NOVEL ELECTROMAGNETIC OPTIMIZATION TECHNIQUES, INCLUDING SPACE MAPPING

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Critical Issues of Automated EM Optimization

interfaces between gradient-based optimizers and discretized EM field solvers: interpolation and database

integration of EM analysis with circuit simulation, including harmonic balance simulation of nonlinear circuits

Geometry Capture™: user-defined optimizable structures of arbitrary geometry

Space Mapping™ optimization: intelligent correlation between engineering models: EM models, empirical models and equivalent circuit models

smoothness and continuity of response interpolation

robustness of optimization algorithms and uniqueness of the solutions

parallel and massively parallel EM analyses

Background

assume that X_{os} (optimization space) and X_{em} (EM space) have the same dimensionality, i.e.,

$$x_{os} \in \mathbb{R}^n \quad \text{and} \quad x_{em} \in \mathbb{R}^n,$$

but may not represent the same parameters

the X_{os}-space model can be comprised of empirical models, or an efficient coarse-grid EM model

the X_{em}-space model is typically a fine-grid EM model but, ultimately, can represent actual hardware prototypes

we assume that the X_{os}-space model responses, $R_{os}(x_{os})$, are much faster to calculate but less accurate than the X_{em}-space model responses, $R_{em}(x_{em})$

we initially perform optimization in X_{os} to obtain the optimal design x_{os}^*, for instance in the minimax sense

subsequently, apply SM to find the mapped solution $\bar{x}_{em}$ in X_{em} to reproduce the optimal performance predicted by the empirical model

The Concept of Space Mapping
(Bandler, Biernacki, Chen, Grobelny and Hemmers, 1994)

our aim is to find an appropriate mapping, P, from the X_{em}-space to the X_{os}-space, i.e.,

$$x_{os} = P(x_{em})$$

such that

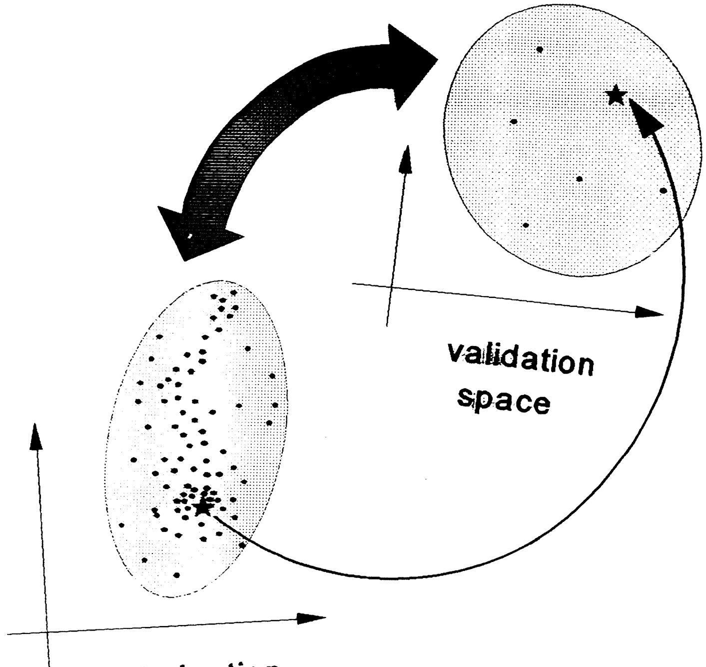
$$R_{os}(P(x_{em})) \approx R_{em}(x_{em})$$

we assume that such a mapping exists and is one-to-one within some local modeling region encompassing our SM solution

once the mapping is established, the SM solution is

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

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



optimization model: $\boldsymbol{R}_{os}(\boldsymbol{x}_{os})$

EM model: $\boldsymbol{R}_{em}(\boldsymbol{x}_{em})$

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

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

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

Original Space Mapping Method

the mapping is established through an iterative process

to obtain the initial approximation to the mapping, $P^{(0)}$, we perform EM analyses at a preselected set of base points in X_{em} around the starting point

as the first base point we may select the starting point, i.e.,

$$x_{em}^{(1)} = x_{os}^{*}$$

assuming x_{em} and x_{os} represent the same physical parameters, followed by additional base points chosen by perturbation as

$$x_{em}^{(i)} = x_{em}^{(1)} + \Delta x_{em}^{(i-1)}, \quad i = 2, 3, \ldots, m$$

this is followed by parameter extraction optimization in X_{os} to obtain the set of corresponding base points $x_{os}^{(i)}$ according to

$$\underset{x_{os}^{(i)}}{\text{minimize}} \; \| R_{os}(x_{os}^{(i)}) - R_{em}(x_{em}^{(i)}) \|$$

for $i = 1, 2, \ldots, m$, where $\| \cdot \|$ indicates a suitable norm

Original Space Mapping Method (continued)

at the jth iteration, both sets may be expanded to contain m_j points which are used to establish the updated mapping $P^{(j)}$

the current approximation $P^{(j)}$ is used to estimate $\bar{x}_{em}$ as

$$x_{em}^{(m_j+1)} = P^{(j)^{-1}}(x_{os}^*)$$

the process continues until the termination condition

$$\| R_{os}(x_{os}^*) - R_{em}(x_{em}^{(m_j+1)}) \| \leq \epsilon$$

is satisfied, where ϵ is a small positive constant, then $P^{(j)}$ is our desired P

if not, the set of base points in X_{em} is augmented by $x_{em}^{(m_j+1)}$ and correspondingly, $x_{os}^{(m_j+1)}$ determined by parameter extraction augments the set of base points in X_{os}

upon termination, we set $\bar{x}_{em} = x_{em}^{(m_j+1)} = P^{(j)^{-1}}(x_{os}^*)$ as the SM solution

Aggressive Approach to Space Mapping
(Bandler, Biernacki, Chen, Hemmers and Madsen, 1995)

at the SM solution, $R_{em}(x_{em}^{(M)})$ will closely match $R_{os}(x_{os}^{*})$,

$$\| R_{os}(x_{os}^{*}) - R_{em}(x_{em}^{(M)}) \| \leq \epsilon$$

where M is the number of iterations needed to converge to an SM solution

hence, after an additional parameter extraction optimization in X_{os}, the resulting point

$$x_{os}^{(M)} = P(x_{em}^{(M)})$$

approaches the point x_{os}^{*} (optimal solution in X_{os}), or

$$\| x_{os}^{(M)} - x_{os}^{*} \| \leq \eta \quad \text{as} \quad j \to M$$

where η is a small positive constant

by setting η to 0, we consider the set of n nonlinear equations

$$f(x_{em}) = \mathbf{0}$$

of the form

$$f(x_{em}) = P(x_{em}) - x_{os}^{*}$$

where x_{os}^{*} is a given vector

Aggressive Space Mapping - Quasi-Newton Iteration

let $x_{em}^{(j)}$ be the jth approximation to the solution and $f^{(j)}$ written for $f(x_{em}^{(j)})$

the next iterate is found by a quasi-Newton iteration

$$x_{em}^{(j+1)} = x_{em}^{(j)} + h^{(j)}$$

by solving the linear system

$$B^{(j)} h^{(j)} = -f^{(j)}$$

$B^{(j)}$ is an approximation to the Jacobian matrix

$$J(x_{em}^{(j)}) = \left. \left(\frac{\partial f^T(x_{em})}{\partial x_{em}} \right)^T \right|_{x_{em} = x_{em}^{(j)}}$$

in our implementation, $B^{(1)}$ is set to the identity matrix

the approximation to the Jacobian matrix is updated by the classic Broyden formula (*Broyden, 1965*)

$$B^{(j+1)} = B^{(j)} + \frac{f(x_{em}^{(j)} + h^{(j)}) - f(x_{em}^{(j)}) - B^{(j)} h^{(j)}}{h^{(j)T} h^{(j)}} h^{(j)T}$$

Aggressive Space Mapping - Implementation

begin with a point, $x_{os}^{*} \triangleq \arg\min \{H(x_{os})\}$, representing the optimal design in X_{os} where $H(x_{os})$ is some appropriate objective function

Step 0. initialize $x_{em}^{(1)} = x_{os}^{*}$, $B^{(1)} = \mathbf{1}$, $f^{(1)} = P(x_{em}^{(1)}) - x_{os}^{*}$, $j = 1$; stop if $\| f^{(1)} \| \leq \eta$

Step 1. solve $B^{(j)} h^{(j)} = -f^{(j)}$ for $h^{(j)}$

Step 2. set $x_{em}^{(j+1)} = x_{em}^{(j)} + h^{(j)}$

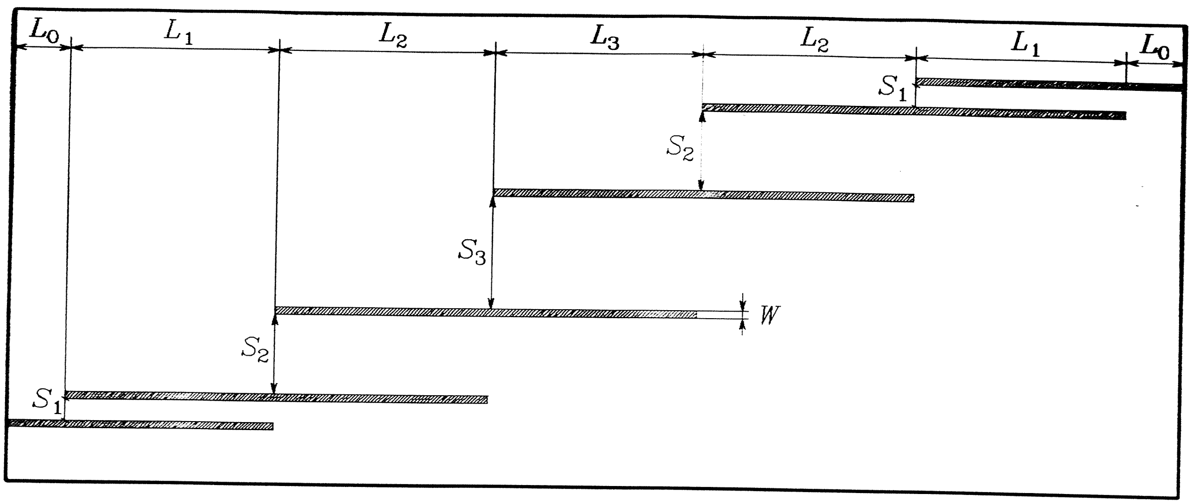
Step 3. evaluate $P(x_{em}^{(j+1)})$

Step 4. compute $f^{(j+1)} = P(x_{em}^{(j+1)}) - x_{os}^{*}$; if $\| f^{(j+1)} \| \leq \eta$, stop

Step 5. update $B^{(j)}$ to $B^{(j+1)}$

Step 6. set $j = j + 1$; go to *Step* 1

The HTS Quarter-Wave Parallel Coupled-Line Filter
(*Westinghouse, 1993*)



20 mil thick lanthanum aluminate substrate

the dielectric constant is 23.4

the x and y grid sizes for ***em*** simulation are 1.0 and 1.75 mil

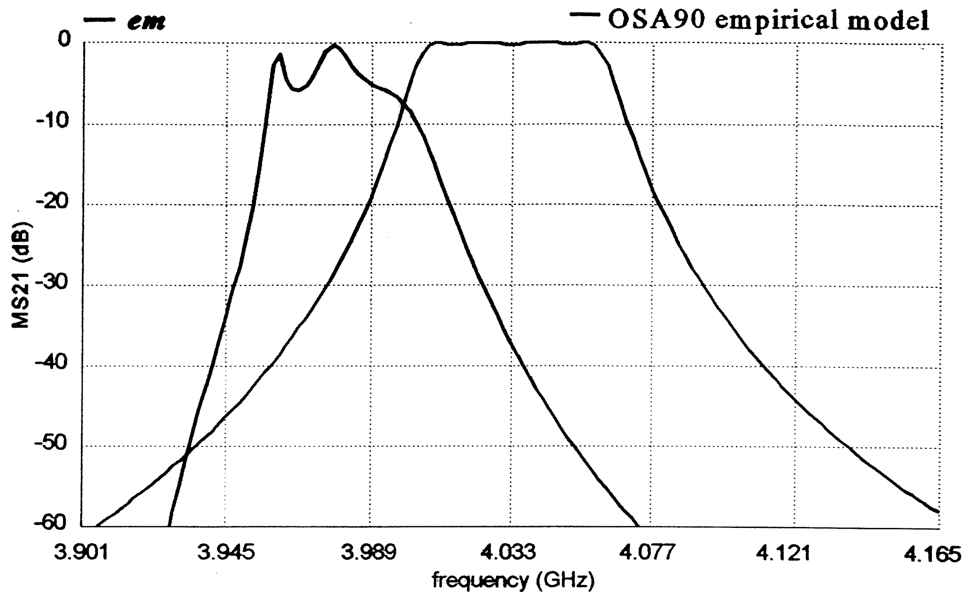
100 elapsed minutes are needed for ***em*** analysis at a single frequency on a Sun SPARCstation 10

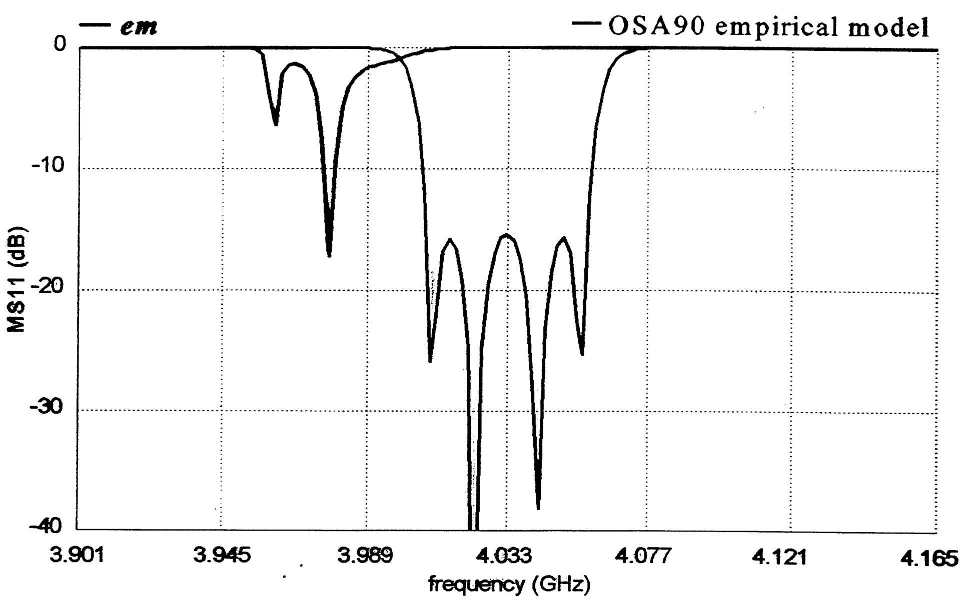
design specifications

$|S_{21}| < 0.05$ for $f < 3.967$ GHz and $f > 4.099$ GHz

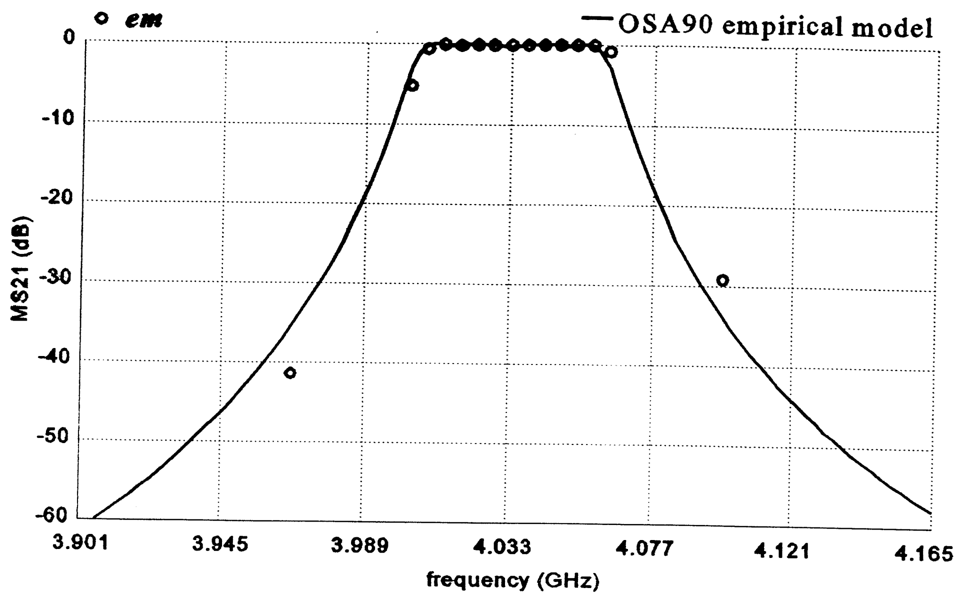
$|S_{21}| > 0.95$ for 4.008 GHz $< f < 4.058$ GHz

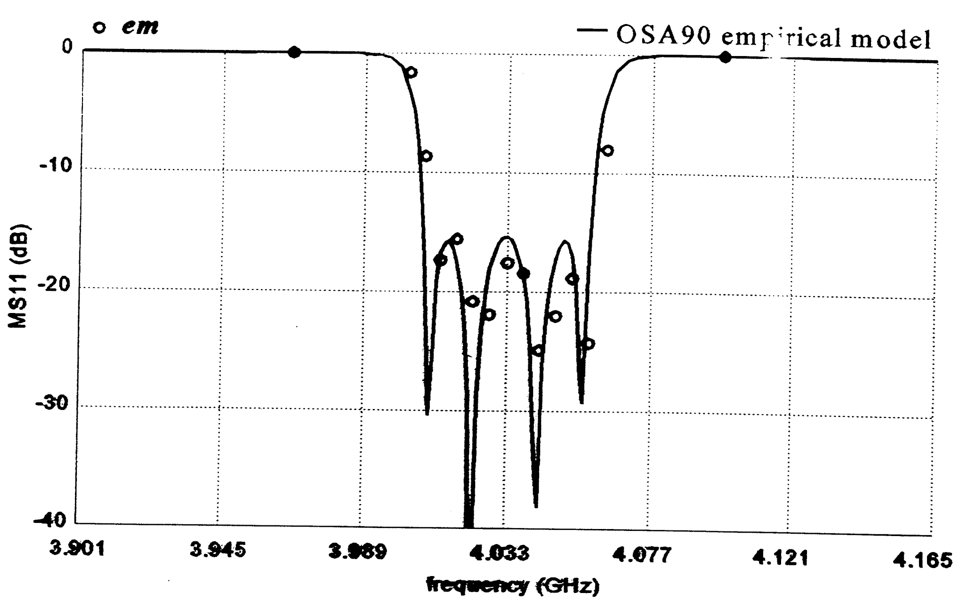
Starting Point of EM Optimization: Design Using Empirical Circuit Model





Solution by Aggressive Space Mapping After 3 Iterations





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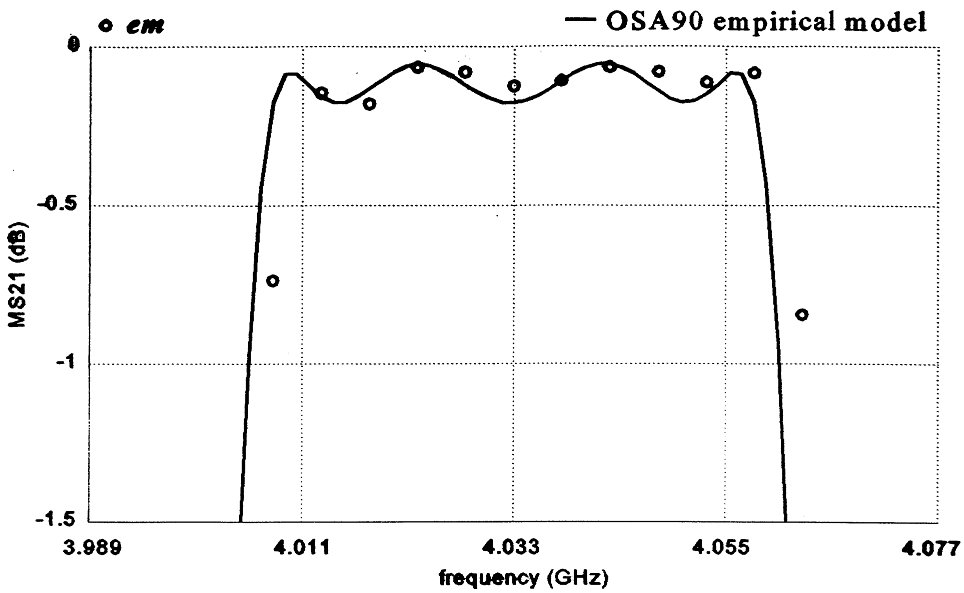
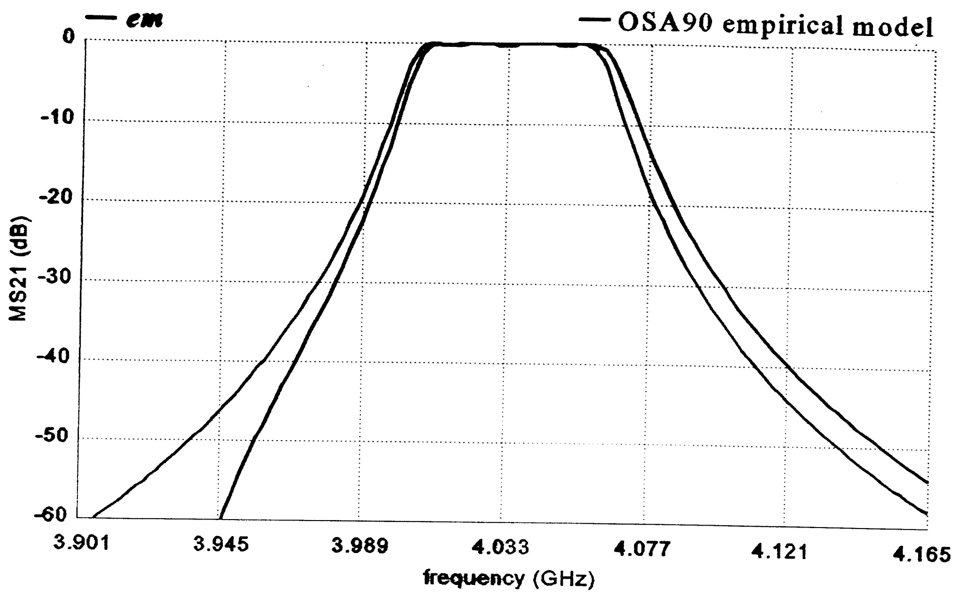
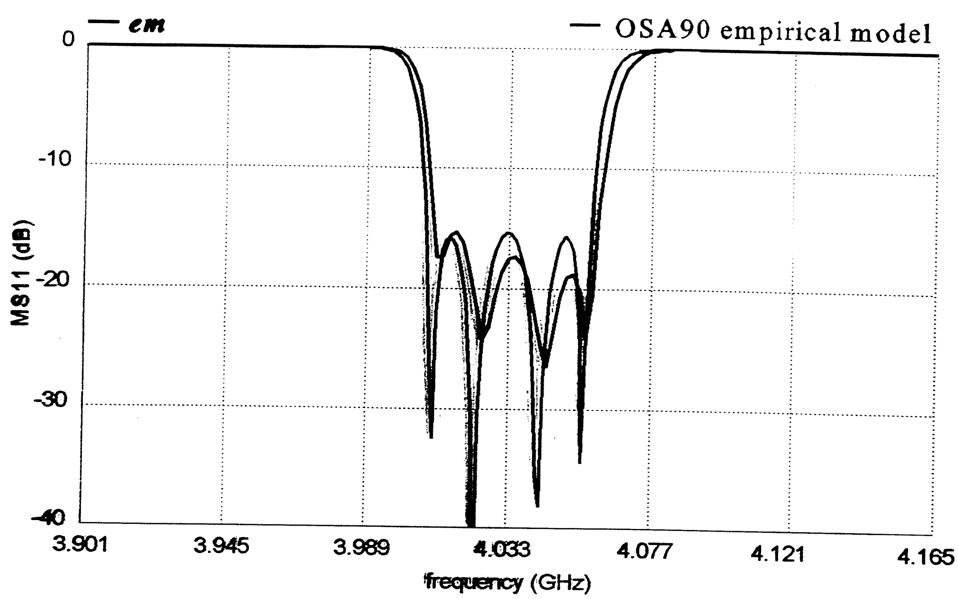
Solution by Aggressive Space Mapping
Detail of the Passband



Solution by Aggressive Space Mapping
Fine Frequency Sweep

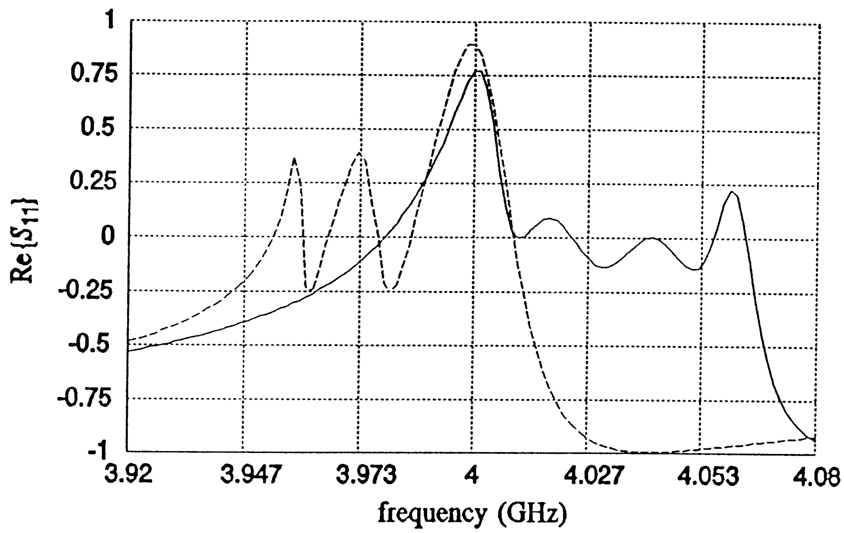




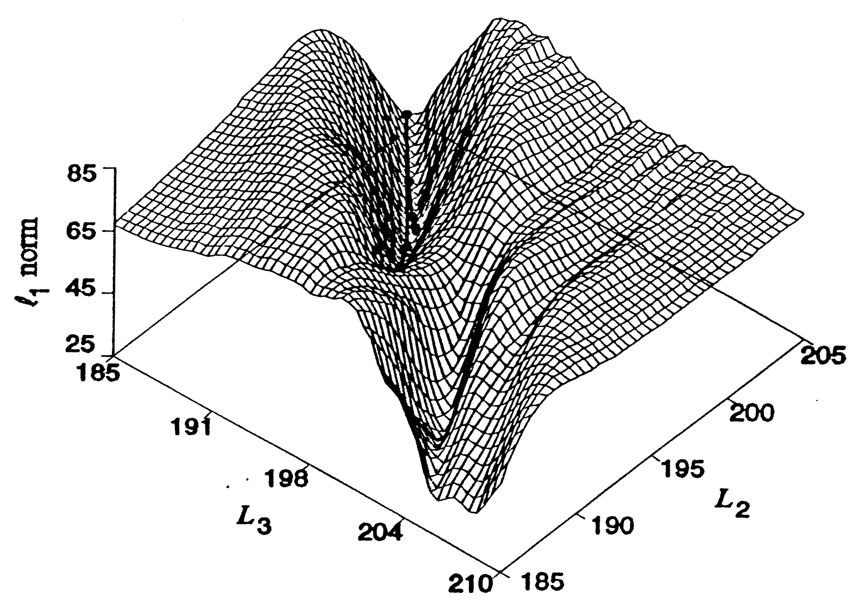
Frequency Space Mapping for Parameter Extraction

parameter extraction can be a serious challenge, especially at the starting point, if the model responses are misaligned

Re$\{S_{11}\}$ using OSA90/hope (—) and *em* (---) at x_{os}^*



straightforward optimization from such a starting point can lead to a local minimum



Frequency Space Mapping - Mapping and Alignment

to better condition the parameter extraction subproblem

first, we align R_{os} and R_{em} along the frequency axis using

$$\omega_{os} = P_{\omega}(\omega)$$

this frequency space mapping can be as simple as

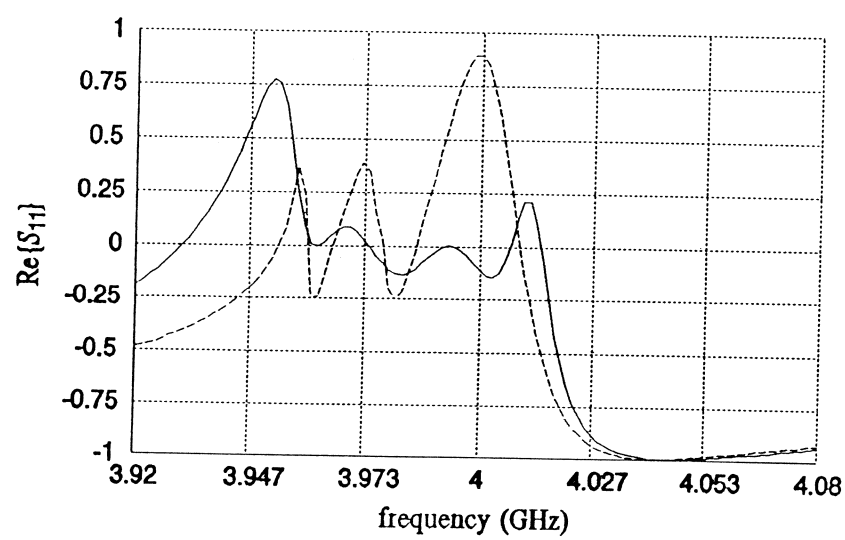
$$\omega_{os} = \sigma\,\omega + \delta$$

at the starting point, we determine σ_o and δ_o by

$$\underset{\sigma_o,\ \delta_o}{\text{minimize}}\ \| R_{os}(x_{os}, \sigma_o, \delta_o) - R_{em}(x_{em}) \|$$

where x_{os} and x_{em} are fixed and $x_{os} = x_{em}$

resulting alignment between OSA90/hope (—) and *em* (---):



Frequency Space Mapping: Sequential FSM (SFSM) Algorithm

we perform a sequence of optimizations to gradually achieve the identity Frequency Space Mapping

we optimize x_{os} to match R_{os} and R_{em}:

$$\underset{x_{os}^{(j)}}{\text{minimize}} \; \| R_{os}(x_{os}^{(j)}, \sigma^{(j)}, \delta^{(j)}) - R_{em}(x_{em}) \|$$

the values $\sigma^{(j)}$ and $\delta^{(j)}$ are updated according to

$$\sigma^{(j)} = 1 + (\sigma_o - 1)\frac{(K - j)}{K}$$

and

$$\delta^{(j)} = \delta_o \frac{(K - j)}{K},$$

respectively, for $j = 0, 1, ..., K$

K determines the number of steps in the sequence

larger values of K increase the probability of success in the parameter extraction subproblem at the expense of longer optimization time

Frequency Space Mapping:
Exact Penalty Function (EPF) Algorithm

we perform only one optimization to achieve the identity Frequency Space Mapping and optimize $\boldsymbol{x}_{os}$ to match $\boldsymbol{R}_{os}$ to $\boldsymbol{R}_{em}$

the ℓ_1 norm version of the EPF formulation is given by

$$\underset{x_{os},\, \sigma,\, \delta}{\text{minimize}} \quad \{\| R_{os}(x_{os}, \sigma, \delta) - R_{em}(x_{em}) \|_1 + \alpha_1 |\sigma - 1| + \alpha_2 |\delta|\}$$

the minimax version is given by

$$\underset{x_{os},\, \sigma,\, \delta}{\text{minimize}} \left\{ \max_{1 \le i \le 4} \left[U(x_{os}, \sigma, \delta),\; U(x_{os}, \sigma, \delta) - \alpha_i g_i \right] \right\}$$

where

$$U(x_{os}, \sigma, \delta) = \| R_{os}(x_{os}, \sigma, \delta) - R_{em}(x_{em}) \|$$

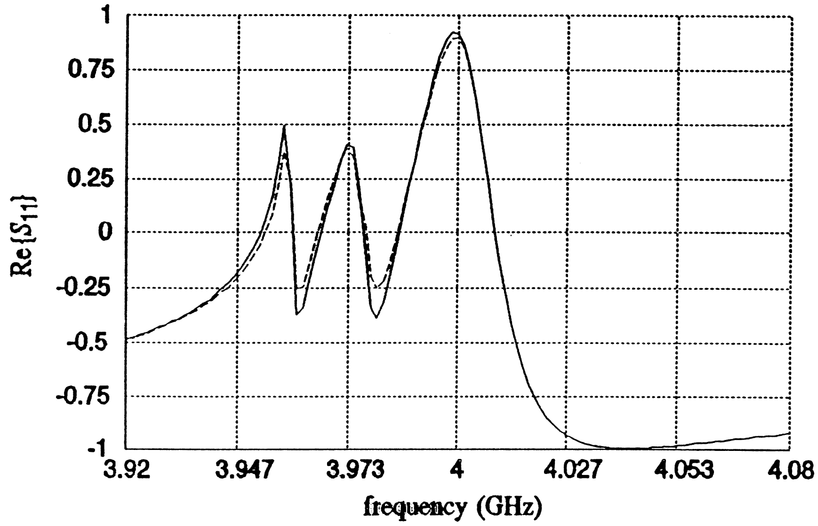
and

$$g(\sigma, \delta) = \begin{bmatrix} \sigma - 1 \\ 1 - \sigma \\ \delta \\ -\delta \end{bmatrix}$$

in both EPF formulations, α_i are kept fixed and must be sufficiently large to obtain the identity mapping and hence the solution to the parameter extraction problem

Frequency Space Mapping - Results

Re$\{S_{11}\}$ using OSA90/hope (—) and *em* (---)



resulting match after applying the FSM algorithm