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ABSTRACT

This paper is dedicated to automated electromagnetic (EM) optimization of arbitrary 3D microwave structures. Emphasis is on recent advances and integration of EM simulators directly into the linear/nonlinear circuit design process, transparently to the designer. Based on the OSA90/hope™ engine, OSA provides RF/microwave designers with Empipe3D™, a tool for design optimization using Maxwell® Eminence or HFSS. We describe efficient Datapipe™ connections between our optimization driver and these EM field solvers. Integration of advanced interpolation and database techniques in order to reduce the number of EM field analyses is outlined. We present the concept of the Geometry Capture™ technique for parameterizing arbitrary 3D structures. The advantages of Space Mapping™ optimization are demonstrated by aligning the results of Maxwell® Eminence simulations with those obtained from the mode-matching analysis. Designs of a waveguide mitered bend and an H-plane iris filter illustrate the approach and its benefits.

INTRODUCTION

Commercial EM simulators are becoming increasingly faster and more accurate [1-3]. Accordingly, engineers are pushing frontiers beyond traditional uses of EM simulators. In order to realize their full potential, EM simulators have to be optimizer-driven to automatically adjust designable parameters [4-6]. The new thrust is to integrate EM simulations directly into the linear/nonlinear circuit design process transparently to the designer.

Our EM optimization systems are built around OSA90™ [7] optimization engine using the Datapipe™ architecture. We have made several Datapipe™ connections between OSA90™ and EM field solvers including MoM, FEM, TLM and mode-matching (MM) codes. This presentation is focused on Empipe3D™ product and its role in microwave/RF CAD, particularly in the emerging new era of circuit optimization with EM simulators. Empipe3D™ [7] is a direct electromagnetic optimization software system driving the finite element based solvers Maxwell® Eminence [1] offered by Ansoft Corporation and HFSS [2] offered by Hewlett-Packard.

We present advanced interpolation and database techniques [4] which are integrated within the Empipe3D™ optimization driver to reduce the number of EM field analyses required as well as to facilitate gradient calculations. Empipe3D™ permits user directed parameterization and optimization of geometrical and material parameters in an EM-based design process, through our Geometry Capture™ technique. We also describe the novel concept of Space Mapping™ (SM) [8,9] suitable for optimization of computationally intensive models. Optimization is performed through automatic alignment of the results of two separate EM models: (1) accurate but slow "fine" model, and (2) fast but less accurate "coarse" model.

To illustrate our approach a waveguide mitered bend is optimized using Ansoft's Maxwell® Eminence and a waveguide H-plane filter with rounded edges is optimized using SM where Maxwell® Eminence serves as the fine model, and MM simulation of the same structure with sharp edges serves as the coarse model.

DATAPIPE™ ARCHITECTURE

The open architecture of our optimization engine OSA90™ [7] is based on the Datapipe™ technology [6,10]. Several Datapipe™ protocols are available for connecting external programs through interprocess pipes. This facilitates high-speed data connections to external *executable* programs, even across networks. The Datapipe™ architecture allows the users to create fully optimizable interconnections of components, subcircuits, simulators and mathematical functions, supported by fully integrated expression processing capabilities.

The OSA90™ 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. All these optimizers become instantly available to any program connected through Datapipes. Furthermore, the Datapipe™ technology allows the users to enhance their own software with OSA90™'s friendly user interface, graphics, expression parser, 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.

INTEGRATION OF INTERPOLATION AND DATABASES

Interpolation and database techniques are integrated within the Empipe3D™ optimization driver to reduce the number of EM field analyses required as well as to facilitate gradient calculations [4]. If interpolation is employed, EM simulations are performed at on-grid points only. For off-grid points, user-selectable linear or advanced quadratic interpolation is employed. Also, user has a choice of interpolating *S*, *Y* or *Z* parameters in either rectangular or polar form. 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.

The results of on-grid EM 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™

Geometry Capture™ is a user-friendly tool for parameterization of geometrical structures for the purpose of layout-based design. 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 [11].

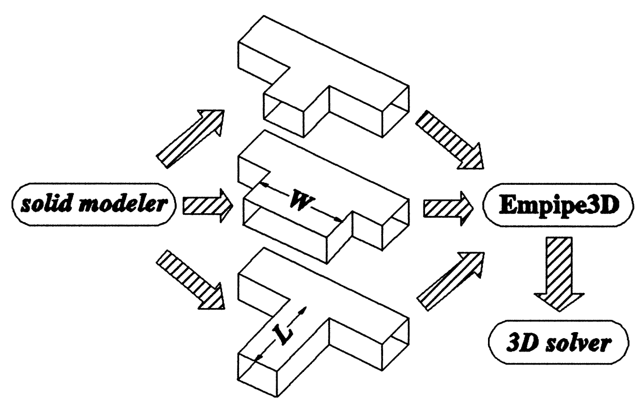


Fig. 1. The process of Geometry Capture™ for 3D structures.

The Geometry Capture™ technique is illustrated in Fig. 1. User parameterization is facilitated by processing the native files of the EM simulator. In Empipe3D™ the optimization variables are captured from a set of Maxwell® Eminence or HFSS projects that reflect the structure evolution in response to parameter changes. The user's graphical inputs are processed to define optimizable variables. 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. An example of the Geometry Capture™ form editor is shown in Fig. 2.

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. Empipe3D™ provides a convenient form editor for selecting optimization variables and defining specifications, illustrated in Figs. 3 and 4. Upper and lower bounds can be imposed on the variables to limit the parameter values during optimization. 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.

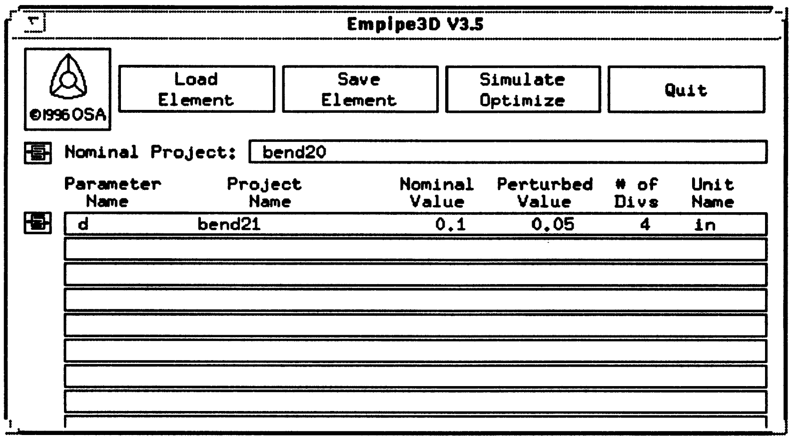


Fig. 2. The Geometry Capture™ form editor.

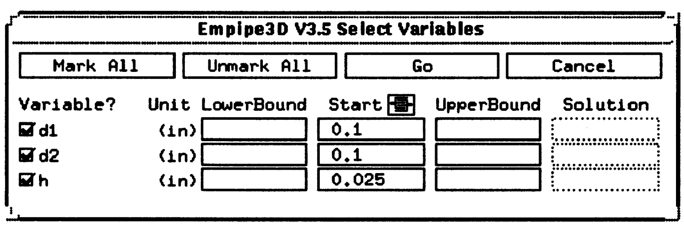


Fig. 3. The "Select Variables" window.

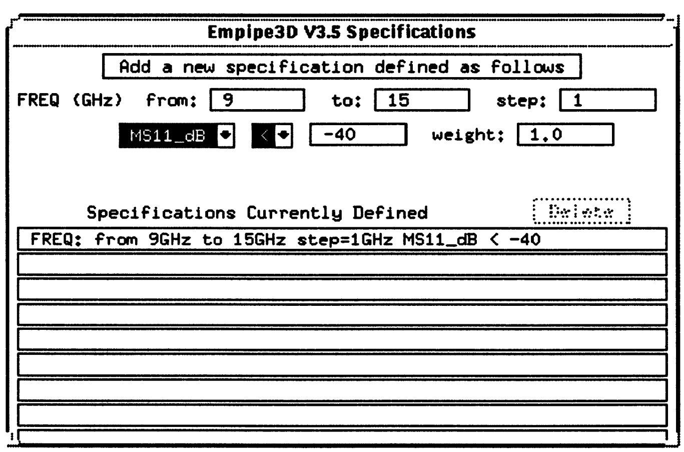


Fig. 4. The "Specifications" window.

SPACE MAPPING™ OPTIMIZATION [8,9]

Models in two distinct space are considered: the EM space, denoted by X_{em}, and the optimization space, denoted by X_{os}. We assume that the X_{os} (coarse) model is computationally much more efficient, but less accurate than the X_{em} (fine) model. The X_{em} model can be an accurate FEM model or a MM model with high number of modes. The X_{os} may include empirical models or EM models with a coarse grid. We wish to find a mapping P between the two spaces

$$x_{os} = P(x_{em}) \tag{1}$$

such that

$$R_{os}(P(x_{em})) \approx R_{em}(x_{em}) \tag{2}$$

where $R_{em}(x_{em})$ and $R_{os}(x_{os})$ are the responses of the fine model and the coarse model, respectively.

Our aim is to avoid direct optimization in the CPU-intensive X_{em} space. Instead, the bulk of the computation involved in optimization is carried out in the X_{os} space. We perform optimization in X_{os} to obtain the optimal design x_{OS}^* and then use SM to find the solution in X_{em} as

$$\bar{x}_{em} = P^{-1}(x_{os}^*) \tag{3}$$

P is found by an iterative process starting from $x_{em}^1 = x_{os}^*$. In the aggressive SM procedure, the mapping function is updated through a quasi-Newton iteration with first-order derivative approximations based on the classic Broyden formula [9].

In a number of applications, the aggressive SM strategy has enabled us to achieve optimal or near-optimal results after very few fine model EM simulations.

DESIGN OPTIMIZATION OF A MITERED WAVEGUIDE BEND [4]

Automated design of a single-section 45° mitered waveguide bend, sketched in Fig. 5., is used to illustrate fully 3D EM optimization using Empipe3D™. 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) is selected as an optimization parameter. 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 of the design parameter is taken as $d = 0.1$ inch. It is allowed to change between 0 and 0.375 inch, with the discretization step $\delta = 0.025$ 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, when the convergence criterion for Maxwell® Eminence (the Allowable Delta S) is set to 10^{-4} using no more than 9 adaptive steps. It is important to note that only 9 Maxwell® Eminence simulations are needed because of time saving offered by the integrated database/interpolation feature of Empipe3D™. The response of the optimized structure, presented in Fig. 6, achieved the return loss of about 29 dB.

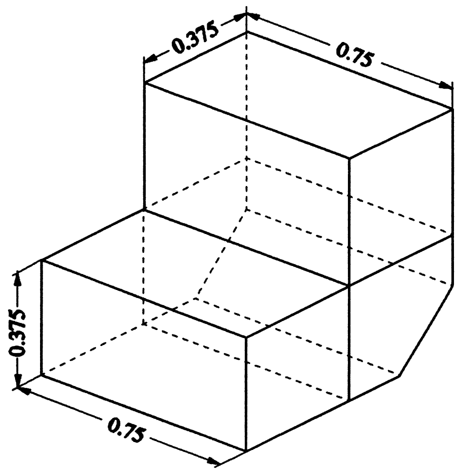


Fig. 5. Geometry of the optimized WR-75 mitered bend.

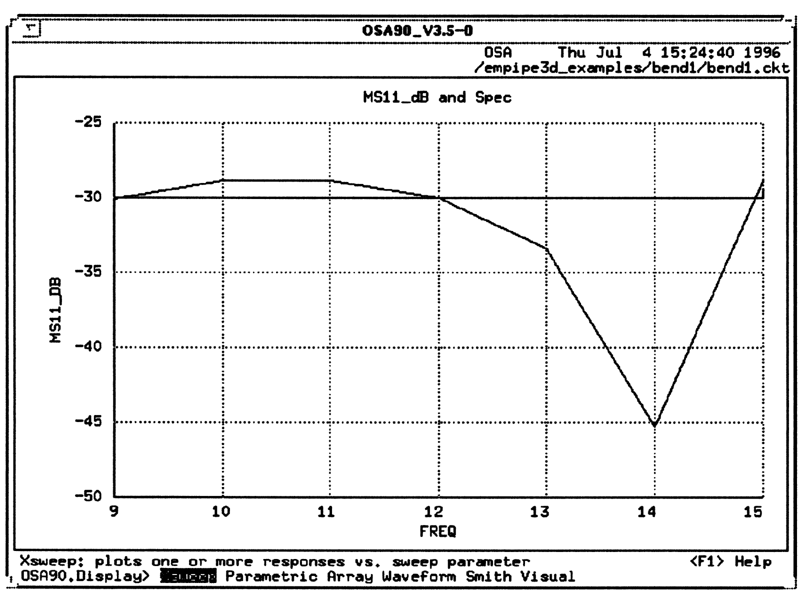
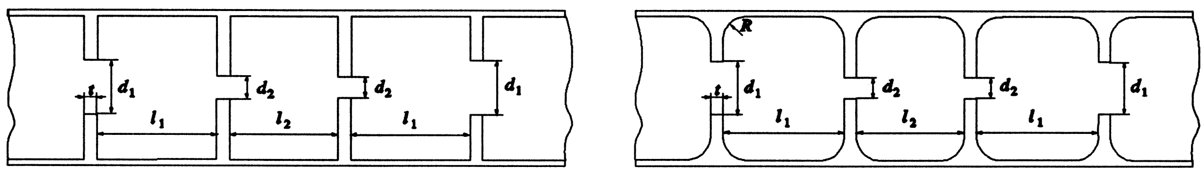


Fig. 6. Response of the optimized geometry of a single-section miter, d_{opt} = 0.2897 inch.

SPACE MAPPING™ OPTIMIZATION OF H-PLANE RESONATOR FILTER [12]

In the SM optimization procedure, the MM waveguide library serves as the OS model and the FEM simulator as the EM model. We address the design of the H-plane resonator filter shown in Fig. 7. The waveguide cross-section is 15.8 × 7.9 mm, while the thickness of the irises is t = 0.4 mm. The radius of the corners is R = 1 mm. The iris and resonator dimensions d_1, d_2, l_1 and

l_2 are selected as the optimization variables.



(*a*) (*b*)

Fig. 7. Structures for Space Mapping™ optimization: (*a*) OS model, for hybrid MM/network theory; (*b*) fine model, for FEM analysis.

First, minimax optimization of the OS model is performed with the following specifications

$$|S_{21}| \text{ (dB)} < -35 \quad \text{for } 13.5 \le f \le 13.6 \text{ GHz}$$
$$|S_{11}| \text{ (dB)} < -20 \quad \text{for } 14.0 \le f \le 14.2 \text{ GHz}$$
$$|S_{21}| \text{ (dB)} < -35 \quad \text{for } 14.6 \le f \le 14.8 \text{ GHz}$$

The minimax solution x_{os}^* is d_1 = 6.04541, d_2 = 3.21811, l_1 = 13.0688 and l_2 = 13.8841. It yields the target response for SM. Focusing on the passband, we treat responses in the region 13.96 $\le f \le$ 14.24 GHz. The responses obtained using both models at the point x_{os}^* are shown in Fig. 8. Some discrepancy is evident.

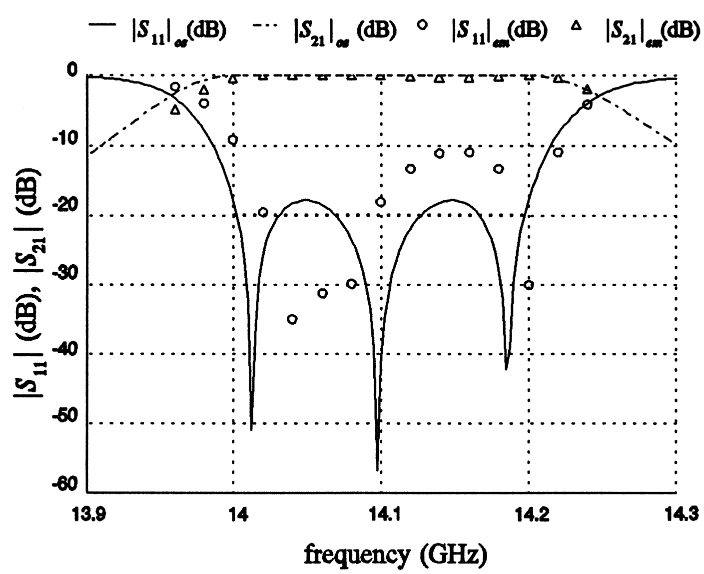


Fig. 8. Magnitudes of S_{11} and S_{21} of the H-plane filter before Space Mapping™ optimization, as simulated using RWGMM (curves) and by Maxwell® Eminence (points).

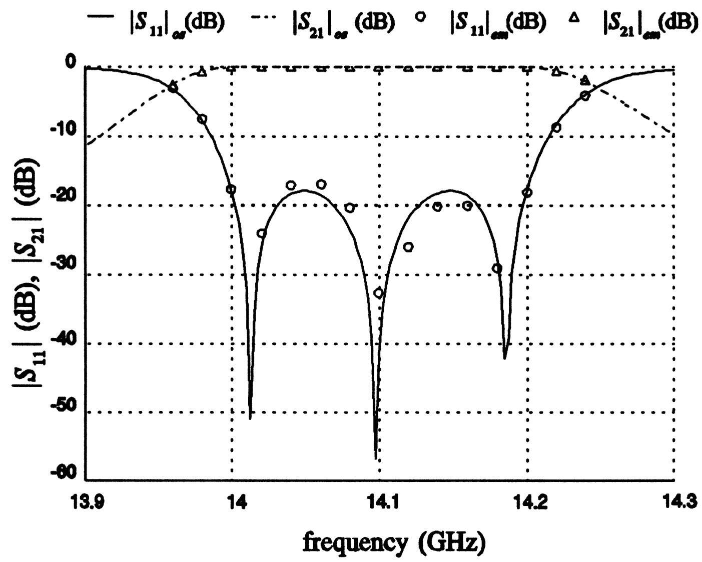


Fig. 9. Space Mapping™ optimized FEM responses (points) of the H-plane filter compared with the target OS responses (curves).

The optimized response shown in Fig. 9 corresponds to point d_1 = 6.17344, d_2 = 3.29027, l_1 = 13.0302 and l_2 = 13.8859. The solution was obtained after only 4 FEM simulations by Maxwell® Eminence. Fifteen frequency points were used with Maxwell® Eminence.

We verified the SM results by directly optimizing the H-plane filter using Empipe3D™ driving the Maxwell® Eminence solver. Essentially the same solution was found.

CONCLUSIONS

We have reviewed concepts and formulations relevant to EM optimization of arbitrary structures based on 3D field simulation carried out using Maxwell® Eminence or HFSS, as implemented in our Empipe3D™ optimization tool. First, the Datapipe™ technology has been found to be an effective and efficient means 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 outlined the Geometry Capture™ technique for user parameterization of geometrical structures, a key to design optimization of arbitrary structures. Finally, the Space Mapping™ technique is used to combine the speed of circuit-level optimization with the accuracy of FEM Maxwell® Eminence/HFSS simulations.

Successful EM optimization of 3D devices, such as mitered waveguide bend and an H-plane iris filter has been performed using the techniques described here.

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