EM OPTIMIZATION
USING SPACE MAPPING

J.W. Bandler

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J.W. Bandler

Optimization Systems Associates Inc.
P.O. Box 8083, Dundas, Ontario
Canada L9H 5E7

Email osa@osacad.com URL http://www.osacad.com

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USING EM AND CIRCUIT SIMULATION TECHNIQUES
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Introduction

commercial EM simulators are becoming increasingly faster and more accurate

in order to realize their full potential, EM simulators have to be optimizer-driven to automatically adjust designable parameters

the new thrust is to integrate EM simulations directly into the linear/nonlinear circuit design process transparently to the designer

numerical methods offer excellent accuracy at the expense of heavy demand on computer resources

practical use of EM simulators is often limited to design validation

it is commonly perceived that iterative optimization methods would require too many EM simulations and consequently consume excessive CPU time

the objective of Space Mapping is to avoid direct optimization of computationally intensive models

Overview of Presentation

electromagnetic (EM) optimization

Space Mapping (SM) optimization

SM optimization of an HTS filter

combining decomposition and SM in a coherent strategy

optimization of an interdigital filter

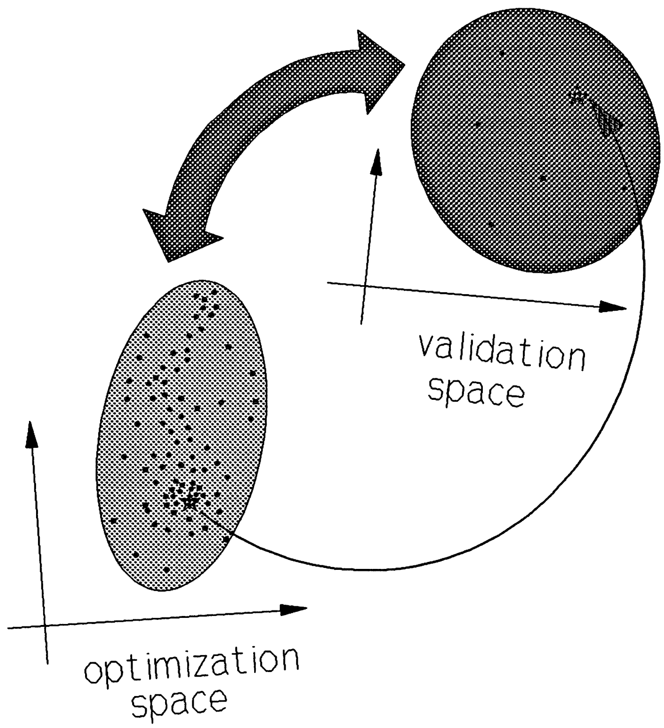
SM optimization using hybrid mode-matching (MM) /network theory and finite-element (FEM) models

SM optimization of an H-plane waveguide filter with rounded corners

Monte Carlo analysis of manufacturing tolerances using SM

SM between coarse and fine hybrid MM/network theory models

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



optimization model: $R_{os}(x_{os})$

EM model: $R_{em}(x_{em})$

Space Mapping: $x_{os} = P(x_{em})$

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

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

The Advantages of Space Mapping

the aim is to avoid direct optimization in the CPU-intensive X_{em} space

the bulk of the computation involved in optimization is carried out in the X_{os} space

the optimal solution is mapped from the X_{os} space to the X_{em} space using the inverse mapping P^{-1}

we expect to obtain a rapidly improved design after each fine model simulation

significantly more efficient than the "brute force" direct EM optimization

a fundamentally new concept in engineering-oriented optimization practice

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

new algorithm aggressively exploits *every* EM simulation

avoids upfront EM analyses at many base points

applies the classical Broyden update to the mapping

quasi-Newton iteration

$$x_{em}^{(j+1)} = x_{em}^{(j)} - B^{(j)^{-1}} \left(P^{(j)} (x_{em}^{(j)}) - x_{os}^{*} \right)$$

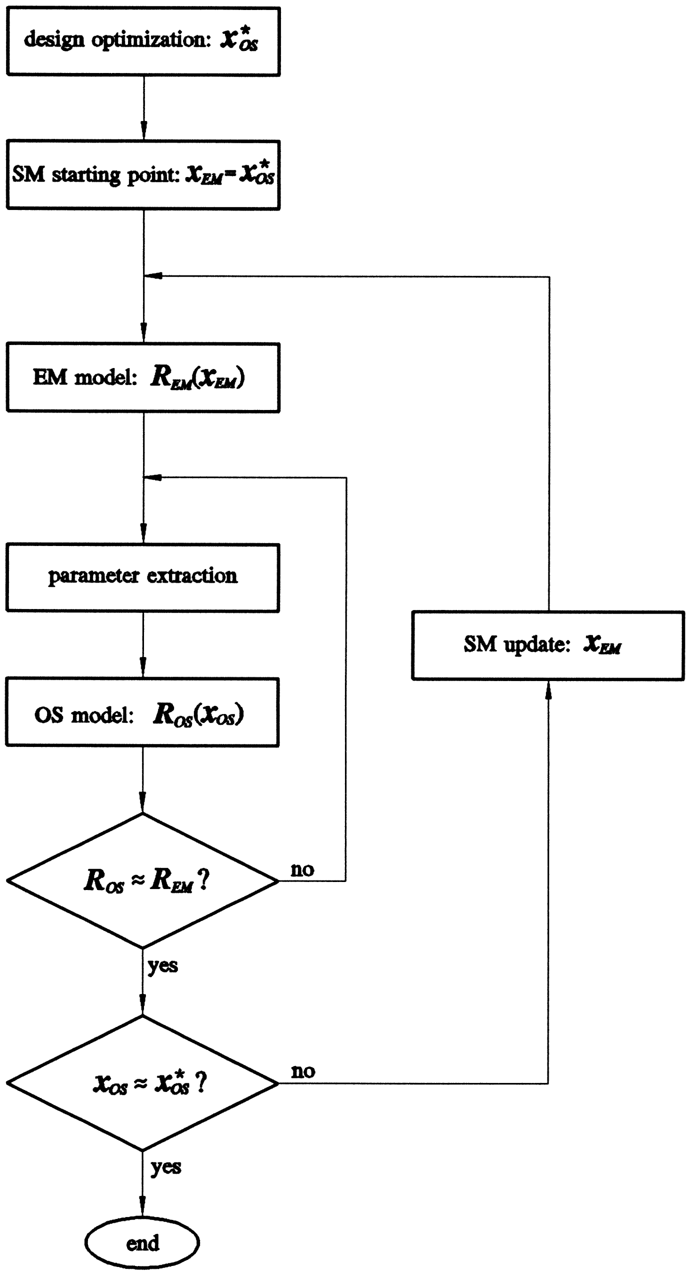
Broyden update:

$$B^{(j+1)} = B^{(j)} + \frac{\left(P^{(j+1)} (x_{em}^{(j+1)}) - x_{os}^{*} \right) h^{(j)^T}}{h^{(j)^T} h^{(j)}}$$

where

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

Fully Automated Space Mapping Optimization



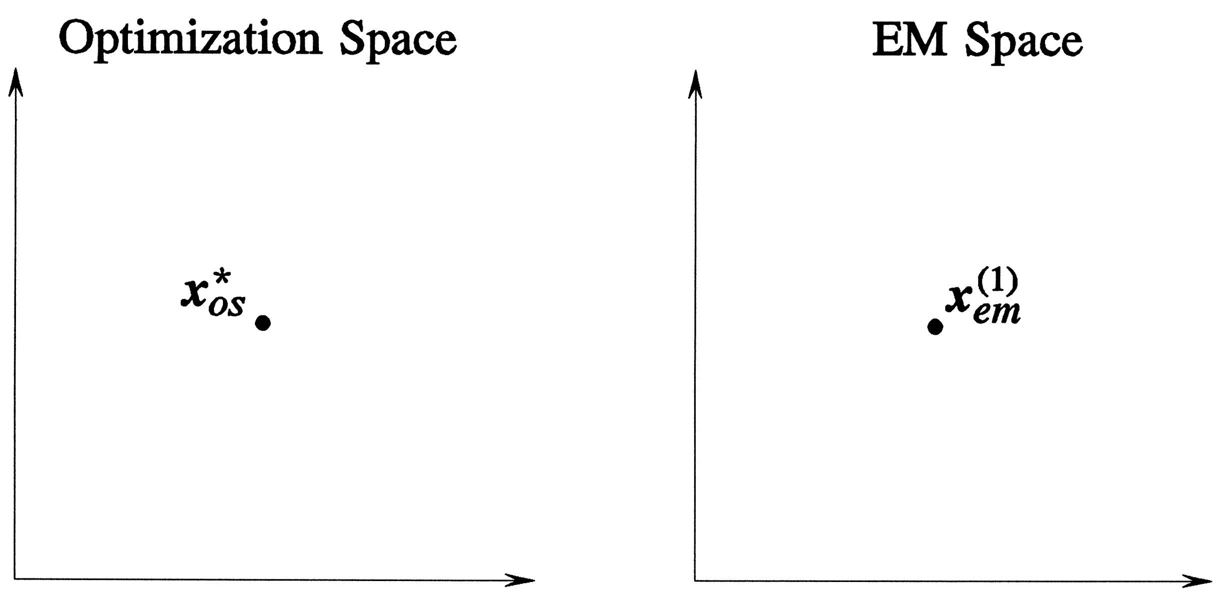
two-level Datapipe architecture

Illustration of Aggressive Space Mapping Optimization

Step 0

find the optimal design x_{os}^* in Optimization Space

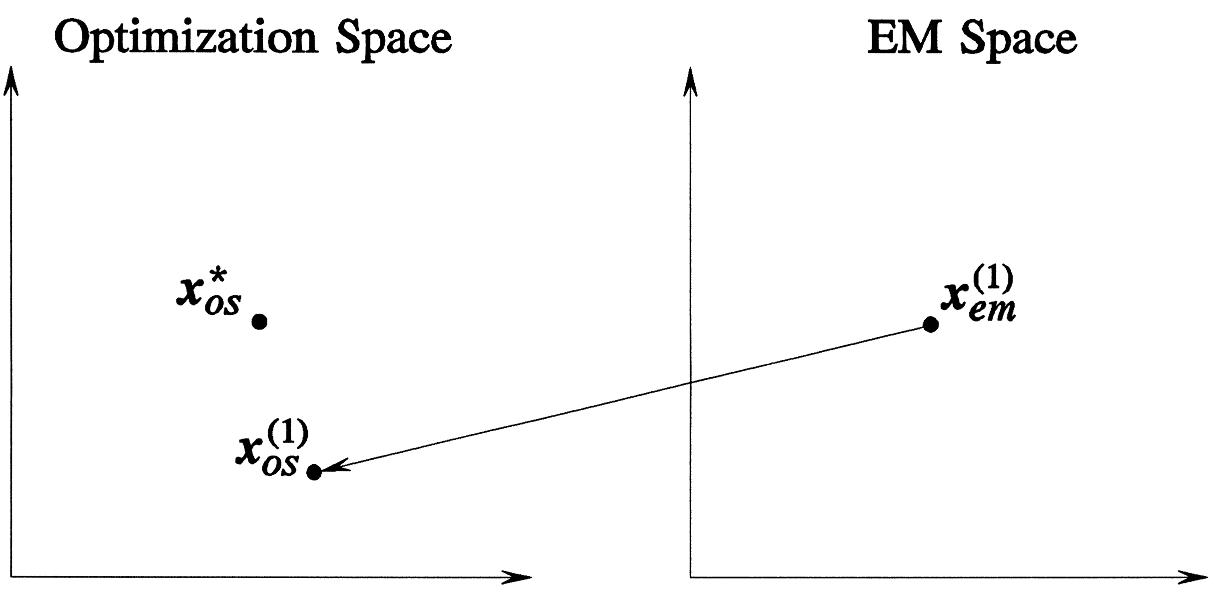
Step 1



set $x_{em}^{(1)} = x_{os}^*$ assuming x_{em} and x_{os} represent the same physical parameters

Illustration of Aggressive Space Mapping Optimization

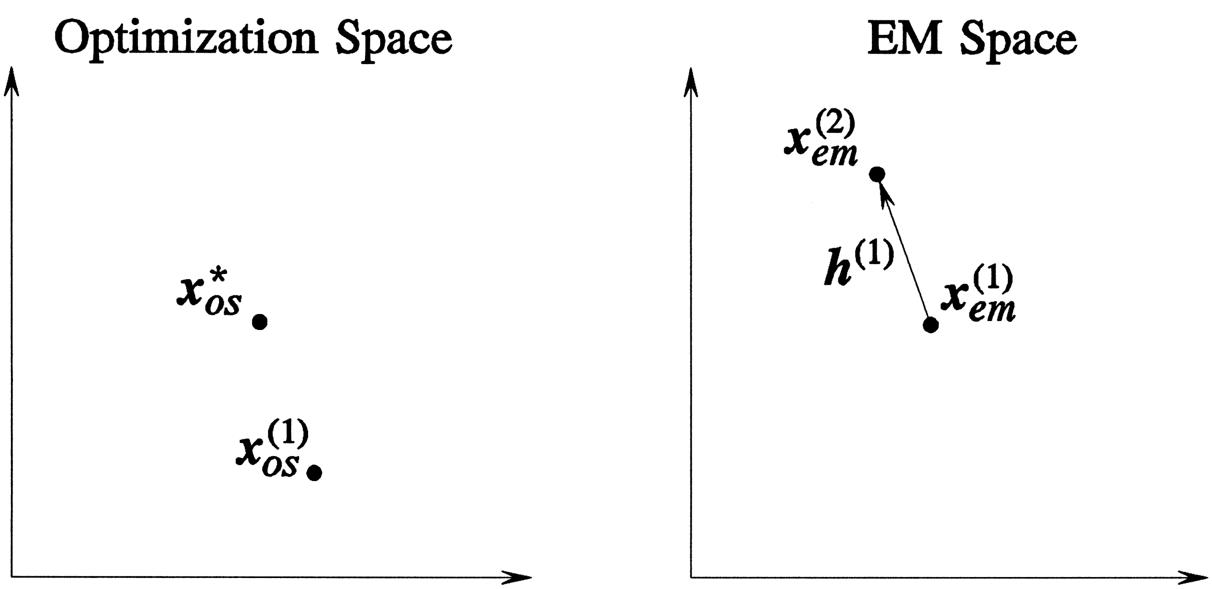
Step 2



perform X_{os}-space model parameter extraction

Illustration of Aggressive Space Mapping Optimization

Step 3



initialize Jacobian approximation $B^{(1)} = \mathbf{1}$

obtain $x_{em}^{(2)}$ by solving

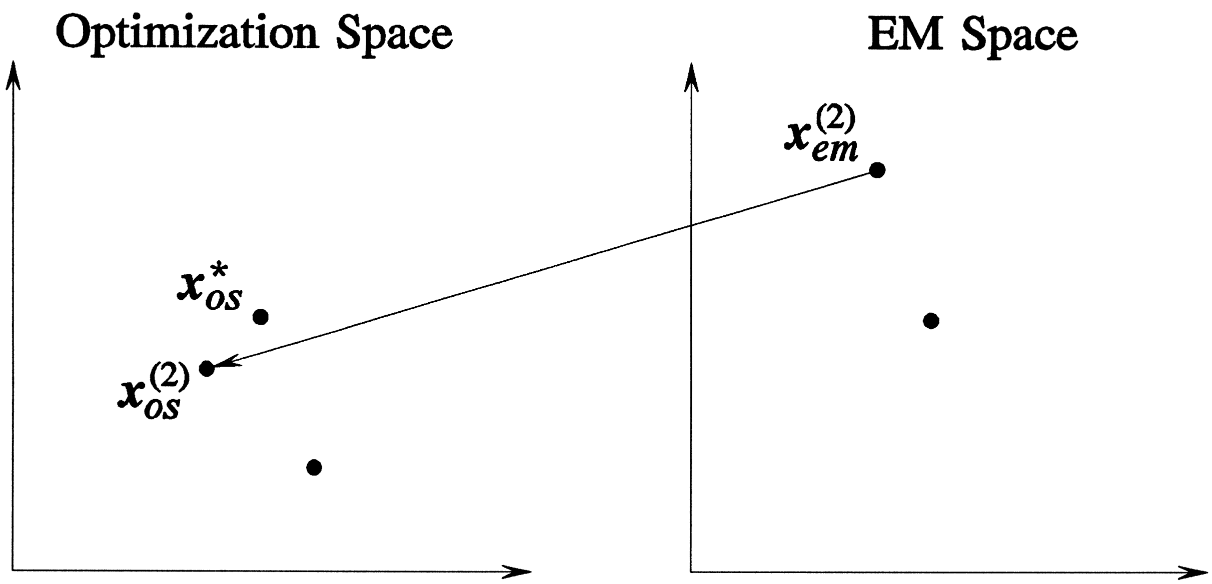
$$B^{(1)}h^{(1)} = -f^{(1)}$$

where

$$f^{(1)} = x_{os}^{(1)} - x_{os}^*$$

Illustration of Aggressive Space Mapping Optimization

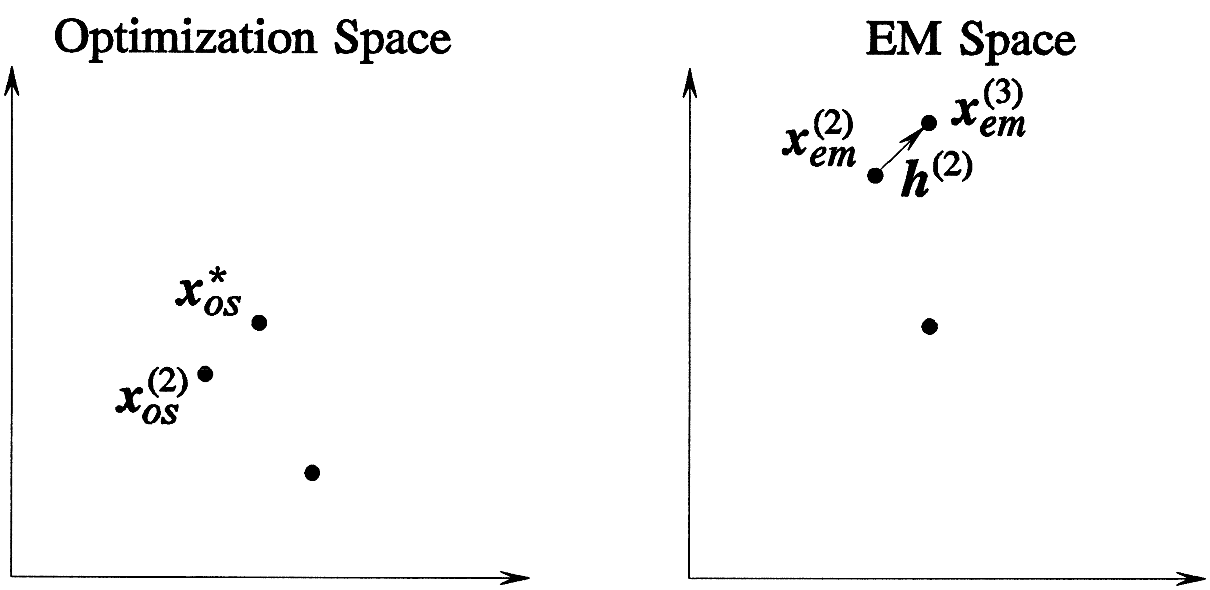
Step 4



perform X_{os}-space model parameter extraction

Illustration of Aggressive Space Mapping Optimization

Step 5



update Jacobian approximation from $B^{(1)}$ to $B^{(2)}$

obtain $x_{em}^{(3)}$ by solving

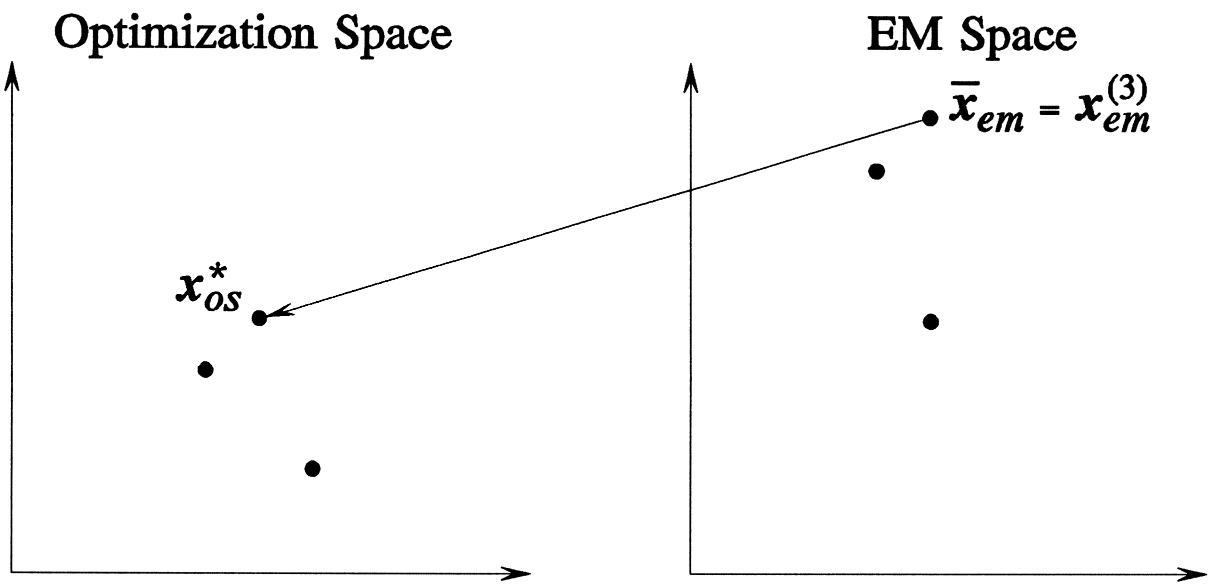
$$B^{(2)}h^{(2)} = -f^{(2)}$$

where

$$f^{(2)} = x_{os}^{(2)} - x_{os}^{*}$$

Illustration of Aggressive Space Mapping Optimization

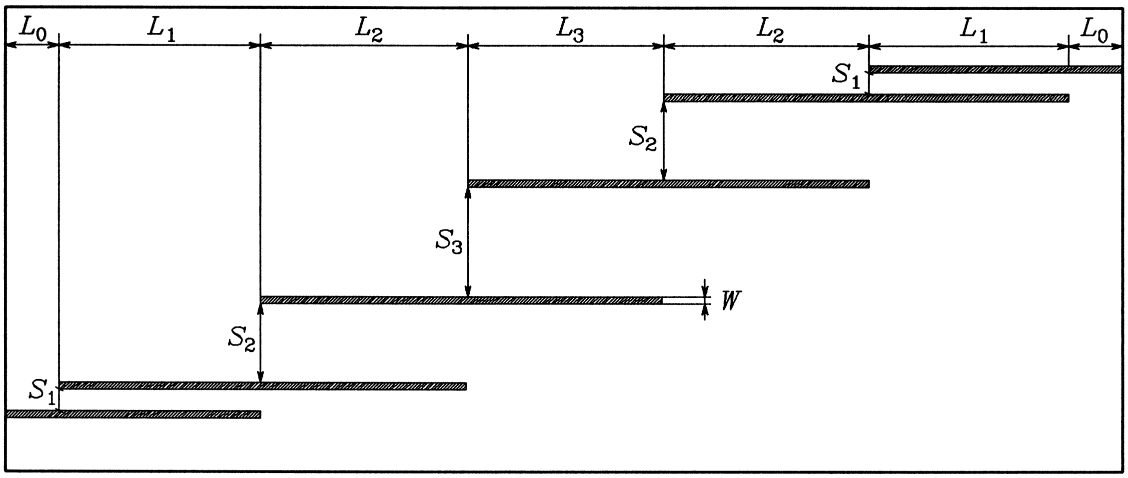
Step 6



perform X_{os}-space model parameter extraction

if $\| x_{os}^{(3)} - x_{os}^{*} \| \leq \epsilon$ then $\bar{x}_{em} = x_{em}^{(3)}$ is considered as the SM solution

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

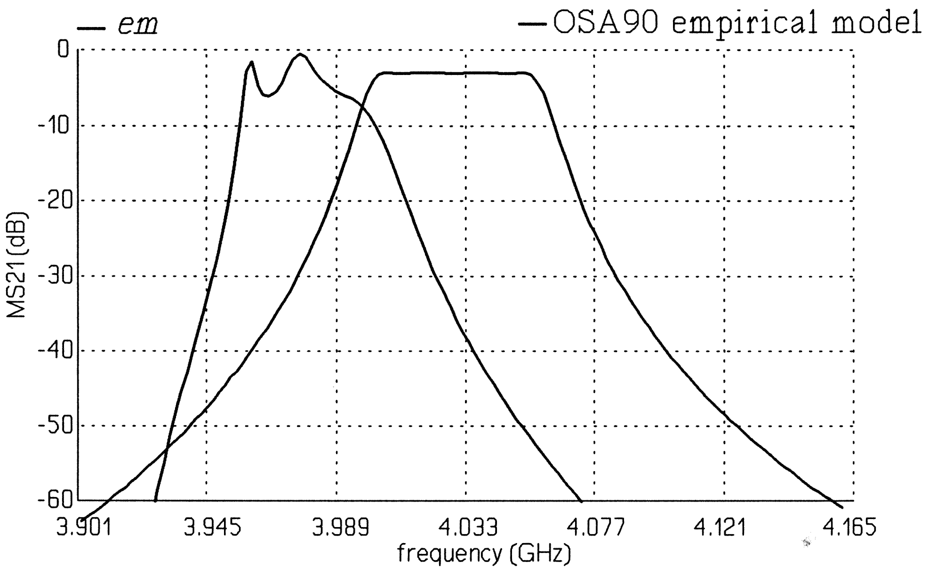
100 elapsed minutes are needed for ***em*** analysis at a single frequency on a Sun SPARCstation 10

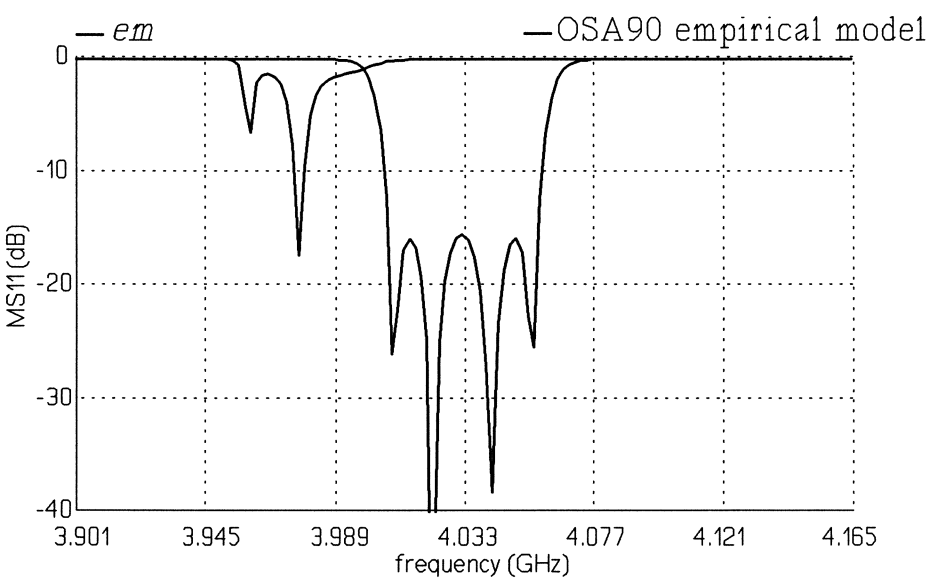
design specifications

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

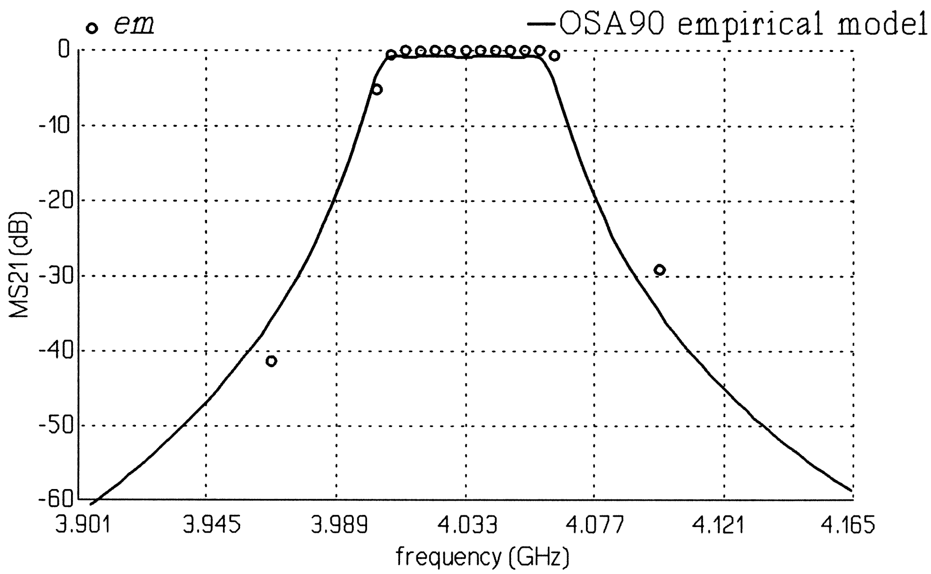
$|S_{21}| > 0.95$ for $4.008 \text{ GHz} < f < 4.058$ GHz

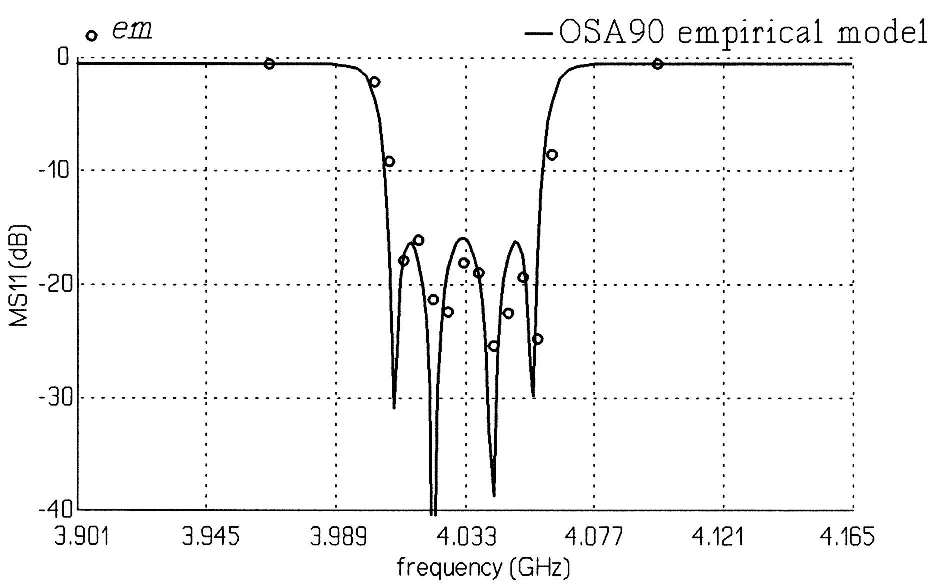
Starting Point of EM Optimization: Design Using Empirical Circuit Model





Solution by Aggressive Space Mapping After 3 Iterations





Decomposition

partitions a complex structure into a few smaller substructures

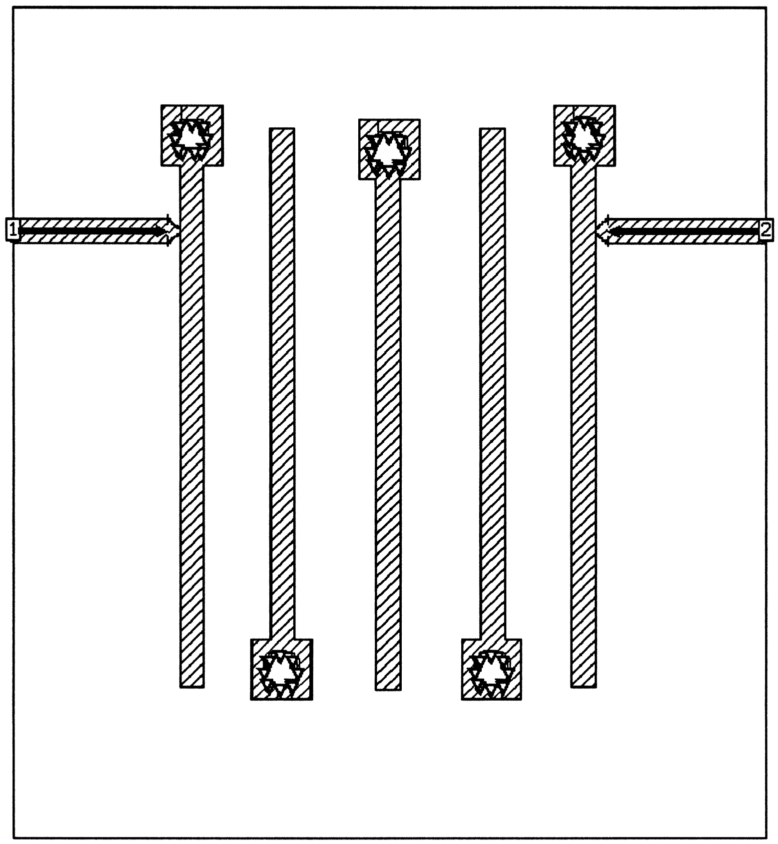
each substructure is analyzed separately

the results are combined to obtain the response of the overall structure

2D analytical methods or even empirical formulas can be used for some non-critical regions

full-wave 3D models are adopted for the analysis of the key substructures

A Five-Pole C-Band Interdigital Filter



15 mil thick alumina substrate with $\varepsilon_r = 9.8$.

the width of each microstrip is chosen to be 10 mil

quarter wavelength resonators

Interdigital Filter Design

specifications

passband cutoff	f_1 = 4.9 GHz, f_2 = 5.3 GHz
passband ripple	r = 0.1 dB
isolation bandwidth	BWI = 0.95 GHz
isolation	DBI = 30 dB

the order of the filter is determined as 5

all other dimensions including the gaps and the positions of the tapped lines are obtained by synthesis (*Matthaei et al., 1964*)

design variables include two gaps between the resonators and four lengths of microstrip lines from an appropriate position of each resonator to its ends

the size of the vias is fixed

The Fine Model of the Interdigital Filter

full-wave EM simulations of the whole structure using Sonnet's *em*

for good accuracy the grid size has to be sufficiently small

selected grid size: 1×1 mil

about 1.5 CPU hours per frequency point on a Sun SPARCstation 10

much longer if losses are included

this translates into considerable EM simulation time for fine frequency sweeps

direct optimization would require many EM analyses and consequently excessive CPU time

Dimensions and Material Parameters of the Filter

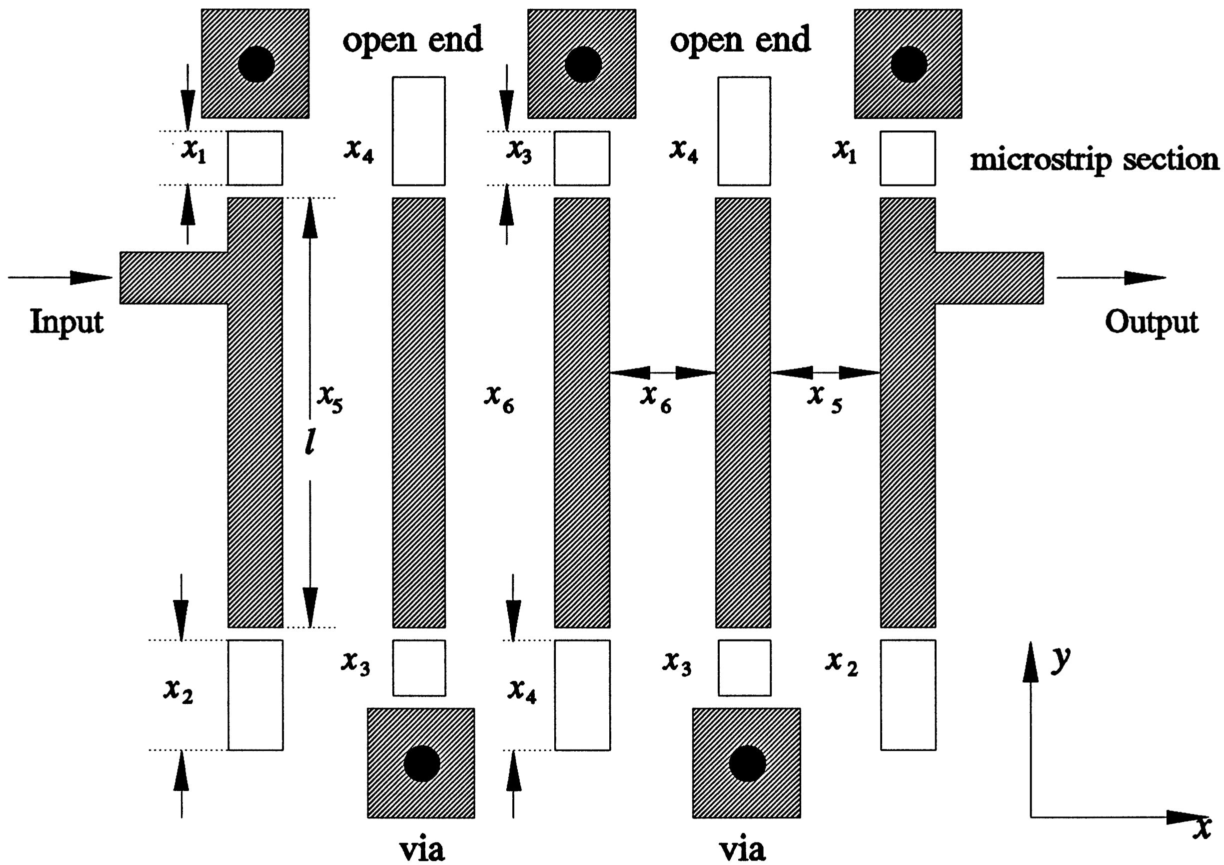
FILTER MATERIAL PARAMETERS AND GEOMETRICAL DIMENSIONS

Parameter	Value
substrate dielectric constant	9.8
substrate thickness (mil)	15
conducting metal thickness (mil)	0
substrate dielectric loss tangent	0/0.001*
conductivity of the metal	$\infty/5.8\times10^{7}$*
shielding cover height (mil)	75
width of input/output lines (mil)	10
width of each resonator (mil)	10
via diameter (mil)	13
via pad dimensions (mil $\times$ mil)	25 $\times$ 25

* loss tangent and conductivity for simulations without and with losses, respectively

Decomposition of the Interdigital Filter

the coarse model is constructed using decomposition



the substructures are analyzed separately using either EM models with a coarse grid or empirical models

the partial results are then combined through circuit theory to obtain the response of the overall filter

The Coarse Model of the Interdigital Filter

the center shaded 12-port network is analyzed by *em* with a very coarse grid: 5 × 10 mil

the vias have fixed dimensions - one via is analyzed by *em* with a grid of 1 × 1 mil only once; in subsequent simulations all vias are represented by their reflection coefficient

all other parts including the microstrip line sections and the open ends are analyzed using the empirical models of OSA90/hope

less than 1 CPU minute per frequency point on a Sun SPARCstation 10

off-grid responses, when needed during optimization, are obtained by interpolation

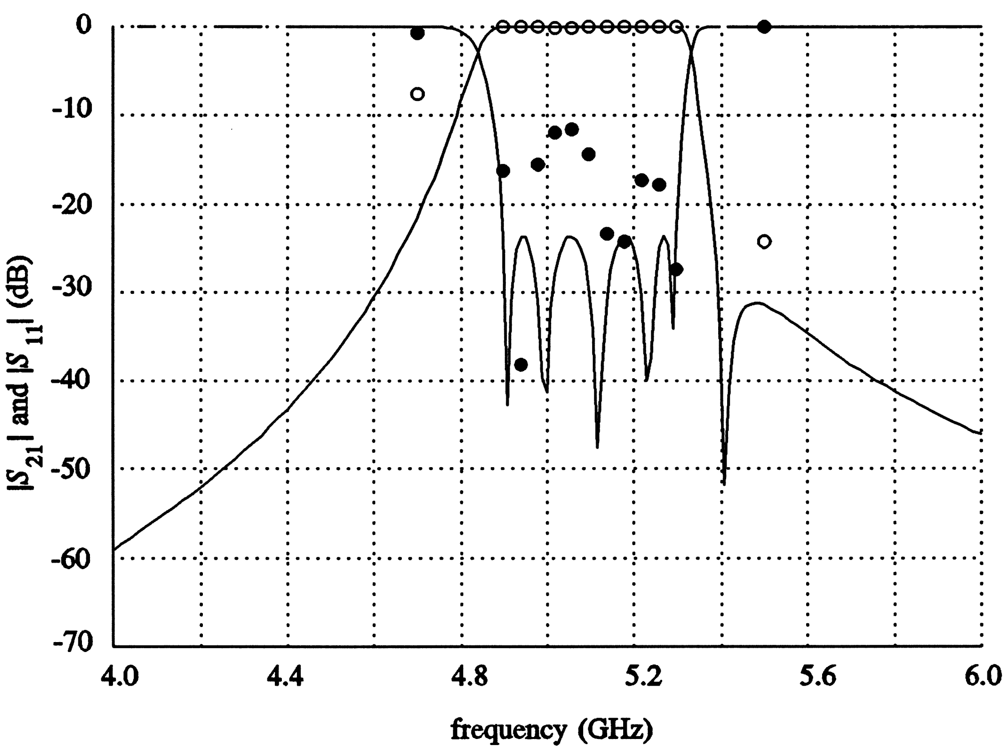
the coarse model retains most of the adjacent and non-adjacent couplings, thus it provides reasonably accurate results at dramatically faster speed

Design Procedure

first, we optimize the filter using the coarse model

minimax solution x^*_{os} is obtained

we check this coarse model solution using the fine model at a few selected frequencies



solid curves optimized $|S_{11}|$ and $|S_{21}|$ responses of the coarse model at the optimal point x^*_{os}

circles fine model responses at x^*_{os}

Results of EM Validation

the fine model responses deviate significantly from the optimized coarse model responses

the passband return loss is only about 11 dB and the bandwidth is wider than specified

discrepancies may be due to the coarse grid and some couplings not taken into account by the coarse model

WHAT'S NEXT?

typically, engineers manually tune the design and try to meet design specifications

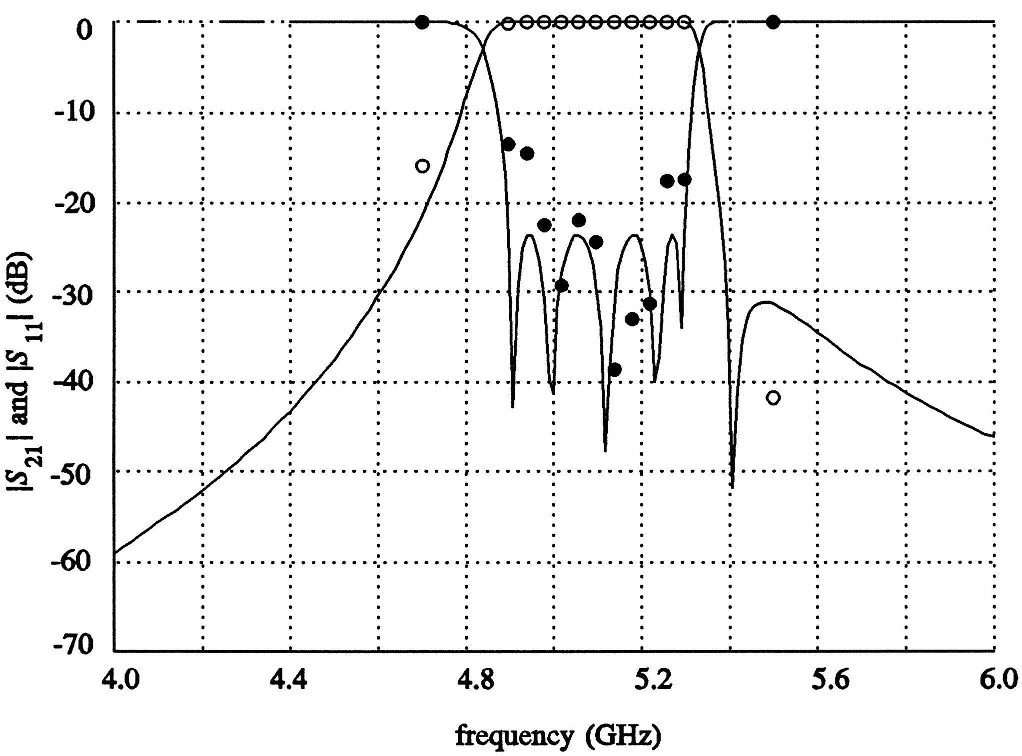
we offer an automated approach using Space Mapping

Space Mapping Optimization of the Interdigital Filter

SM optimization starts with $x_{em}^{(1)} = x_{os}^{*}$

after the first iteration, a new point $x_{em}^{(2)}$ in the X_{em} space is obtained

the fine model responses of this new point are compared with the coarse model optimal responses

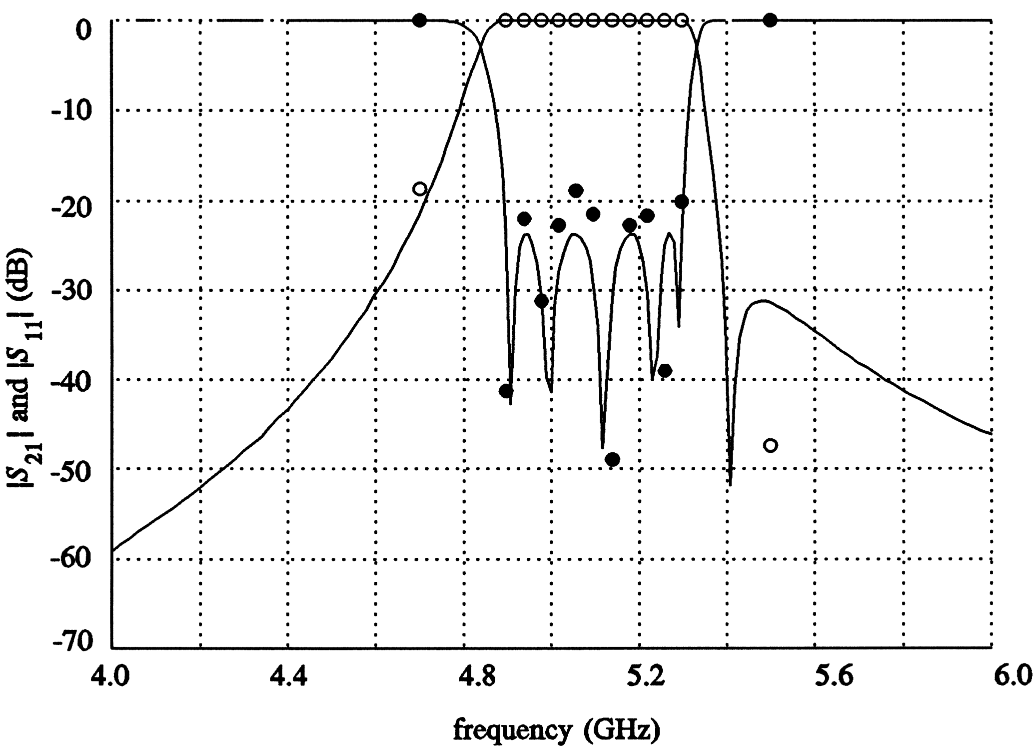


return loss is improved and the bandwidth is reduced at the lower frequency end

Second Iteration of Space Mapping

another iteration of SM produces $x_{em}^{(3)}$

the fine model responses at $x_{em}^{(3)}$ at 13 frequency points are compared with the coarse model optimal responses



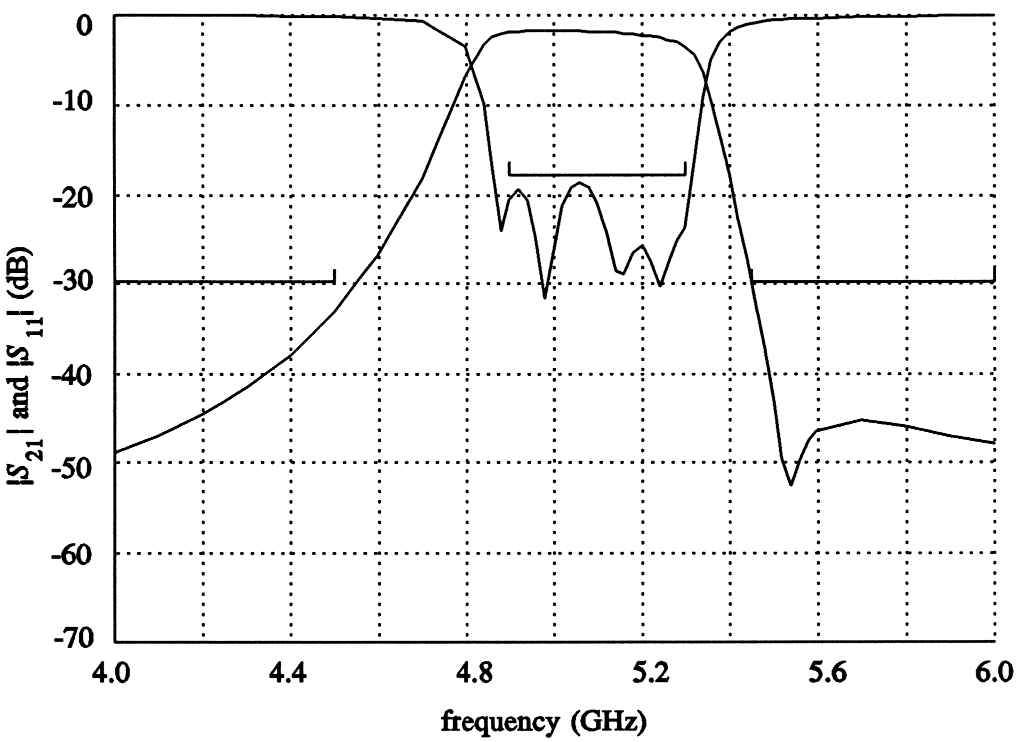
only three EM simulations of the fine model were needed

Final EM Validation

a dense frequency sweep is desired

here, simulation includes the conductor and dielectric losses

the fine model responses at $x_{em}^{(3)}$



the passband return loss is better than 18.5 dB

Space Mapping Using MM/Network Theory and FEM

optimization space (OS) model - the RWGMM library of waveguide MM models (Fritz Arndt) connected by network theory

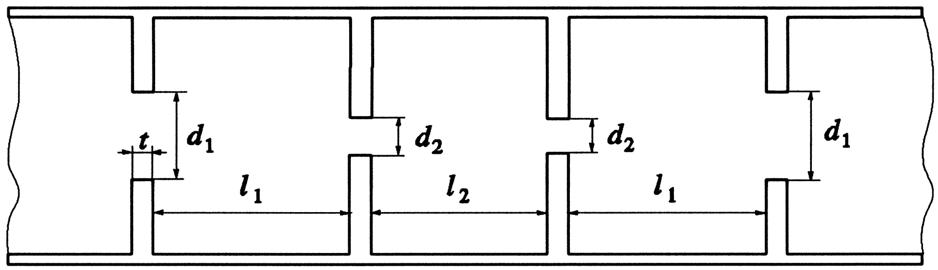
- computationally efficient
- accurately treats a variety of predefined geometries
- ideally suited for modeling complex waveguide structures decomposable into available library building blocks

EM space or "fine" model - Maxwell Eminence 3D FEM-based field simulator

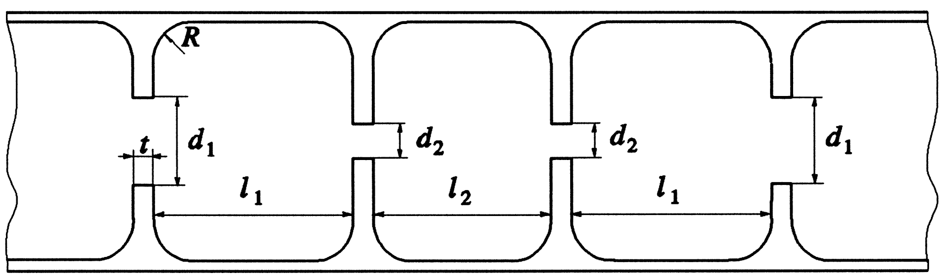
- capable of analyzing arbitrary shapes
- computationally very intensive

Optimization of the H-Plane Resonator Filter

OS model, for hybrid MM/network theory simulation



fine model, for analysis by FEM



the waveguide cross-section is 15.8 × 7.9 mm

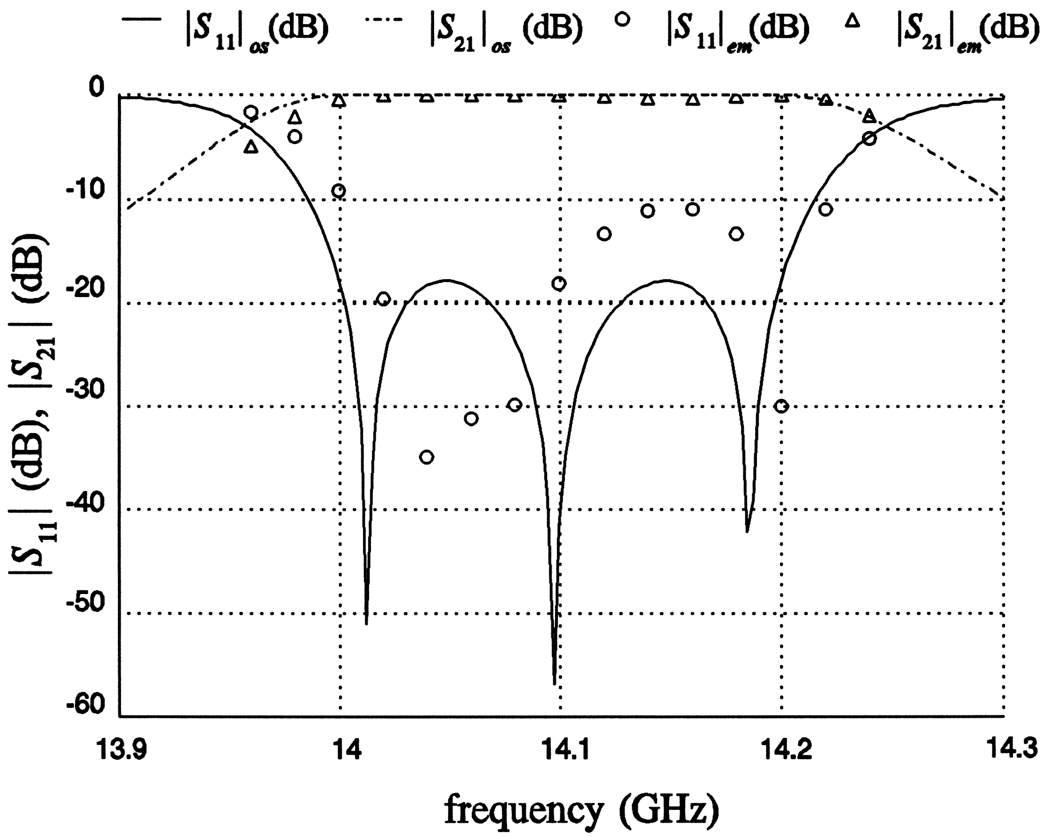
$t = 0.4$ mm, $R = 1$ mm

optimization variables: d_1, d_2, l_1 and l_2

design specifications

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

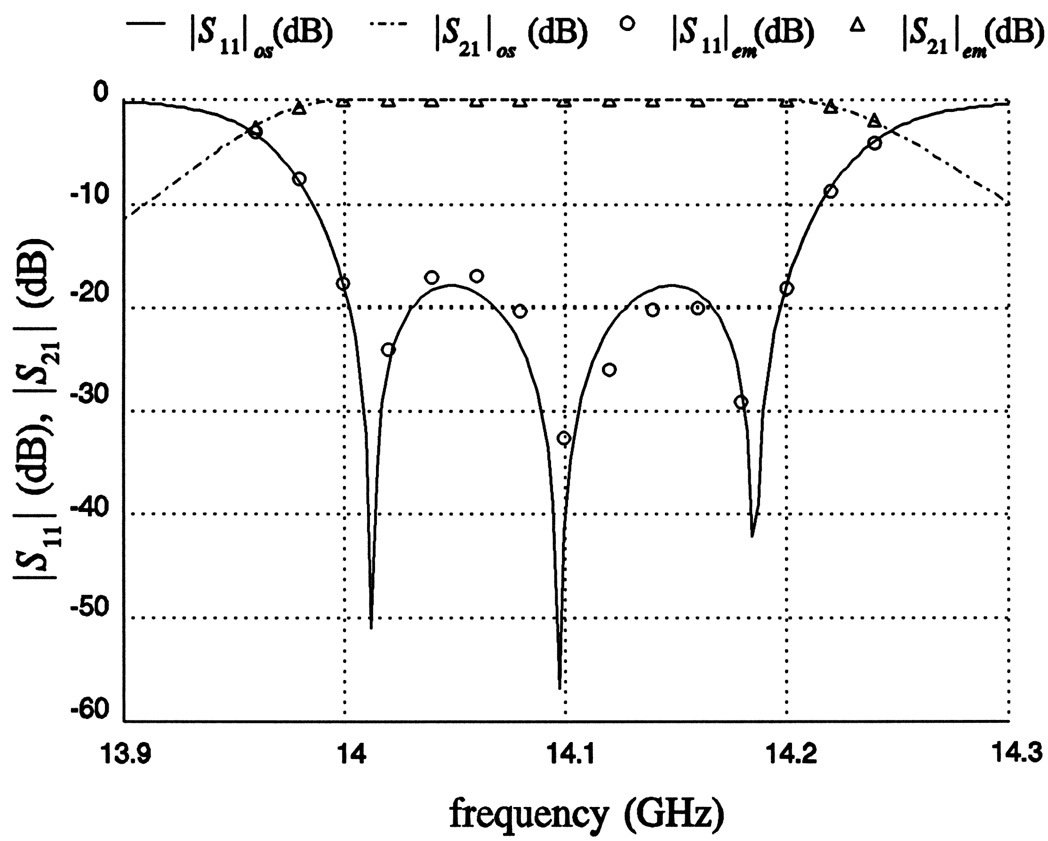
Starting Point Response Focusing on the Passband



the minimax solution in OS space, x_{OS}^*, yields the target response for SM

$d_1 = 6.04541$, $d_2 = 3.21811$, $l_1 = 13.0688$ and $l_2 = 13.8841$

SM Optimized FEM Response

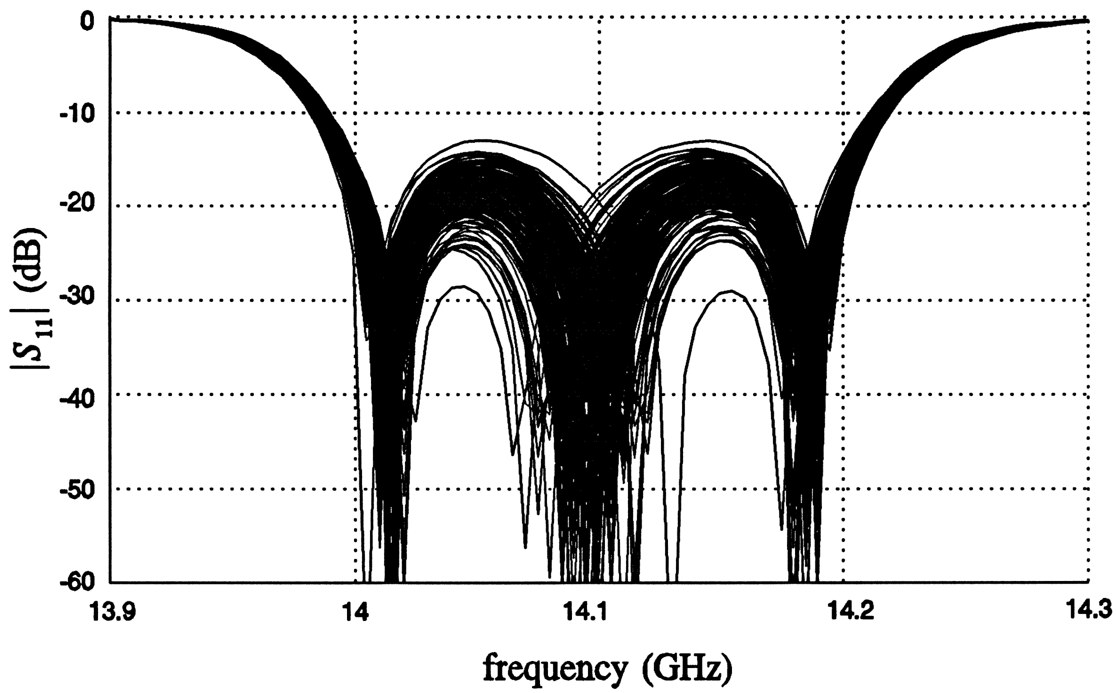


only 4 Maxwell Eminence simulations lead to the optimal solution

$d_1 = 6.17557, d_2 = 3.29058, l_1 = 13.0282$ and $l_2 = 13.8841$

direct optimization using Empipe3D confirms that the SM solution is optimal

Monte Carlo Analysis of the H-Plane Filter



the statistical outcomes were randomly generated from normal distribution with a standard deviation of 0.0333%

the yield estimated from 200 outcomes is 88.5% w.r.t. the specification of $|S_{11}| < -15$ dB in the passband

increasing the standard deviation to 0.1% results in yield dropping to 19% for 200 outcomes

SM Optimization Using Coarse and Fine MM Models

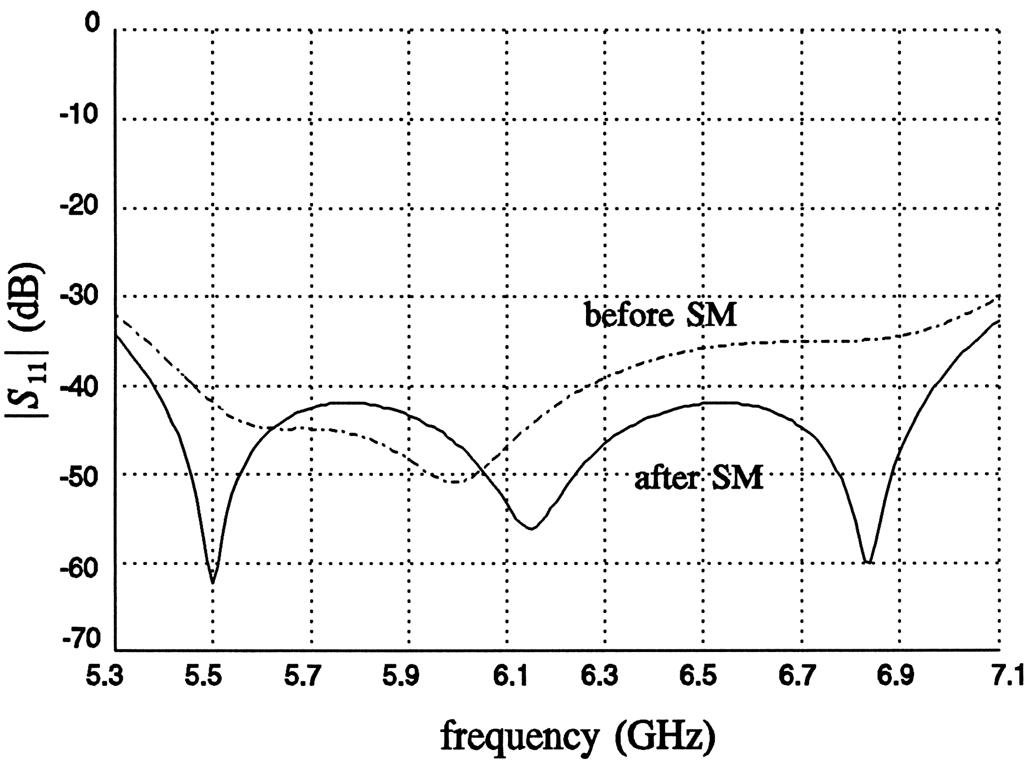
large number of higher-order modes may be used to model waveguide discontinuities

increasing the number of modes improves accuracy at the expense of higher computational cost

SM may enhance the efficiency of the MM-based optimization

fine model	including many modes
coarse model	using one or very few modes

SM Between Two MM Models - Three-Section Transformer

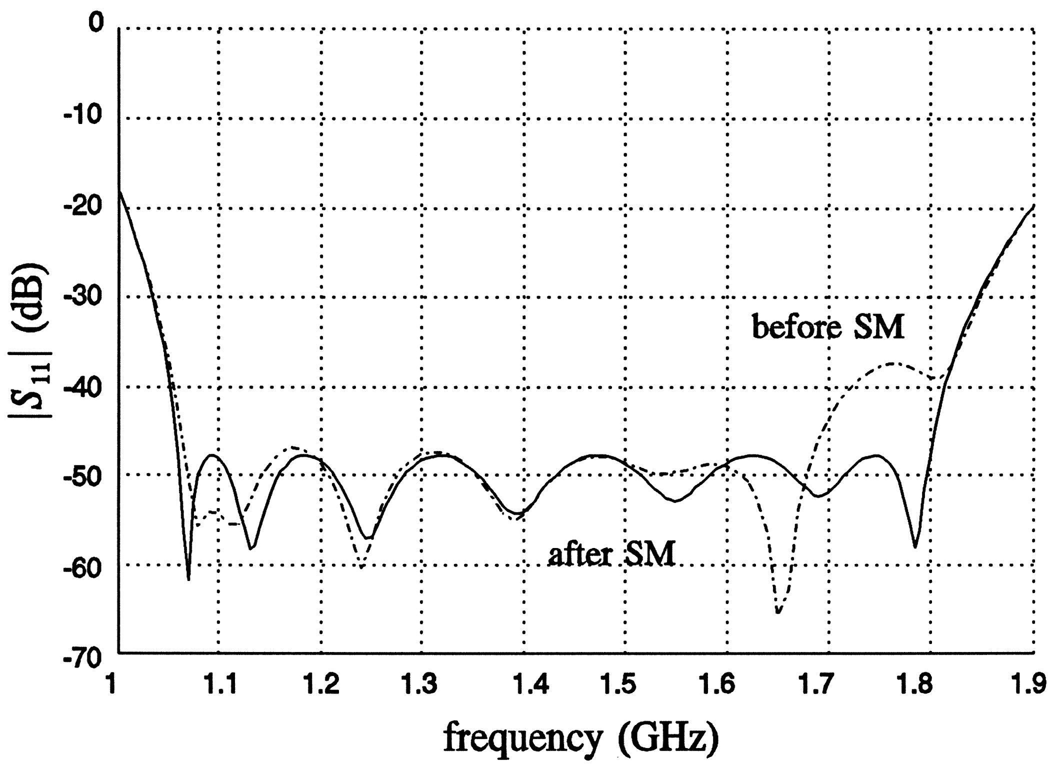


$|S_{11}|$ (dB) simulated by RWGMM before and after two steps of SM

one mode used in the coarse model

the fine model includes all the modes below the cut-off frequency of 50 GHz (the number of modes varies from 49 to 198)

SM Between Two MM Models - Seven-Section Transformer



$|S_{11}|$ (dB) simulated by RWGMM before and after 14 steps of SM

one mode used in the coarse model

the fine model includes all the modes below the cut-off frequency of 50 GHz (at least 180 modes)

Conclusions

SM promises the accuracy of EM and physical simulation and the speed of circuit-level optimization

accurate but computationally intensive fine model calibrates computationally efficient coarse models

our approach has broad applicability and can profoundly change the way the EM simulators are perceived and used as a CAD tool

a coherent framework combines the power of aggressive SM with decomposition

decomposition further accelerates the coarse model simulation

applications of aggressive SM to filter optimization using network theory, MM and FEM

highly efficient means for Monte Carlo analysis of microwave circuits carried out with the accuracy of FEM simulation

SM optimization based on coarse and fine MM models with different numbers of modes

References

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