Circuit Optimization Using EM Simulators: A New Era in Microwave/RF CAD

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ABSTRACT

We review OSA's products for microwave circuit optimization. Emphasis is on recent advances in the state of the art in automated electromagnetic (EM) design. The integrated CAD environment facilitates EM optimization of linear and nonlinear microwave circuits. We combine EM analyses of passive structures with circuit models of active devices for large-signal nonlinear harmonic balance optimization, even for yield-driven design. Designs of a class B frequency doubler and a waveguide mitered bend illustrate the approach and its benefits.

BACKGROUND TO OSA

Established in 1983, Optimization Systems Associates Inc. (OSA) has been providing the microwave community with the state-of-the-art CAD technology, particularly for design optimization, including both performance- and yield-driven design.

OSA's DEVICE, CIRCUIT AND EM OPTIMIZATION PRODUCTS

Empipe3D   released in 1996, Empipe3D is a direct electromagnetic optimization software system driving the 3D field solvers Maxwell® Eminence offered by Ansoft Corporation and HFSS offered by Hewlett-Packard.

Empipe   first released in 1992, is a direct electromagnetic optimization software system driving the field solver *em*™ of Sonnet Software, Inc.; in 1996, a concise version with a fresh and intuitive user interface, named **EmpipeExpress**, was crafted to respond to the optimization needs of the majority of *em* users.

OSA90/hope   first released in 1991, is a general CAD software system offering simulation, modeling, statistical analysis, nominal and yield optimization, and data visualization for linear and nonlinear analog circuits; in addition to linear simulations it features a built-in nonlinear harmonic balance simulator with a comprehensive library of both linear and nonlinear component models.

HarPE first released in 1989, is a well-established powerful CAD software system dedicated to complete nonlinear device characterization including advanced statistical modeling and parameter extraction; HarPE provides users with simulation and design optimization capabilities for single nonlinear device circuits.

OSA's products are powered by the **OSA90** optimization engine. Its open architecture allows the users to create fully optimizable interconnections of components, subcircuits, simulators and mathematical functions, supported by fully integrated expression processing capabilities. OSA90 features powerful and robust gradient-based optimizers: ℓ_1, ℓ_2, Huber, minimax, quasi-Newton, conjugate gradient, as well as non-gradient simplex, random and simulated annealing optimizers.

This presentation is focused on the Empipe family of products and its role in microwave/RF CAD, particularly in the emerging new era of circuit optimization with EM simulators.

INTERFACES TO POPULAR EM SIMULATORS

The products within the Empipe family interact with a few well-established commercial EM simulators which need to be acquired from the respective vendors.

em is an efficient full-wave EM field solver for predominantly planar circuits. With full accuracy up to millimeter-wave frequencies, *em* simulates arbitrary geometries accounting for dispersion, coupling, surface waves, radiation, metallization and dielectric losses, etc. It is recommended whenever high simulation accuracy is needed in the design process.

Maxwell Eminence and HFSS are finite element based solvers for full-wave EM field analysis of three-dimensional passive structures. They are capable of computing S-parameter responses, electromagnetic field distributions and radiative effects at microwave frequencies.

Fast EM simulations of waveguide discontinuities based on the mode-matching technique are possible with the use of Fritz Arndt library of fast and accurate waveguide building blocks. This library is directly interfaced to OSA90/hope.

DATAPIPE TECHNOLOGY

OSA90 is equipped with several Datapipe protocols for connecting external programs through UNIX interprocess pipes. This facilitates high-speed data connections to external *executable* programs, even across networks. Datapipes are flexibly defined in the input file. The user specifies a set of inputs from OSA90 to the external program and defines outputs to be returned. The external programs are run in separate processes and communicate with OSA90 in a manner similar to subroutine calls. Specialized Datapipe-based interfaces exist for a number of applications, including the popular analog circuit simulator SPICE and several electromagnetic simulators (including *em*, HFSS and Maxwell Eminence).

The Datapipe technology allows the users to enhance their own software with OSA90's friendly user interface, graphics, expression parser, optimization and statistical features. By linking several separate programs through OSA90 the users can form their own functionally integrated CAE systems.

EXPRESSION COMPOSITION

OSA90 supports expression composition featuring constants, variables, vectors, matrices, typical algebraic operations, and a rich set of built-in mathematical functions. The user can create user-defined functions and postprocess responses. The built-in functions include operations such as solving linear equations, finding eigenvalues, the Discrete Fourier Transform, cubic spline interpolation, piecewise linear interpolation and estimating data statistics. Conditional expressions are also supported. All user-defined variables and functions can be used for optimization.

POWERFUL OPTIMIZERS

OSA90's optimizers offer unrivalled accuracy and efficiency. Optimization variables can include circuit parameters, bias voltages, input power levels, Datapipe inputs and abstract variables. You can optimize built-in and user-defined circuit responses, Datapipe outputs and abstract error functions. You can invoke OSA90 itself through Datapipe to create a simulation/optimization hierarchy of virtually unlimited depth.

GEOMETRY CAPTURE

The Empipe family of products offers OSA's exclusive Geometry Capture technology for parametric design encapsulation of arbitrary structures. Geometry Capture is a user-friendly tool for defining EM-optimizable, user-parameterized structures.

User parameterization is facilitated by processing the native files of the respective EM simulators. In Empipe, designable parameters and optimization variables are automatically captured from a set of "geo" files created using *xgeom*. In Empipe3D the optimization variables are captured from a set of Maxwell Eminence or HFSS projects. These projects, or "geo" files reflect the structure evolution in response to parameter changes.

The user's graphical inputs are processed to define optimizable variables. Once a structure is captured, the modified project files are automatically generated, and then the field solver is invoked to display and optimize the S-parameter responses. The captured structures are as easy to use as conventional circuit elements. In addition to geometrical dimensions, dielectric and other material parameters can also be selected for optimization.

The Geometry Capture technique is illustrated in Fig. 1. An example of the Empipe3D's Geometry Capture form editor is shown in Fig. 2.
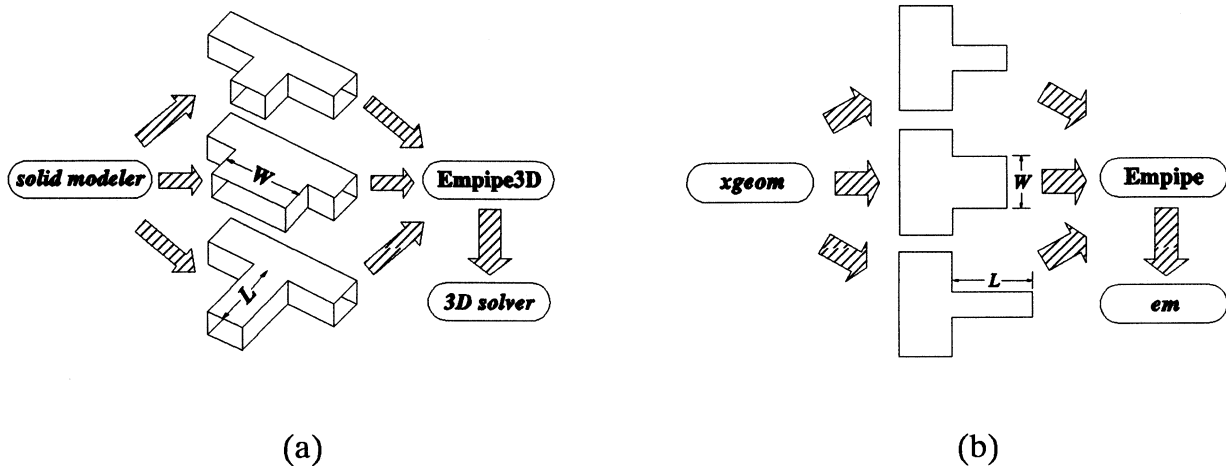
(a)   (b)

Fig. 1. The process of Geometry Capture for (a) 3D, and (b) planar structures.

Fig. 2. The Geometry Capture form editor.

INTERPOLATION AND DATABASE FOR EFFICIENT OPTIMIZATION

The Empipe products are equipped with advanced interpolation and database techniques to achieve unrivalled efficiency and accuracy. Discretization of the geometrical parameters for on-grid *em* simulation is automatically handled by Empipe. The results are stored in a database system to avoid duplicate EM simulations. For off-grid points, user-selectable linear or quadratic interpolation is employed. Also selectable by the user are the parameters to be interpolated: S, Y or Z, in either rectangular or polar form. In Empipe3D, parameter discretization and response interpolation are the means to reduce the number of calls to the field solver. However, the user can disable these features, in which case the field solver is invoked for all simulations.

GRAPHICAL DISPLAY OF RESPONSES

The Empipe products offer a rich set of graphical display options, including response function(s) versus frequency or an arbitrary variable, parametric plot of two responses, Smith chart, polar plot, contours and even 3D visualization. S, Y and Z parameters, two-port insertion loss and group delay are automatically derived from the field solver output. Graphical plots can be saved to HPGL and PostScript files.

AUTOMATIC GENERATION OF PROJECT FILES

In addition to automated optimization, the Empipe products can help the user in manual evaluation of different design variations. Once the parameters are defined, the user can evaluate different versions of the design simply by changing the parameter values. All the necessary project files are automatically generated. This entirely eliminates the demand for designer's time that would otherwise be required to redraw the structures.

In order to reduce computation time, large structures can be decomposed into several substructures, individually simulated by the EM simulator and then connected via circuit theory in OSA90.

ENHANCED SIMULATION CAPABILITIES

The results of EM field analysis can be seamlessly integrated into a full fledged circuit simulator not only for linear small-signal analysis, but also for nonlinear large-signal harmonic balance simulation and optimization. These features are available by combining the Empipe products with OSA90/hope which offers a comprehensive library of linear and nonlinear device models and the flexibility of a general purpose simulation and optimization system.

HARMONIC BALANCE SIMULATION OF A FREQUENCY DOUBLER

The large-signal nonlinear simulation capabilities can be illustrated using a class B frequency doubler shown in Fig. 3 [5]. The doubler consists of a single FET (NE71000) and a number of distributed microstrip elements including two radial stubs and two large bias pads.

Significant couplings between the distributed microstrip elements exist in the doubler, e.g., between the radial stubs and the bias pads. In order to take them into account the entire structure between the two capacitors is parameterized and considered as a whole to be simulated by *em*. Ten parameters denoted as ϕ_1, ϕ_2, ..., ϕ_{10} are selected as design variables. The *em* results are directly returned to OSA90/hope through Empipe for harmonic balance simulation and optimization. For the active device we use the built-in Curtice and Ettenberg FET model. The model parameters are extracted from the typical DC and S parameters using HarPE.
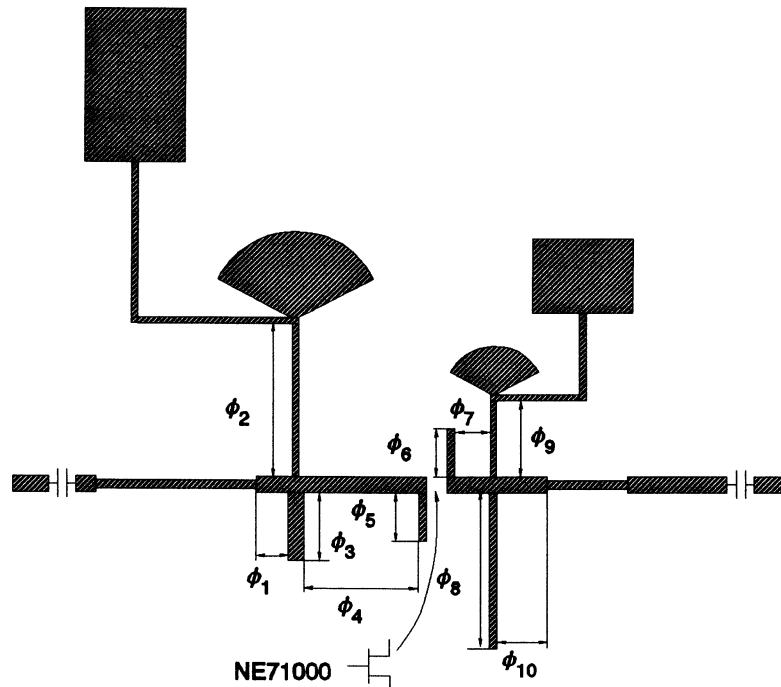
Fig. 3. Circuit structure of the class B frequency doubler.

OPTIMIZATION VARIABLES AND DESIGN SPECIFICATIONS

The Empipe products provide a convenient form editor for selecting optimization variables (Fig. 4) and defining specifications (Fig. 5). By clicking on the structure button, a complete set of project files, corresponding to the starting (or nominal) parameter values entered in the respective boxes, will be automatically generated. Upper and lower bounds can be imposed on the variables to limit the parameter values during optimization.

Fig. 4. The "Select Variables" window.

The S-parameter responses computed by the field solver can be optimized with respect to upper, lower and/or single specifications over one or more user-selected frequency ranges. Optional weighting factors can also be defined.
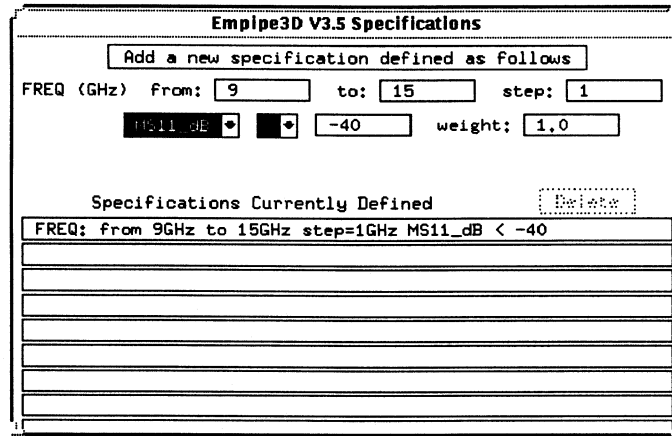
Fig. 5. The "Specifications" window.

DESIGN OPTIMIZATION OF THE FREQUENCY DOUBLER

The design specifications imposed on the doubler responses included conversion gain $\geq$ 3 dB and spectral purity $\geq$ 20 dB at 7 GHz and 10 dBm input power.

Fig. 7 shows the conversion gain versus input power before and after minimax optimization. Significant improvement of the circuit performance is obtained and all specifications are satisfied after optimization.
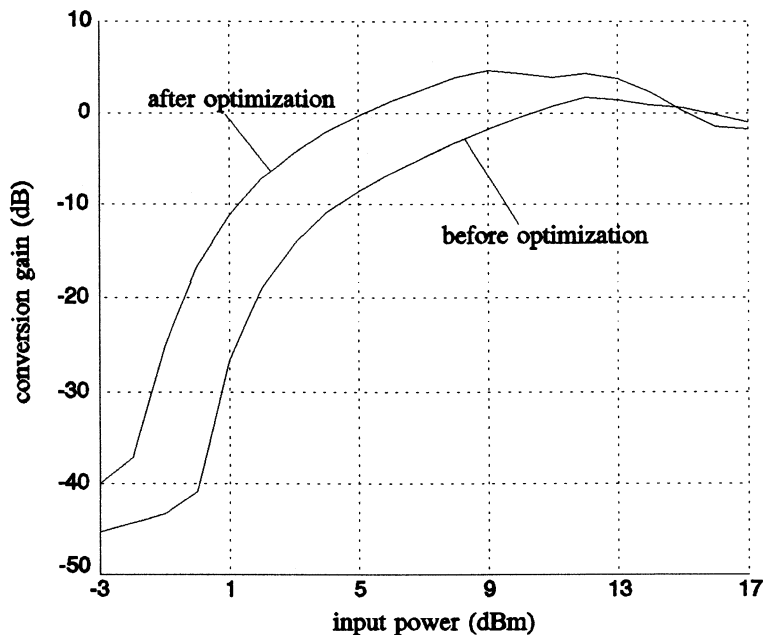

Fig. 7.   Conversion gain of the frequency doubler versus input power before and after optimization.

DESIGN OF AN OPTIMAL MITERED WAVEGUIDE BEND

To illustrate fully 3D EM optimization we apply Empipe3D to design a single-section mitered waveguide bend sketched in Fig. 8. Just one parameter controls the location of the 45 degree bend. We use the distance d between the edge of the miter and the edge of the non-mitered bend ($d = 0$ corresponds to the non-mitered bend). The design specification is set for the return loss $\geq$ 30 dB over the full bandwidth of $9 \leq f \leq 15$ GHz.
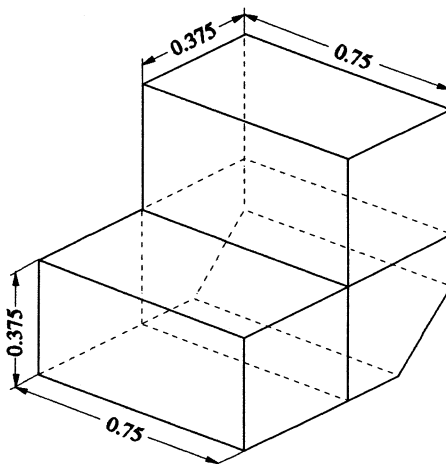
Fig. 8. Geometry of the optimized WR-75 mitered bend.

A standard gradient-based minimax optimization has been performed. The starting value is set to $d = 0.1$ inch and the bounds are set to 0 and 0.375 inch. The solution, $d_{opt} = 0.2897$ inch is reached after 14 iterations. The total CPU time of a Sun SPARCstation 10 with 32 Mb RAM is about 23 hours. It is important to note that only 9 Maxwell Eminence simulations were needed because of the time saving offered by the integrated database/ interpolation feature of Empipe3D. The response of the optimized structure achieved the return loss of about 29 dB.

REFERENCES

[1]   *em*™ and *xgeom*™, Sonnet Software, Inc., 1020 Seventh North Street, Suite 210, Liverpool, NY 13088.

[2]   *HFSS*™, HP EEsof, 1400 Fountaingrove Parkway, Santa Rosa, CA 95401.

[3]   *Maxwell*™ *Eminence*, Ansoft Corporation, Four Station Square, Suite 660, Pittsburgh, PA 15219.

[4]   *OSA90/hope*™, *Empipe*™, *Empipe3D*™, *EmpipeExpress*™ and *HarPE*™, Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7.

[5]   "CAD review: the 7GHz doubler circuit," *Microwave Engineering Europe*, May 1994, pp. 43-53.