Recent Trends in Space Mapping Technology

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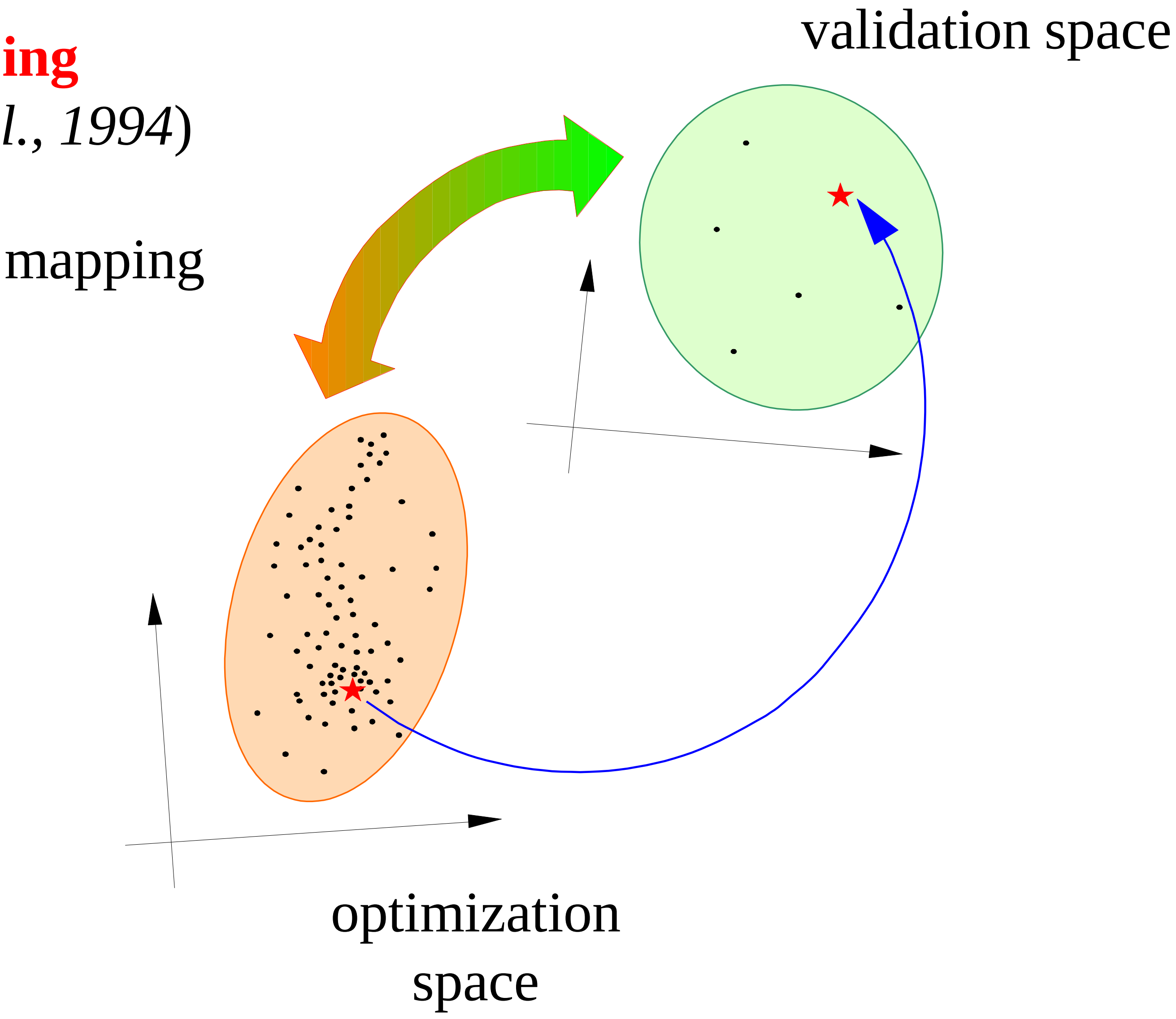
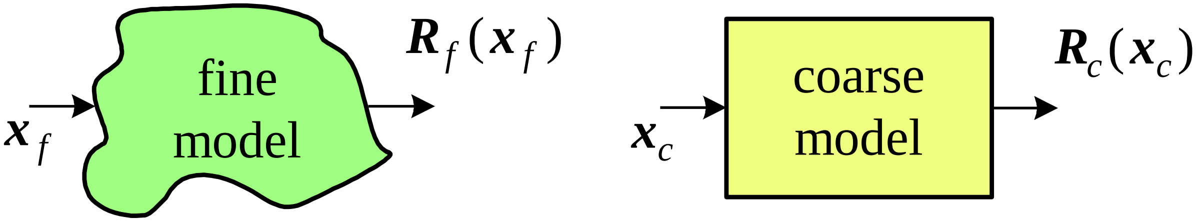
Space Mapping

(*Bandler et al., 1994*)



The Space Mapping Concept

(*Bandler et al., 1994-*)



$\boldsymbol{x}_f$

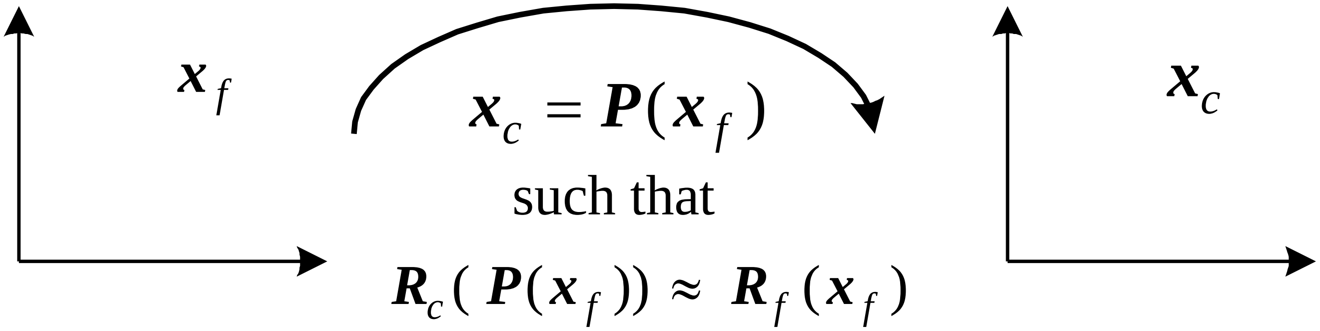
fine
model

$\boldsymbol{R}_f(\boldsymbol{x}_f)$

$\boldsymbol{x}_c$

coarse
model

$\boldsymbol{R}_c(\boldsymbol{x}_c)$



$\boldsymbol{x}_f$

$\boldsymbol{x}_c$

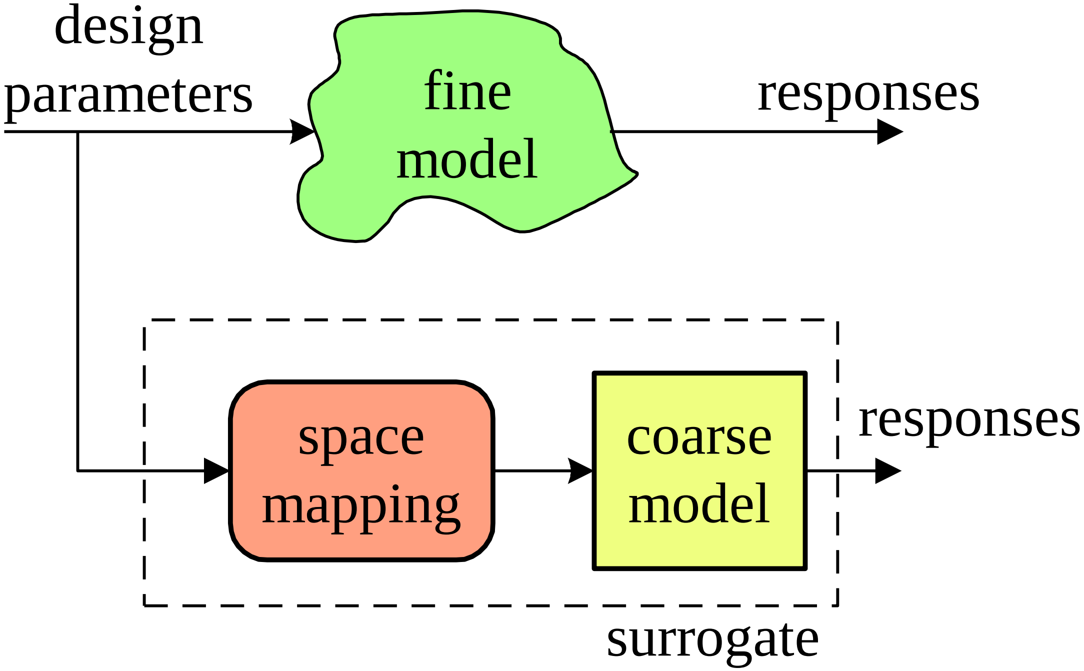
$$\boldsymbol{x}_c = \boldsymbol{P}(\boldsymbol{x}_f)$$

such that

$$\boldsymbol{R}_c(\boldsymbol{P}(\boldsymbol{x}_f)) \approx \boldsymbol{R}_f(\boldsymbol{x}_f)$$

Explicit Space Mapping Concept

(*Bandler et al., 1994-*)


design parameters

fine model

responses

space mapping

coarse model

responses

surrogate

used in the microwave industry (e.g., Com Dev, 2003-2004, for optimization of dielectric resonator filters and multiplexers)

Space Mapping: a Glossary of Terms

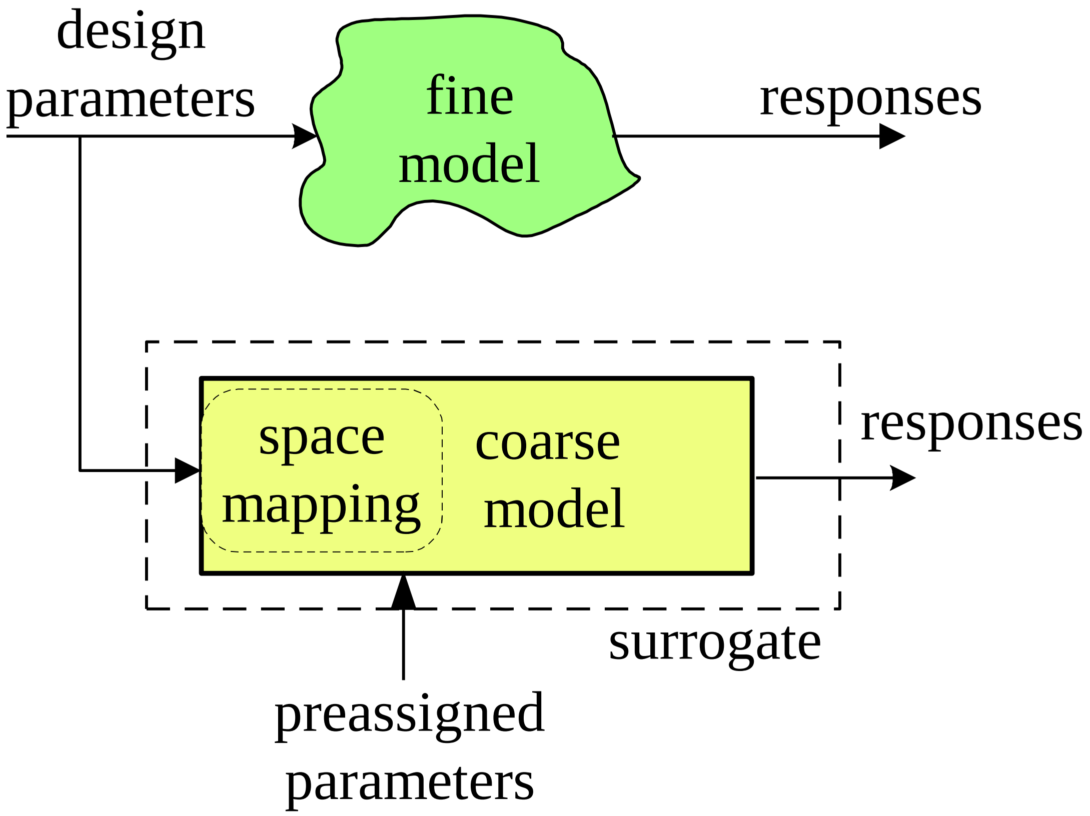
Space Mapping	transformation, link, adjustment, correction, shift (in parameters or responses)
Coarse Model	simplification or convenient representation, companion to the fine model, auxiliary representation, cheap model idealized model
Fine Model	accurate representation of system considered, device under test, component to be optimized, expensive model

Space Mapping: a Glossary of Terms

Surrogate	model, approximation or representation to be used, or to act, in place of, or as a substitute for, the system under consideration
Updated Surrogate	mapped or enhanced coarse model corrected coarse model
Surrogate Model	alternative expression for Surrogate
Target Response	response the fine model should achieve, (usually) optimal response of an idealized “coarse” model, an enhanced coarse model, or surrogate

Implicit Space Mapping Concept

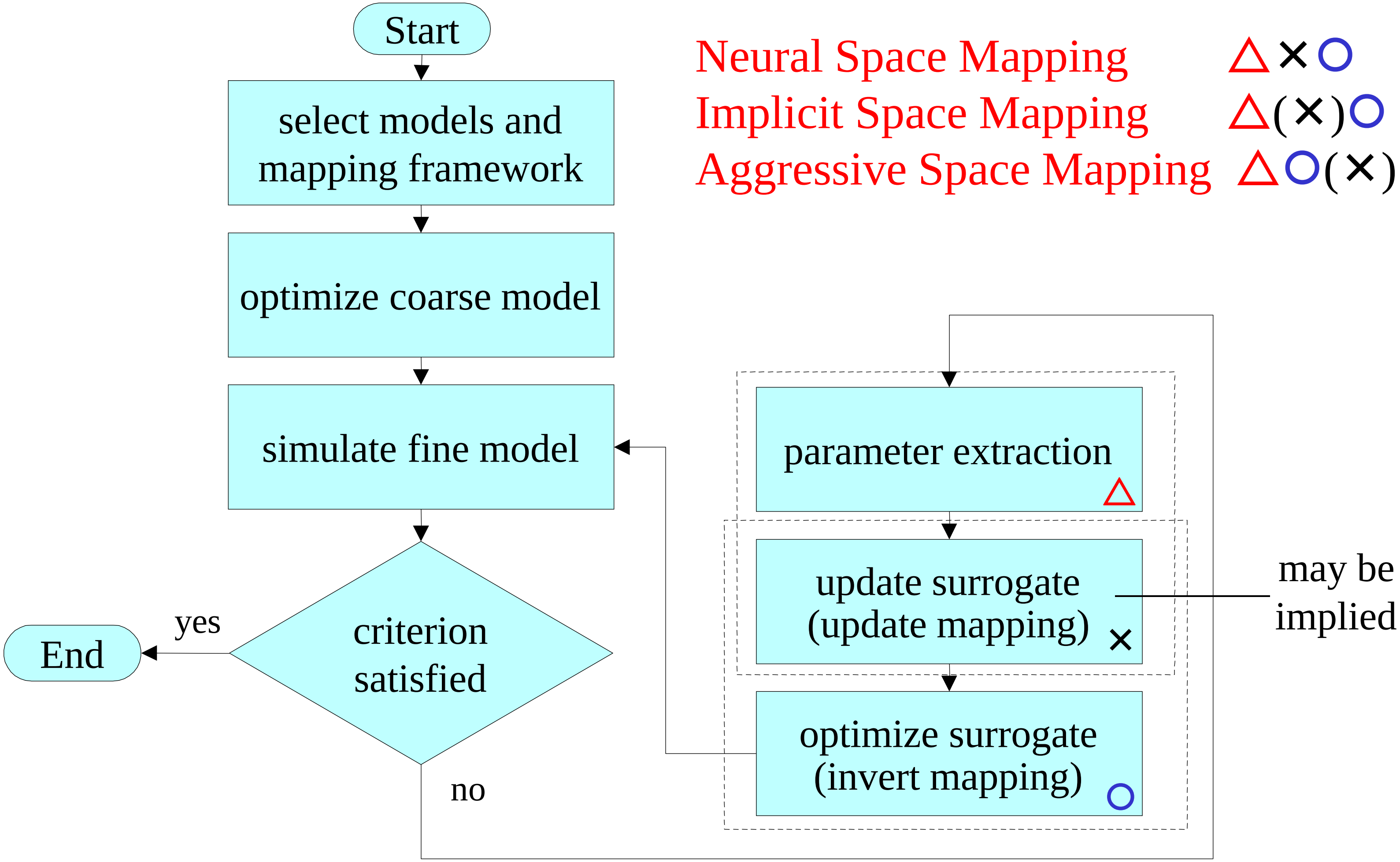
(*Bandler et al., 2004*)



Space Mapping Framework

(*Bandler et al., 2004*)

Neural Space Mapping △×○
Implicit Space Mapping △(×)○
Aggressive Space Mapping △○(×)



Start

select models and mapping framework

optimize coarse model

simulate fine model

criterion satisfied

yes

End

no

parameter extraction △

update surrogate (update mapping) ×

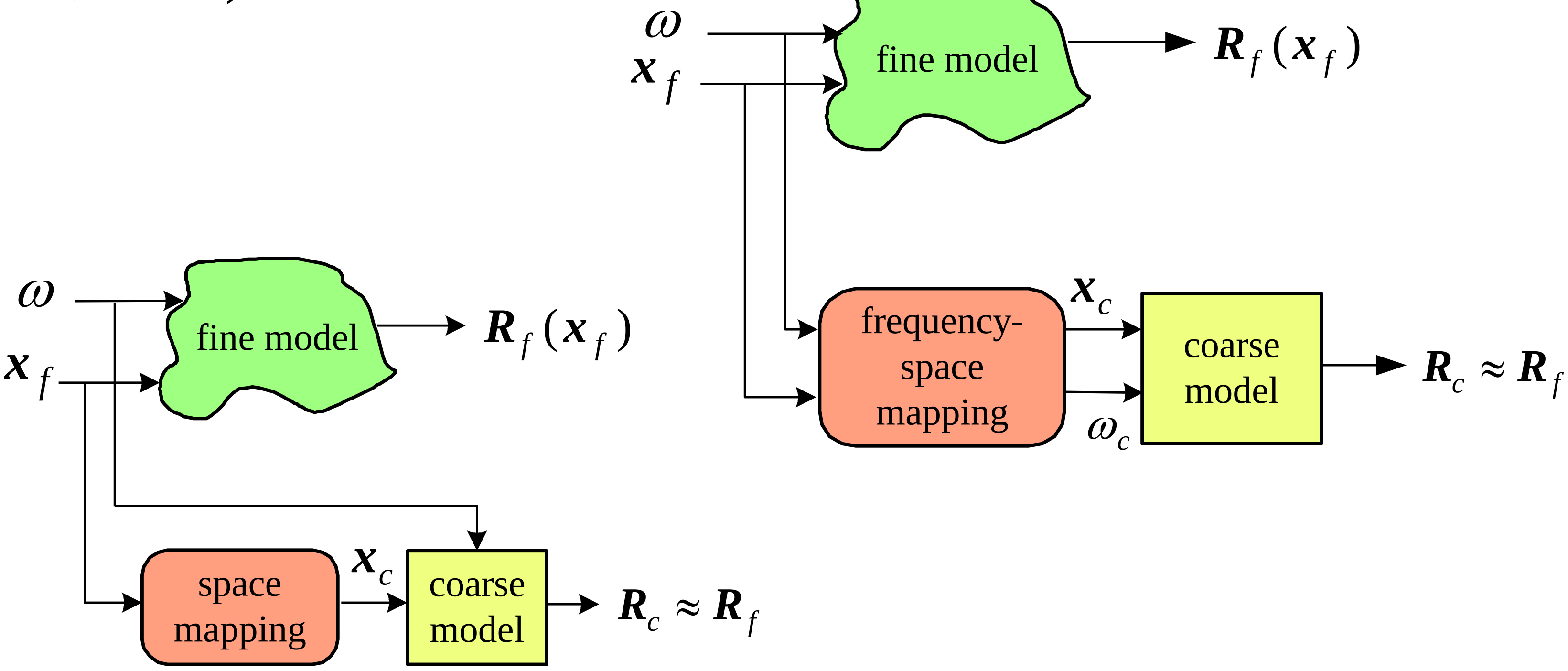
optimize surrogate (invert mapping) ○

may be implied

Model Enhancement—the SM Tableau Approach

(*Bandler et al., 2001*)

used in the RF industry (Philips) for new library models
(*Snel, 2001*)



Space Mapping Application to SAAB 9-3 Sport Sedan

(*Redhe et al., 2001-2003, Sweden*)

[type “saab space mapping” into Google]

In crashworthiness finite element simulations, each evaluation is expensive. Space Mapping reduces the total computing time to optimize the vehicle structure up to 50% compared to traditional optimization.

Space Mapping has been applied to the complete FE model of the new Saab 9-3 Sport Sedan. Intrusion into the passenger compartment area after the impact was reduced by 32% with no reduction in other crashworthiness responses.

Space Mapping Implementation and Applications 1

RF and microwave implementation (*Bandler et al., 1994-2004*)

civil engineering structural design (*Leary et al., 2000*)

SAAB crashworthiness design (*Redhe et al., 2001-2003*)

generating microwave neural models (*Devabhaktuni et al., 2002*)

combline filter design (*Swanson and Wenzel, 2001*)

microwave filter design (*Harscher, et al., 2002, 2003*)

CAD of integrated passive elements on PCBs (*Draxler, 2002*)

Space Mapping Implementation and Applications 2

CAD technique for microstrip filter design
(*Ye and Mansour, 1997*)

SM models (model enhancement) for RF components (*Snel, 2001*)

multilayer microwave circuits (LTCC) (*Pavio et al., 2002*)

cellular power amplifier output matching circuit (*Lobeek, 2002*)

multilevel ASM strategy applied to filter optimization
(*Safavi-Naeini et al., 2002*)

coupled resonator filter (*Pelz, 2002*)

Space Mapping Implementation and Applications 3

LTCC RF passive circuit design (*Wu et al., 2002-2004*)

waveguide filter design (*Steyn et al., 2001*)

inductively coupled filters (*Soto et al., 2000*)

magnetic systems (*Choi et al., 2001*)

Implicit Space Mapping optimization with preassigned parameters (*Bandler et al., 2002-2004*)

Output Space Mapping optimization (*Bandler et al., 2003-2004*)

Space Mapping Implementation and Applications 4

EM-based optimization of microwave oscillators
(*Rizzoli et al., 2003*)

circuit level, neuro-SM modeling of nonlinear devices
(*Zhang et al., 2003-2004*)

optimization of dielectric resonator filters and multiplexers
(*Ismail et al., 2003-2004*)

waveguide filter design (*Morro et al., 2003*)

optimal control of partial differential equations
(*Hintermueller and Vicente, 2003*)

Space Mapping Implementation and Applications 5

modeling and simulation of photonic devices
(*Feng and Huang, 2003*)

design of comb filters using implicit SM (*Gentili et al., 2003*)

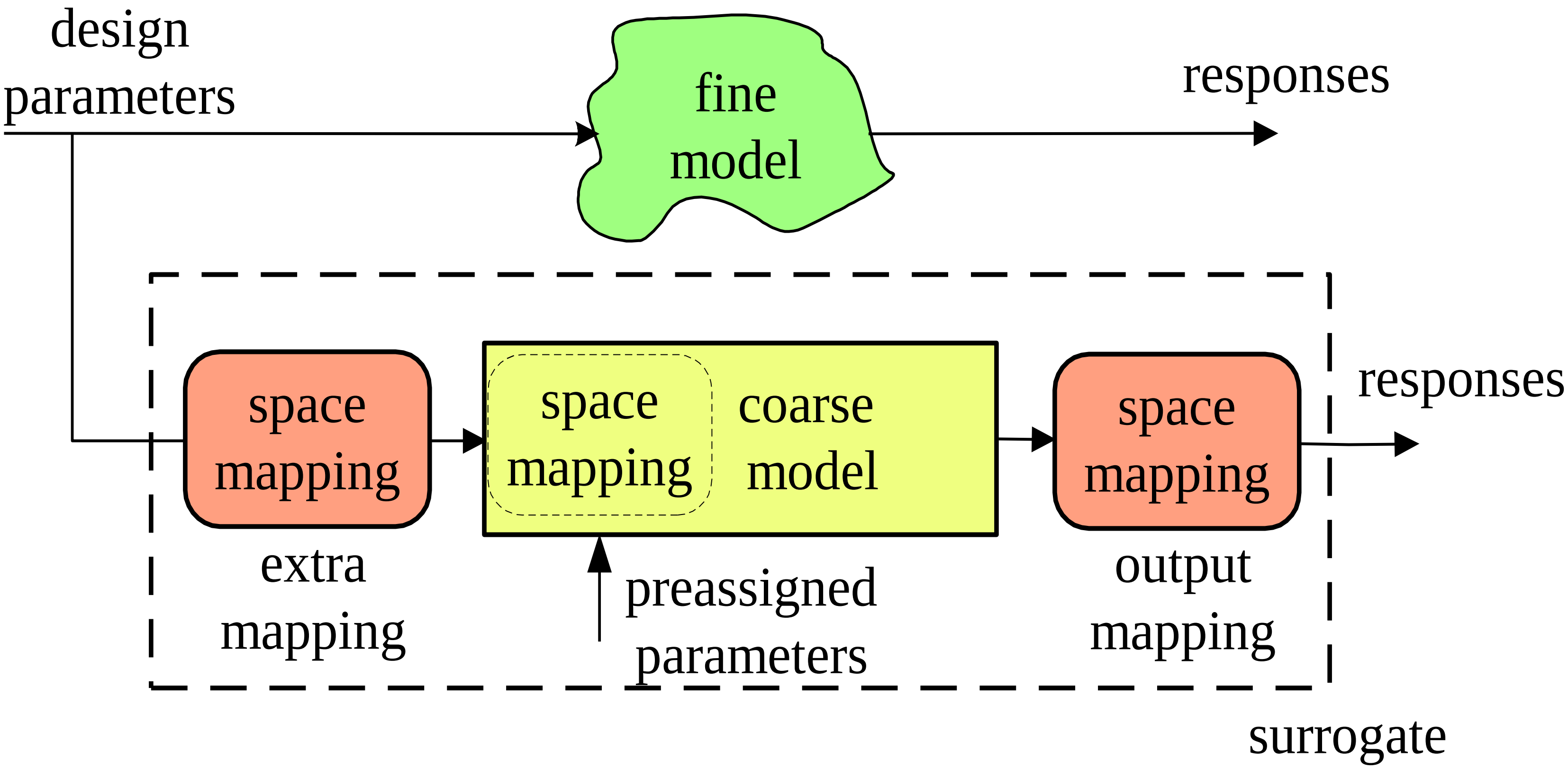
optimization of antireflection coatings in photonic devices
(*Feng et al., 2003*)

time-domain design, CMOS drivers, using linear inverse and neuro inverse SM (*Rayas-Sánchez, 2004*)

Space Mapping Interpolating Surrogates (SMIS) for highly optimized EM-based design (*Bandler et al., 2004*)

Implicit, Extra and Output Space Mappings

(*Bandler et al., 2003*)



design parameters

fine model

responses

space mapping

extra mapping

space mapping

coarse model

preassigned parameters

space mapping

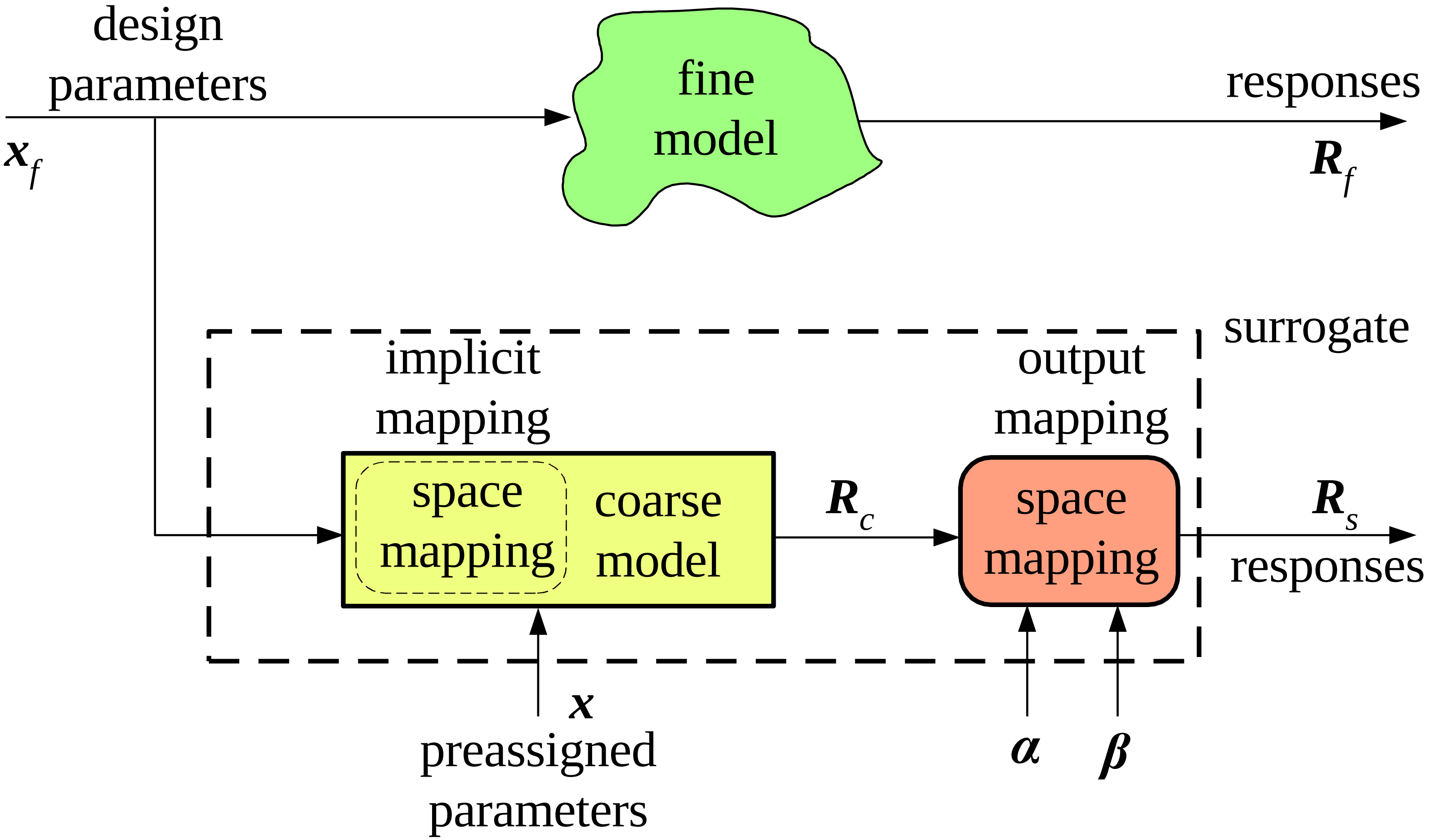
output mapping

responses

surrogate

Implicit and Output Space Mappings

(*Bandler et al., 2003*)



design parameters

$\boldsymbol{x}_f$

fine model

responses

$\boldsymbol{R}_f$

surrogate

implicit mapping

space mapping

coarse model

$\boldsymbol{R}_c$

output mapping

space mapping

$\boldsymbol{R}_s$

responses

$\boldsymbol{x}$

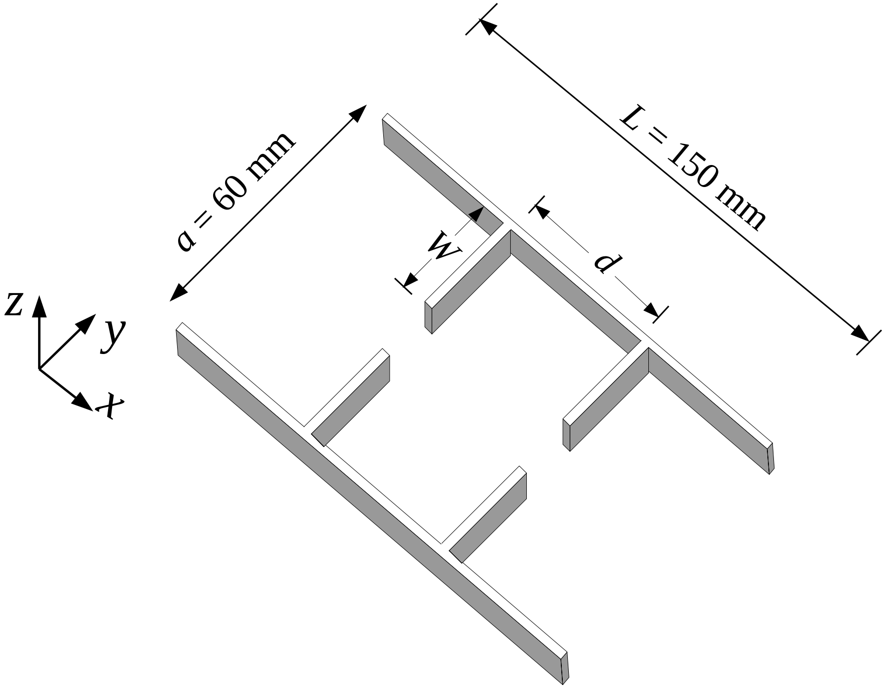
preassigned parameters

$\boldsymbol{\alpha}$ $\boldsymbol{\beta}$

Single Resonator Filter (*Bakr et. al, 2002*)

design of *d* and *W* with the waveguide dimensions fixed
(a = 60 mm and L = 150 mm)

Matlab implemented 2D TLM simulator is used (*Bakr 2004*)



Single Resonator Filter

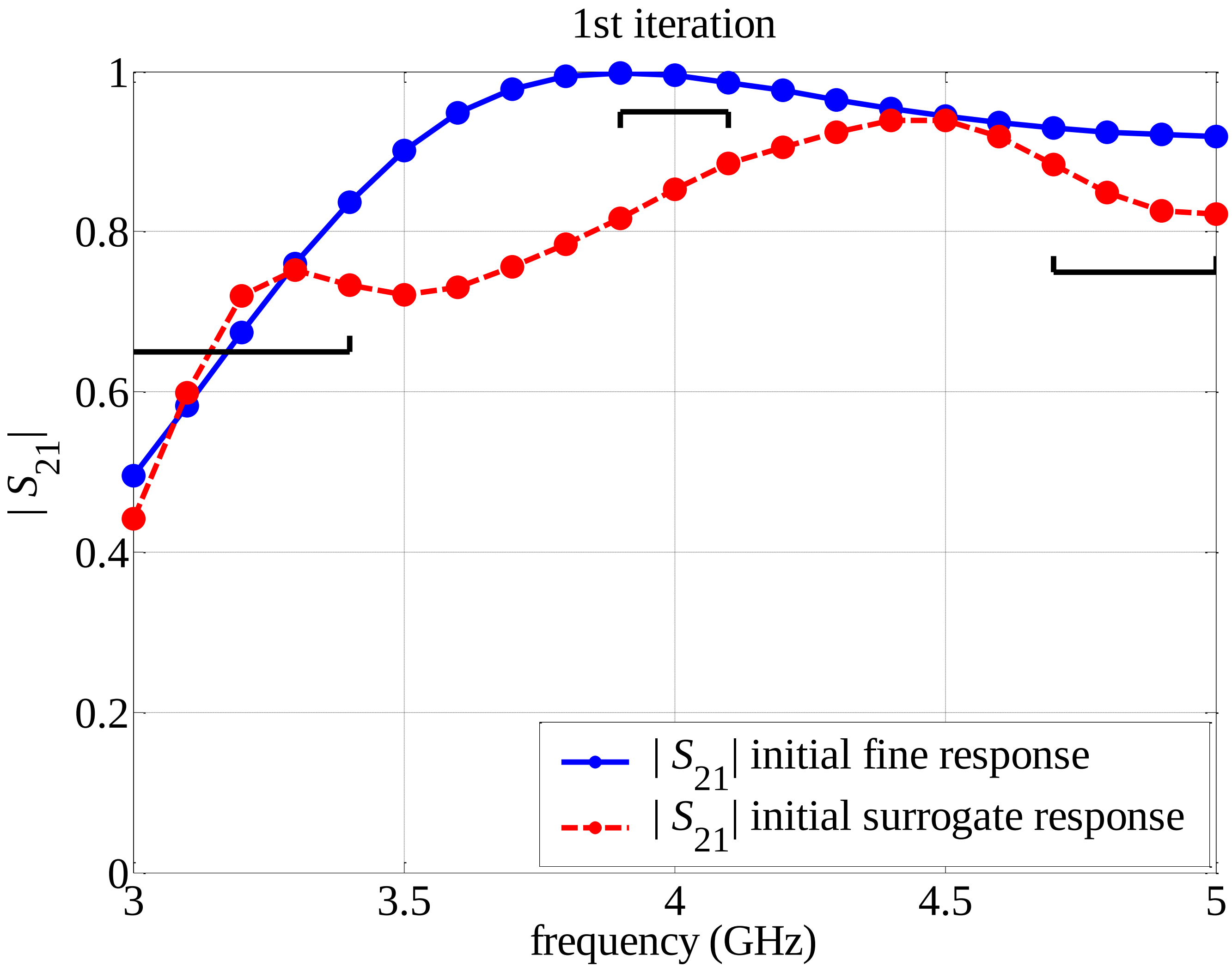
3.0 GHz $\leq \omega \leq$ 5.0 GHz with 0.1GHz step (21 points)

design parameters $x_f = [d \;\; W]^T$

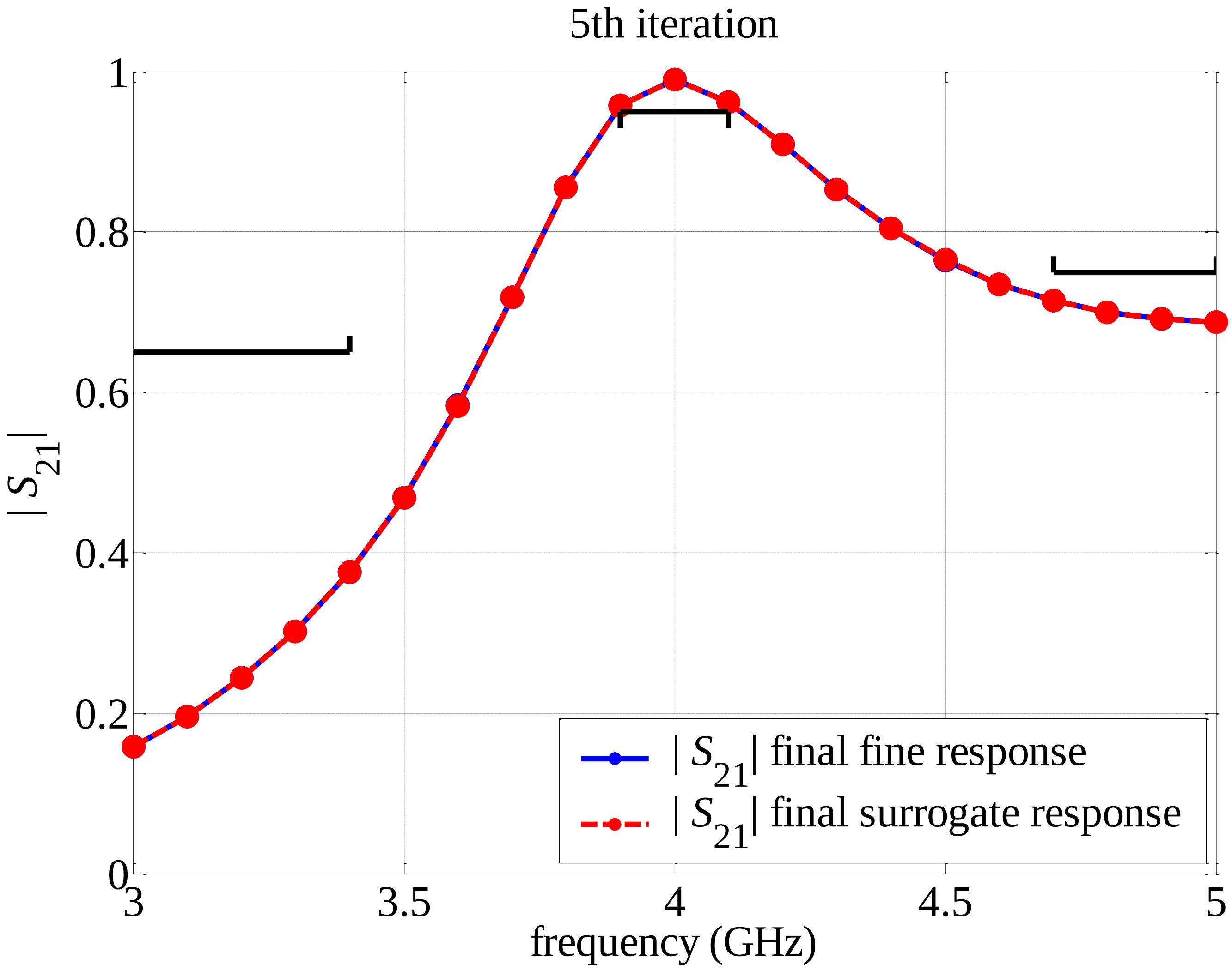
preassigned parameter $x = \varepsilon_r$

Fine Model	**Coarse Model**
$dx = dy = 1$ mm	$dx = dy = 5$ mm
$\Delta d = 2dx,\ \Delta W = dy$	$\Delta d = 2dx,\ \Delta W = dy$
$Nx = 150$	$Nx = 30$
$Ny = 30$	$Ny = 6$
Johns boundary	absorbing boundary at 4 GHz

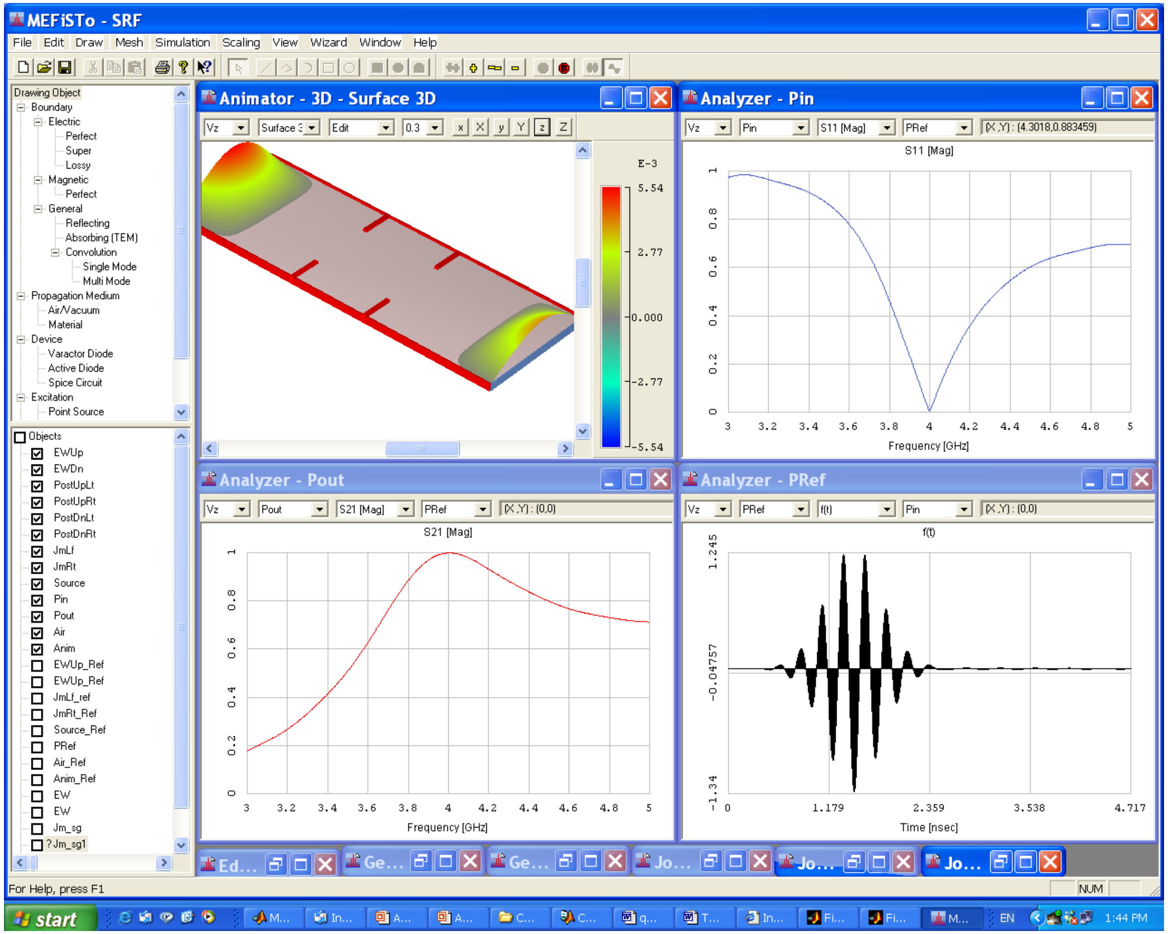
Single Resonator Filter



Single Resonator Filter



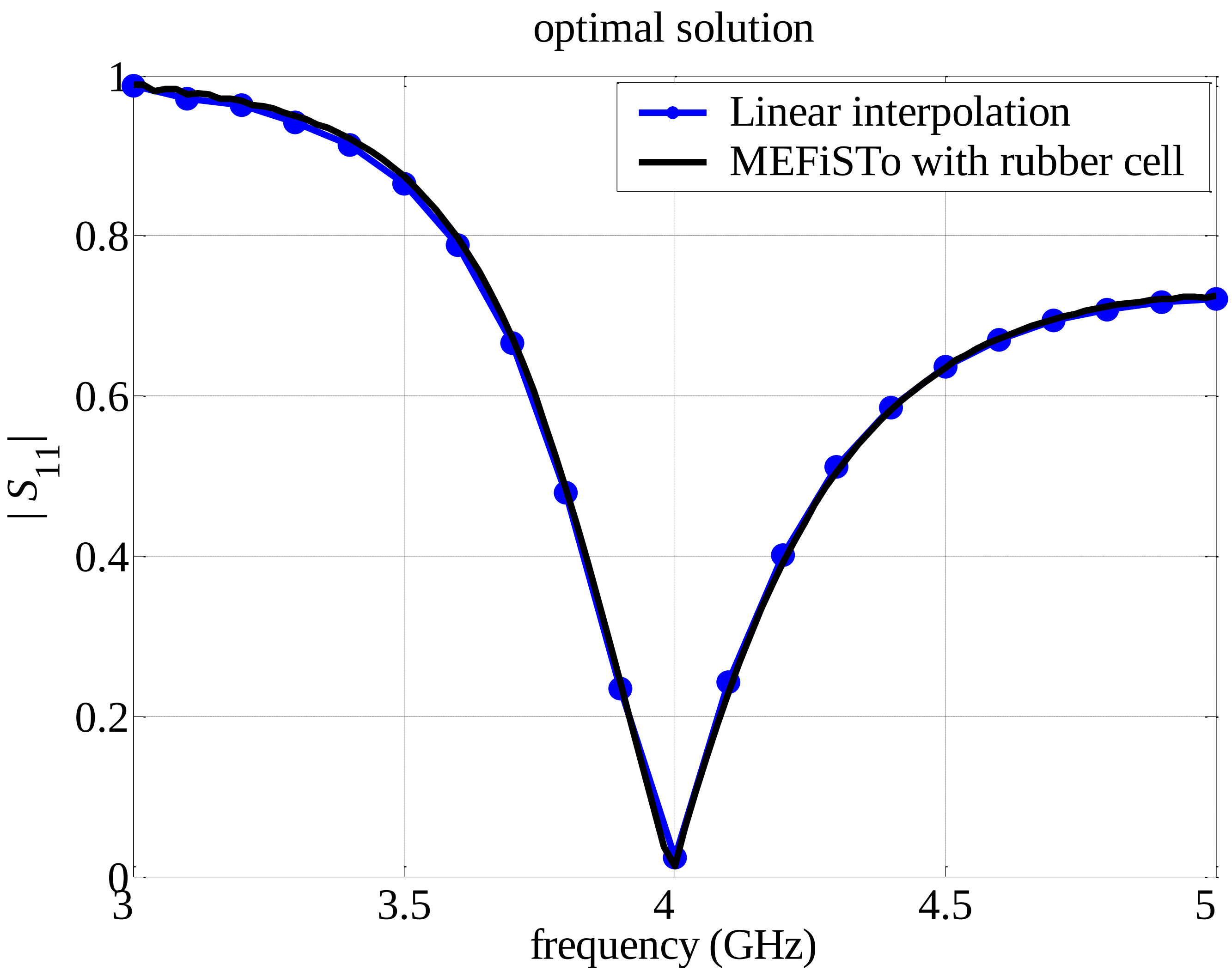
Single Resonator Filter MEFiSTo Validation



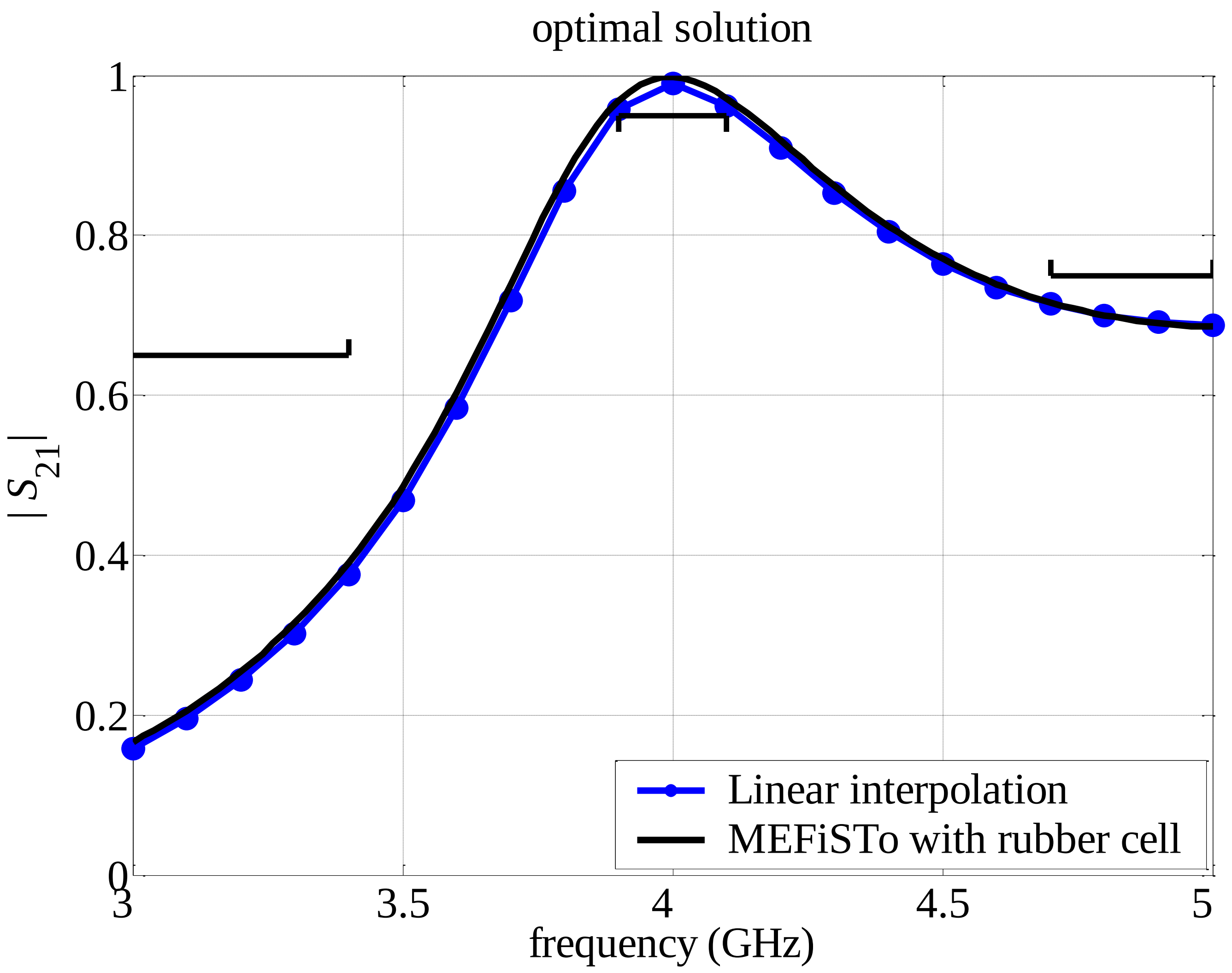
☐ Objects
☑ EWUp
☑ EWDn
☑ PostUpLt
☑ PostUpRt
☑ PostDnLt
☑ PostDnRt
☑ JmLf
☑ JmRt
☑ Source
☑ Pin
☑ Pout
☑ Air
☑ Anim
☐ EWUp_Ref
☐ EWUp_Ref
☐ JmLf_ref
☐ JmRt_Ref
☐ Source_Ref
☐ PRef
☐ Air_Ref
☐ Anim_Ref
☐ EW
☐ EW
☐ Jm_sg
☐ ? Jm_sg1

For Help, press F1

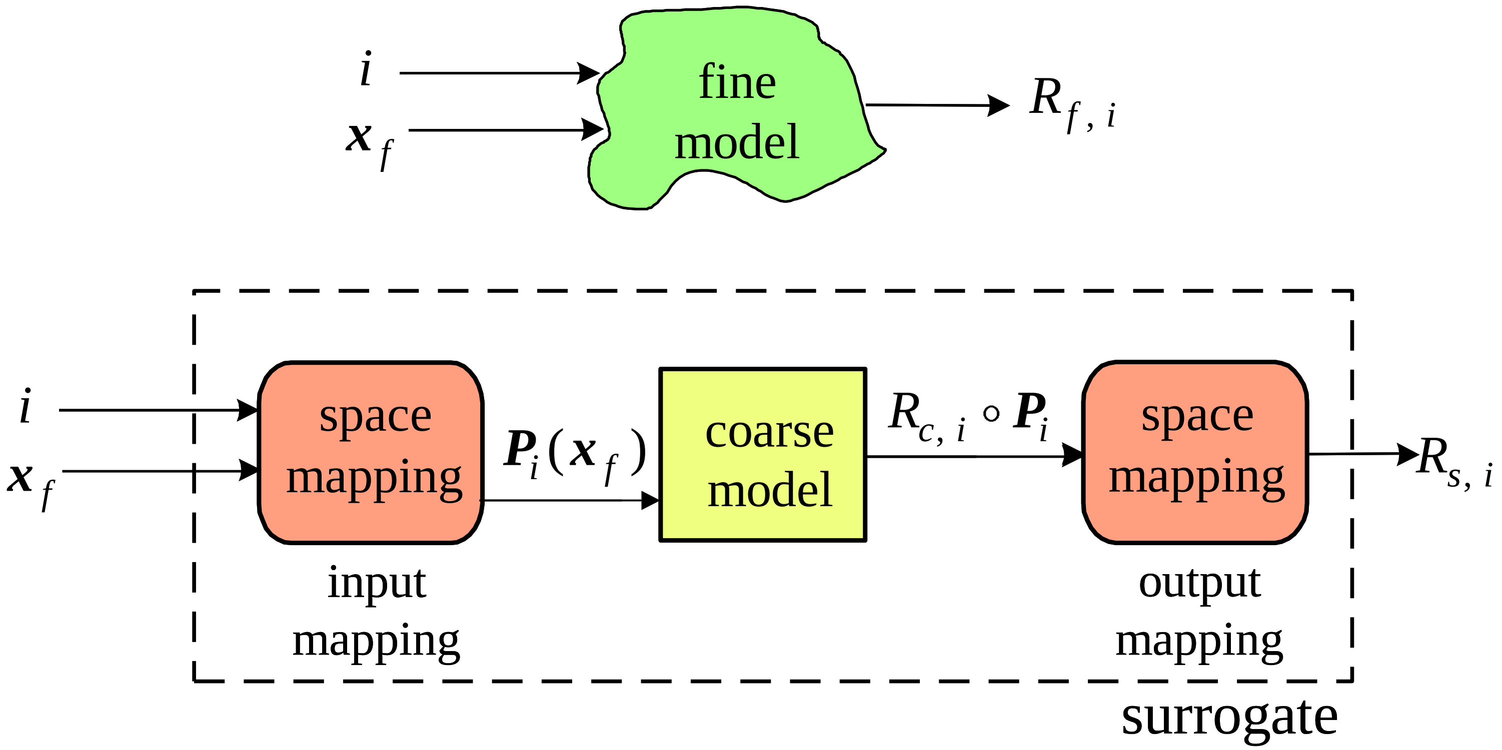
Single Resonator Filter Final Design



Single Resonator Filter Final Design



SM-based Interpolating Surrogate (SMIS) Concept



i

$\boldsymbol{x}_f$

fine model

$R_{f,i}$

i

$\boldsymbol{x}_f$

space mapping

input mapping

$\boldsymbol{P}_i(\boldsymbol{x}_f)$

coarse model

$R_{c,i} \circ \boldsymbol{P}_i$

space mapping

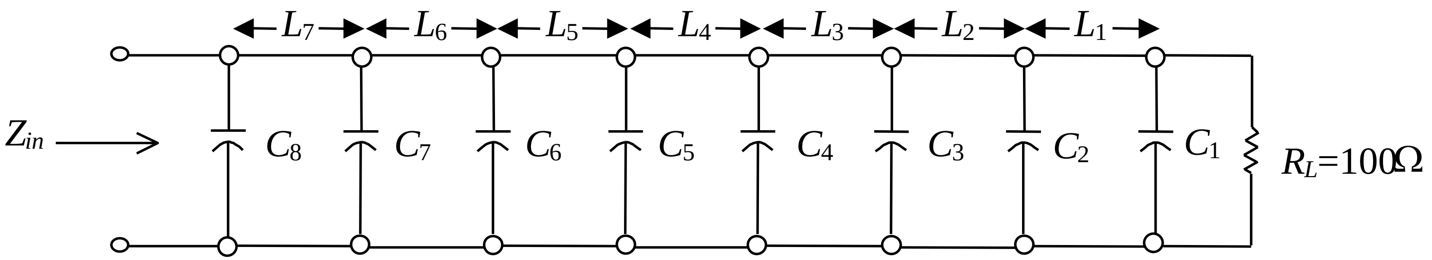
output mapping

$R_{s,i}$

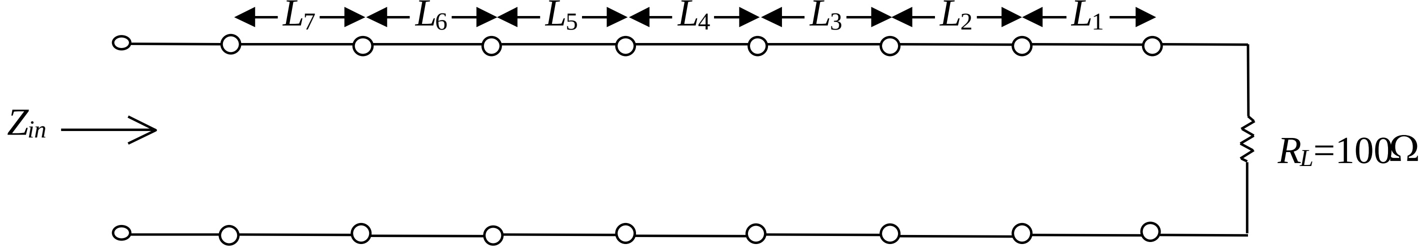
surrogate

Seven-Section Capacitively-Loaded Impedance Transformer Matlab Implementation (*Bandler, 2001*)

fine model



coarse model



R_g = 50 Ω, C_1, . . . , C_8 = 0.025 pF
68 point frequency sweep

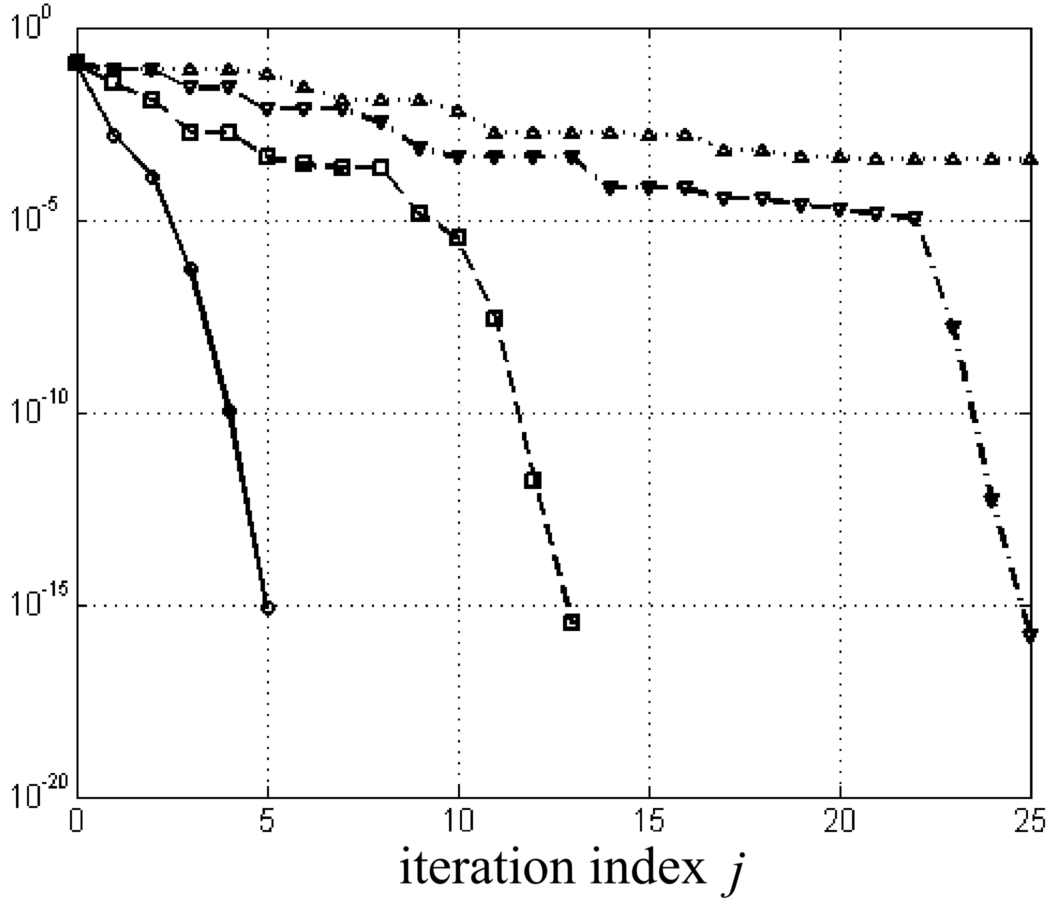
specifications
$|S_{11}| \le 0.07$ for 1 GHz ≤ ω ≤ 7.7 GHz

Seven-Section Capacitively-Loaded Impedance Transformer Matlab Implementation (*Bandler, Hailu et al., 2004*)

parameter	initial solution (m)	solution reached by the SMIS algorithm (m)	solution reached by direct optimization (m)
L_1	0.01724138	0.01564205	0.01564205
L_2	0.01724138	0.01638347	0.01638347
L_3	0.01724138	0.01677145	0.01677145
L_4	0.01724138	0.01697807	0.01697807
L_5	0.01724138	0.01709879	0.01709879
L_6	0.01724138	0.01723238	0.01723238
L_7	0.01724138	0.01625988	0.01625988

Seven-Section Capacitively-Loaded Impedance Transformer Matlab Implementation (*Bandler, Hailu et al., 2004*)

$$U_f^{(j+1)} - U_f^*$$



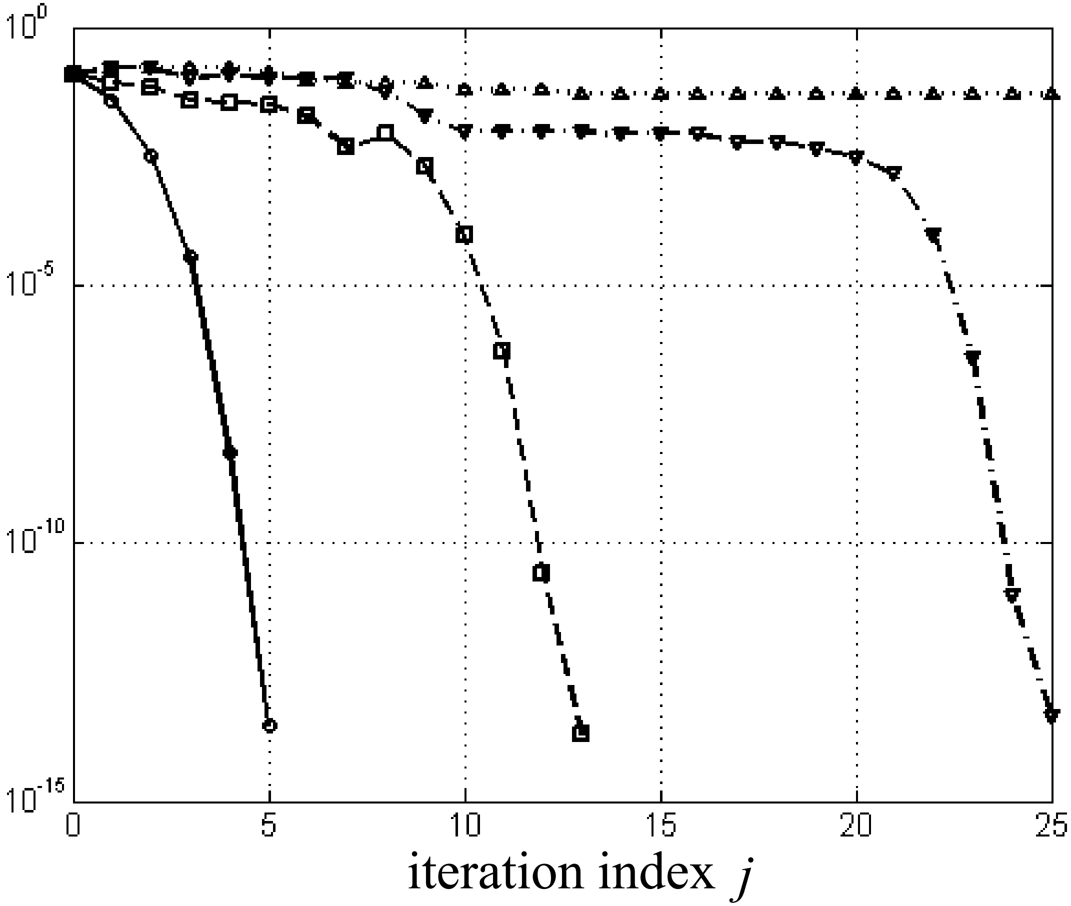
HASM using Broyden (△)

$$U_f = \max_{1 \le i \le m} \left| S_{11,i} \right|$$

SMIS algorithm (○) , Hald-Madsen algorithm (□) , HASM (▽) using exact gradients

Seven-Section Capacitively-Loaded Impedance Transformer Matlab Implementation (*Bandler, Hailu et al., 2004*)

$$\left\| \boldsymbol{x}_f^{(j+1)} - \boldsymbol{x}_f^{*} \right\|_2$$



HASM using Broyden (△)

SMIS algorithm (○) , Hald-Madsen algorithm (□) , HASM (▽) using exact gradients

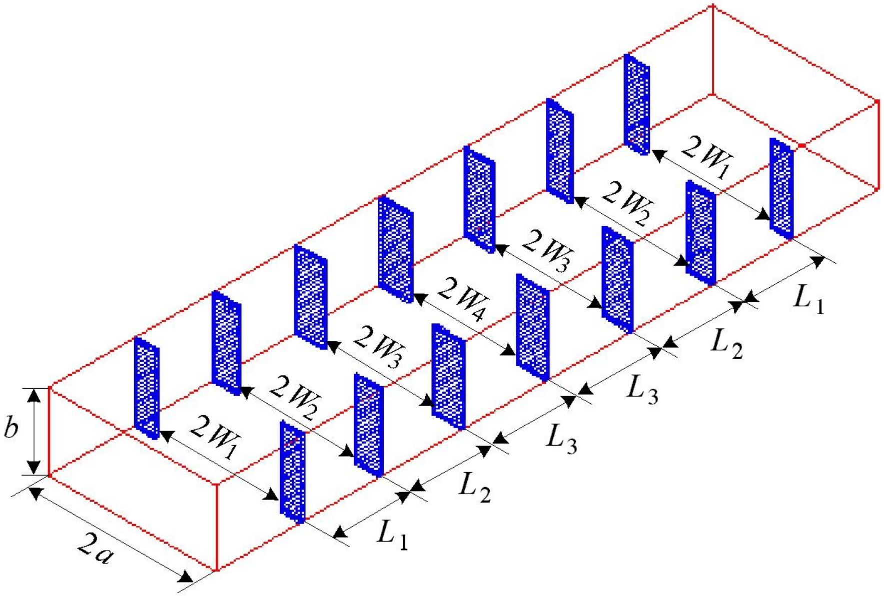
Optimization methods used on the Section Capacitively-Loaded Impedance Transformer (*Bandler, Hailu et al., 2004*)

method	number of iterations	number of fine model evaluations
fminimax*	14	153
HASM	25	26
Hald-Madsen	13	13
SMIS	5	6

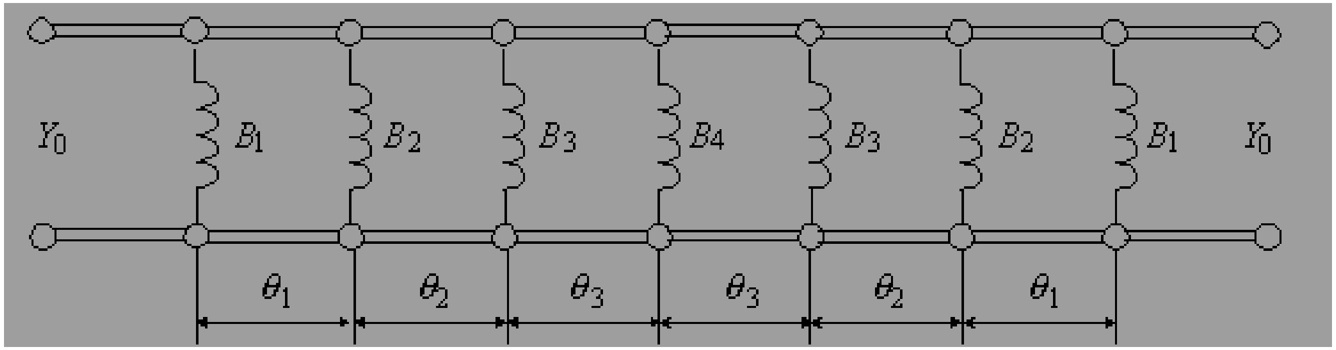
*the fminimax routine available in the Matlab Optimization Toolbox

H-plane Waveguide Filter Design (*Young et. al., 1963, Bakr et al., 1999*)

H-plane filter



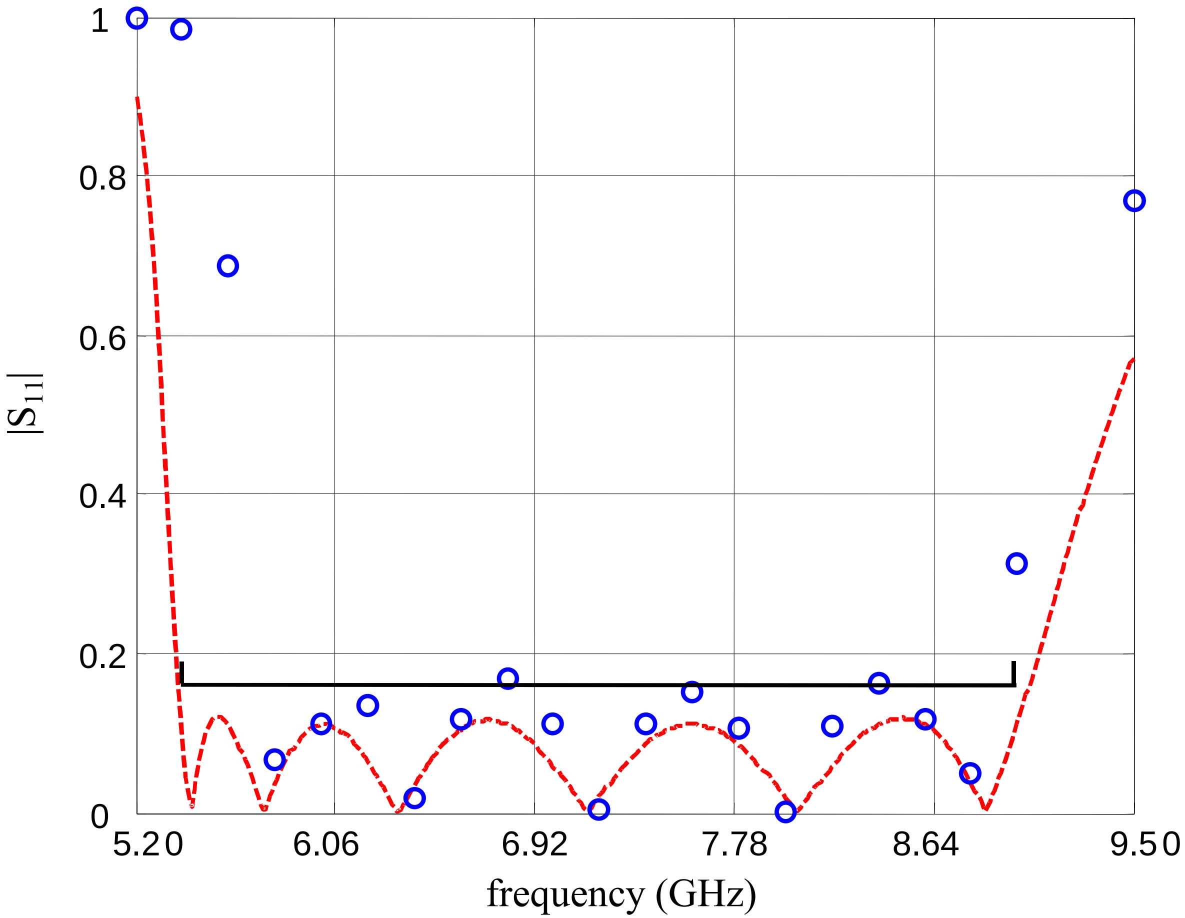
circuit model (*Marcuvitz,1951*)



H-plane Waveguide Filter Design

optimal coarse model response (---)

initial fine model* response (○)

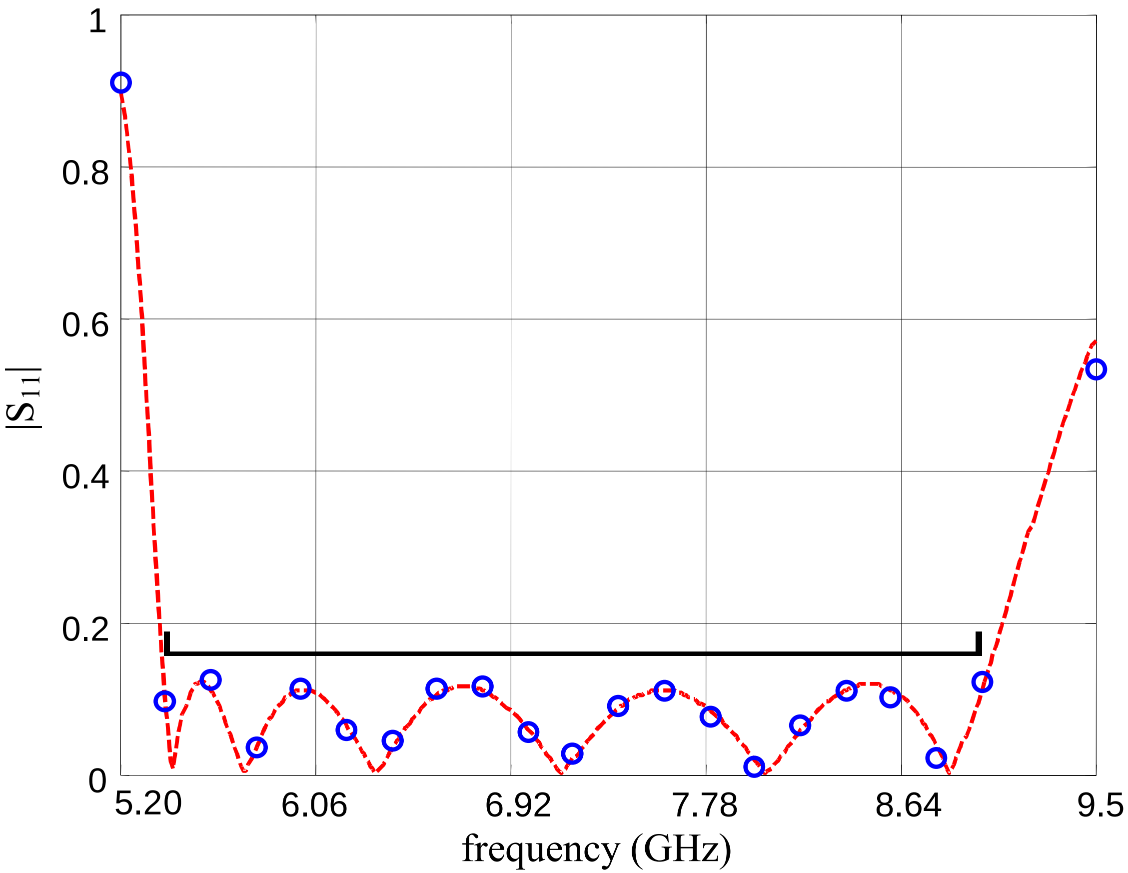


*the fine model exploits Agilent HFSS

H-plane Waveguide Filter Design

optimal coarse model response (---)

fine model* (○)
SMIS algorithm,
3 iterations,
4 frequency sweeps
(excluding Jacobian estimations)



*the fine model exploits Agilent HFSS

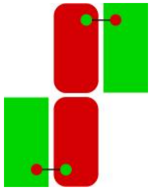
Space Mapping Technology: Current and Future Work

new framework and optimization algorithms
rigorous convergence proofs
(collaboration with Dr. K. Madsen, DTU, Denmark)

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

TLM-based modeling and design (with Dr. M. Bakr)

exploitation of adjoint sensitivities for coarse and fine model EM solvers (with Drs. M. Bakr and N. Nikolova)



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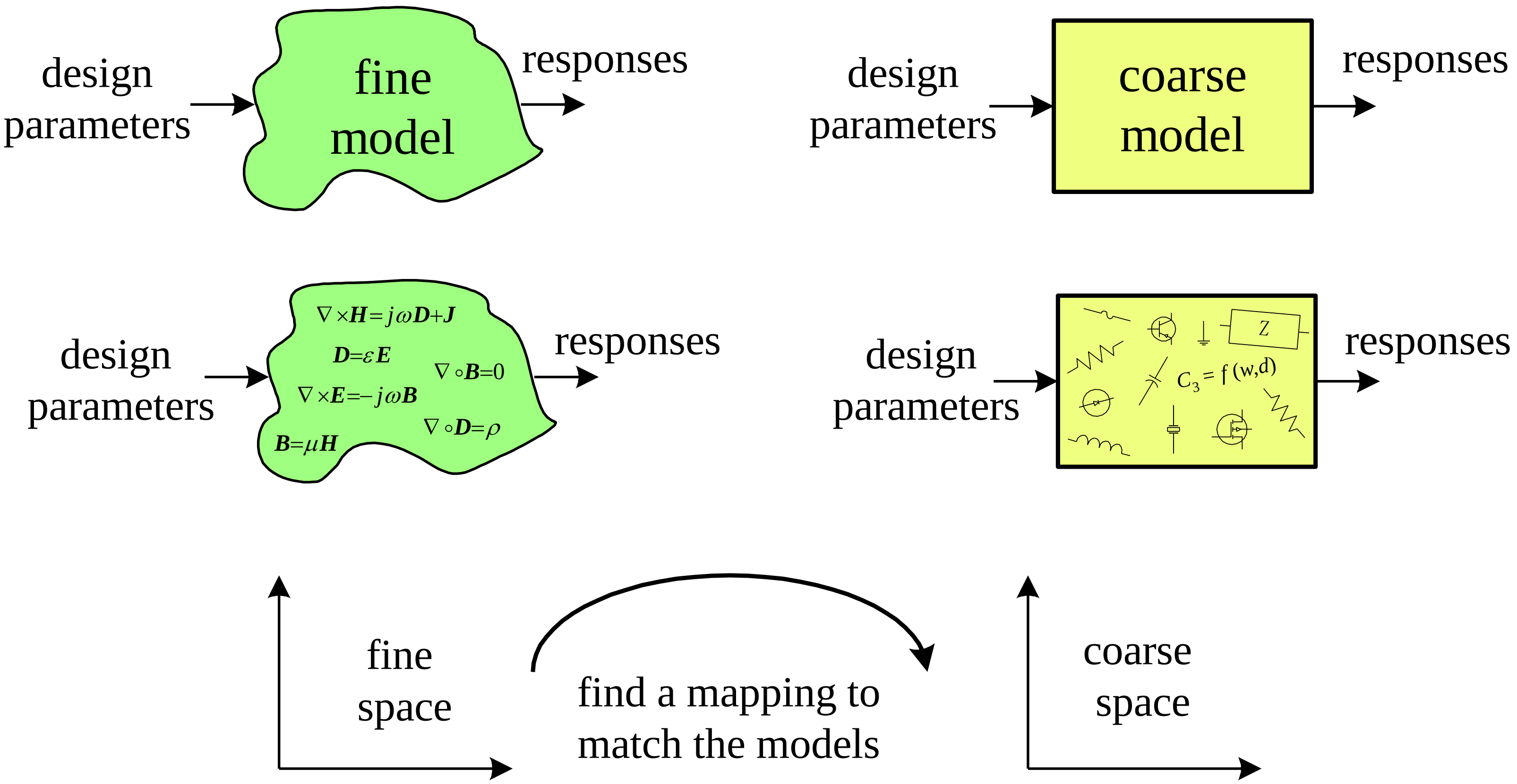
J.W. Bandler, Q.S. Cheng, D.M. Hailu and N.K. Nikolova, “A space-mapping design framework,” *IEEE Trans. Microwave Theory and Tech.*, vol. 52, pp. 2601–2610, Nov. 2004.

J.W. Bandler, D.M. Hailu, K. Madsen and F. Pedersen, “A space-mapping interpolating surrogate algorithm for highly optimized EM-based design of microwave devices,” *IEEE Trans. Microwave Theory and Tech.*, vol. 52, pp. 2593–2600, Nov. 2004.

Linking Companion Coarse (Empirical) and Fine (EM) Models



design parameters → fine model → responses

design parameters → coarse model → responses

design parameters → responses

$\nabla \times \boldsymbol{H} = j\omega \boldsymbol{D} + \boldsymbol{J}$

$\boldsymbol{D} = \varepsilon \boldsymbol{E}$

$\nabla \circ \boldsymbol{B} = 0$

$\nabla \times \boldsymbol{E} = -j\omega \boldsymbol{B}$

$\nabla \circ \boldsymbol{D} = \rho$

$\boldsymbol{B} = \mu \boldsymbol{H}$

design parameters → responses

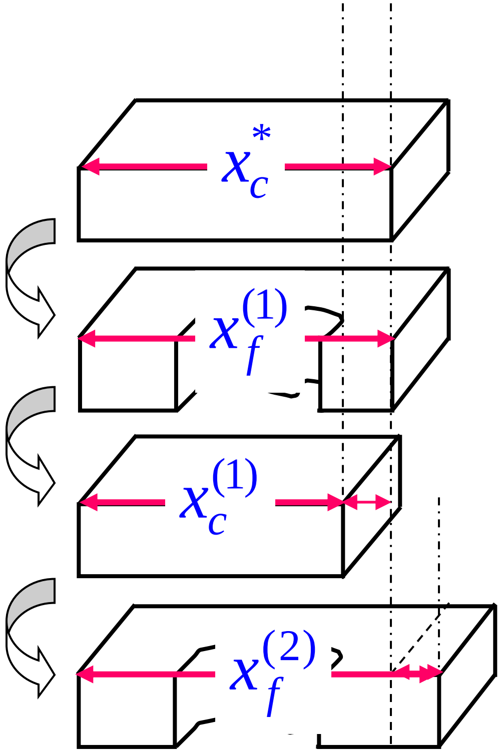
fine space

find a mapping to match the models

coarse space

Aggressive Space Mapping Practice—Cheese Cutting Problem

(*Bandler et al., 2002*)



optimal coarse model

initial guess

PE

prediction

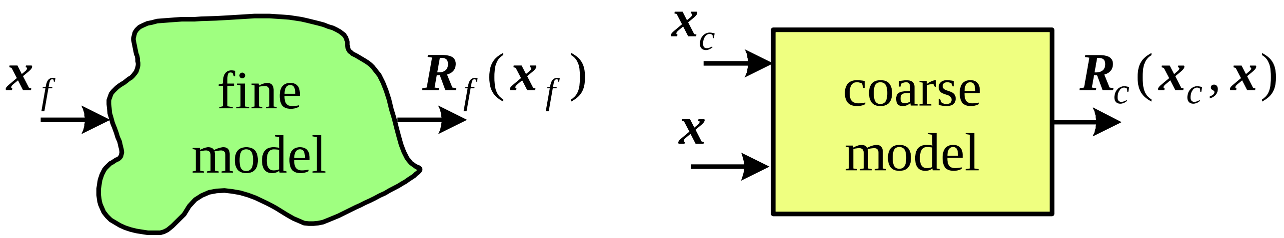
$$x_f^{(1)} = x_c^*$$

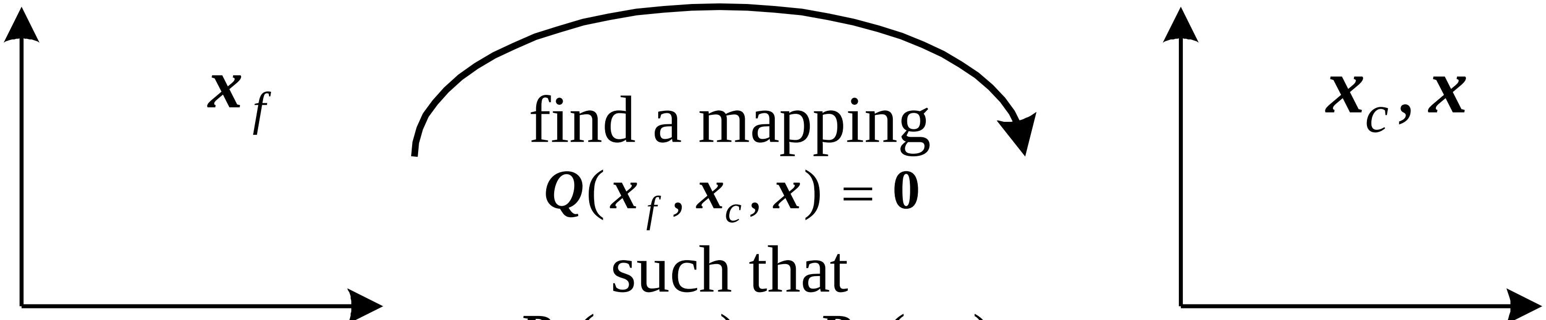
$$x_f^{(2)} = x_f^{(1)} + P^{-1}(x_c^* - x_c^{(1)})$$

$$x_f^{(2)} = x_f^{(1)} + x_c^* - x_c^{(1)}$$

Implicit Space Mapping Theory: Modeling

implicit mapping $\boldsymbol{Q}$ between the spaces $\boldsymbol{x}_f$, $\boldsymbol{x}_c$ and $\boldsymbol{x}$





find a mapping

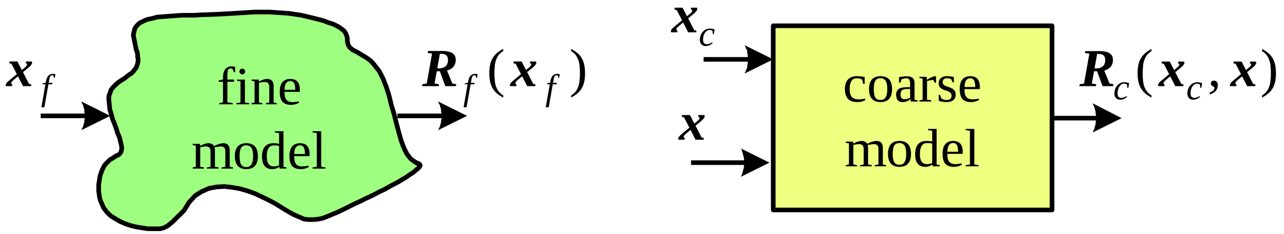
$$\boldsymbol{Q}(\boldsymbol{x}_f, \boldsymbol{x}_c, \boldsymbol{x}) = \boldsymbol{0}$$

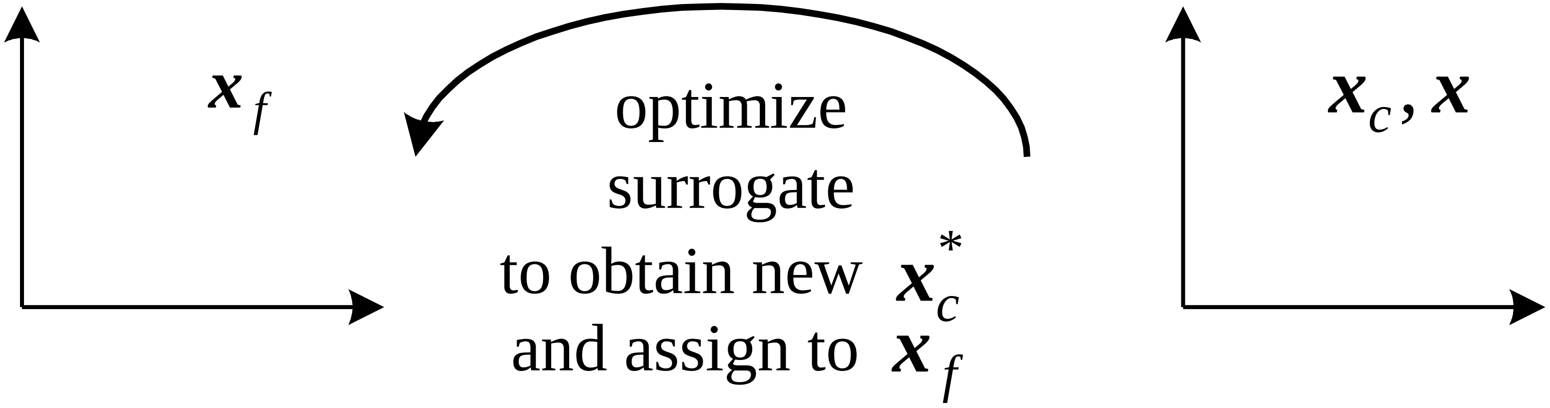
such that

$$\boldsymbol{R}_c(\boldsymbol{x}_c, \boldsymbol{x}) \approx \boldsymbol{R}_f(\boldsymbol{x}_f)$$

Implicit Space Mapping Theory: Prediction

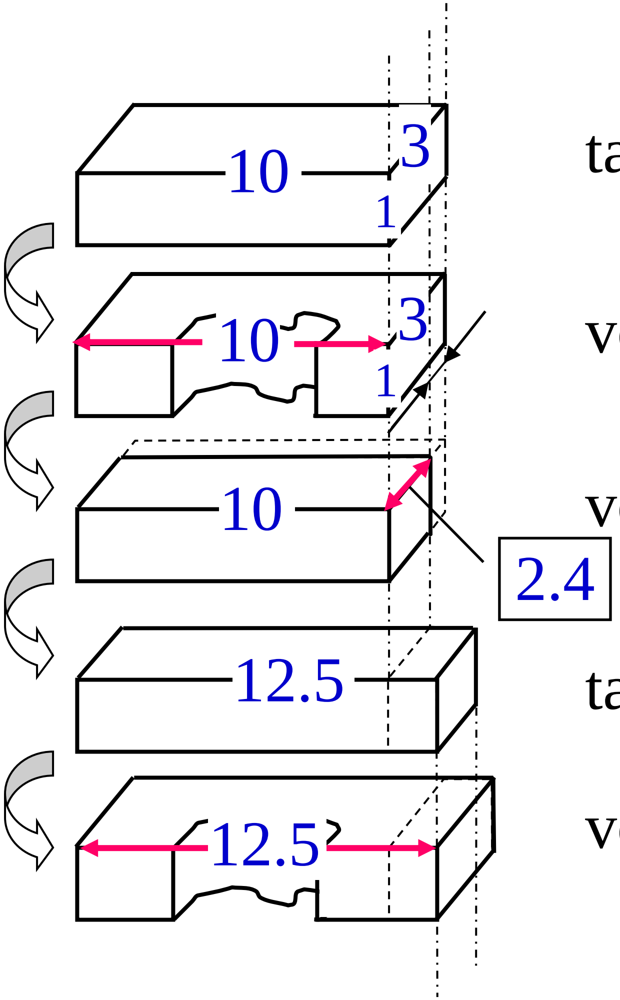
implicit mapping $\boldsymbol{Q}$ between the spaces $\boldsymbol{x}_f$, $\boldsymbol{x}_c$ and $\boldsymbol{x}$





optimize
surrogate
to obtain new $\boldsymbol{x}_c^*$
and assign to $\boldsymbol{x}_f$

Cheese Cutting Problem—A Numerical Example of ISM



optimal coarse model — target volume =30

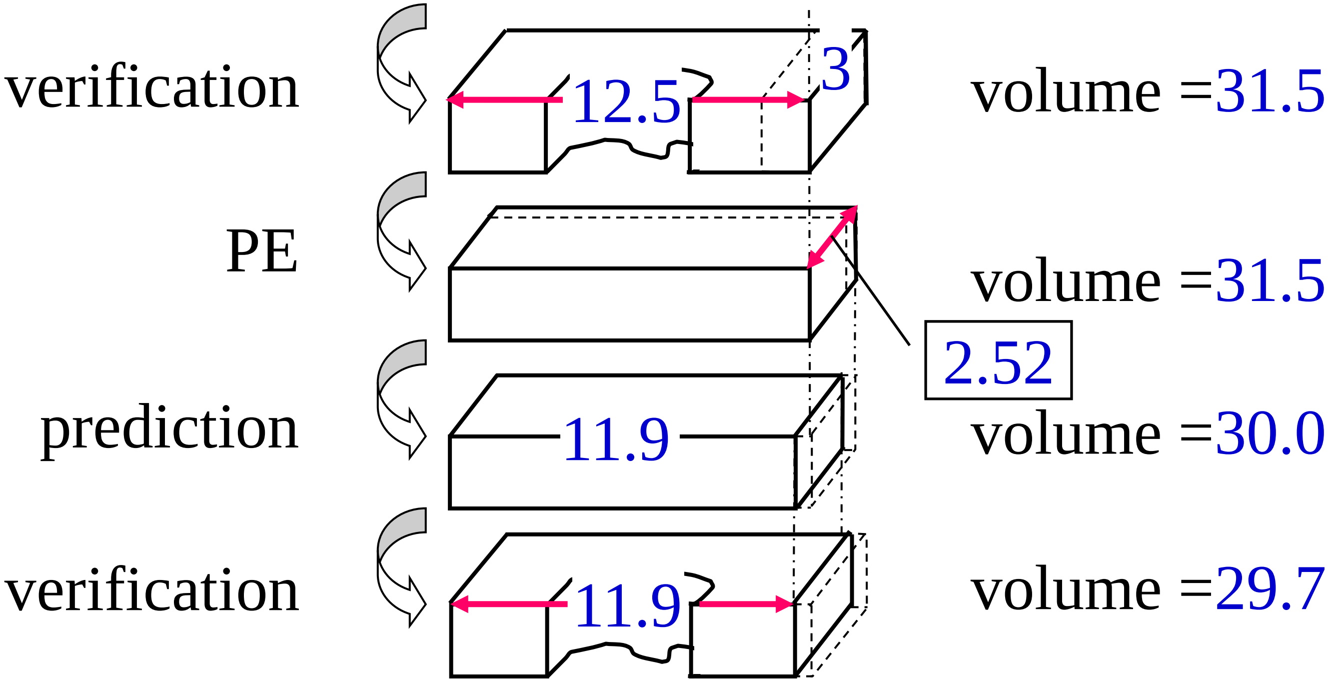
initial guess — volume =24

PE — volume =24

prediction — target volume =30

verification — volume =31.5

Cheese Cutting Problem—A Numerical Example of ISM



verification — volume =31.5

PE — volume =31.5

prediction — volume =30.0

verification — volume =29.7

⋮

Single Resonator Filter

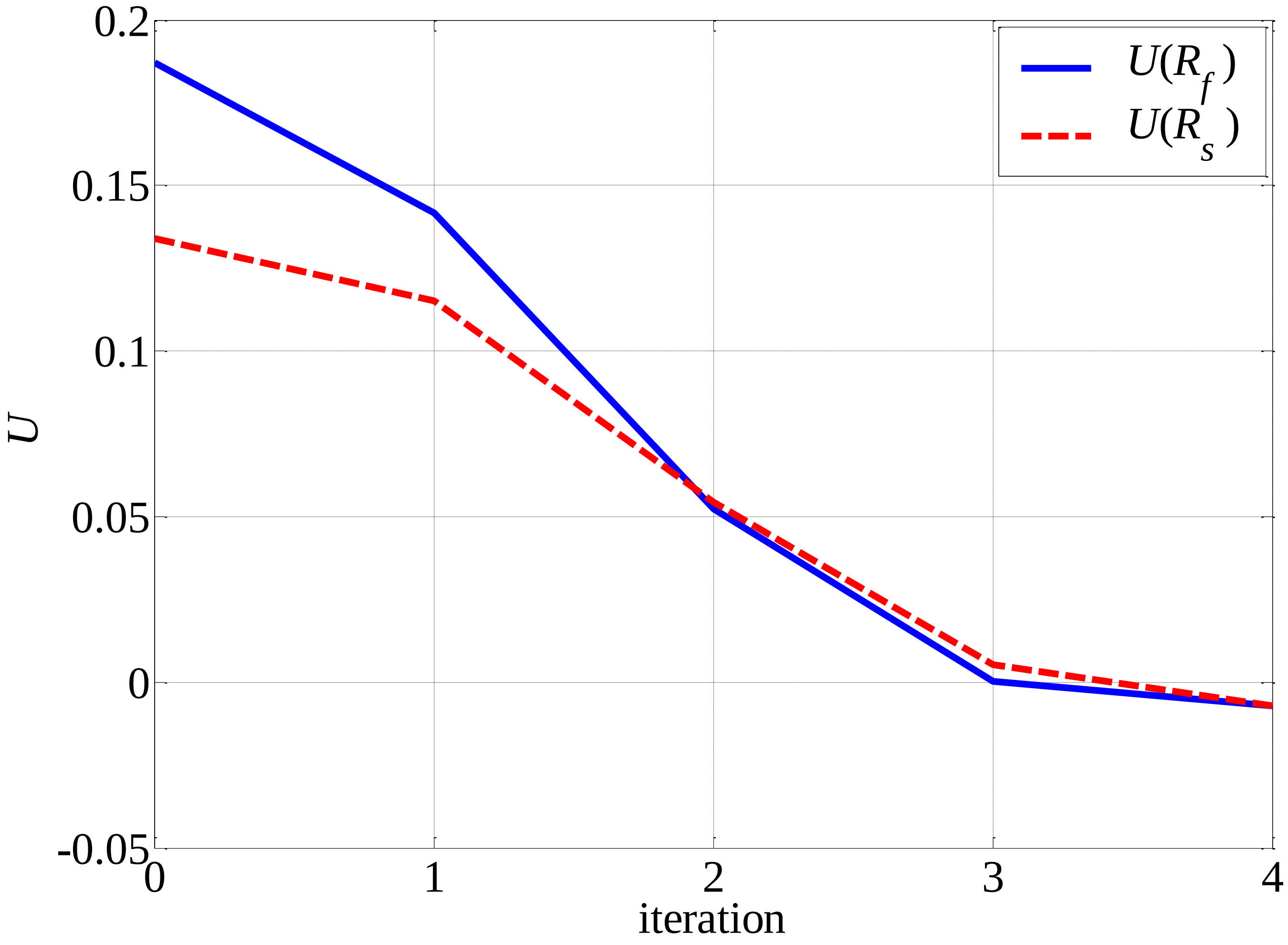
minimax objective function with upper and lower design specifications

$$|S_{21}| \le 0.65 \text{ for } 3.0 \text{ GHz} \le \omega \le 3.4 \text{ GHz}$$

$$|S_{21}| \ge 0.95 \text{ for } 3.9 \text{ GHz} \le \omega \le 4.1 \text{ GHz}$$

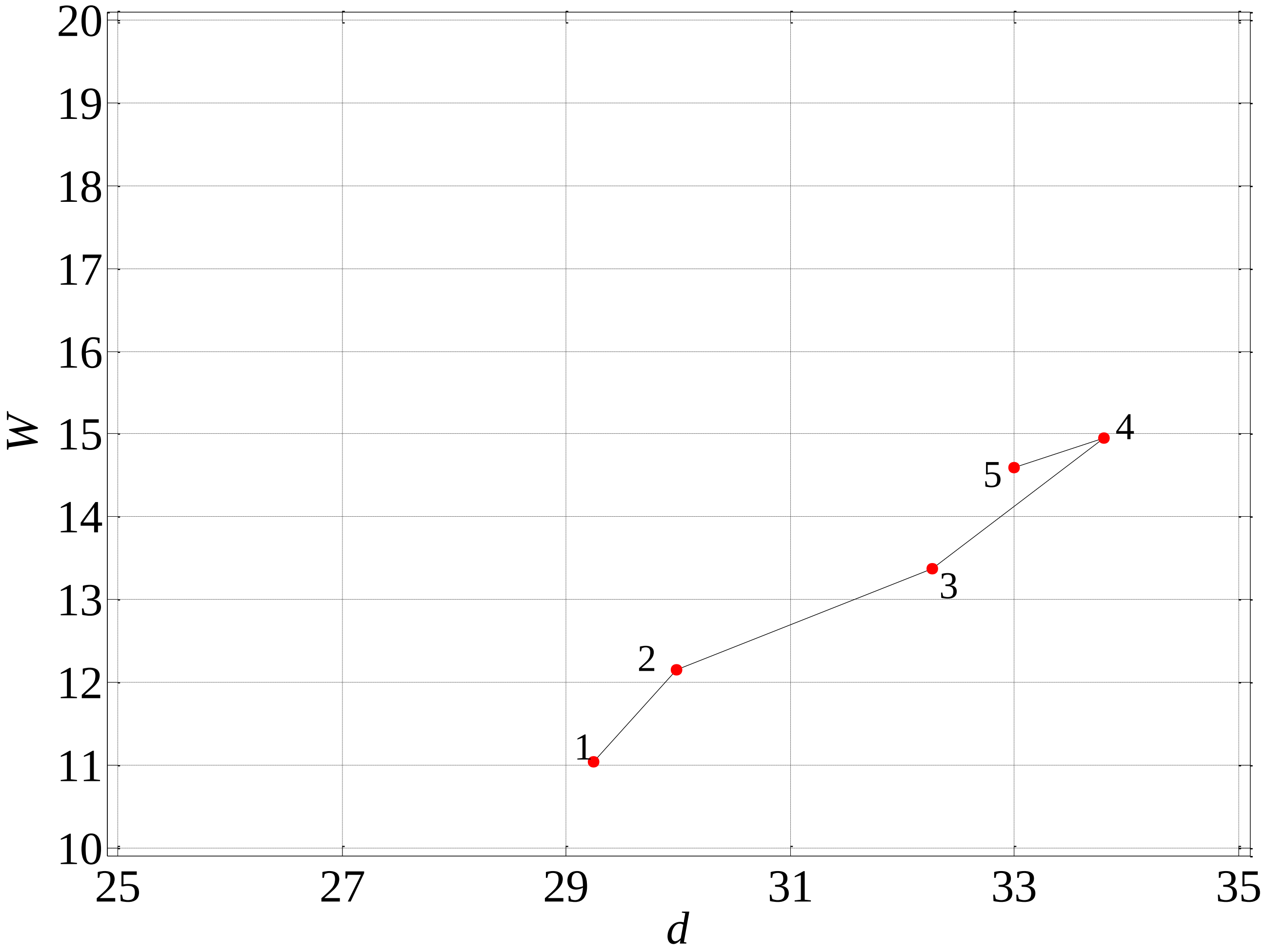
$$|S_{21}| \le 0.75 \text{ for } 4.7 \text{ GHz} \le \omega \le 5.0 \text{ GHz}$$

Single Resonator Filter

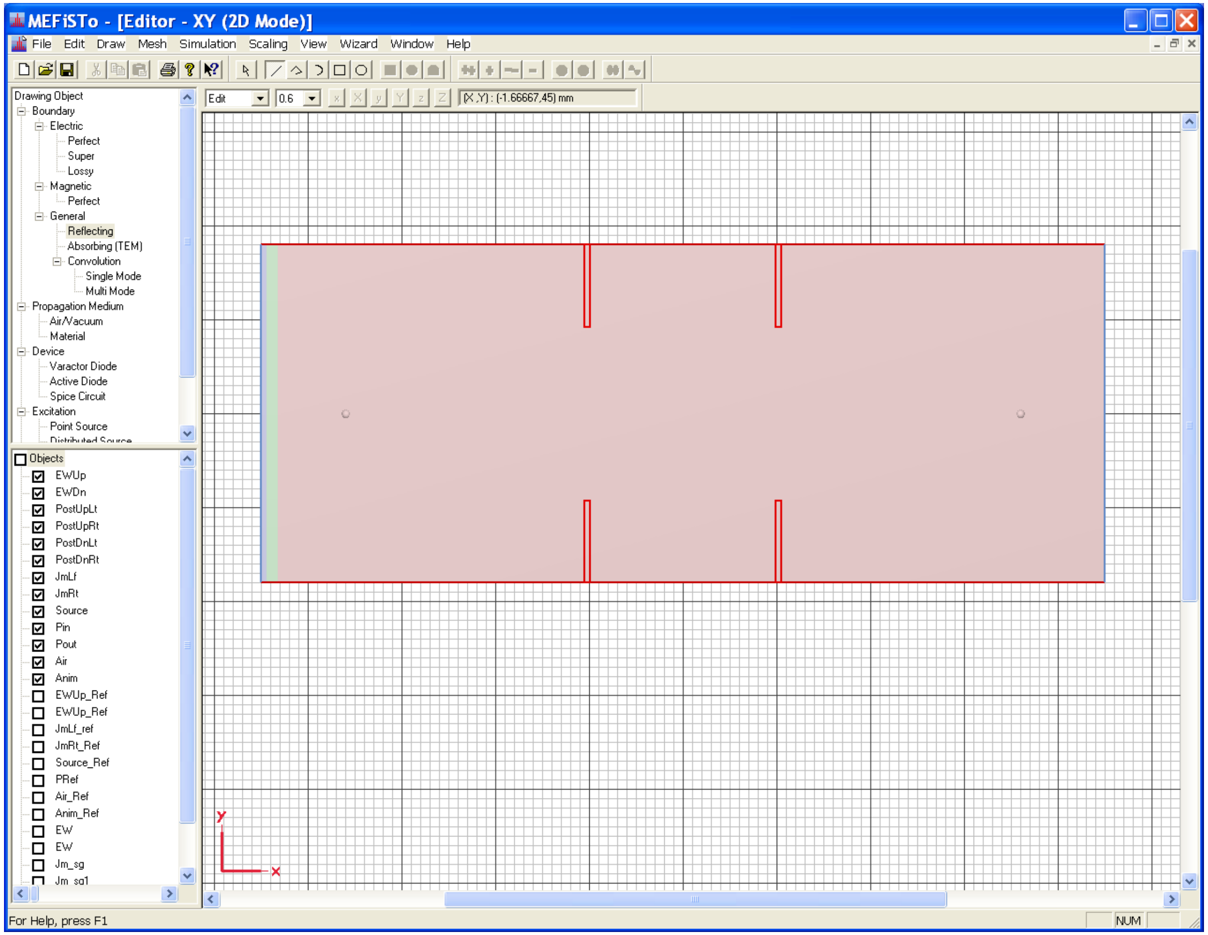


Single Resonator Filter

FM modeling grid

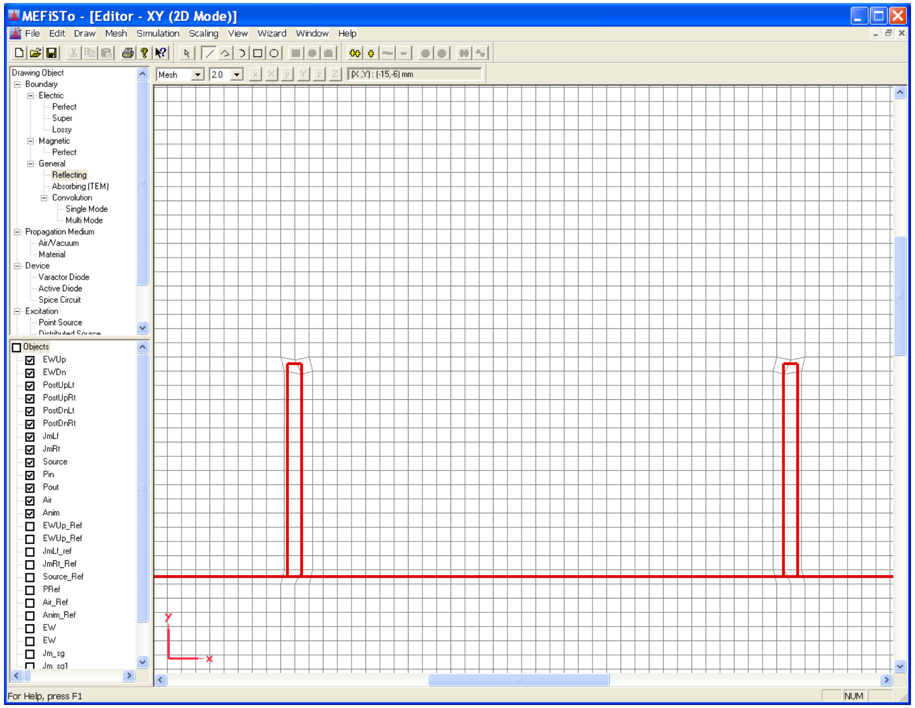


Single Resonator Filter MEFiSTo Validation

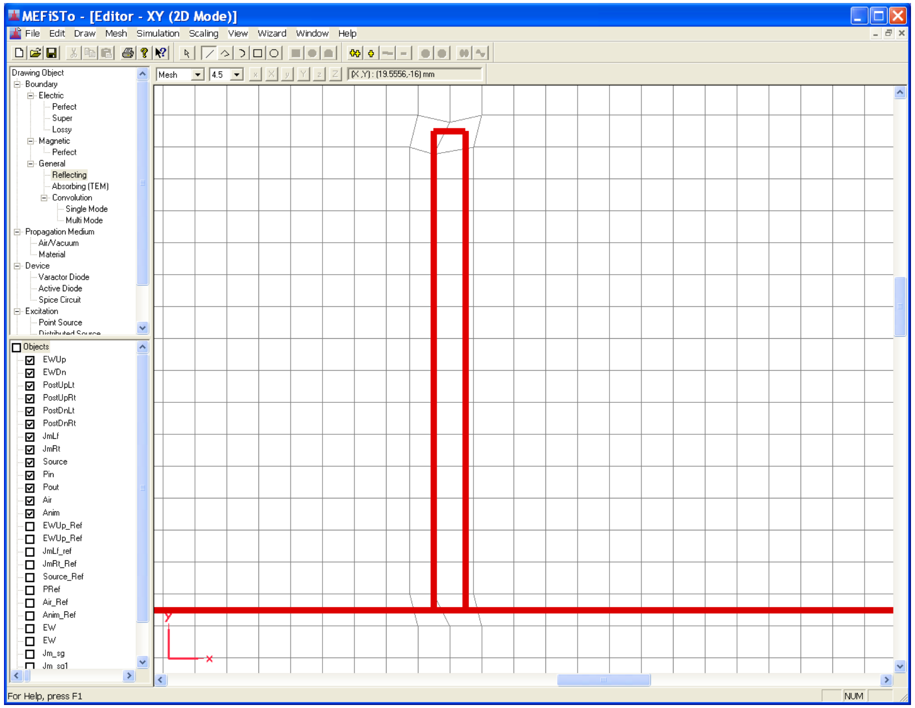


Single Resonator Filter Rubber Cell

locally conformal TLM cell (*So and Hoefer, 2003*)



Mesh 2.0 (X,Y) : (-15,-6) mm



Mesh 4.5 (X,Y) : (19.5556,-16) mm

H-plane Waveguide Filter Design

design parameters L_1, L_2, L_3, W_1, W_2, W_3, W_4

design specifications

$$\left|S_{11}\right| \le 0.16, \text{ for } 5.4 \text{ GHz} \le \omega \le 9.0 \text{ GHz}$$

$$\left|S_{11}\right| \ge 0.85, \text{ for } \omega \le 5.2 \text{ GHz}$$

$$\left|S_{11}\right| \ge 0.5, \text{ for } \omega \ge 9.5 \text{ GHz}$$

23 points per frequency sweep

H-plane Waveguide Filter Design

parameter	initial solution	solution reached by the SMIS algorithm
W_1	0.48583	0.51397
W_2	0.43494	0.47244
W_3	0.40433	0.44501
W_4	0.39796	0.44627
L_1	0.65585	0.63142
L_2	0.65923	0.63922
L_3	0.67666	0.65705

all values are in inches

Space Mapping Technology: Current and Future Work

new framework and optimization algorithms

rigorous convergence proofs

methodologies for device and component model enhancement

TLM-based modeling and design

exploitation of adjoint sensitivities
for coarse and fine model EM solvers