SPACE MAPPING OPTIMIZATION OF WAVEGUIDE FILTERS USING FINITE ELEMENT AND MODE-MATCHING ELECTROMAGNETIC SIMULATORS

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Outline

Space Mapping models

hybrid mode-matching/network theory

finite-element (FEM)

fully automated Space Mapping optimization

statistical approach to parameter extraction

error functions for parameter extraction

EM optimization of an H-plane resonator filter with rounded corners

multi-point parameter extraction

tolerance simulation using Space Mapping

Space Mapping between two hybrid MM/network theory models

Space Mapping (SM)

to avoid direct optimization of computationally intensive models

automatic alignment of two distinct models

two different EM simulators are used here

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

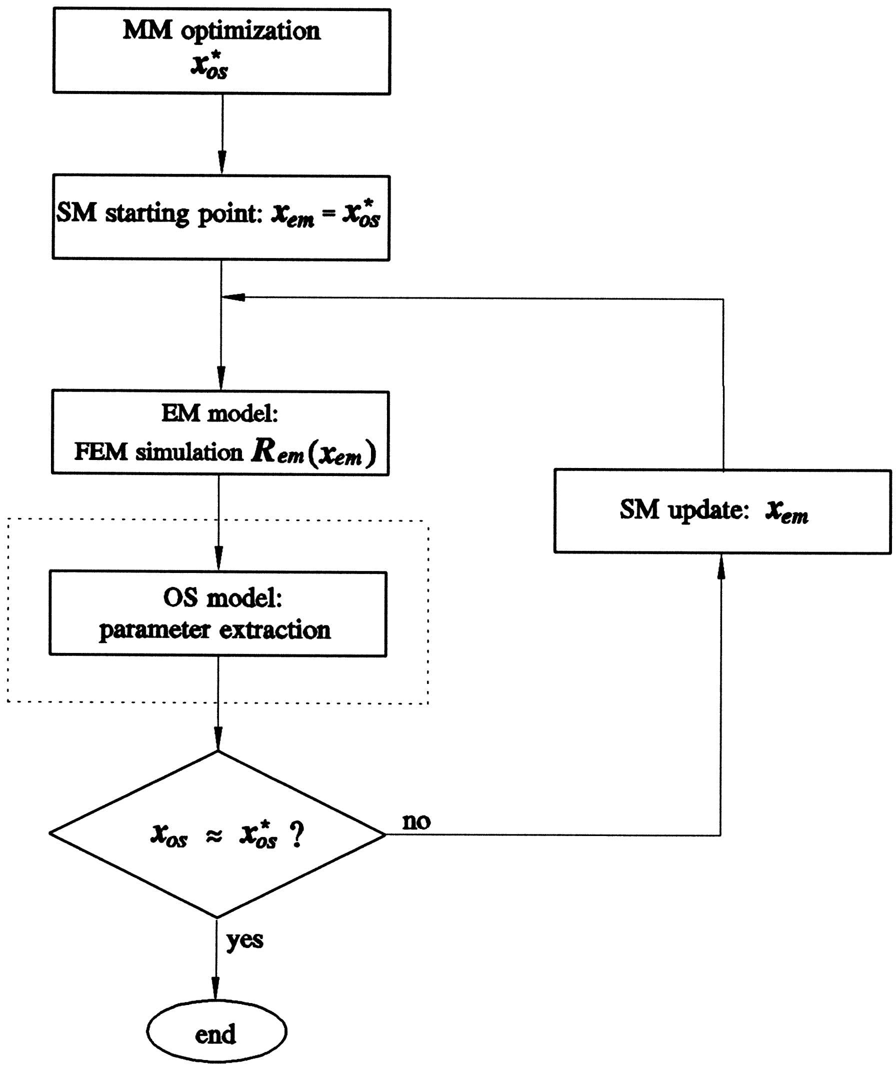
- computationally efficient
- accurately treats a variety of predefined geometries
- ideally suited for modeling complex waveguide structures decomposable into available library building blocks

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

- capable of analyzing arbitrary shapes
- computationally very intensive

Fully Automated SM Optimization

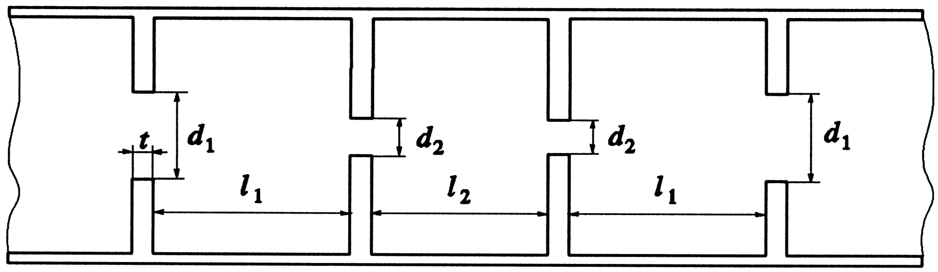
two-level Datapipe architecture



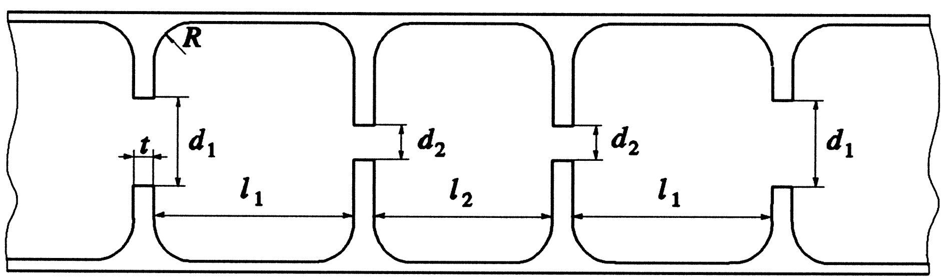
within the parameter extraction the Datapipe techniques can be utilized to connect external model simulators

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

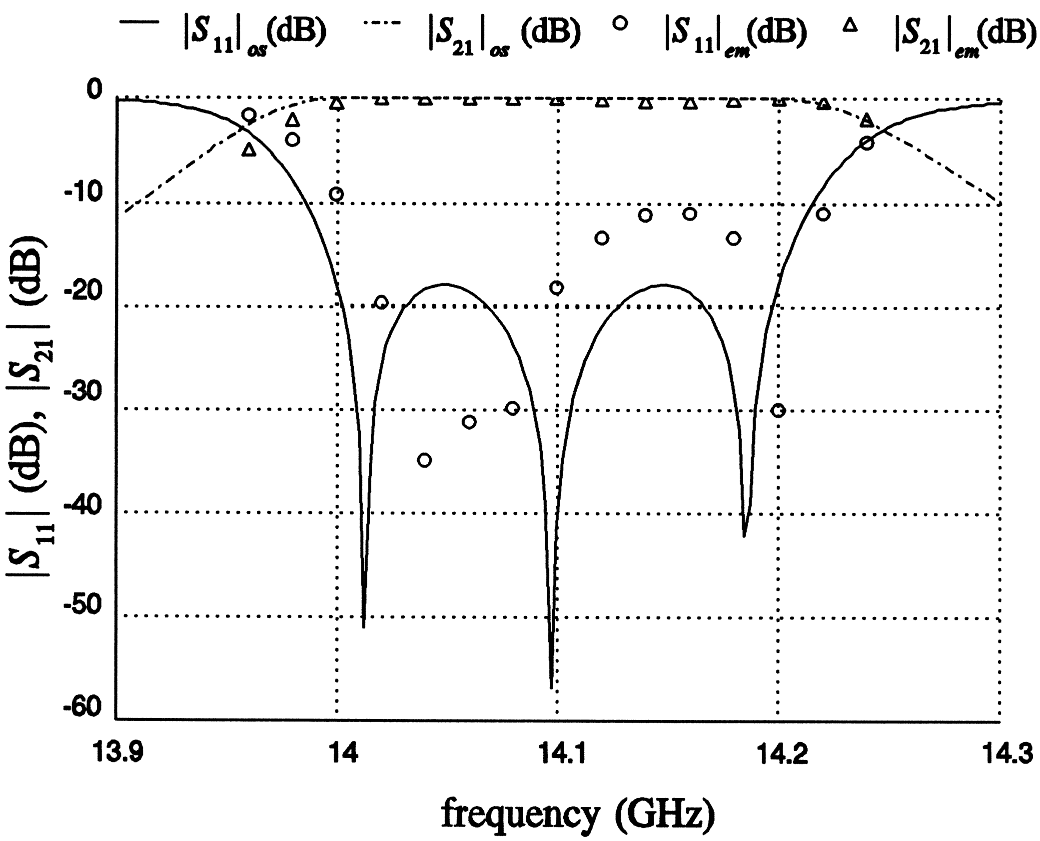
$t = 0.4$ mm, $R = 1$ mm

optimization variables: d_1, d_2, l_1 and l_2

design specifications

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

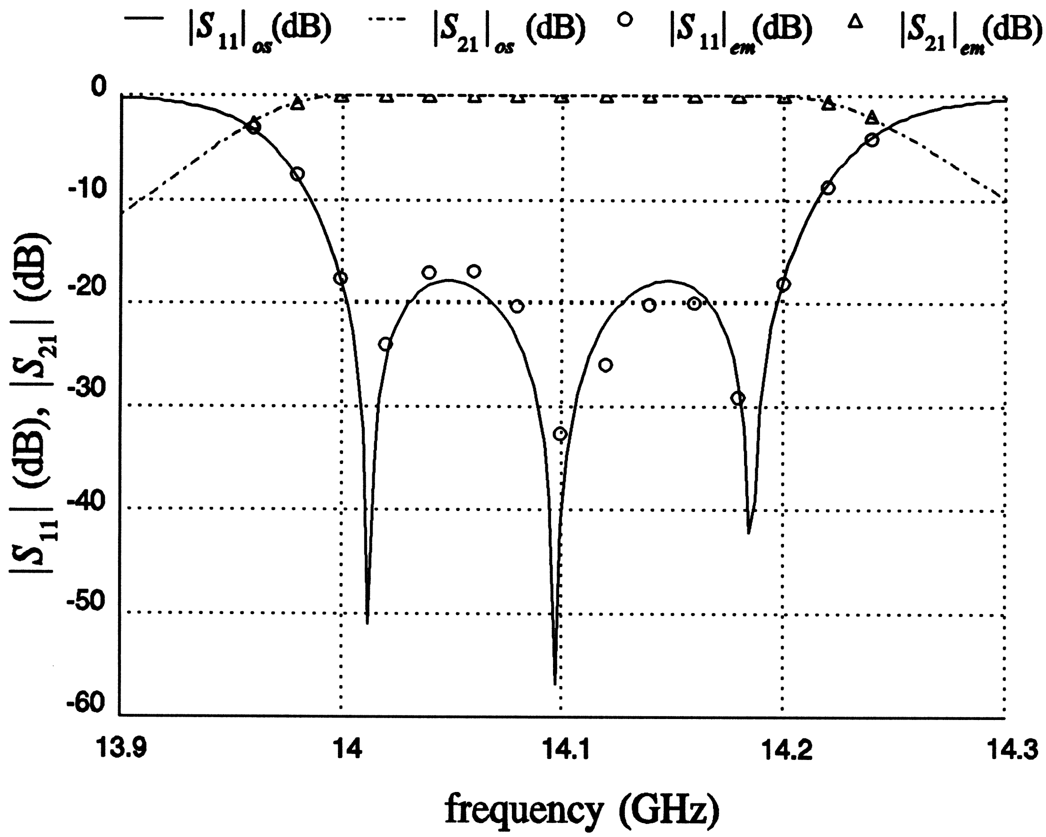
Starting Point Response Focusing on the Passband



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

SM Iterations

EM space

Point	d_1	d_2	l_1	l_2
x_{em}^1	6.04541	3.21811	13.0688	13.8841
x_{em}^2	6.19267	3.32269	12.9876	13.8752
x_{em}^3	6.17017	3.29692	13.0536	13.8812
x_{em}^4	6.17557	3.29058	13.0282	13.8841

values of all optimization variables are in millimetres

OS space

Point	d_1	d_2	l_1	l_2	$\| x_{os}^* - x_{os}^i \|$
x_{os}^1	5.89815	3.11353	13.1500	13.8930	0.19823
x_{os}^2	6.07714	3.25445	12.9757	13.8757	0.10519
x_{os}^3	6.03531	3.22421	13.1119	13.8806	0.04482
x_{os}^4	6.04634	3.22042	13.0618	13.8831	0.00750

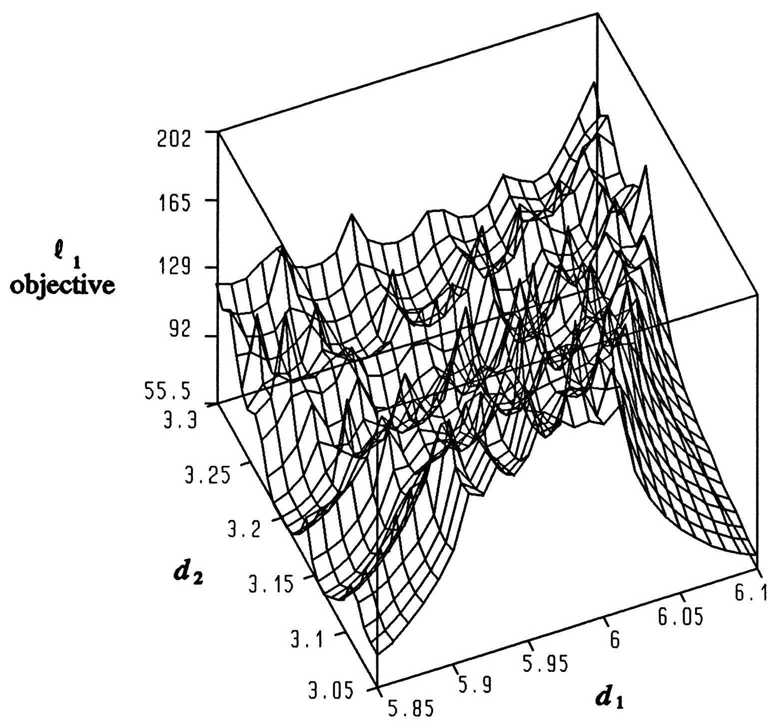
values of all optimization variables are in millimetres

Error Functions for Parameter Extraction

design specifications in the passband were formulated using $|S_{11}|$ (dB)

designer may be tempted to use this formulation

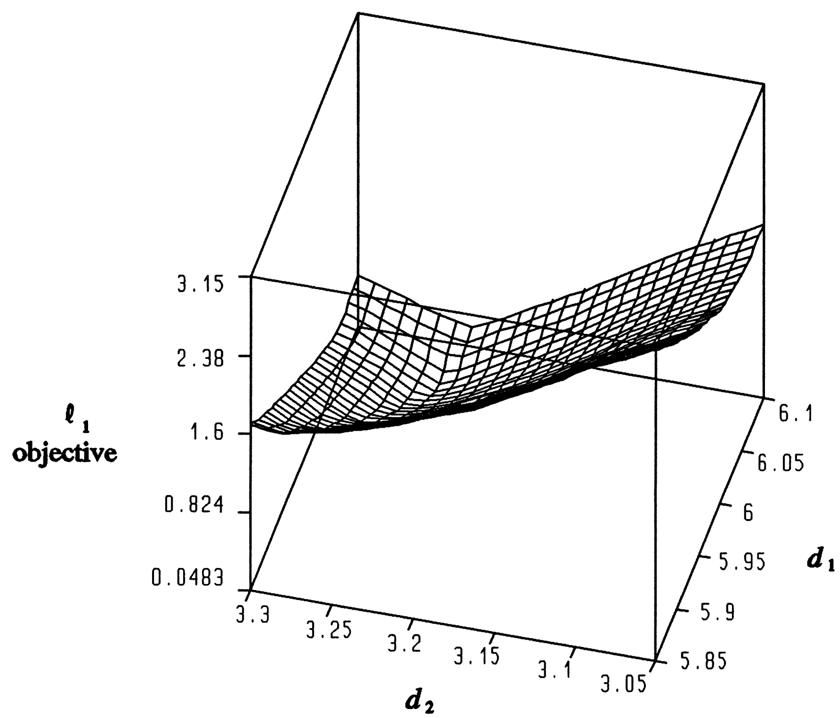
ℓ_1 error in terms of $|S_{11}|$ (dB) for the second step of SM



an excellent example to investigate the robustness of parameter extraction

Error Functions for Parameter Extraction

ℓ_1 error in terms of $|S_{21}|$ for the second step of SM



no difficulty in the parameter extraction

the SM iterations proceeded flawlessly

Statistical Parameter Extraction

to overcome potential pitfalls arising out of inaccurate or nonunique solutions

perform standard ℓ_1 parameter extraction starting from x_{os}^*

if the optimized response matches well the EM model response, continue with the SM iterations

otherwise, we turn to statistical exploration of the OS model

Statistical Exploration Region

the key is to establish the exploration region

*k*th SM step

determine the multidimensional interval $\boldsymbol{\delta}$

$$\boldsymbol{\delta} = \boldsymbol{x}_{os}^{k-1} - \boldsymbol{x}_{os}^{*}$$

the statistical exploration may be limited to the region

$$x_{osi} \in [\, x_{osi}^{*} - 2\,|\delta_i|,\, x_{osi}^{*} + 2\,|\delta_i|\,]$$

elliptical multidimensional domain with semiaxes $2|\delta_i|$

$$\sum_i (x_{osi} - x_{osi}^{*})^2 / |\delta_i|^2 \leq 4$$

Algorithm for Statistical Parameter Extraction

Step 1 initialize the exploration region

Step 2 generate N_s starting points

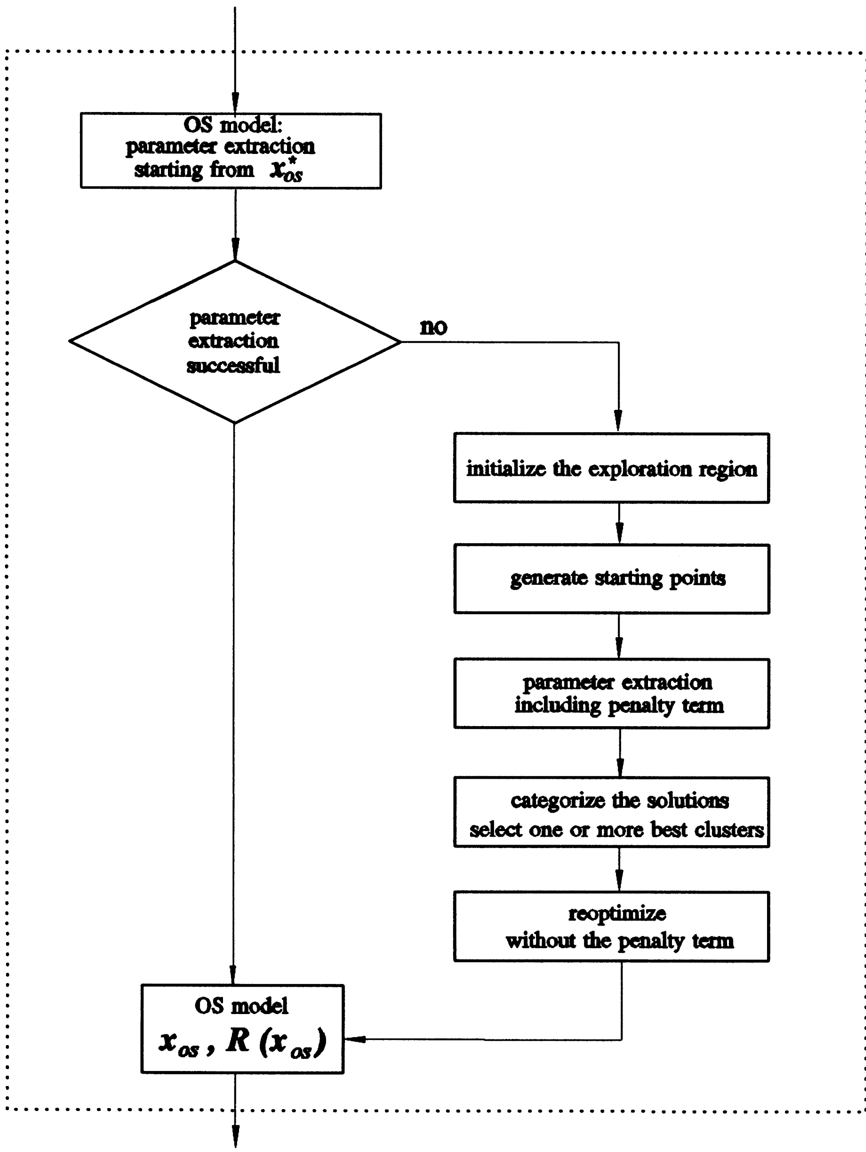
Step 3 perform N_s parameter extractions from the N_s starting points including the penalty function

$$\lambda \| x_{os}^{k} - x_{os}^{*} \|$$

Step 4 categorize the solutions, select one or more best clusters of the solutions

Step 5 focus the clusters by reoptimizing without the penalty term

Flow-Chart of Statistical Parameter Extraction

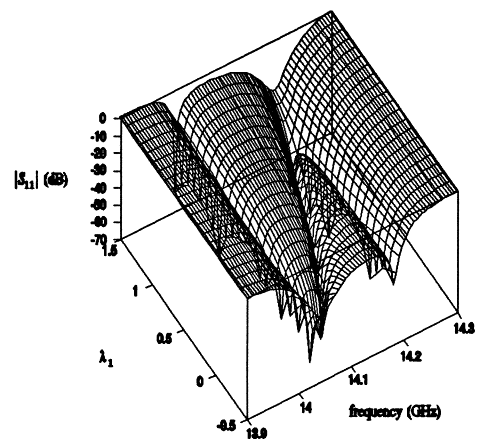


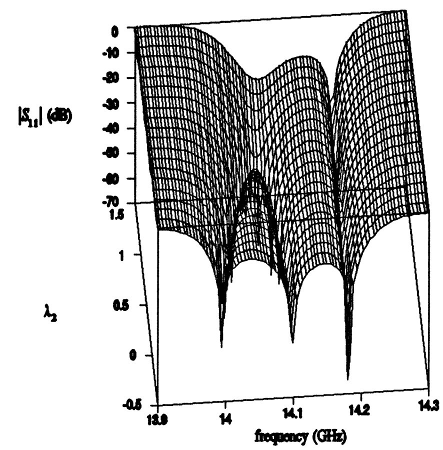
approach has been automated using three-level Datapipe architecture

potential for parallelization

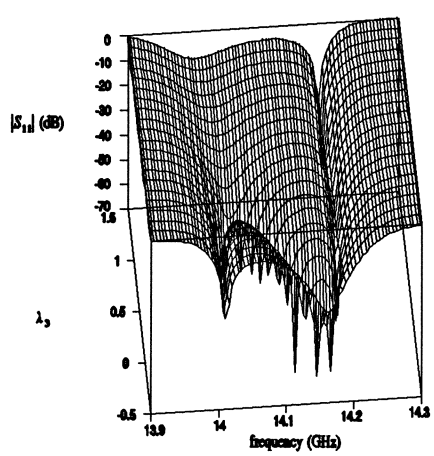
Variation of Responses Defined by the First SM Step

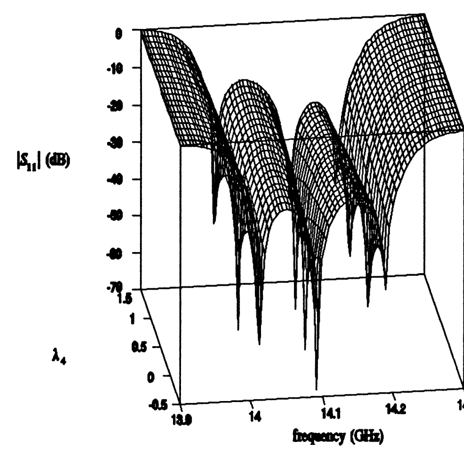
openings of irises varied





lengths of resonators varied

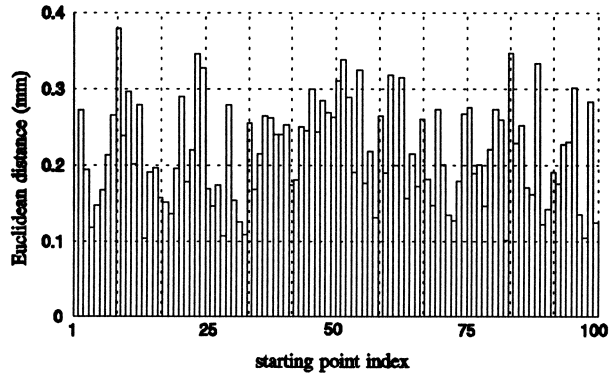




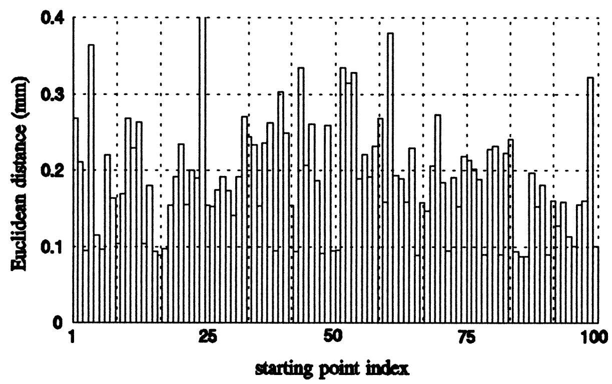
parameters varied in the range of the first aggressive SM step: $\lambda_i = 0$ at x_{os}^* and $\lambda_i = 1$ at x_{os}^1

Euclidean Distances in Statistical Parameter Extraction

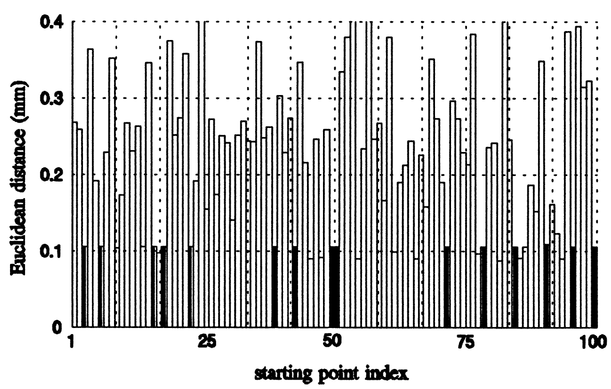
randomly generated starting points w.r.t. x_{os}^*



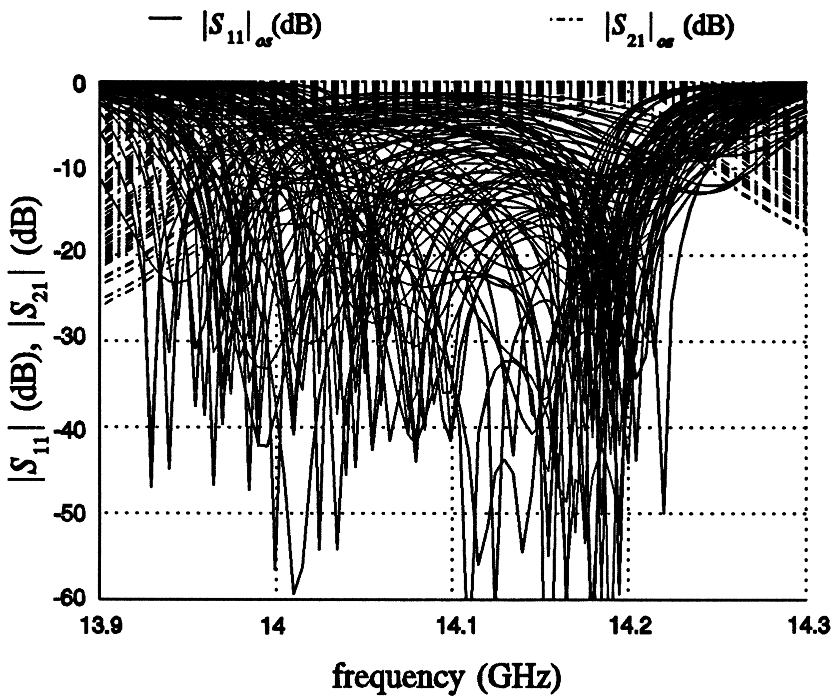
converged points after the first step

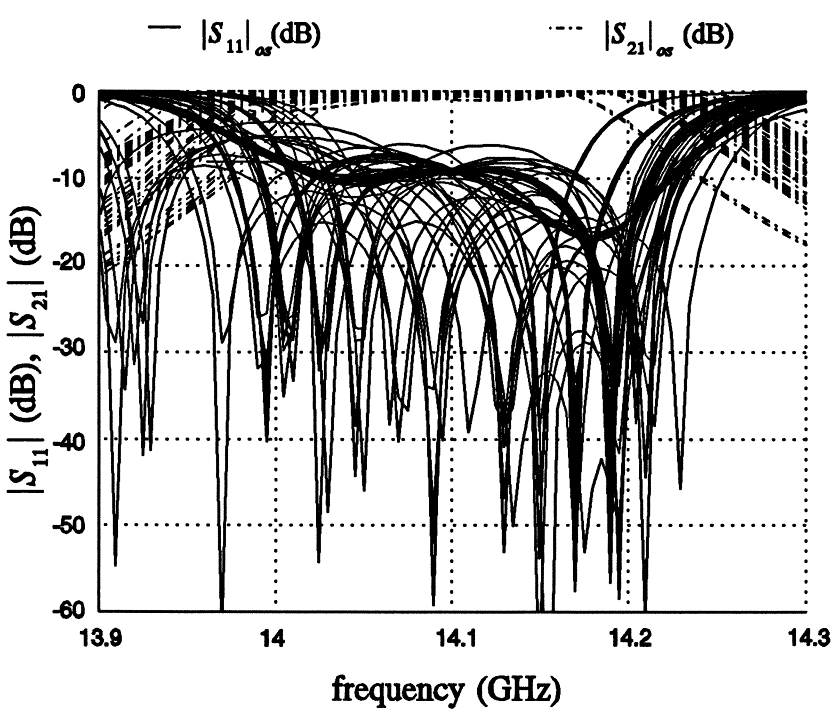


converged points after the second stage

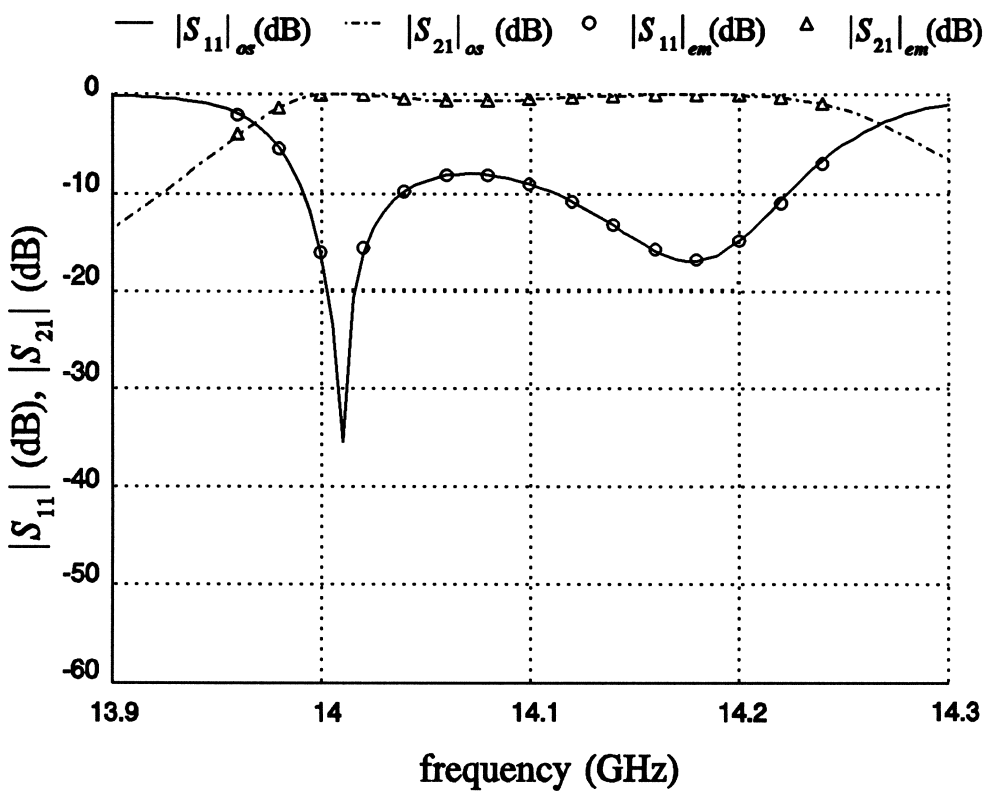


Responses Before and After Statistical Parameter Extraction





Responses After Successful Parameter Extraction

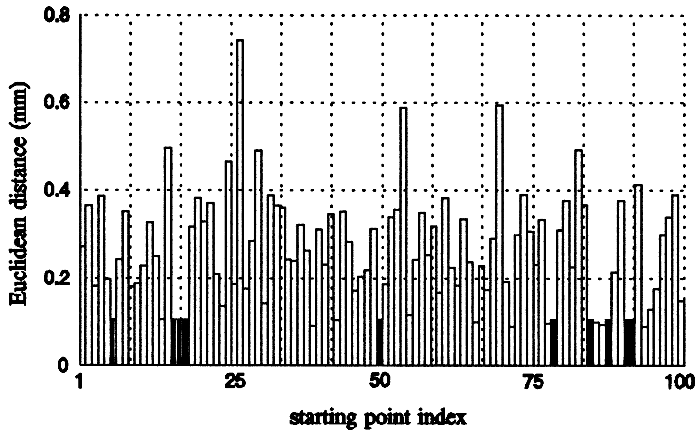


responses corresponding to the cluster of 15 points which converged to the same solution

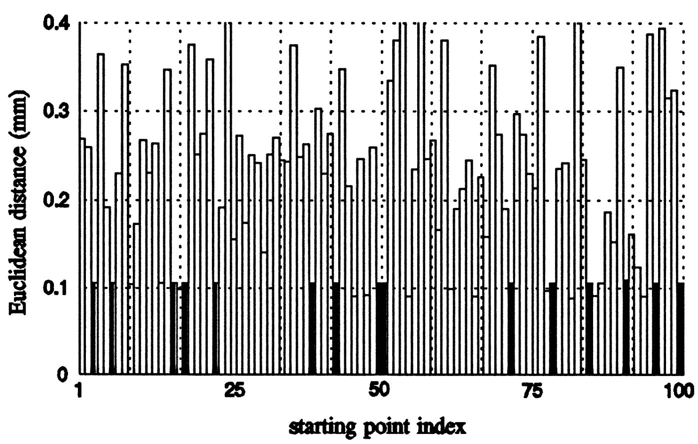
Influence of the Penalty Term

error functions defined in terms of $|S_{11}|$ (dB)

10% success when no penalty term is used



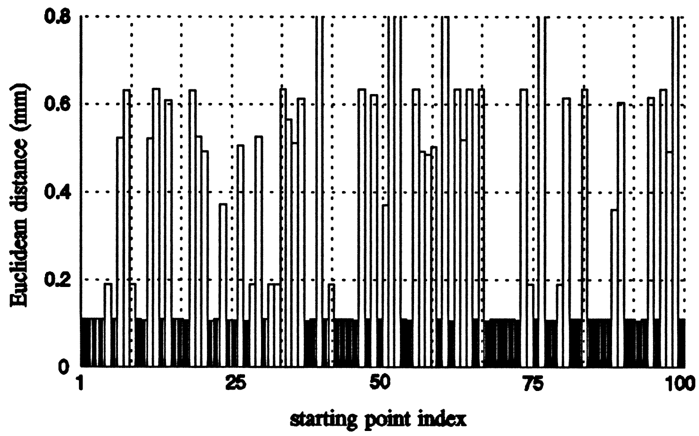
inclusion of penalty term yields 15% success



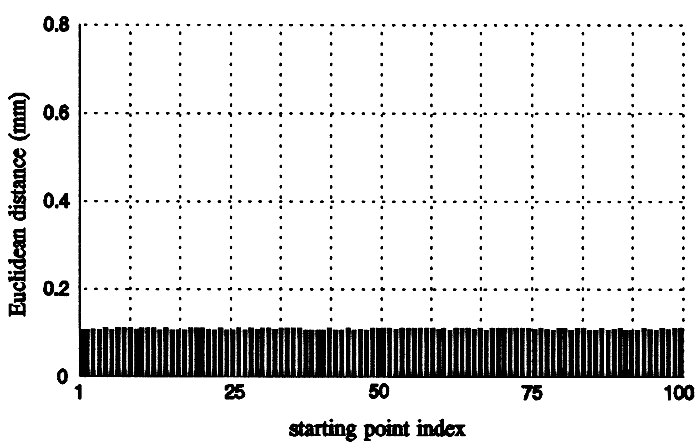
Error Function Defined in Terms of $|S_{21}|$

starting from the default point, x_{os}^*, yields good result

52% success when no penalty term is used



inclusion of penalty term yields 100% success



Multi-Point Parameter Extraction

a similar concept exploited in multi-circuit modeling

instead of minimizing

$$\| R_{os}(x^i_{os}) - R_{em}(x^i_{em}) \|$$

at a single point, we minimize

$$\| R_{os}(x^i_{os} + \Delta x) - R_{em}(x^i_{em} + \Delta x) \|$$

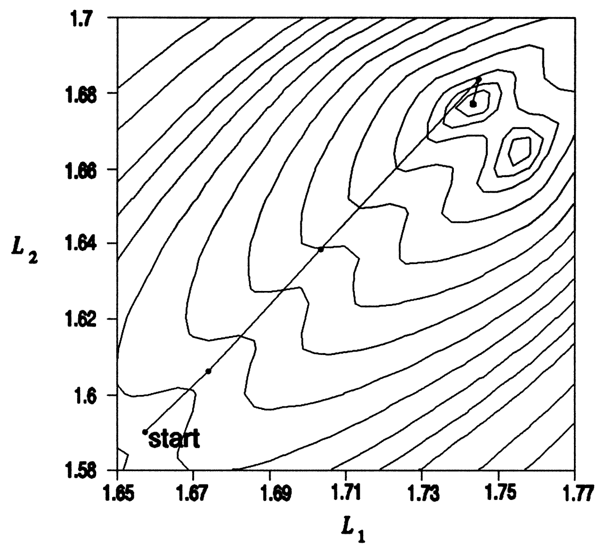
with a selected set of Δx (small perturbation to x^i_{os} and x^i_{em})

sharpen the parameter extraction result

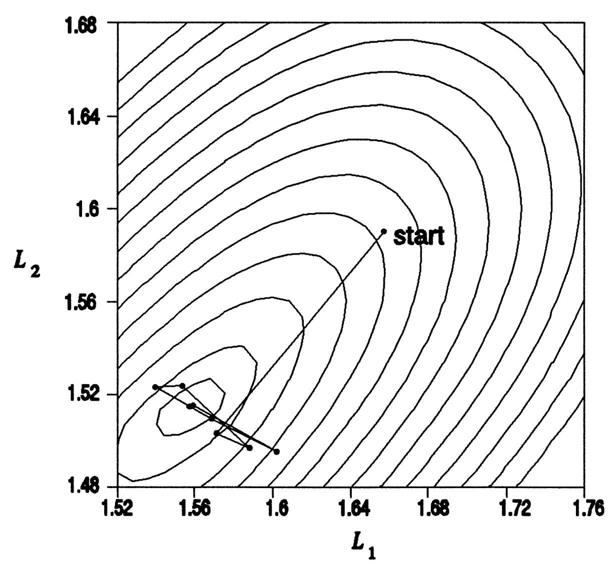
we are attempting to match not only the response, but also a first-order change in the response

applied to design of two-section waveguide transformer

Single-Point Parameter Extraction

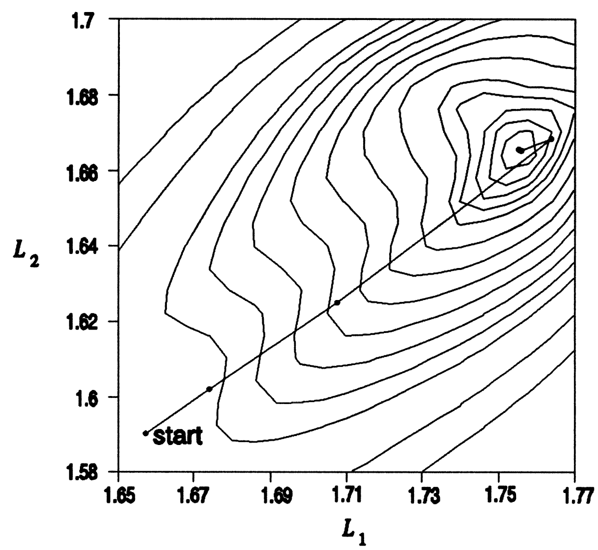


parameter extraction is non-unique

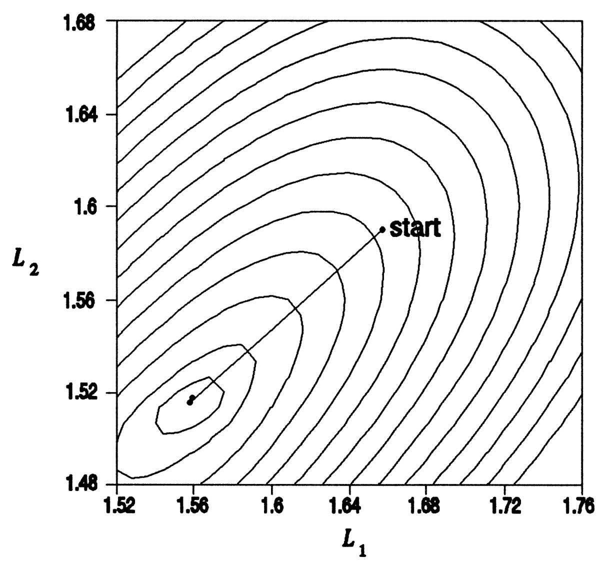


SM steps oscillate around the solution

Multi-Point Parameter Extraction



parameter extraction has a unique solution



the SM convergence is dramatically improved

Tolerance Simulation Using SM

first, the mapping is established during nominal SM optimization

statistical outcomes in the EM space are mapped to the corresponding points in the OS space

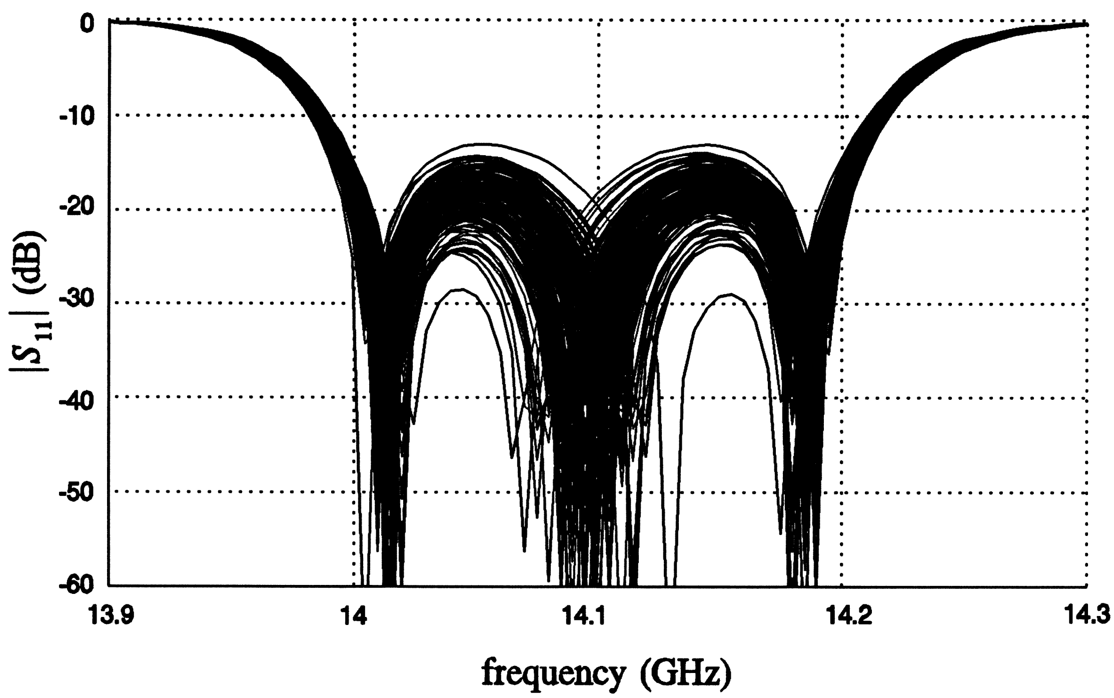
we are able to rapidly estimate the effects of manufacturing tolerances, benefitting from

the accuracy of the FEM model

the speed of the hybrid MM/network theory simulations

the CPU time required for the Monte Carlo analysis is comparable to just a single full FEM simulation

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

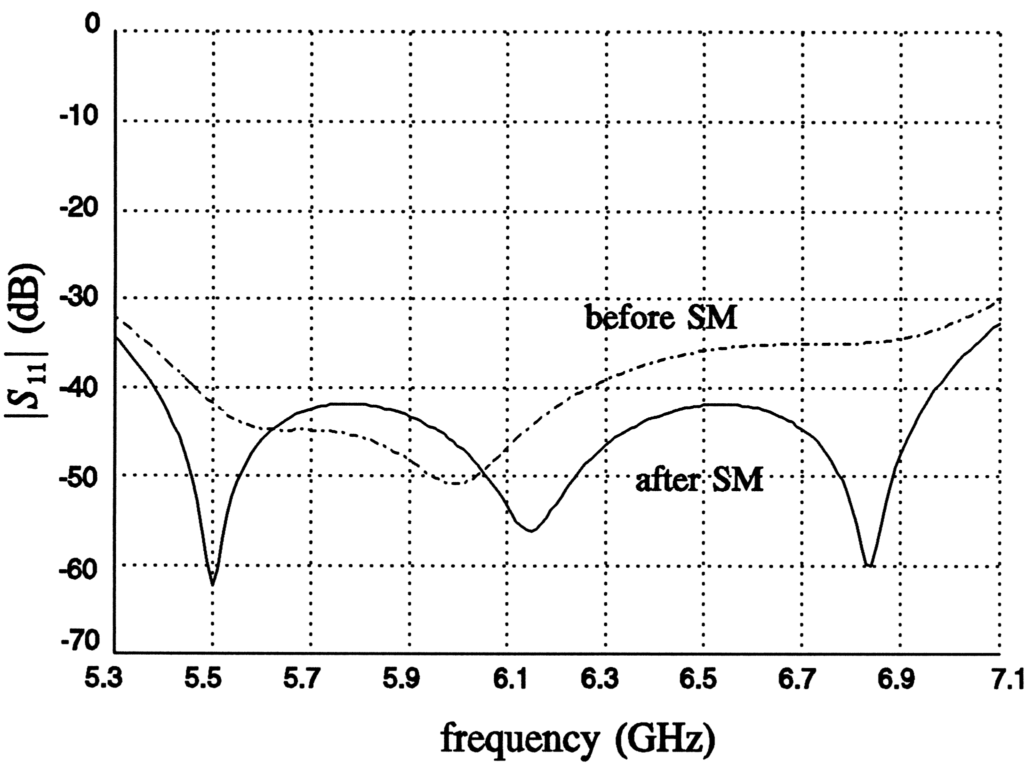
large number of higher-order modes may be used to model waveguide discontinuities

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

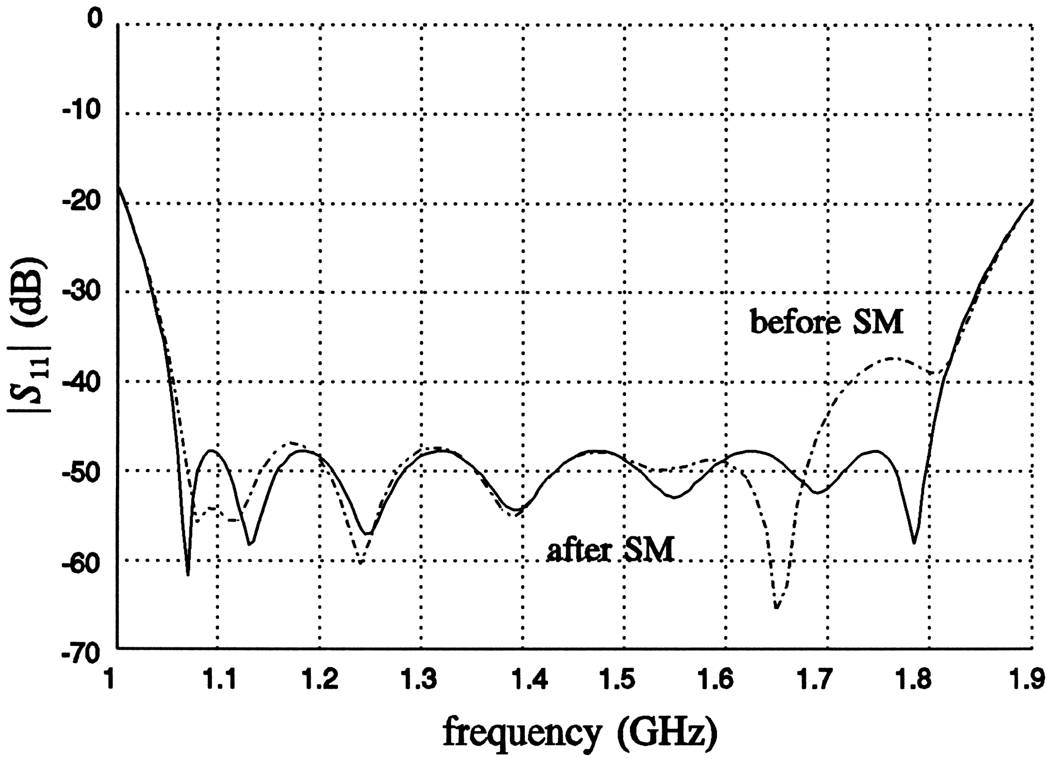


$|S_{11}|$ (dB) simulated by RWGMM before and after two steps of SM

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

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

approaches addressing uniqueness of parameter extraction

- statistical parameter extraction incorporating the ℓ_1 error and penalty function concepts

- multi-point approach

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