AUTOMATED ELECTROMAGNETIC OPTIMIZATION OF 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

EM Simulators

numerically solving Maxwell's equations

finite element method FEM
integral equation/boundary element method IE/BEM
transmission-line method TLM
finite difference time-domain method FDTD
mode matching method MM
method of moments MoM

unsurpassed accuracy

extended validity ranges

capability of handling fairly arbitrary geometries

EM simulators will not realize their full potential to the designer unless they are optimizer-driven to automatically adjust designable parameters

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

Datapipe technology allows users to enhance their own software with OSA90's friendly user interface, graphics, expression parser, optimization and statistical features

Datapipe Connections to OSA90 Optimization Engine

em - Sonnet's efficient full-wave MoM field solver for predominantly planar circuits (through Empipe)

Maxwell Eminence and HFSS - Ansoft's and HP's FEM based solvers for full-wave EM field analysis of 3D passive structures (through Empipe3D)

2d-tlm and 3d-tlm - 2D and 3D time-domain TLM based simulators (Hoefer, University of Victoria)

RWGMM - Fritz Arndt's MM library of fast and accurate waveguide building blocks

SPICE - analog circuit simulator

MM solvers developed at the University of Perugia

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

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

response function $R(\boldsymbol{ö})$ is interpolated using

$$R(\boldsymbol{ö}) = R_{EM}(\boldsymbol{ö}^{c}) + \boldsymbol{è}^{T}\,\mathrm{sign}\boldsymbol{È}\;\mathrm{Ä}\boldsymbol{R}_{EM}(\boldsymbol{B})$$

where

$$\mathrm{Ä}\boldsymbol{R}_{EM}(\boldsymbol{B}) = [\; R_{EM}(\boldsymbol{ö}^{1})\text{-}R_{EM}(\boldsymbol{ö}^{c}) \;\; \ldots \;\; R_{EM}(\boldsymbol{ö}^{n})\text{-}R_{EM}(\boldsymbol{ö}^{c}) \;]^{T}$$

and

R_{EM}	the interpolated response
$\boldsymbol{ö}^{c}$	the center base point (on-grid)
$\boldsymbol{ö}^{1}, \boldsymbol{ö}^{2}, \ldots, \boldsymbol{ö}^{n}$	n base points obtained by perturbing each parameter $ö_i$ by its discretization step d_i (on-grid)
$\boldsymbol{è}$ and $\boldsymbol{È}$	the relative deviation of the off-grid point $\boldsymbol{ö}$ from $\boldsymbol{ö}^{c}$, 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

$$\frac{\partial R(\boldsymbol{\varphi})}{\partial \boldsymbol{\varphi}} = \boldsymbol{D}^{-1}\,\mathrm{sign}\Big[\,\Delta \boldsymbol{R}_{EM}(\boldsymbol{B})$$

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

Library Approach to Parameterization

in our earlier work (*Empipe Version 1.1, 1992*) we created a library of predefined elements that were already parameterized and ready for optimization

applicability is limited to structures that are decomposable into available library elements

even a comprehensive library would not satisfy all microwave designers, simply because of their creativity in devising new structures

inherently omits possible proximity couplings

Geometry Capture

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

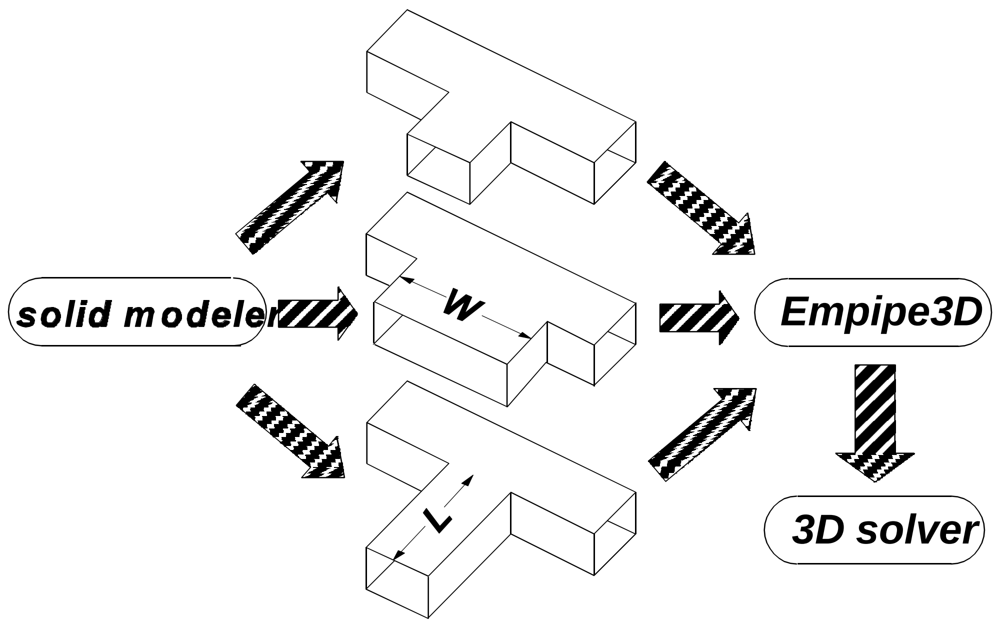
once a structure is captured

the modified project files are automatically generated

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

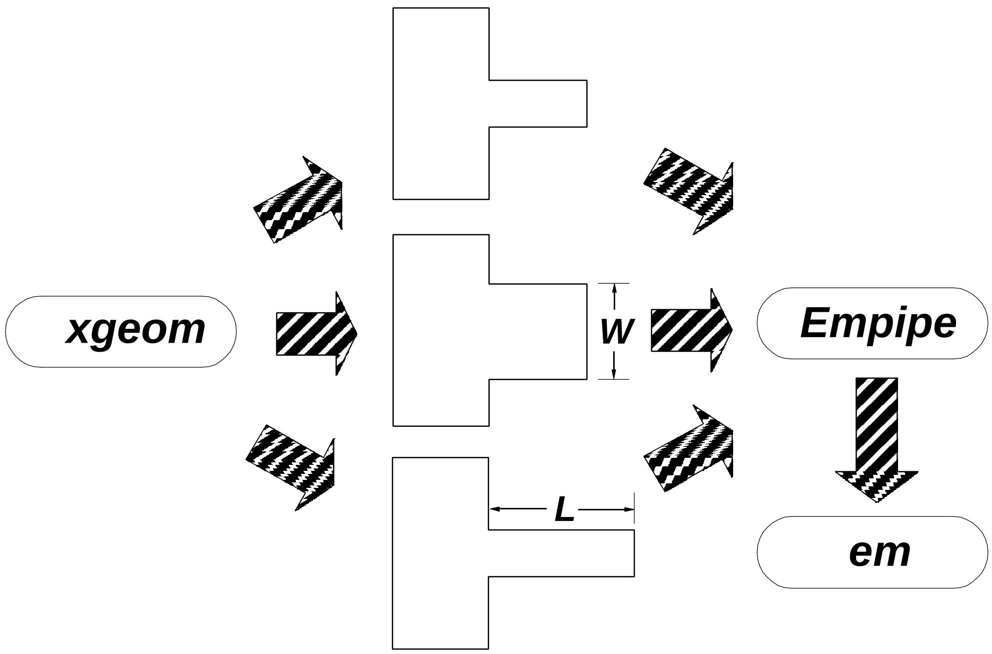
dielectric and other material parameters can also be selected for optimization

The Process of Geometry Capture



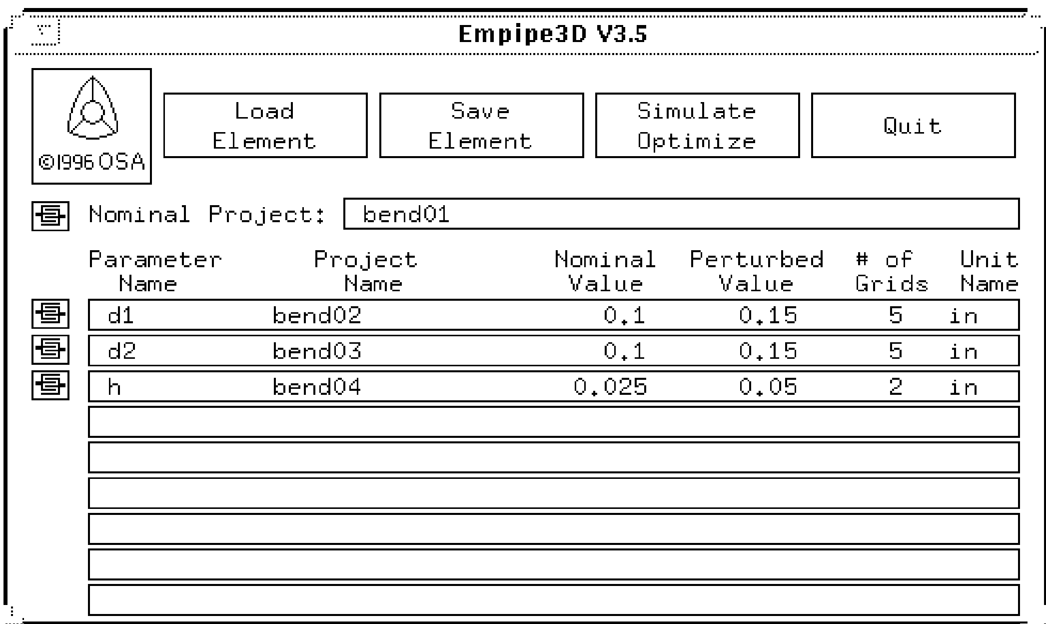
parameterization of 3D structures

The Process of Geometry Capture



parameterization of planar structures

The Geometry Capture Form Editor



"# of Grids"	the number of interpolation intervals
"Unit Name"	IN (inch), MIL (milli-inch), etc.

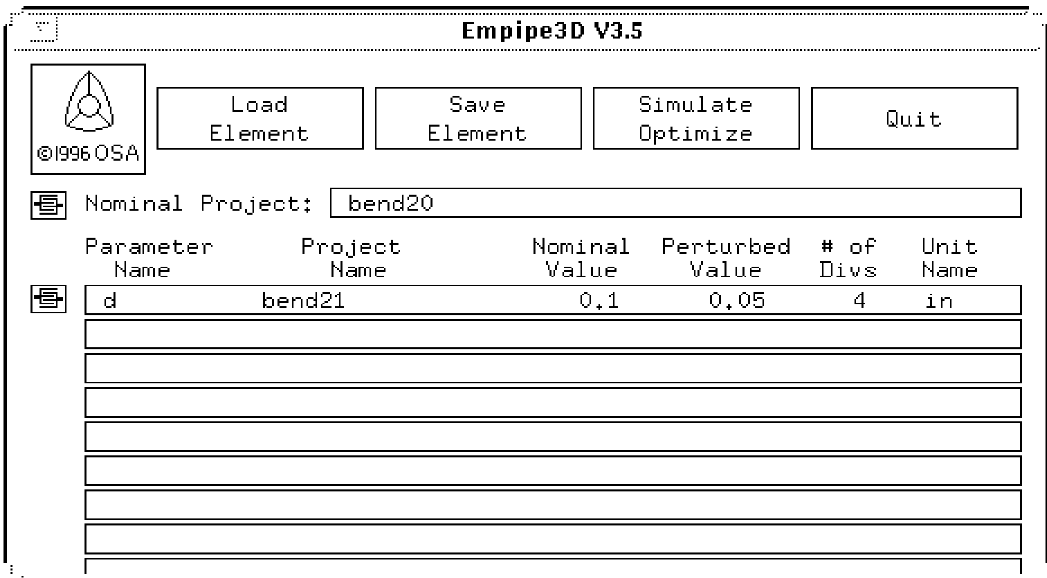
nominal project:

bend01	$d_1 = 0.1$	$d_2 = 0.1$	$h = 0.025$

perturbed projects:

bend02	$d_1 = 0.15$	$d_2 = 0.1$	$h = 0.025$
bend03	$d_1 = 0.1$	$d_2 = 0.15$	$h = 0.025$
bend04	$d_1 = 0.1$	$d_2 = 0.1$	$h = 0.05$

Geometry Capture Form Editor



"# of Divs"	the number of interpolation intervals	
"Unit Name"	IN (inch), MIL (milli-inch), etc.	
nominal project:	bend20	d = 0.1 inch
perturbed project:	bend21	d = 0.05 inch

Space Mapping (SM)

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

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 $\boldsymbol{x}^1_{EM} = \boldsymbol{x}^*_{OS}$

in the *i*th step the $\boldsymbol{X}_{EM}$ model is simulated at $\boldsymbol{x}^i_{EM}$

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

$$\underset{\boldsymbol{x}^i_{OS}}{\text{minimize}} \; \| \boldsymbol{R}_{OS}(\boldsymbol{x}^i_{OS}) - \boldsymbol{R}_{EM}(\boldsymbol{x}^i_{EM}) \|$$

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

Aggressive Space Mapping Optimization

the next iterate is found by a quasi-Newton step

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

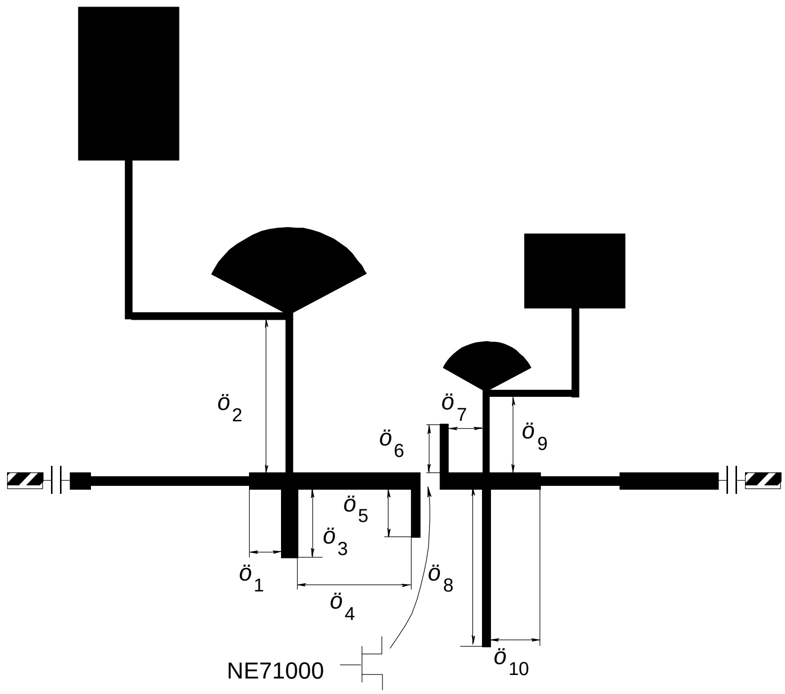
where

$\boldsymbol{B}^i$ 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

Optimization of a Class B Frequency Doubler



the entire structure between two capacitors is parameterized and simulated by ***em***

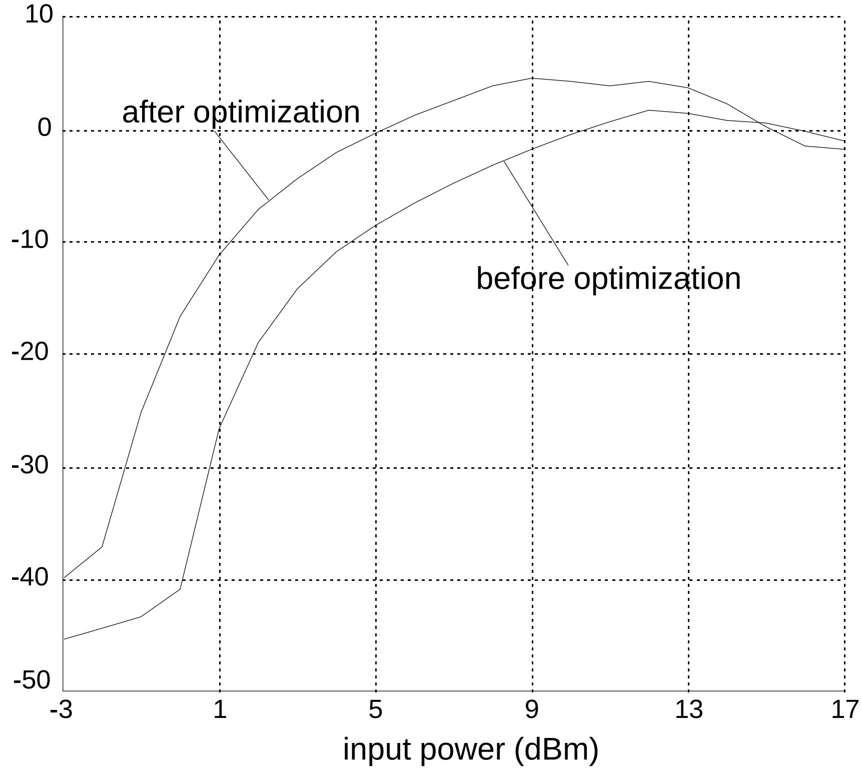
the built-in Curtice and Ettenberg FET model used for the active device

ten parameters, $\ddot{o}_i$ selected as design variables

design specifications at 7 GHz and 10 dBm input power

conversion gain $\geq$ 3 dB
spectral purity $\geq$ 20 dB

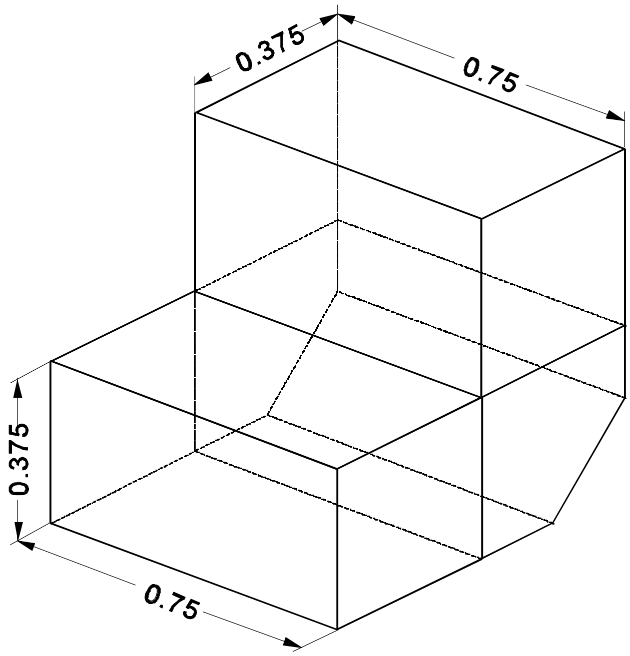
Optimization of Frequency Doubler Conversion Gain



significant improvement of the circuit performance is obtained

all specifications are satisfied after minimax optimization

Design of an Optimal Mitered Waveguide Bend



fully 3D EM optimization using Empipe3D and HFSS

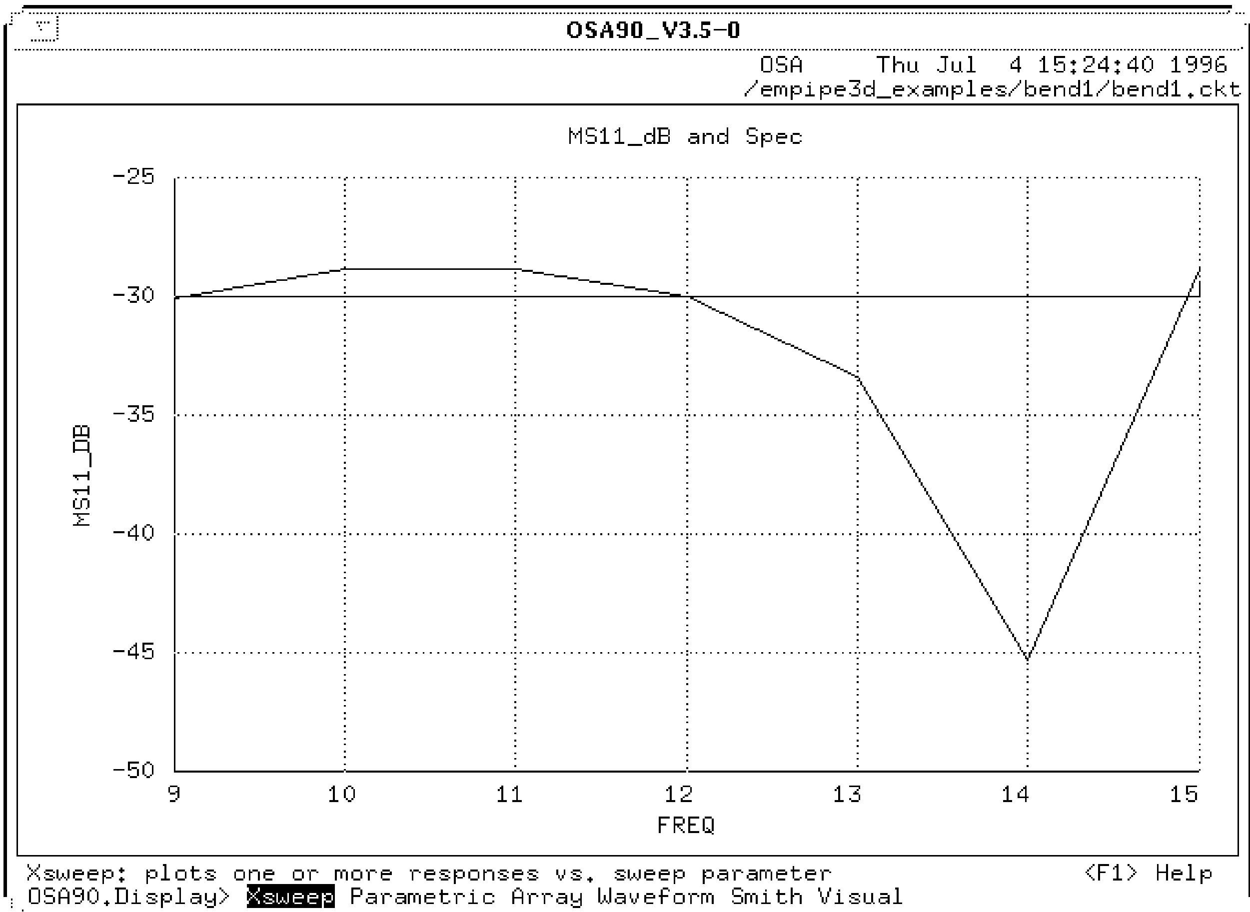
just one parameter controls the location of the 45° bend

design specification

return loss $\geq$ 30 dB

over the full bandwidth of $9 \leq f \leq 15$ GHz

Waveguide Bend Response After Optimization



the response of the optimized structure achieved a return loss of about 29 dB

the solution, d_{opt} = 0.2897 inch, is reached after 14 iterations starting from d = 0.1 inch, using only 9 FEM simulations

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