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Applications of Space Mapping Optimization Technology to Filter Design

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Applications of Space Mapping Optimization Technology to Filter Design

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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)

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

Space Mapping optimization exploiting surrogate models
(Bakr et al., 2000)

state-of-the-art SMX system
(Bandler et al., 2000)

Expanded Space Mapping Design Framework
exploiting preassigned parameters
(Bandler et al., 2001)



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)

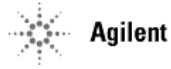
Space Mapping - a fundamental new theory for design with CPU intensive simulators (1994)



Selected Milestones

optimization of planar structures with arbitrary geometry (1994)

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



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, Pavo, 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)



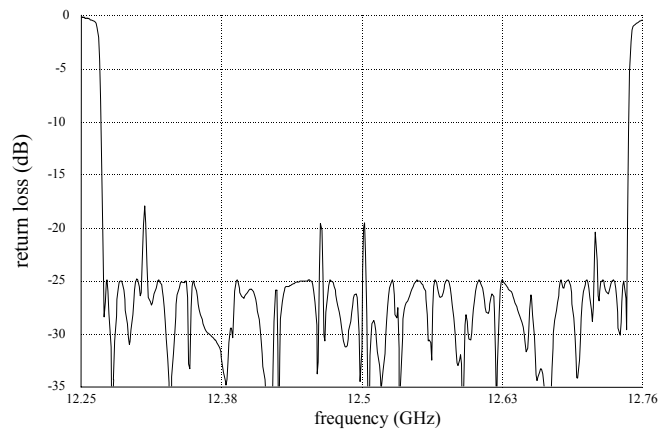
First International Workshop on Surrogate Modelling and Space Mapping for Engineering Optimization (2000)

Neural Inverse Space Mapping optimization (NISM) (2001)

Expanded Space Mapping Design Framework (ESMDF) (2001)

14 Channel Multiplexer Tolerance Optimization

(OSA, 1997)



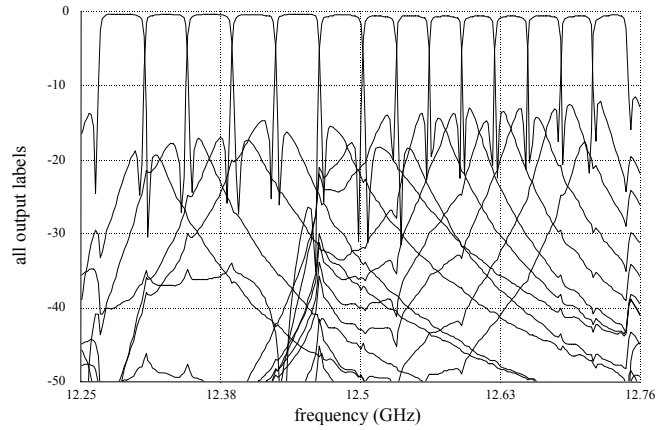
common port return loss after nominal optimization

112 optimization variables, 511 frequency points



14 Channel Multiplexer Tolerance Optimization

(OSA, 1997)

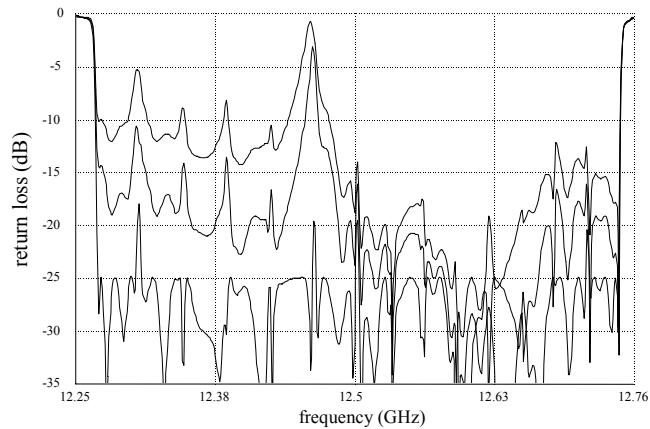


channel insertion loss after nominal optimization



14 Channel Multiplexer Tolerance Optimization

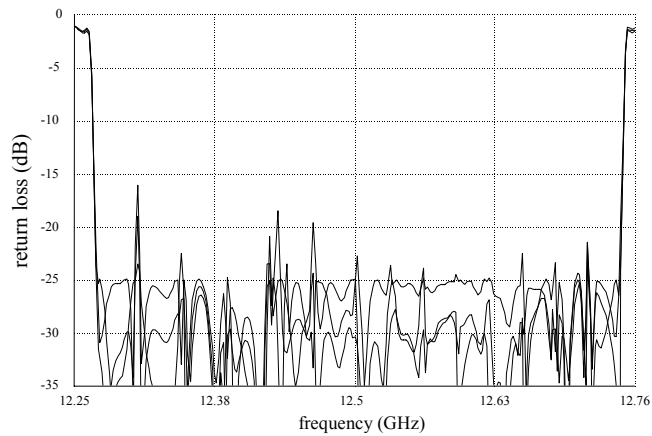
(OSA, 1997)



common port return loss with tolerances

14 Channel Multiplexer Tolerance Optimization

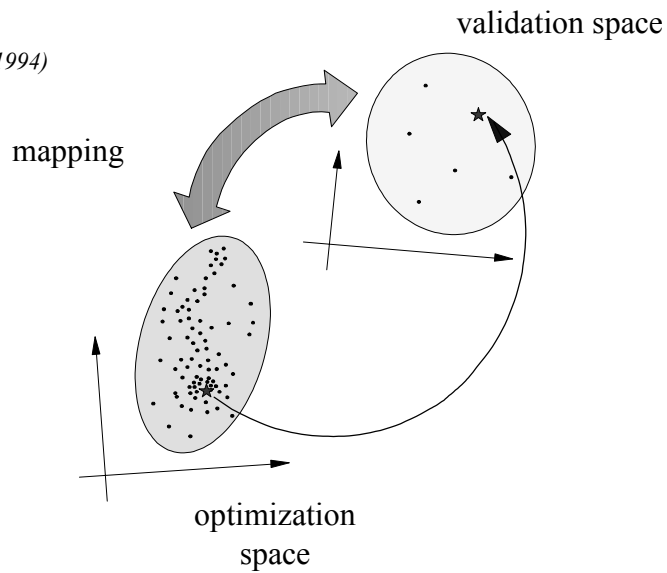
(OSA, 1997)



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 (SM) 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

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

the i th iteration surrogate model is

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

the mapped coarse model utilizes the frequency-sensitive mapping

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

where

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

the parameters $\mathbf{B}^{(i)} \in \Re^{n \times n}$, $\mathbf{s}^{(i)} \in \Re^{n \times 1}$, $\mathbf{t}^{(i)} \in \Re^{n \times 1}$, $\mathbf{c}^{(i)} \in \Re^{n \times 1}$, $\sigma^{(i)} \in \Re^{1 \times 1}$ and $\gamma^{(i)} \in \Re^{1 \times 1}$ 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)

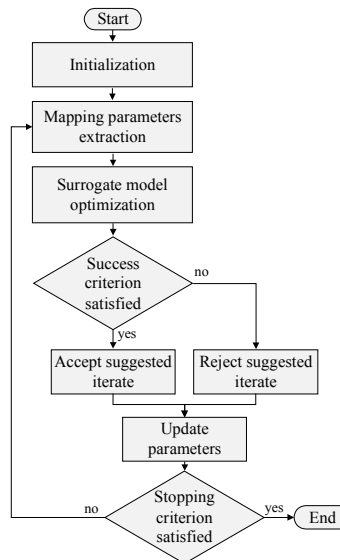
the mapping parameters are obtained through the optimization process

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

where

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

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

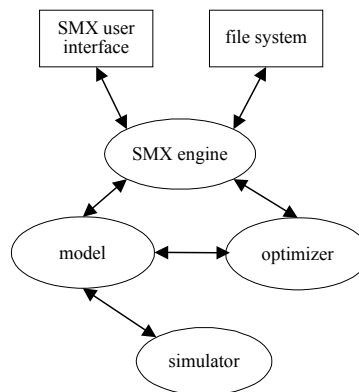
- minimax
- Huber
- Space Mapping using Surrogate Models

it can be interfaced to

- OSA90/hope (*Optimization Systems Associates, 1997*)
- Momentum (*Agilent EEsof EDA*)
- user supplied executable programs

Object Oriented SMX Architecture

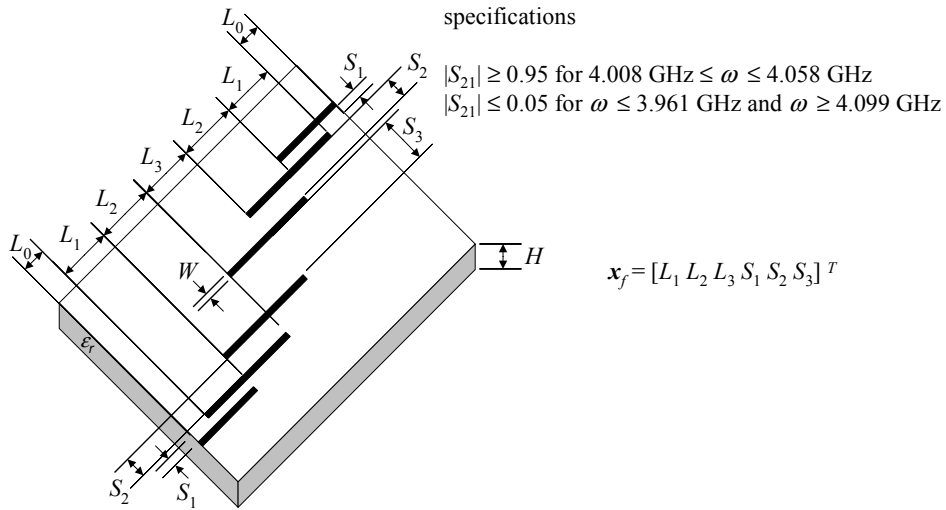
SMX system includes 6 modules





HTS Filter Design

(Bandler et al., 1994)



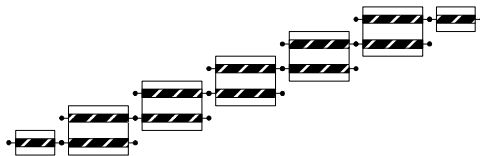
HTS Filter Design (Test Case)

“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:

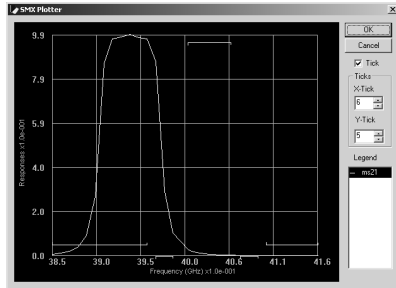
OSA90/hope™ built-in models of microstrip lines and coupled microstrip lines (open circuits are ideally open)



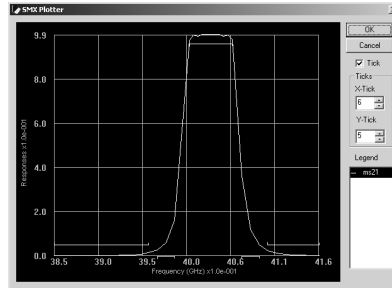
HTS Filter Design (Test Case)

“fine” model (OSA90) responses

initial response



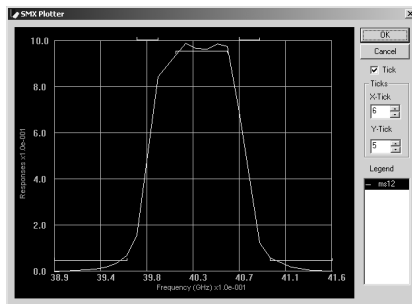
optimal response



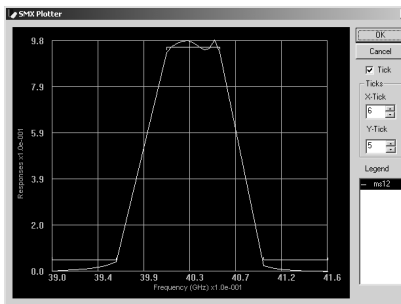
HTS Filter Design

“fine” model: Momentum
 (Agilent EEsof EDA)

SMX optimization



refined by Momentum optimization



Expanded Space Mapping Design Framework
Exploiting Preassigned Parameters

(Bandler et al., 2001)

Key Preassigned Parameters (KPP) are not used in the design optimization

examples of KPP: dielectric constant, substrate height, etc.

the coarse model response is very sensitive to changes in KPP

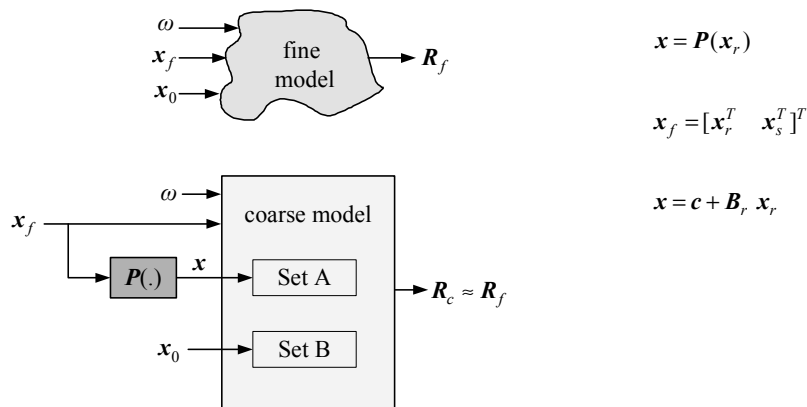
the coarse model is calibrated to match the fine model by allowing the KPP to change in certain coarse model components

the algorithm establishes a mapping from some optimizable parameters to KPP

the mapping is updated iteratively until we reach the optimal solution

Expanded Space Mapping Design Framework
Exploiting Preassigned Parameters

(Bandler et al., 2001)





Coarse Model Decomposition

let N be the number of coarse model components

let the set I be

$$I = \{1, 2, \dots, N\}$$

let \mathbf{x}_i represents the KPP of the i th component, $i \in I$

Set A: contains the coarse model components for which the coarse model response is sensitive to their KPP

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



Coarse Model Decomposition

Step 1 for all $i \in I$ evaluate

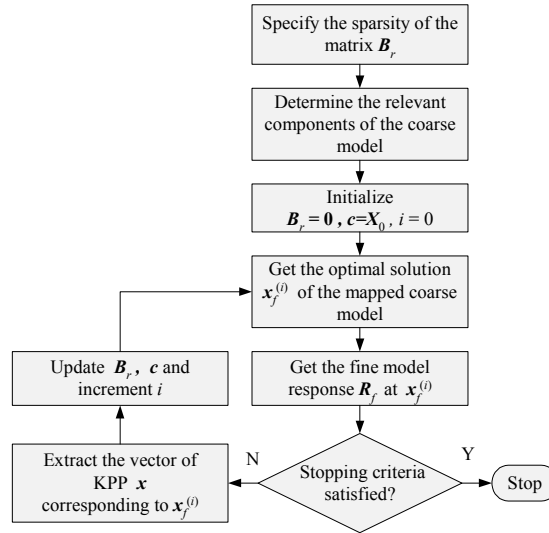
$$S_i = \left\| \left(\frac{\partial \mathbf{R}_c^T}{\partial \mathbf{x}_i} \mathbf{D} \right)^T \right\|_F$$

Step 2 evaluate

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

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

Expanded Space Mapping Optimization Algorithm



Expanded Space Mapping Optimization Algorithm

mapped coarse model optimization

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

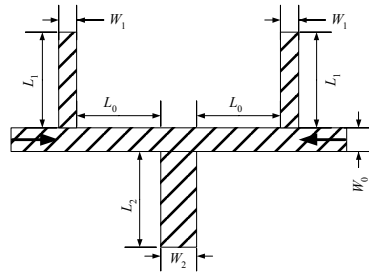
KPP extraction

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

stopping criterion

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

Microstrip Bandstop Filter with Open Stubs



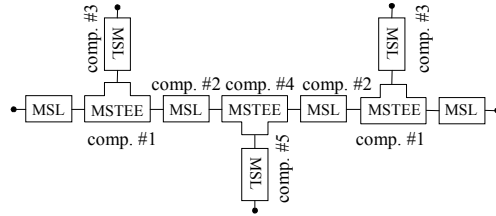
“fine” model: Momentum
(Agilent EEs of EDA)

“coarse” model: OSA90

specifications

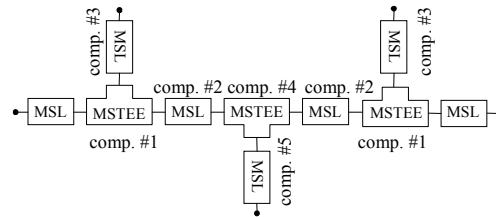
$$|S_{21}| \geq -1 \text{ dB for } \omega \geq 12 \text{ GHz and } \omega \leq 8 \text{ GHz}$$

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



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

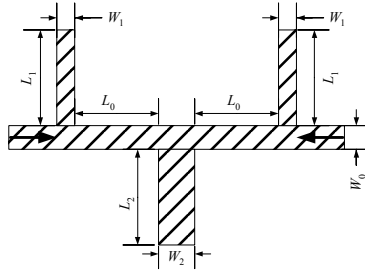
$$\epsilon_r = 9.4, H = 25 \text{ mil}$$

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

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

Microstrip Bandstop Filter with Open Stubs

coarse model decomposition



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

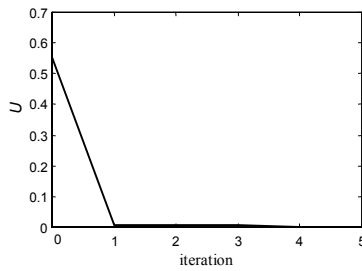
$$\mathbf{x}_r = [W_1 \quad W_2]^T$$

$$\mathbf{x} = [x_2^T \quad x_3^T \quad x_5^T]^T \quad \mathbf{x}_i = [\varepsilon_{ri} \quad H_i]^T$$

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

Microstrip Bandstop Filter with Open Stubs

fine model objective function



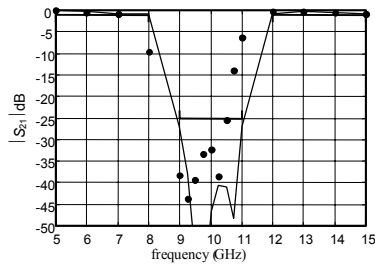
elapsed time by Expanded Space Mapping optimization algorithm: 1.5 hr



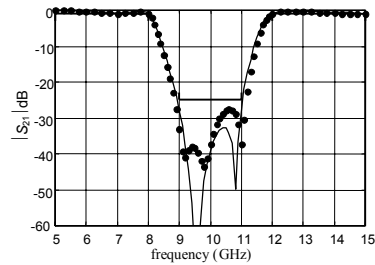
Microstrip Bandstop Filter with Open Stubs

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 direct 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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UML Training in Object Oriented Analysis and Design page at http://www.cragssystems.co.uk/uml_training_080.htm.