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Abstract

The focus of this paper is automated electromagnetic (EM) optimization of microwave circuits and structures. We address the challenges in EM optimization in general and applications to microwave circuit design in particular. We describe an efficient Datapipe connection between an optimization driver and several EM field solvers. Advanced interpolation and database techniques are integrated in order to reduce the number of EM field analyses. We describe the Geometry Capture technique for parameterizing arbitrary geometrical structures. The novel concept of Space Mapping is also reviewed. The technique is employed to carry out the bulk of computations using a coarse (fast) model while the fine model (accurate but CPU intensive EM simulations) is used to align the coarse model and guide the optimization process. Practical industrial applications illustrate the effectiveness of our approach. The examples include a planar microstrip circuit suitable for a commercial method-of-moments solver, and a waveguide structure which is analyzed by a 3D finite-element solver.

INTRODUCTION

The most significant features of EM simulators (the finite element method FEM, the integral equation/boundary element method IE/BEM, the transmission-line method TLM, the finite difference time-domain method FDTD, the mode matching method MM, the method of moments MoM) [1-9] include their unsurpassed accuracy, extended validity ranges, and the capability of handling fairly arbitrary geometrical structures. In order to take full advantage of these features the structures may need to be simulated in their entirety. Decomposition into substructures, which might be desired from the point of view of computational efficiency, should be considered only if no significant couplings are neglected. This means that increasingly more complex structures need to be accurately simulated. Therefore, the efficiency of CAD techniques employing EM simulators is of utmost importance.

EM simulators will not realize their full potential to the designer unless they are optimizer-driven to automatically adjust designable parameters [10-13]. To this end we have made several Datapipe connections between our optimization engine OSA90 [14], which features state-of-the-art direct search, gradient based and simulated annealing algorithms, and EM field solvers including MoM, FEM, TLM and mode-matching codes. Advanced interpolation and database techniques are integrated within the optimization driver to reduce the number of EM field analyses required as well as to facilitate gradient calculations within a fixed grid meshing scheme.

We have developed a Geometry Capture technique for parameterizing planar and solid models in arbitrary formats. A parametric abstraction is derived from a set of incremental models, accommodating not only parameters representing linear dimensions, but also material parameters and composite geometrical evolutions.

We also describe the novel concept of Space Mapping [15,16]. A coarse model is employed to carry out the bulk of computations in the optimization process. The coarse model can be an empirical model, an equivalent circuit model or an EM model with a coarse resolution. A fine model is used to align the coarse model and guide the optimization process. We have developed an aggressive strategy incorporating the Broyden update to establish a mapping between the coarse and fine models.

To illustrate our approach a planar microstrip frequency doubler is analyzed by a commercial MoM solver and a waveguide structure is simulated by a 3D FEM commercial solver. Both circuits are optimized using the techniques described in this paper.

DATAPIPE ARCHITECTURE

The open architecture of our optimization engine OSA90 [14] is based on the Datapipe technology. It allows the users to create fully optimizable interconnections of components, subcircuits, simulators and mathematical functions, supported by fully integrated expression processing capabilities. Several Datapipe protocols are available 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, both commercial and academic:

(1) Empipe [14] interface to ***em*** [5] - an efficient full-wave MoM 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,

(2) Empipe3D [14] interface to Maxwell Eminence [6] and HFSS [7] - FEM based solvers for full-wave EM field analysis of three-dimensional passive structures; Maxwell Eminence and HFSS are capable of computing the *S*-parameter responses, EM field distributions and radiative effects at microwave frequencies,

(3) interfaces to 2d-tlm and 3d-tlm [2,17] - 2D and 3D time-domain TLM based EM solvers,

(4) interfaces to rwgmm - Fritz Arndt library of fast and accurate waveguide building blocks [4] - MM solvers for fast EM simulations of waveguide discontinuities,

(5) interfaces to MM solvers developed at the University of Perugia [12].

Our optimization engine 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. Optimization variables can include circuit parameters, bias voltages, input power levels, Datapipe inputs and abstract variables. The responses that can be optimized include built-in and user-defined circuit responses, Datapipe outputs and abstract error functions.

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. OSA90 can invoke itself through Datapipe to create a simulation/optimization hierarchy of virtually unlimited depth.

INTERPOLATION AND DATABASE TECHNIQUES

Interpolation and database techniques are integrated within the optimization driver to reduce the number of EM field analyses required as well as to facilitate gradient calculations. Interpolation may be necessitated by an EM simulator if the particular solver used employs a fixed grid meshing scheme, for example ***em***. If not enforced by the solver, interpolation is still a highly desirable feature.

If interpolation is employed, EM simulations are performed at on-grid points only. For off-grid points, user-selectable linear or quadratic interpolation schemes have been adopted. Also selectable by the user are the parameters to be interpolated: S, Y or Z, in either rectangular or polar form. For example, in the case of linear interpolation we have [18]

$$R(\phi) = R_{EM}(\phi^{c}) + \theta^{T}\,\mathrm{sign}\Theta\;\Delta\boldsymbol{R}_{EM}(\boldsymbol{B}) \tag{1}$$

where

$$\Delta\boldsymbol{R}_{EM}(\boldsymbol{B}) = [\; R_{EM}(\phi^{1})\text{-}R_{EM}(\phi^{c}) \quad R_{EM}(\phi^{2})\text{-}R_{EM}(\phi^{c}) \;\;\ldots\;\; R_{EM}(\phi^{n})\text{-}R_{EM}(\phi^{c}) \;]^{T} \tag{2}$$

R_{EM} denotes the response being interpolated, ϕ^{c} is the center (on-grid) base point, and ϕ^{1}, ϕ^{2}, ..., ϕ^{n} are n (also on-grid) base points obtained by perturbing each parameter ϕ_i by its (plus or minus) discretization step d_i, one at a time. θ and Θ represent the relative (w.r.t. the discretization step) deviation of the off-grid point ϕ from ϕ^{c}, arranged in a vector or a diagonal matrix form, respectively. The gradient of (1), which is the function actually seen by the optimizer, is also readily available as

$$\frac{\partial R(\phi)}{\partial \phi} = \boldsymbol{D}^{-1}\,\mathrm{sign}\Theta\;\Delta\boldsymbol{R}_{EM}(\boldsymbol{B}) \tag{3}$$

where $\boldsymbol{D} = \mathrm{diag}\{d_i\}$.

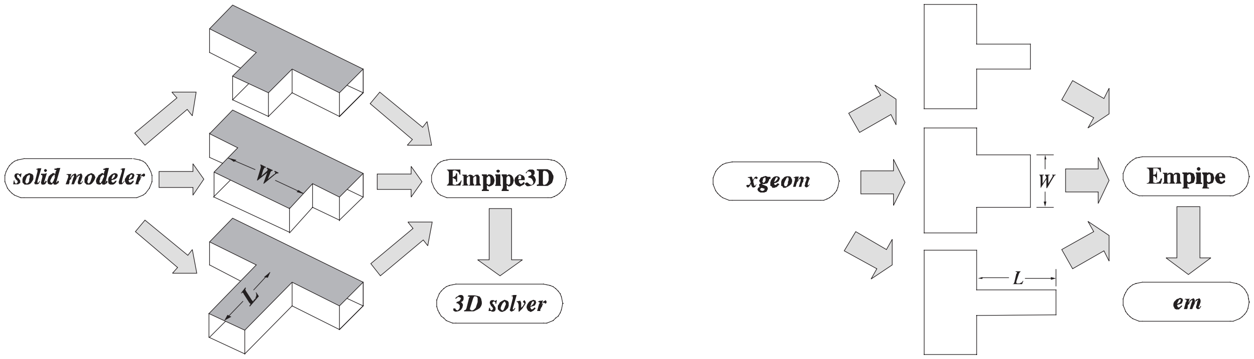
The results of on-grid simulations are stored in a database system for efficient re-use during subsequent interpolations at other off-grid points for which some or all of the base points may have already been simulated.

GEOMETRY CAPTURE

This section addresses the critical issue [19,20] of parameterization of geometrical structures for the purpose of layout-based design, in particular automated EM optimization. As the optimization process proceeds, revised structures must be automatically generated. Moreover, each such structure must be physically meaningful and should follow the designer's intention w.r.t. allowable modifications and possible limits. It is of utmost importance to leave the parameterization process to the user. In our earlier work (*Empipe Version 1.1, 1992*) we created a library of predefined elements (lines, junctions, bends, gaps, etc.), that were already parameterized and ready for optimization. The applicability of that approach is, however, limited to structures that are decomposable into the available library elements. Moreover, even a comprehensive library would not satisfy all microwave designers, simply because of their creativity in devising new structures. Furthermore, the library approach inherently omits possible proximity couplings between the elements since they are individually simulated by an EM solver and connected by a circuit-level simulator.

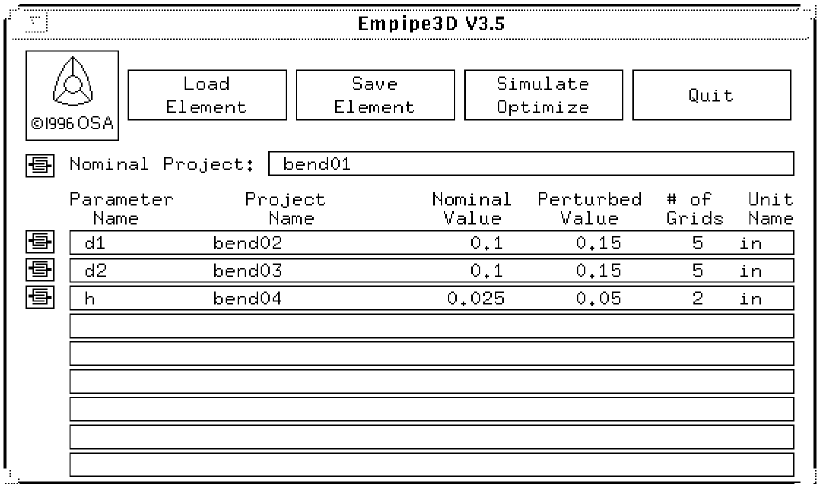
Geometry Capture facilitates user parameterization of arbitrary structures by processing the native files of the respective EM simulators. In Empipe, designable parameters and optimization variables are automatically captured from a set of "geo" files created using ***xgeom***. In Empipe3D the optimization 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, for instance, 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.



Nominal Project: bend01

Parameter Name	Project Name	Nominal Value	Perturbed Value	# of Grids	Unit Name
d1	bend02	0.1	0.15	5	in
d2	bend03	0.1	0.15	5	in
h	bend04	0.025	0.05	2	in

Fig. 2. The Geometry Capture form editor.

SPACE MAPPING OPTIMIZATION

We consider models in two distinct spaces, namely the optimization space denoted by $\boldsymbol{X}_{OS}$, and the EM space denoted by $\boldsymbol{X}_{EM}$. We assume that the $\boldsymbol{X}_{OS}$ model is much faster to evaluate but less accurate than the $\boldsymbol{X}_{EM}$ model. The $\boldsymbol{X}_{OS}$ model can be an empirical model or a coarse-resolution EM model. We wish to find a mapping $\boldsymbol{P}$ between these two spaces, i.e., a function that maps the parameters of one model onto the parameters of the other model:

$$\boldsymbol{x}_{OS} = \boldsymbol{P}(\boldsymbol{x}_{EM}) \tag{4}$$

such that

$$\boldsymbol{R}_{OS}\,(\boldsymbol{P}(\boldsymbol{x}_{EM})) \approx \boldsymbol{R}_{EM}\,(\boldsymbol{x}_{EM}) \tag{5}$$

where $\boldsymbol{R}_{OS}(\boldsymbol{x}_{OS})$ and $\boldsymbol{R}_{EM}(\boldsymbol{x}_{EM})$ denote the model responses in the respective spaces.

The purpose of Space Mapping (SM) is to avoid direct optimization in the computationally expensive $\boldsymbol{X}_{EM}$ space. We perform optimization in $\boldsymbol{X}_{OS}$ to obtain the optimal design $\boldsymbol{x}^{*}_{OS}$ and then use SM to find the mapped solution in $\boldsymbol{X}_{EM}$ as

$$\overline{\boldsymbol{x}}_{EM} = \boldsymbol{P}^{-1}(\boldsymbol{x}^{*}_{OS}) \tag{6}$$

$\boldsymbol{P}$ is found by an iterative process starting from $\boldsymbol{x}^{1}_{EM} = \boldsymbol{x}^{*}_{OS}$. At the ith step, the $\boldsymbol{X}_{EM}$ model is simulated at $\boldsymbol{x}^{i}_{EM}$, i.e., the current parameter values. If the $\boldsymbol{X}_{EM}$ model does not produce the desired responses we perform parameter extraction of the $\boldsymbol{X}_{OS}$ model to find $\boldsymbol{x}^{i}_{OS}$ which minimizes

$$\| \boldsymbol{R}_{OS}(\boldsymbol{x}^{i}_{OS}) - \boldsymbol{R}_{EM}(\boldsymbol{x}^{i}_{EM}) \| \tag{7}$$

where $\|\cdot\|$ denotes a suitable norm. In the aggressive SM strategy the next iterate is found by a quasi-Newton step

$$\boldsymbol{x}^{i+1}_{EM} = \boldsymbol{x}^{i}_{EM} + (\boldsymbol{B}^{i})^{-1}(\boldsymbol{x}^{*}_{OS} - \boldsymbol{x}^{i}_{OS}) \tag{8}$$

which employs an approximate Jacobian matrix $\boldsymbol{B}^{i}$. The matrix $\boldsymbol{B}^{i}$ is subsequently updated using the Broyden formula [21].

In a number of applications, the aggressive Space Mapping strategy has enabled us to achieve optimal or near-optimal results after very few fine model EM simulations. Furthermore, the mapping established at the solution can be utilized for efficient statistical analysis of manufacturing tolerances.

EXAMPLES

Harmonic Balance Simulation and Optimization of a Frequency Doubler

We perform EM based simulation and optimization of a class B frequency doubler shown in Fig. 3 [22]. 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 $\phi_1, \phi_2, \ldots, \phi_{10}$ 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.

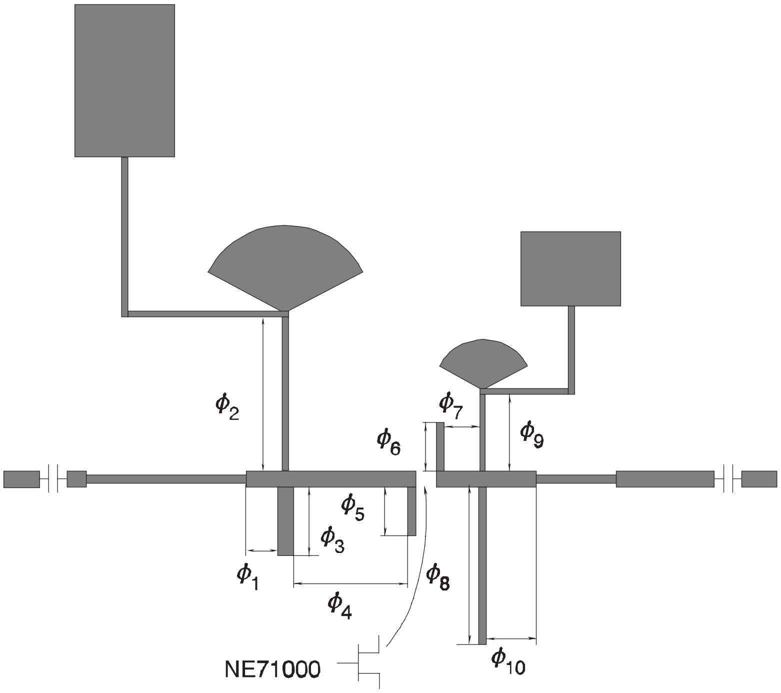


Fig. 3. Circuit structure of the class B frequency doubler.

The design specifications imposed on the doubler responses included conversion gain ≥ 3 dB and spectral purity ≥ 20 dB at 7 GHz and 10 dBm input power. Fig. 4 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.

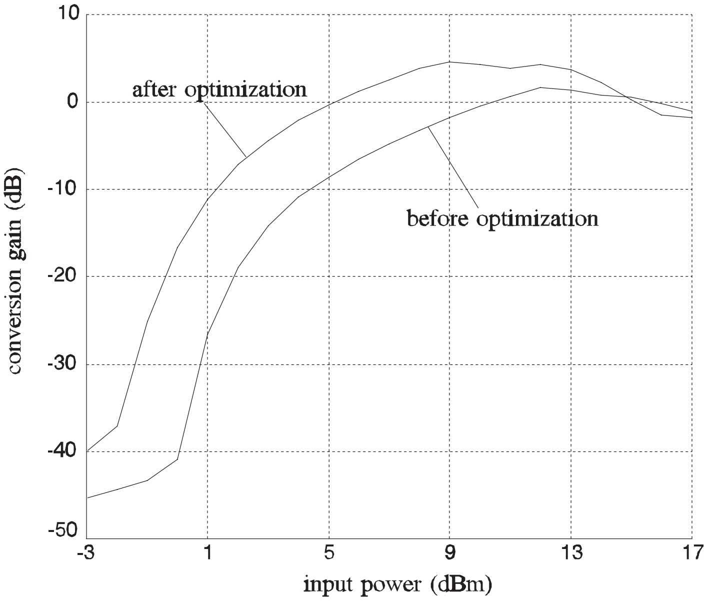


Fig. 4. Conversion gain of the frequency doubler versus input power before and after optimization.

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. 5. 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 ≥ 30 dB over the full bandwidth of $9 \leq f \leq 15$ GHz.

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 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.

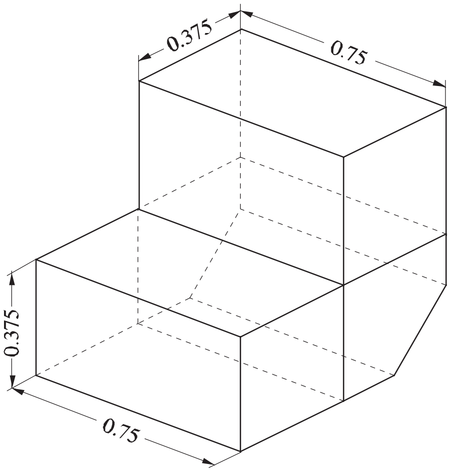


Fig. 5. Geometry of the optimized WR-75 mitered bend.

CONCLUSIONS

The increasing computing power of modern workstations and PCs and advances in computational electromagnetics, including a rapidly growing number of available field solvers, direct exploitation of EM simulation techniques in circuit design optimization becomes both tempting and tractable. Nevertheless, slowness of such solvers, particularly when practical industrial are to be effectively solved, requires sophisticated approaches which can reduce the number of EM simulations needed to successfully complete optimization.

In this context we have reviewed a number of recent developments in the area of automated EM optimization of microwave circuits and structures. First, the Datapipe technology has been found to be an effective and efficient tool to drive a variety of disjoint EM simulators. Particularly useful in reducing the number of EM simulations is the interpolation approach integrated with a database system of simulated results. We have also presented the Geometry Capture technique for user parameterization of geometrical, structures, a key to design optimization of arbitrary structures. Finally, the Space Mapping technique is a very promising approach to design optimization when extremely CPU intensive simulators are used. It combines the speed of circuit-level optimization with the accuracy of EM simulations.

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