1989, and the Doctor of Engineering degree from the University of Electro-Communications, Tokyo, Japan, in 1997.

From 1997 to 1998 she was a postdoctoral fellow with the Department of Electrical and Computer Engineering, DalTech, Dalhousie University, Halifax, Nova Scotia. During this period she was involved in teaching and in research projects concerning time-domain electromagnetic field simulation, modeling and design of RF/microwave multilayer passive structures, printed circuit boards and printed antennas.

In 1998, she was granted a Postdoctoral Fellowship by the Natural Sciences and Engineering Research Council of Canada (NSERC). From 1998 to 1999, she was with the Simulation Optimization Systems Research Laboratory, McMaster University, Canada, where she was involved in projects concerning the implementation and development of novel, highly efficient optimization algorithms for microwave structure design.

In 1999 she became Assistant Professor of Electrical and Computer Engineering at McMaster University, where she teaches and carries out research in electromagnetics, microwaves, antennas and computer-aided design.

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[41...] *Dr. Bandler delivered many additional international R&D seminars and presentations.*

RESEARCH PROJECTS
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