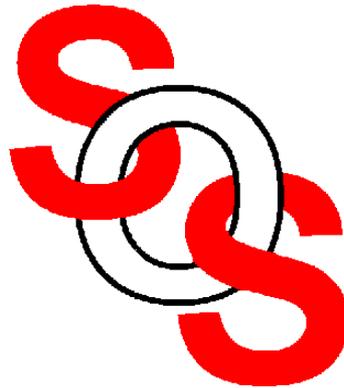


Applications of Space Mapping Optimization Technology to Filter Design

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Simulation Optimization Systems Research Laboratory
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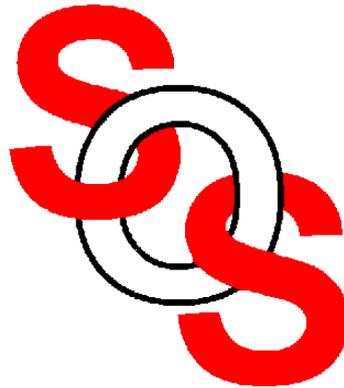
presented at

WORKSHOP ON STATE-OF-THE-ART FILTER DESIGN USING EM AND CIRCUIT SIMULATION TECHNIQUES
2001 IEEE MTT-S International Microwave Symposium, Phoenix, AZ, May 20, 2001

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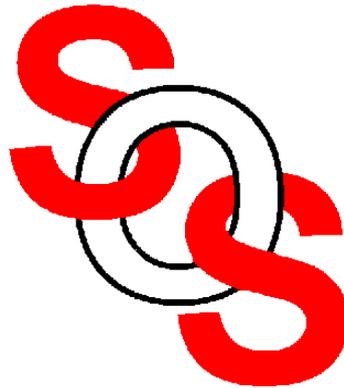


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Abstract

One of the frontiers that remains in the optimization of large engineering systems is the successful application of optimization procedures in problems where direct optimization is not practical. The recent exploitation of surrogates in conjunction with “true” models, the development of artificial neural network approaches to device modeling and the implementation of space mapping are attempts to address this issue.

Our original “Space Mapping” concept, first conceived in 1993, and the subsequent Aggressive Space Mapping approach to engineering design optimization will be discussed, along with new variations. Aggressive space mapping optimization closely follows the traditional experience and intuition of designers. It has been amply demonstrated as a very natural and flexible way of systematically optimizing microwave filters.

Space mapping optimization intelligently links companion “coarse” and “fine” models of different complexities, e.g., full-wave electromagnetic simulations and empirical circuit-theory based simulations, to accelerate iterative design optimization of engineering structures. New trust region space mapping optimization algorithms will be mentioned.

We briefly review the Expanded Space Mapping Design Framework (ESMDF) concept in which we allow preassigned parameters, not used in optimization, to change in some components of the coarse model. Other recent developments include the introduction of the object oriented SMX system to facilitate implementation of our algorithms in conjunction with certain commercial simulators. Extensive filter design examples complement the presentation.



Outline

review of selected milestones in CAD of microwave filters
(Bandler et al., 1969-2001)



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(*Bandler et al., 1969-2001*)

results of minimax and tolerance optimization of
14 channel waveguide multiplexer with 112 optimization variables
(*OSA, 1997*)



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Selected Milestones

optimization of waveguide circuits (1969)

adjoint sensitivities for microwave circuits (1970)

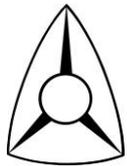
cost-driven worst-case design with optimized tolerances (1972)

centering, tolerance assignment integrated with tuning at the design stage (1974)

integrated approach to microwave design with tolerances and uncertainties (1975)

yield-driven optimization for general statistical distributions (1976)

fault diagnosis, parameter extraction, and optimal tuning and alignment (1980)



Optimization Systems Associates (OSA) (1983)



Selected Milestones

waveguide multiplexer minimax optimization system
embodying exact adjoint sensitivities (1984)

introduction of powerful minimax optimizers into **EEsof's Touchstone** (1985)

foundation of multi-circuit L1 modeling (1986)

yield-driven design for **Compact Software's Super-Compact** (1987)

nonlinear adjoint (harmonic balance) exact sensitivities (1988)

FAST, novel technique for high-speed nonlinear sensitivities (1989)

efficient quadratic approximation for statistical design (1989)

OSA's OSA90 optimization engine for performance- and yield-driven design (1990)



Selected Milestones

design optimization with external simulators, circuit-theoretic and field-theoretic (1991)

gradient quadratic approximation for yield optimization (1991)

physics-based design and yield optimization of MMICs (1991)

OSA's Empire connection of **OSA90/hope** with Sonnet Software's *em* field simulator (1992)



microstrip filter design using direct EM field simulation (1993)

yield-driven direct electromagnetic optimization (1993)

robustizing modeling and design using Huber functions (1993)

EM design of high-temperature superconducting (HTS) microwave filters (1994)

Space Mapping - a fundamental new theory for design with CPU intensive simulators (1994)



Selected Milestones

optimization of planar structures with arbitrary geometry (1994)

OSA's breakthrough **Geometry Capture** technique
(1995): now used by **Agilent EEs of EDA**



Agilent

Aggressive **Space Mapping** for EM design (1995)

novel heterogeneous parallel yield-driven EM CAD (1995)

IMS workshop on Automated Circuit Design Using Electromagnetic Simulators
(Arndt, Bandler, Chen, Hofer, Jain, Jansen, PAVIO, Pucel, Sorrentino, Swanson, 1995)

parameterization of arbitrary geometrical structures (1996)

fully-automated **Space Mapping** optimization of 3D structures (1996)



Selected Milestones



OSA's Empipe3D connection of OSA90/hope with Hewlett-Packard's HFSS and Ansoft's Maxwell Eminence full-wave 3D simulators (1996)

Space Mapping optimization with finite element (FEM) and mode matching (MM) EM simulators (1997)



HP acquires OSA, expanding HP's CAE portfolio (1997)

integration of OSA's Empipe3D with HP HFSS by HP EEsof launches HFSS Optimization (1998)

HP EEsof builds OSA technology into HP Momentum initiating Momentum Optimization (1998)

further developments in Aggressive Space Mapping (1998-)

Generalized Space Mapping (GSM) tableau approach to device modeling (1999)



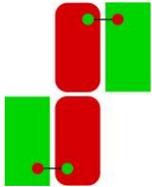
Selected Milestones

Neuro Space Mapping (NSM) device modeling (1999)



research begins on surrogate model/space mapping
optimization algorithms (1999)

the SMX engineering optimization system (2000)



First International Workshop on Surrogate Modelling
and Space Mapping for Engineering Optimization (2000)

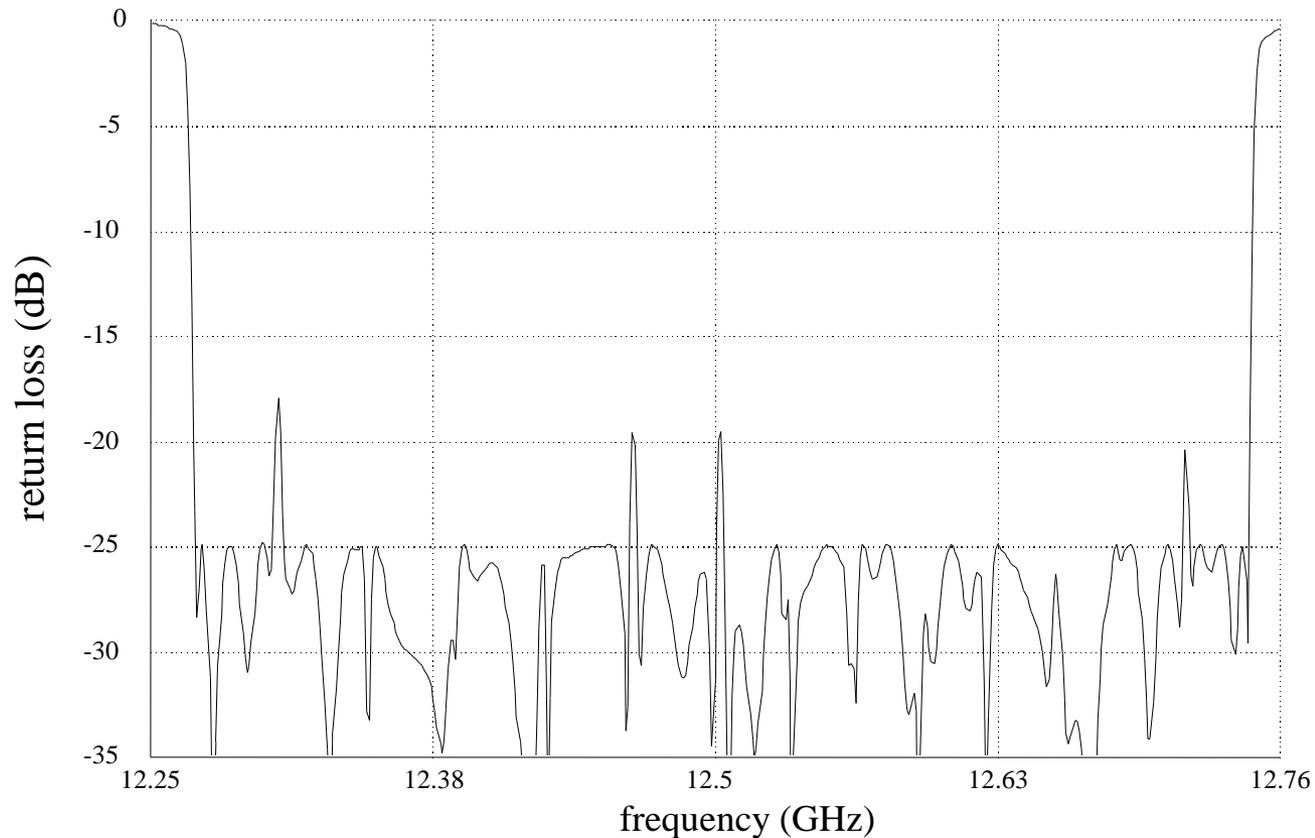
Neural Inverse Space Mapping (NISM) optimization (2001)

Expanded Space Mapping Design Framework (ESMDF) (2001)



14 Channel Multiplexer Tolerance Optimization

(OSA, 1997)



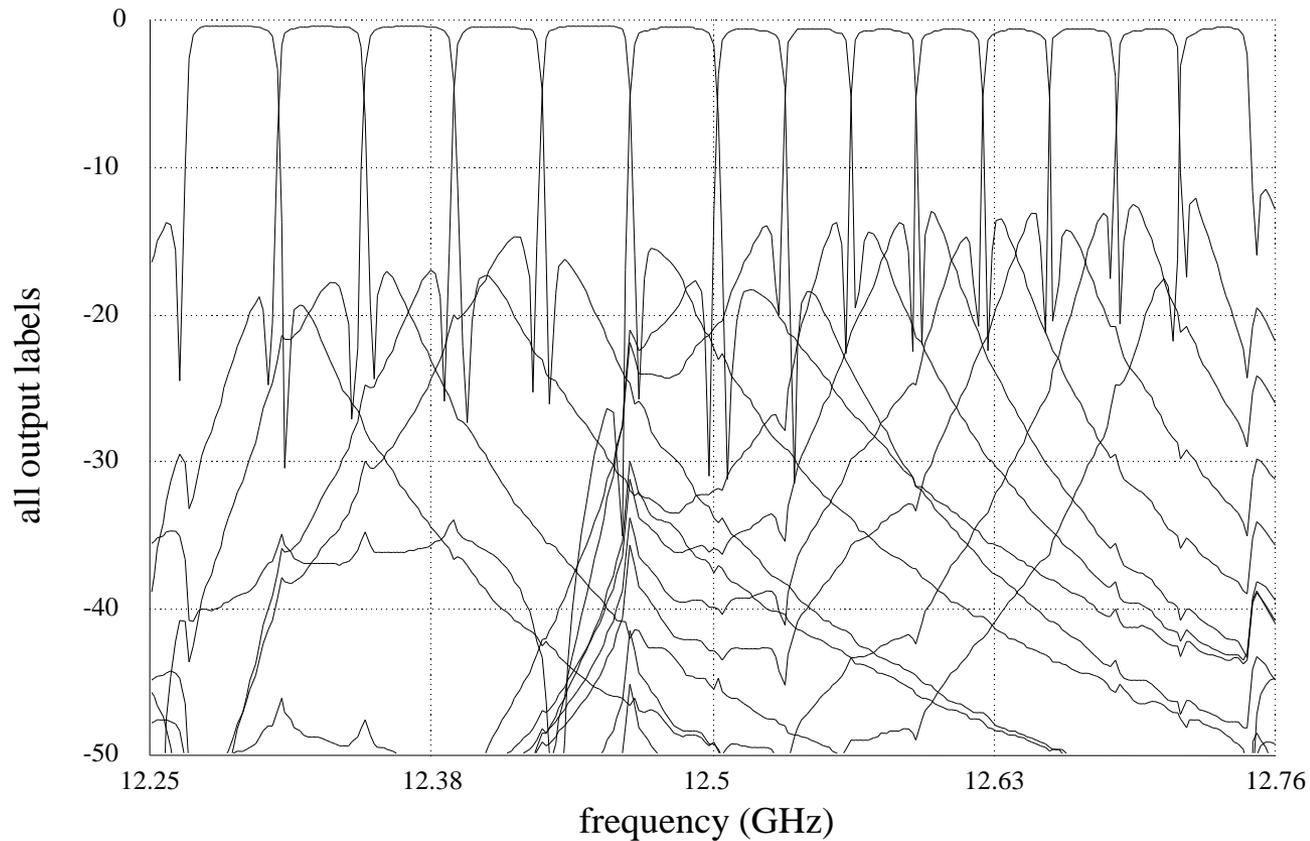
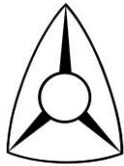
common port return loss after nominal optimization

112 optimization variables, 511 frequency points



14 Channel Multiplexer Tolerance Optimization

(OSA, 1997)

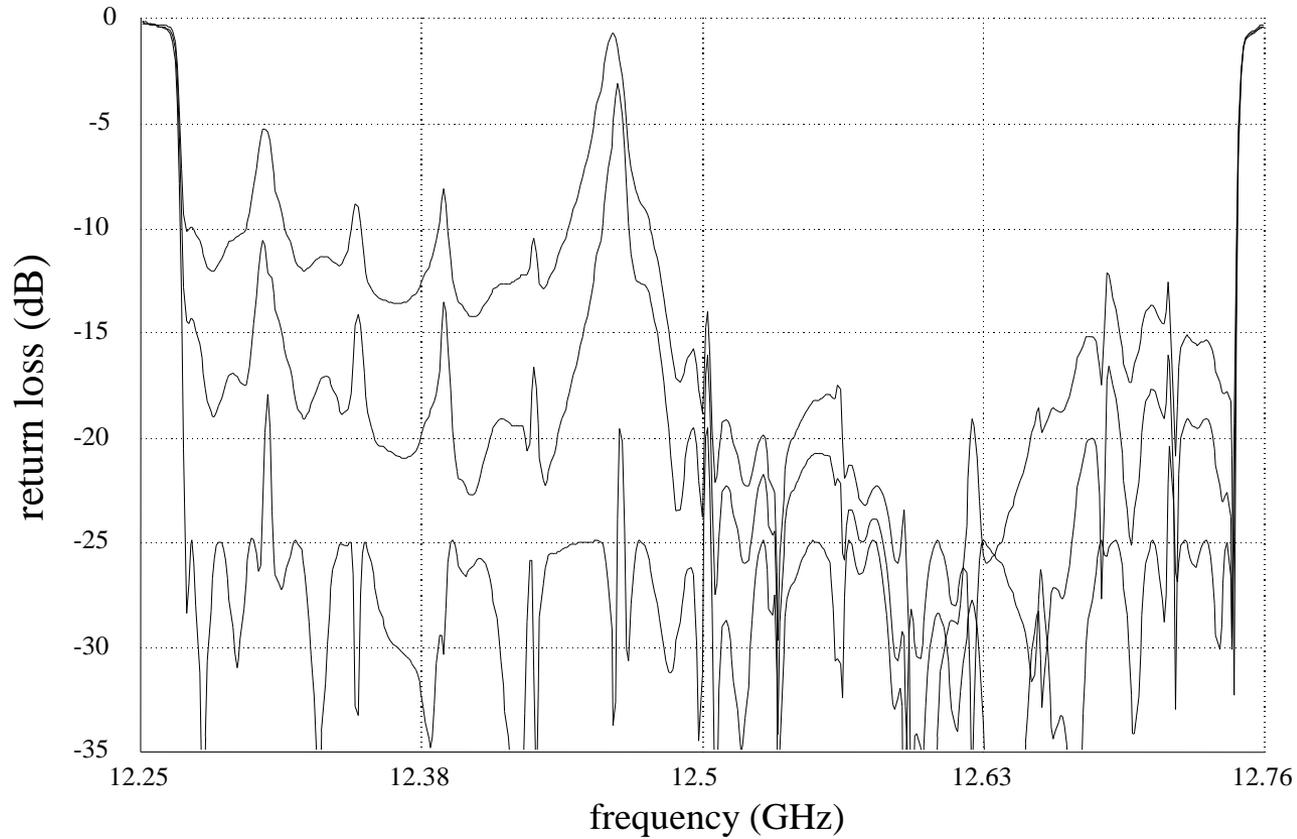


channel insertion loss after nominal optimization



14 Channel Multiplexer Tolerance Optimization

(OSA, 1997)

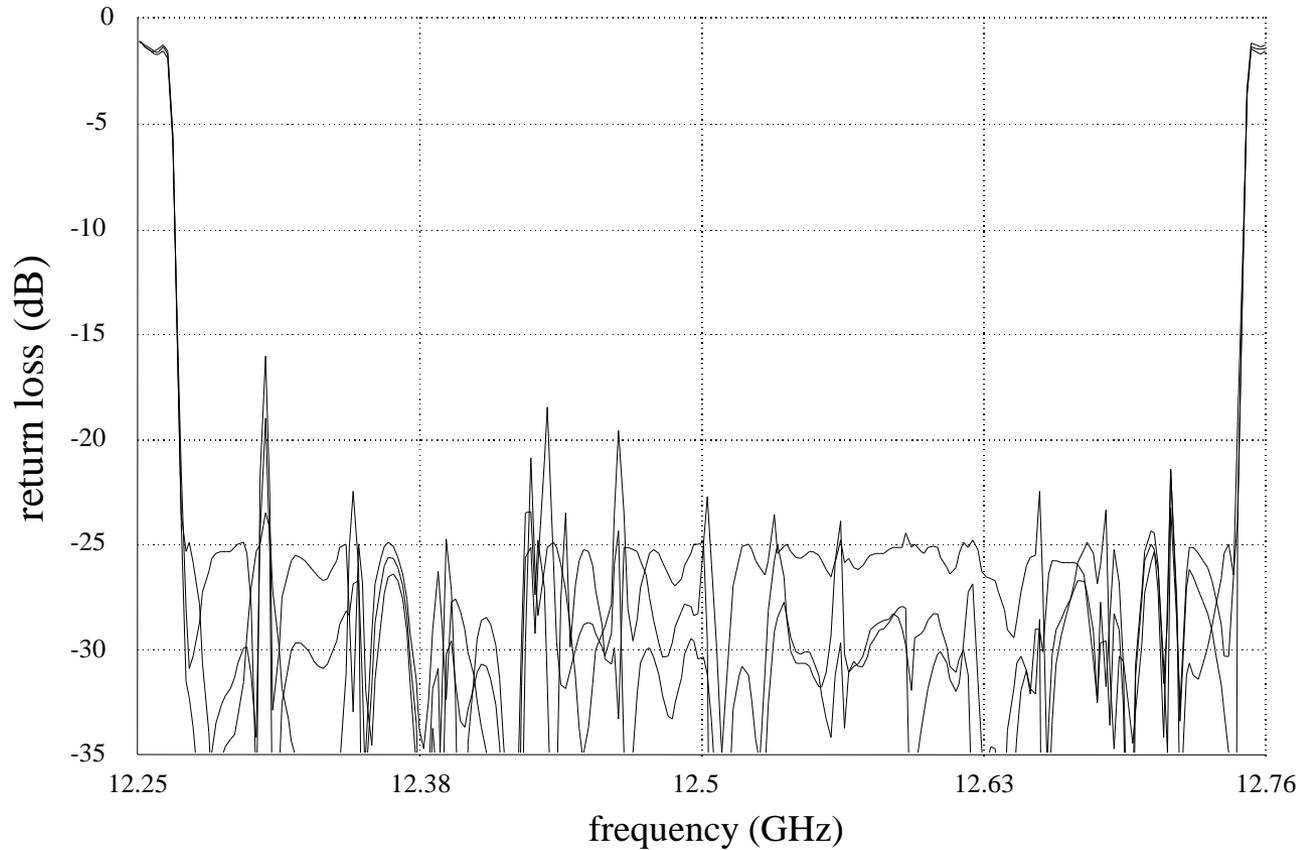
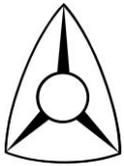


common port return loss with tolerances



14 Channel Multiplexer Tolerance Optimization

(OSA, 1997)

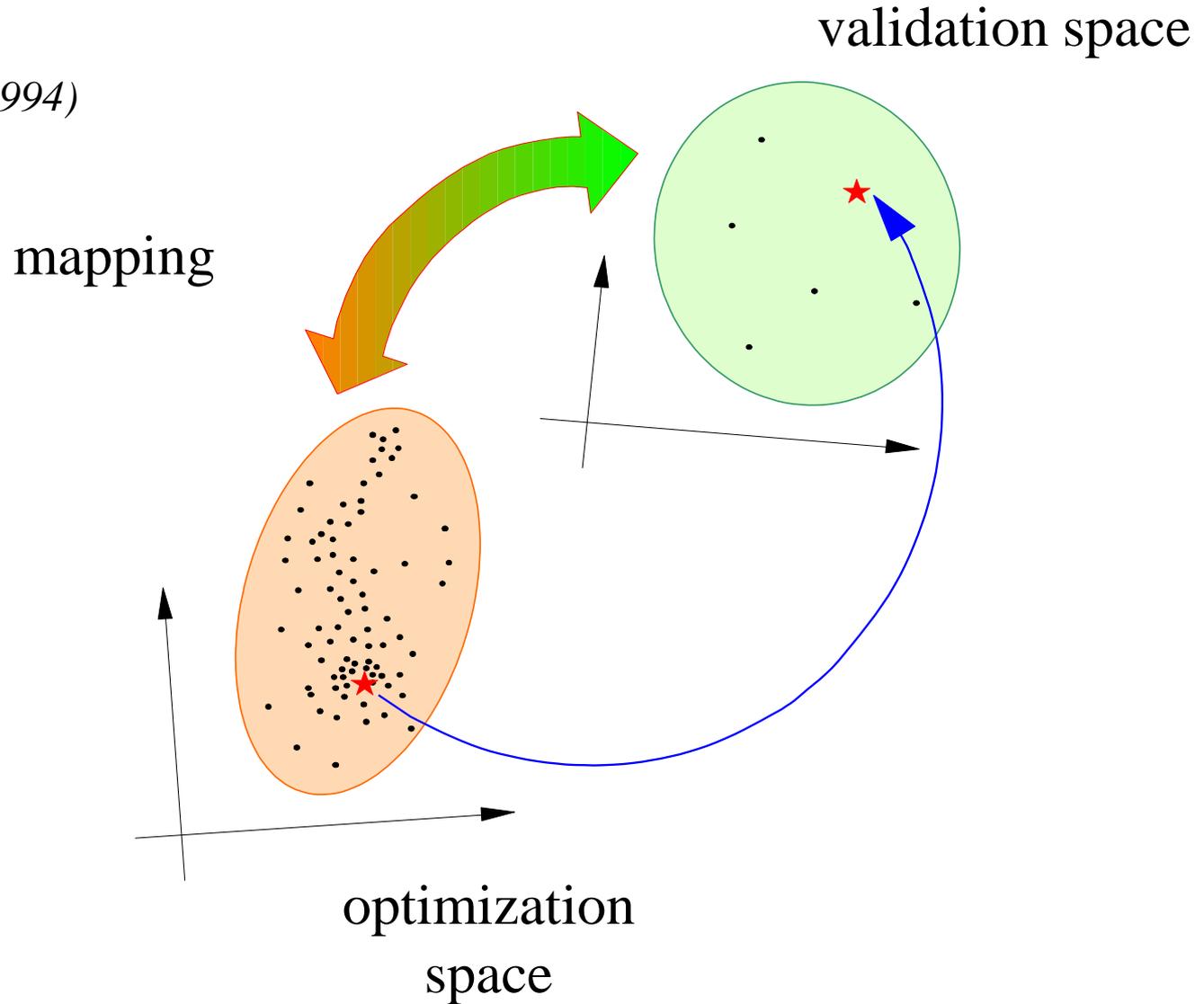


common port return loss after optimization with tolerances



Space Mapping

(Bandler et al., 1994)





Space Mapping Optimization Exploiting Surrogates

(Bakr et al., 2000)

a powerful new **Space Mapping** optimization algorithm

formulated as a general optimization problem of a surrogate model

this model is a convex combination of a mapped coarse model
and a linearized fine model

it exploits a linear frequency-sensitive mapping



The Surrogate Model

the surrogate model at the i th iteration is a convex combination of a mapped coarse model and a linearized fine model:

$$\mathbf{R}_s^{(i)}(\mathbf{x}_f) = \lambda^{(i)} \mathbf{R}_m^{(i)}(\mathbf{x}_f) + (1 - \lambda^{(i)}) (\mathbf{R}_f(\mathbf{x}_f^{(i)}) + \mathbf{J}_f^{(i)} \Delta \mathbf{x}_f), \quad \lambda^{(i)} \in [0, 1]$$

$$\Delta \mathbf{x}_f = \mathbf{x}_f - \mathbf{x}_f^{(i)}$$

the mapped coarse model utilizes the frequency-sensitive mapping

$$\mathbf{R}_m^{(i)}(\mathbf{x}_f, \omega) = \mathbf{R}_c(\mathbf{P}^{(i)}(\mathbf{x}_f, \omega), \mathbf{P}_\omega^{(i)}(\mathbf{x}_f, \omega))$$

where

$$\begin{bmatrix} \mathbf{P}^{(i)}(\mathbf{x}_f, \omega) \\ \mathbf{P}_\omega^{(i)}(\mathbf{x}_f, \omega) \end{bmatrix} = \begin{bmatrix} \mathbf{B}^{(i)} & \mathbf{s}^{(i)} \\ \mathbf{t}^{(i)T} & \sigma^{(i)} \end{bmatrix} \begin{bmatrix} \Delta \mathbf{x}_f \\ \omega \end{bmatrix} + \begin{bmatrix} \mathbf{c}^{(i)} \\ \gamma^{(i)} \end{bmatrix}$$

the parameters $\mathbf{B}^{(i)} \in \mathfrak{R}^{n \times n}$, $\mathbf{s}^{(i)} \in \mathfrak{R}^{n \times 1}$, $\mathbf{t}^{(i)} \in \mathfrak{R}^{n \times 1}$, $\mathbf{c}^{(i)} \in \mathfrak{R}^{n \times 1}$, $\sigma^{(i)} \in \mathfrak{R}^{1 \times 1}$ and $\gamma^{(i)} \in \mathfrak{R}^{1 \times 1}$ are obtained such that the mapped coarse model approximates the fine model over a given set of fine model points $V^{(i)}$ and frequencies ω



The Surrogate Model (continued)

the mapping parameters are obtained through the optimization process
(*Bakr et al., 1998-2001*)

$$[\mathbf{B}^{(i)}, \mathbf{s}^{(i)}, \mathbf{t}^{(i)}, \sigma^{(i)}, \mathbf{c}^{(i)}, \gamma^{(i)}] = \arg \left\{ \min_{\mathbf{B}, \mathbf{s}, \mathbf{t}, \sigma, \mathbf{c}, \gamma} \left\| \begin{bmatrix} \mathbf{e}_1^T & \mathbf{e}_2^T & \cdots & \mathbf{e}_{N_p}^T \end{bmatrix}^T \right\| \right\}$$

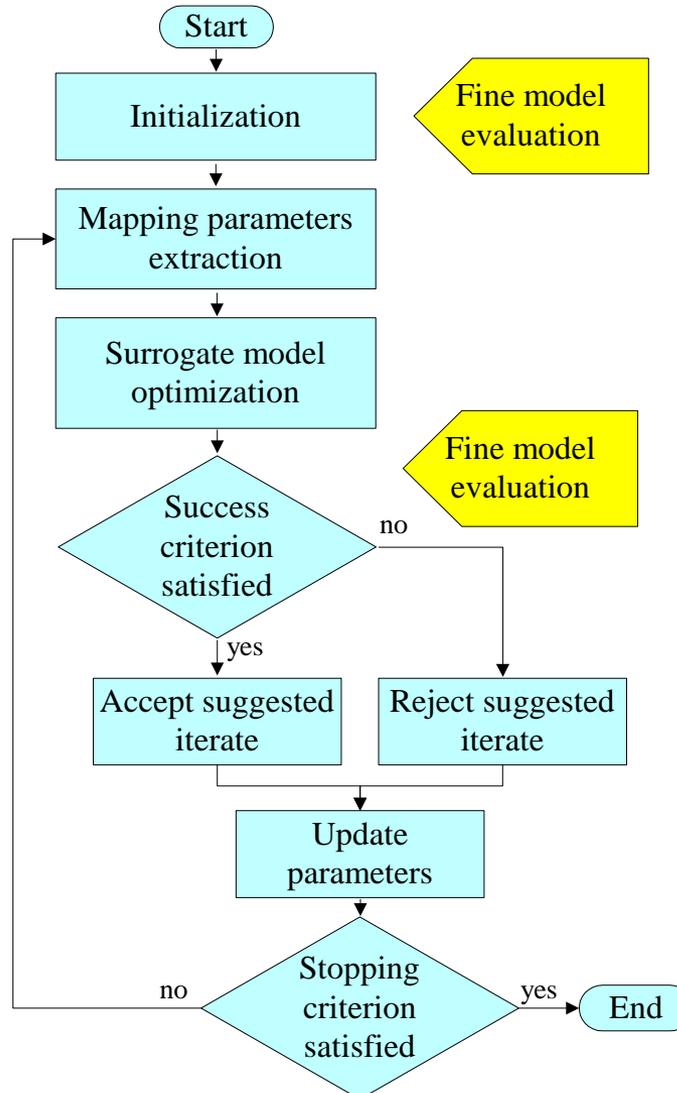
where

$$\mathbf{e}_k = \mathbf{R}_m^{(i)}(\mathbf{x}_f^{(k)}) - \mathbf{R}_f(\mathbf{x}_f^{(k)}) \quad \forall \mathbf{x}_f^{(k)} \in V^{(i)}$$

(multipoint parameter extraction)



The Algorithm Flowchart





The SMX System
(Bandler et al., 2000)

SMX is a new generation engineering optimization system

it currently provides the following optimization capabilities

minimax

Huber

Space Mapping using Surrogate Models

it can be interfaced to

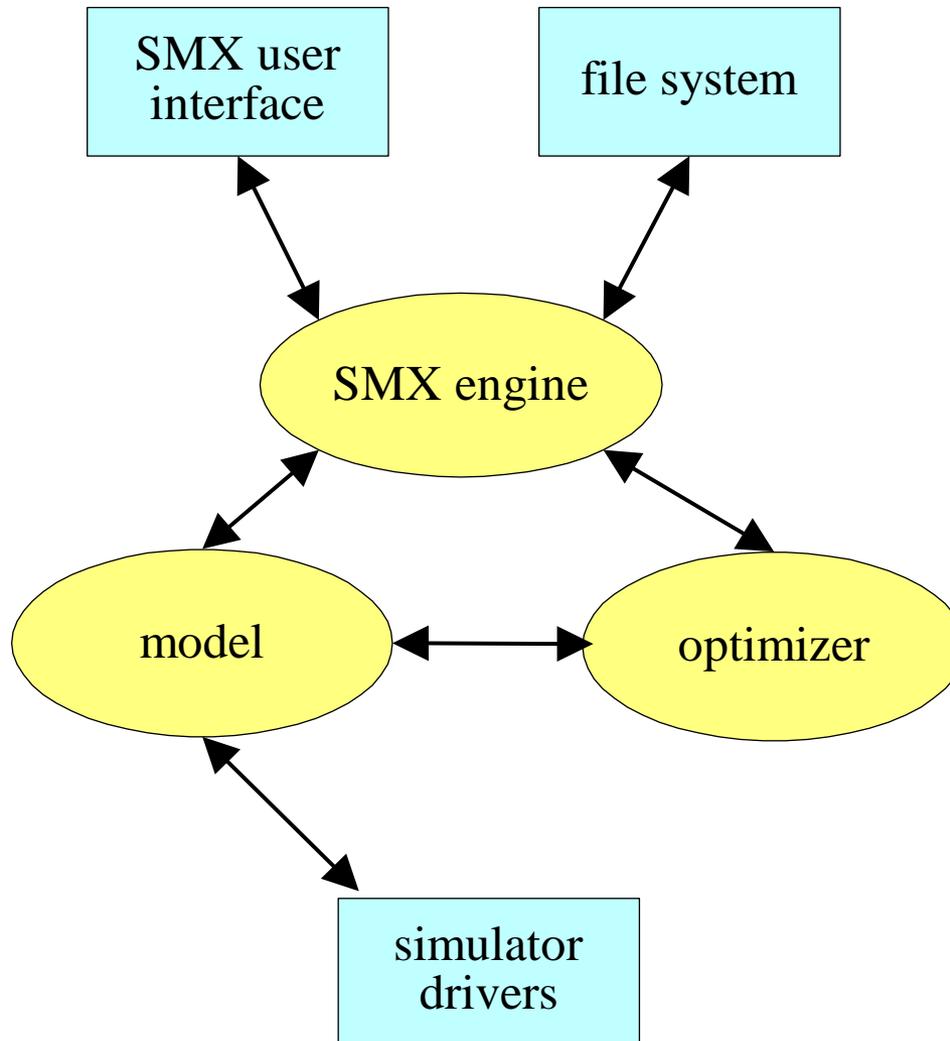
OSA90/hope (*Optimization Systems Associates, 1997*)

Momentum (*Agilent EEs of EDA*)

user supplied executable programs



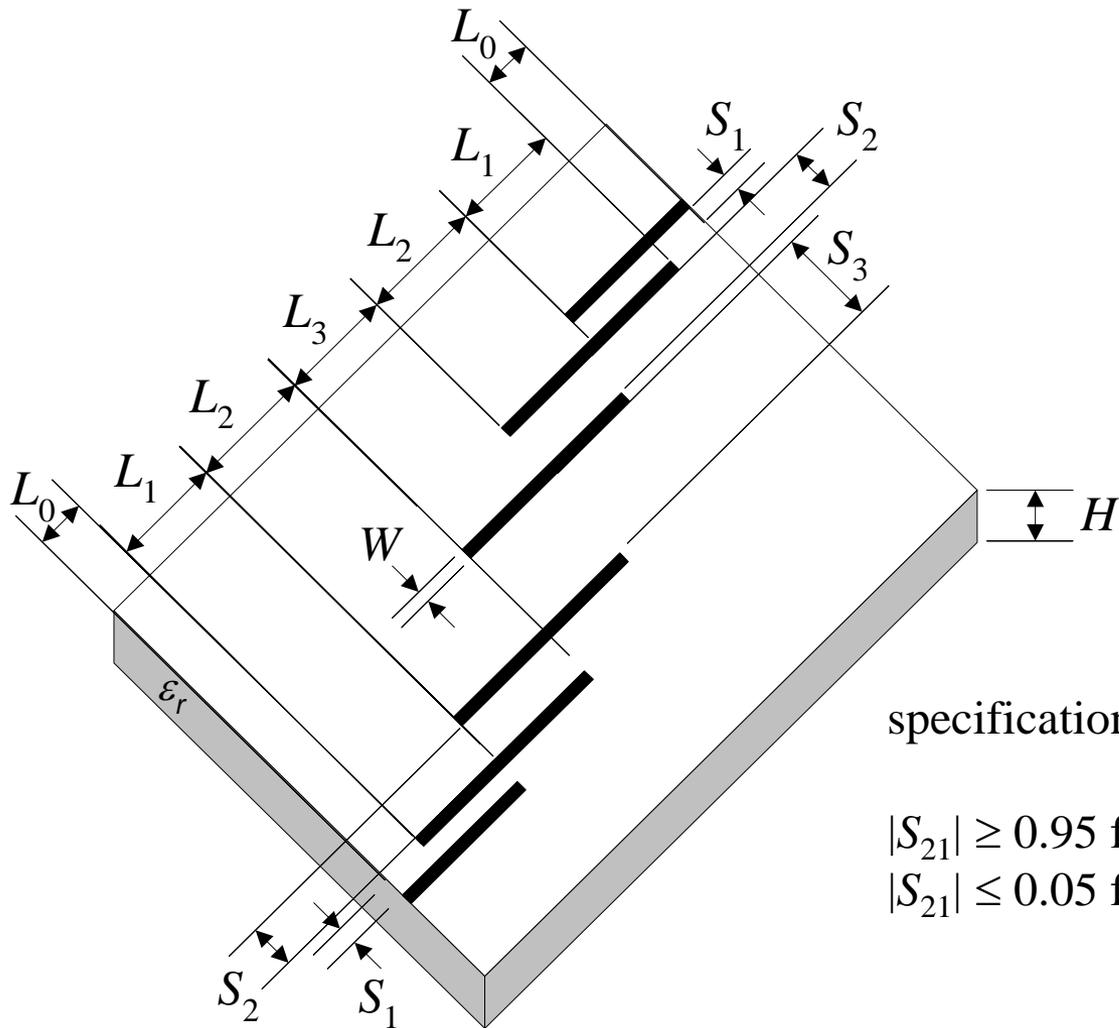
SMX System Decomposition





HTS Quarter-Wave Parallel Coupled-Line Microstrip Filter

(Westinghouse, 1993)



we take $L_0 = 50$ mil, $H = 20$ mil,
 $W = 7$ mil, $\epsilon_r = 23.425$, loss
tangent = 3×10^{-5} ; the
metalization is considered
lossless

the design parameters are

$$\mathbf{x}_f = [L_1 \ L_2 \ L_3 \ S_1 \ S_2 \ S_3]^T$$

specifications

$$|S_{21}| \geq 0.95 \text{ for } 4.008 \text{ GHz} \leq \omega \leq 4.058 \text{ GHz}$$

$$|S_{21}| \leq 0.05 \text{ for } \omega \leq 3.961 \text{ GHz and } \omega \geq 4.099 \text{ GHz}$$



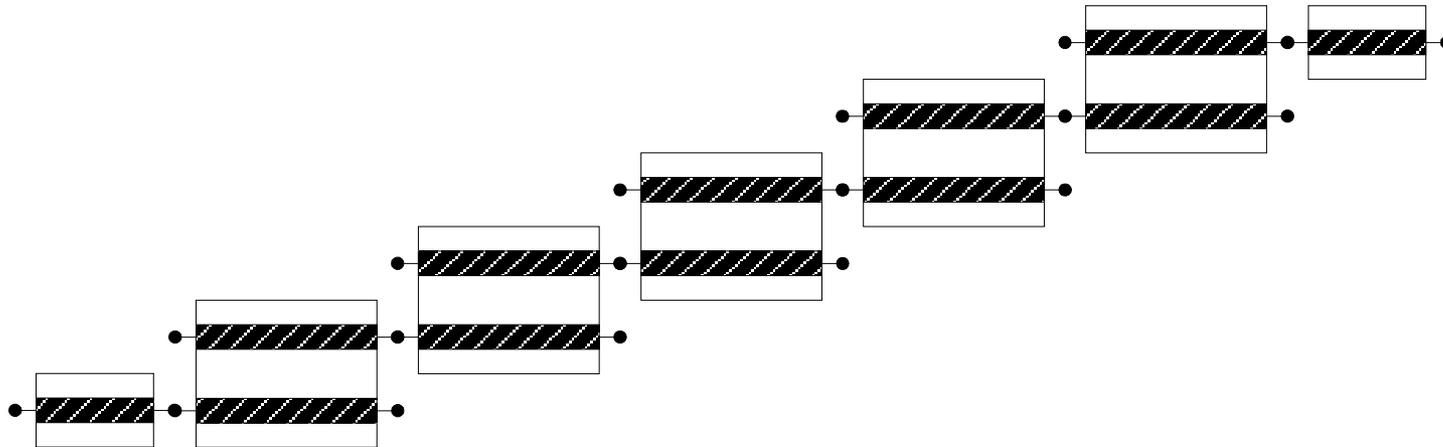
HTS Filter Design (Test Case)

“fine” model:

OSA90/hope built-in models of microstrip lines and coupled microstrip lines (open circuits are modeled by an empirical model for a microstrip open stub)

“coarse” model:

OSA90/hope built-in models of microstrip lines and coupled microstrip lines (open circuits are ideally open)



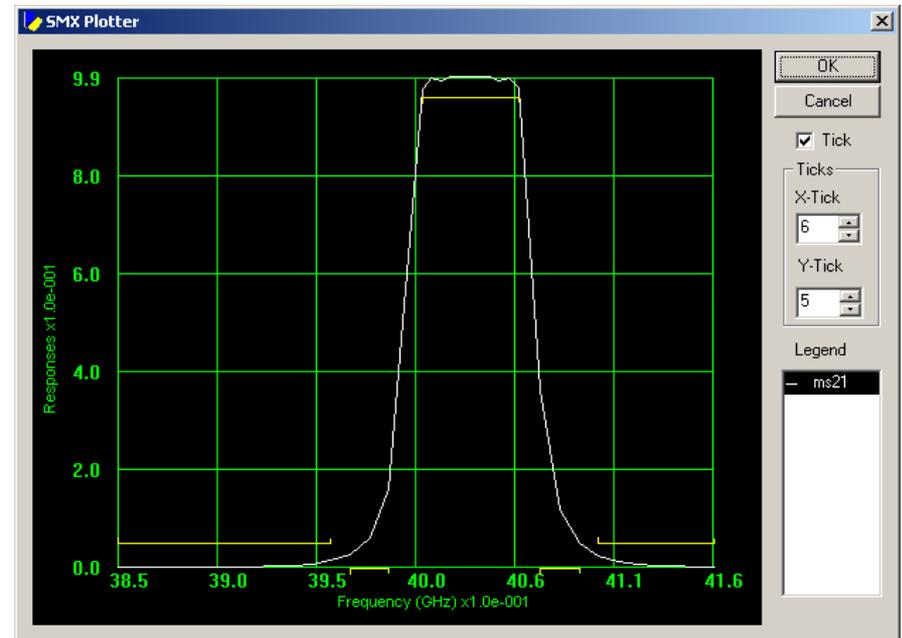
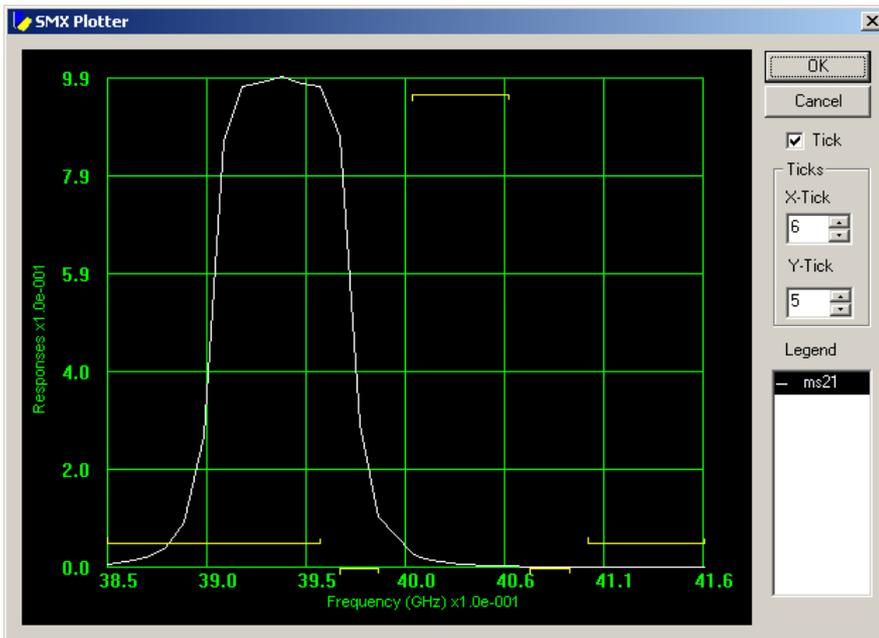


HTS Filter Design (Test Case)

“fine” model: OSA90/hope

initial response

optimal response



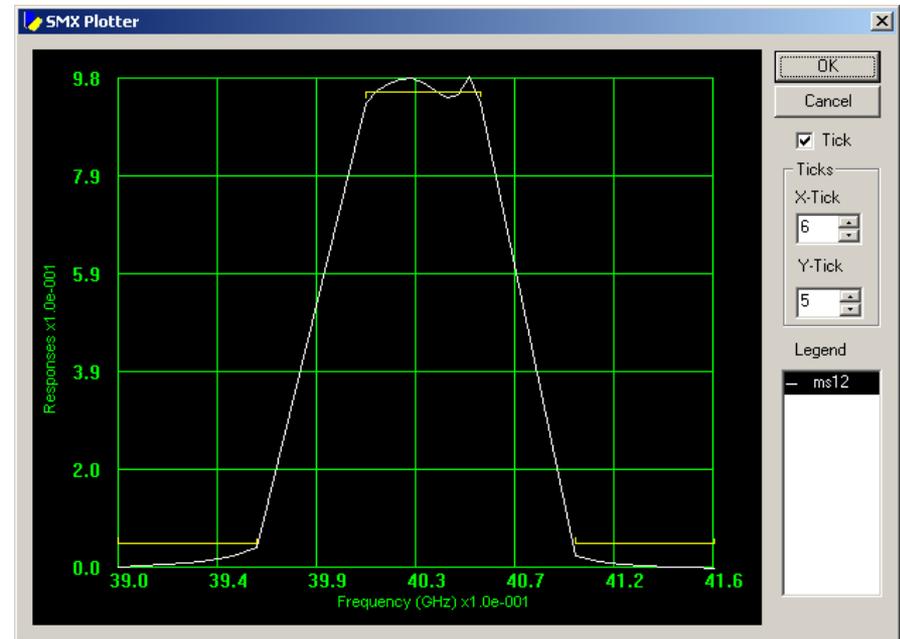
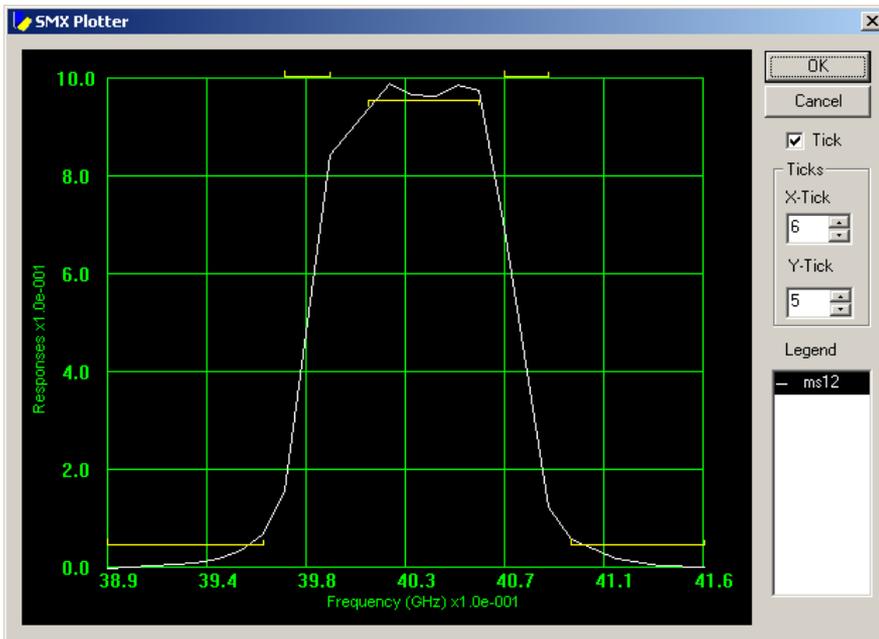


HTS Filter Design

“fine” model: **Momentum** (*Agilent EEsof EDA*)

SMX optimization
(4 iterations, 5 fine model simulations)

refined by **Momentum** optimization





Expanded Space Mapping Design Framework

Exploiting Preassigned Parameters

(Bandler et al., 2001)

the **KPP** are assumed to be non-optimizable

examples: dielectric constant, substrate height, etc.

the coarse model is very sensitive to **KPP**

the coarse model is calibrated to match the fine model by tuning the **KPP**

our algorithm establishes a mapping from some optimizable parameters to **KPP**

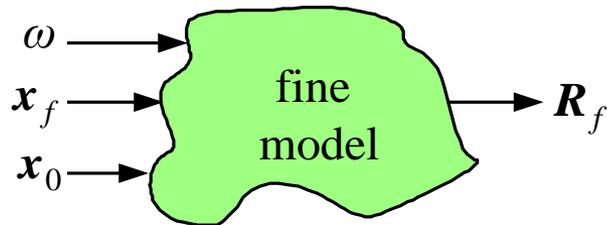
the mapping is updated iteratively



Expanded Space Mapping Design Framework

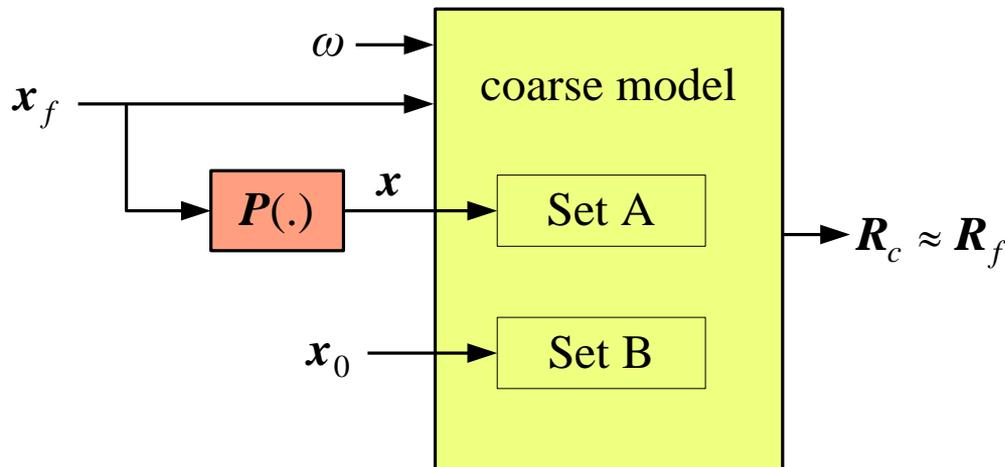
Exploiting Preassigned Parameters

(Bandler et al., 2001)



$$\mathbf{x} = P(\mathbf{x}_r)$$

$$\mathbf{x}_f = [\mathbf{x}_r^T \quad \mathbf{x}_s^T]^T$$

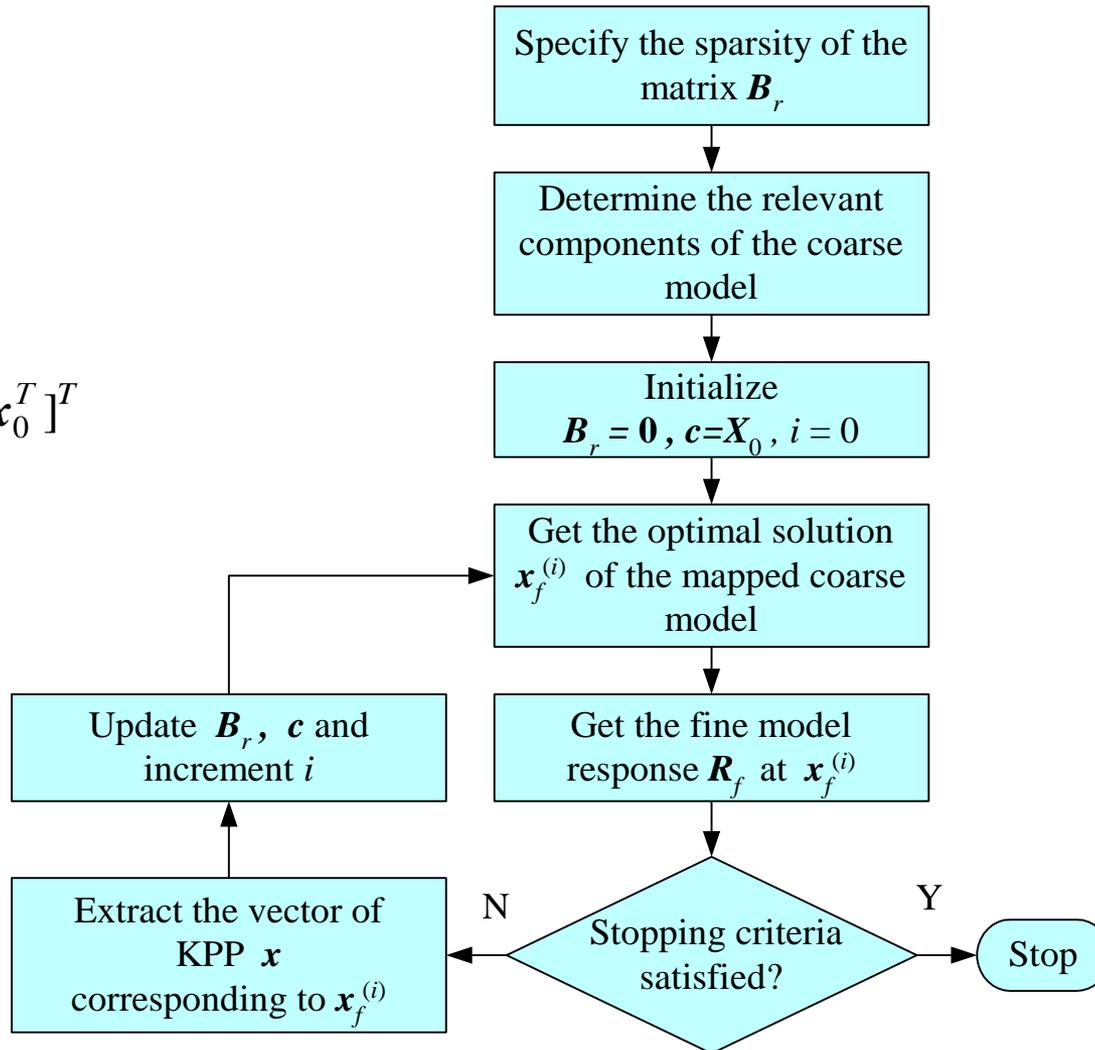


$$\mathbf{x} = \mathbf{c} + \mathbf{B}_r \mathbf{x}_r$$



Expanded Space Mapping Optimization Algorithm

$$\mathbf{X}_0 = [\mathbf{x}_0^T \ \mathbf{x}_0^T \ \cdots \ \mathbf{x}_0^T]^T$$





Coarse Model Decomposition

x_i represents the **KPP** of the i th component, $i \in I = \{1, 2, \dots, N\}$

N is the number of coarse model components

Set A: contains “relevant” coarse model components

Set B: contains coarse model components for which the coarse model is insensitive to their **KPP**



Coarse Model Decomposition

Step 1 for all $i \in I$ evaluate

$$S_i = \left\| \left(\frac{\partial \mathbf{R}_c^T}{\partial \mathbf{x}_i} \mathbf{D} \right)^T \right\|_F, \quad \mathbf{D} = \text{diag}(\mathbf{x}_0)$$

Step 2 evaluate

$$\hat{S}_i = \frac{S_i}{\max_{j \in I} \{S_j\}}, \quad i \in I$$

Step 3 put the i th component in Set A if $\hat{S}_i \geq \beta$
otherwise put it in Set B ($\beta = 0.2$)



Expanded Space Mapping Optimization Algorithm

mapped coarse model optimization

$$\mathbf{x}_f^{(i)} = \arg \min_{\mathbf{x}_f} U(\mathbf{R}_c(\mathbf{x}_f, \mathbf{B}_r \mathbf{x}_r + \mathbf{c}))$$

KPP extraction

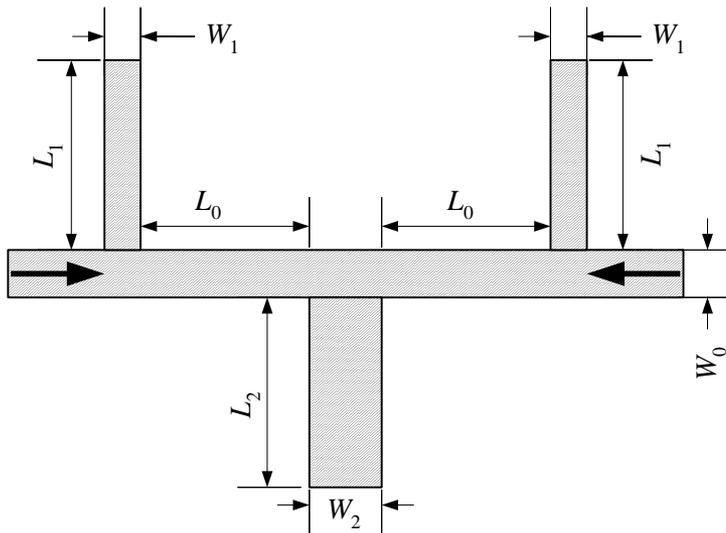
$$\mathbf{x}^{(i)} = \arg \min_{\mathbf{x}} \left\| \mathbf{R}_f(\mathbf{x}_f^{(i)}) - \mathbf{R}_c(\mathbf{x}_f^{(i)}, \mathbf{x}) \right\|$$

stopping criterion

$$\left\| \mathbf{x}_f^{(i)} - \mathbf{x}_f^{(i-1)} \right\| \leq \varepsilon$$



Microstrip Bandstop Filter with Open Stubs



“fine” model: Momentum
(Agilent EEsof EDA)



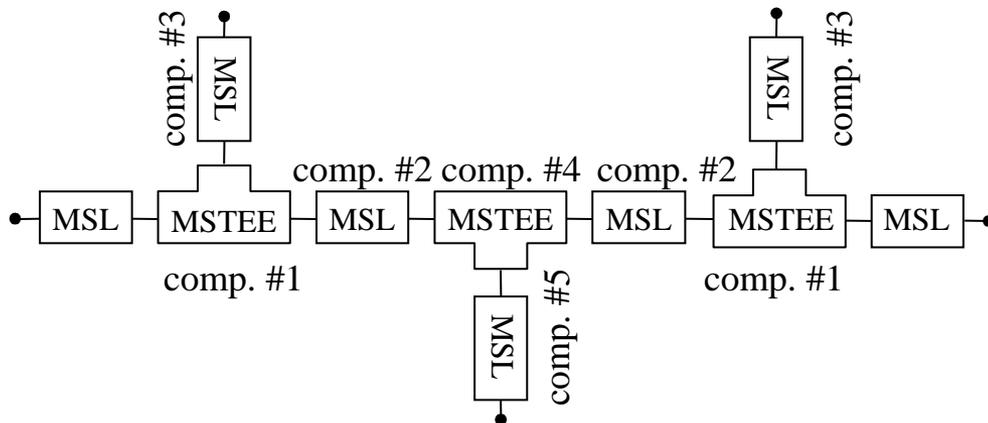
“coarse” model: OSA90/hope



specifications

$$|S_{21}| \geq -1 \text{ dB for } \omega \geq 12 \text{ GHz and } \omega \leq 8 \text{ GHz}$$

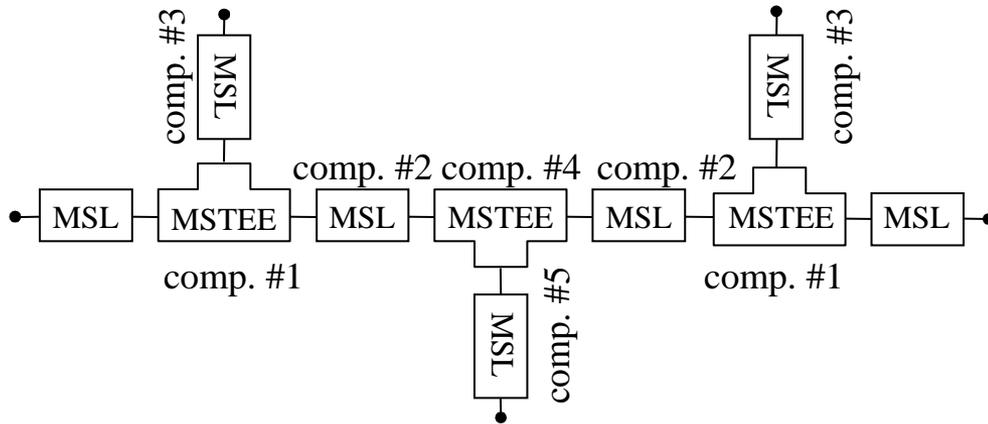
$$|S_{21}| \leq -25 \text{ dB for } 9 \text{ GHz} \leq \omega \leq 11 \text{ GHz}$$





Microstrip Bandstop Filter with Open Stubs

coarse model decomposition



$$S_i = \left\| \left(\frac{\partial \mathbf{R}_c^T}{\partial \mathbf{x}_i} \mathbf{D} \right)^T \right\|_F$$

Component #	\hat{S}_i
1	0.1420
2	0.6359
3	0.8395
4	0.1858
5	1.0000

$\epsilon_r = 9.4, H = 25 \text{ mil}$

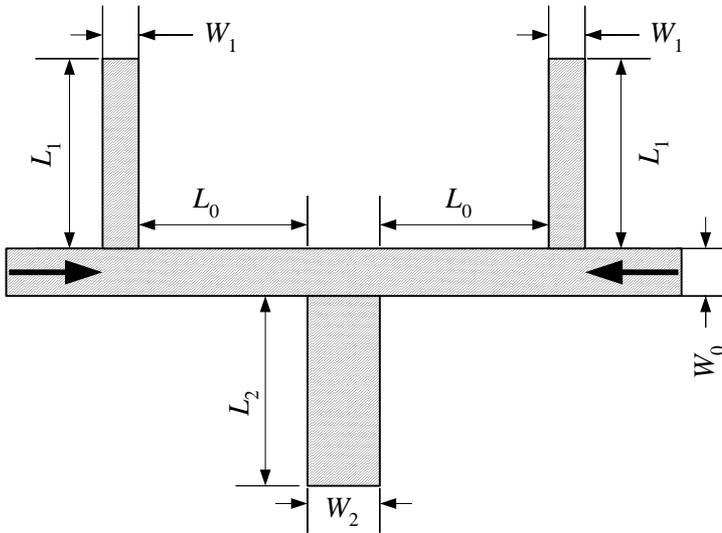
$\mathbf{x}_i = [\epsilon_{ri} \quad H_i]^T, \quad i = 1, \dots, 5$

hence $\mathbf{x} = [\mathbf{x}_2^T \quad \mathbf{x}_3^T \quad \mathbf{x}_5^T]^T$



Microstrip Bandstop Filter with Open Stubs

coarse model decomposition



$$\mathbf{x}_f = [W_1 \quad W_2 \quad L_0 \quad L_1 \quad L_2]^T$$

$$\mathbf{x}_r = [W_1 \quad W_2]^T$$

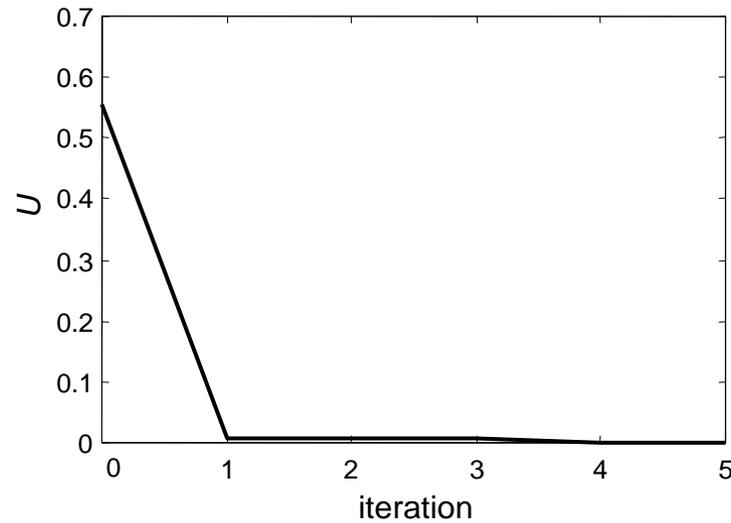
$$\mathbf{x} = [\mathbf{x}_2^T \quad \mathbf{x}_3^T \quad \mathbf{x}_5^T]^T \quad \mathbf{x}_i = [\varepsilon_{ri} \quad H_i]^T$$

$$\mathbf{x} = \mathbf{c} + \mathbf{B}_r \mathbf{x}_r$$



Microstrip Bandstop Filter with Open Stubs

fine model objective function



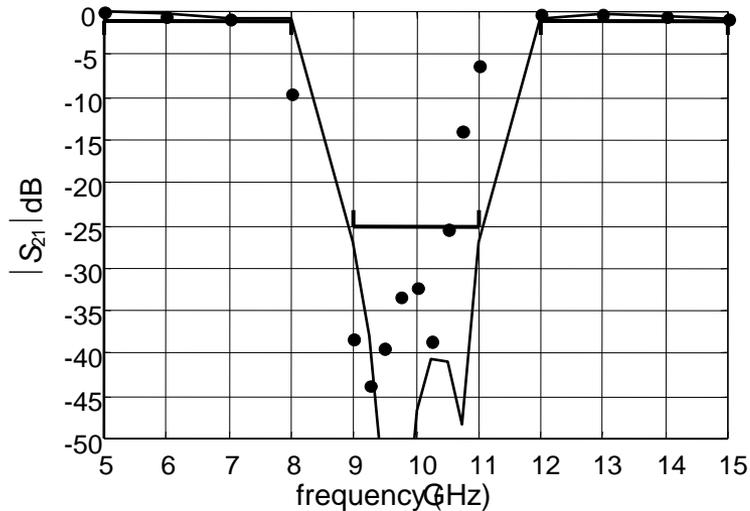
elapsed time by **Expanded Space Mapping** optimization algorithm: 1.5 hr



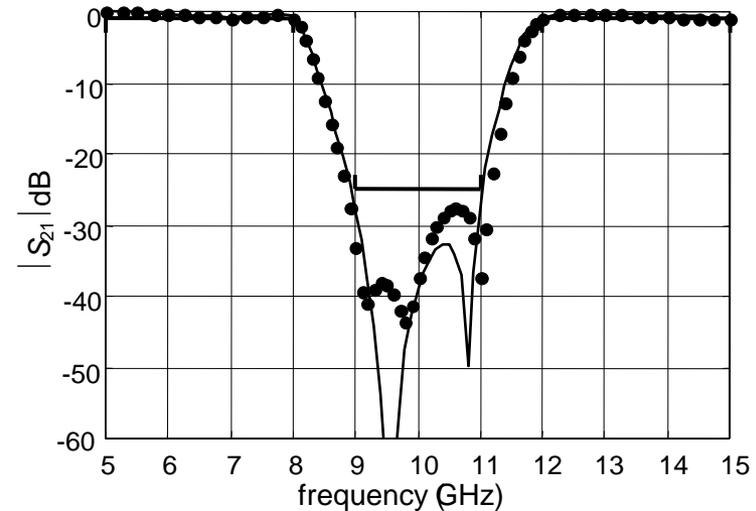
Microstrip Bandstop Filter with Open Stubs

the algorithm converges in 5 iterations, 6 **Momentum** sweeps

initial response



optimal response



elapsed time by **Expanded Space Mapping** optimization algorithm: 1.5 hr

elapsed time by **Momentum** optimization (using quadratic interpolation): 10 hr



Conclusions

we review the surrogate model approach to **SM** optimization

the surrogate model is a convex combination of a mapped coarse model and a linearized fine model

object-oriented **SMX** optimization system implements this approach

certain simulators can be driven by **SMX**

we expand the original space mapping approach

we deliberately change the **KPP** in “relevant components” of the coarse model to align it with the fine model

a mapping is established from the optimization variables to the **KPP**



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