Design Optimization Via Surrogate Modeling and Space Mapping

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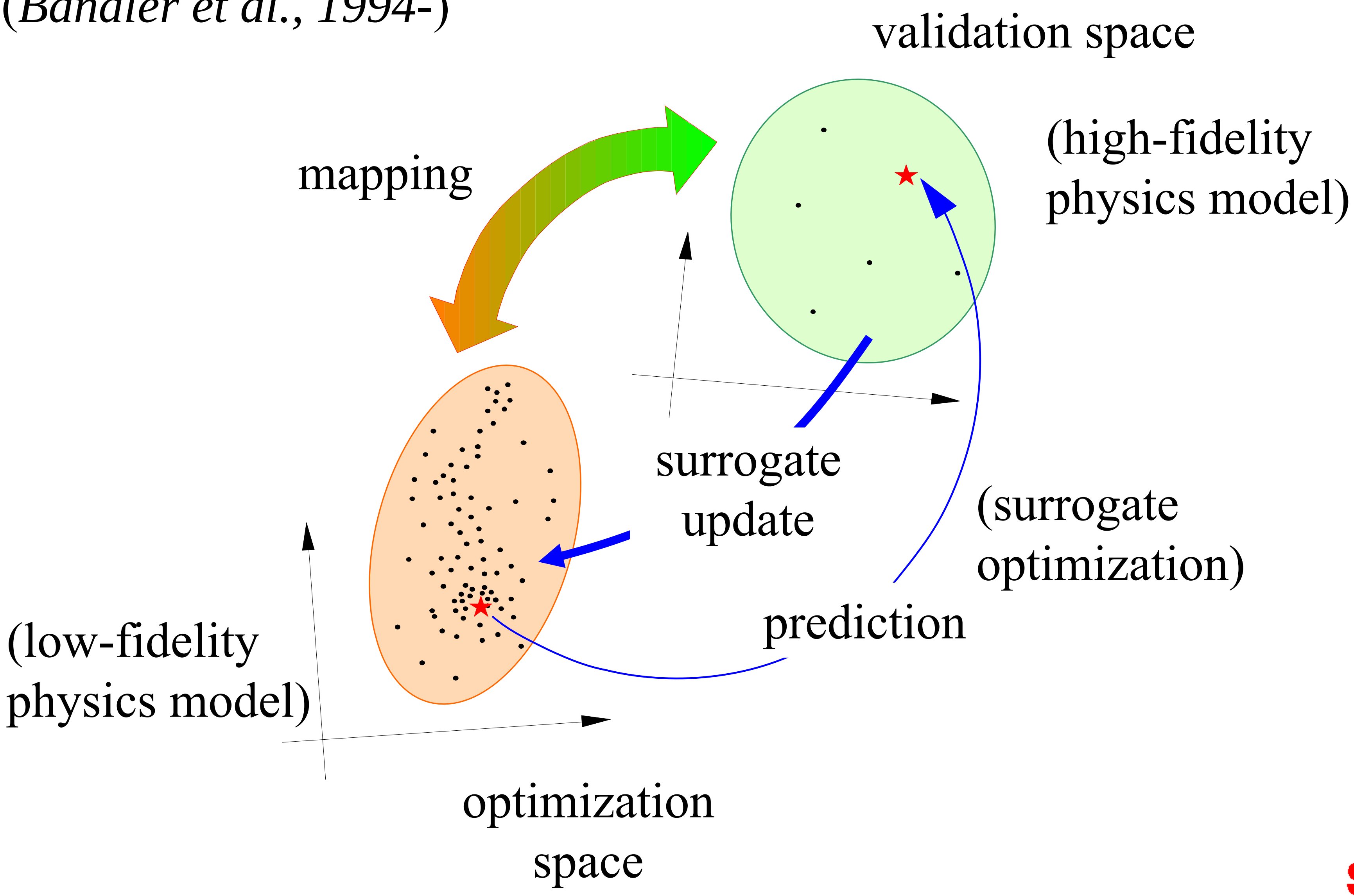
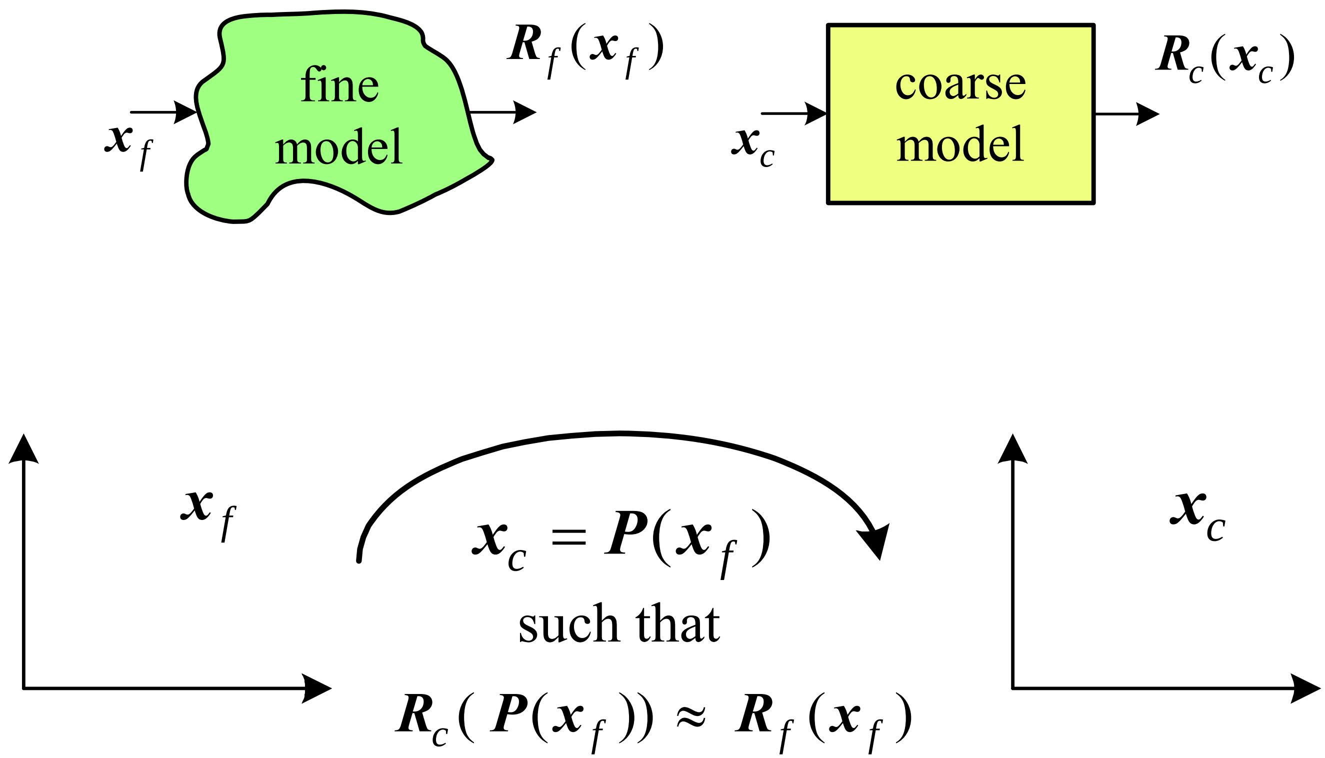
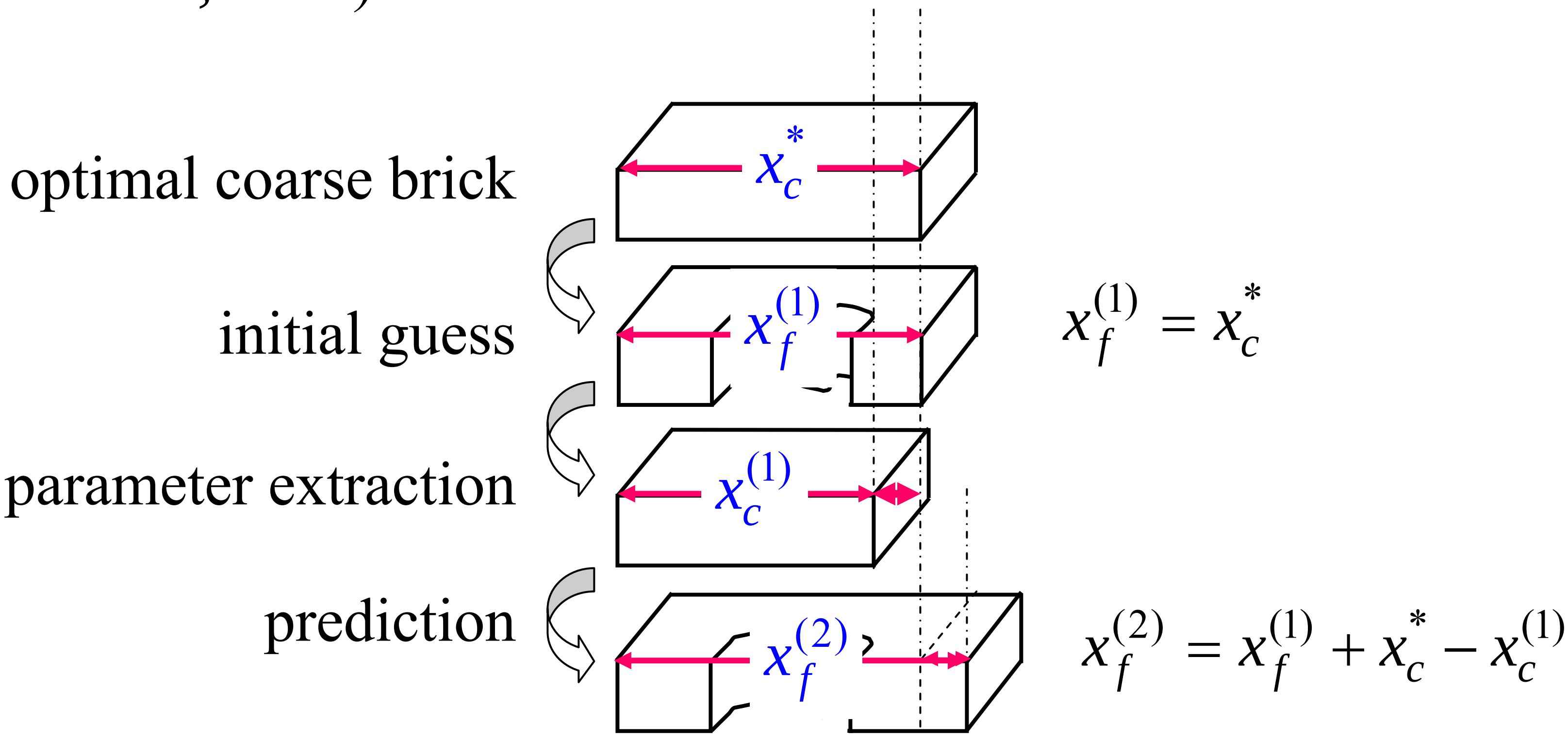
The Space Mapping Concept
(*Bandler et al., 1994-*)



The Space Mapping Concept
(Bandler et al., 1994-)



Aggressive Space Mapping Practice—Cheese-Cutting Problem
(*Bandler, 2002*)

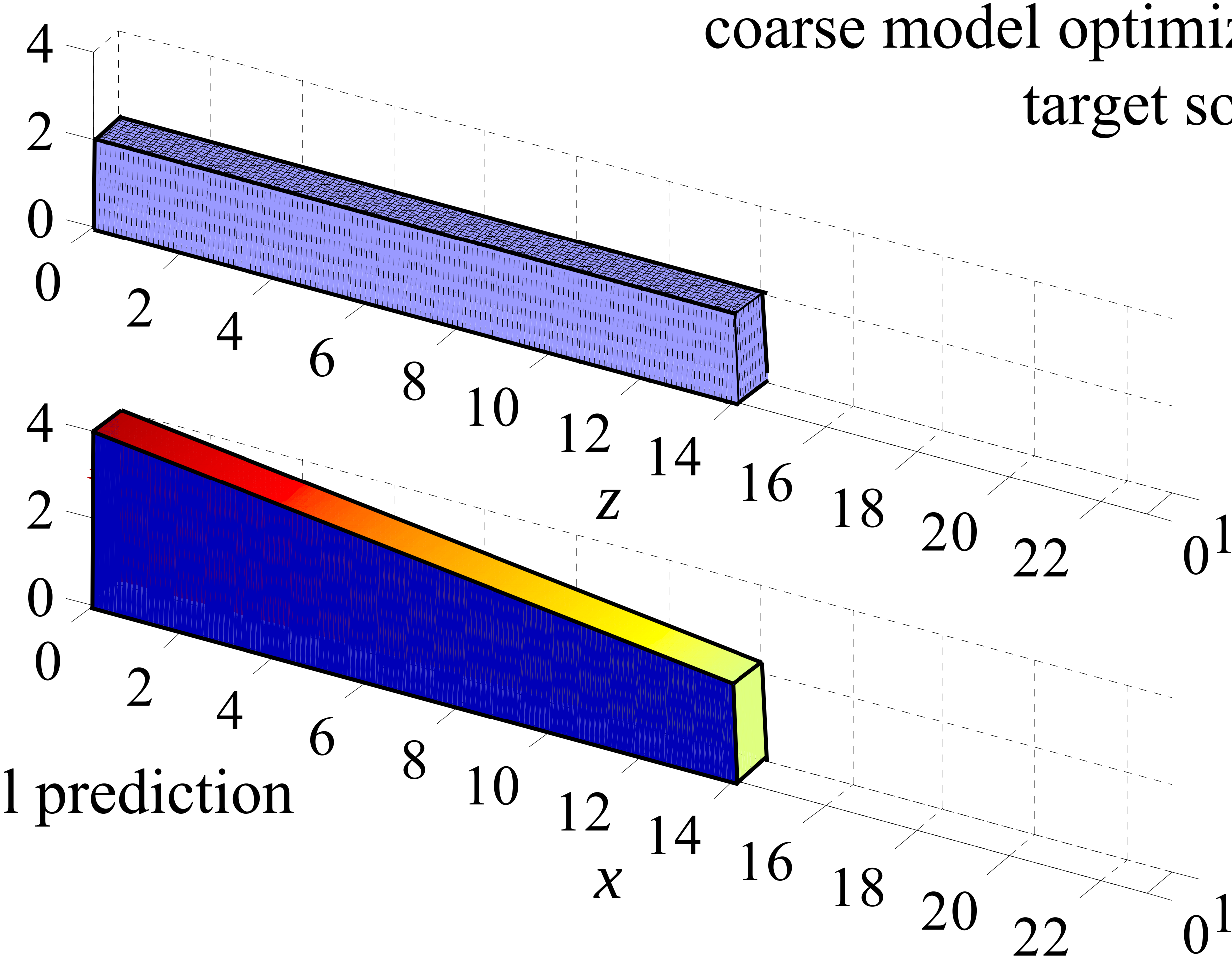


coarse model can be imaginary
actual human brain process
different person may have different imaginary coarse model
space mapping is a mathematical representation of brain process

ASM: The Wedge-Cutting Illustration (*Dakroury et al., 2002*)

Initialization

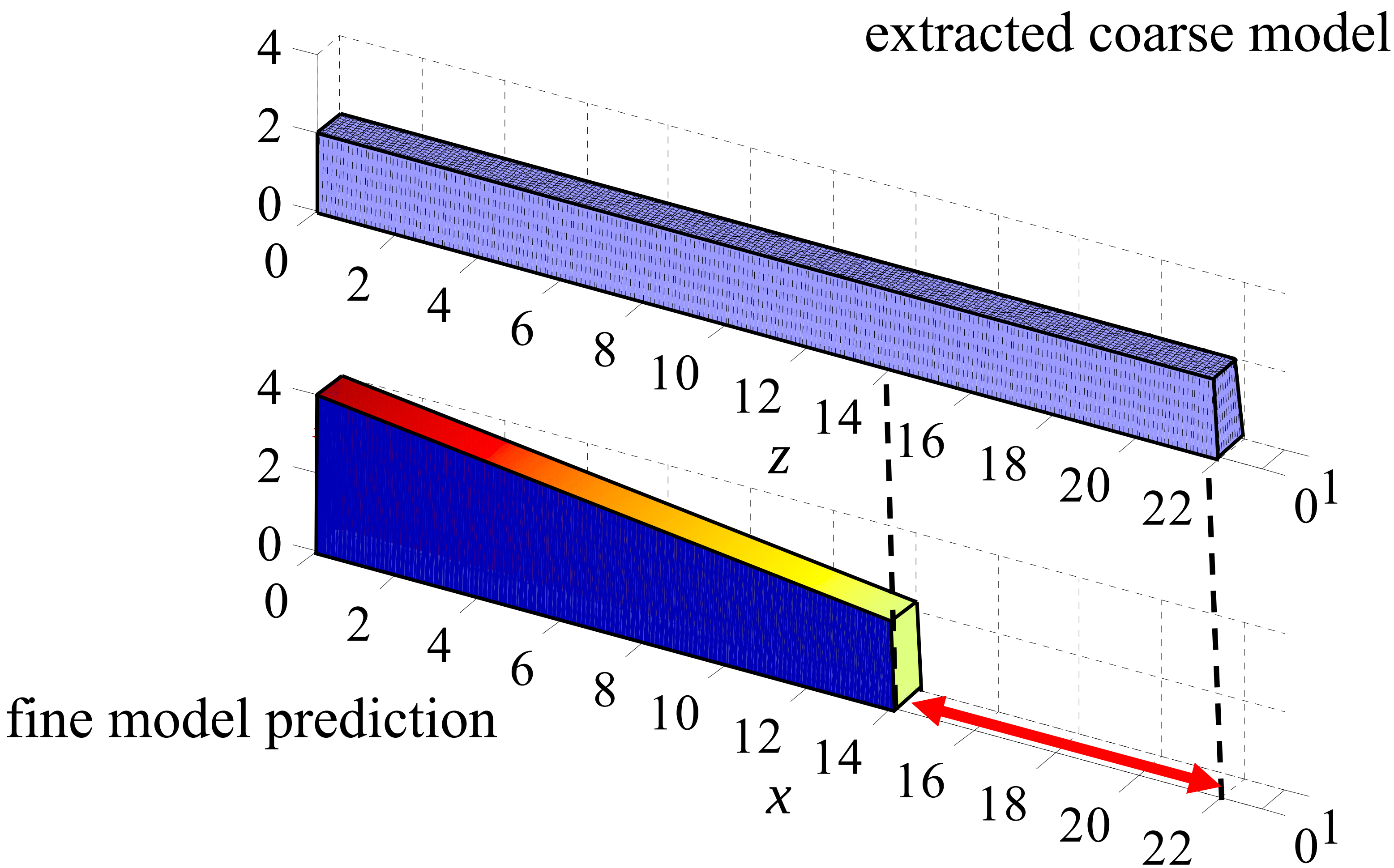
coarse model optimization
target solution



fine model prediction

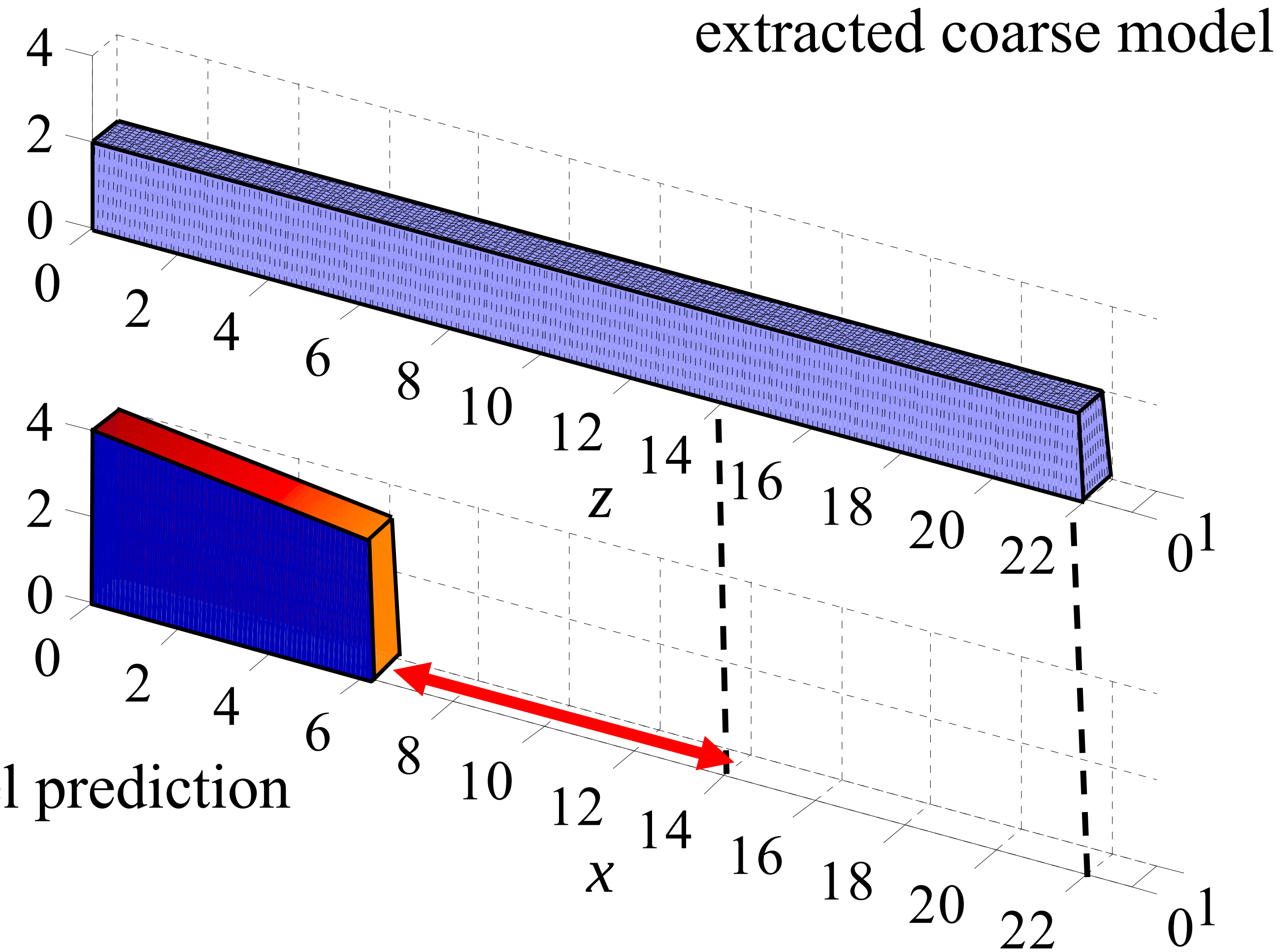
ASM: The Wedge-Cutting Illustration (*Dakroury et al., 2002*)

Iteration 1



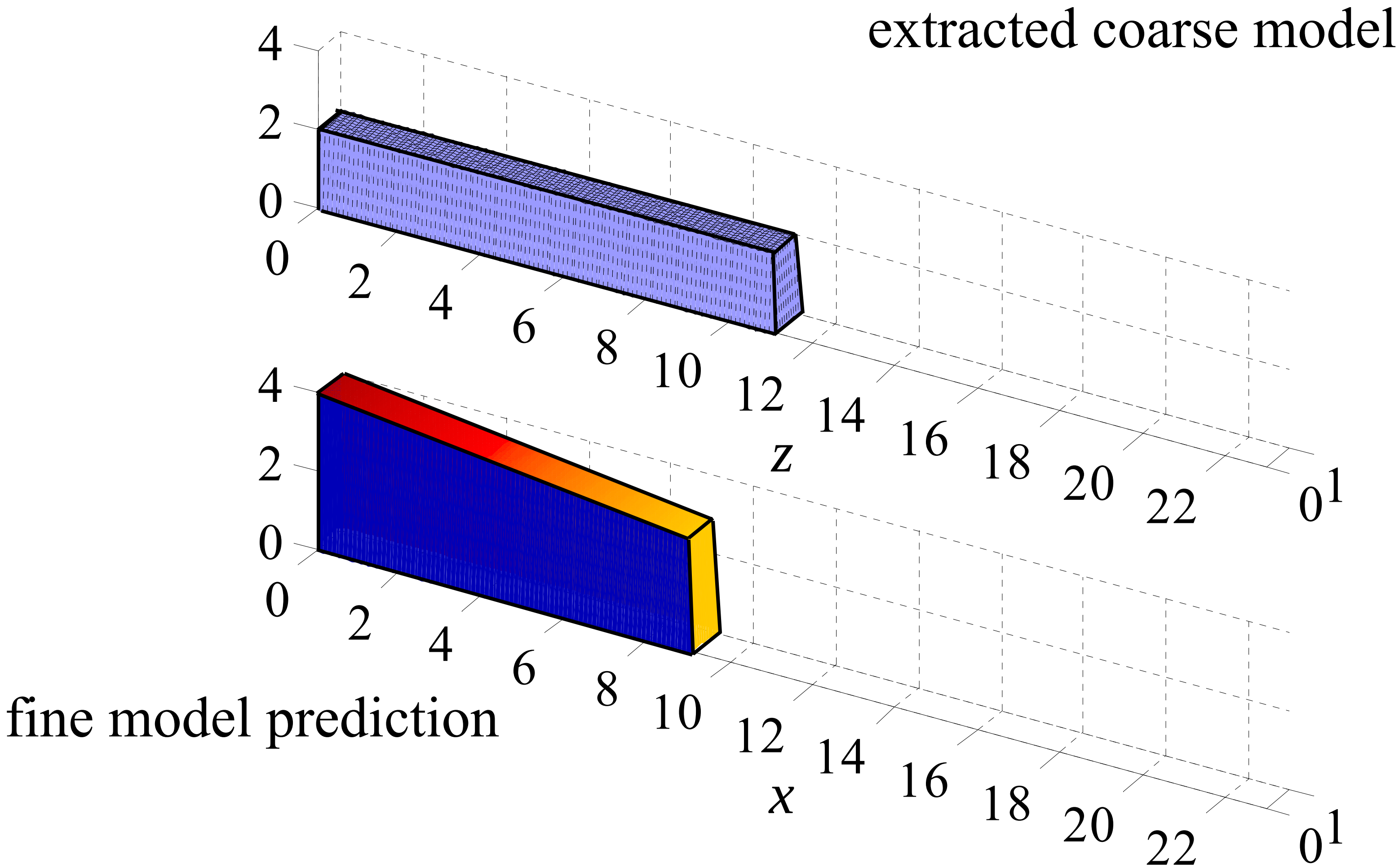
ASM: The Wedge-Cutting Illustration (*Dakroury et al., 2002*)

Iteration 1



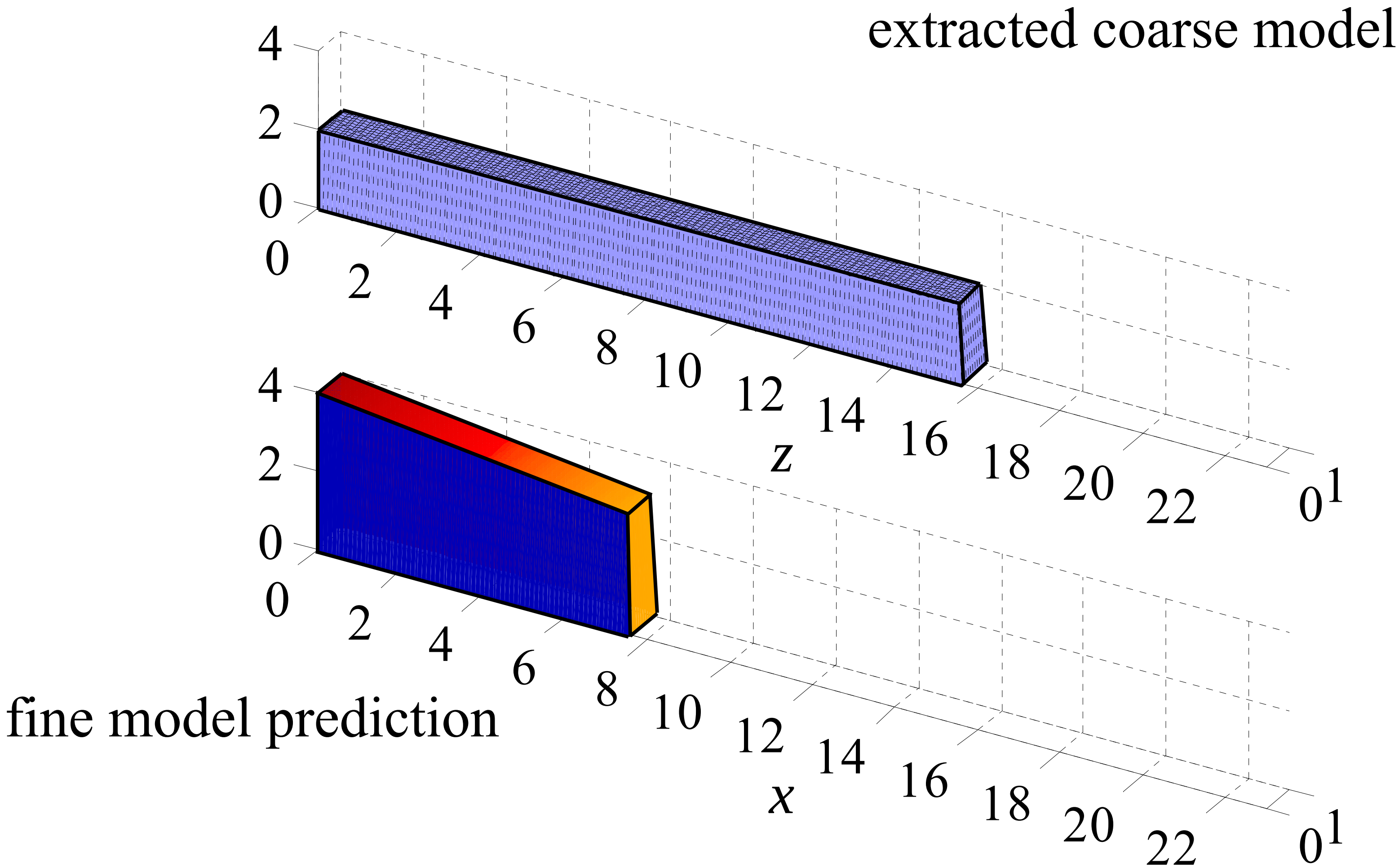
ASM: The Wedge-Cutting Illustration (*Dakroury et al., 2002*)

Iteration 2



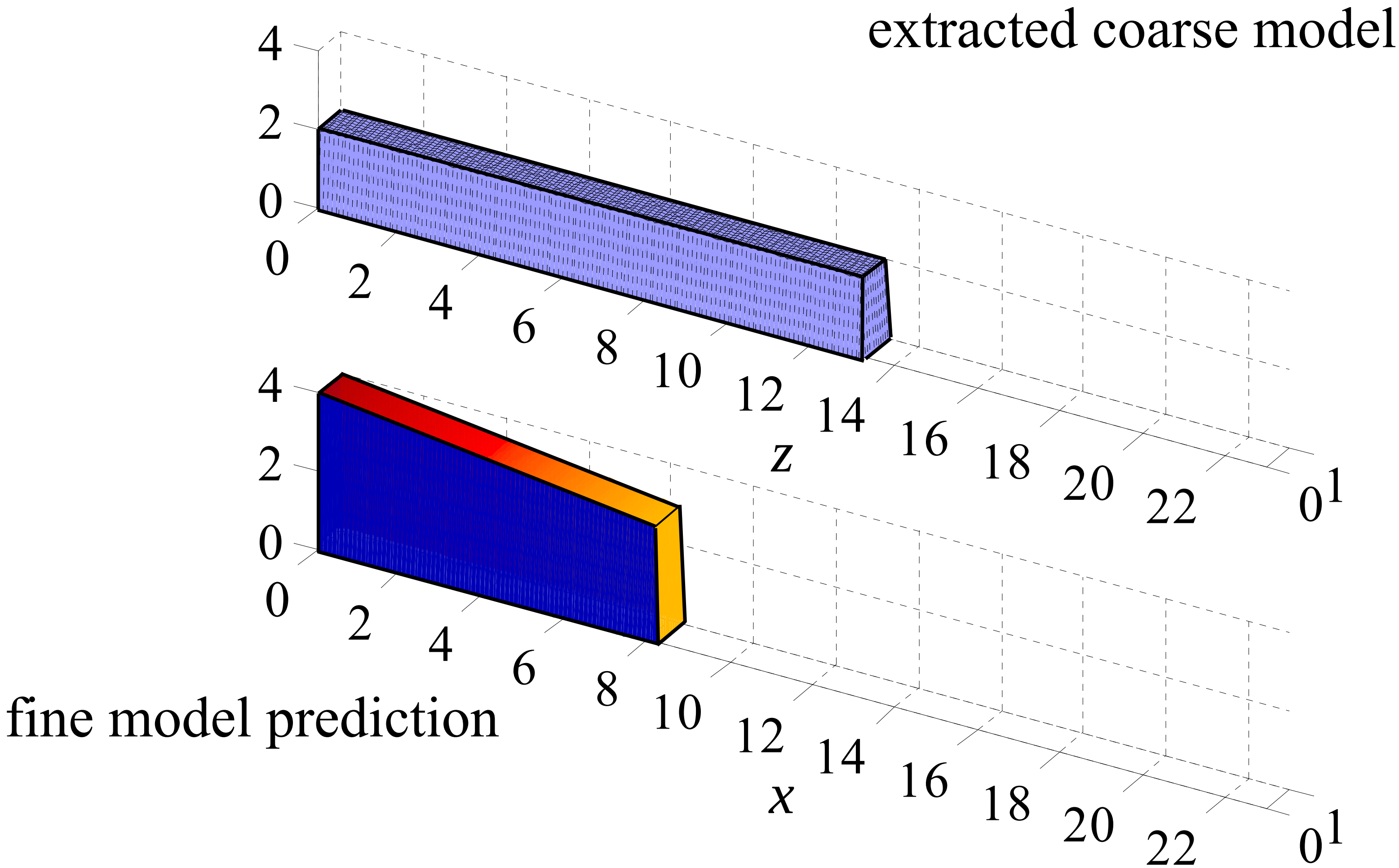
ASM: The Wedge-Cutting Illustration (*Dakroury et al., 2002*)

Iteration 3



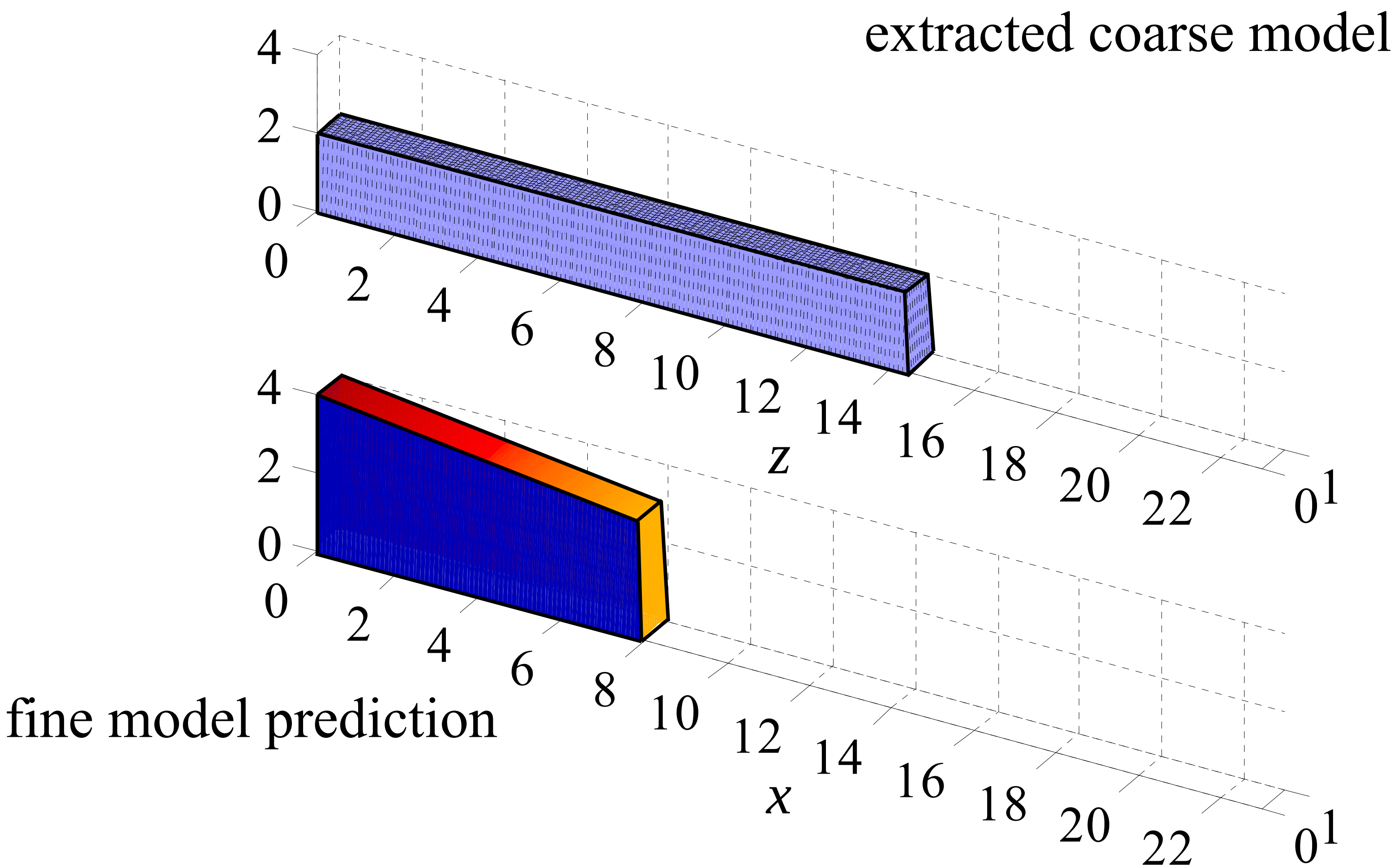
ASM: The Wedge-Cutting Illustration (*Dakroury et al., 2002*)

Iteration 4



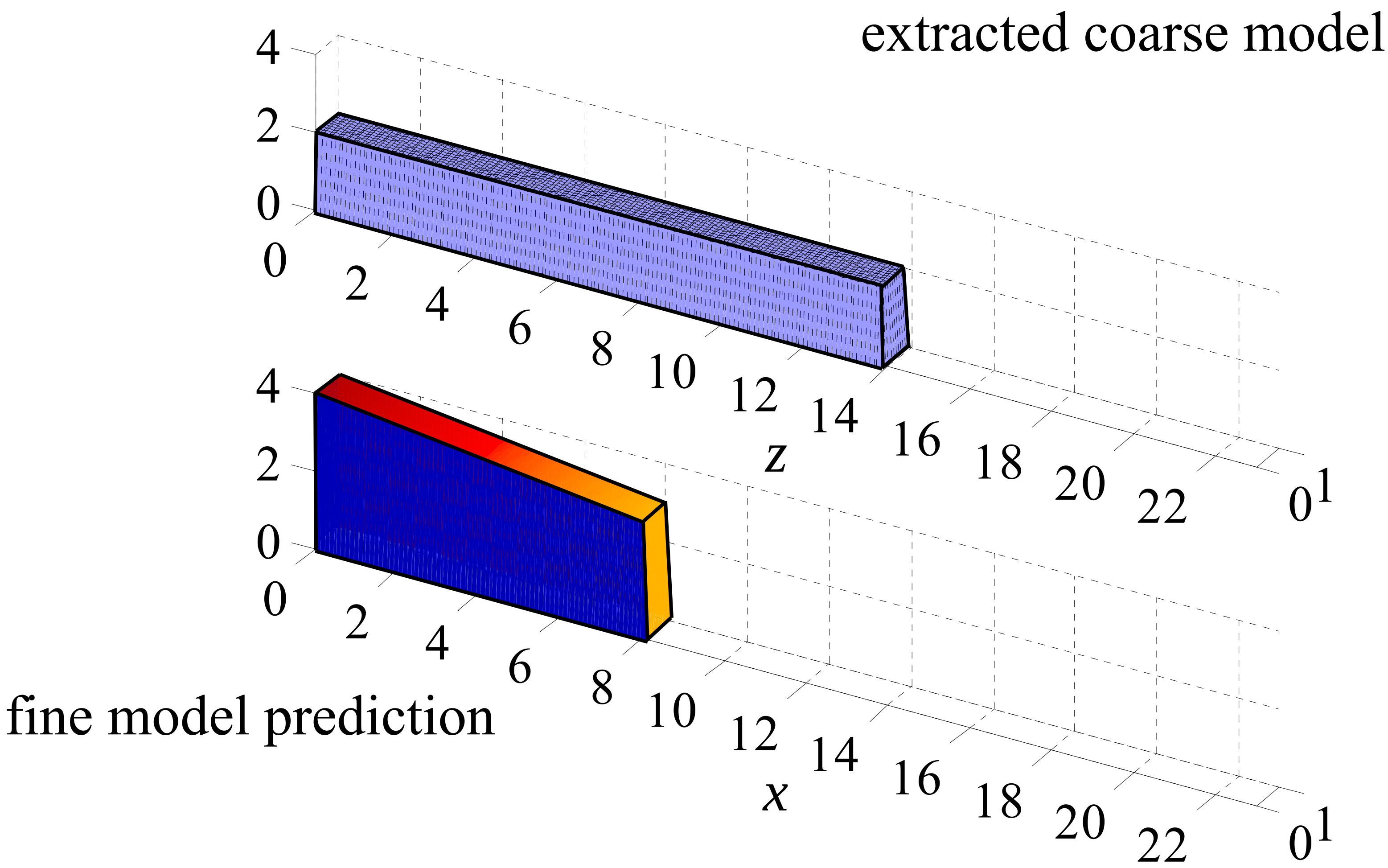
ASM: The Wedge-Cutting Illustration (*Dakroury et al., 2002*)

Iteration 5



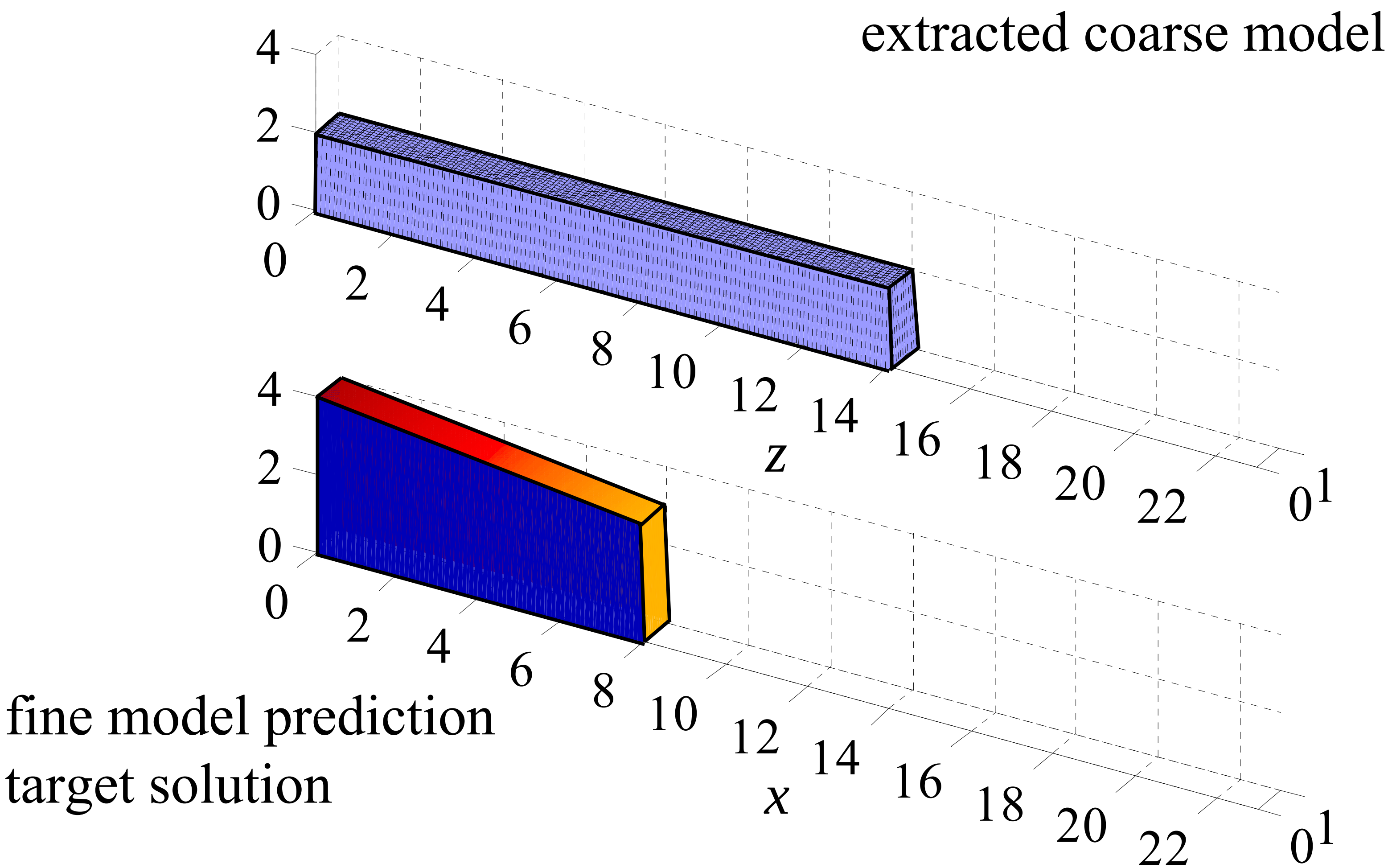
ASM: The Wedge-Cutting Illustration (*Dakroury et al., 2002*)

Iteration 6

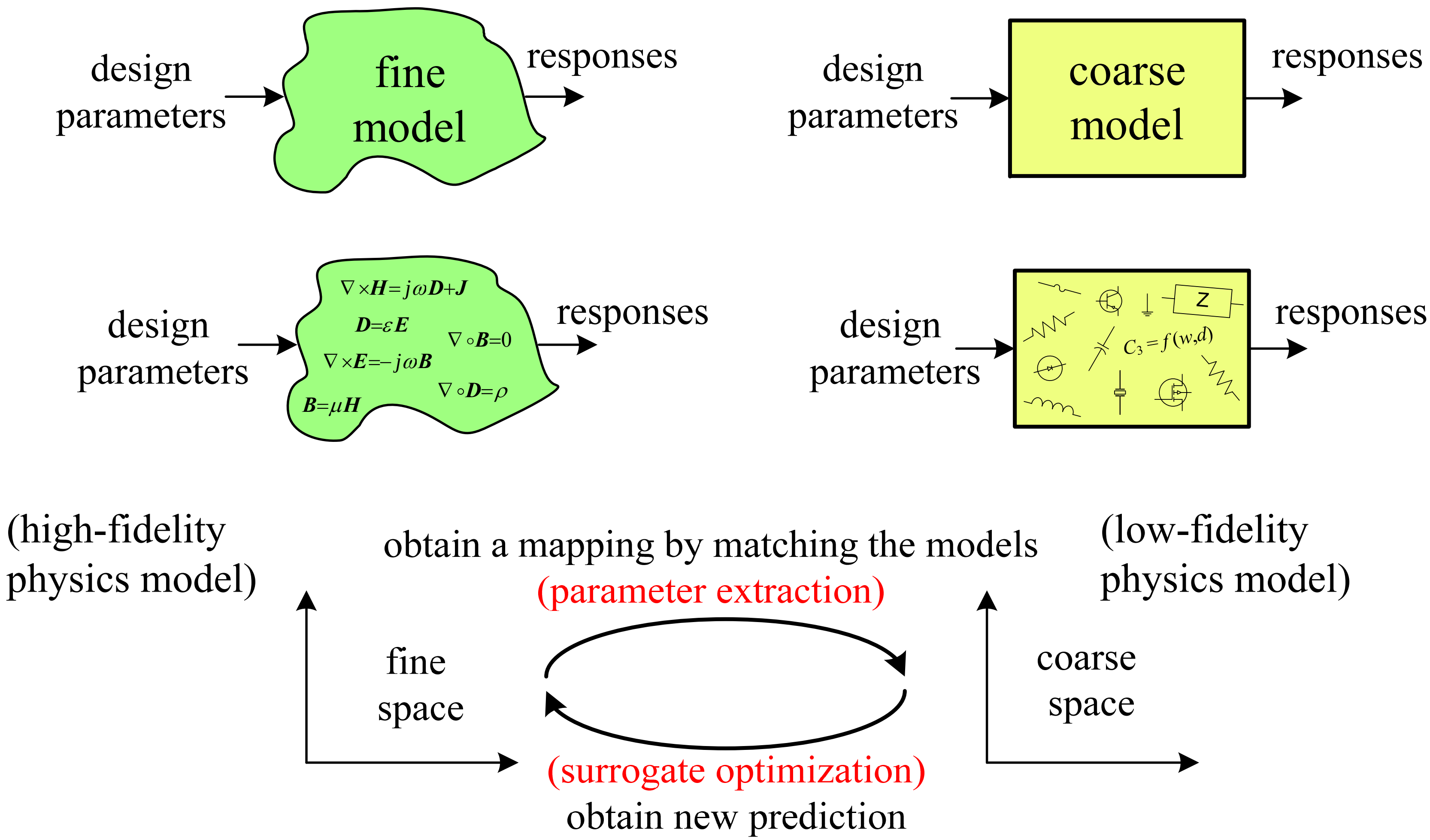


ASM: The Wedge-Cutting Illustration (*Dakroury et al., 2002*)

Iteration 7

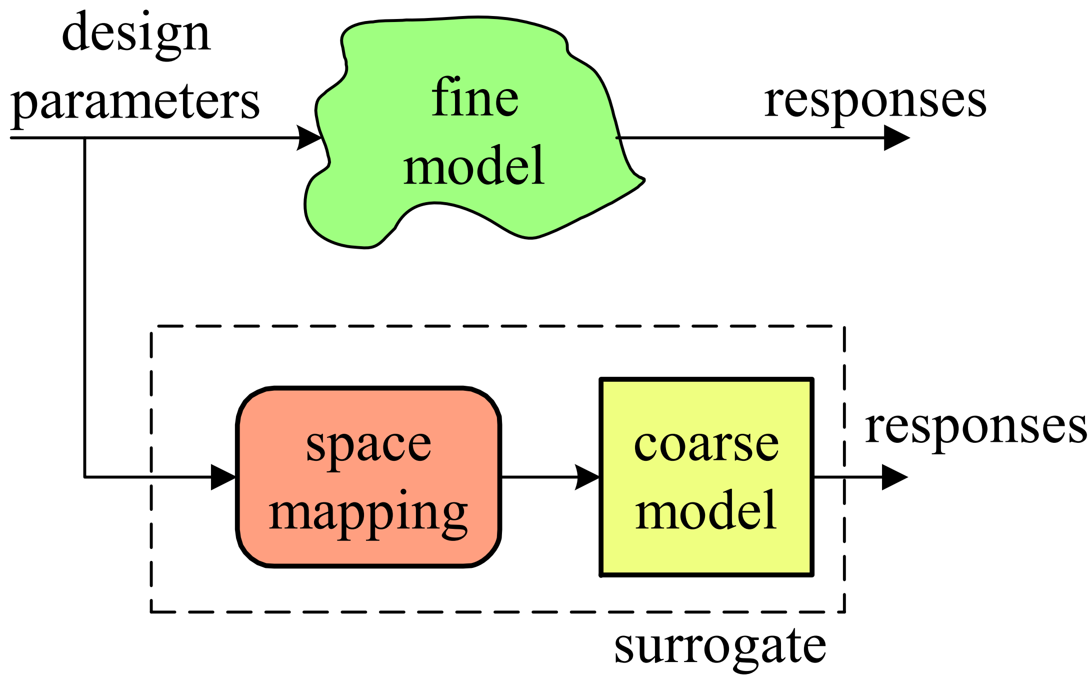


Linking Companion Coarse (Empirical) and Fine (EM) Models Via Space Mapping (*Bandler et al., 1994-*)



Explicit (Input) Space Mapping Concept

(*Bandler et al., 1994-*)



used in the microwave industry (e.g., Com Dev, since 2003, for optimization of dielectric resonator filters and multiplexers)

Aggressive Space Mapping Optimization
(*Bandler et al., 1995*)

corresponds to solving the nonlinear system of equations

$$\boldsymbol{f}(\boldsymbol{x}_f) \triangleq \boldsymbol{P}(\boldsymbol{x}_f) - \boldsymbol{x}_c^*, \quad \boldsymbol{f} \rightarrow \boldsymbol{0}$$

equivalently, "solve"

$$\boldsymbol{x}_c = \boldsymbol{x}_c^*$$

Aggressive Space Mapping **Optimization**

(*Bandler et al., 1995*)

iteratively solves the nonlinear system

$$\boldsymbol{f}(\boldsymbol{x}_f) = \boldsymbol{0}$$

the quasi-Newton step $\boldsymbol{h}^{(j)}$ in the fine space is given by

$$\boldsymbol{B}^{(j)}\boldsymbol{h}^{(j)} = -\boldsymbol{f}^{(j)}$$

the next iterate

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

Aggressive Space Mapping Optimization

(*Bandler et al., 1995*)

Broyden update

$$\boldsymbol{B}^{(j+1)} = \boldsymbol{B}^{(j)} + \frac{\boldsymbol{f}^{(j+1)} - \boldsymbol{f}^{(j)} - \boldsymbol{B}^{(j)}\boldsymbol{h}^{(j)}}{\boldsymbol{h}^{(j)T}\boldsymbol{h}^{(j)}}\boldsymbol{h}^{(j)T}$$

Aggressive Space Mapping **Optimization**

(*Bandler et al., 1995*)

$$\boldsymbol{f}^{(j)} = \boldsymbol{x}_c^{(j)} - \boldsymbol{x}_c^* \ ,$$

$$\boldsymbol{B}^{(j)}\boldsymbol{h}^{(j)} = -\boldsymbol{f}^{(j)} \text{ and}$$

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

estimate the fine model Jacobian (*Bakr et al., 1999*)

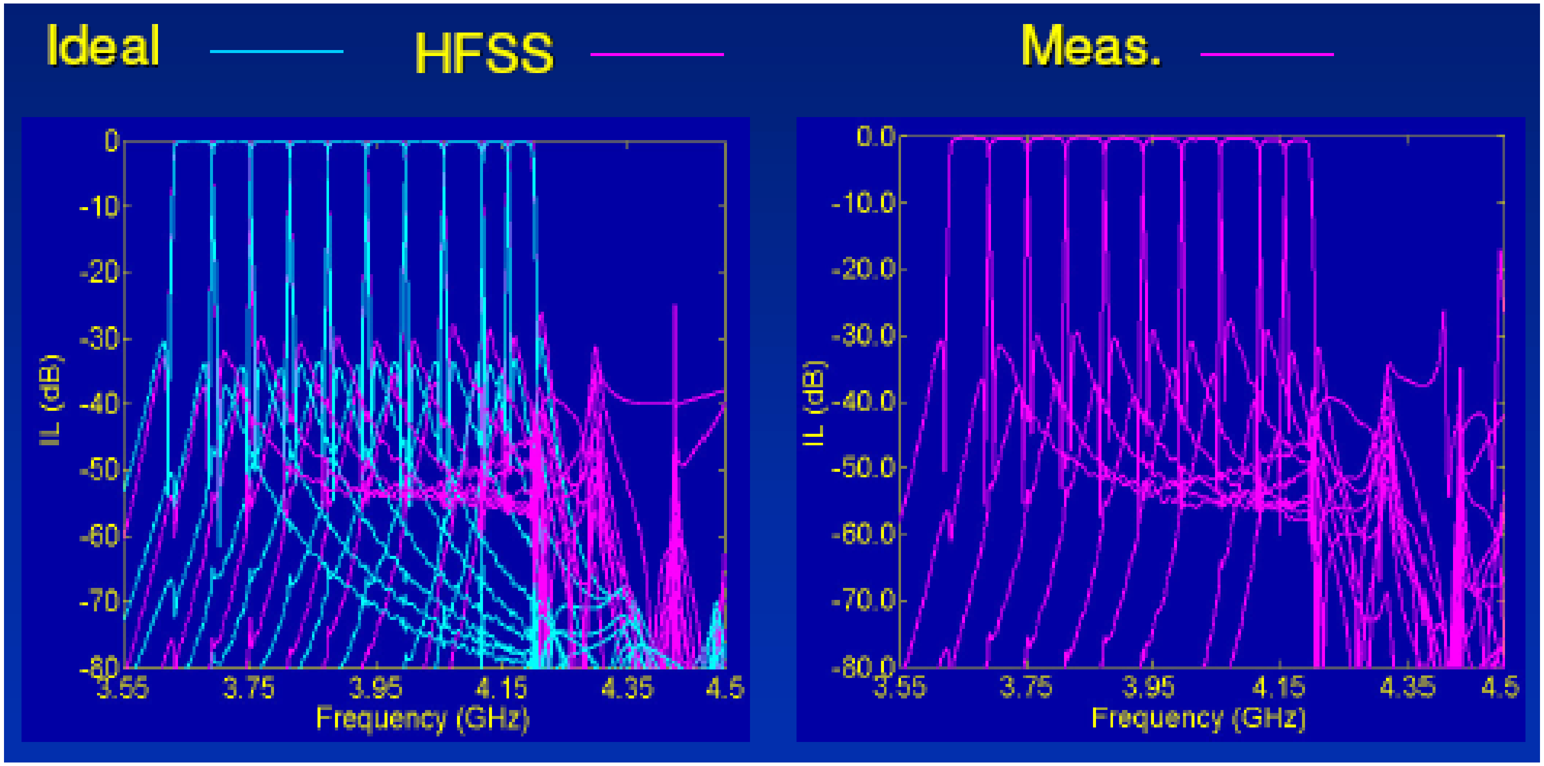
$$\boldsymbol{J}_f(\boldsymbol{x}_f) \approx \boldsymbol{J}_c(\boldsymbol{x}_c)\boldsymbol{B}$$

estimate the mapping matrix

$$\boldsymbol{B} \approx (\boldsymbol{J}_c^T \boldsymbol{J}_c)^{-1} \boldsymbol{J}_c^T \boldsymbol{J}_f$$

Space Mapping Design of Dielectric Resonator Multiplexers
(*Ismail et al., 2003, Com Dev, Canada*)

10-channel output multiplexer, 140 variables, aggressive SM



Space Mapping Crashworthiness Design of Saab 9^3

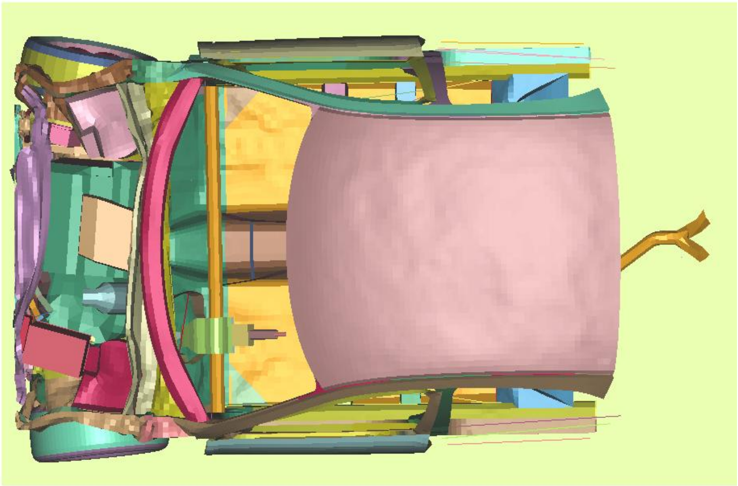
(*Redhe et al., 2001-2004, Sweden*)

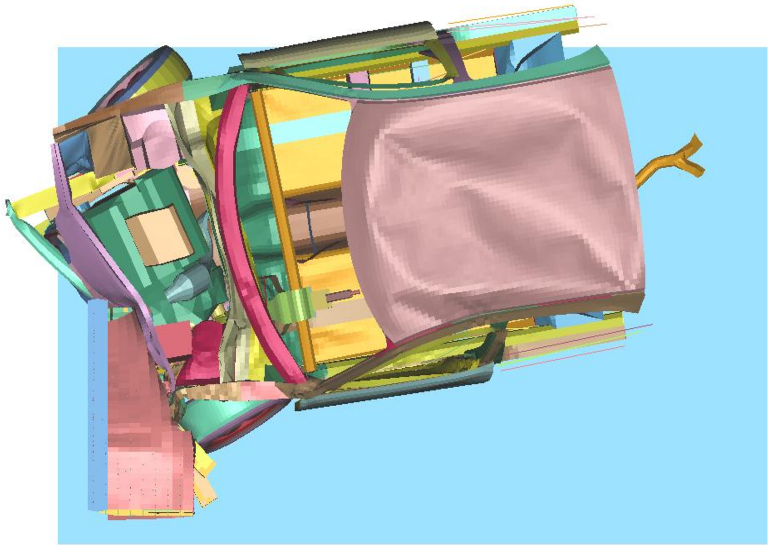
[type “saab space mapping” into Google]

in crashworthiness finite element design, space mapping reduces the total computing time to optimize the vehicle structure more than 50% compared to traditional optimization

when space mapping was applied to the complete FE model of the new Saab 9^3 Sport Sedan, intrusion into the passenger compartment area after impact was reduced by 32% with no reduction in other crashworthiness responses

Space Mapping Crashworthiness Design of Saab 9[3]
Frontal Impact (*Nilsson and Redhe, 2005, Sweden*)

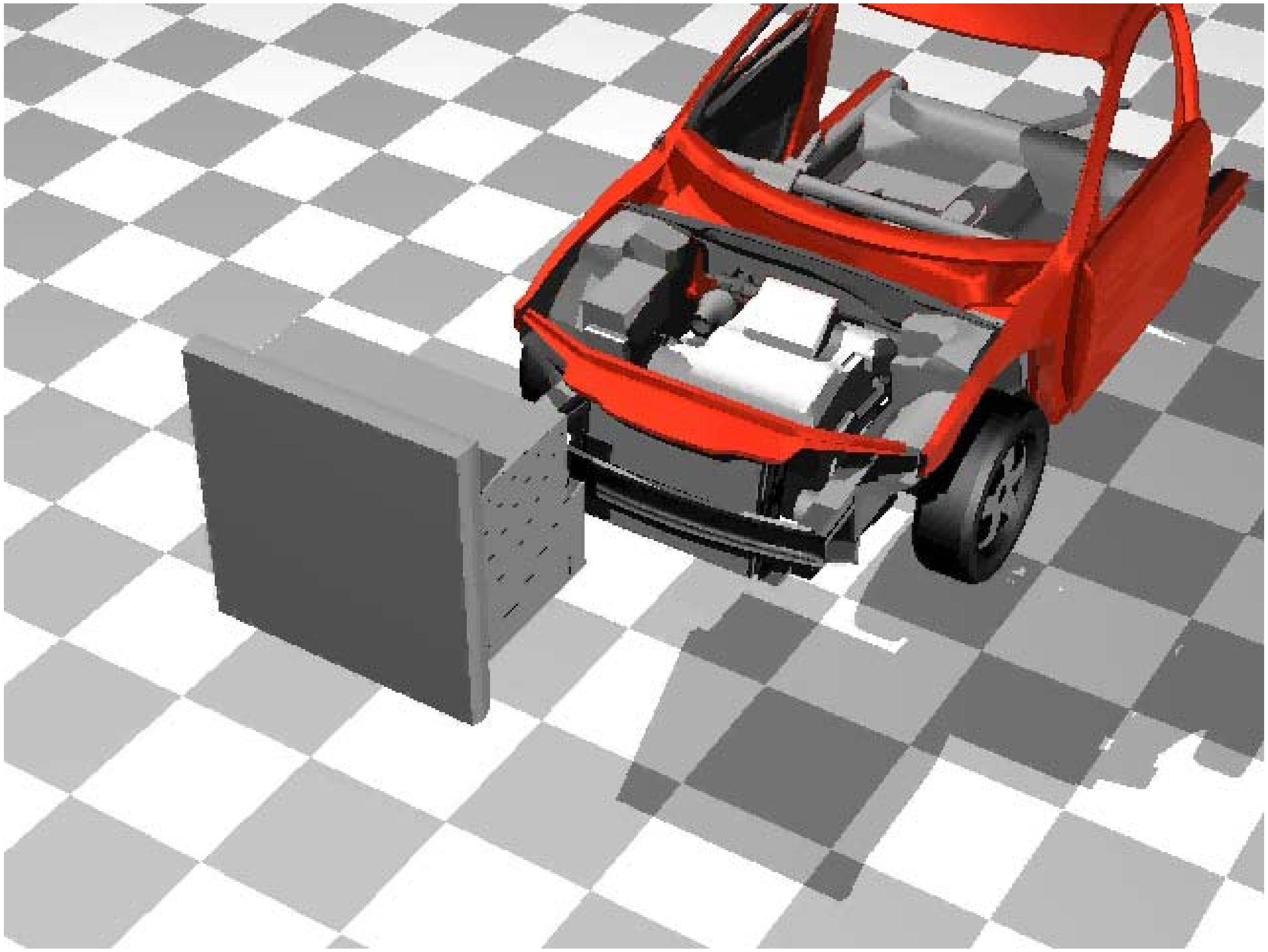




US-NCAP

EU-NCAP

Space Mapping Crashworthiness Design of Saab 9^3 Frontal Impact (*Nilsson and Redhe*, *2005*, *Sweden*)



Space Mapping Crashworthiness Design of Saab 9[3]

(*www.studyinsweden.se, 2005*)

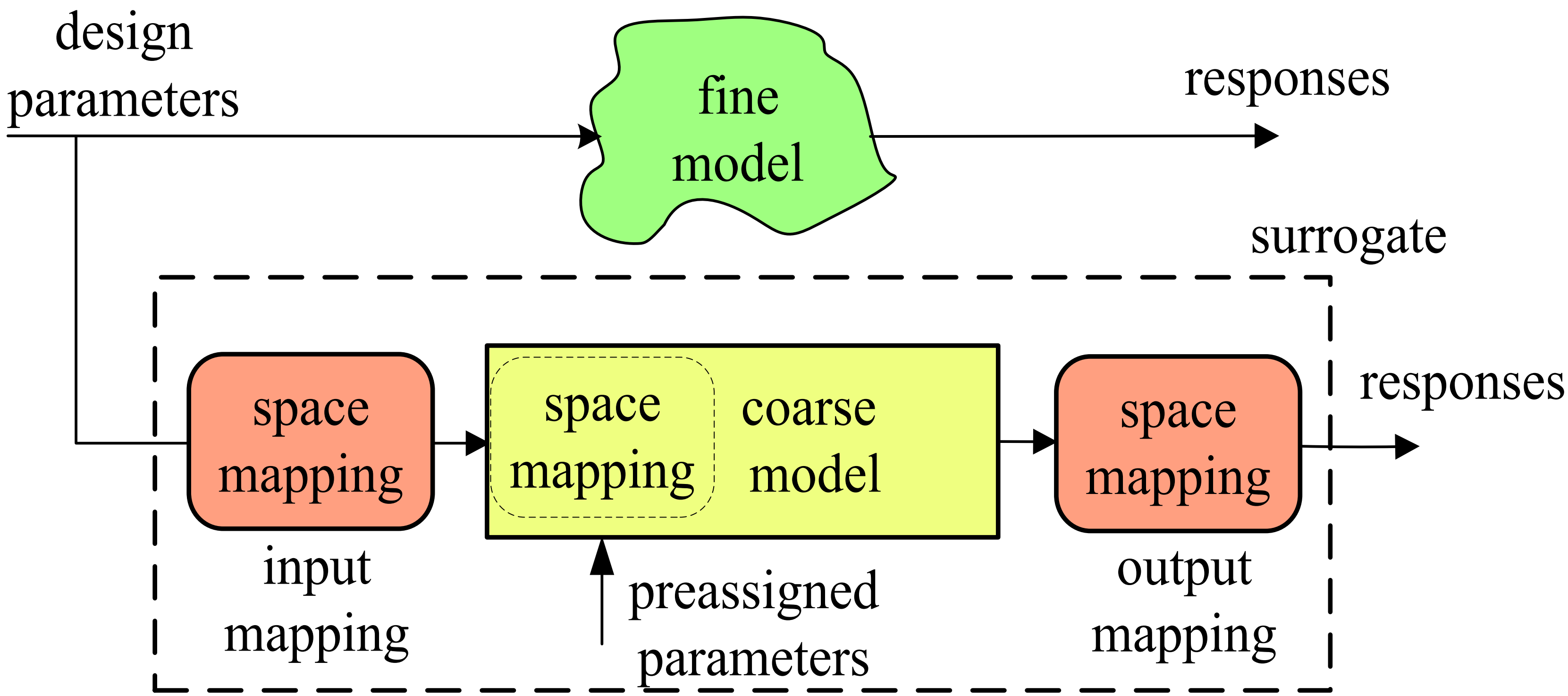
space mapping cuts calculation times by three fourths compared with traditional response surface optimization

driven straight into a steel barrier
at 56 km/h

penetration of the passenger space
was reduced by 32 percent

Implicit, Input and Output **Space Mappings**

(*Bandler et al., 2003*-)



expert engineering knowledge helpful (few designable variables)

expertise helpful in "tuning the surrogate" (many possibilities, e.g., dielectric constant)

engineering expertise perhaps less necessary (many output variables)

The Novice-Expert Continuum

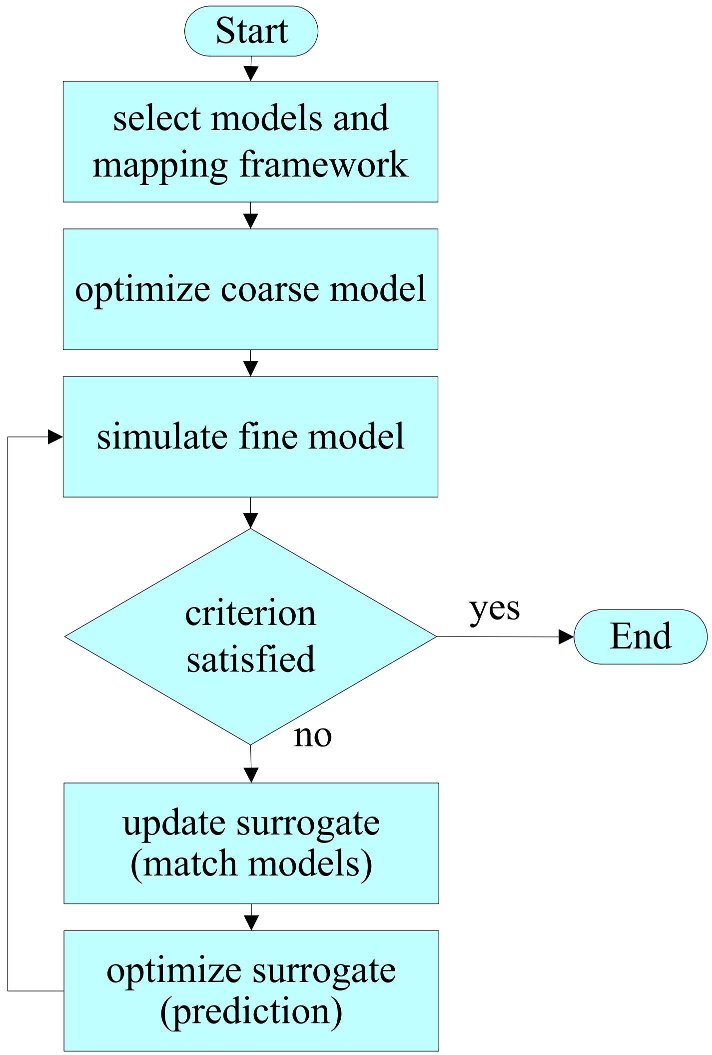
output space mapping: a “band-aid” solution for engineers and non-engineers; the parameter extraction step does not require coarse model re-analysis; good for final touch-ups

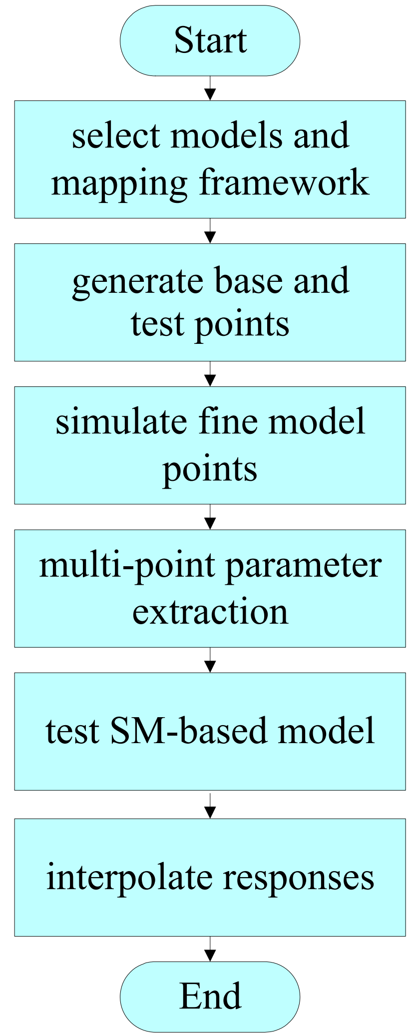
input space mapping: an engineering approach to find and cure the root-cause of a defect; but the parameter extraction step can be a difficult inverse optimization problem to solve w.r.t. the coarse model

tuning space mapping (new): simulator-based expert approach

but all types of space mapping can be viewed as special cases of implicit space mapping

Space Mapping: (1) for Design Optimization, (2) for Modeling

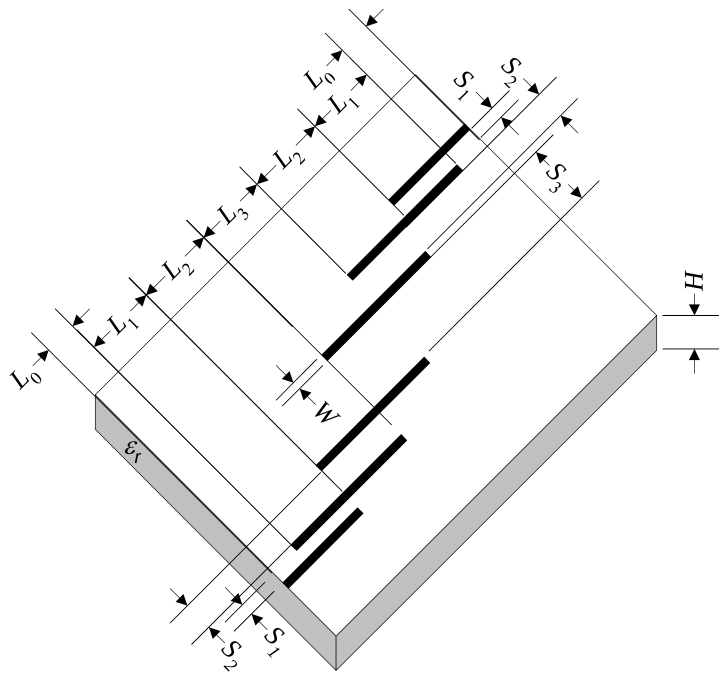


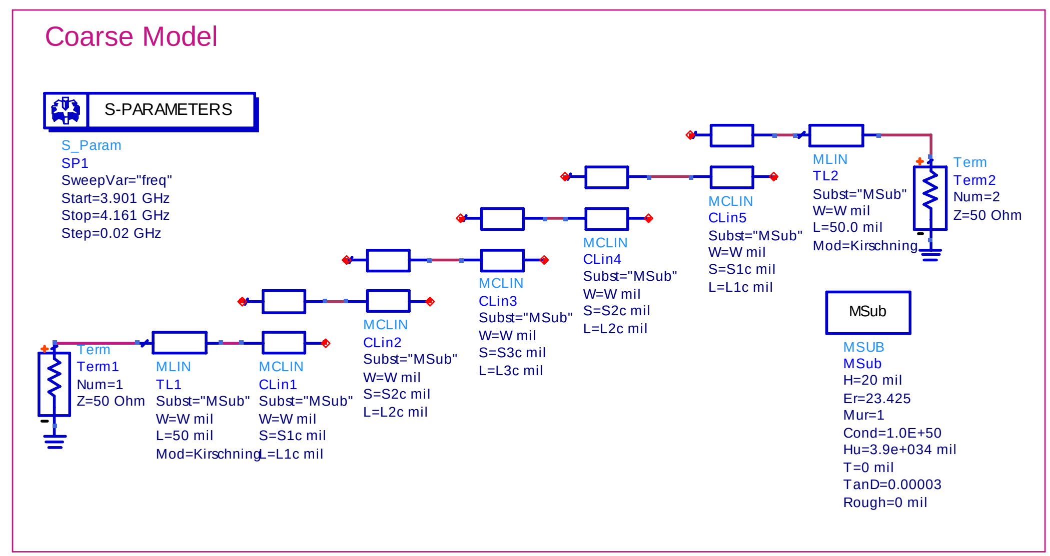


High-Temperature Superconducting (HTS) Filter: Modeling + Optimization

Sonnet ***em*** fine model (*Westinghouse, 1993*)

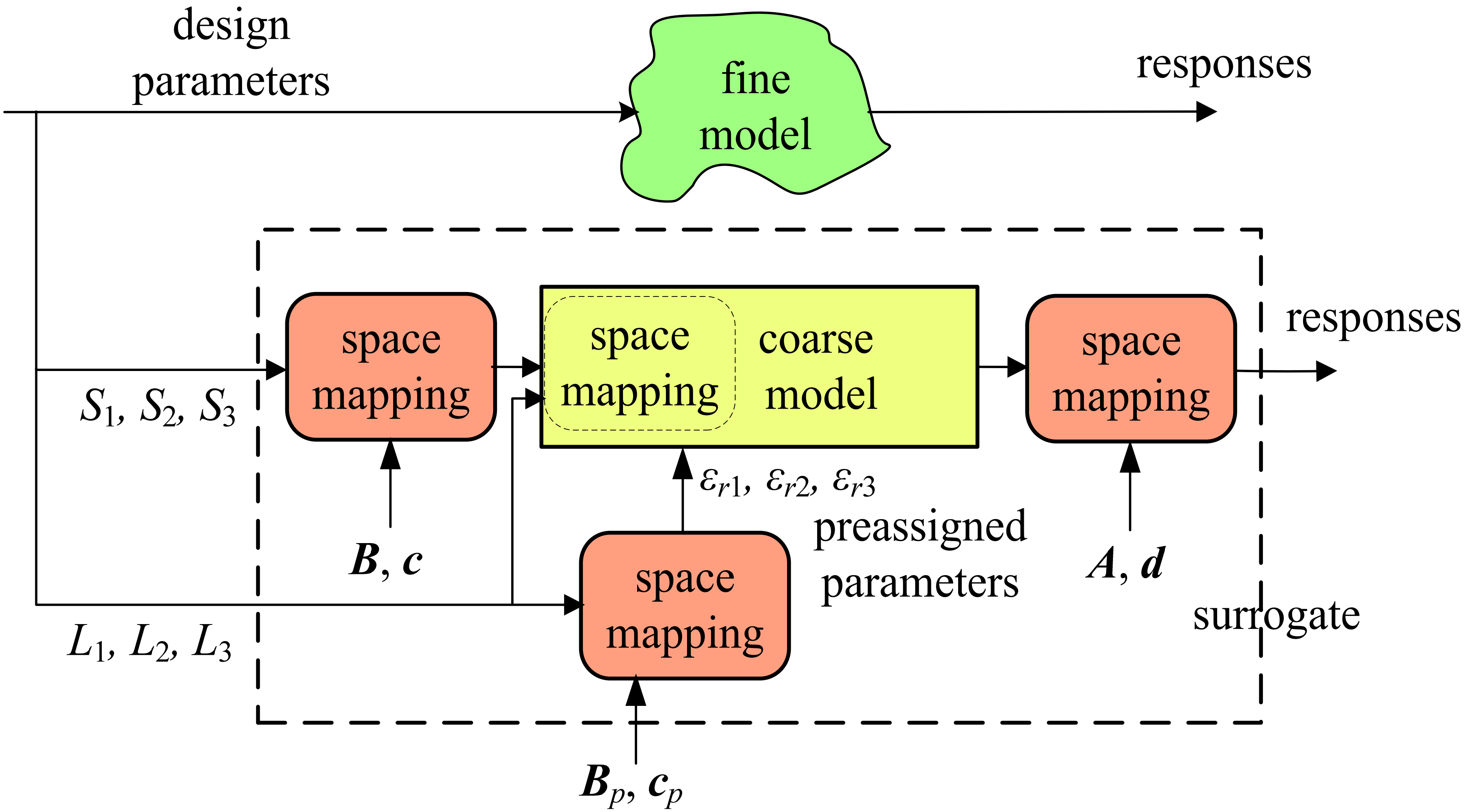
Agilent ADS coarse model (*Bandler et al., 2004*)





Implicit and Output SM Modeling, with Input SM: HTS Filter

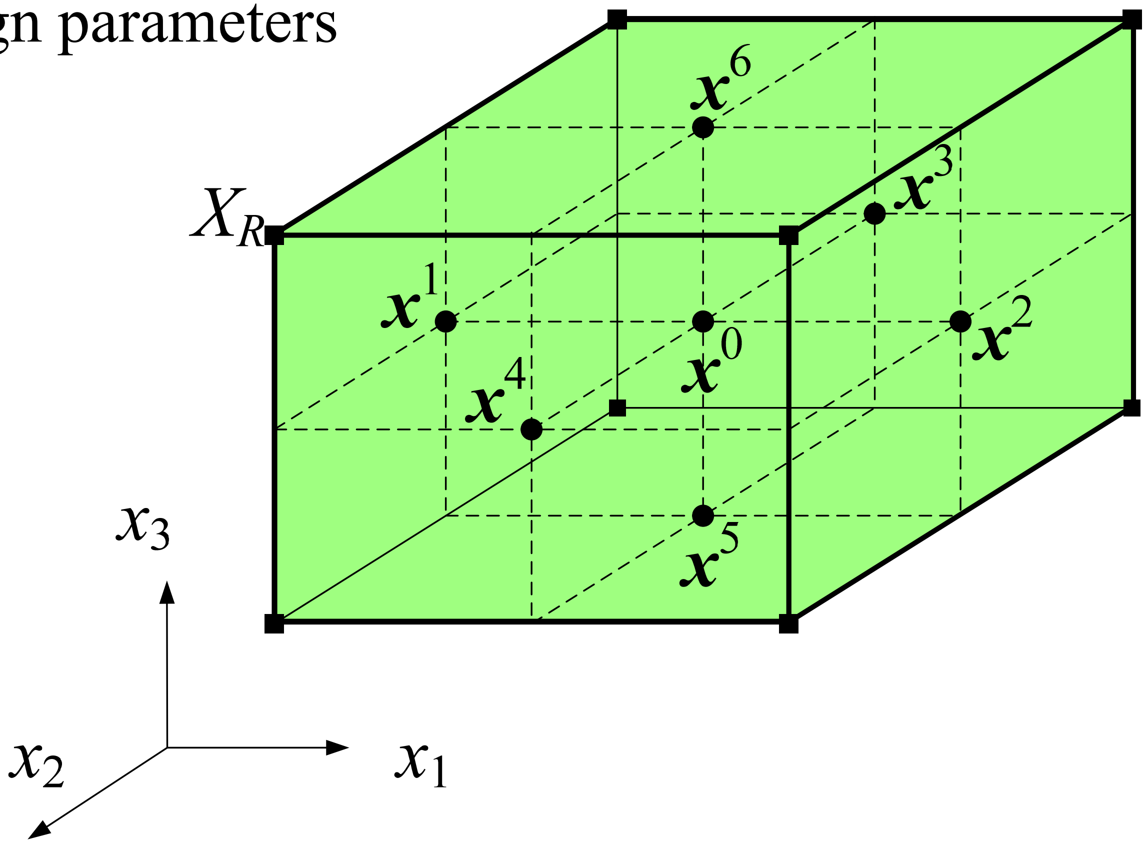
(*Cheng and Bandler, 2006*)



More Base Points for Space-Mapping-based Modeling

(*Bandler et al., 2001*)

2^n more base points located at the corner of the region of interest with n design parameters

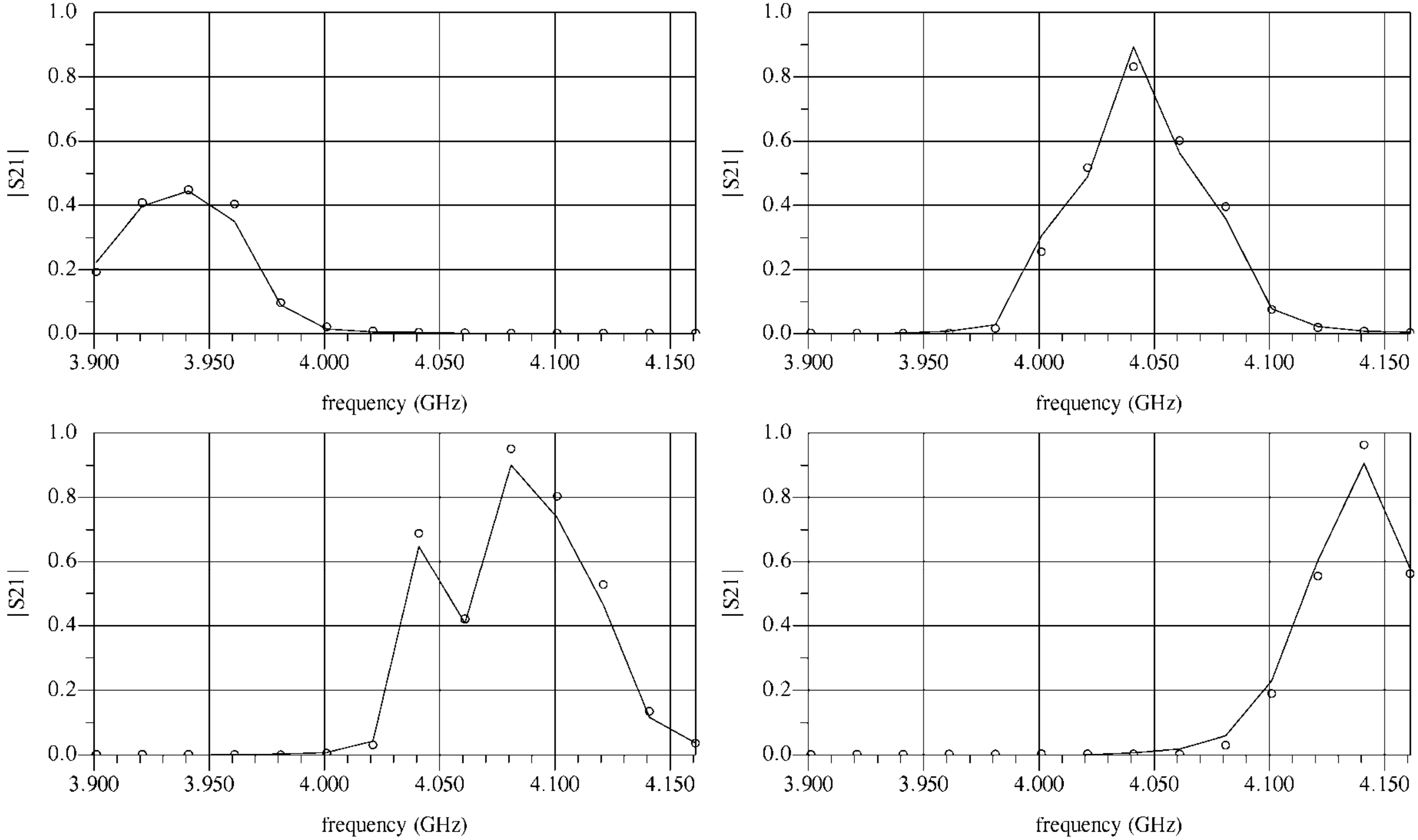


HTS Filter: Modeling Region of Interest

(*Cheng and Bandler, 2006*)

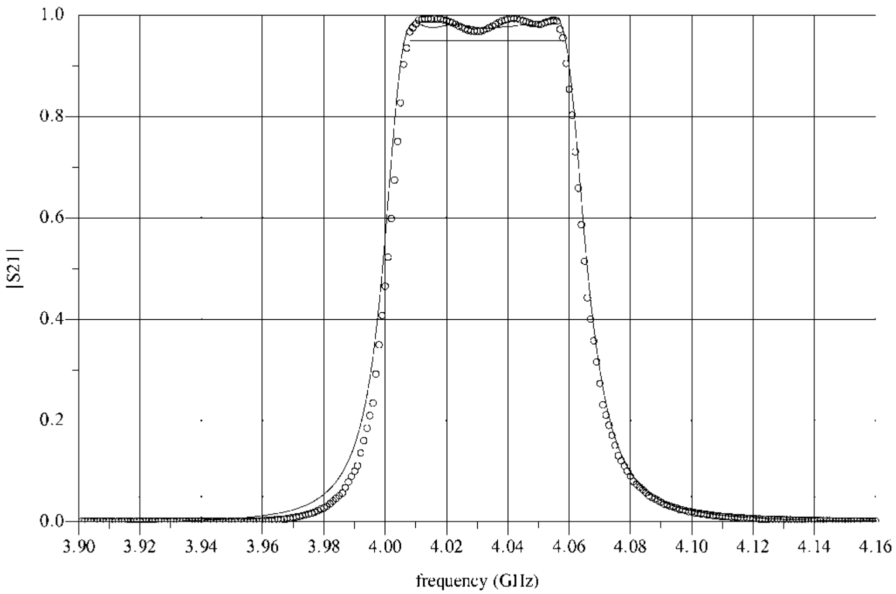
parameters	reference point ($\boldsymbol{x}^0$)	region 1 size ($\boldsymbol{\delta}_1$)	region 2 size ($\boldsymbol{\delta}_2$)	region 3 size ($\boldsymbol{\delta}_3$)	region 4 size ($\boldsymbol{\delta}_4$)	region 5 size ($\boldsymbol{\delta}_5$)
L_1	180	5	6	8	10	45
L_2	200	10	11	15	20	50
L_3	180	5	6	8	10	45
S_1	20	2	3	3	4	5
S_2	80	5	6	8	10	20
S_3	80	10	11	15	20	20

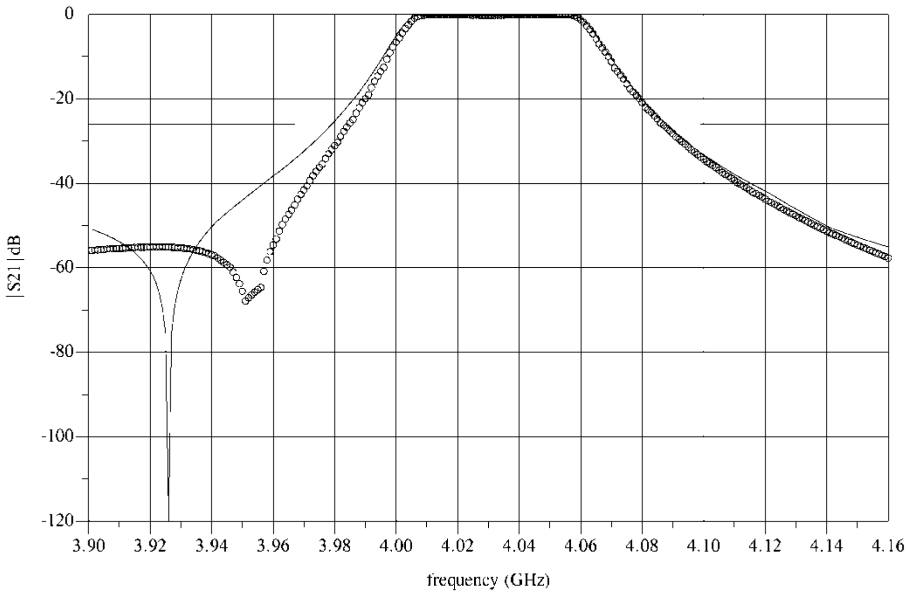
HTS Filter: Implicit SM Modeling Surrogate Test Region 2



fine model (○) $\boldsymbol{R}_s$ surrogate (—)

HTS Filter: Implicit SM Modeling + Surrogate Optimization
(*Cheng and Bandler, 2006*)

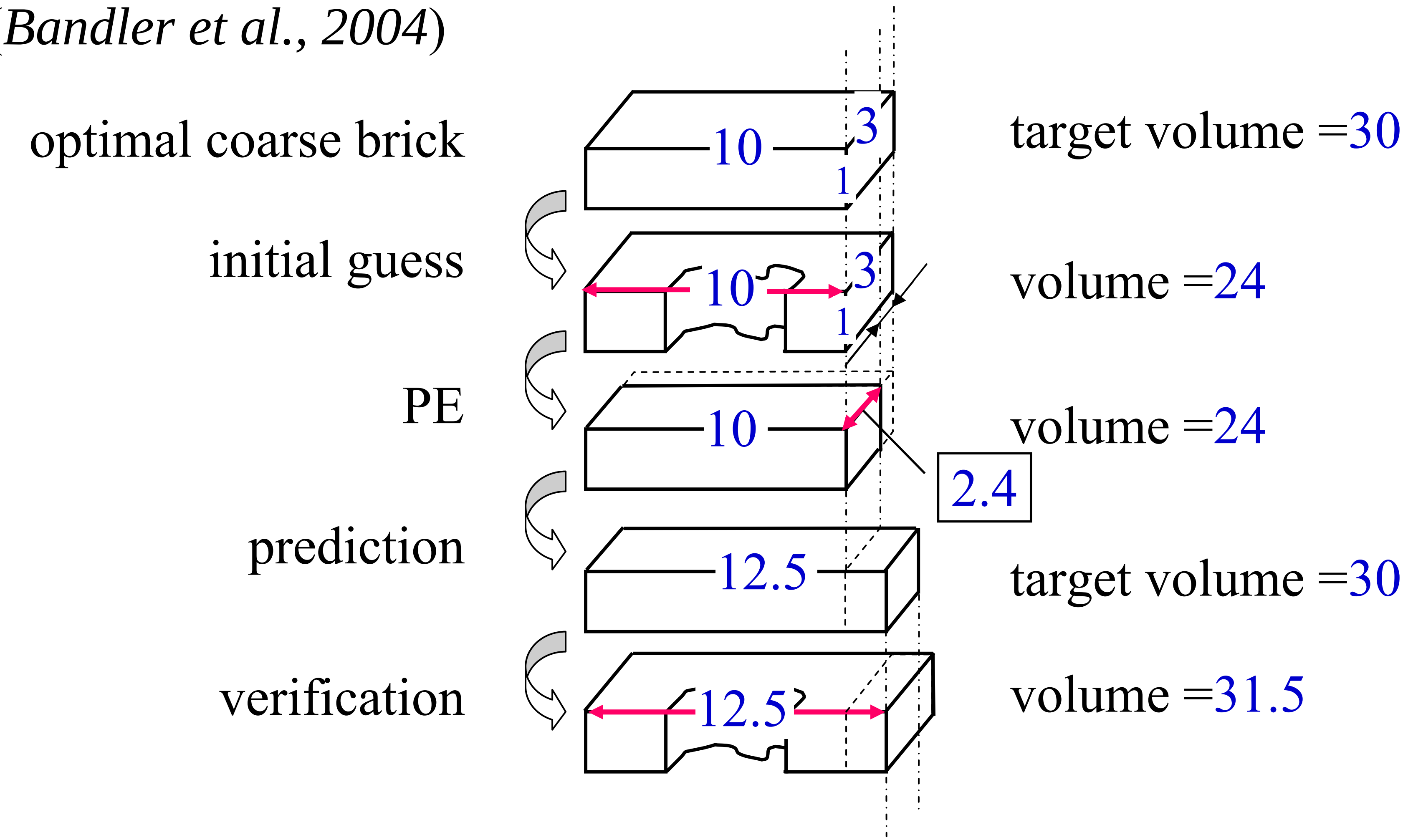




$\boldsymbol{x}_f^* = [172\ 207\ 172\ 20\ 90\ 84]^T$

Implicit Space Mapping Practice—Cheese-Cutting Problem

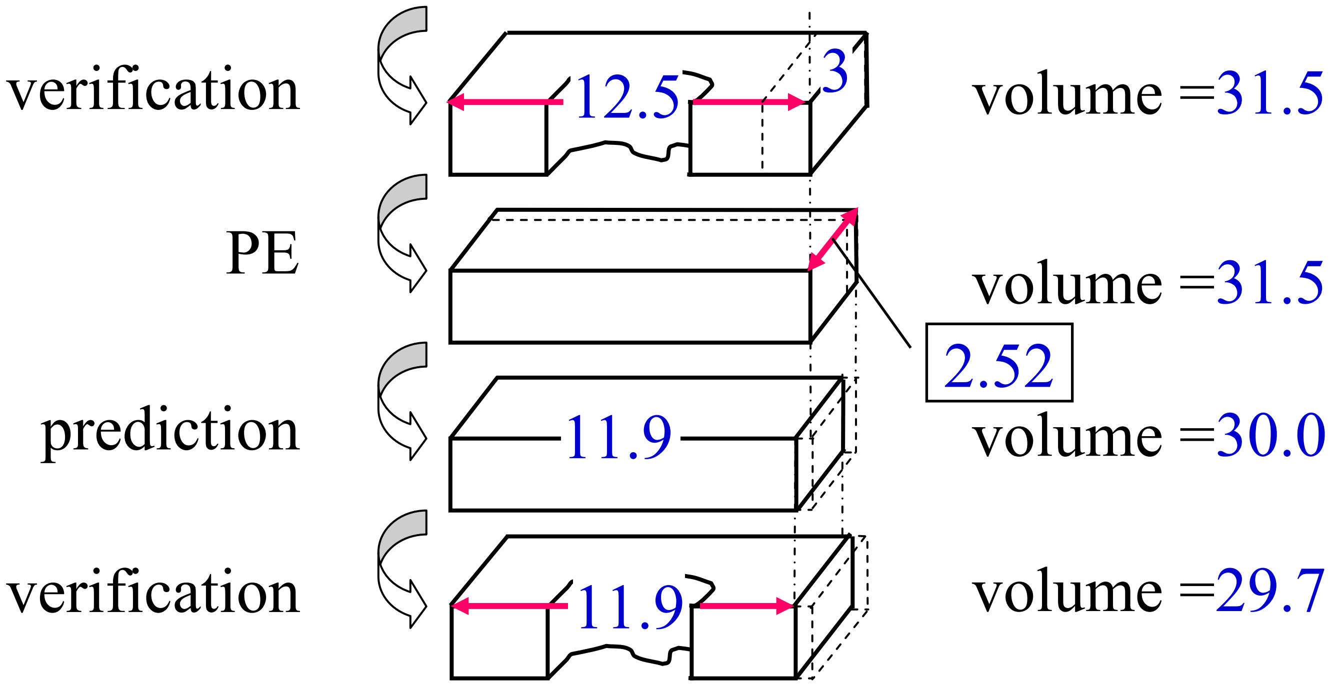
(*Bandler et al., 2004*)



the "coarse" brick is idealized, the algorithm is non-expert

Implicit Space Mapping Practice—Cheese-Cutting Problem

(*Bandler et al., 2004*)



$$\text{error} = (30-29.7)/30\times 100\% = 1\%$$

Implicit Space Mapping Optimization (*Cheng et al., 2008*)

fine model optimal solution

$$\boldsymbol{x}^* = \arg\min_{\boldsymbol{x}} U(\boldsymbol{R}_f(\boldsymbol{x}))$$

surrogate optimization

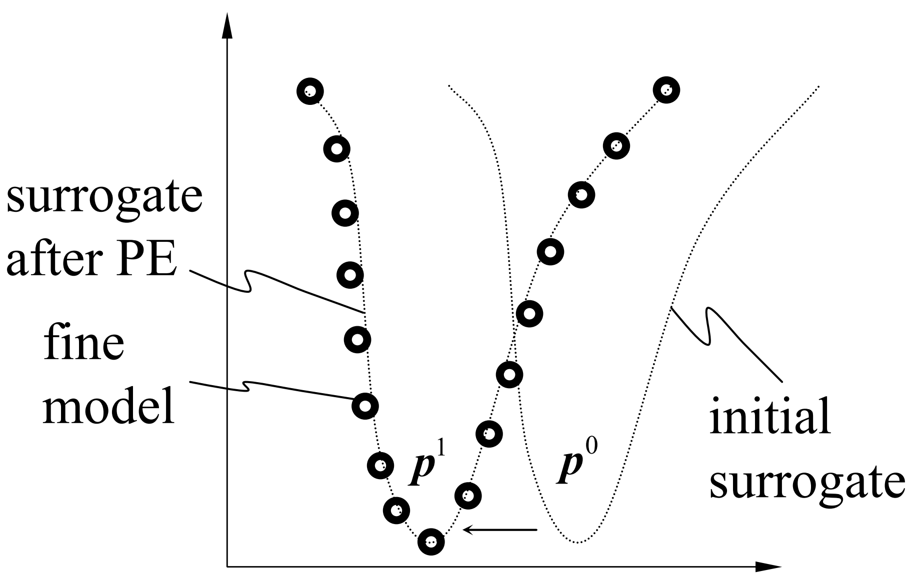
$$\boldsymbol{x}^{k+1} = \arg\min_{\boldsymbol{x}} U(\boldsymbol{R}_c(\boldsymbol{x}, \boldsymbol{p}^k))$$

parameter extraction

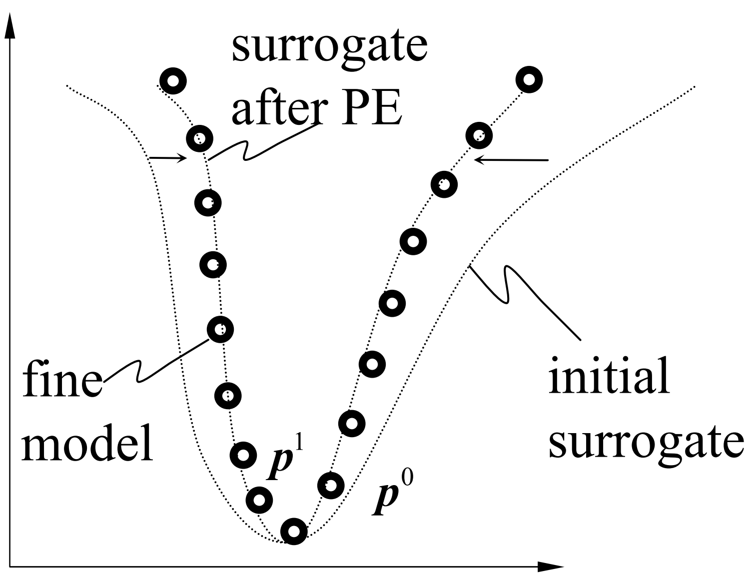
$$\boldsymbol{p}^k = \arg\min_{\boldsymbol{p}} \| \boldsymbol{R}_f(\boldsymbol{x}^k) - \boldsymbol{R}_c(\boldsymbol{x}^k, \boldsymbol{p}) \|$$

Implicit Space Mapping Parameter Extraction
(*Cheng et al., 2008*)

matching the initial surrogate (coarse model) to the fine model

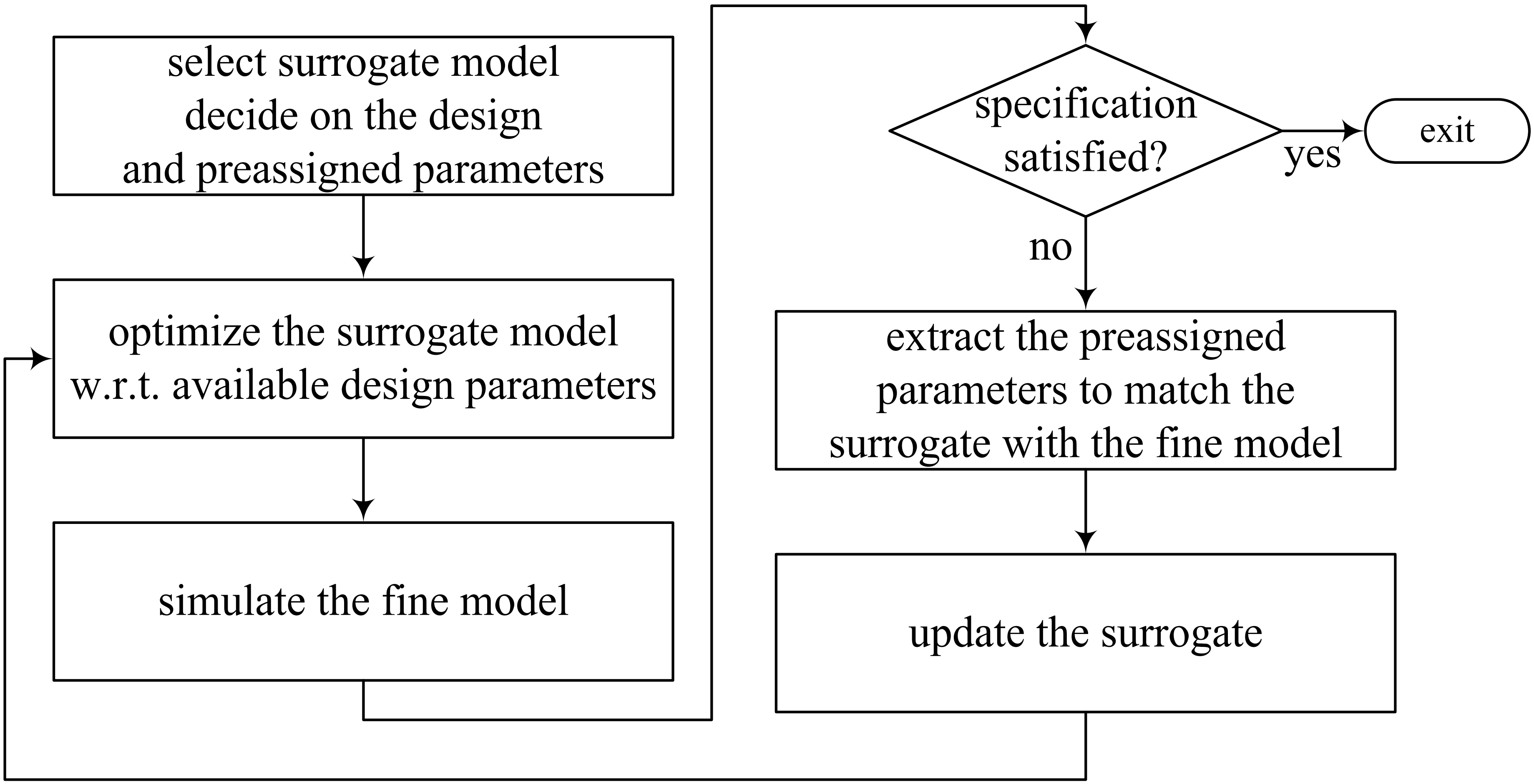


surrogate shifted



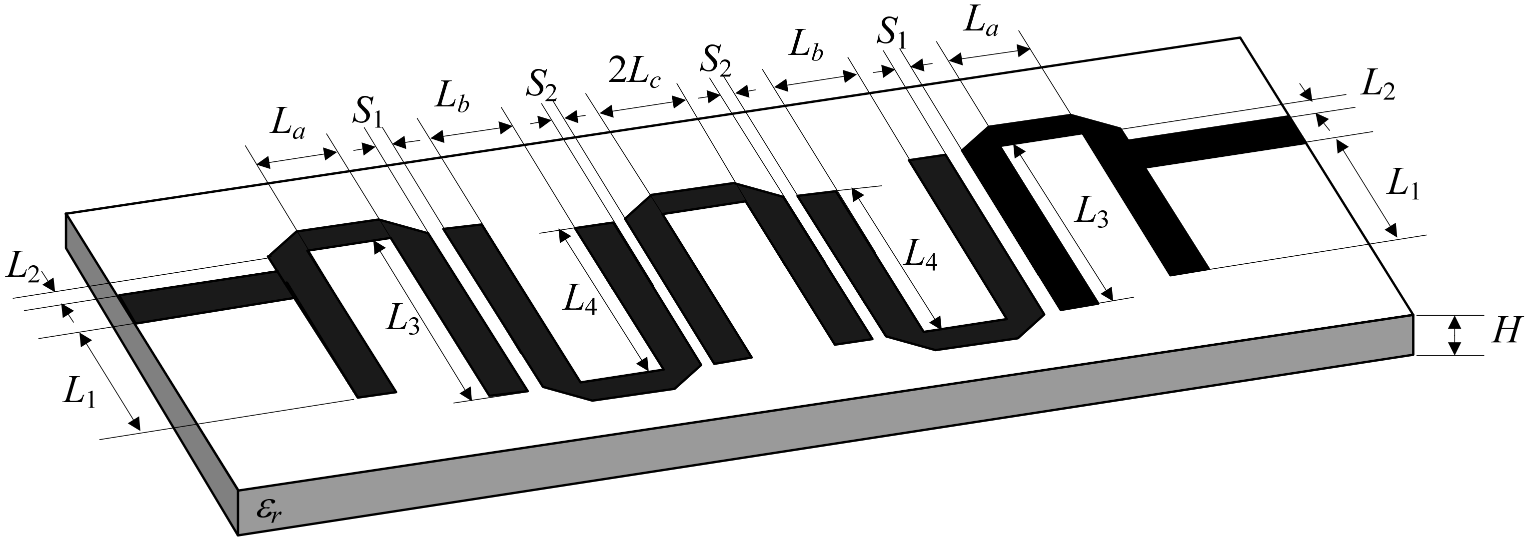
surrogate scaled

Implicit Space Mapping Flowchart (*Cheng et al., 2008*)



Microstrip Hairpin Filter: Implicit SM (*Cheng et al., 2008*)

filter structure (*Brady, 2002*)



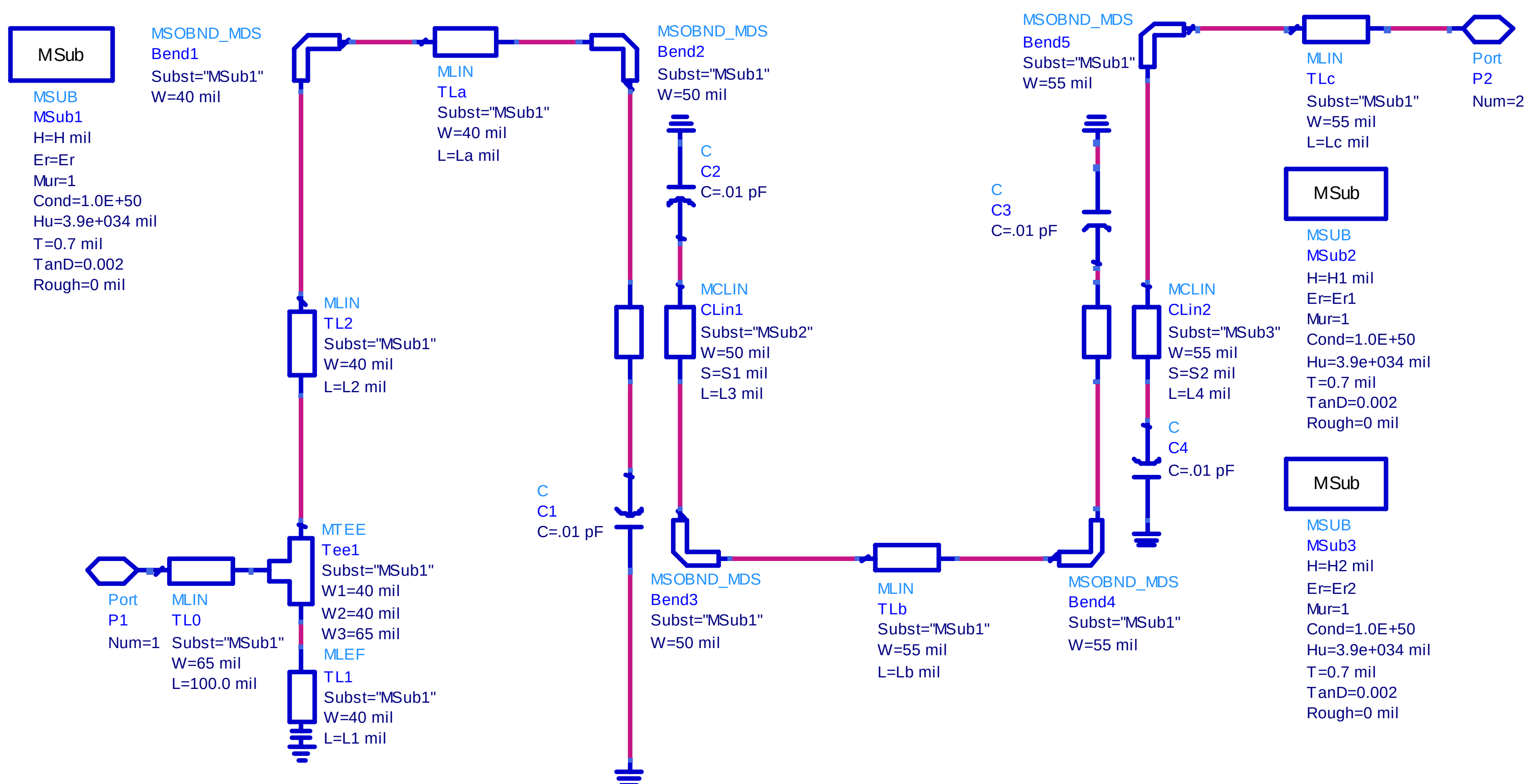
specification

$|S_{11}| < -16$ dB for 3.7 GHz $\leqslant \omega \leqslant$ 4.2 GHz

$|S_{21}| < -28$ dB for $\omega \leqslant$ 3.2 GHz and $\omega \geqslant$ 4.7 GHz.

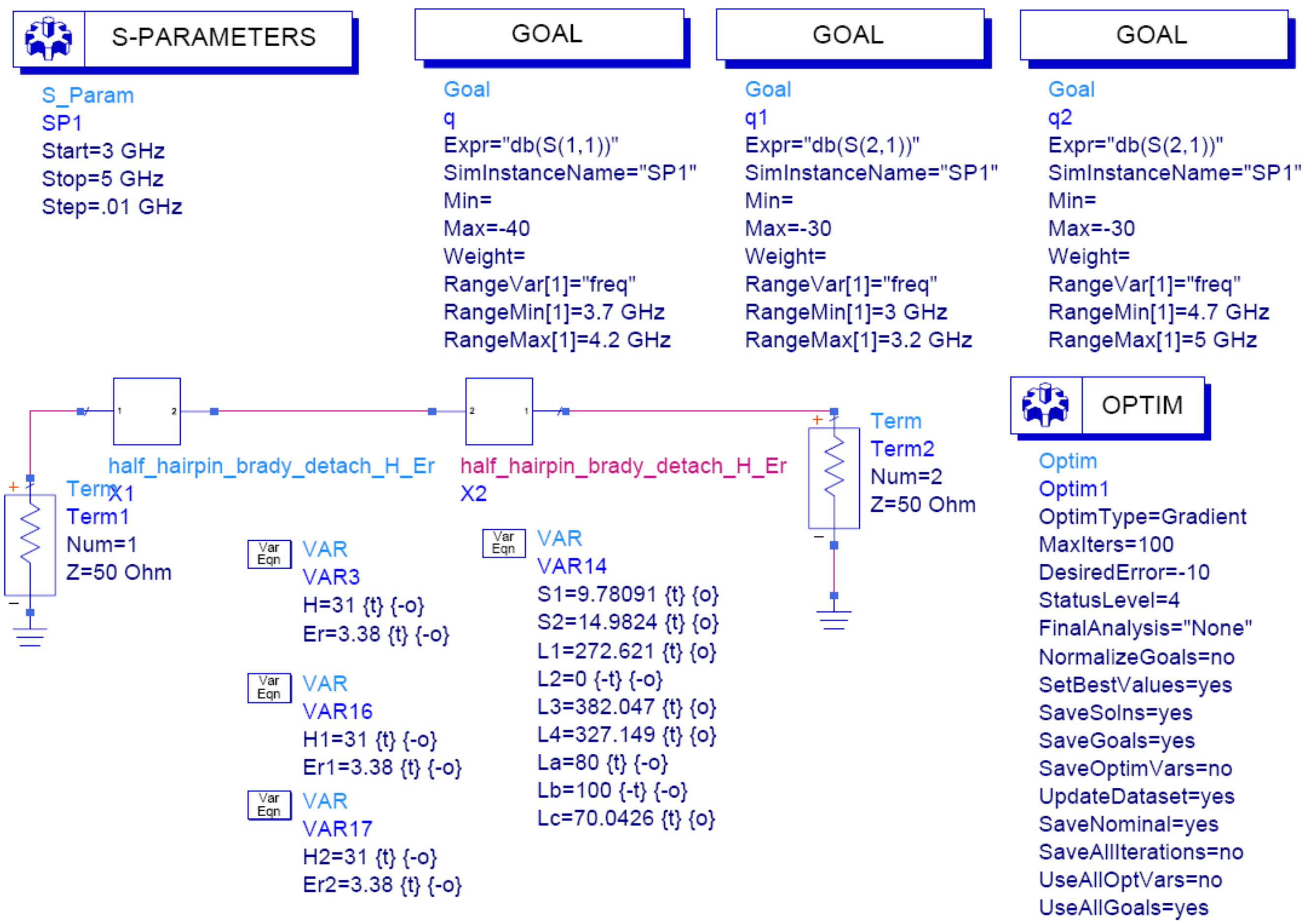
Microstrip Hairpin Filter: Implicit SM (*Cheng et al., 2008*)

coarse model ("half" implementation, *Brady, 2002*)



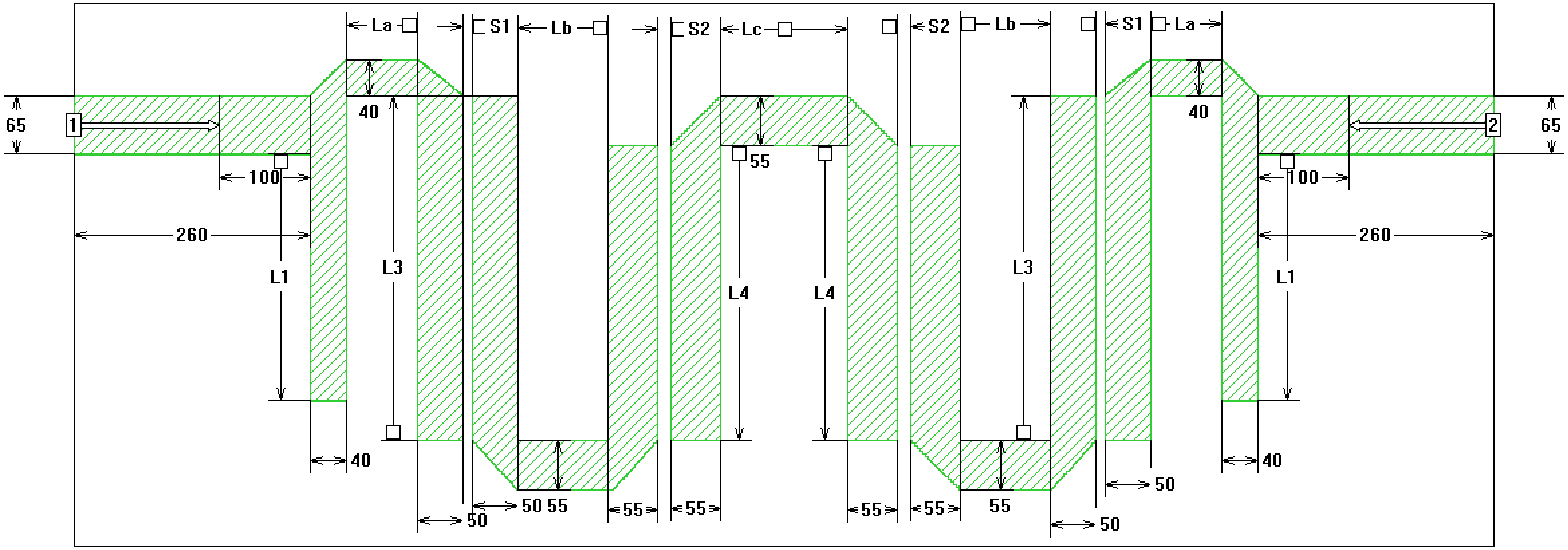
Microstrip Hairpin Filter: Implicit SM (*Cheng et al., 2008*)

coarse model optimization



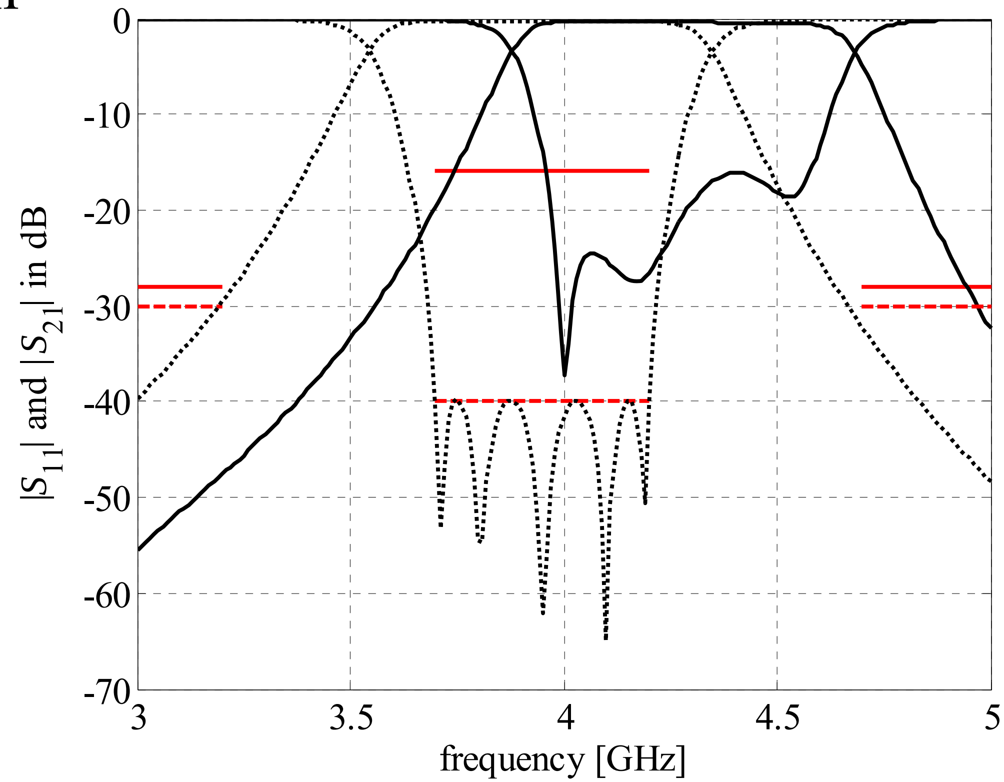
Microstrip Hairpin Filter: Implicit SM (*Cheng et al., 2008*)

fine model in Sonnet ***em***



Microstrip Hairpin Filter: Implicit SM (*Cheng et al., 2008*)

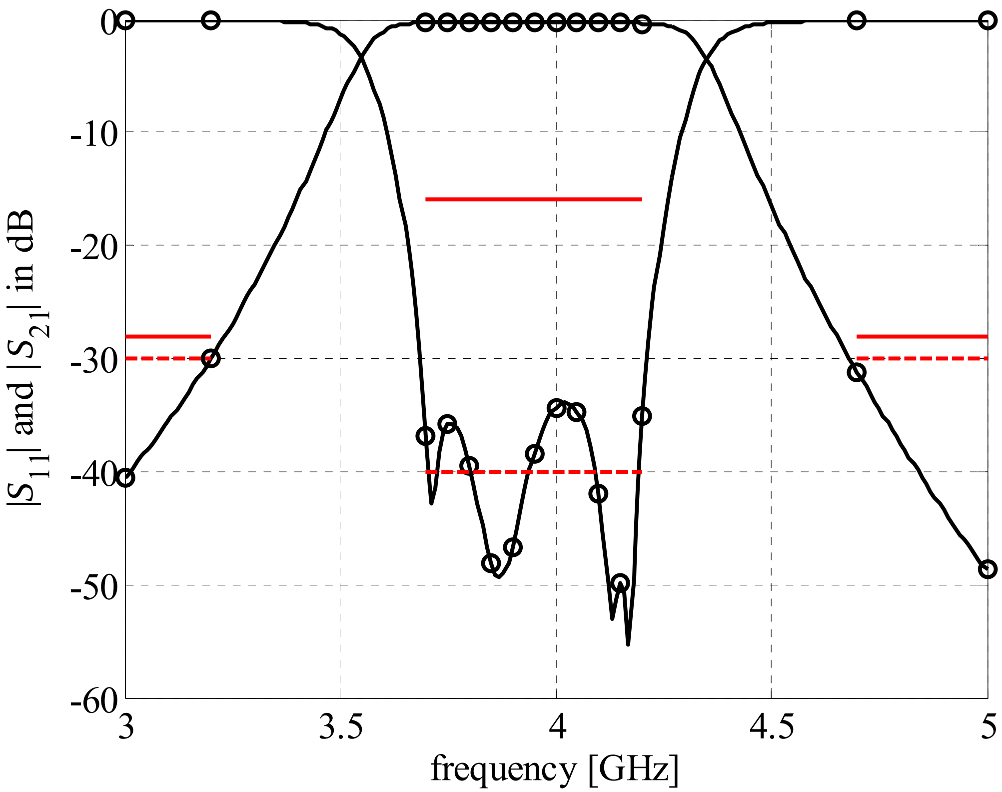
initial design



coarse model optimal (**---**) and fine model initial (—)
desired specification (—) and the tightened specification (**---**)

Microstrip Hairpin Filter: Implicit SM (*Cheng et al., 2008*)

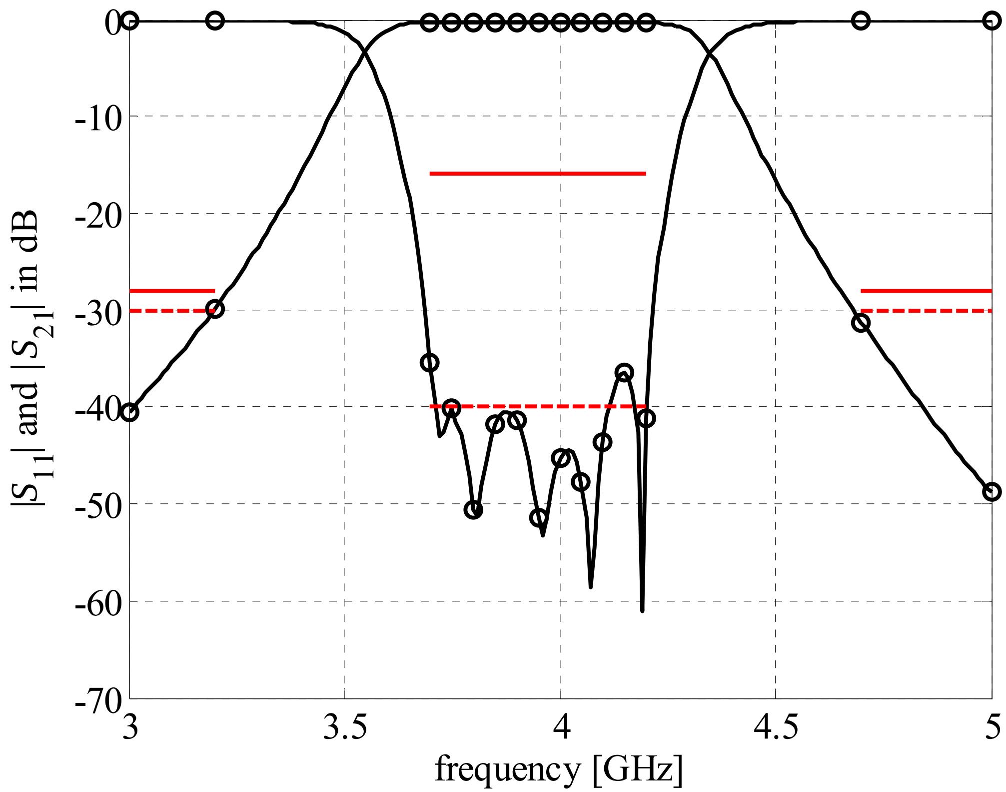
fine model responses after 3 implicit SM iterations



desired specification (—) and the tightened specification (---)

Microstrip Hairpin Filter: Implicit SM (*Cheng et al., 2008*)

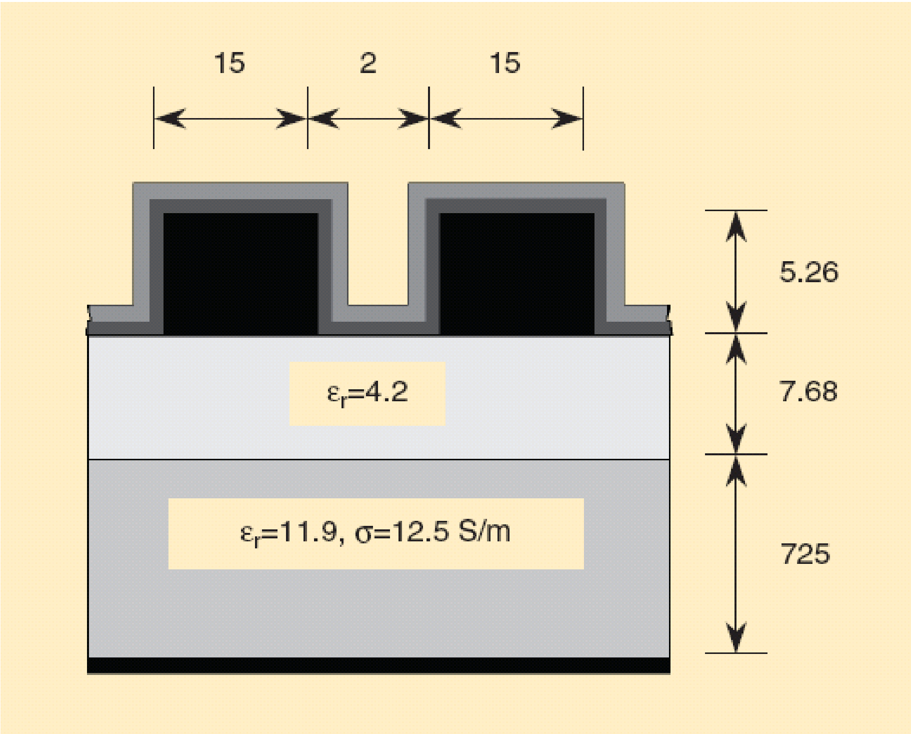
fine model after 3 implicit SM iterations and one output SM



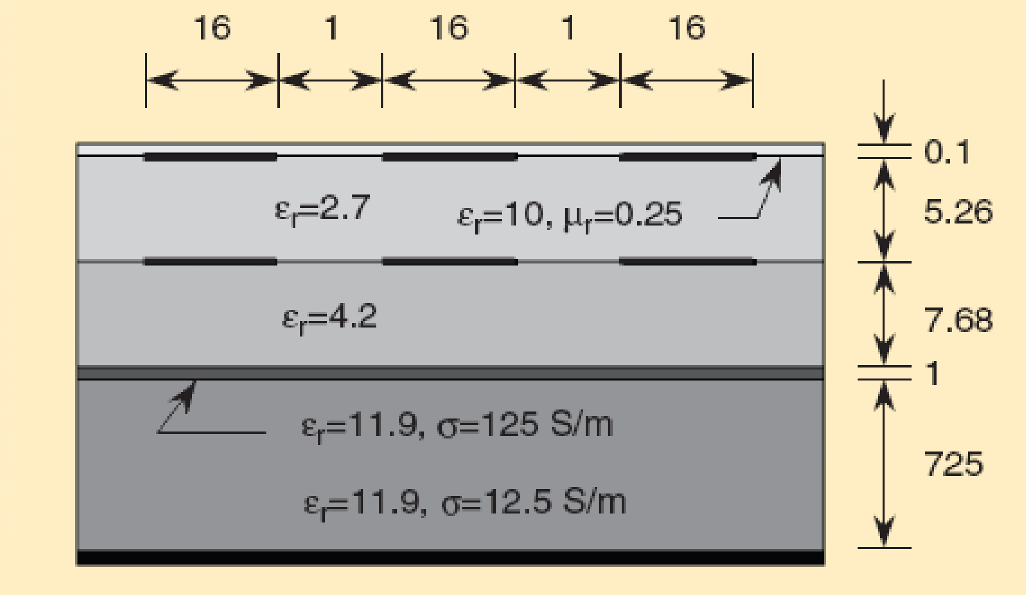
desired specification (—) and the tightened specification (---)

Implicit Space Mapping Design of Thick, Tightly Coupled Conductors (*Rautio, 2004, Sonnet Software*)

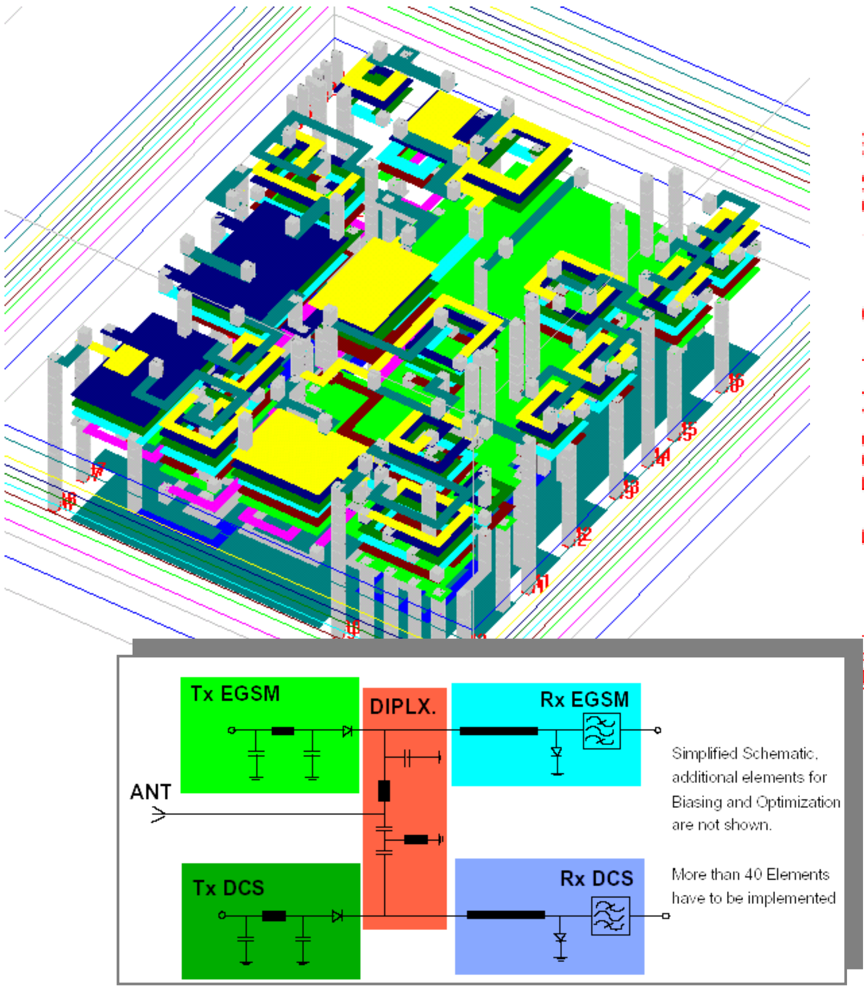
thick, closely spaced conductors
on silicon (fine model)

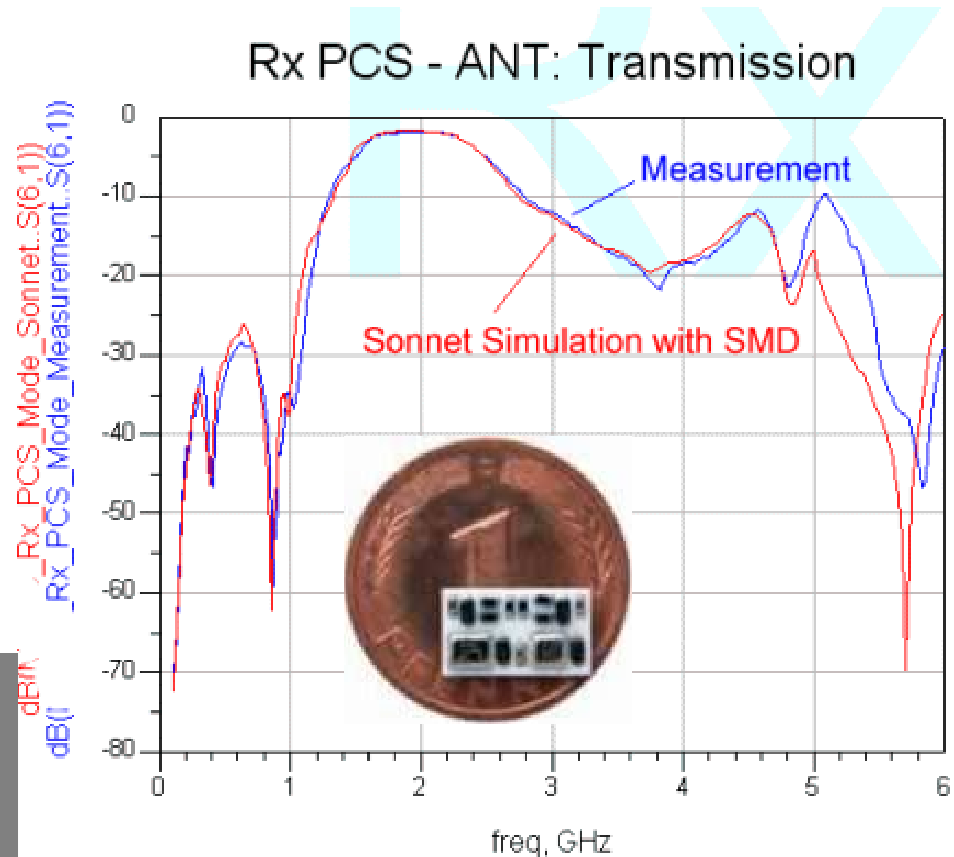


"space-mapping" (top) layer
(coarse model)



EPCOS LTCC/Feb 04 (*Rautio, 2006, Sonnet Software*)





(*courtesy Rautio, 2006*)

SMF: A User-friendly Space Mapping Software Engine
(*Bandler Corp., 2006, Koziel and Bandler, 2007*)

SMF: for SM-based constrained optimization, modeling and statistical analysis

to make space mapping accessible to engineers inexperienced in the art

to incorporate existing space mapping approaches in one package

implementation: a GUI based Matlab package

simulators sockets: Agilent ADS, Sonnet ***em***, FEKO, MEFiSTo, Ansoft Maxwell, Ansoft HFSS

SMF Uses a General Space Mapping Surrogate Model

surrogate model $\boldsymbol{R}_s^{(i)}$ at iteration i

$$\boldsymbol{R}_s^{(i)}(\boldsymbol{x}) = \boldsymbol{A}^{(i)} \cdot \boldsymbol{R}_c(\boldsymbol{B}^{(i)} \cdot \boldsymbol{x} + \boldsymbol{c}^{(i)}, \boldsymbol{G}^{(i)} \cdot \boldsymbol{x} + \boldsymbol{x}_p^{(i)}) + \boldsymbol{d}^{(i)} + \boldsymbol{E}^{(i)} \cdot (\boldsymbol{x} - \boldsymbol{x}^{(i)})$$

where $\boldsymbol{A}^{(i)}$, $\boldsymbol{B}^{(i)}$, $\boldsymbol{c}^{(i)}$, $\boldsymbol{x}_p^{(i)}$ and $\boldsymbol{G}^{(i)}$ are determined using parameter extraction

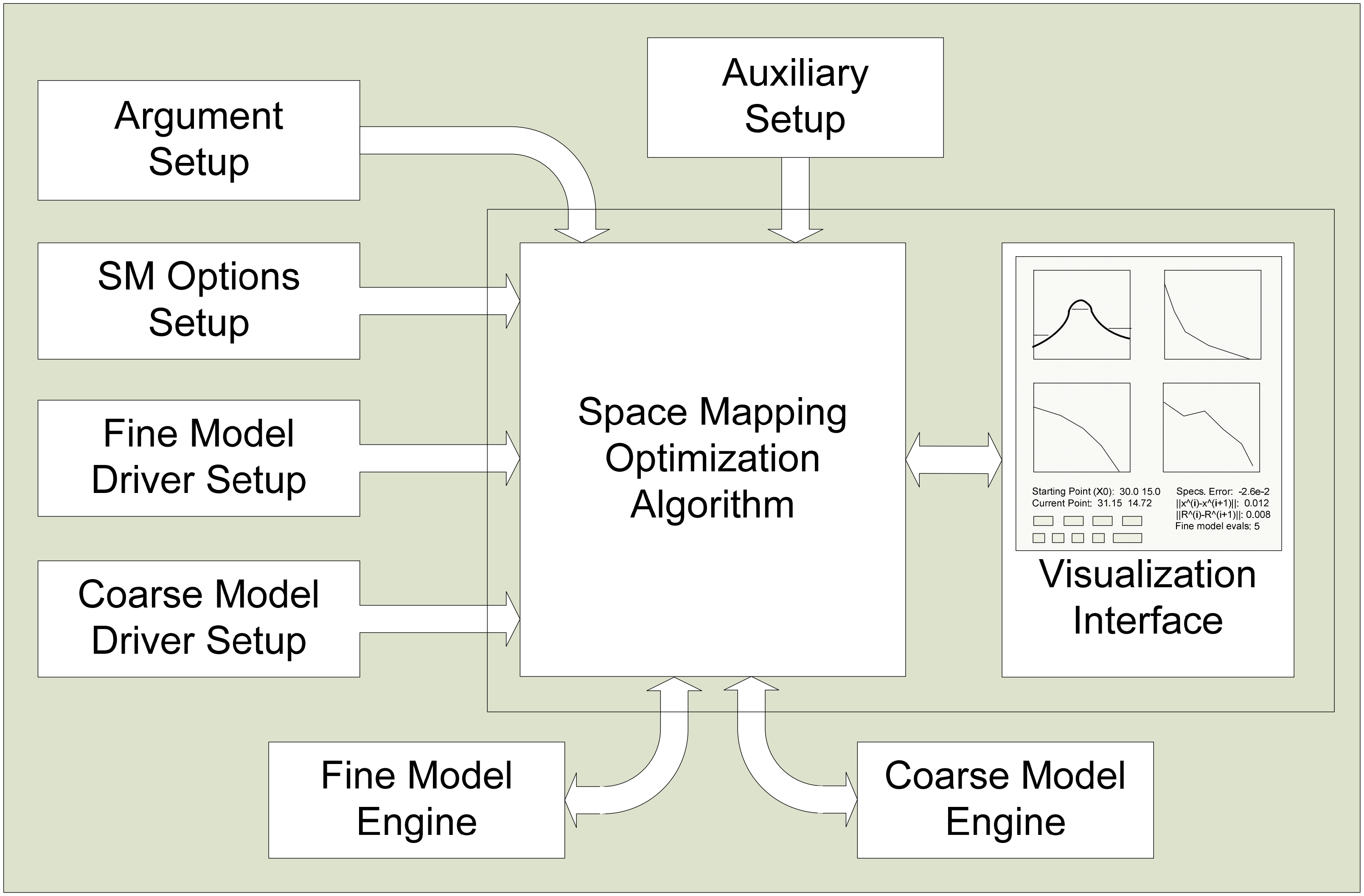
$$(\boldsymbol{A}^{(i)}, \boldsymbol{B}^{(i)}, \boldsymbol{c}^{(i)}, \boldsymbol{x}_p^{(i)}, \boldsymbol{G}^{(i)}) = \arg \min_{(\boldsymbol{A},\boldsymbol{B},\boldsymbol{c},\boldsymbol{x}_p,\boldsymbol{G})} \sum_{k=0}^{i} w_k \| \boldsymbol{R}_f(\boldsymbol{x}^{(k)})$$
$$- \boldsymbol{A} \cdot \boldsymbol{R}_c(\boldsymbol{B} \cdot \boldsymbol{x}^{(k)} + \boldsymbol{c}, \boldsymbol{G} \cdot \boldsymbol{x}^{(k)} + \boldsymbol{x}_p) \|$$
$$+ \sum_{k=0}^{i} v_k \| \boldsymbol{J}_{\boldsymbol{R}_f}(\boldsymbol{x}^{(k)}) - \boldsymbol{J}_{\boldsymbol{R}_s}(\boldsymbol{B} \cdot \boldsymbol{x}^{(k)} + \boldsymbol{c}, \boldsymbol{G} \cdot \boldsymbol{x}^{(k)} + \boldsymbol{x}_p) \|$$

and

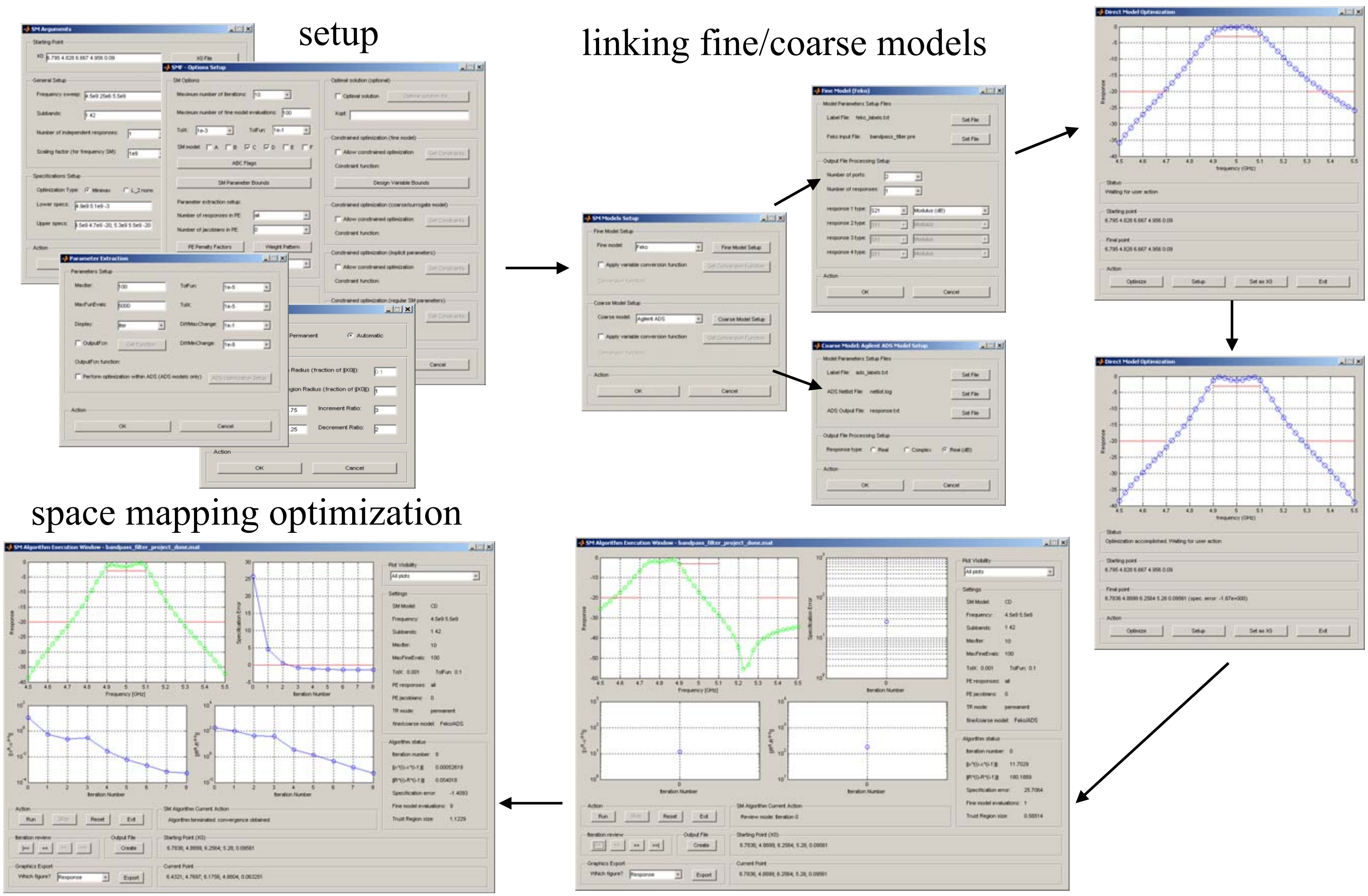
$$\boldsymbol{d}^{(i)} = \boldsymbol{R}_f(\boldsymbol{x}^{(i)}) - \boldsymbol{A}^{(i)} \cdot \boldsymbol{R}_c(\boldsymbol{B}^{(i)} \cdot \boldsymbol{x}^{(i)} + \boldsymbol{c}^{(i)}, \boldsymbol{G}^{(i)} \cdot \boldsymbol{x}^{(i)} + \boldsymbol{x}_p^{(i)})$$

$$\boldsymbol{E}^{(i)} = \boldsymbol{J}_{\boldsymbol{R}_f}(\boldsymbol{x}^{(i)}) - \boldsymbol{J}_{\boldsymbol{R}_s}(\boldsymbol{B}^{(i)} \cdot \boldsymbol{x}^{(i)} + \boldsymbol{c}^{(i)}, \boldsymbol{G}^{(i)} \cdot \boldsymbol{x}^{(i)} + \boldsymbol{x}_p^{(i)})$$

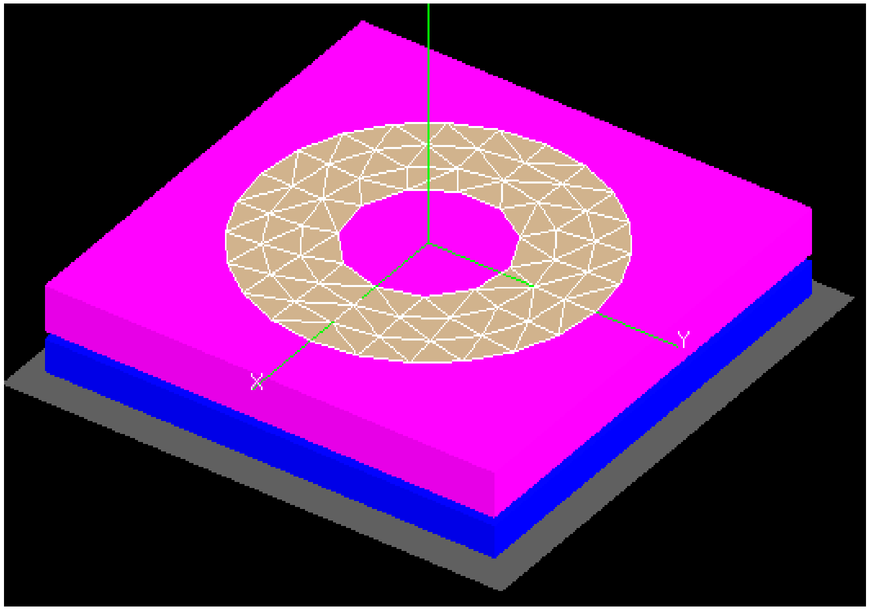
SMF: Optimization Flowchart (*Bandler Corp., 2006*)



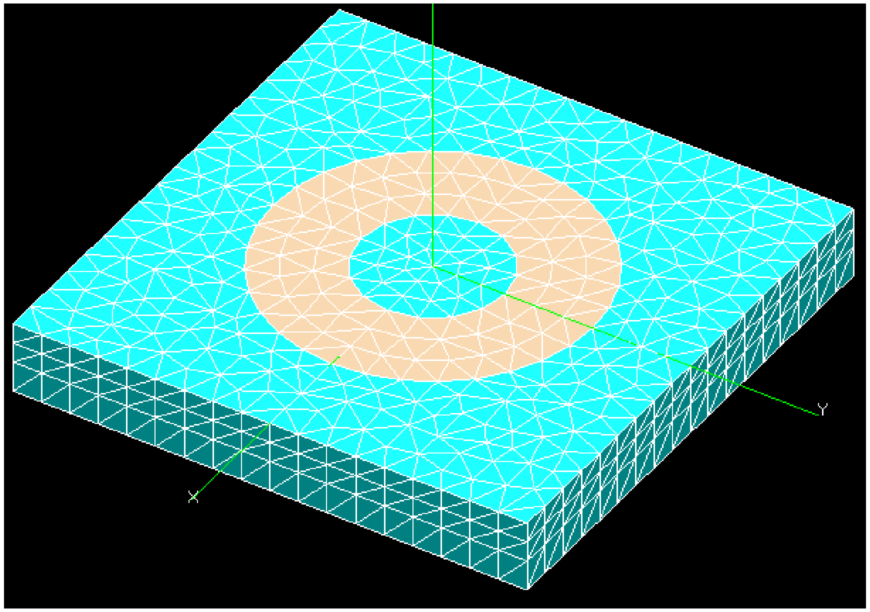
SMF: Optimization Flow



SMF Optimization of Probe-Fed Printed Double Annular Ring Antenna with Finite Ground (*Zhu et al., 2006*)

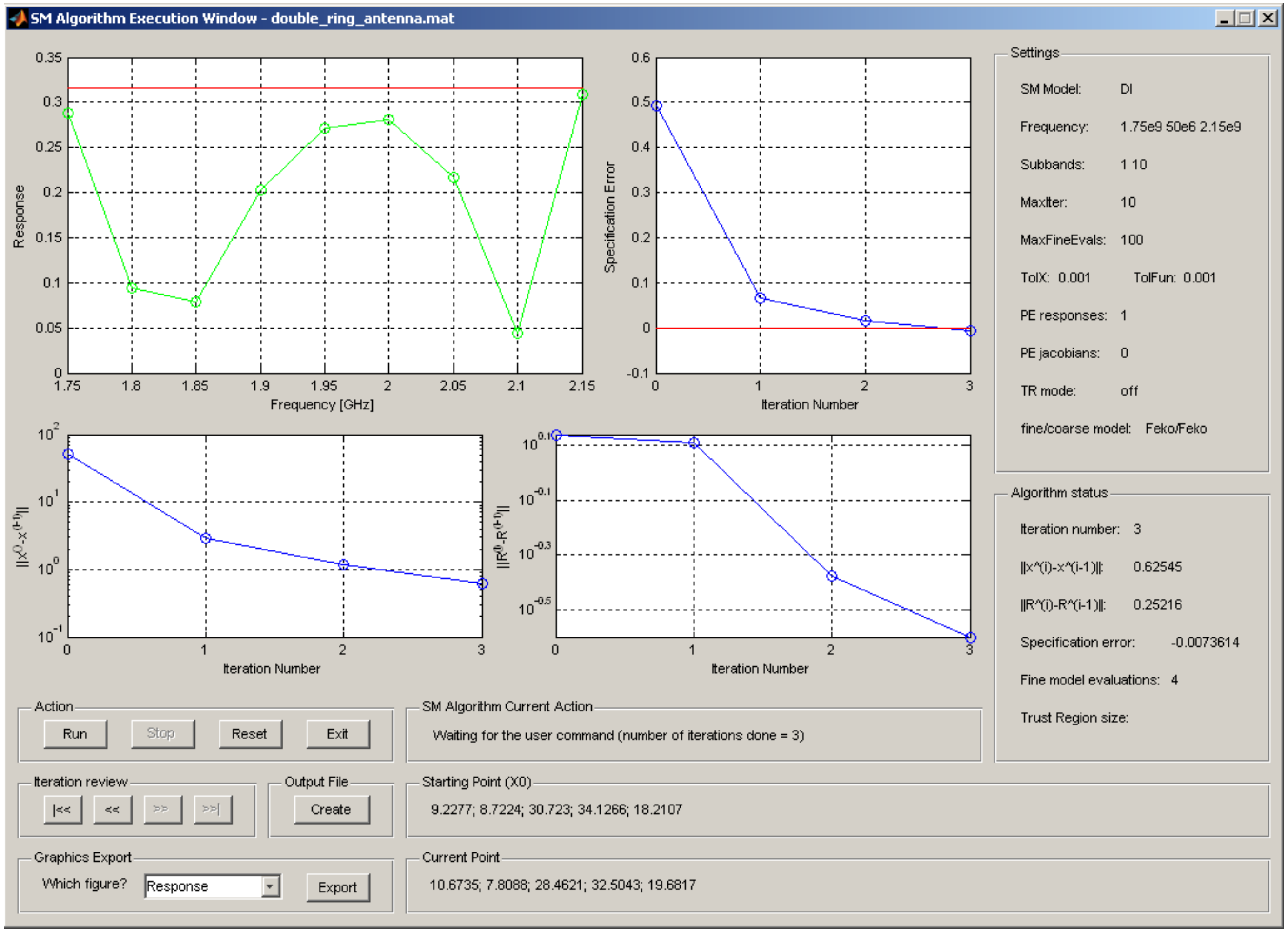


coarse model (FEKO)



fine model (FEKO)

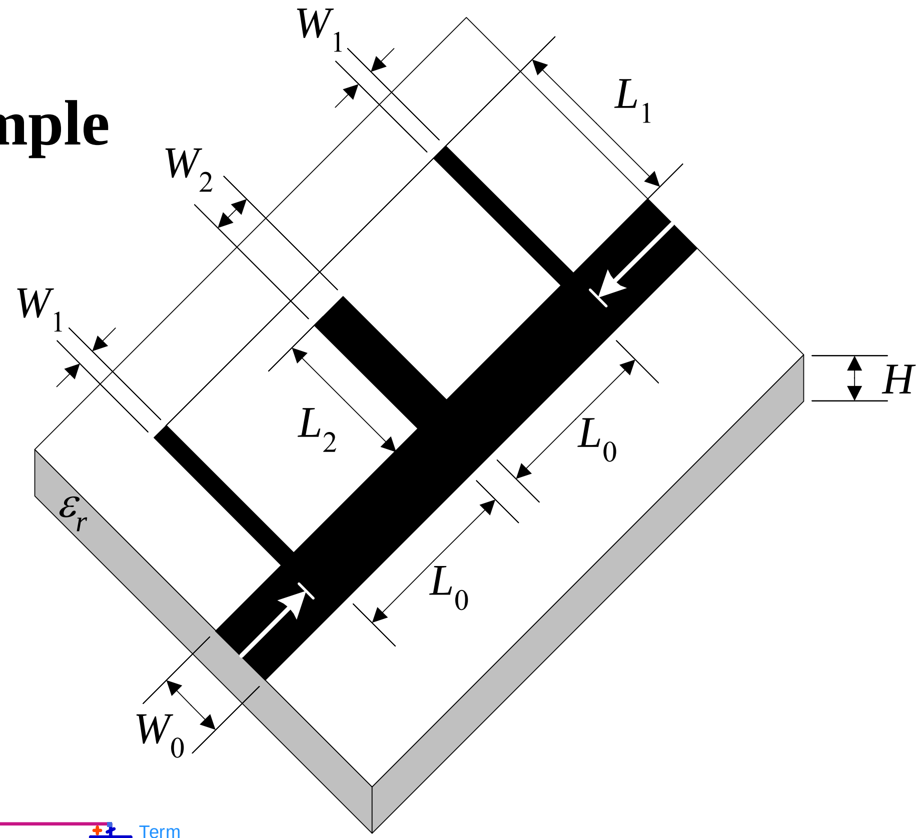
SMF Optimization of Probe-Fed Printed Double Annular Ring Antenna with Finite Ground (*Zhu et al., 2006*)



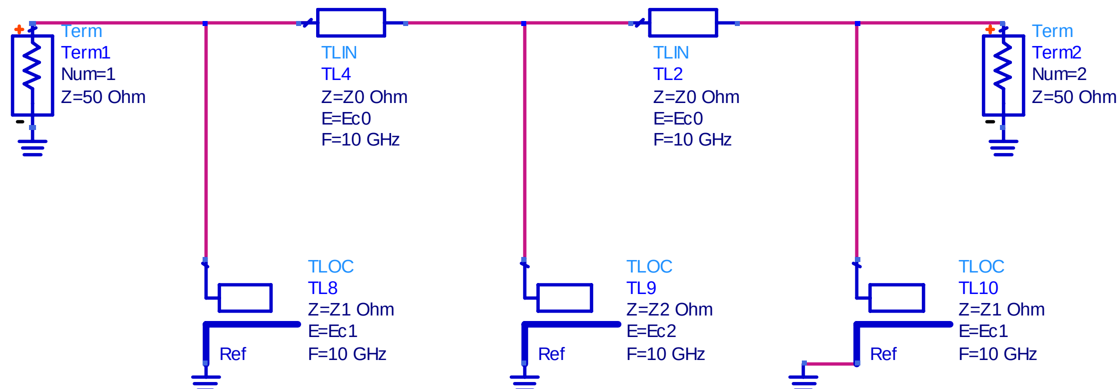
Bandstop Microstrip Filter Example

(*Bandler et al., 2000*)

fine model (Sonnet ***em***)



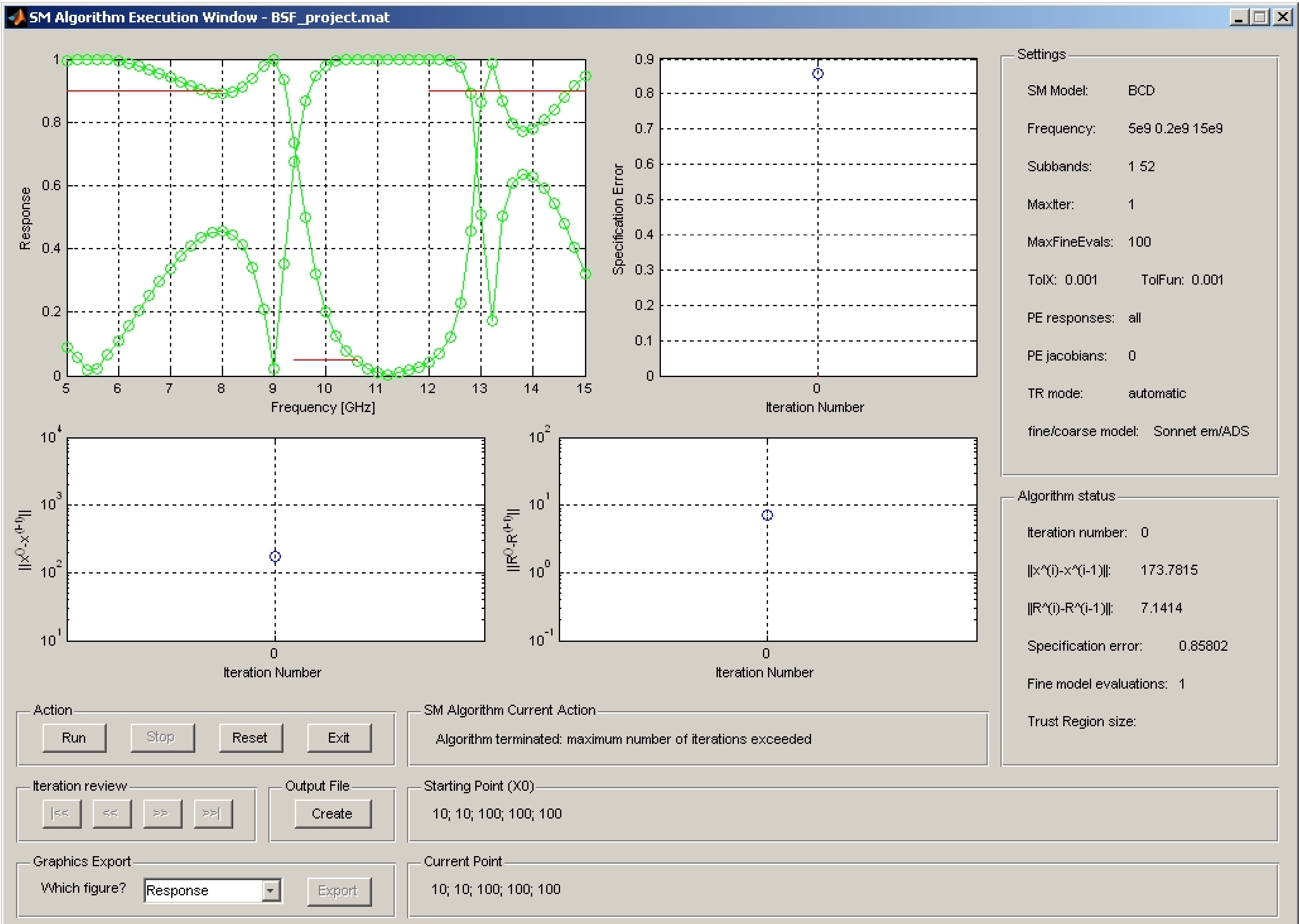
coarse model (Agilent ADS)



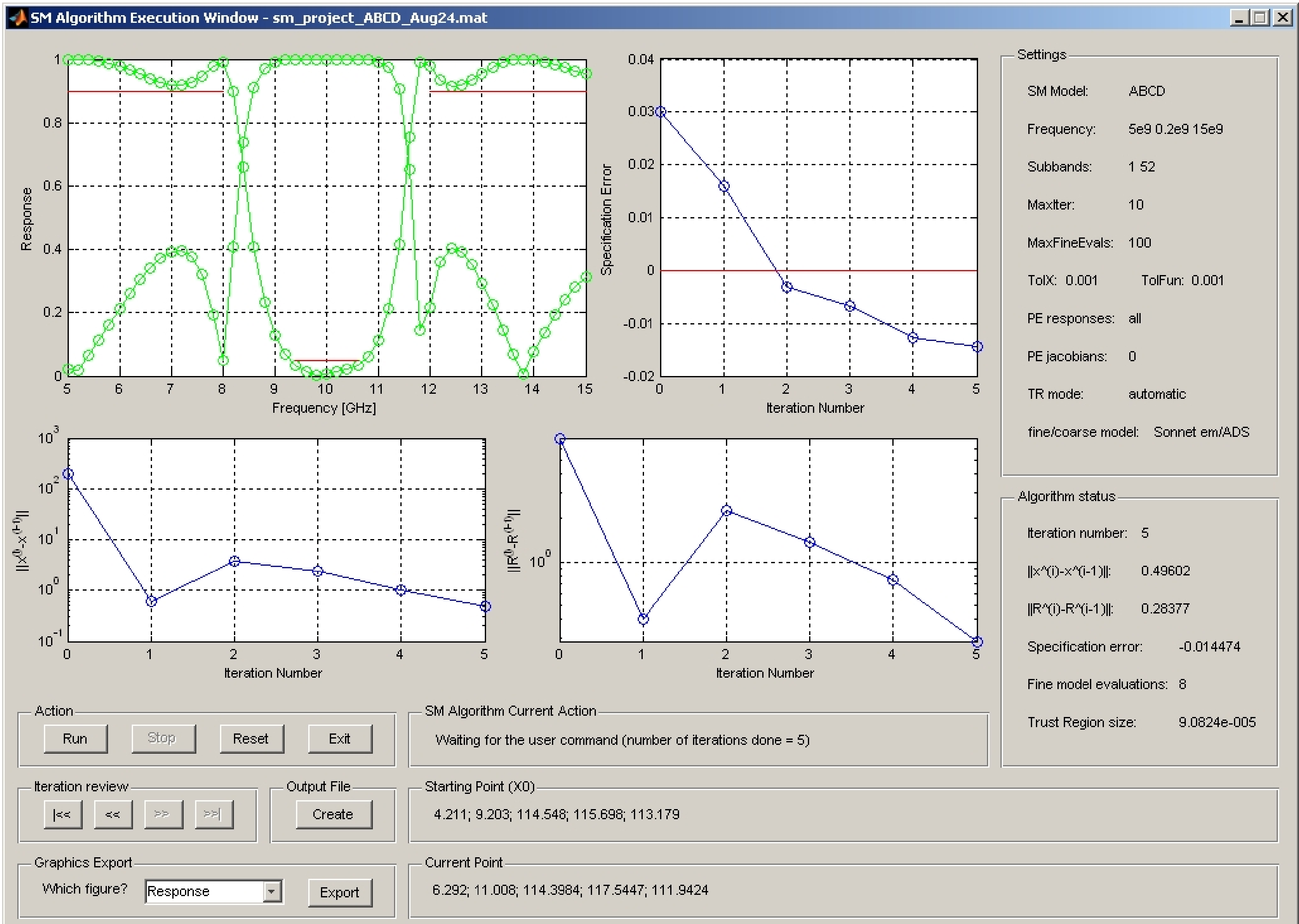
design specs: $|S_{21}| \leq 0.05$ for $9.3 \text{ GHz} \leq \omega \leq 10.7 \text{ GHz}$

$|S_{21}| \geq 0.9$ for $\omega \leq 8$ GHz and $\omega \geq 12$ GHz

SMF Bandstop Microstrip Filter Optimization: Starting Point

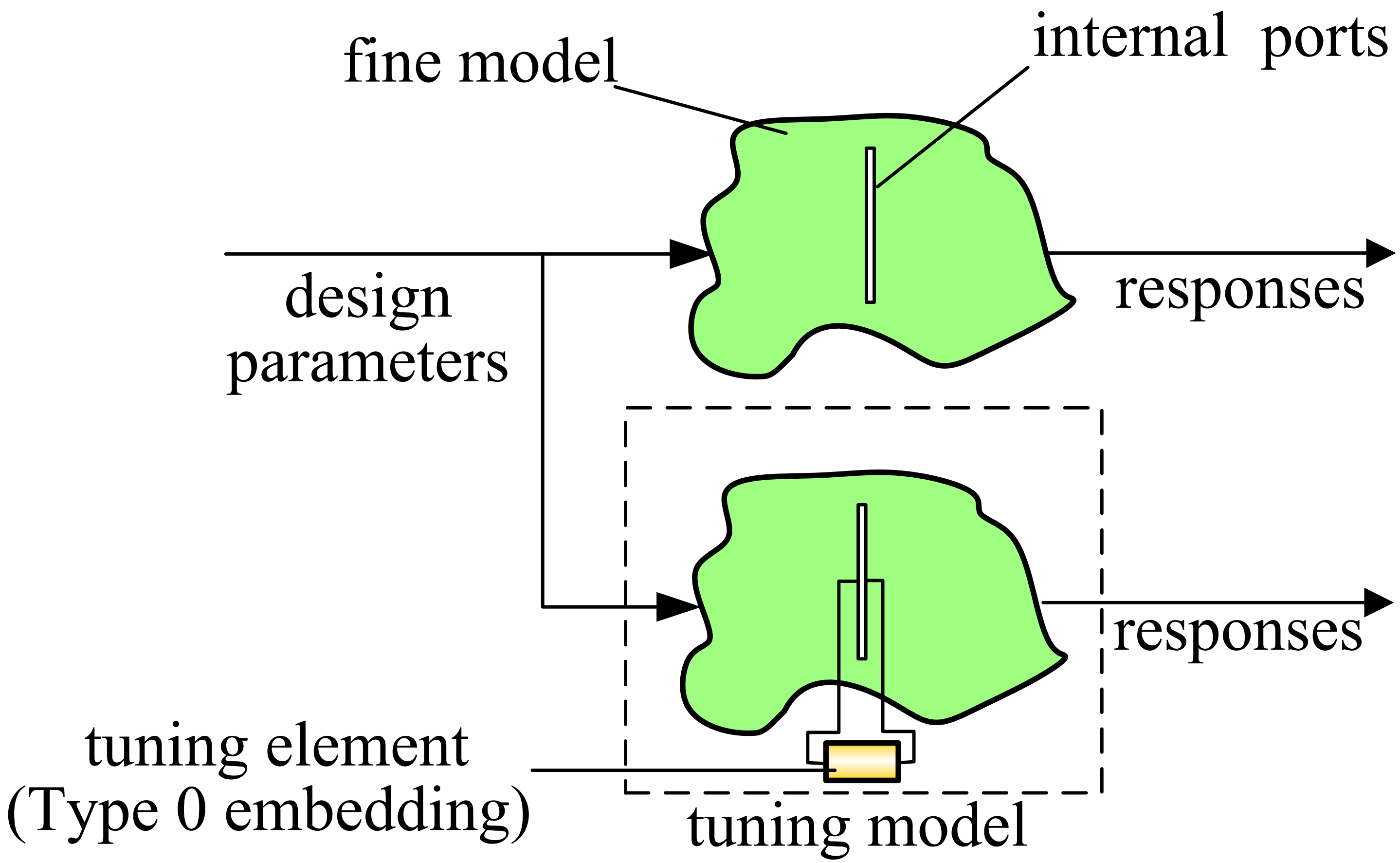


SMF Bandstop Microstrip Filter Optimization: Solution



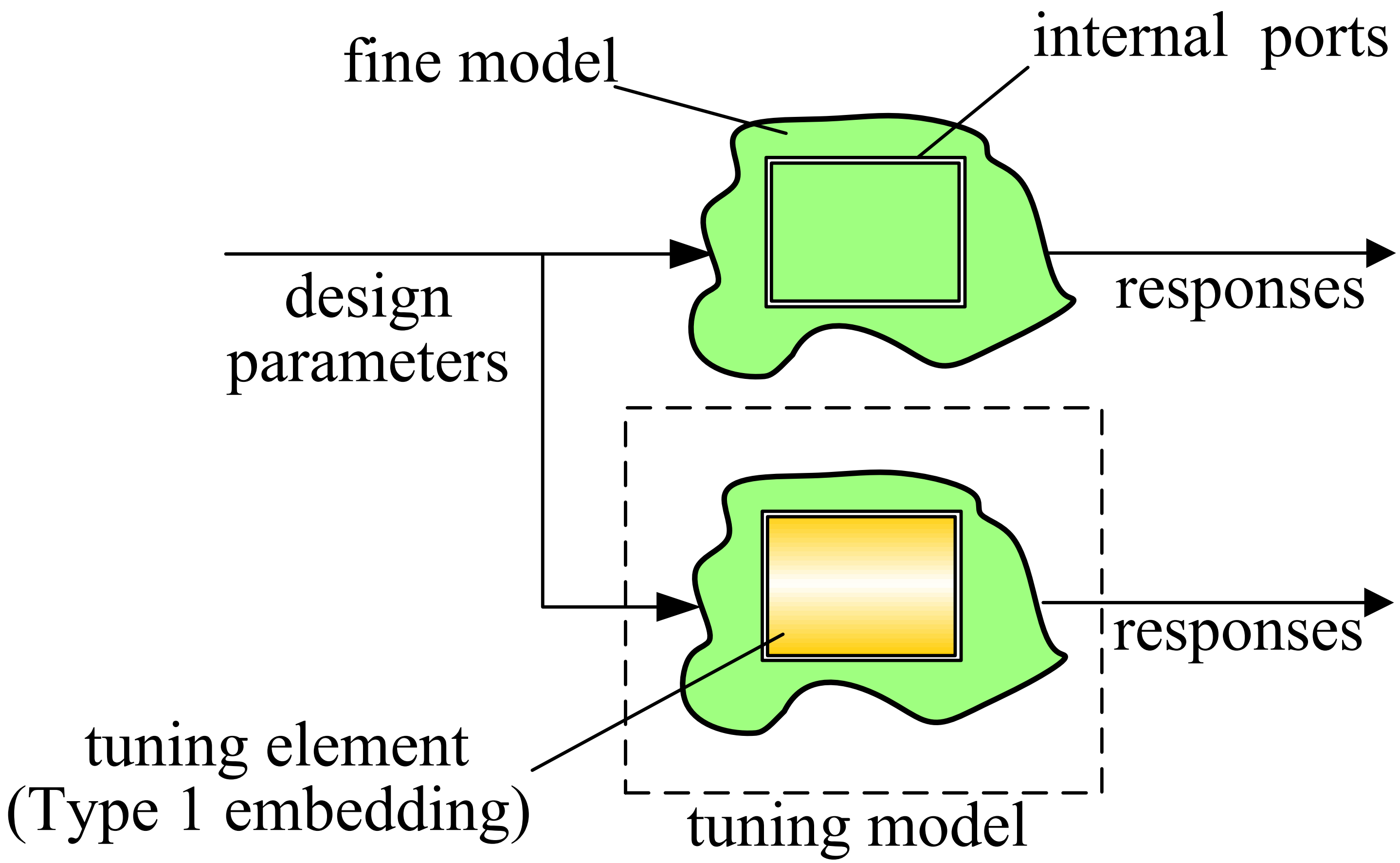
Tuning Space Mapping (TSM): Type 0 Embedding

(*Koziel et al., 2009*)



surrogate based on the auxiliary fine model (fine model with internal tuning ports); it is an expert approach

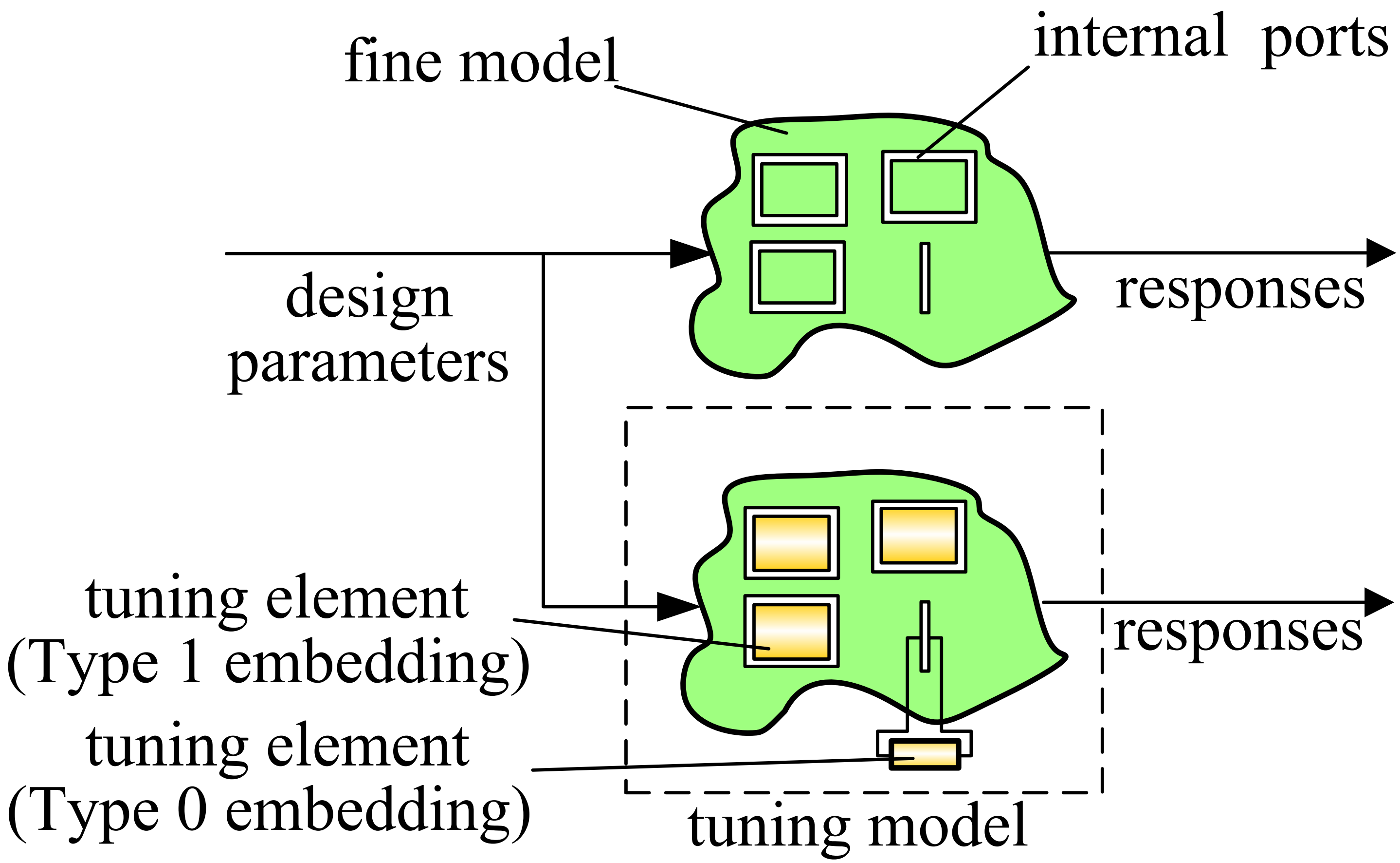
Tuning Space Mapping (TSM): Type 1 Embedding
(*Cheng et al., 2009*)



surrogate based on the auxiliary fine model (fine model with internal tuning ports); it is an expert approach

Tuning Space Mapping (TSM): Type 1 and Type 0 Embedding

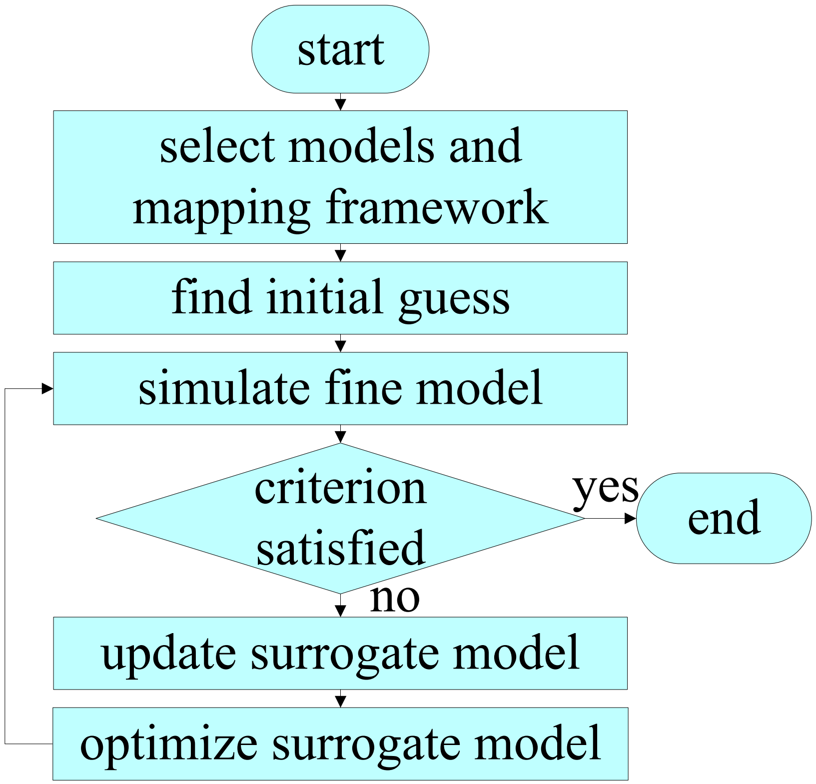
(*Cheng et al., 2009*)



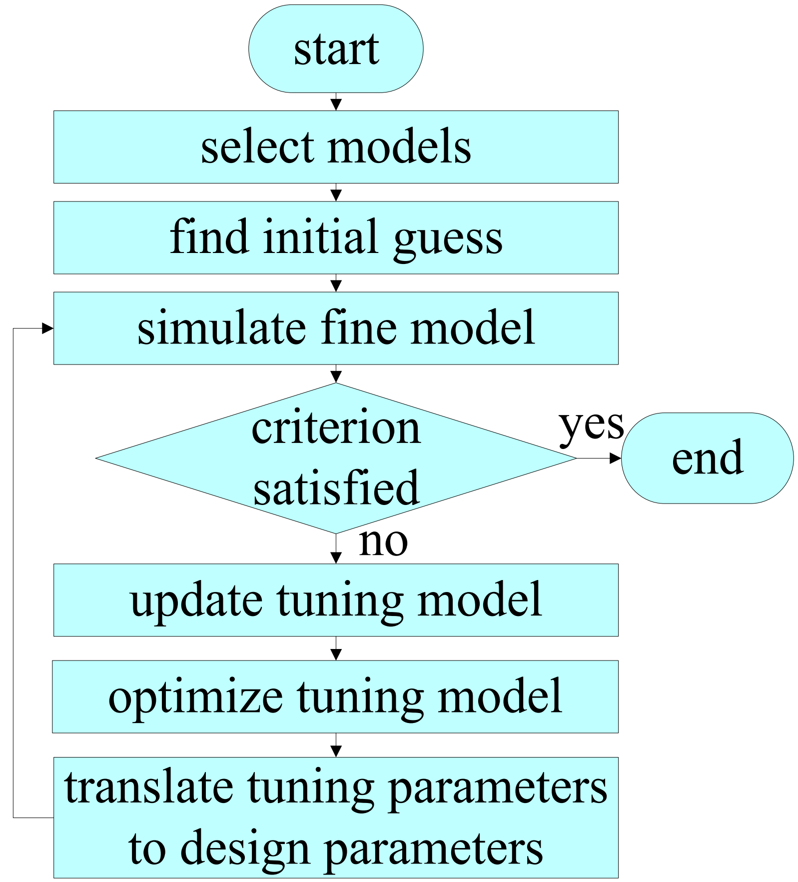
surrogate based on the auxiliary fine model (fine model with internal tuning ports); it is an expert approach

Tuning Space Mapping Flowchart

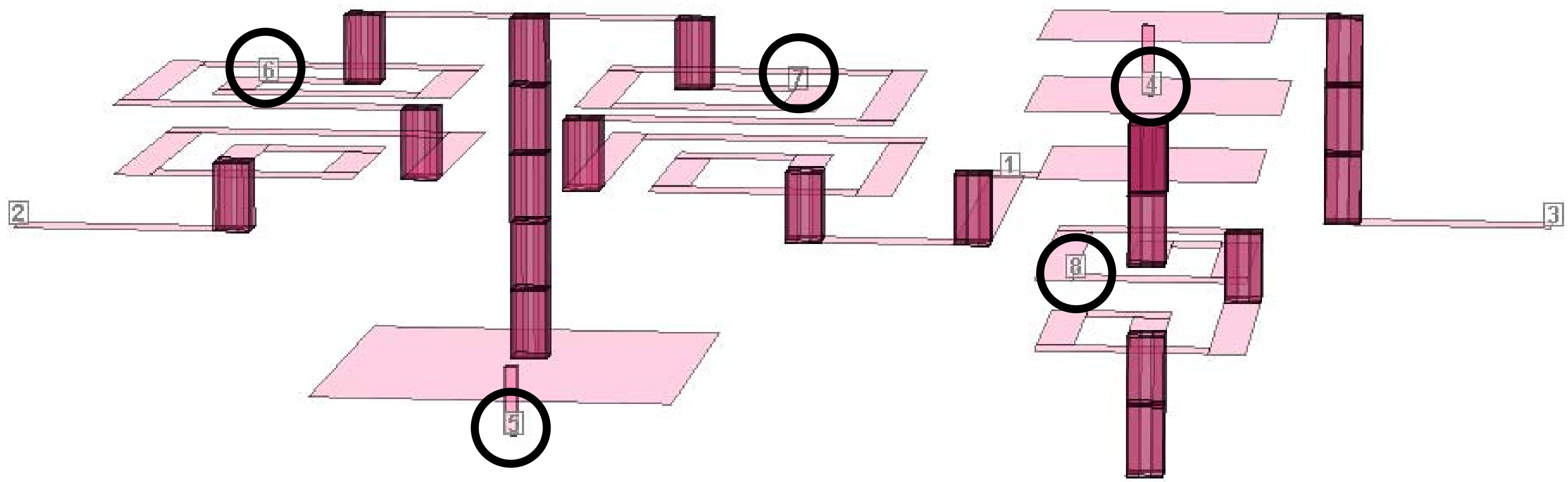
Classical Space Mapping
(*Bandler et al., 2004*)



Tuning Space Mapping
(*Koziel et al., 2008*)



Tuning Methodology (*Rautio, 2005, Sonnet Software*)



circled ports are tuning ports:

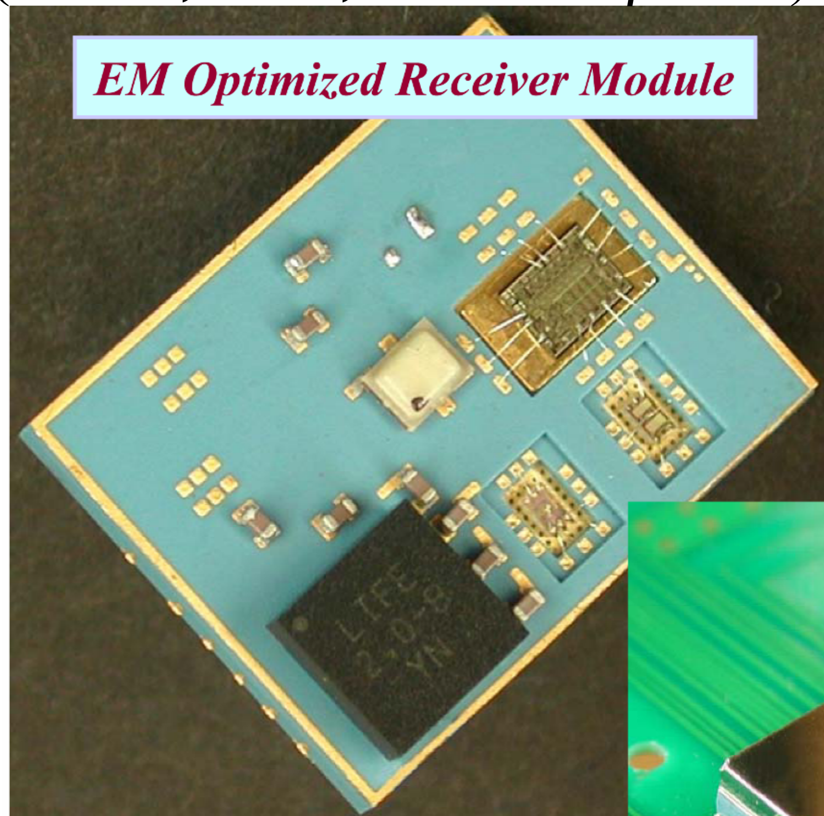
in series with inductors

in shunt with capacitors

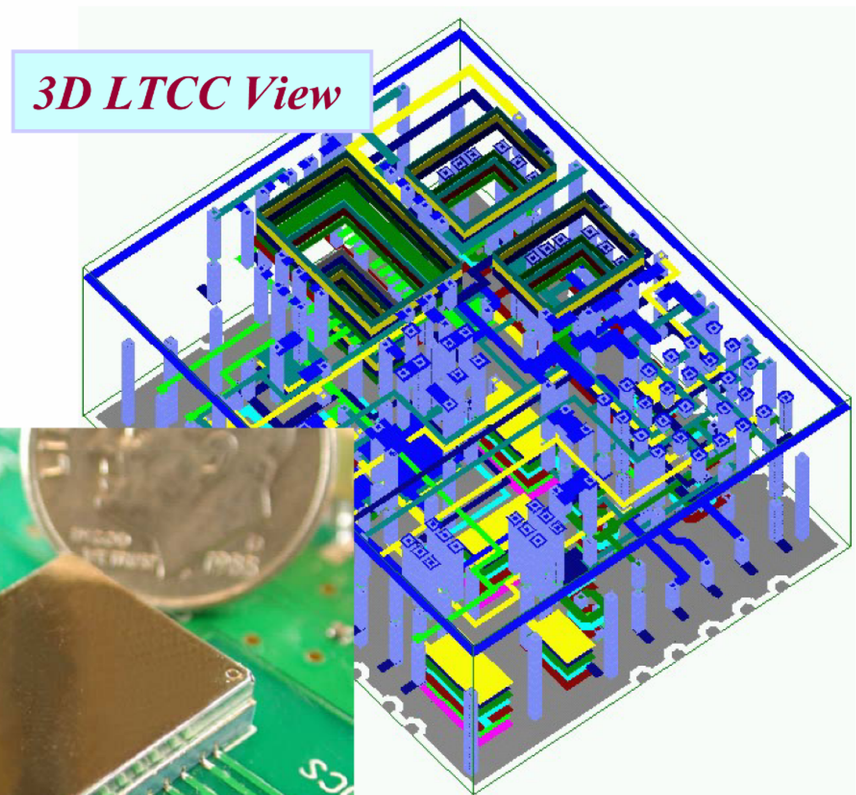
(*courtesy Rautio, 2006*)

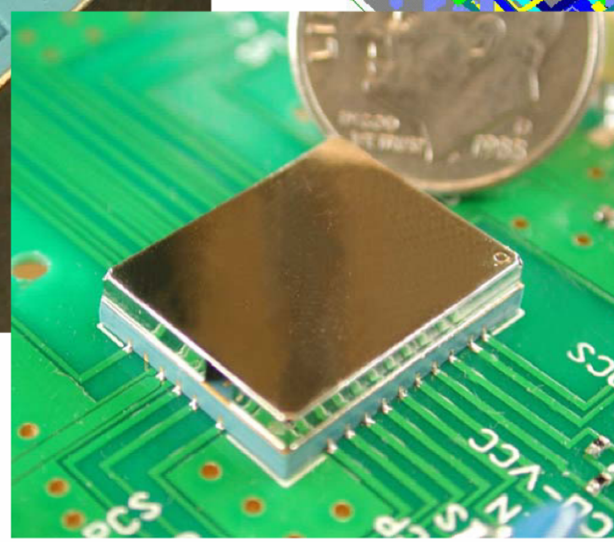
Motorola LTCC Quad Band Receiver

(*Rautio, 2006, Sonnet Software*)



Full Performance in a *Single* Design Pass

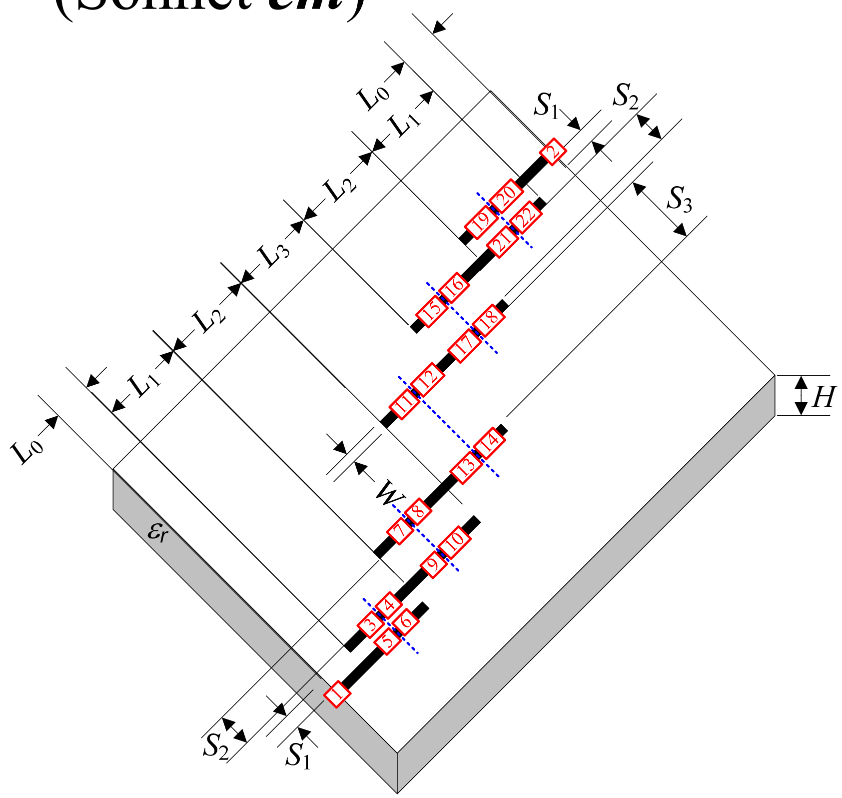




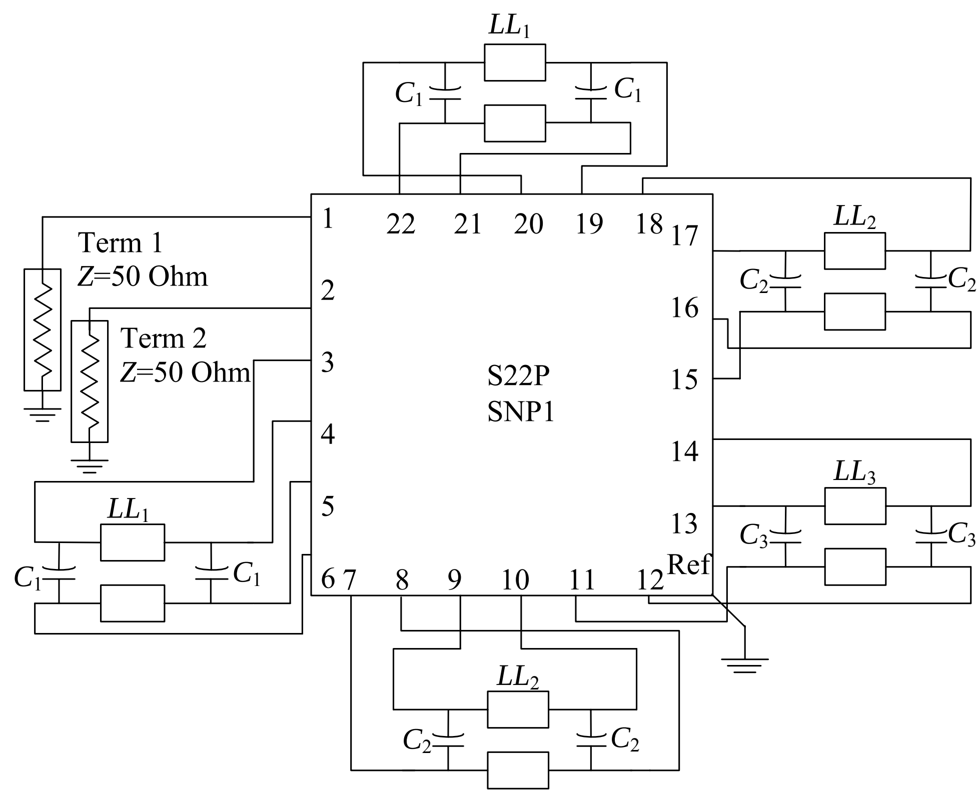
(*courtesy Rautio, 2006*)

Tuning Space Mapping Optimization of HTS Filter (Type 0)
(*Koziel, Meng, Bandler, Bakr, and Cheng, 2009*)

fine model (*Westinghouse, 1993*) with added tuning ports (Sonnet ***em***)



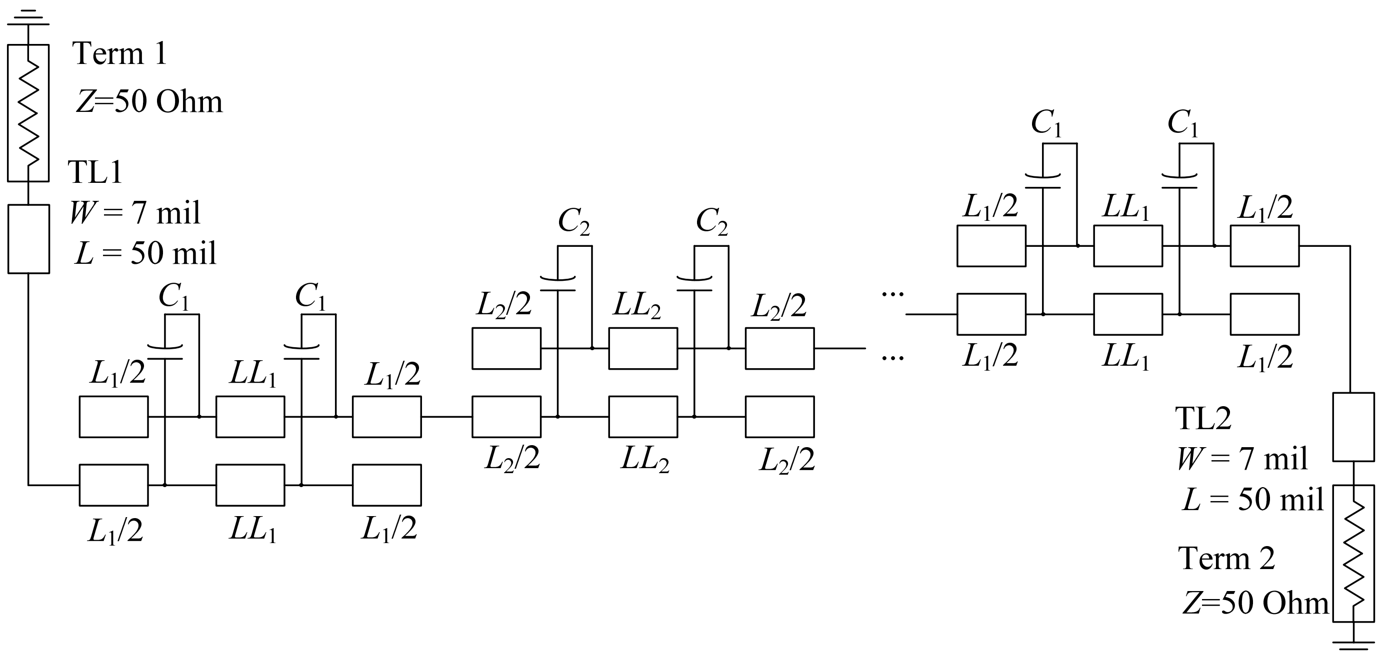
tuning model in ADS with circuit components



Tuning Space Mapping **Optimization of HTS Filter (Type 0)**

(*Koziel, Meng, Bandler, Bakr, and Cheng, 2009*)

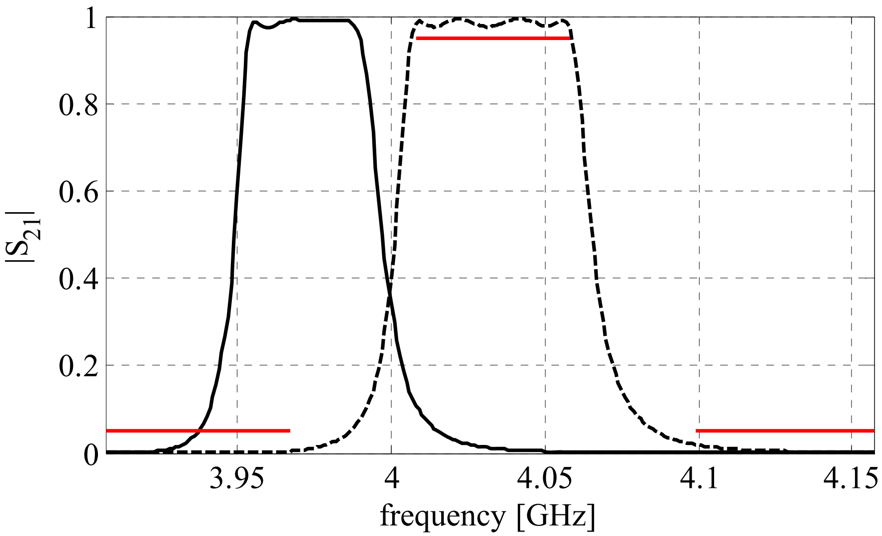
<u>calibration model</u> = <u>coarse model</u> + <u>tuning elements</u>



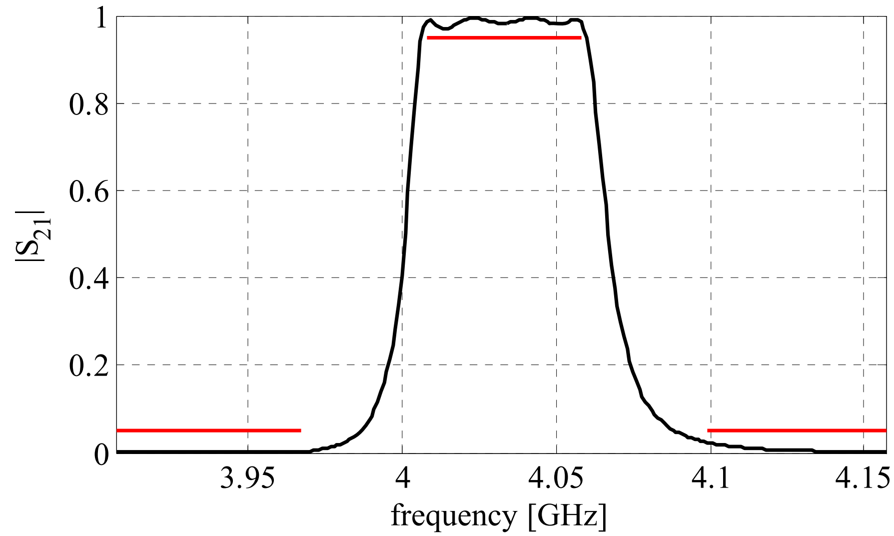
<u>calibration goal</u>: translate the "tuned" tuning parameter values to physical design parameter values

Tuning Space Mapping Optimization of HTS Filter (Type 0)
(*Koziel, Meng, Bandler, Bakr, and Cheng, 2009*)

initial fine model response (—)
optimized tuning model (---)

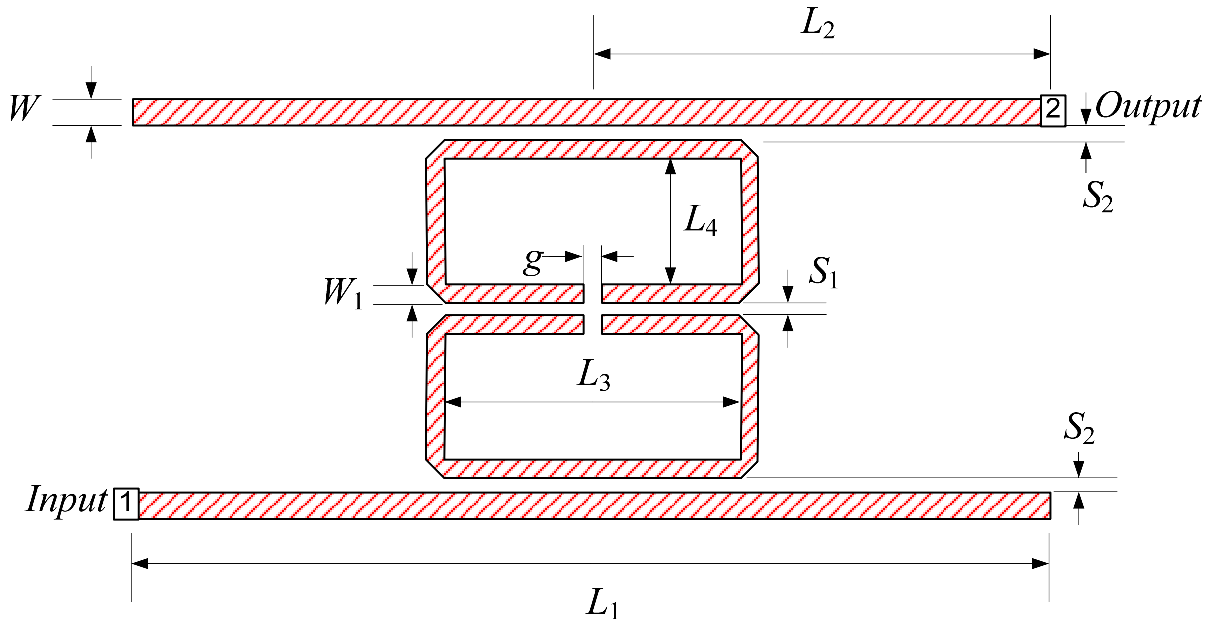


final fine model response
after two TSM iterations



responses from Sonnet ***em*** and Agilent ADS

Open-loop Ring Resonator Bandpass Filter (*Koziel et al., 2008*)



design parameters

$\boldsymbol{x} = [L_1\ \ L_2\ \ L_3\ \ L_4\ \ S_1\ \ S_2\ \ g]^T$ mm

specifications

$|S_{21}| \geq -3$ dB for 2.8 GHz $\leq \omega \leq$ 3.2 GHz

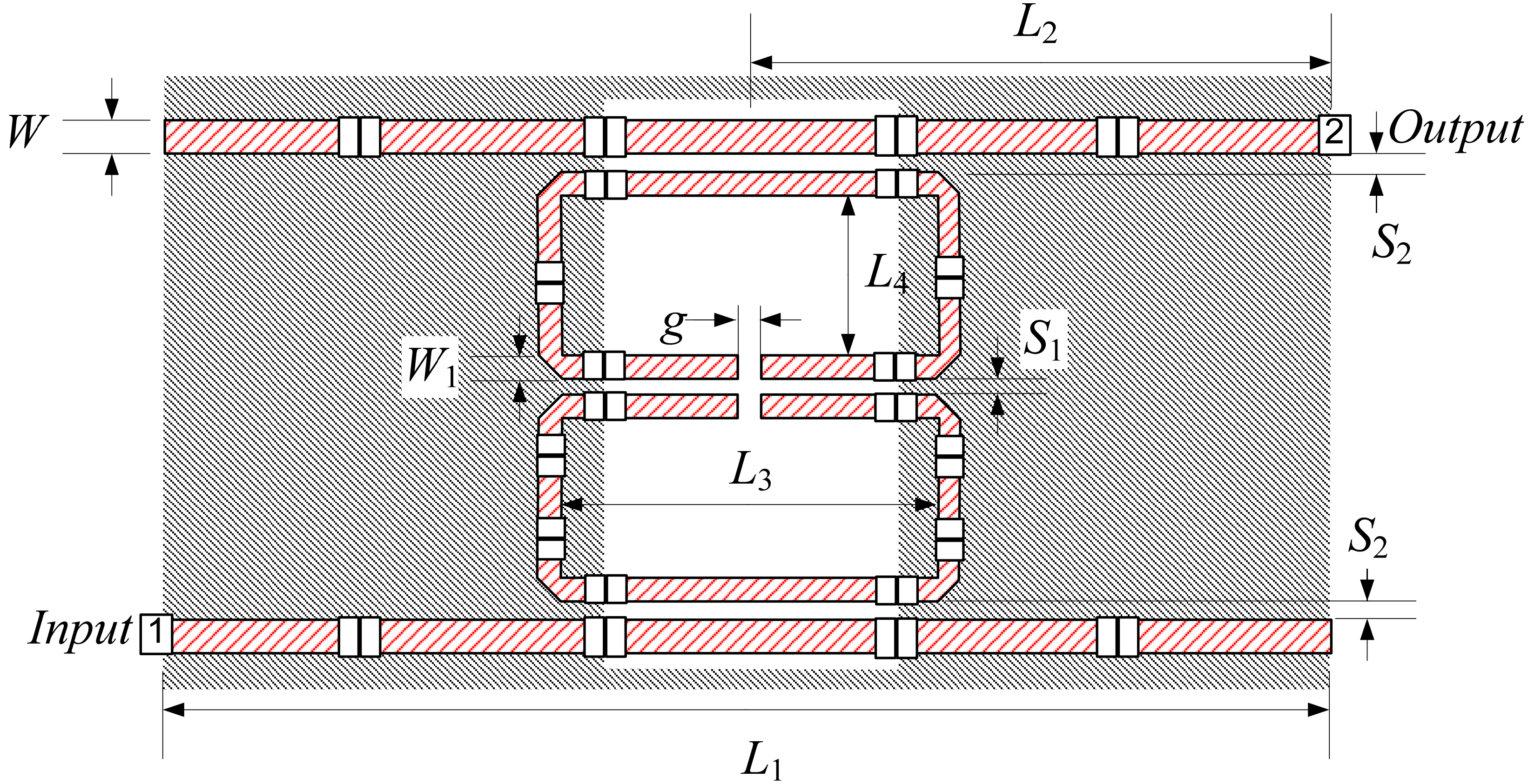
$|S_{21}| \leq -20$ dB for 1.5 GHz $\leq \omega \leq$ 2.5 GHz

$|S_{21}| \leq -20$ dB for 3.5 GHz $\leq \omega \leq$ 4.5 GHz

Open-loop Ring Resonator Bandpass Filter (Type 1 and Type 0)

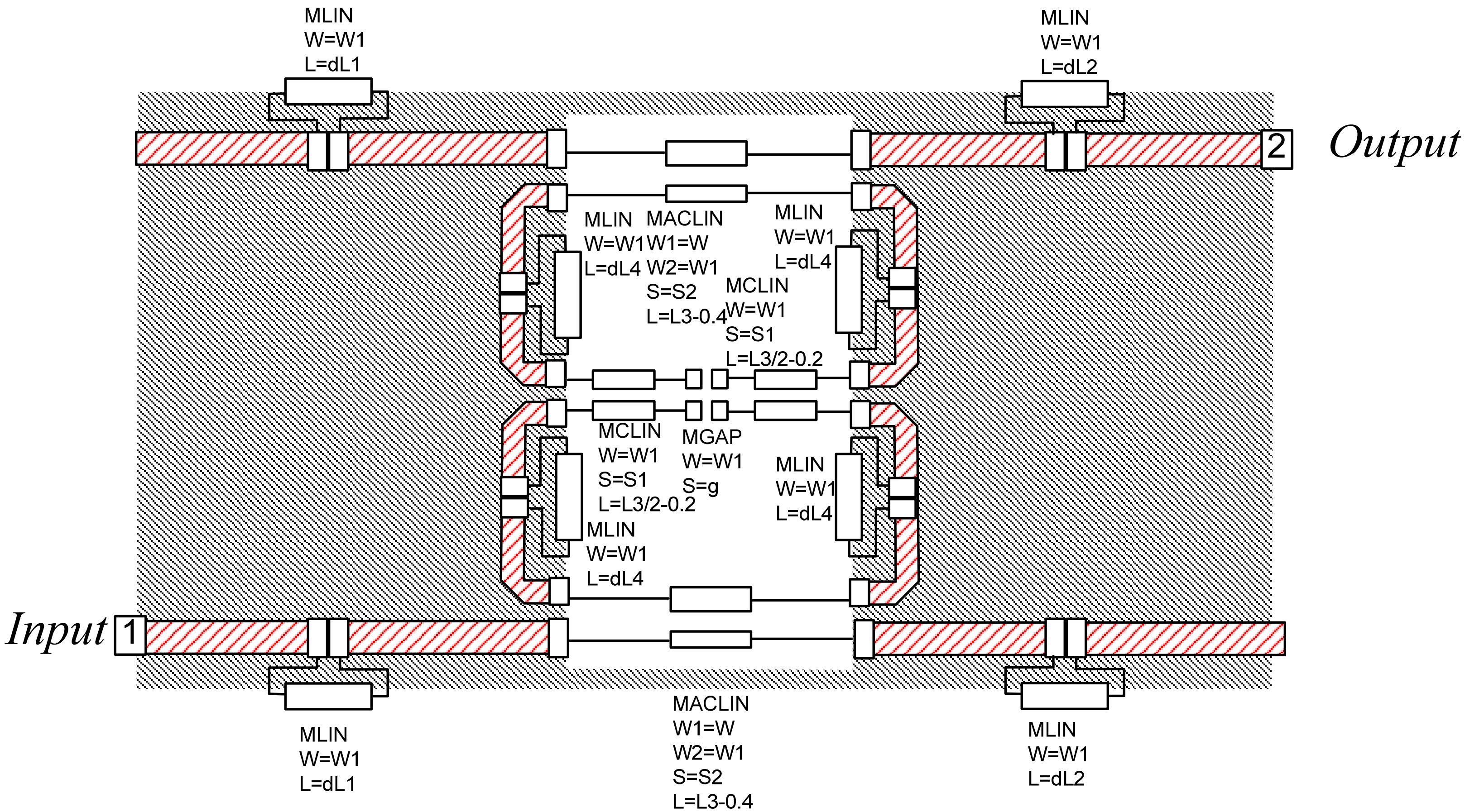
(*Cheng et al., 2010*)

Sonnet ***em*** model with internal (co-calibrated) ports



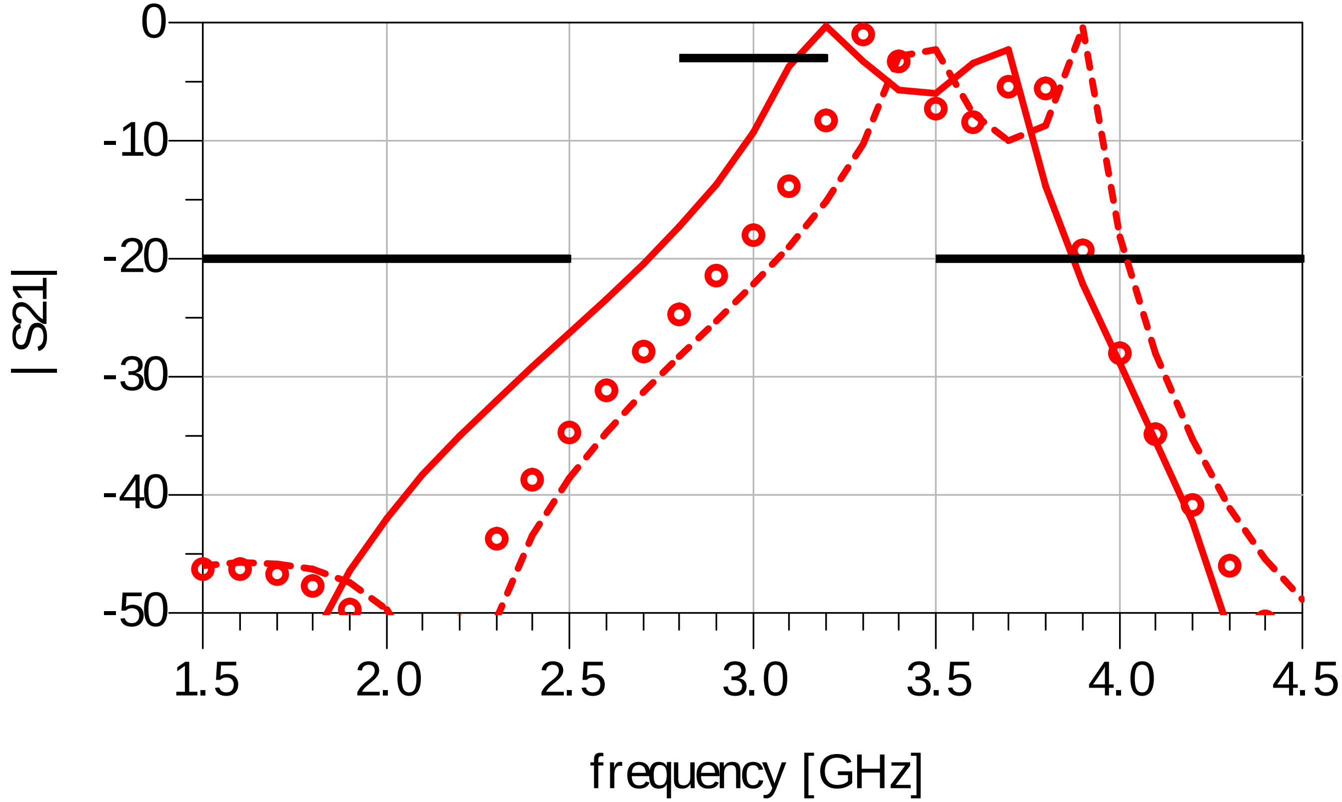
Open-loop Ring Resonator Bandpass Filter (Type 1 and Type 0)
(*Cheng et al., 2010*)

Sonnet ***em*** model with internal (co-calibrated) ports



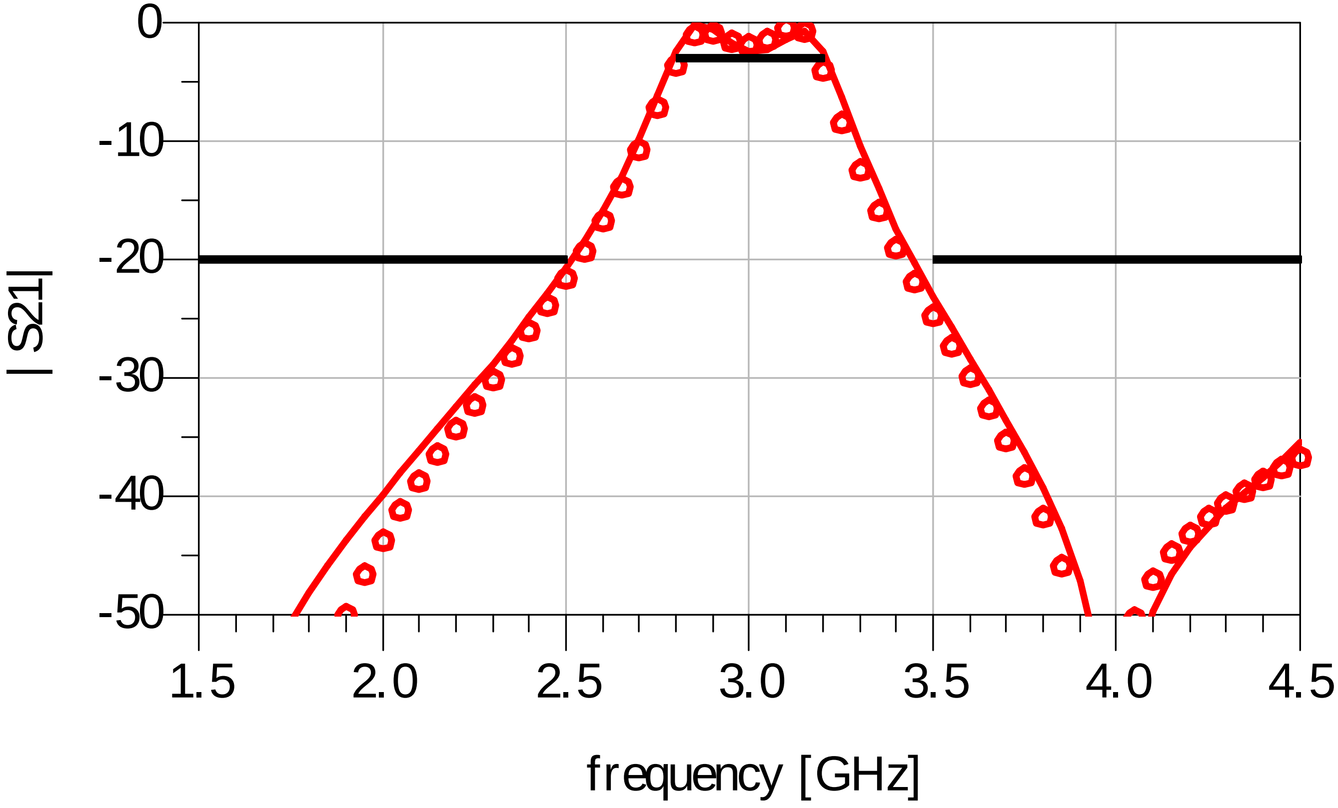
Open-loop Ring Resonator Bandpass Filter (Type 1 and Type 0)
(*Cheng et al., 2010*)

initial responses: tuning model (—), fine model (○),
fine model with co-calibrated ports (---)



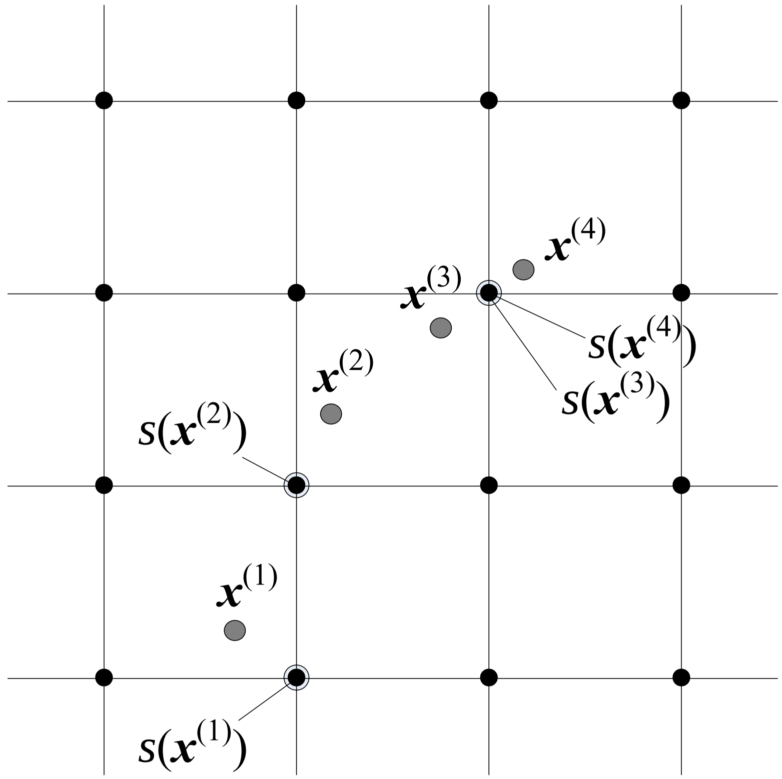
Open-loop Ring Resonator Bandpass Filter (Type 1 and Type 0)
(*Cheng et al., 2010*)

responses after two iterations: the tuning model (—),
corresponding fine model (○)



Space-Mapping-Based Interpolation (*Koziel et al., 2006*)

assumption: the fine model is available on a structured grid



define an interpolated fine model as

$$\bar{\boldsymbol{R}}_f(\boldsymbol{x}^{(i+1)}) = \boldsymbol{R}_f(s(\boldsymbol{x}^{(i+1)})) + \\ + \boldsymbol{R}_s^{(i)}(\boldsymbol{x}^{(i+1)}) - \boldsymbol{R}_s^{(i)}(s(\boldsymbol{x}^{(i+1)}))$$

where snapping function *s*(.) is defined as

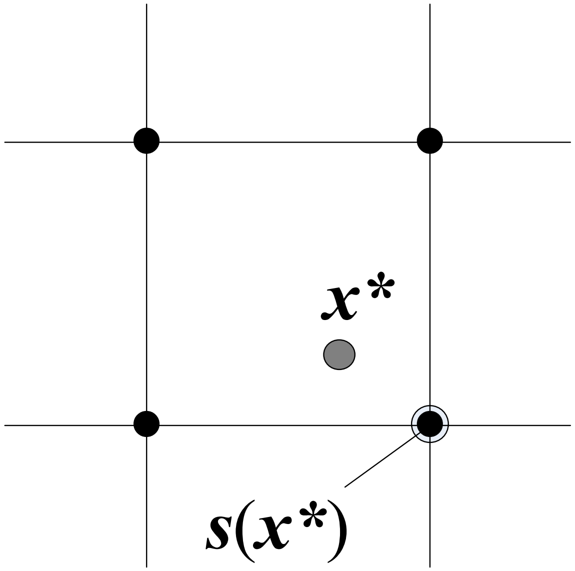
$$s(\boldsymbol{x}) = \left\{ \bar{\boldsymbol{x}} \in \bar{X}_f : \| \boldsymbol{x} - \bar{\boldsymbol{x}} \| = \min_{z \in \bar{X}_f} \| \boldsymbol{z} - \bar{\boldsymbol{x}} \| \wedge \forall_{\boldsymbol{y} = \arg\min_{z \in \bar{X}_f} \|\boldsymbol{z} - \bar{\boldsymbol{x}}\|,\ \boldsymbol{y} \neq \bar{\boldsymbol{x}}} \ \bar{\boldsymbol{x}} \prec \boldsymbol{y} \right\}$$

Response-Corrected Tuning Space Mapping Algorithm
(*Cheng et al., 2010*)

the response-corrected tuning model at optimum $\boldsymbol{x}^*$

$$\bar{\boldsymbol{R}}_s(\boldsymbol{x}) = \boldsymbol{R}_s(\boldsymbol{x}, \boldsymbol{x}_p^*) + \boldsymbol{R}_f(s(\boldsymbol{x}^*)) - \boldsymbol{R}_s(s(\boldsymbol{x}^*), \boldsymbol{x}_p^*)$$

s is a function that snaps a point to the nearest fine model grid point



Yield Analysis and Yield Optimization (*Bandler and Chen, 1988*)

manufactured outcome

$$\boldsymbol{x}^k = \boldsymbol{x} + \boldsymbol{\Delta x}^k, \quad k = 1, 2, \ldots, N$$

for each outcome, an acceptance index is defined

$$I_a(\boldsymbol{x}^k) = \begin{cases} 1, & \text{if } H_p(\boldsymbol{x}^k) \le 0 \\ 0, & \text{if } H_p(\boldsymbol{x}^k) > 0 \end{cases}$$

Yield Y at the nominal point $\boldsymbol{x}$

$$Y(\boldsymbol{x}) \approx \frac{1}{N} \sum_{k=1}^{N} I_a(\boldsymbol{x}^k)$$

Yield Analysis and Yield Optimization (*Bandler and Chen, 1988*)

the optimal yield

$$\boldsymbol{x}^{Y*} = \arg\min_{\boldsymbol{x}} \sum_{k \in K} \alpha_k H_1(\boldsymbol{x}^k)$$

$$K = \left\{ k \;\middle|\; H_1(\boldsymbol{x}^k) > 0 \right\}$$

where

$$\alpha_k = \frac{1}{\left| H_1(\boldsymbol{x}^{(0)} + \Delta \boldsymbol{x}^k) \right|}, \quad k = 1, 2, \ldots, N$$

Yield Analysis and Yield Optimization (*Cheng et al., 2010*)

Step 1 Use tuning space mapping to obtain a nominal optimal design. A tuning model or surrogate is also obtained.

Step 2 Snap the optimal design to the nearest on-grid fine model point.

Step 3 Simulate the snapped design (EM fine model).

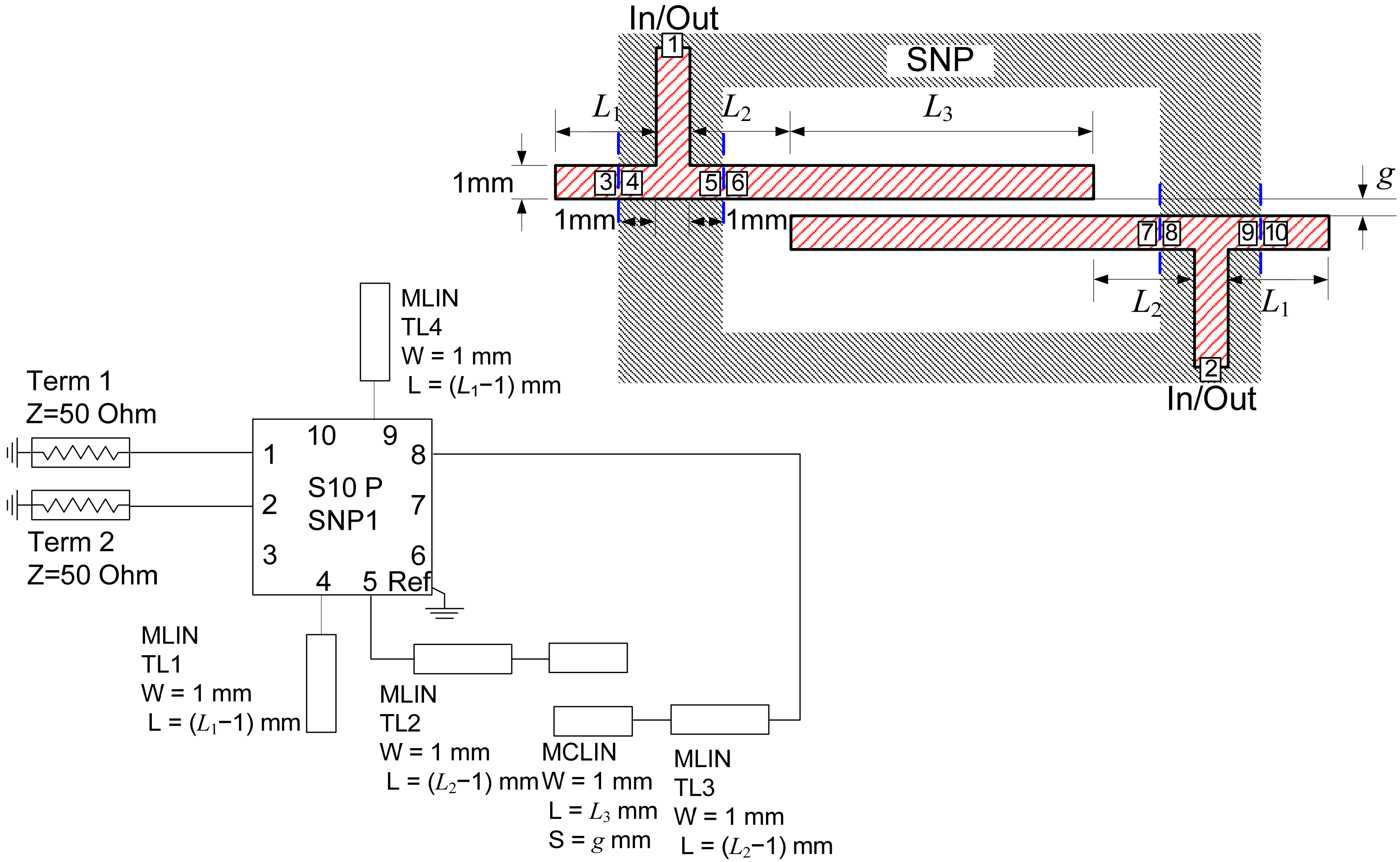
Step 4 Calculate the response difference between the fine model and the surrogate at the nearest on-grid point.

Step 5 Add the response difference to the surrogate to form a new surrogate: the response corrected surrogate.

Step 6 Perform yield analysis and yield optimization on the response-corrected surrogate.

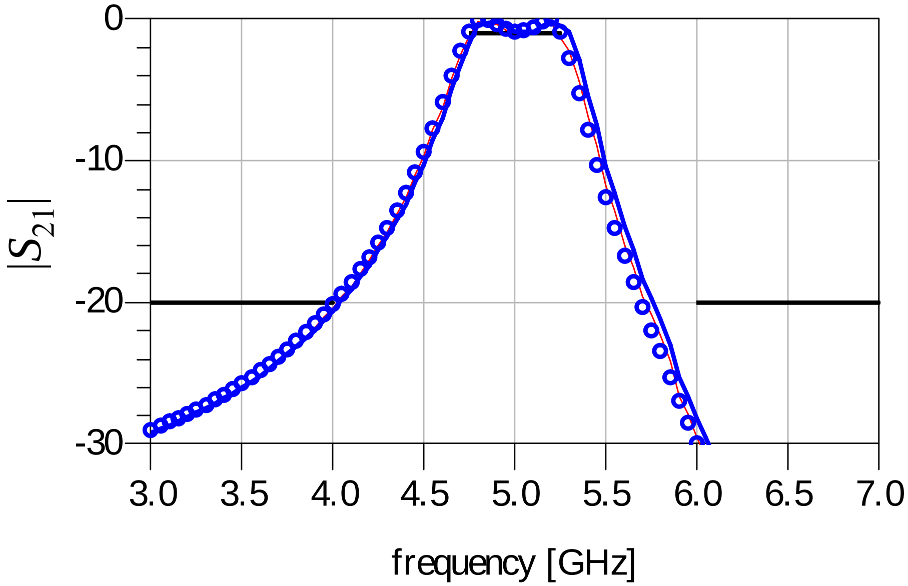
Step 7 Compare this response to that of the fine model.

Second-order Tapped-line Microstrip Filter (Type 1)

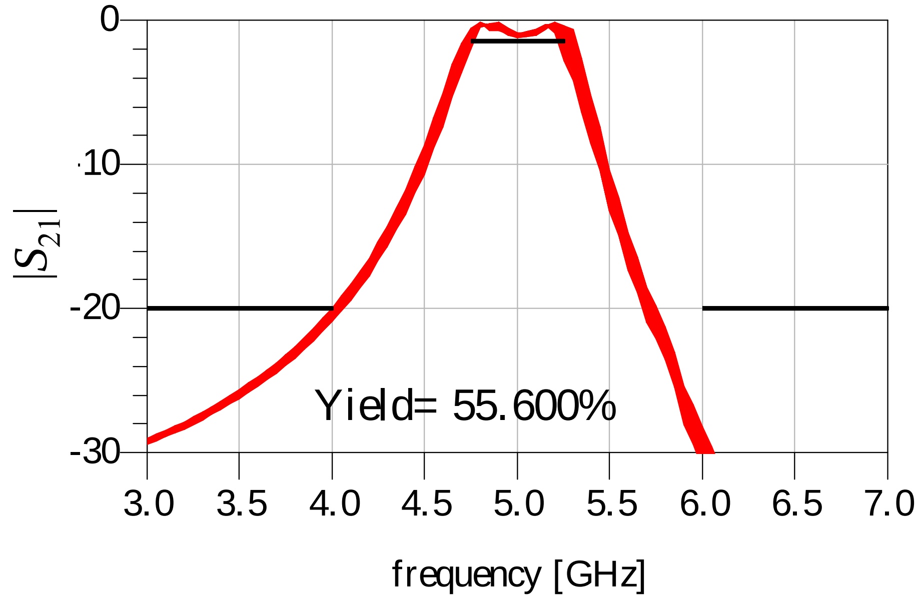


Second-order Tapped-line Microstrip Filter (Type 1)

tuning model (—), fine model (○),
response corrected surrogate (—)

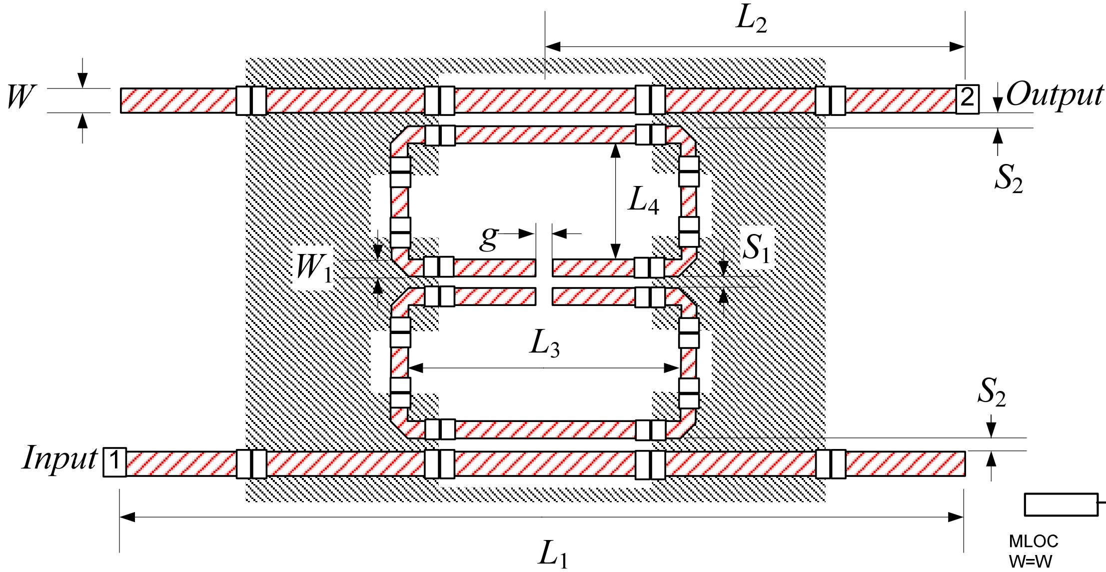


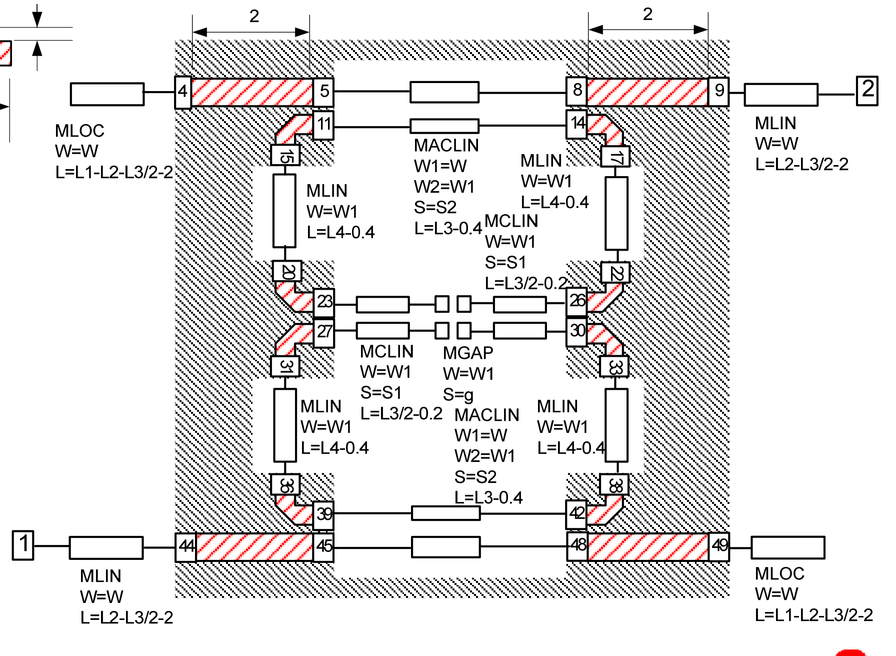
yield analysis (500 trials)



Open-loop Ring Resonator Bandpass Filter (Type 1)

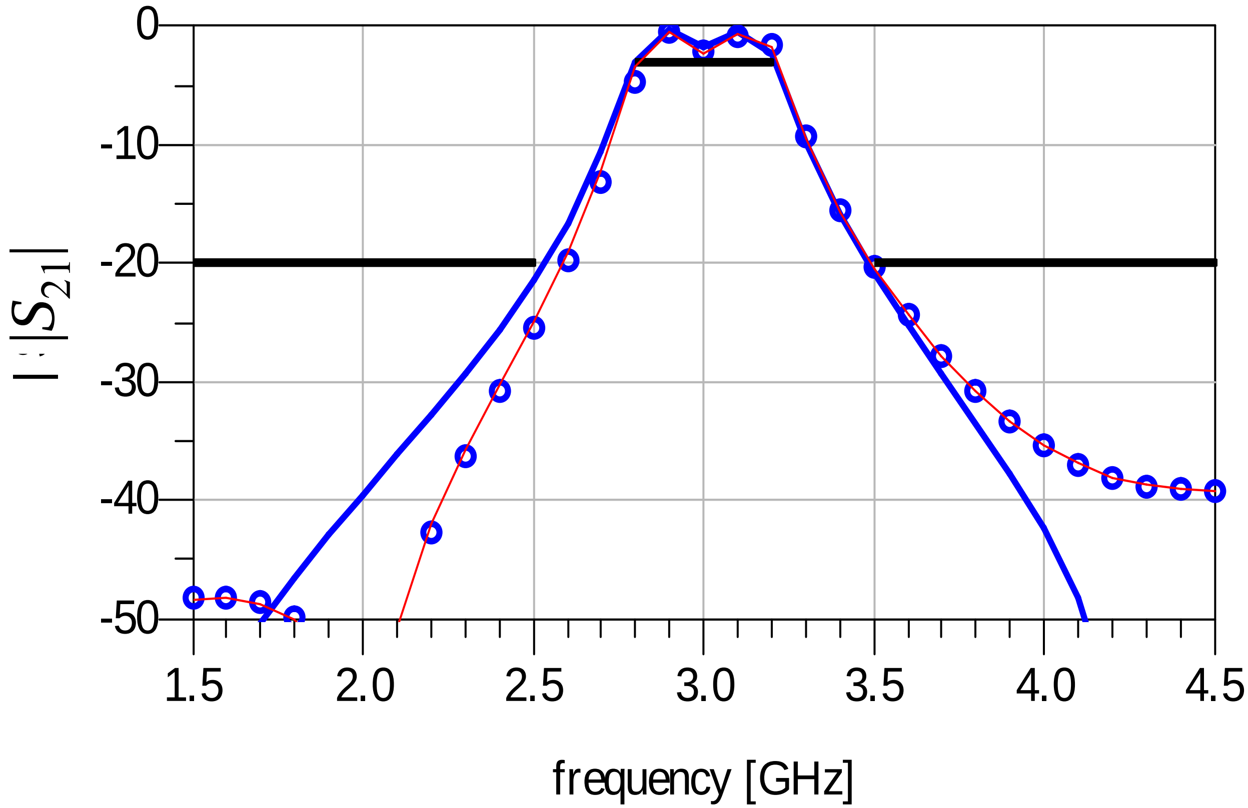
(*Cheng et al., 2010*)





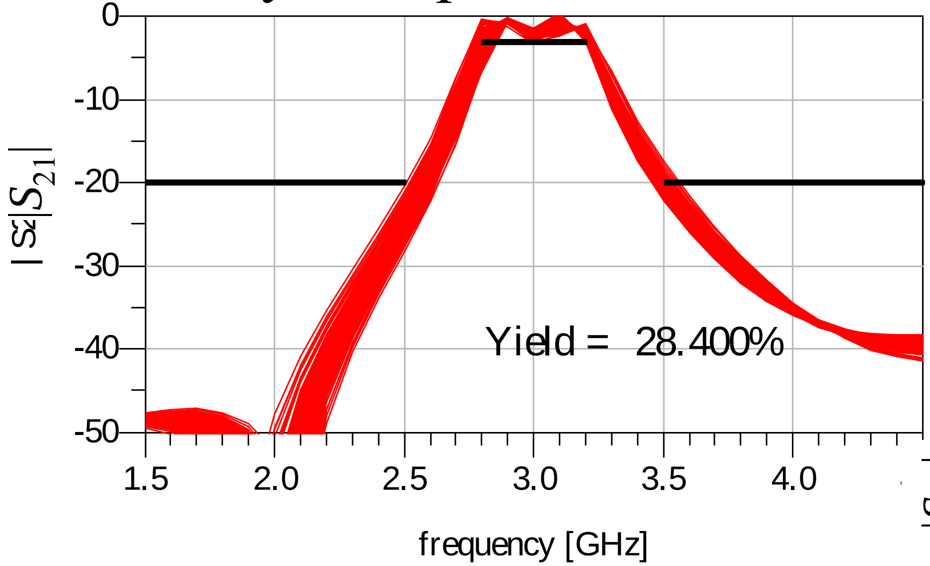
Open-loop Ring Resonator Bandpass Filter (Type 1)
(*Cheng et al., 2010*)

tuning model (—), fine model (○),
response corrected surrogate (—)

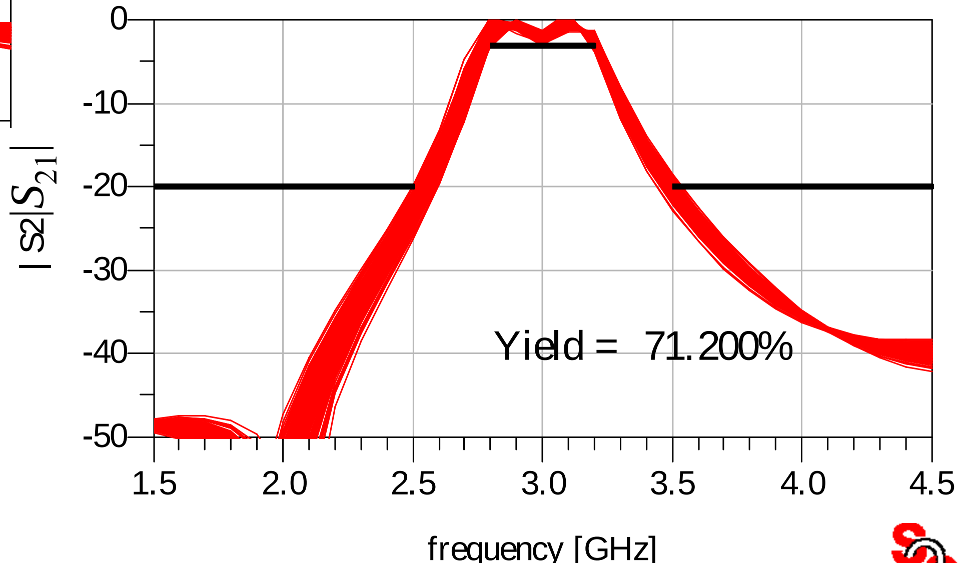


Open-loop Ring Resonator Bandpass Filter (Type 1)
(*Cheng et al., 2010*)

response corrected surrogate
before yield optimization



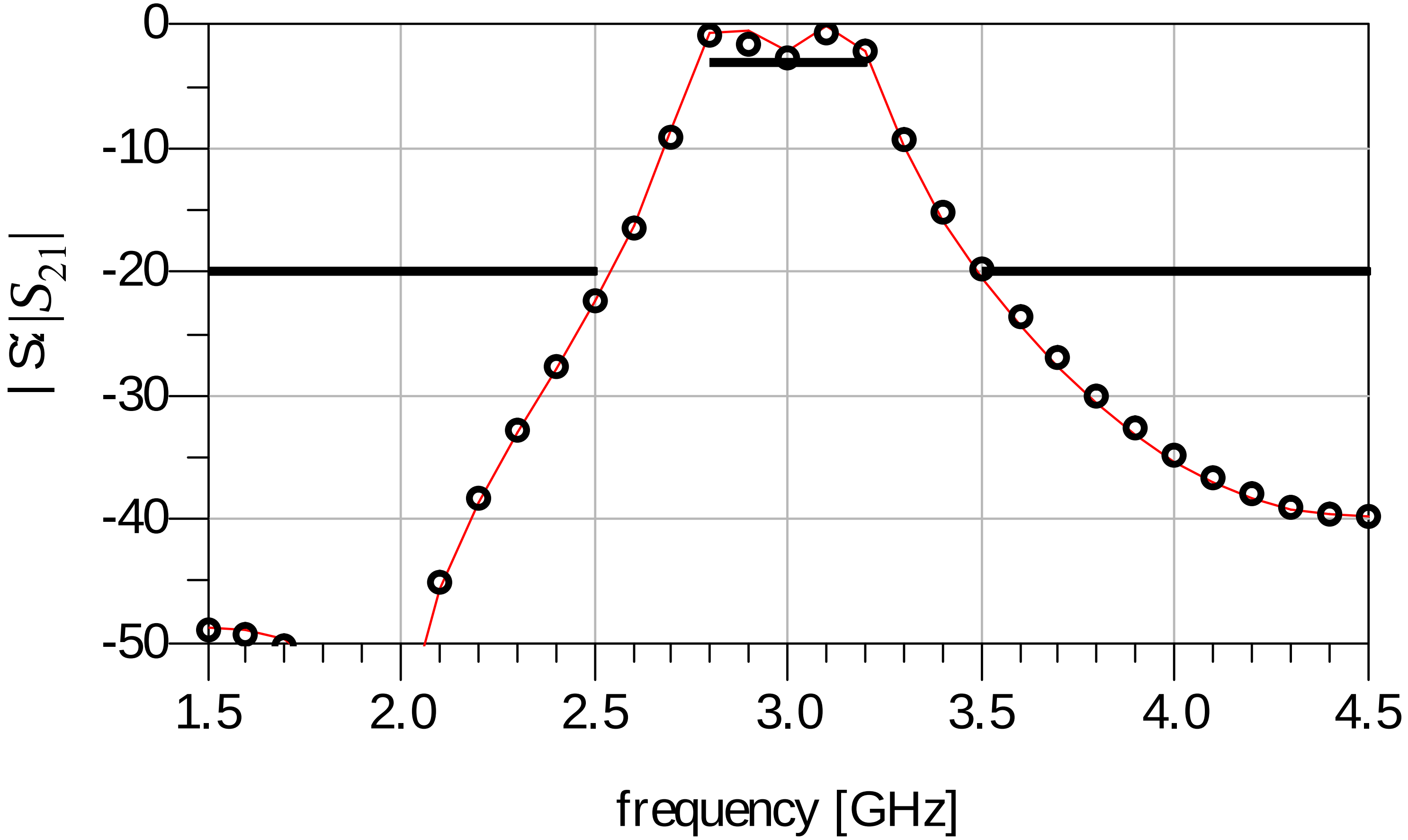
response corrected surrogate
after yield optimization



Open-loop Ring Resonator Bandpass Filter (Type 1)

(*Cheng et al., 2010*)

response corrected surrogate at design center (—)
and final validation on a finer grid (○)



Space Mapping: a Glossary of Terms

space mapping	transformation, link, adjustment, correction, shift (in parameters or responses); "internal" fine-tuning transformation
coarse model	simplification or convenient representation, companion to the fine model, auxiliary representation, cheap model, "idealized" model
fine model	accurate representation of system considered, device under test, component to be optimized, expensive model, an optimization process

Space Mapping: a Glossary of Terms

surrogate	model, approximation or representation to be used, or to act, in place of, or as a (temporary) substitute for, the system under consideration
(updated) surrogate	mapped or enhanced coarse model, corrected coarse model, tuning-parameter-augmented fine-model iterate
surrogate model	alternative expression for surrogate
target response	a response the fine model should achieve, (usually) the optimal response of an idealized "coarse" model, an enhanced coarse model, or surrogate

Space Mapping: a Glossary of Terms

surrogate update	rebuilding of a coarse- or ideal-model-based surrogate using, e.g., parameter extraction; supply new fine-model data to a surrogate
surrogate optimization	prediction of the next fine model; “internal” fine tuning of a tuning-parameter-augmented fine-model iterate (tuning model)
parameter extraction	aligning a coarse model or surrogate with the corresponding fine model

Space Mapping: a Glossary of Terms

companion model	coarse
low fidelity/resolution	coarse
high fidelity/resolution	fine
empirical	coarse
simplified physics	coarse
physics-based	coarse or fine
physically expressive	coarse
device under test	fine
electromagnetic	fine or coarse
simulation model	fine or coarse
computational	fine or coarse
tuning model	coarse (fine model data) + tuning elements
calibration model	coarse + tuning elements

Space Mapping: a Glossary of Terms

tuning-parameter-augmented fine-model iterate (with internal tuning ports) i.e., “tuning model”	surrogate
optimization process	design of fine model
optimization space	(design) optimization parameters for coarse or surrogate models
validation space	design optimization parameters for the fine model

Space Mapping: a Glossary of Terms

neuro	implies use of artificial neural networks
implicit space mapping	space mapping using preassigned, alternative, or other accessible parameters
“not” space mapping	(usually) an expert’s algorithm, where the underlying space mapping concept may not be obvious, or not admitted
parameter transformation	space mapping

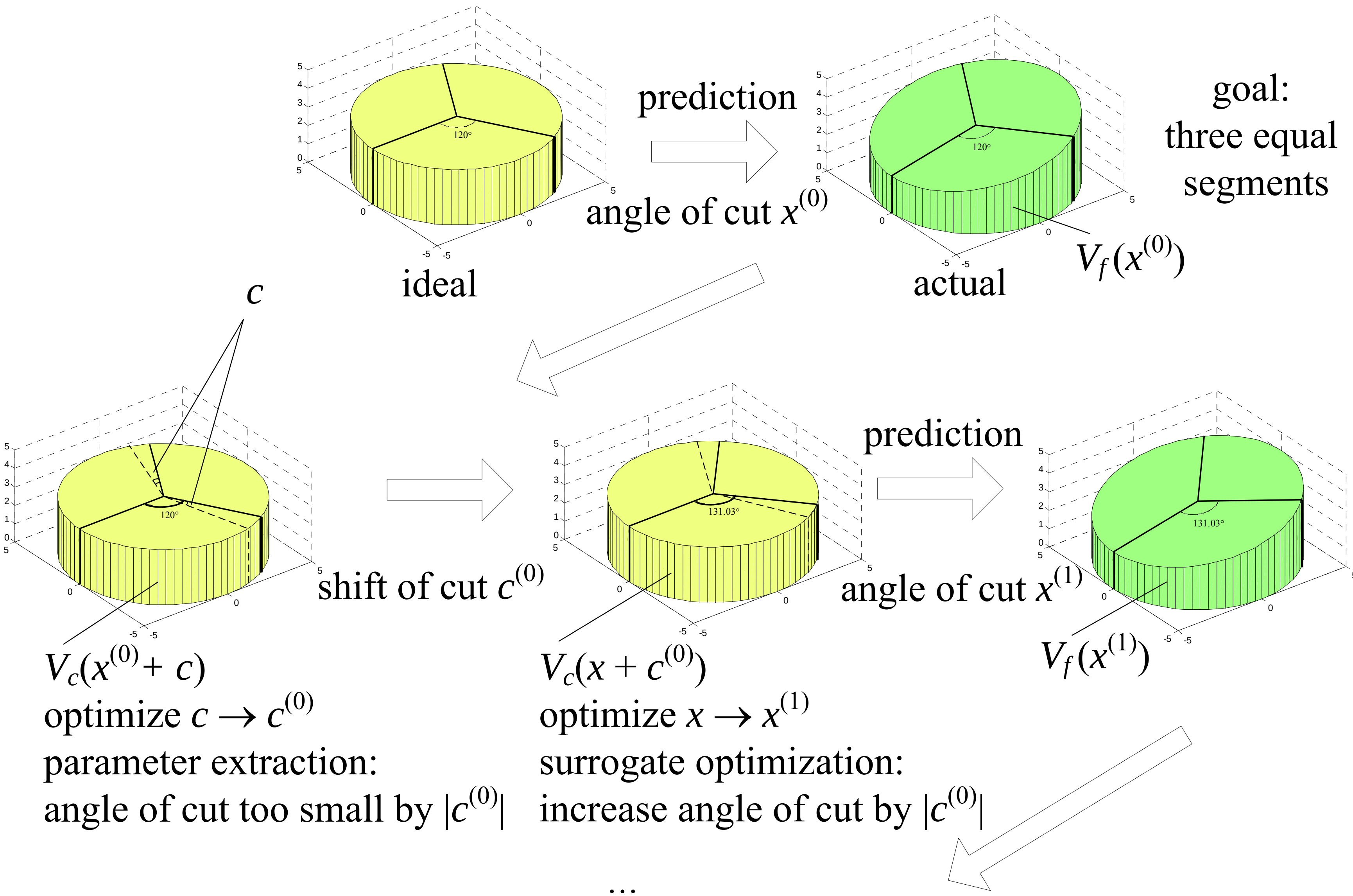
Space Mapping: a Glossary of Terms

(parameter/input) space mapping	mapping, transformation or correction of design variables
(response) output space mapping[1]	mapping, transformation or correction of responses
response surface approximation	linear/quadratic/polynomial approximation of responses w.r.t. design variables

[1]advocated by John E. Dennis, Jr., Rice University
[1]Alexandrov's "high-order model management"

Space Mapping—Cake-Cutting Illustration

(*Cheng and Bandler, 2006*)



Implicit, Input and Output Space Mappings in Agilent ADS: Four ADS Schematics (*Cheng and Bandler*, *2006*)

coarse model optimization

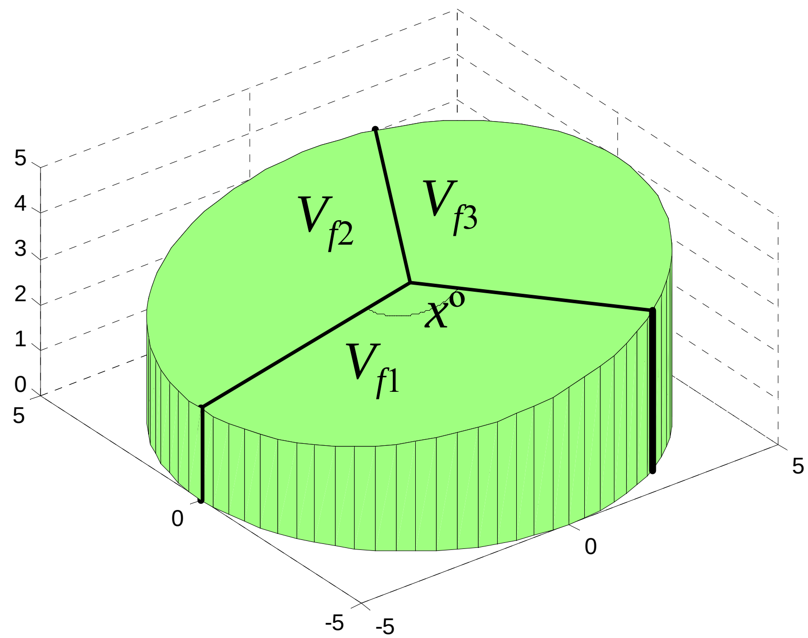
fine model simulation

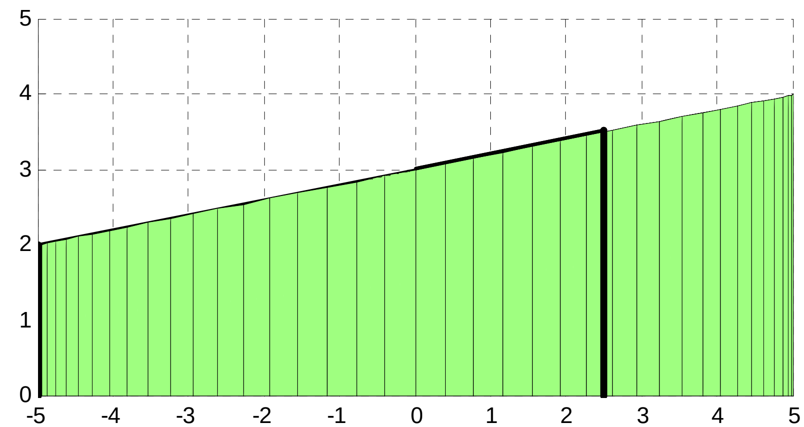
parameter extraction

surrogate re-optimization

Cake-Cutting Problem
(*Cheng and Bandler, 2006*)

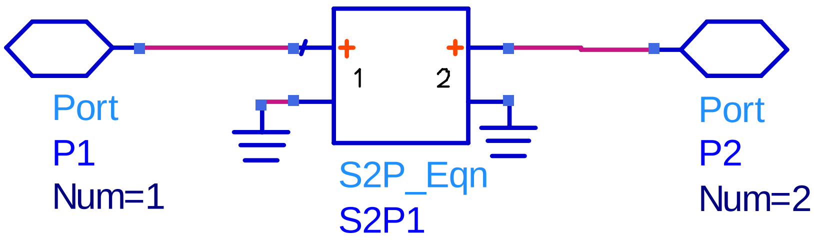
use space mapping to find the optimal angle x of a cut such that the volume of each slice is equal, in this case, $V/3$





ADS Implementation of Cake-Cutting Problem: Fine Model

(*Cheng and Bandler, 2006*)



S[1,1]=if freq equals 1GHz then R1 elseif freq equals 2 GHz then R2 else R3 endif
S[1,2]=
S[2,1]=
S[2,2]=
Z[1]=
Z[2]=

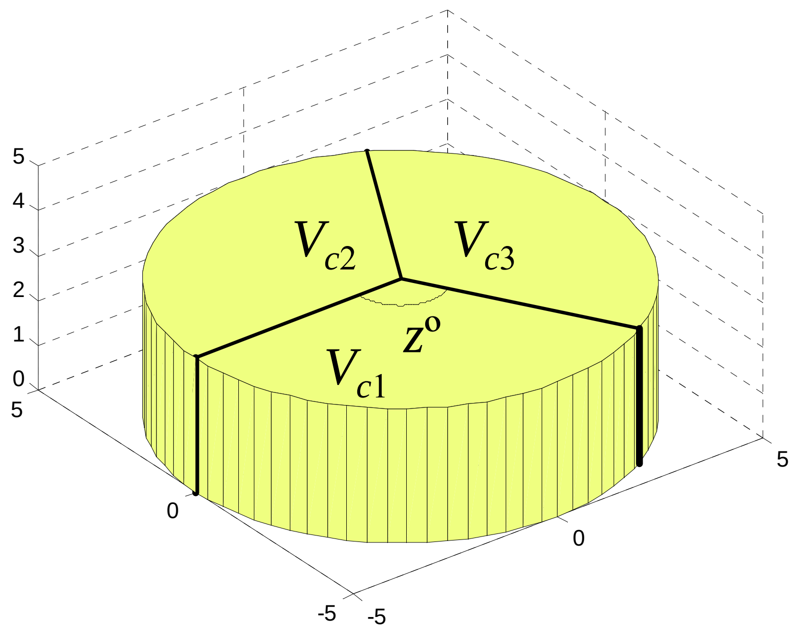
1GHz: V_{f1}
2GHz: V_{f2}
3GHz: V_{f3}

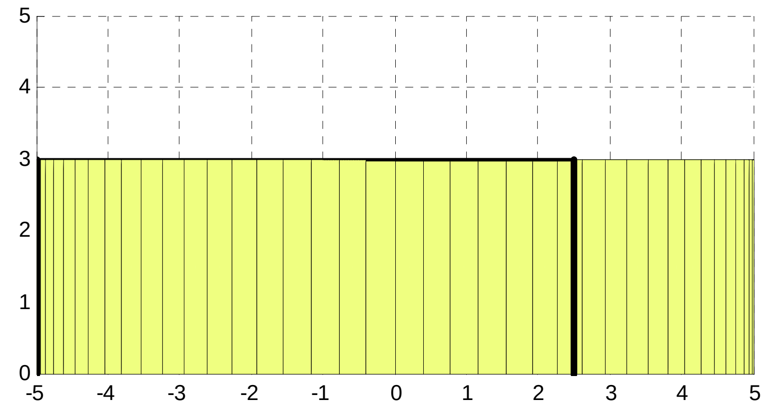
Var Eqn
VAR
VAR1
r = 5
hmid = 1
thita = x/180*pi
hc = 3
Rf = r**2*hmid*thita/2-r**2*hmid*sin(thita)/3 + r**2*h*thita/2
h = 2
Vall = pi * r^2 * hc

Var Eqn
VAR
VAR2
R1 = Rf/Vall
R2 = Rf/Vall
R3 =(Vall-Rf-Rf)/Vall

Proposed Coarse Model Using Only the Shift *c*

(*Cheng and Bandler, 2006*)



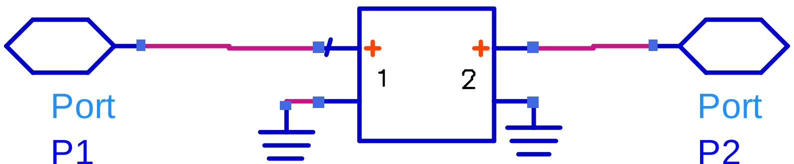


volume $\boldsymbol{V}_c = [V/3\ V/3\ V/3]$ implies $z + c = 120$

initially $c = 0$

ADS Implementation of Cake-Cutting Problem: Coarse Model

(*Cheng and Bandler, 2006*)



S[1,1]=if freq equals 1GHz then R1 elseif freq equals 2 GHz then R2 else R3 endif
S[1,2]=
S[2,1]=
S[2,2]=
Z[1]=
Z[2]=

1GHz: V_{c1}
2GHz: V_{c2}
3GHz: V_{c3}

Var Eqn

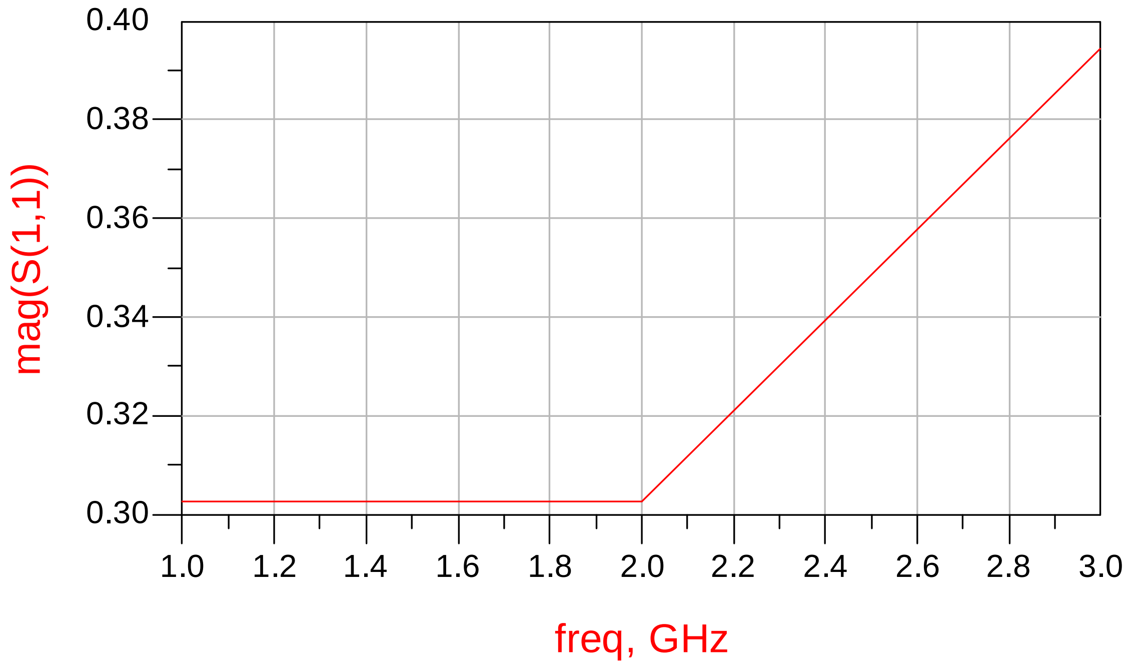
VAR
VAR1
r = 5
thita = x/180*pi
hc = 3
Rc = hc * r**2*thita/2
Vall = pi * r^2 * hc

Var Eqn

VAR
VAR2
R1 = Rc/Vall
R2 = Rc/Vall
R3 =(Vall-Rc-Rc)/Vall

ADS Implementation of Cake-Cutting Problem: Initial Solution

(*Cheng and Bandler, 2006*)



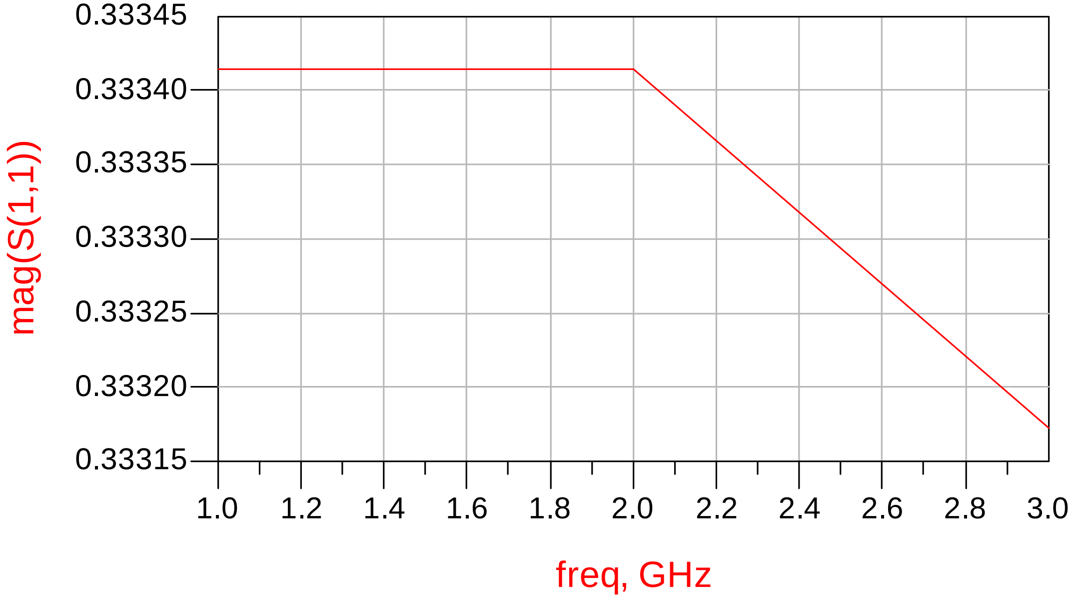
freq	mag(S(1,1))
1.000GHz	0.303
2.000GHz	0.303
3.000GHz	0.395

V_{f1}

V_{f2}

V_{f3}

ADS Implementation of Cake-Cutting Problem: Third Iteration
(*Cheng and Bandler, 2006*)



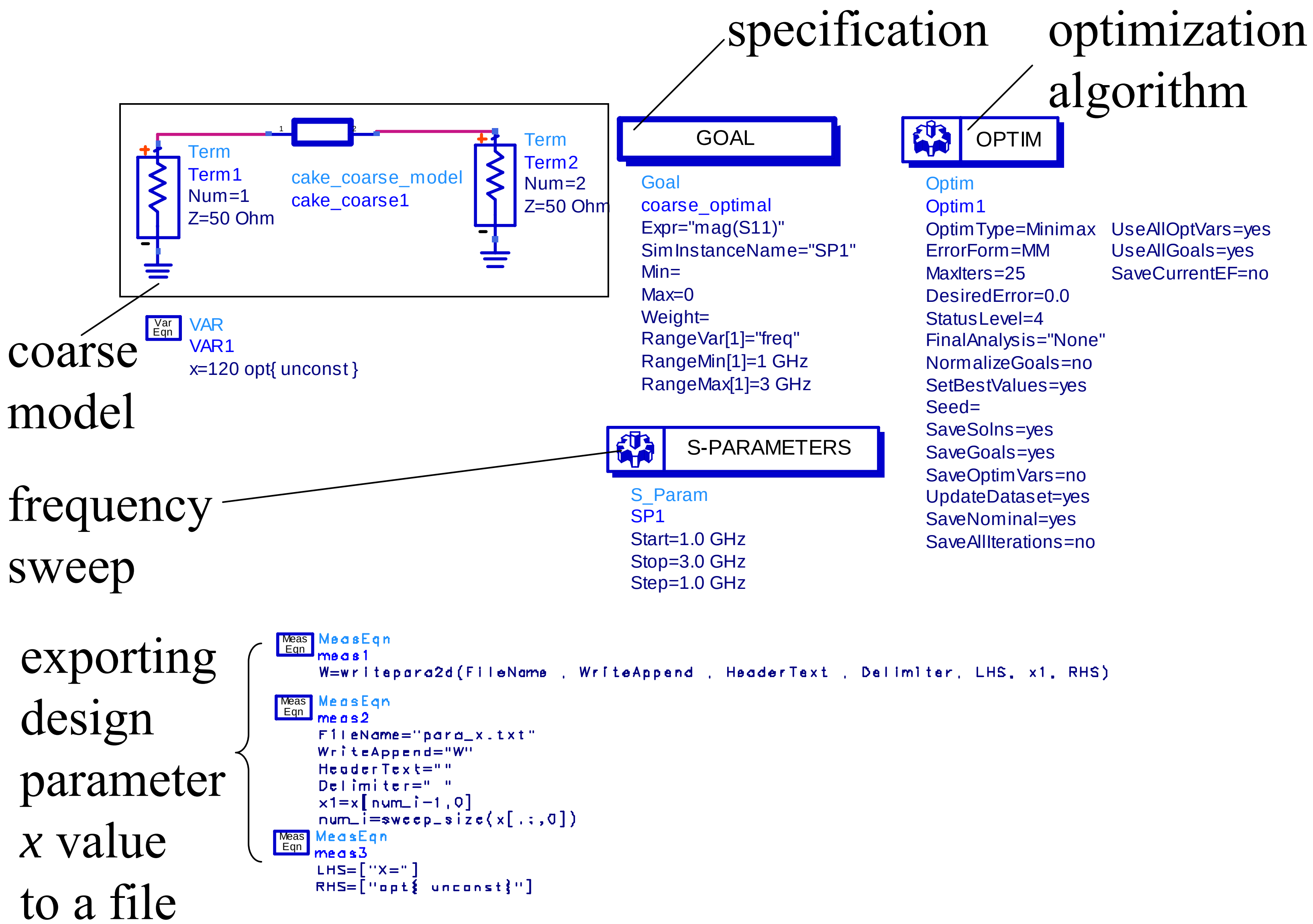
freq	mag(S(1,1))
1.000GHz	0.333
2.000GHz	0.333
3.000GHz	0.333

V_{f1}
V_{f2}
V_{f3}

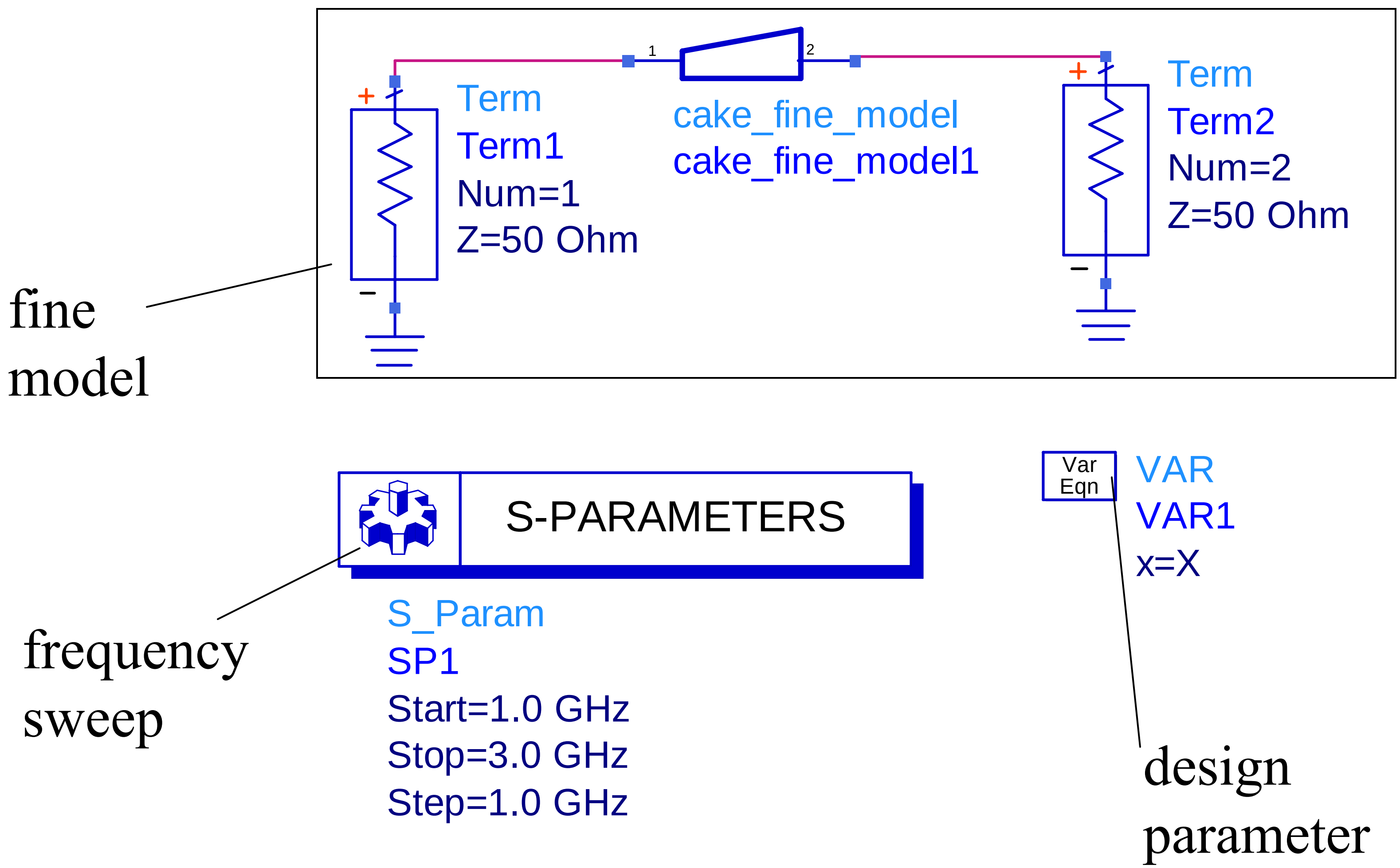
Var
Eqn

VAR
mapping
X= 129.80972100829 opt{ unconst}

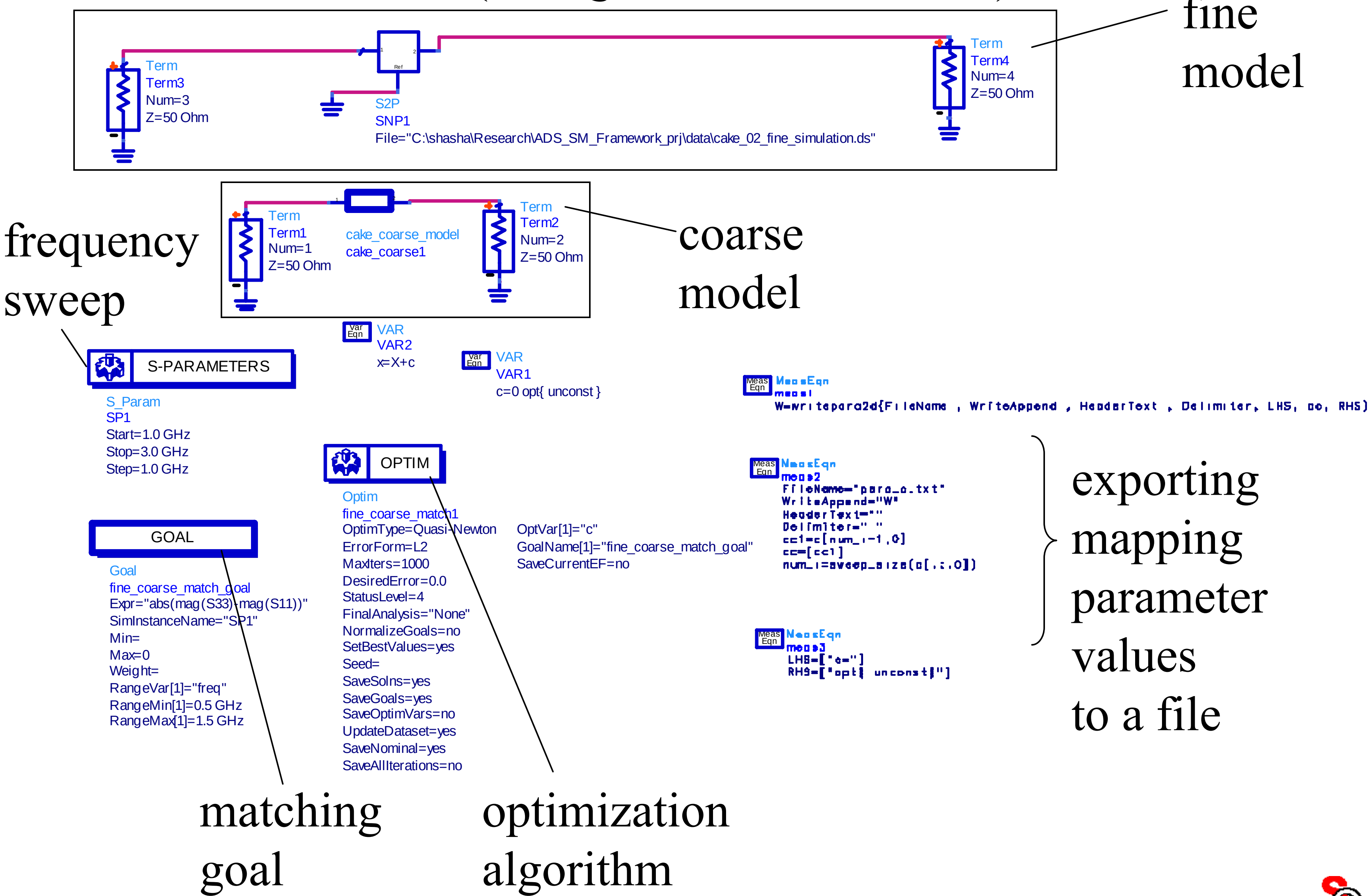
Coarse Model Optimization (*Cheng and Bandler, 2006*)



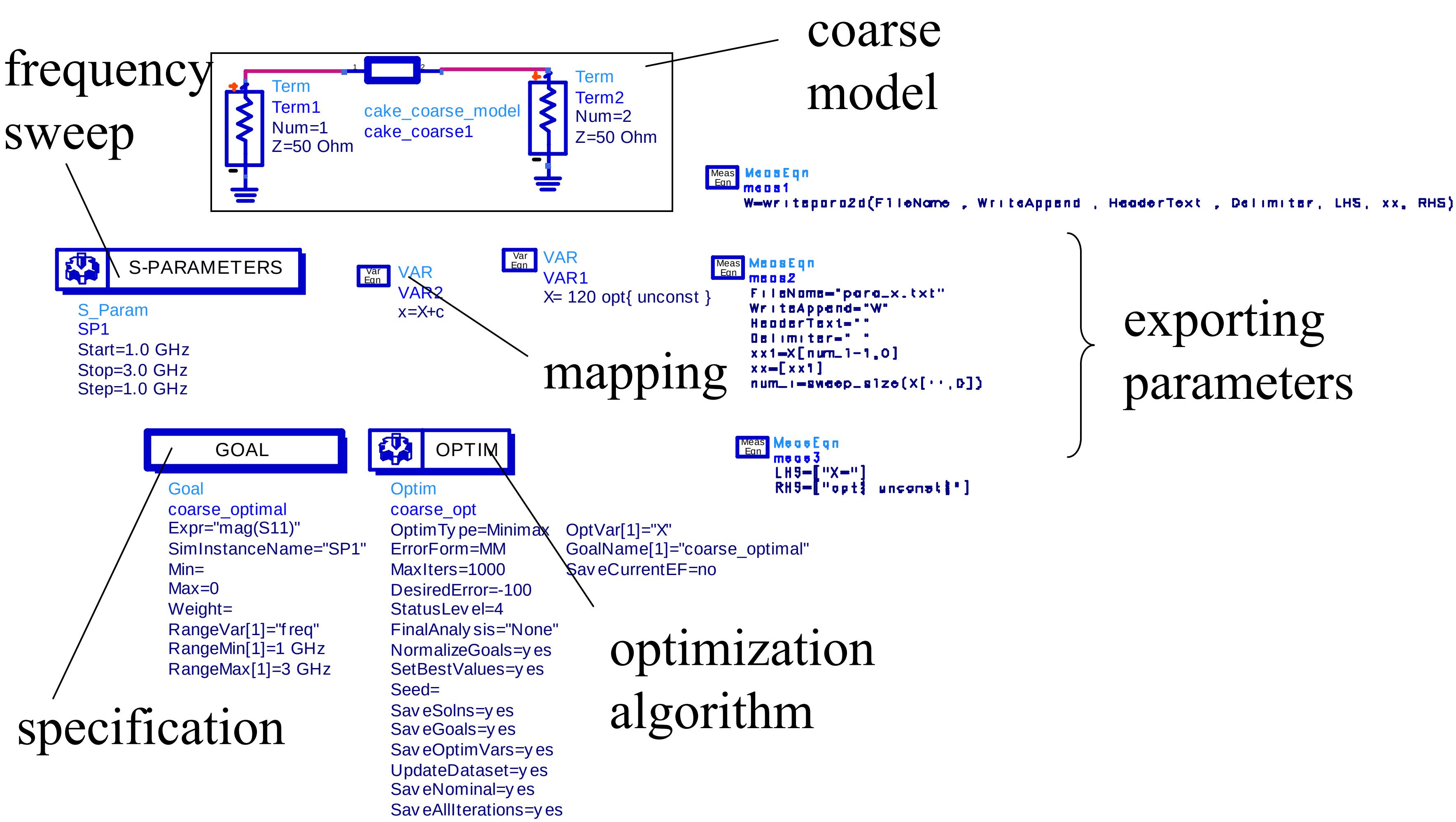
Fine Model Simulation (*Cheng and Bandler, 2006*)



Parameter Extraction (*Cheng and Bandler, 2006*)



Surrogate Re-optimization (*Cheng and Bandler, 2006*)



ADS Space Mapping Implementation Automation Diagram

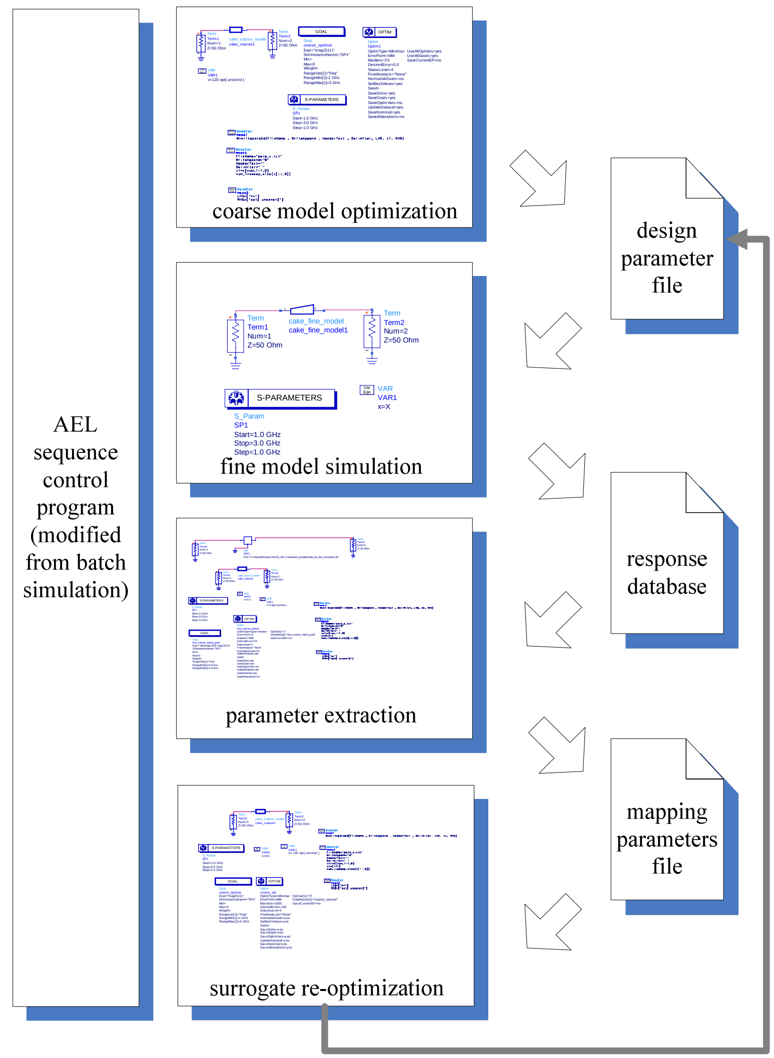
(*Cheng and Bandler, 2006*)

AEL batch simulation program

AEL function save parameter values to a file: writepara2d

AEL function to load parameter values from a file: read_equation_from_file

ADS component to load response: SNP



User Instructions (*Cheng and Bandler, 2006*)

load our AEL functions

create the four schematics using the template, replacing the coarse and fine models, frequency sweep and variables

edit the list file to specify the folder and design names

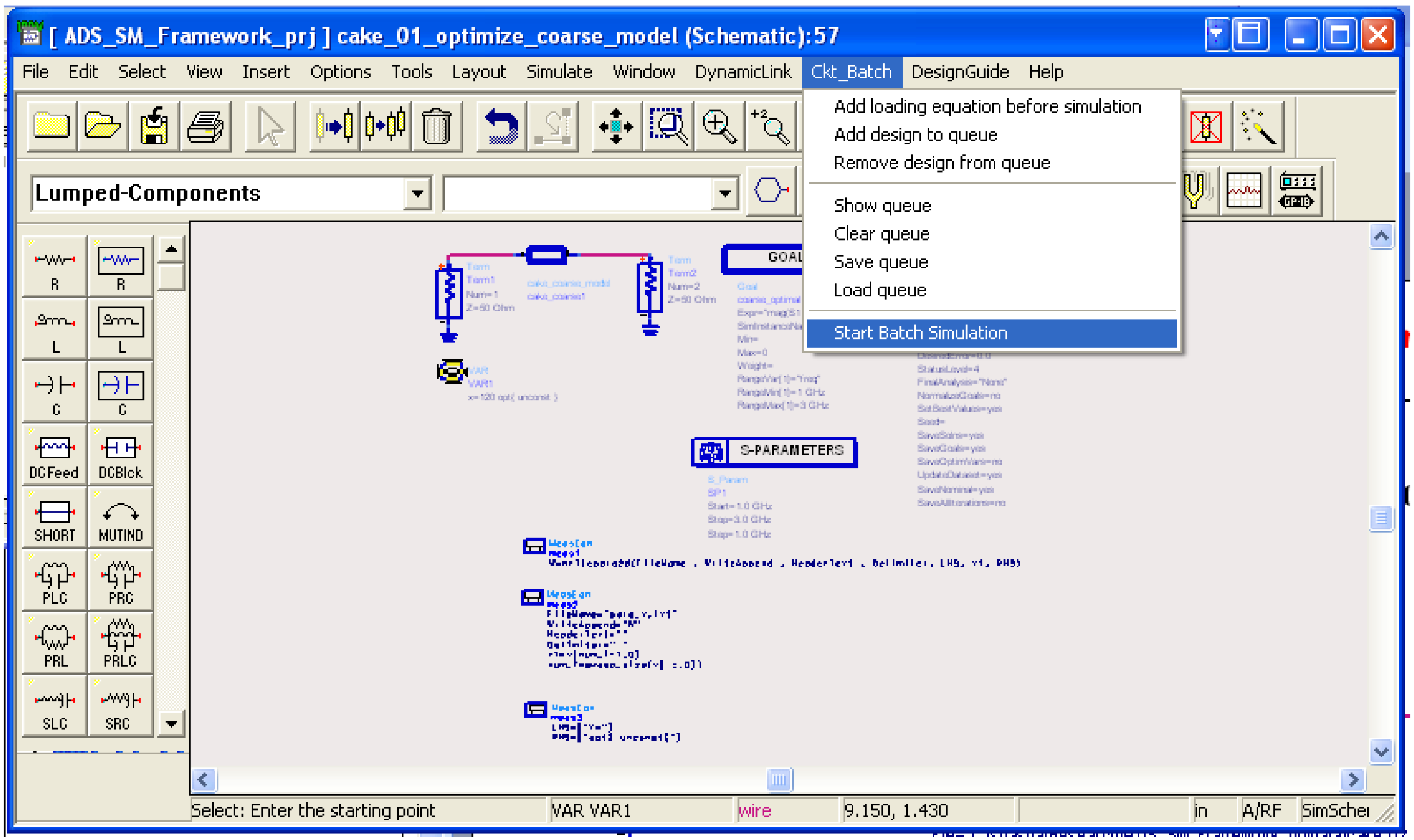
click Load Queue to load the sequence

click Start Batch Simulation to run

ADS SM Implementation: Start

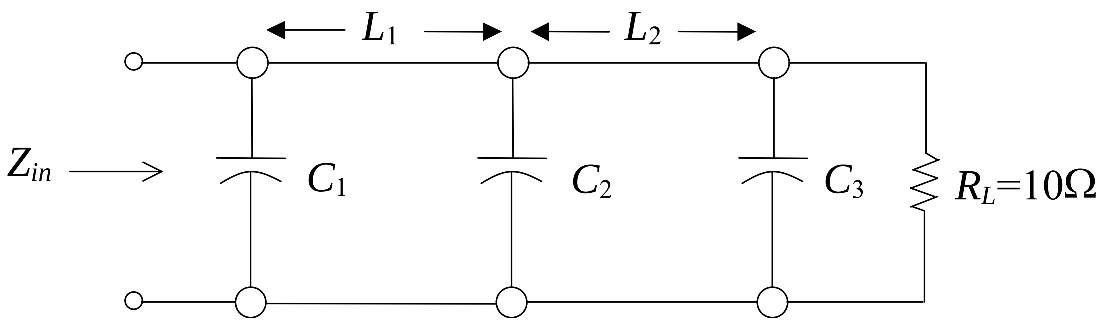
(*Cheng and Bandler, 2006*)

click Start Batch Simulation

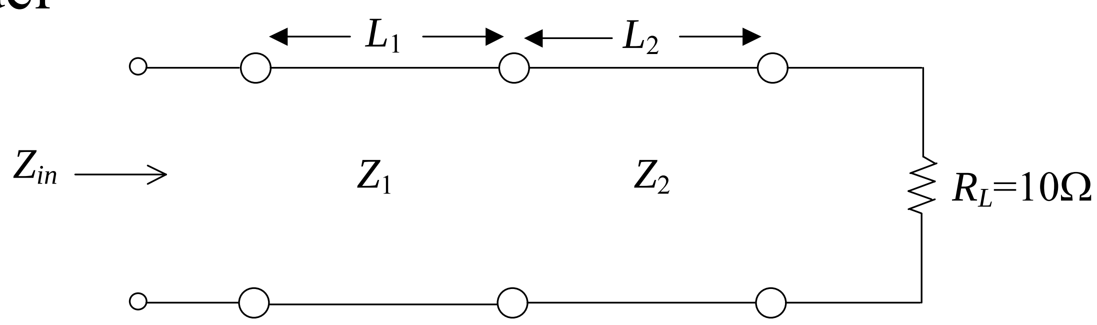


ADS SM Implementation of Two-section Impedance Transformer (*Cheng and Bandler, 2006*)

fine model

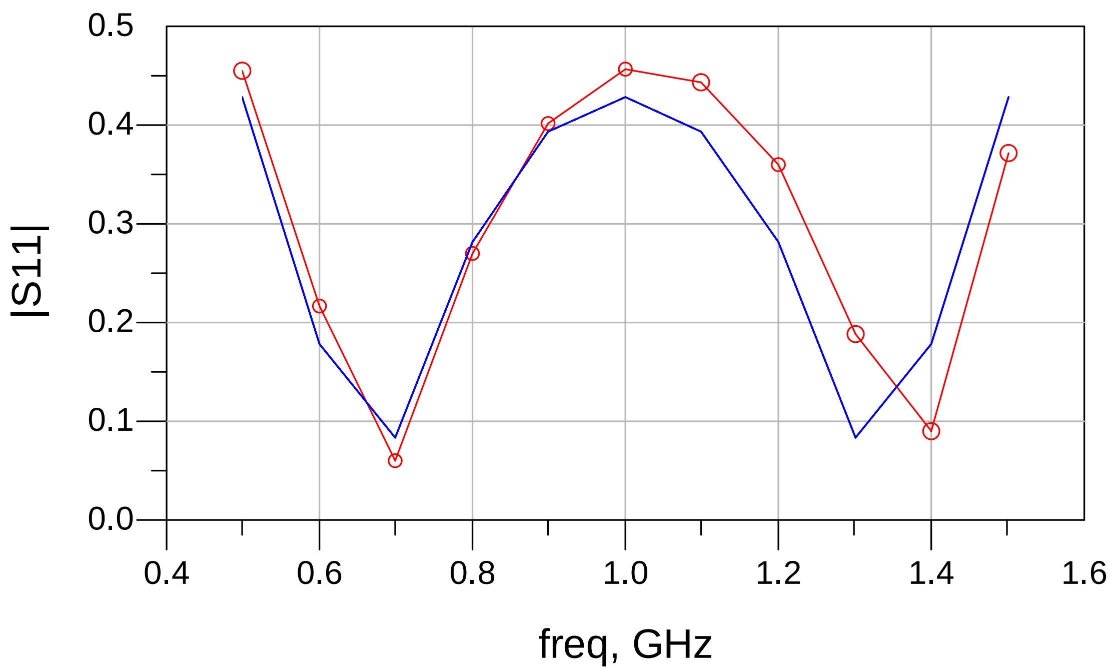


coarse model



ADS SM Implementation of Two-section Impedance Transformer Using *c* and *d*, and Obtained in Four Iterations

(*Cheng and Bandler, 2006*)



Eqn m=max(mag(S(1,1)))

Eqn Spec_Err=m-0.5

m	Spec_Err
0.456	-0.044

Space Mapping Technology: Our Current Work

new SM frameworks, SM modeling, SM optimization, software, convergence proofs, . . . (with S. Koziel, Reykjavik University)

antennas, metamaterials, microwaves, inverse problems, electromagnetic modeling and design (with M. Bakr and N. Nikolova, McMaster)

methodologies for electronic device and component model enhancement (with Q.J. Zhang, Carleton University)

tuning space mapping and its applications (with J.C. Rautio, Sonnet Software)