SMX

A NOVEL OBJECT-ORIENTED OPTIMIZATION SYSTEM

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Outline

the SMSM algorithm *(Bakr et al., 1998-2001)*

SMX system decomposition

examples for the original algorithm

simplified Parameter Extraction procedure

design examples

Introduction

SMSM approach — an iteratively refined surrogate of the fine model is used to solve the design problem

Object-Oriented Design (OOD) abstracts the basic behavior of models and optimizers

SMX can support a number of commercial EM/circuit simulators as well as in-house simulators

SMX provides a user-friendly interface

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:

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

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

the mapped coarse model utilizes the frequency-sensitive mapping

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

where

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

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
(Bakr et al., 1998-2001)

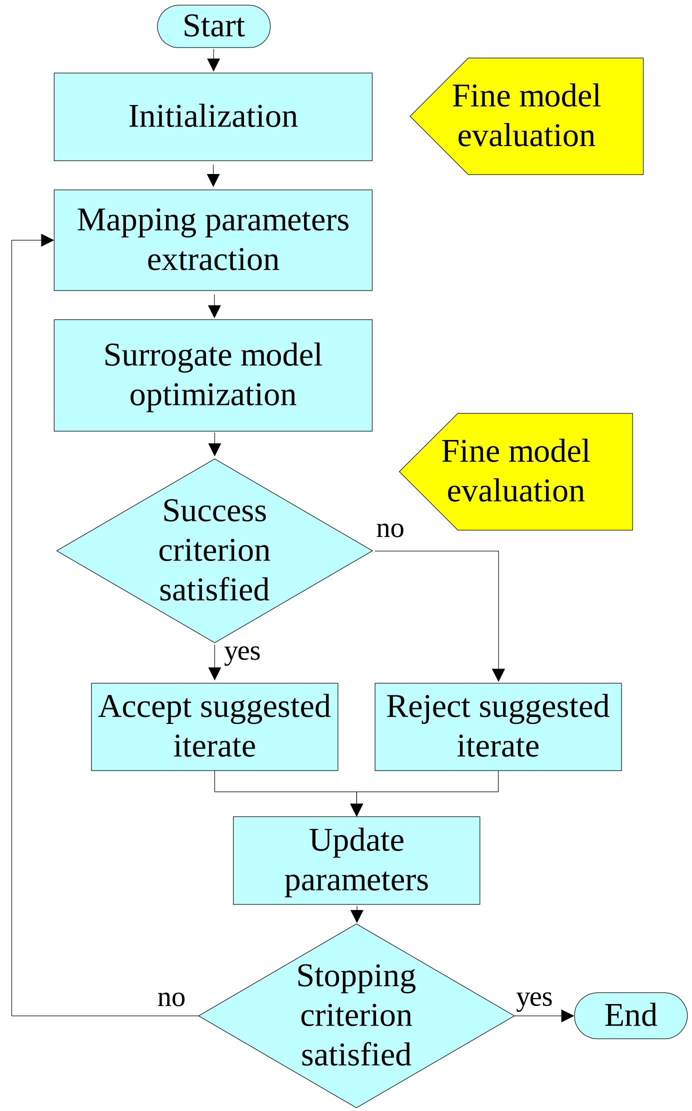
$$[\boldsymbol{B}^{(i)}, \boldsymbol{s}^{(i)}, \boldsymbol{t}^{(i)}, \sigma^{(i)}, \boldsymbol{c}^{(i)}, \gamma^{(i)}] = \arg\left\{ \min_{\boldsymbol{B}, \boldsymbol{s}, \boldsymbol{t}, \sigma, \boldsymbol{c}, \gamma} \left\| \begin{bmatrix} \boldsymbol{e}_1^T & \boldsymbol{e}_2^T & \cdots & \boldsymbol{e}_{N_p}^T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

where

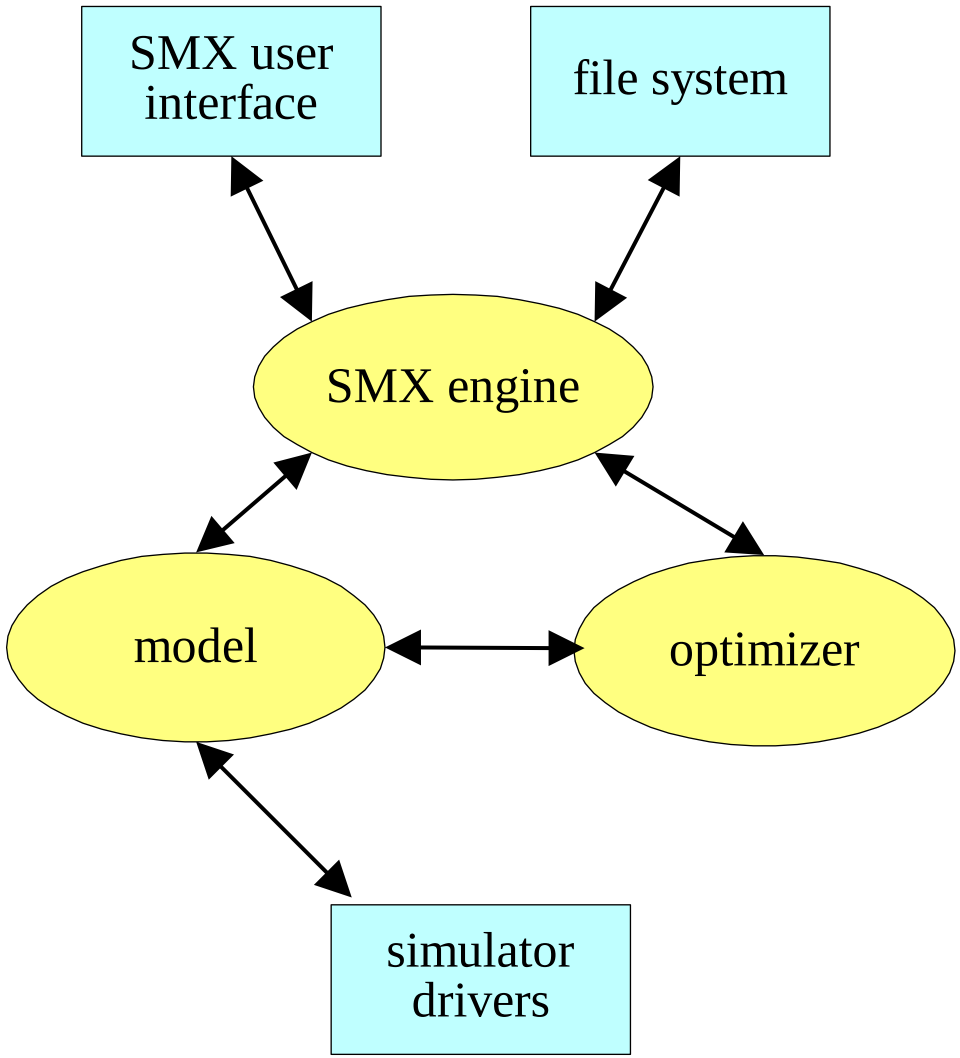
$$\boldsymbol{e}_k = \boldsymbol{R}_m^{(i)}(\boldsymbol{x}_f^{(k)}) - \boldsymbol{R}_f(\boldsymbol{x}_f^{(k)}) \qquad \forall\, \boldsymbol{x}_f^{(k)} \in V^{(i)}$$

(multipoint parameter extraction)

The Algorithm Flowchart



SMX System Decomposition



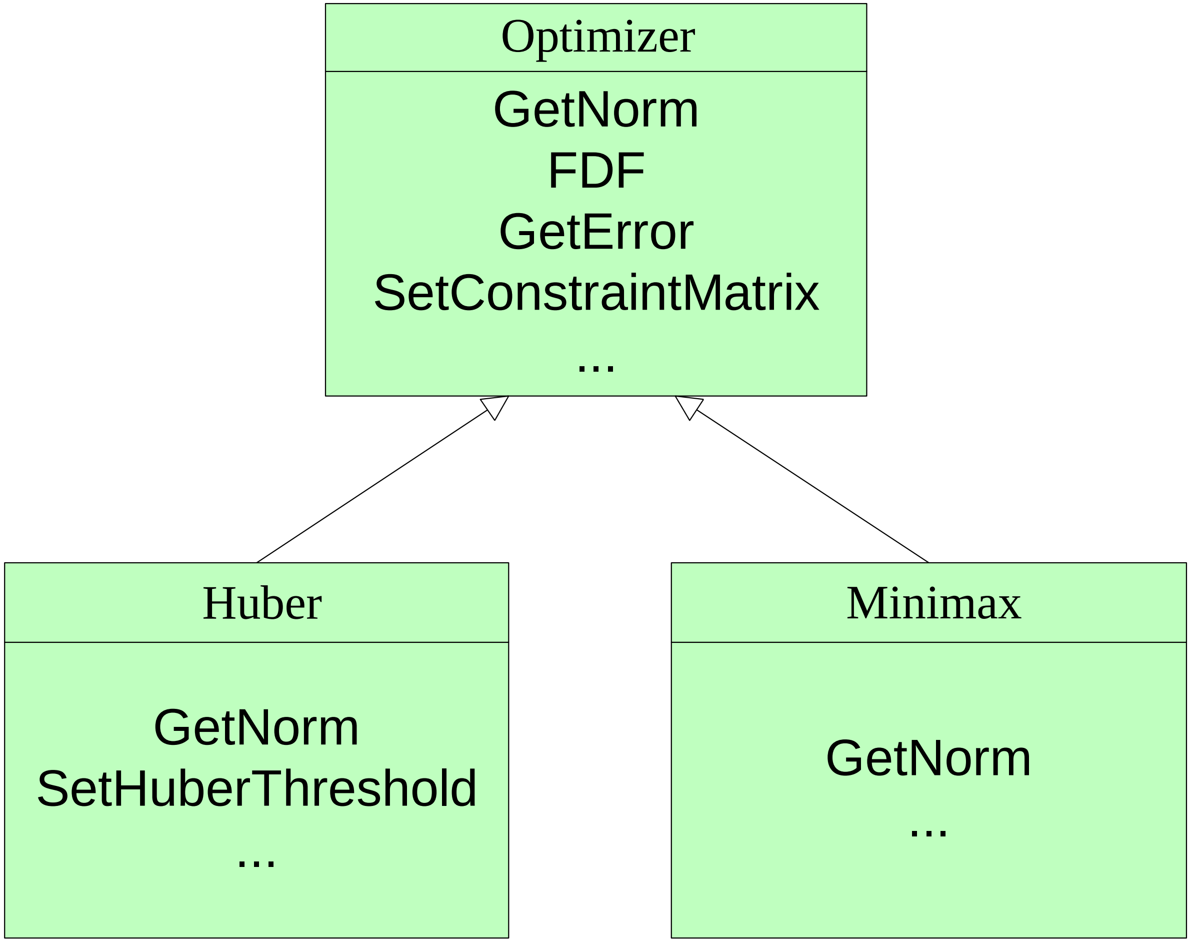
Algorithm Core: SMX Engine

the SMX engine is represented as the SMX_Engine class

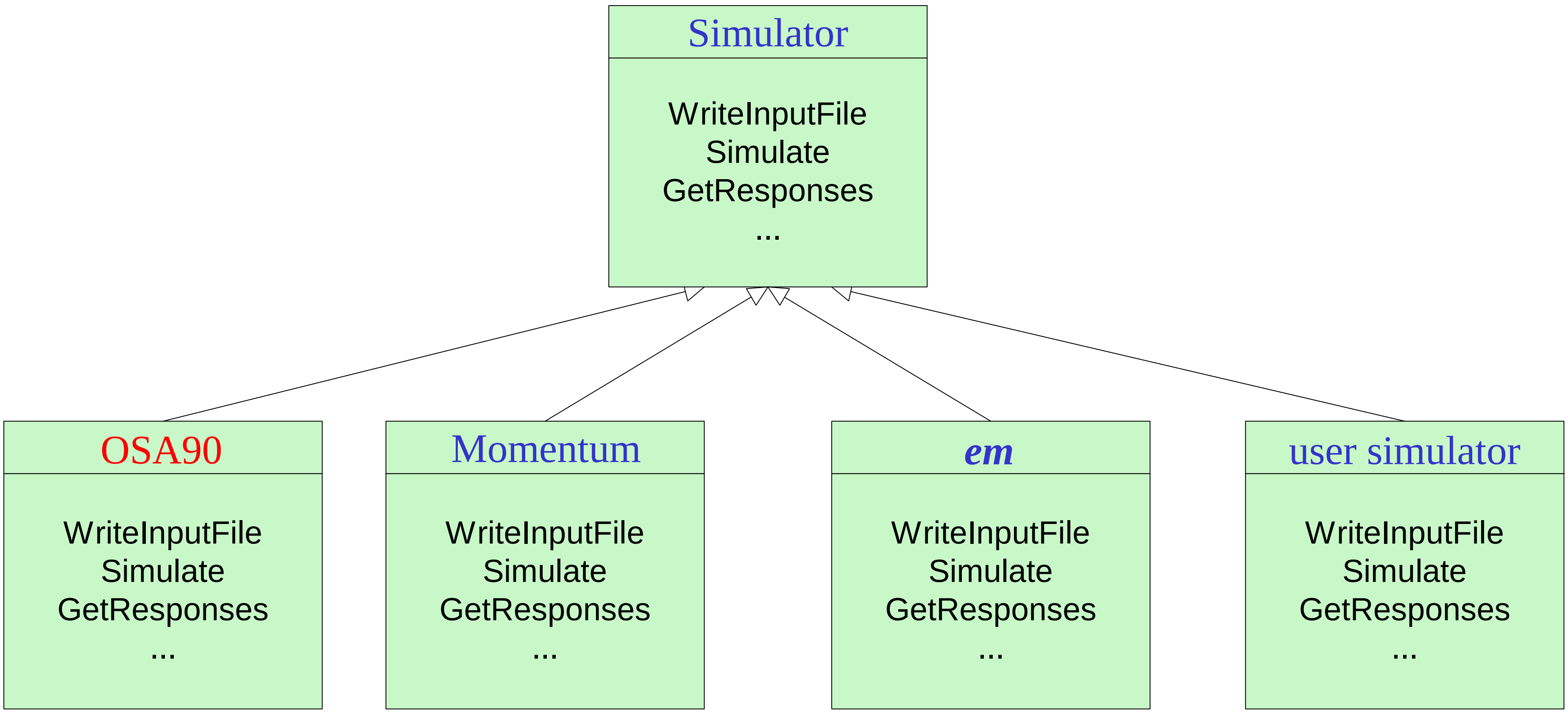
base classes for Space Mapping

- Optimizer — optimization utilities
- Simulator — simulation utilities
- Model — fine, coarse and surrogate model

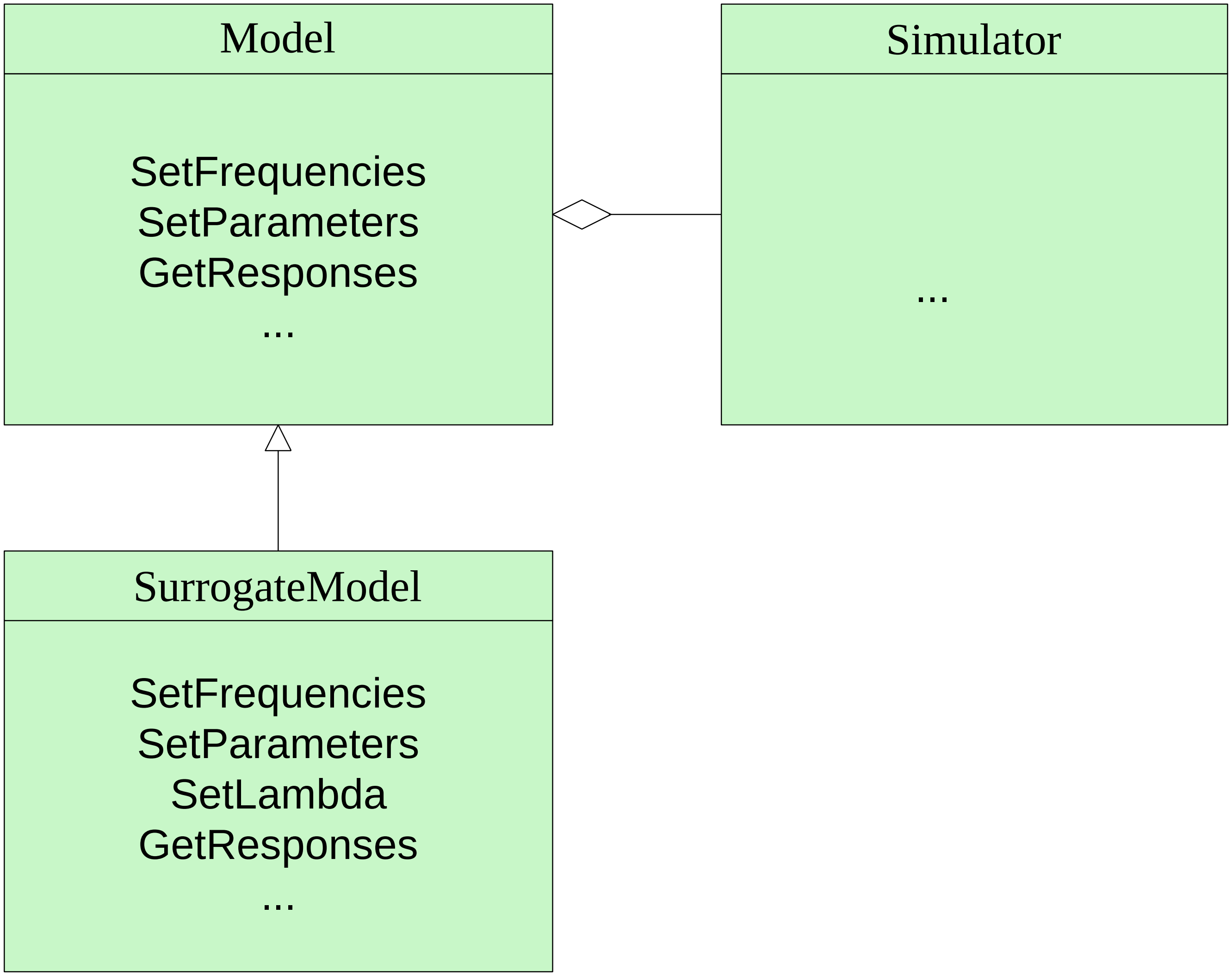
Optimizer Class



Simulator Class



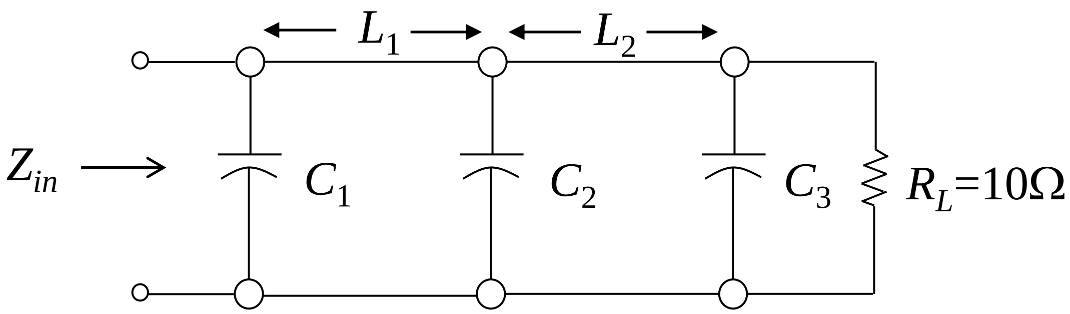
Model and SurrogateModel Class



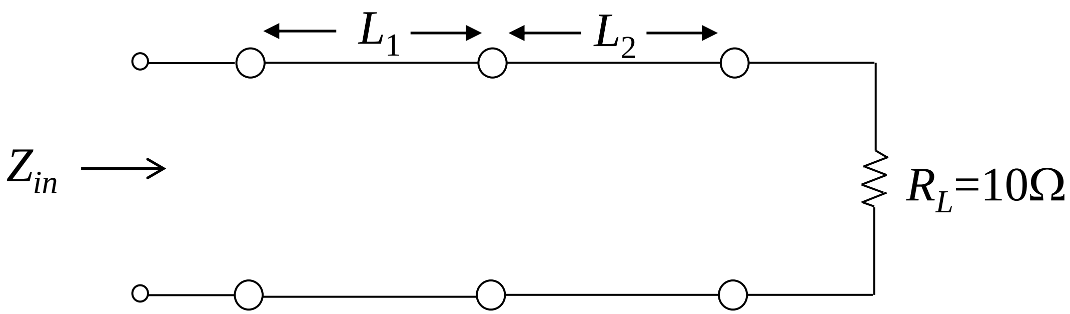
Two-Section 10:1 Capacitively-Loaded Impedance Transformer

(Bandler, 1969)

“fine” model



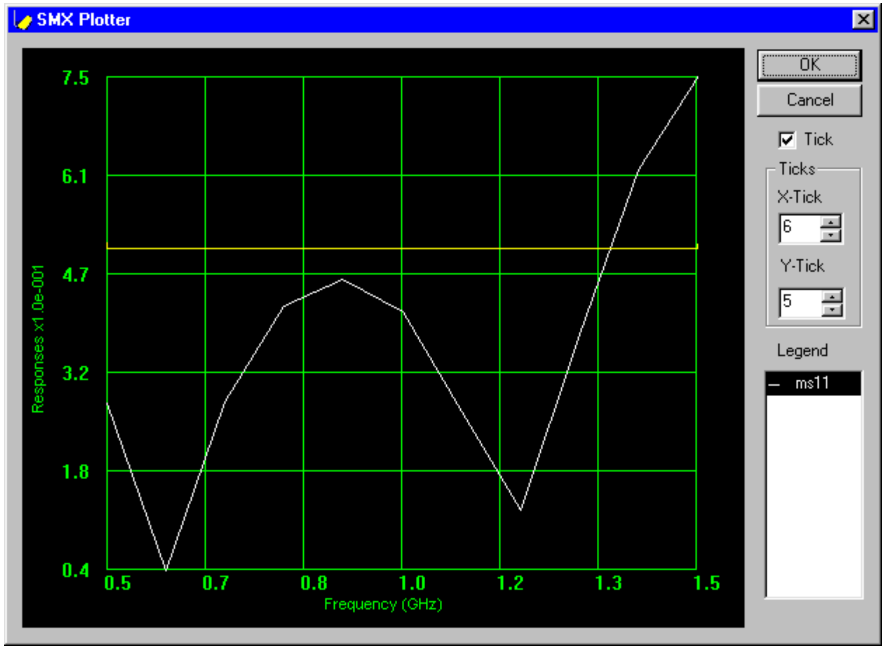
“coarse” model



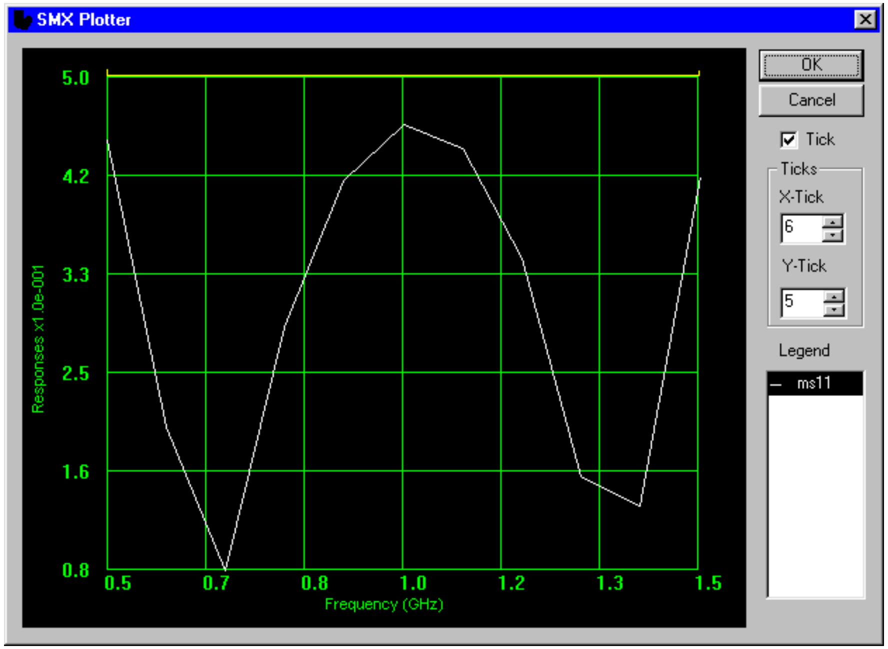
Two-Section Impedance Transformer

“fine” model: OSA90/hope

initial response

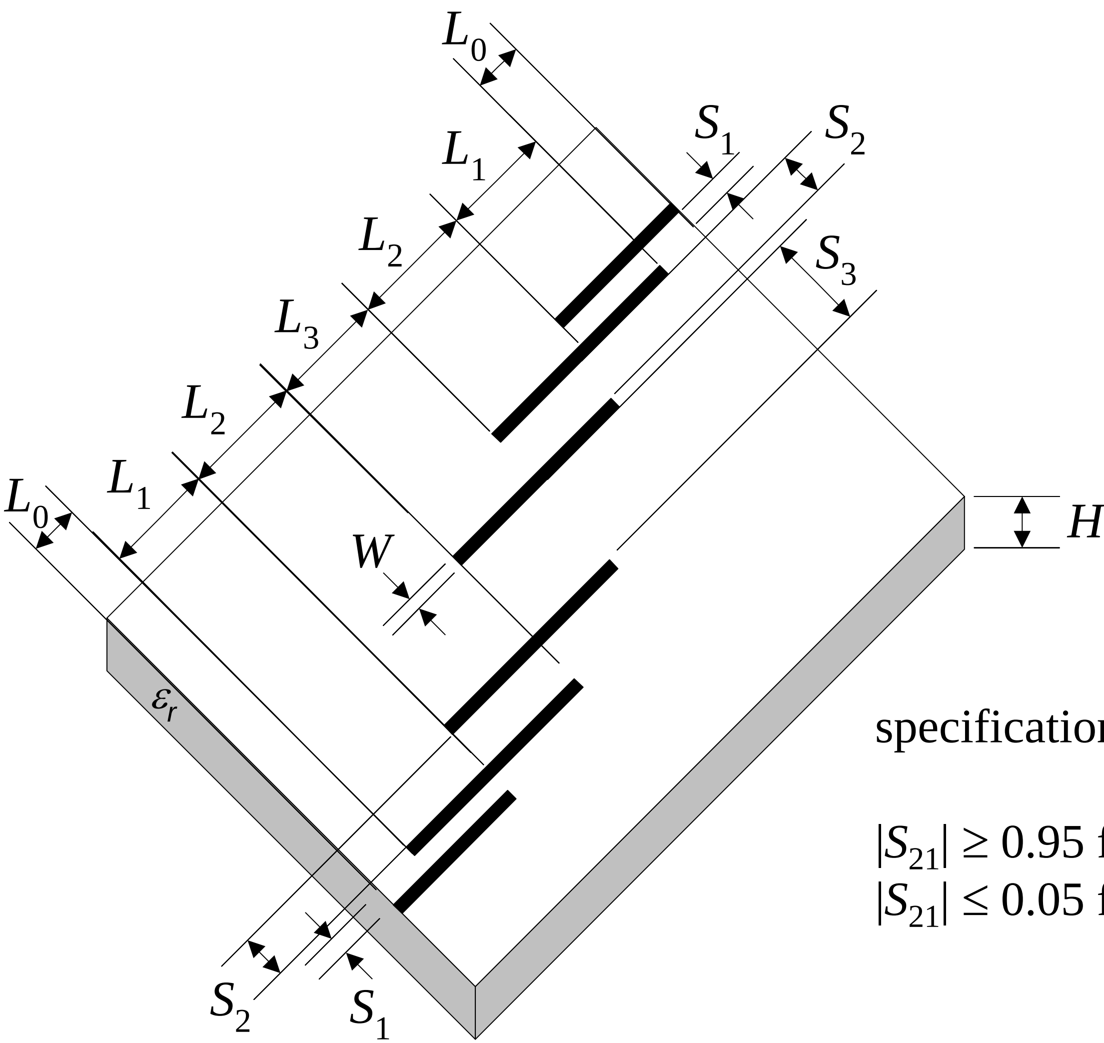


optimal response



HTS Quarter-Wave Parallel Coupled-Line Microstrip Filter

(Westinghouse, 1993)



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

the design parameters are

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

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

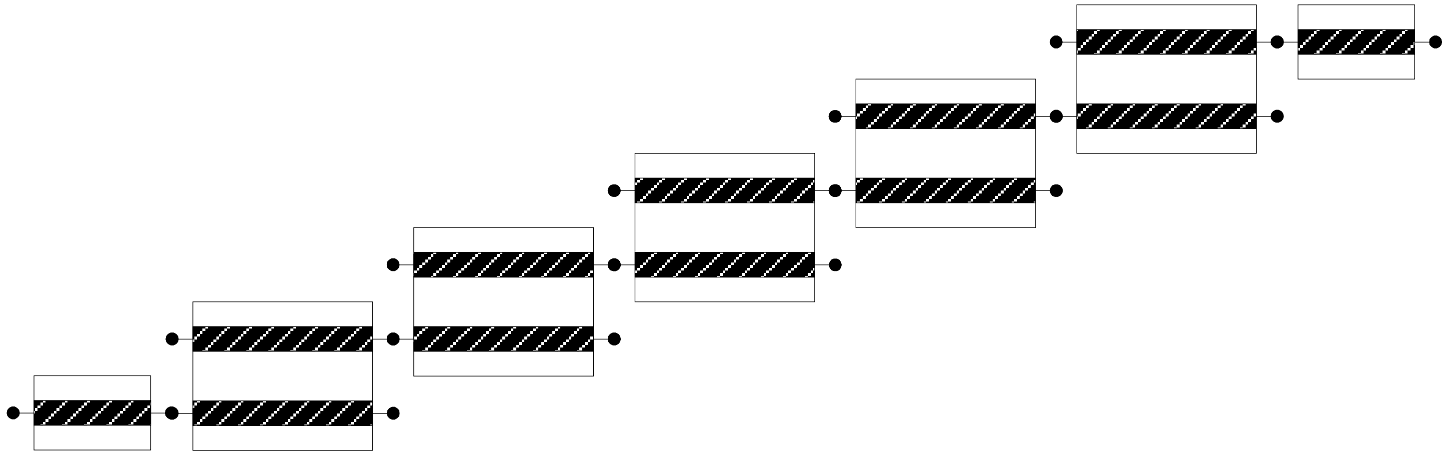
HTS Filter Design (Test Case)

"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:

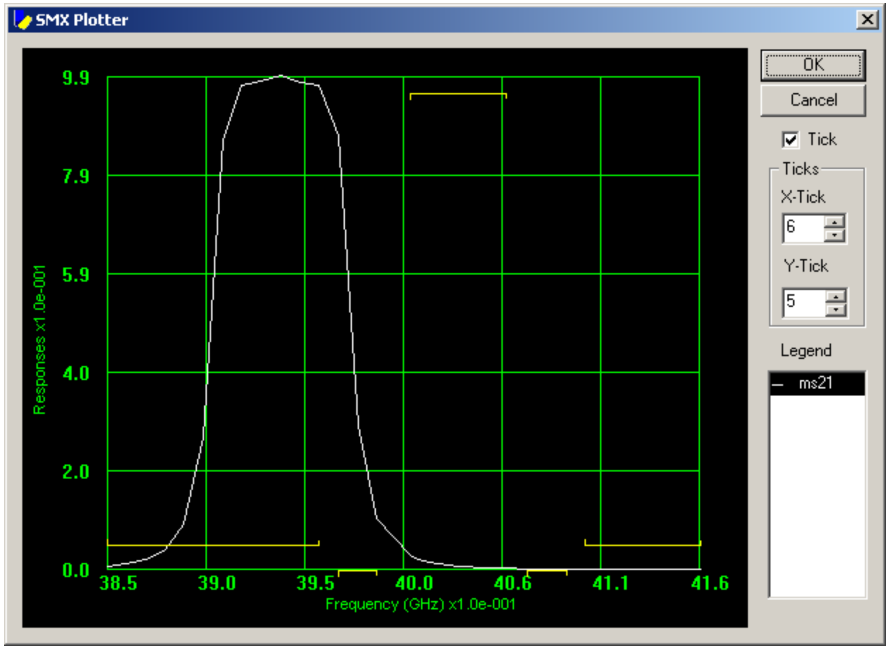
OSA90/hope built-in models of microstrip lines and coupled microstrip lines (open circuits are ideally open)



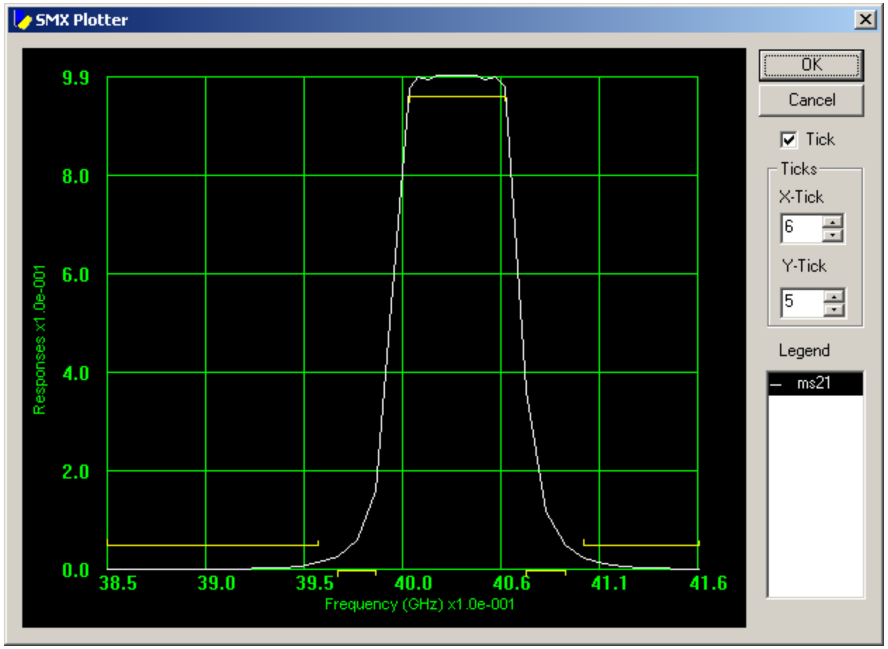
HTS Filter Design (Test Case)

“fine” model: OSA90/hope

initial response



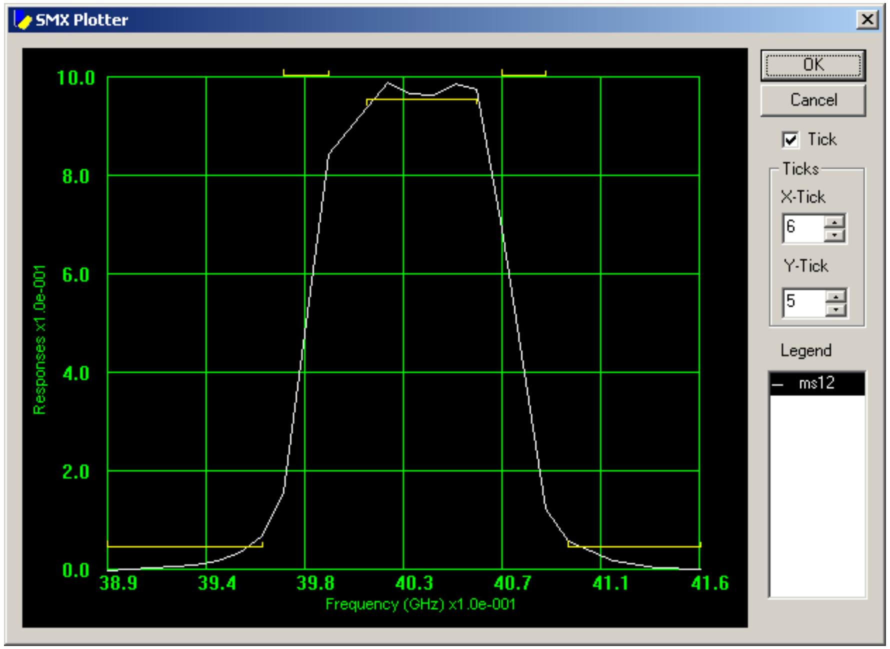
optimal response



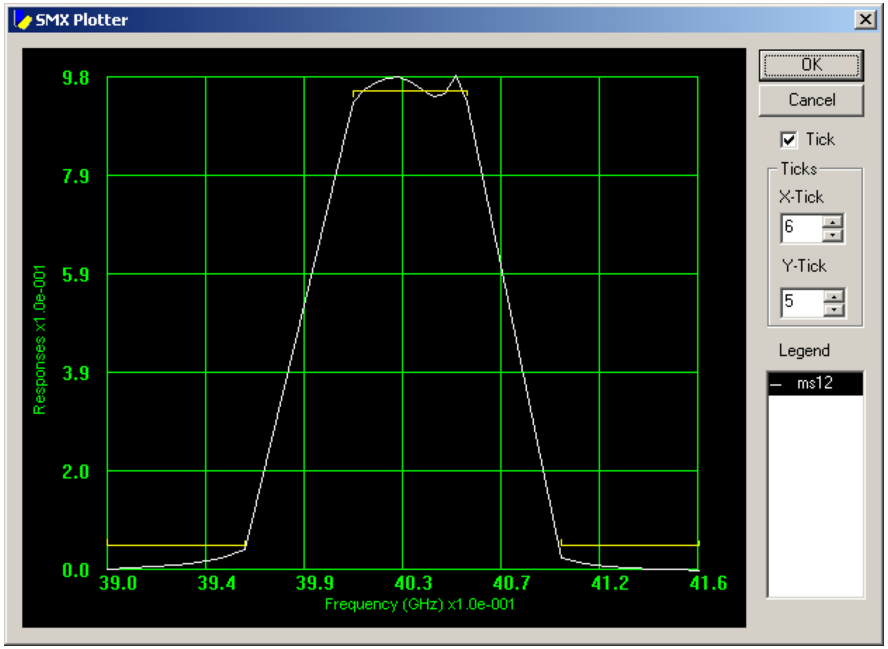
HTS Filter Design

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

SMX optimization (4 iterations, 5 fine model simulations)



refined by Momentum optimization



Simplified Parameter Extraction Procedure

we have noticed that the vectors ***s*** and ***t*** are practically zero

the matrix ***B*** is updated using Broyden update

extract only $\boldsymbol{x}_c$, σ and γ at a single point $\boldsymbol{x}_f^{(i)}$

$$[\ \sigma^{(i)}, \boldsymbol{x}_c^{(i)},\ \gamma^{(i)}] = \arg\left\{ \min_{\sigma,\, \boldsymbol{x}_c,\, \gamma} \left\| [\boldsymbol{e}_1^T \quad \boldsymbol{e}_2^T \quad \cdots \quad \boldsymbol{e}_{N_f}^T\ ]^T \right\| \right\}$$

$$\boldsymbol{e}_k = \boldsymbol{R}_c(\boldsymbol{x}_c, \sigma\omega_k + \gamma) - \boldsymbol{R}_f(\boldsymbol{x}_f, \omega_k)$$

where N_f is the number of frequency points per frequency sweep

Algorithm Summary

Step 1 initialize

$$\boldsymbol{x}_f^{(1)} = \boldsymbol{x}_c^*,\ \lambda^{(1)} = 1,\ \boldsymbol{J}_f^{(1)} = \boldsymbol{J}_c^*,\ \delta^{(1)} = 1,\ \boldsymbol{B}^{(1)} = \boldsymbol{I},\ \boldsymbol{s} = \boldsymbol{0},\ \boldsymbol{t} = \boldsymbol{0},\ \text{and } i = 1$$

Step 2 apply the simplified parameter extraction procedure

Step 3 obtain the tentative step by solving

$$\boldsymbol{h}^{(i)} = \arg\left\{\min_{\boldsymbol{h}} U(\boldsymbol{R}_s(\boldsymbol{x}_f^{(i)} + \boldsymbol{h}))\right\},\ \|\boldsymbol{h}\| \le \delta^{(i)}$$

Step 4 check if step is successful

$$\boldsymbol{x}_f^{(i+1)} = \begin{cases} \boldsymbol{x}_f^{(i)} + \boldsymbol{h}^{(i)} & \text{if } U(\boldsymbol{R}_f(\boldsymbol{x}_f^{(i)} + \boldsymbol{h}^{(i)})) < U(\boldsymbol{R}_f(\boldsymbol{x}_f^{(i)})) \\ \boldsymbol{x}_f^{(i)} & \text{otherwise} \end{cases}$$

Algorithm Summary (continued)

Step 5 update $\boldsymbol{B}$ *(Broyden, 1965)*

$$\boldsymbol{B}^{(i+1)} = \boldsymbol{B}^{(i)} + \frac{\boldsymbol{x}_c^{(i+1)} - \boldsymbol{x}_c^{(i)} - \boldsymbol{B}^{(i)}\boldsymbol{h}^{(i)}}{\boldsymbol{h}^{(i)T}\boldsymbol{h}^{(i)}}\boldsymbol{h}^{(i)T}$$

$$\boldsymbol{h}^{(i)} = \boldsymbol{x}_f^{(i+1)} - \boldsymbol{x}_f^{(i)}$$

Step 6 update $\boldsymbol{J}_f$, δ, and λ

Step 7 check the stopping criterion, if satisfied then stop

Step 8 set i=i+1 and go to Step 2

Update Parameters

$$\boldsymbol{J}_f^{(i+1)} = \boldsymbol{J}_f^{(i)} + \frac{\boldsymbol{R}_f^{(i+1)} - \boldsymbol{R}_f^{(i)} - \boldsymbol{J}_f^{(i)}\boldsymbol{h}^{(i)}}{\boldsymbol{h}^{(i)T}\boldsymbol{h}^{(i)}}\boldsymbol{h}^{(i)T}$$

$$\boldsymbol{h}^{(i)} = \tilde{\boldsymbol{x}}_f^{(i+1)} - \boldsymbol{x}_f^{(i)}$$

$$\delta_{i+1} = \begin{cases} 2\delta_i & \text{if } \; r > 0.75 \\ \delta_i / 3 & \text{if } \; r < 0.1 \\ \delta_i & \text{otherwise} \end{cases}$$

$$r = \frac{U(\boldsymbol{R}_f(\boldsymbol{x}_f^{(i)})) - U(\boldsymbol{R}_f(\boldsymbol{x}_f^{(i)} + \boldsymbol{h}^{(i)}))}{U(\boldsymbol{R}_s(\boldsymbol{x}_f^{(i)})) - U(\boldsymbol{R}_s(\boldsymbol{x}_f^{(i)} + \boldsymbol{h}^{(i)}))}$$

Update Parameters (continued)

$$\lambda^{(i+1)} = \begin{cases} 1 & \left\|\boldsymbol{E}_l^{(i)}\right\| > 2\left\|\boldsymbol{E}_m^{(i)}\right\| \\ \dfrac{\left\|\boldsymbol{E}_l^{(i)}\right\|}{\left\|\boldsymbol{E}_l^{(i)}\right\| + \left\|\boldsymbol{E}_m^{(i)}\right\|} & \text{otherwise} \end{cases}$$

$$\boldsymbol{E}_m^{(i)} = \boldsymbol{R}_m^{(i)}(\boldsymbol{x}_f^{(i)} + \boldsymbol{h}^{(i)}) - \boldsymbol{R}_f(\boldsymbol{x}_f^{(i)} + \boldsymbol{h}^{(i)})$$

$$\boldsymbol{E}_l^{(i)} = \boldsymbol{R}_f(\boldsymbol{x}_f^{(i)}) + \boldsymbol{J}_f^{(i)}\boldsymbol{h}^{(i)} - \boldsymbol{R}_f(\boldsymbol{x}_f^{(i)} + \boldsymbol{h}^{(i)})$$

Stopping Criteria

maximum number of iterations reached

optimization parameters step length

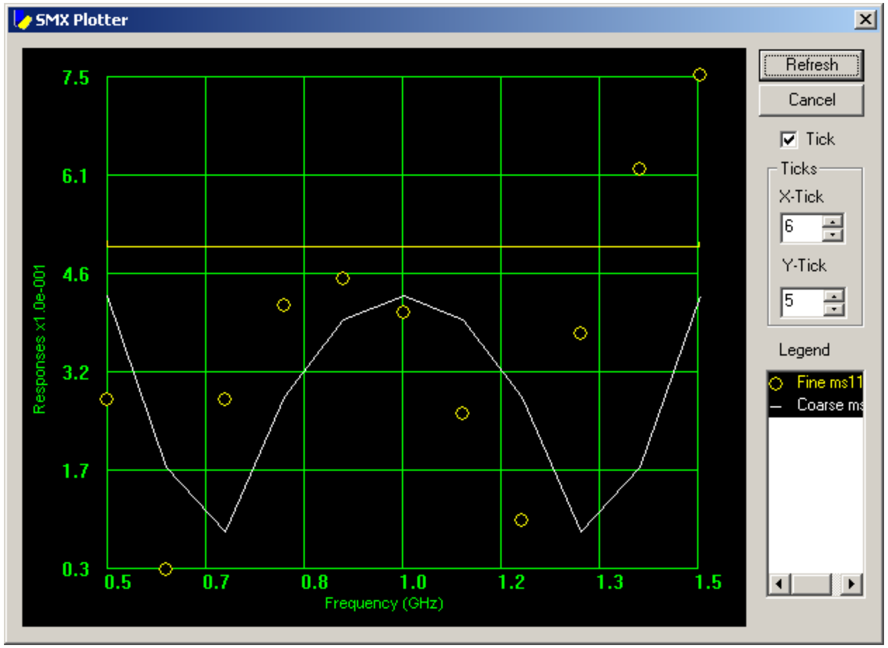
$$\frac{\left\| \boldsymbol{x}_f^{(i+1)} - \boldsymbol{x}_f^{(i)} \right\|_2}{\left\| \boldsymbol{x}_f^{(i)} \right\|_2} < \varepsilon$$

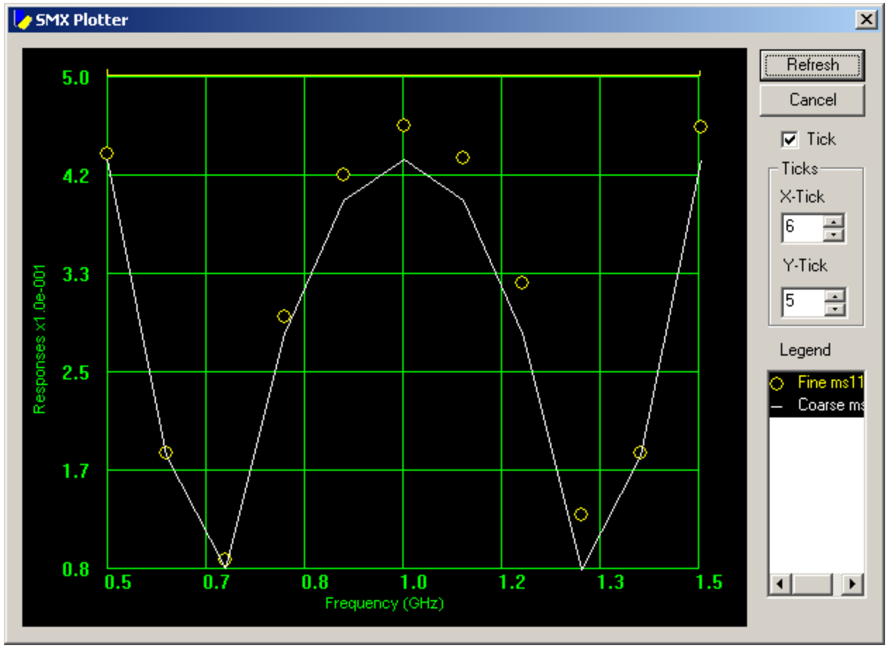
Two-Section Impedance Transformer

"fine" and "coarse" model: OSA90/hope

initial response

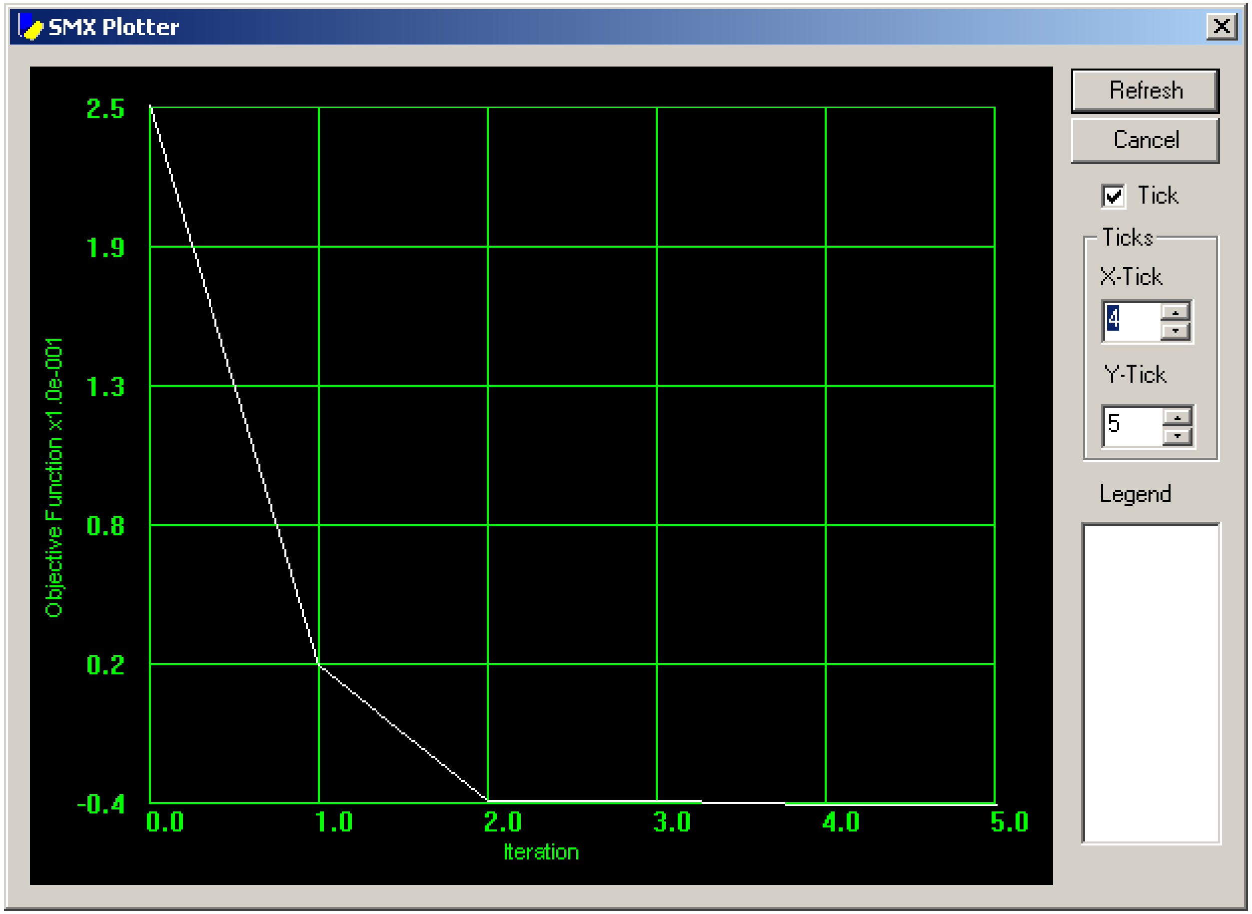
optimal response





Two-Section Impedance Transformer Objective Function

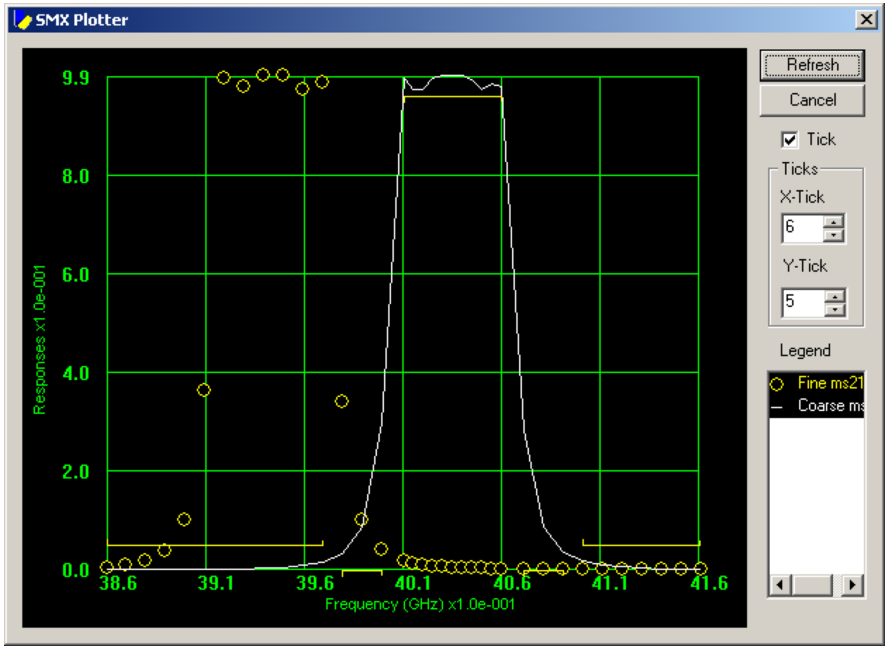
5 iterations, 6 fine model simulations



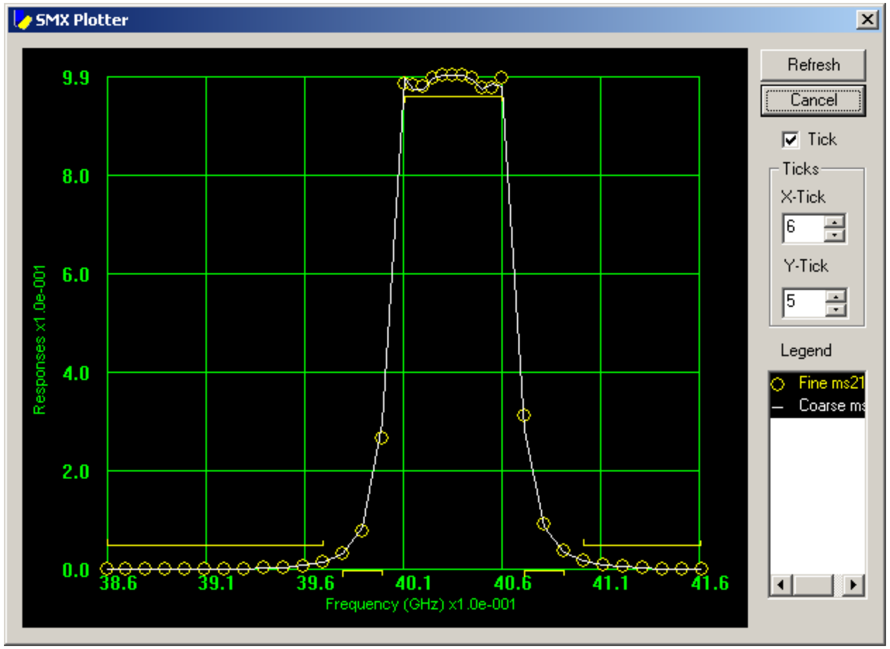
HTS Filter Design

“fine” and “coarse” model: OSA90/hope

initial response



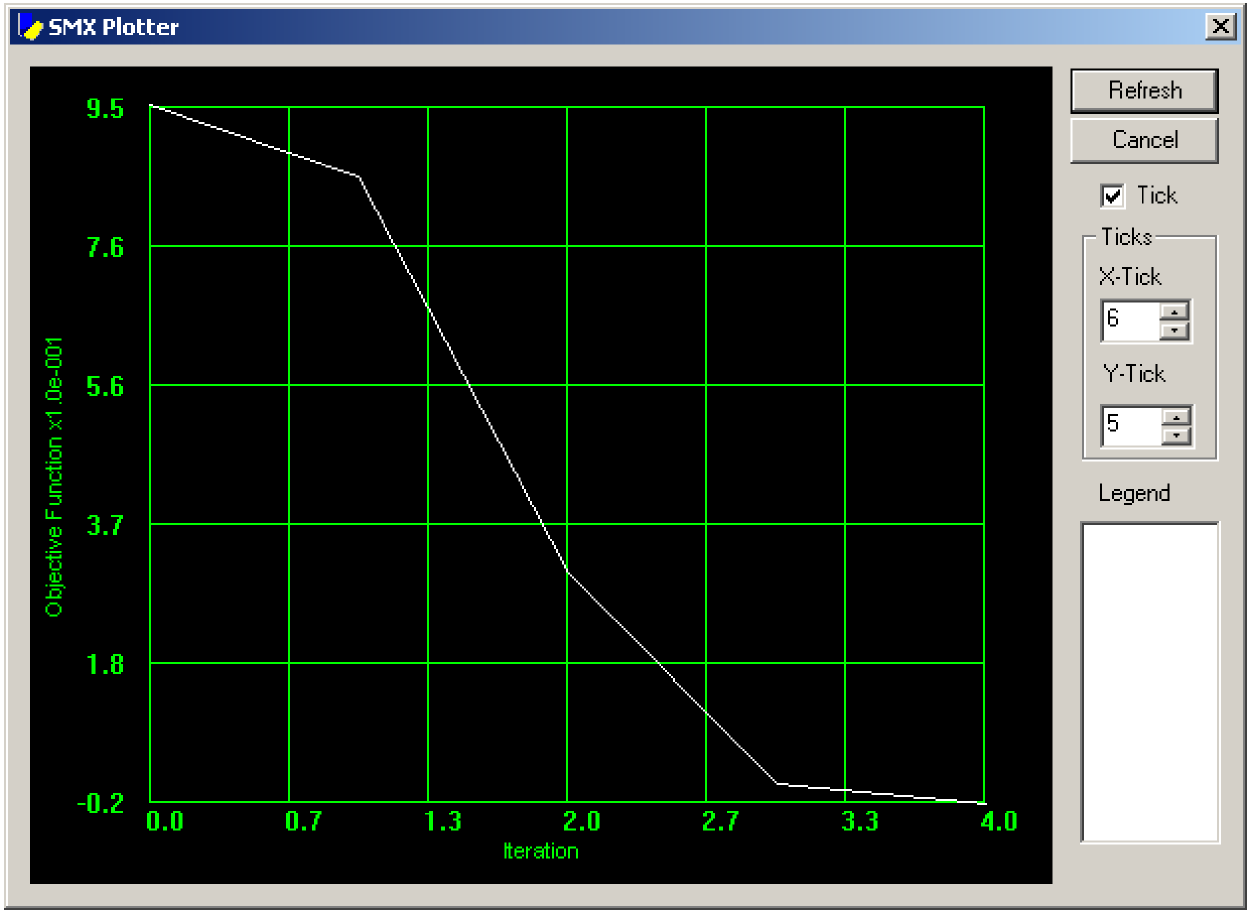
optimal response



(specification slightly different from previous design)

HTS Filter Design Objective Function

4 iterations, 5 fine model simulations



Conclusions

the SMX system design is formally presented for the first time

state-of-the-art optimization technology is utilized

object-oriented programming is used to construct the system

new optimization methods and new simulators can be plugged in

the SMX is a powerful tool for engineering optimization and algorithm research

the original SMX parameter extraction procedure is effectively simplified

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