AUTOMATED ELECTROMAGNETIC OPTIMIZATION FOR RF, WIRELESS AND MICROWAVE CIRCUITS

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Outline

EM optimization for microwave circuit design

efficient Datapipe architecture

integration of advanced interpolation and intelligent database techniques

Geometry Capture technique

Space Mapping optimization

optimization examples

- a planar microstrip circuit analyzed by a MoM solver
- a waveguide structure simulated by a 3D FEM solver

EM Optimization

increasingly more complex structures need to be accurately simulated in their entirety

decomposition into substructures should be considered only if no significant couplings are neglected

the efficiency of CAD techniques employing EM simulators is of utmost importance

optimization engine OSA90 connected through Datapipe to external EM simulators

Datapipe Architecture

high-speed data connections to external executable programs, even across networks

allows the users to create fully optimizable interconnections of components, subcircuits, simulators and mathematical functions

uses UNIX interprocess pipes

the external programs are run in separate processes and communicate with OSA90 in a manner similar to subroutine calls

Interpolation and Database Techniques

reduce the number of EM field analyses to facilitate gradient calculations

interpolation is necessary if the solver employs a fixed grid meshing scheme (for example ***em***)

linear or quadratic interpolation

user selectable S, Y or Z parameter interpolation, in either rectangular or polar form

the results of on-grid EM simulations are stored in a database

for subsequent on-grid simulations the results are simply retrieved from the database

Linear Interpolation

(*Bandler et al., 1997*)

response function $R(\phi)$ is interpolated using

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

where

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

and

R_{em}	the interpolated response
ϕ^c	the center base point (on-grid)
$\phi^1, \phi^2, \ldots, \phi^n$	n base points obtained by perturbing each parameter ϕ_i by its discretization step d_i (on-grid)
θ and Θ	the relative deviation of the off-grid point ϕ from ϕ^c, in a vector or a diagonal matrix form

Gradient Evaluation

the interpolated response is the function actually seen by the optimizer

the gradient of the interpolated response

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

where

$\boldsymbol{D}$ discretization steps d_i arranged in a diagonal matrix

Parameterization of Geometrical Structures

for layout-based design

as the optimization process proceeds, revised structures must be automatically generated

each such structure must be physically meaningful

the new structure should follow the designer's intention w.r.t. allowable modifications and possible limits

Geometry Capture
(*Bandler et al., 1996*)

facilitates user parameterization of arbitrary structures

it is of utmost importance to leave the parameterization process to the user

processing the native files of the respective EM simulators

Empipe	a set of "geo" files created using ***xgeom***
Empipe3D	a set of Maxwell Eminence or HFSS projects

projects or "geo" files reflect the structure evolution in response to parameter changes

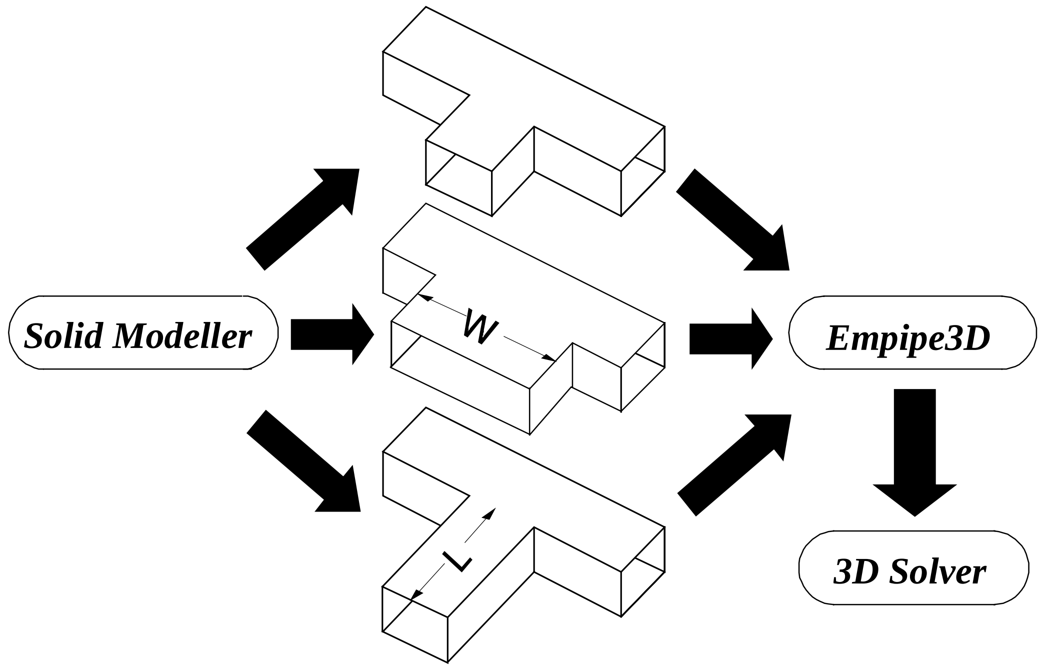
once a structure is captured

the modified project files are automatically generated

the captured structures are as easy to use as conventional circuit elements

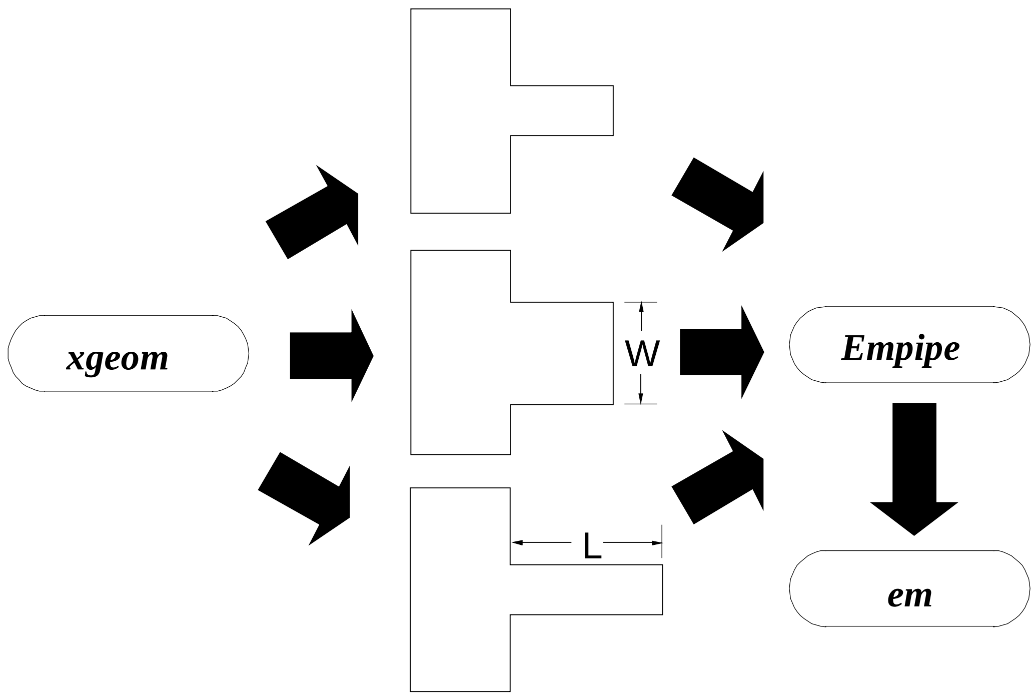
dielectric and other material parameters can also be selected for optimization

The Process of Geometry Capture



parameterization of 3D structures

The Process of Geometry Capture



parameterization of planar structures

Space Mapping (SM)
(*Bandler et al., 1994*)

models in two distinct spaces

$\boldsymbol{X}_{os}$ optimization space

$\boldsymbol{X}_{em}$ EM space

$\boldsymbol{X}_{os}$ model can be an empirical model or a coarse EM model, much faster but less accurate than the $\boldsymbol{X}_{em}$ model

SM establishes a mapping $\boldsymbol{P}$ between the two spaces

$$\boldsymbol{x}_{os} = \boldsymbol{P}(\boldsymbol{x}_{em})$$

to match the responses of both models

$$\boldsymbol{R}_{os}(\boldsymbol{P}(\boldsymbol{x}_{em})) \approx \boldsymbol{R}_{em}(\boldsymbol{x}_{em})$$

the purpose of SM is to avoid direct optimization in the computationally expensive $\boldsymbol{X}_{em}$ space

Space Mapping Optimization
(*Bandler et al., 1994*)

first, the optimal design $\boldsymbol{x}_{os}^{*}$ in $\boldsymbol{X}_{os}$ is found

SM is used to find the mapped solution in $\boldsymbol{X}_{em}$ as

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

$\boldsymbol{P}$ is found iteratively starting from $\boldsymbol{x}_{em}^{(1)} = \boldsymbol{x}_{os}^{*}$

in the ith step the $\boldsymbol{X}_{em}$ model is simulated at $\boldsymbol{x}_{em}^{(i)}$

if the $\boldsymbol{X}_{em}$ model does not produce the desired responses, we perform parameter extraction of the $\boldsymbol{X}_{os}$ model

$$\underset{\boldsymbol{x}_{os}^{(i)}}{\text{minimize}} \left\| \boldsymbol{R}_{os}(\boldsymbol{x}_{os}^{(i)}) - \boldsymbol{R}_{em}(\boldsymbol{x}_{em}^{(i)}) \right\|$$

the next iterate $\boldsymbol{x}_{em}^{(i+1)}$ is found using the inverse mapping

Aggressive Space Mapping Optimization
(*Bandler et al., 1995*)

the next iterate is found by a quasi-Newton step

$$\boldsymbol{x}_{em}^{(i+1)} = \boldsymbol{x}_{em}^{(i)} + (\boldsymbol{B}^{(i)})^{-1}(\boldsymbol{x}_{os}^{*} - \boldsymbol{x}_{os}^{(i)})$$

where

$\boldsymbol{B}^{(i)}$ approximate Jacobian matrix, updated using the Broyden formula

the aggressive SM strategy has enabled us to achieve optimal or near-optimal results after very few EM model simulations

the mapping established at the solution can be utilized for efficient statistical analysis of manufacturing tolerances

Comments on the Parameter Extraction Step

the parameter extraction step aims at finding a point $\boldsymbol{x}_{os}$ whose coarse model responses match corresponding fine model responses

the extracted coarse model parameters may be nonunique

nonuniqueness of the parameter extraction step hinders the convergence of the aggressive Space Mapping technique

to overcome problems caused by nonuniqueness of the parameter extraction step a multi-point parameter extraction step was suggested (*Bandler et al., 1996*)

the step aims at matching not only the response but also the first-order derivative of the two models

the extracted coarse model point $\boldsymbol{x}_{os}$ is obtained by solving

$$\underset{\boldsymbol{x}_{os}}{\text{minimize}} \; \left\| \boldsymbol{R}_{os}(\boldsymbol{x}_{os} + \Delta\boldsymbol{x}) - \boldsymbol{R}_{em}(\boldsymbol{x}_{em} + \Delta\boldsymbol{x}) \right\|$$

simultaneously for a set of perturbations $\Delta\boldsymbol{x}$

this step is more likely to improve the uniqueness of the parameter extraction step

Trust Region Aggressive Space Mapping Algorithm
(*Bakr et al., 1998*)

using $\boldsymbol{f}^{(i)} = \boldsymbol{P}(\boldsymbol{x}_{em}^{(i)}) - \boldsymbol{x}_{os}^{*}$
solve $(\boldsymbol{B}^{(i)T}\boldsymbol{B}^{(i)} + \lambda \boldsymbol{I})\boldsymbol{h}^{(i)} = -\boldsymbol{B}^{(i)T}\boldsymbol{f}^{(i)}$ for $\boldsymbol{h}^{(i)}$

this corresponds to minimizing $\left\| \boldsymbol{f}^{(i)} + \boldsymbol{B}^{(i)}\boldsymbol{h}^{(i)} \right\|_2^2$ subject to $\left\| \boldsymbol{h}^{(i)} \right\|_2 \le \delta$ where δ is the size of the trust region

λ, which correlates to δ, can be determined (*Moré et al., 1983*)

single point parameter extraction is performed at the new point $\boldsymbol{x}_{em}^{(i+1)} = \boldsymbol{x}_{em}^{(i)} + \boldsymbol{h}^{(i)}$ to get $\boldsymbol{f}^{(i+1)}$

if $\boldsymbol{f}^{(i+1)}$ satisfies a certain success criterion for the reduction in the l_2 norm of the vector $\boldsymbol{f}$, the point $\boldsymbol{x}_{em}^{(i+1)}$ is accepted and the matrix $\boldsymbol{B}^{(i)}$ is updated using Broyden's update

otherwise a temporary point is generated using $\boldsymbol{x}_{em}^{(i+1)}$ and $\boldsymbol{f}^{(i+1)}$ and is added to the set of points to be used for multi-point parameter extraction

a new $\boldsymbol{f}^{(i+1)}$ is obtained through multi-point parameter extraction

Trust Region Aggressive Space Mapping Algorithm
(*Bakr et al., 1998*)

the last three steps are repeated until a success criterion is satisfied or the step is declared a failure

step failure has two forms

(1) $\boldsymbol{f}$ may approach a limiting value without satisfying the success criterion or
(2) the number of fine model points simulated since the last successful step reaches n+1

Case (1): the parameter extraction is trusted but the linearization used is suspect; the size of the trust region is decreased and a new point $\boldsymbol{x}_{em}^{(i+1)}$ is obtained

Case (2): sufficient information is available for an approximation to the Jacobian of the fine model responses w.r.t. the fine model parameters used to predict the new point $\boldsymbol{x}_{em}^{(i+1)}$

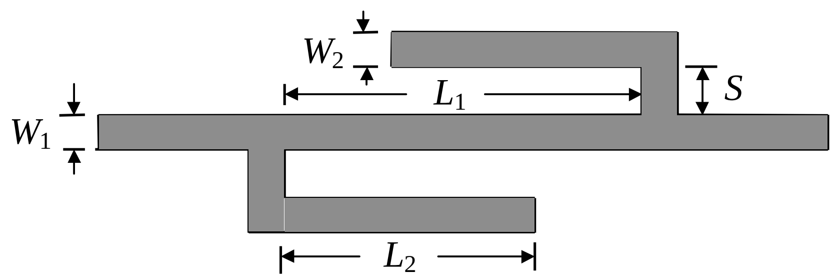
the mapping between the two spaces is exploited in the parameter extraction step by solving

$$\underset{\boldsymbol{x}_{os}}{minimize} \; \left\| \boldsymbol{R}_{os}(\boldsymbol{x}_{os} + \boldsymbol{B}^{(i)}(\boldsymbol{x} - \boldsymbol{x}_{em}^{(i+1)})) - \boldsymbol{R}_{em}(\boldsymbol{x}) \right\|$$

simultaneously for a set of points $\boldsymbol{x}$

Double-Folded Stub Microstrip Filter

(*Rautio, 1992*)



passband specifications: $|S_{21}| \geq$ -3 dB for $f \leq$ 9.5 GHz and 16.5 GHz $\leq f$

stopband specifications: $|S_{21}| \leq$ -30 dB for 12 GHz $\leq f \leq$14 GHz

designable parameters: L_1, L_2 and S; W_1=W_2=4.8 mil

substrate thickness is 5 mil and the relative dielectric constant is assumed to be 9.9

coarse model: a coarse grid Sonnet ***em*** model with $\Delta x = \Delta y =$ 4.8 mil

Double-Folded Stub Microstrip Filter Fine Model

fine model: a fine grid Sonnet ***em*** model with $\Delta x = \Delta y = 1.6$ mil

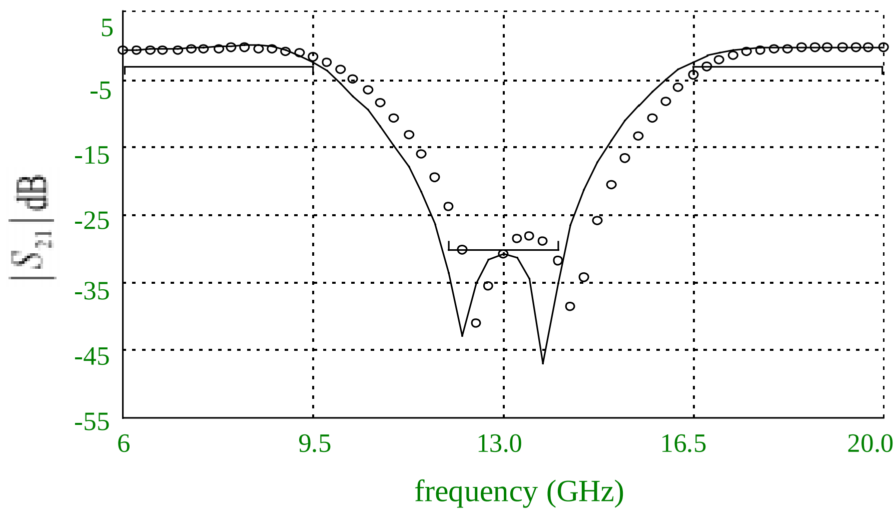
final design is obtained in 2 iterations, requiring 5 fine model points

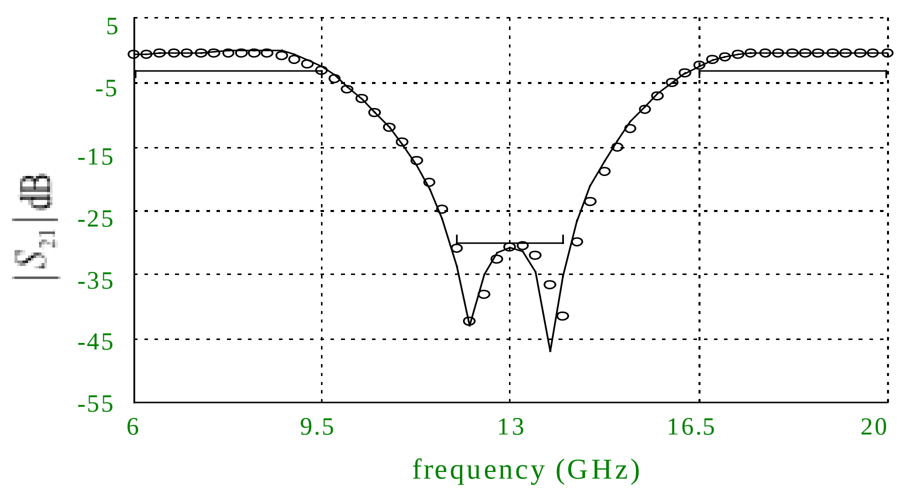
four ***xgeom*** projects were generated to capture the geometry of the filter

OSA's Empipe linear interpolation is used to simulate off-grid points

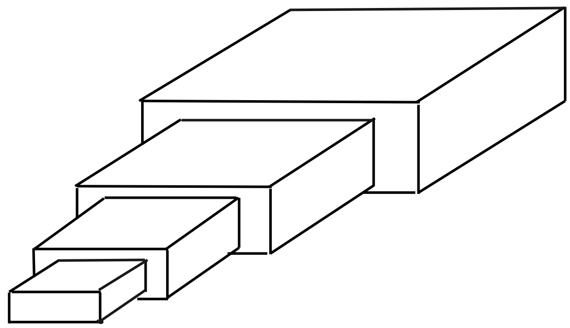
Double-Folded Stub Microstrip Filter Responses

the optimal coarse model (—) response and the fine model response (o) at the initial and final designs





Two-Section Waveguide Transformer



design specifications: : $VSWR \leq 1.01$ for 5.8 GHz $\leq f \leq$ 6.6 GHz

optimizable parameters: length and height of each waveguide section

coarse model: an analytical model that neglects junction discontinuity

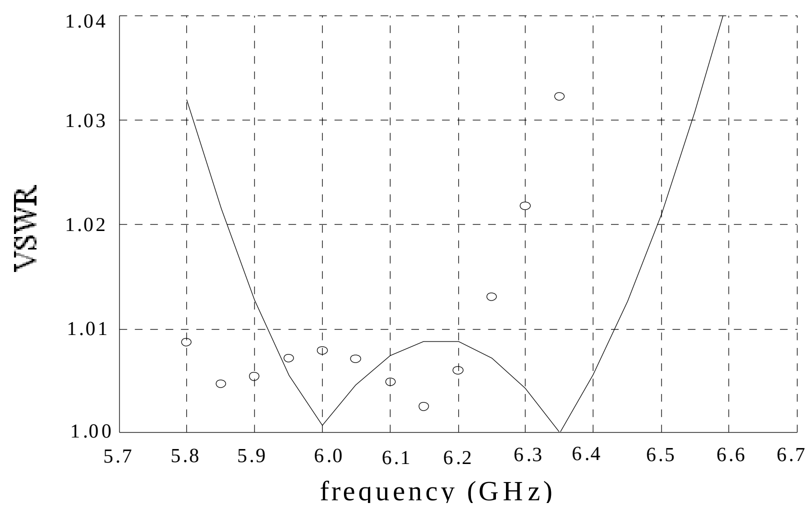
fine model exploits the 3D solver Maxwell Eminence

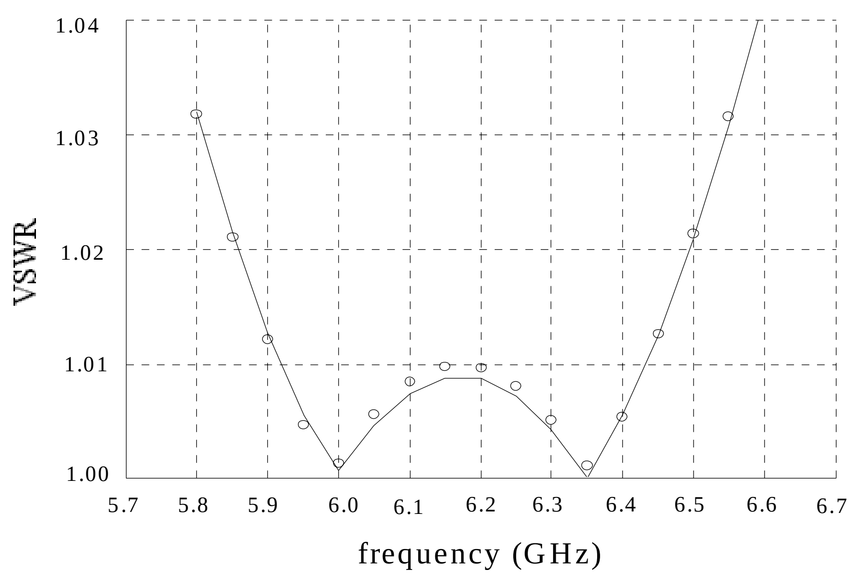
five Maxwell Eminence projects were needed by Empipe3D to parameterize the four designable parameters

the optimal design is obtained in 3 iterations requiring 5 Maxwell Eminence simulations

Two-Section Waveguide Transformer Responses

the optimal coarse model (—) response and the fine model response (o) at the initial and final designs





Conclusions

review of recent developments in the area of automated EM optimization of microwave circuits and structures

Datapipe technology has been found to be an effective and efficient tool to drive a variety of disjoint EM simulators

interpolation integrated with a database system of simulated results reduces the required number of EM simulations

Geometry Capture technique for user parameterization of geometrical structures is a key to design optimization of arbitrary structures

Space Mapping technique is very promising when extremely CPU intensive simulators are used for optimization

Space Mapping combines the speed of circuit-level optimization with the accuracy of EM simulations