Applications of Space Mapping Optimization Technology to Filter Design

J.W. Bandler, M.H. Bakr, Q.S. Cheng, M.A. Ismail and J.E. Rayas-Sánchez

Simulation Optimization Systems Research Laboratory
McMaster University

Bandler Corporation, www.bandler.com
john@bandler.com

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

Applications of Space Mapping Optimization Technology to Filter Design

J.W. Bandler, M.H. Bakr, Q.S. Cheng, M.A. Ismail and J.E. Rayas-Sánchez

McMaster University, bandler@mcmaster.ca, http://www.sos.mcmaster.ca
Bandler Corporation, john@bandler.com, http://www.bandler.com

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)

Simulation Optimization Systems Research Laboratory
McMaster University
BANDLER CORPORATION

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)

Simulation Optimization Systems Research Laboratory
McMaster University

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 Empipe 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

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, Hoefer, Jain, Jansen, Pavio, Pucel, Sorrentino, Swanson, 1995)

parameterization of arbitrary geometrical structures (1996)

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

Simulation Optimization Systems Research Laboratory
McMaster University
BANDLER CORPORATION

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)

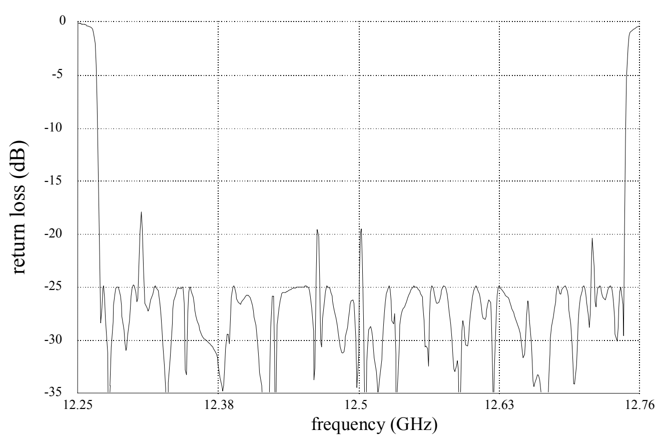
Neural Inverse Space Mapping optimization (NISM) (2001)

Expanded Space Mapping Design Framework (ESMDF) (2001)

Simulation Optimization Systems Research Laboratory
McMaster University

BANDLER CORPORATION

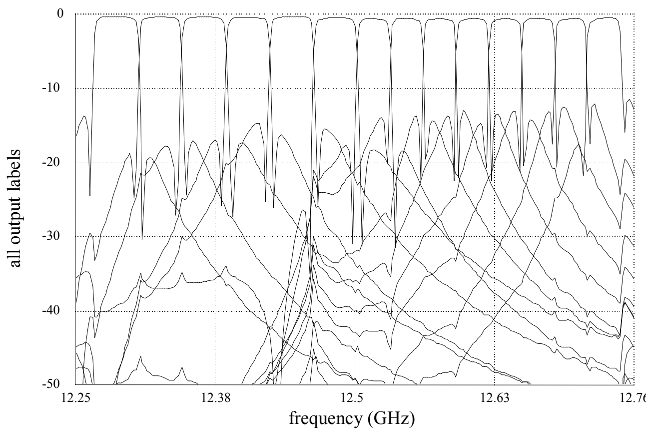
14 Channel Multiplexer Tolerance Optimization
(OSA, 1997)



common port return loss after nominal optimization

112 optimization variables, 511 frequency points

14 Channel Multiplexer Tolerance Optimization
(OSA, 1997)

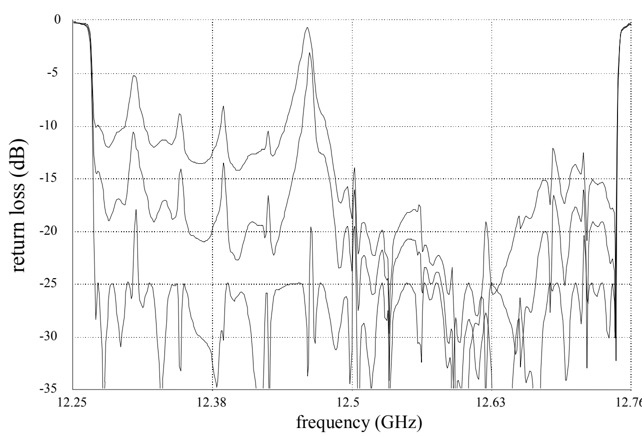


channel insertion loss after nominal optimization

Simulation Optimization Systems Research Laboratory
McMaster University

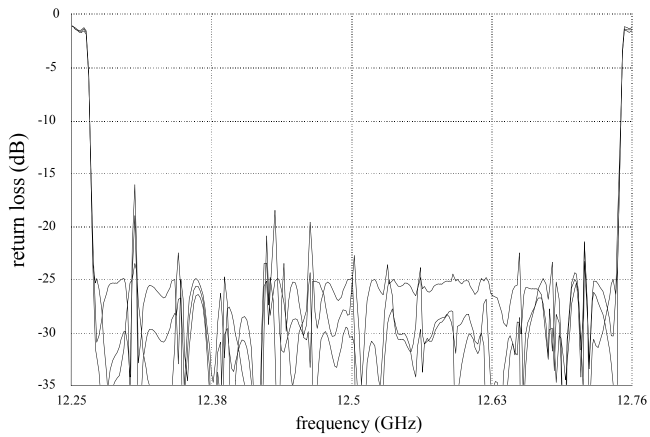
BANDLER CORPORATION

14 Channel Multiplexer Tolerance Optimization
(OSA, 1997)



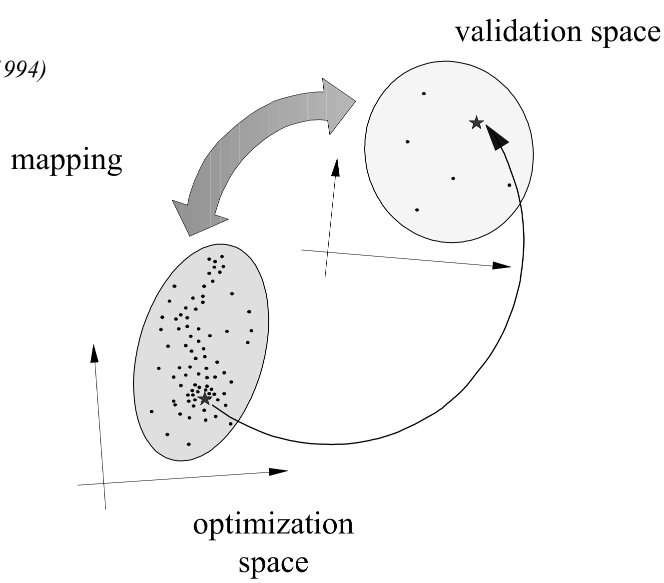
common port return loss with tolerances

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 ith iteration surrogate model is

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

the mapped coarse model utilizes the frequency-sensitive mapping

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

where

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

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

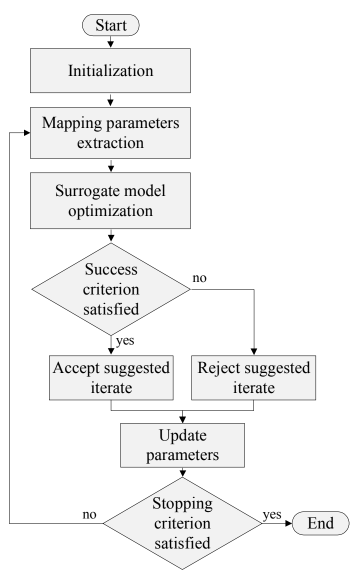
$$[\boldsymbol{B}^{(i)}, \boldsymbol{s}^{(i)}, \boldsymbol{t}^{(i)}, \sigma^{(i)}, \boldsymbol{c}^{(i)}, \gamma^{(i)}] = \arg\left\{ \min_{\boldsymbol{B}, \boldsymbol{s}, \boldsymbol{t}, \sigma, \boldsymbol{c}, \gamma} \left\| \begin{bmatrix} \boldsymbol{e}_1^T & \boldsymbol{e}_2^T & \cdots & \boldsymbol{e}_{N_p}^T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

where

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

Simulation Optimization Systems Research Laboratory
McMaster University
BANDLER CORPORATION

The Algorithm Flowchart



The SMX System
(Bandler et al., 2000)

SMX is a new generation engineering optimization system

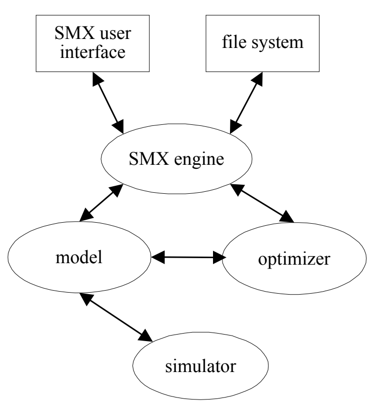
it currently provides the following optimization capabilities
minimax
Huber
Space Mapping using Surrogate Models

it can be interfaced to
OSA90/hope *(Optimization Systems Associates, 1997)*
Momentum *(Agilent EEsof EDA)*
user supplied executable programs

Simulation Optimization Systems Research Laboratory
McMaster University
BANDLER CORPORATION

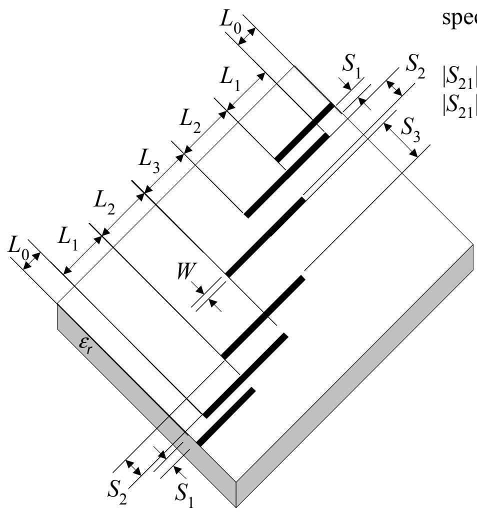
Object Oriented SMX Architecture

SMX system includes 6 modules



HTS Filter Design

(Bandler et al., 1994)



specifications

$|S_{21}| \geq 0.95$ for 4.008 GHz $\leq \omega \leq$ 4.058 GHz
$|S_{21}| \leq 0.05$ for $\omega \leq$ 3.961 GHz and $\omega \geq$ 4.099 GHz

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

Simulation Optimization Systems Research Laboratory
McMaster University

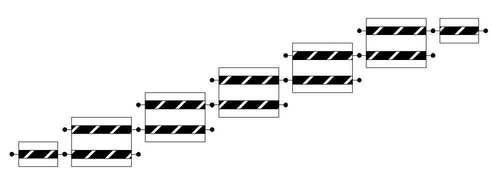
HTS Filter Design (Test Case)

“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:

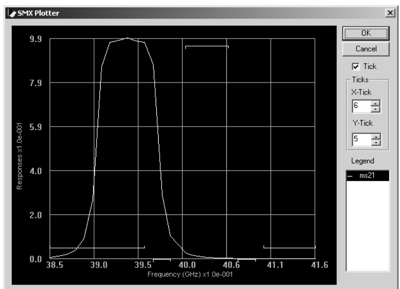
OSA90/hope™ built-in models of microstrip lines and coupled microstrip lines (open circuits are ideally open)



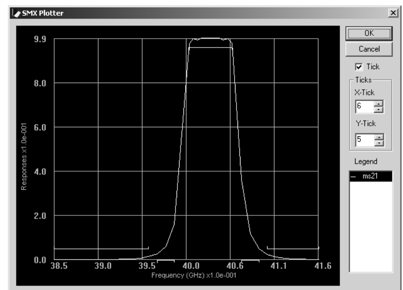
HTS Filter Design (Test Case)

“fine” model (OSA90) responses

initial response



optimal response

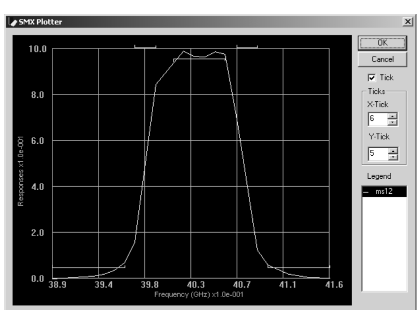


Simulation Optimization Systems Research Laboratory
McMaster University

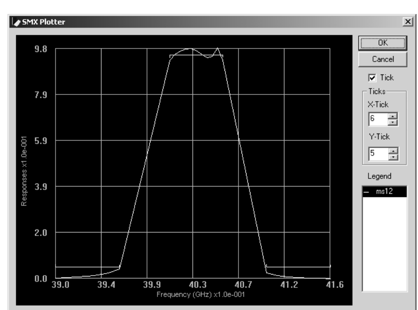
HTS Filter Design

“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

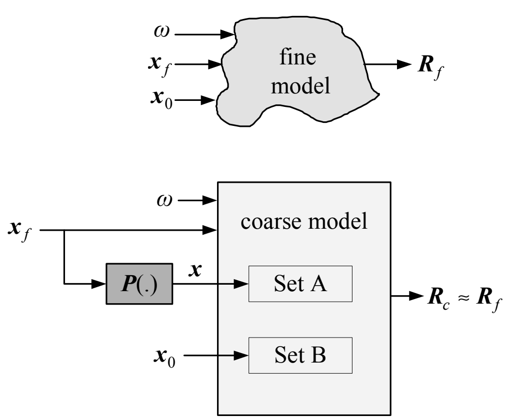
the coarse model is calibrated to match the fine model by allowing the KPP to change in certain coarse model components

the algorithm establishes a mapping from some optimizable parameters to KPP

the mapping is updated iteratively until we reach the optimal solution

Simulation Optimization Systems Research Laboratory
McMaster University

Expanded Space Mapping Design Framework
Exploiting Preassigned Parameters
(Bandler et al., 2001)



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

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

$$\boldsymbol{x} = \boldsymbol{c} + \boldsymbol{B}_r\, \boldsymbol{x}_r$$

Coarse Model Decomposition

let N be the number of coarse model components

let the set I be

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

let $\boldsymbol{x}_i$ represents the KPP of the ith 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

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

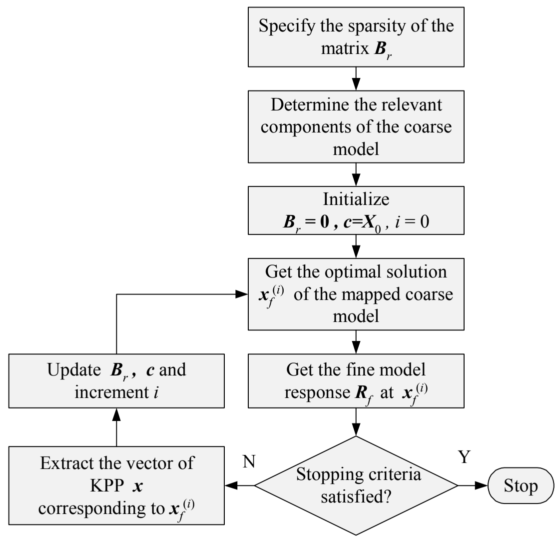
Step 2 evaluate

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

Step 3 put the ith component in Set A if $\hat{S}_i \geq \delta$

otherwise put it in Set B (δ = 0.2)

Expanded Space Mapping Optimization Algorithm



Simulation Optimization Systems Research Laboratory
McMaster University

Expanded Space Mapping Optimization Algorithm

mapped coarse model optimization

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

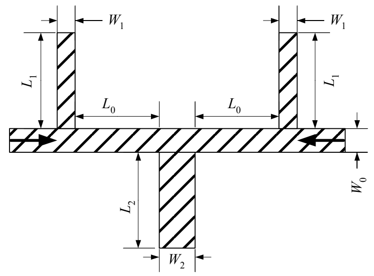
KPP extraction

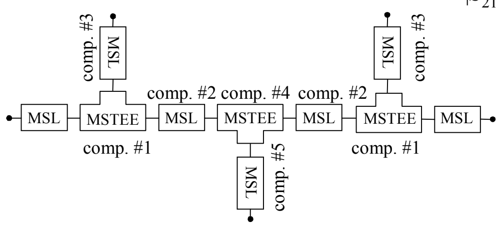
$$\boldsymbol{x}^{(i)} = \arg \min_{\boldsymbol{x}} \left\| \boldsymbol{R}_f(\boldsymbol{x}_f^{(i)}) - \boldsymbol{R}_c(\boldsymbol{x}_f^{(i)}, \boldsymbol{x}) \right\|$$

stopping criterion

$$\left\| \boldsymbol{x}_f^{(i)} - \boldsymbol{x}_f^{(i\text{-}1)} \right\| \le \varepsilon$$

Microstrip Bandstop Filter with Open Stubs





"fine" model: Momentum
(Agilent EEsof EDA)

"coarse" model: OSA90

specifications

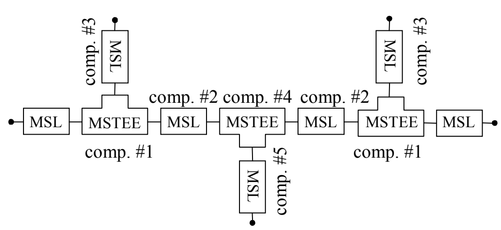
$|S_{21}| \geq -1$ dB for $\omega \geq 12$ GHz and $\omega \leq 8$ GHz

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

Simulation Optimization Systems Research Laboratory
McMaster University
BANDLER CORPORATION

Microstrip Bandstop Filter with Open Stubs

coarse model decomposition



$\varepsilon_r = 9.4$, $H = 25$ mil

$$\boldsymbol{x}_i = [\varepsilon_{ri} \quad H_i]^T, \quad i = 1, \cdots, 5$$

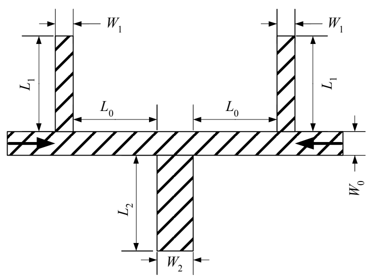
$$S_i = \left\| \left(\frac{\partial \boldsymbol{R}_c^{\mathrm{T}}}{\partial \boldsymbol{x}_i} \boldsymbol{D} \right)^{\mathrm{T}} \right\|_F$$

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

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

Microstrip Bandstop Filter with Open Stubs

coarse model decomposition



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

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

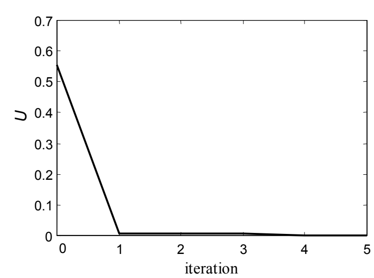
$$\boldsymbol{x} = [\boldsymbol{x}_2^T \ \boldsymbol{x}_3^T \ \boldsymbol{x}_5^T]^T \quad \boldsymbol{x}_i = [\varepsilon_{ri} \quad H_i]^T$$

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

Simulation Optimization Systems Research Laboratory
McMaster University

Microstrip Bandstop Filter with Open Stubs

fine model objective function

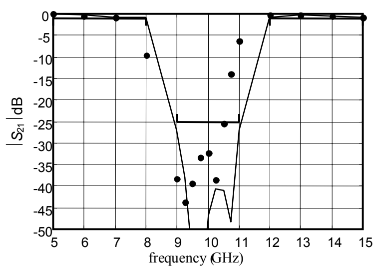


elapsed time by Expanded Space Mapping optimization algorithm: 1.5 hr

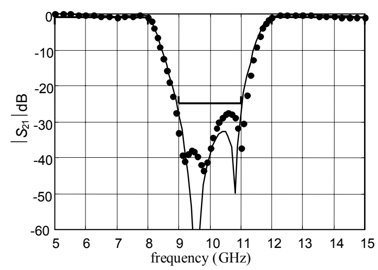
Microstrip Bandstop Filter with Open Stubs

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

References

J.W. Bandler and S.H. Chen, "Circuit optimization: the state of the art," *IEEE Trans. Microwave Theory Tech*., vol. 36, 1988, pp. 424-443.

C. Petzold, *Programming Windows*, Microsoft Press 1990.

J.W. Bandler, R.M. Biernacki, S.H. Chen, P.A. Grobelny and R.H. Hemmers, "Space mapping technique for electromagnetic optimization," *IEEE Trans. Microwave Theory Tech.*, vol. 42, 1994, pp. 2536-2544.

J.W. Bandler, R.M. Biernacki, S.H. Chen, W.J. Gestinger, P.A. Grobelny, C. Moskowitz and S.H. Talisa, "Electromagnetic design of high-temperature super-conducting filters," *Int. J. Microwave and Millimeter-Wave Computer-Aided Engineering*, vol. 5, 1995, pp. 331-343.

J.W. Bandler, R.M. Biernacki, S.H. Chen, R.H. Hemmers and K. Madsen, "Electromagnetic optimization exploiting aggressive space mapping," *IEEE Trans. Microwave Theory Tech.*, vol. 43, 1995, pp. 2874-2882.

Empipe™ Version 4.0, formerly Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1997, now Agilent EEsof EDA, 1400 Fountaingrove Parkway, Santa Rosa, CA 95403-1799.

OSA90/hope™ Version 4.0, formerly Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1997, now Agilent EEsof EDA, 1400 Fountaingrove Parkway, Santa Rosa, CA 95403-1799.

M.H. Bakr, J.W. Bandler, R.M. Biernacki, S.H. Chen and K. Madsen, "A trust region aggressive space mapping algorithm for EM optimization," *IEEE Trans. Microwave Theory Tech.*, vol. 46, 1998, pp. 2412-2425.

V. Torczon and M.W. Trosset, "Using approximations to accelerate engineering design optimization," *Technical Report* 98-33, *ICASE*, Langley Research Center, Hampton, Virginia 23681-2199, 1998.

References (continued)

N. Alexandrov, J.E. Dennis, Jr., R.M. Lewis and V. Torczon, "A trust region framework for managing the use of approximation models in optimization," *Structural Optimization*, vol. 15, 1998, pp. 16-23.

em™ Version 5.1a*,* Sonnet Software, Inc., 1020 Seventh North Street, Suite 210, Liverpool, NY 13088, 1998.

J.W. Bandler and J.E. Rayas-Sánchez, "Circuit CAD and modeling through space mapping," *IEEE MTT-S Int. Microwave Symp.*, Workshop WSFD (Anaheim, CA), 1999.

M.H. Bakr, J.W. Bandler, N. Georgieva and K. Madsen, "A hybrid aggressive space mapping algorithm for EM optimization," *IEEE Trans. Microwave Theory Tech.*, vol. 47, 1999, pp. 2440-2449.

A.J. Booker, J.E. Dennis, Jr., P.D. Frank, D. B. Serafini, V. Torczon and M.W. Trosset, "A rigorous framework for optimization of expensive functions by surrogates," *Structural Optimization*, vol. 17, 1999, pp. 1-13.

J.W. Bandler, M.A. Ismail, J.E. Rayas-Sánchez and Q.J. Zhang, "Neuromodeling of microwave circuits exploiting space mapping technology," *IEEE Trans. Microwave Theory Tech.*, vol. 47, 1999, pp. 2417-2427.

Momentum™ Version 3.5, Agilent EEsof EDA, 1400 Fountaingrove Parkway, Santa Rosa, CA 95403-1799, 1999.

M.H. Bakr, J.W. Bandler, K. Madsen, J.E. Rayas-Sánchez and J. Søndergaard, "Space-mapping optimization of microwave circuits exploiting surrogate models," *IEEE Trans. Microwave Theory Tech*., vol. 48, 2000, pp. 2297-2306.

J.W. Bandler, M.A. Ismail, J.E. Rayas-Sánchez and Q.J. Zhang, "Neural inverse space mapping EM-optimization," *IEEE MTT-S Int. Microwave Symp. Digest* (Phoenix, AZ), 2001.

References (continued)

J.W. Bandler, M.A. Ismail and J.E. Rayas-Sánchez, "Expanded space mapping design framework exploiting preassigned parameters," *IEEE MTT-S Int. Microwave Symp. Digest* (Phoenix, AZ), 2001.

M.H. Bakr, J.W. Bandler, Q.S. Cheng, M.A. Ismail and J.E. Rayas-Sánchez, "SMX—A novel object-oriented optimization system," *IEEE MTT-S Int. Microwave Symp. Digest* (Phoenix, AZ), 2001.

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