Space Mapping Approaches to EM-based Device Modeling and Component Design

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WORKSHOP ON MICROWAVE COMPONENT DESIGN USING SPACE MAPPING METHODOLOGIES
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Abstract

The Space Mapping concept intelligently links companion "coarse" and "fine" engineering models of different complexities, e.g., full-wave electromagnetic (EM) simulations and empirical circuit-theory based models. Space mapping optimization closely follows the traditional experience and intuition of designers. Our original 1993 concept and the subsequent Aggressive Space Mapping approach to engineering design optimization will be discussed. Recent developments include neural space mapping and the introduction of the object oriented SMX system to facilitate implementation with commercial simulators. We have developed a comprehensive Space Mapping framework to engineering device modeling. Tableau-based approach, it permits many different practical implementations. The accuracy of available empirical models can be significantly enhanced in selected regions of interest. We present microstrip examples yielding remarkable modeling improvement. It has been reported to be useful in the RF industry for development of new library models. We briefly review the new Implicit Space Mapping (ISM) concept in which we allow preassigned parameters, not used in optimization, to change in some components of the coarse model. Extensive filter design examples, exploiting full wave EM simulators, complement the presentation. Implementation in software such as Agilent Momentum and ADS will be discussed. 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.

Outline

Space Mapping intelligently links companion “coarse” and “fine” models—full-wave electromagnetic (EM) simulations and empirical models

Space Mapping optimization follows traditional experience of designers

we discuss the 1993 concept and subsequent Aggressive Space Mapping

Outline

object oriented SMX system facilitates commercial simulators

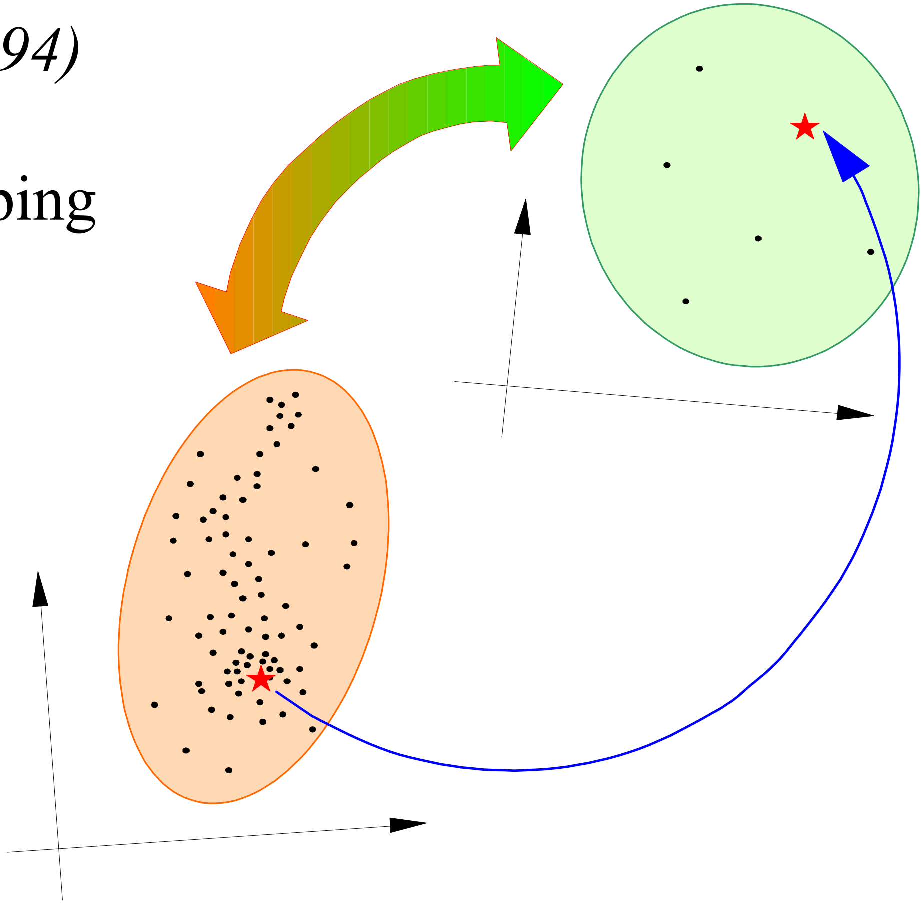
tableau approach enhances accuracy of available empirical models (already used in the RF industry for new library models)

Implicit Space Mapping (ISM), where preassigned parameters change in coarse model

filter design, implementation in Agilent Momentum and ADS

Space Mapping

(Bandler et al., 1994)



validation space

mapping

optimization space

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
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
Surrogate Model	alternative expression for coarse model
Target Response	response the fine model should achieve, (usually) optimal response of a coarse model, enhanced coarse model, or surrogate

Space Mapping: a Glossary of Terms

Companion	coarse
Low Fidelity	coarse
High Fidelity	fine
Empirical	coarse
Physics-based	coarse or fine
Device under Test	fine
Electromagnetic	fine or coarse
Simulation	fine or coarse
Computational	fine or coarse

Space Mapping: a Glossary of Terms

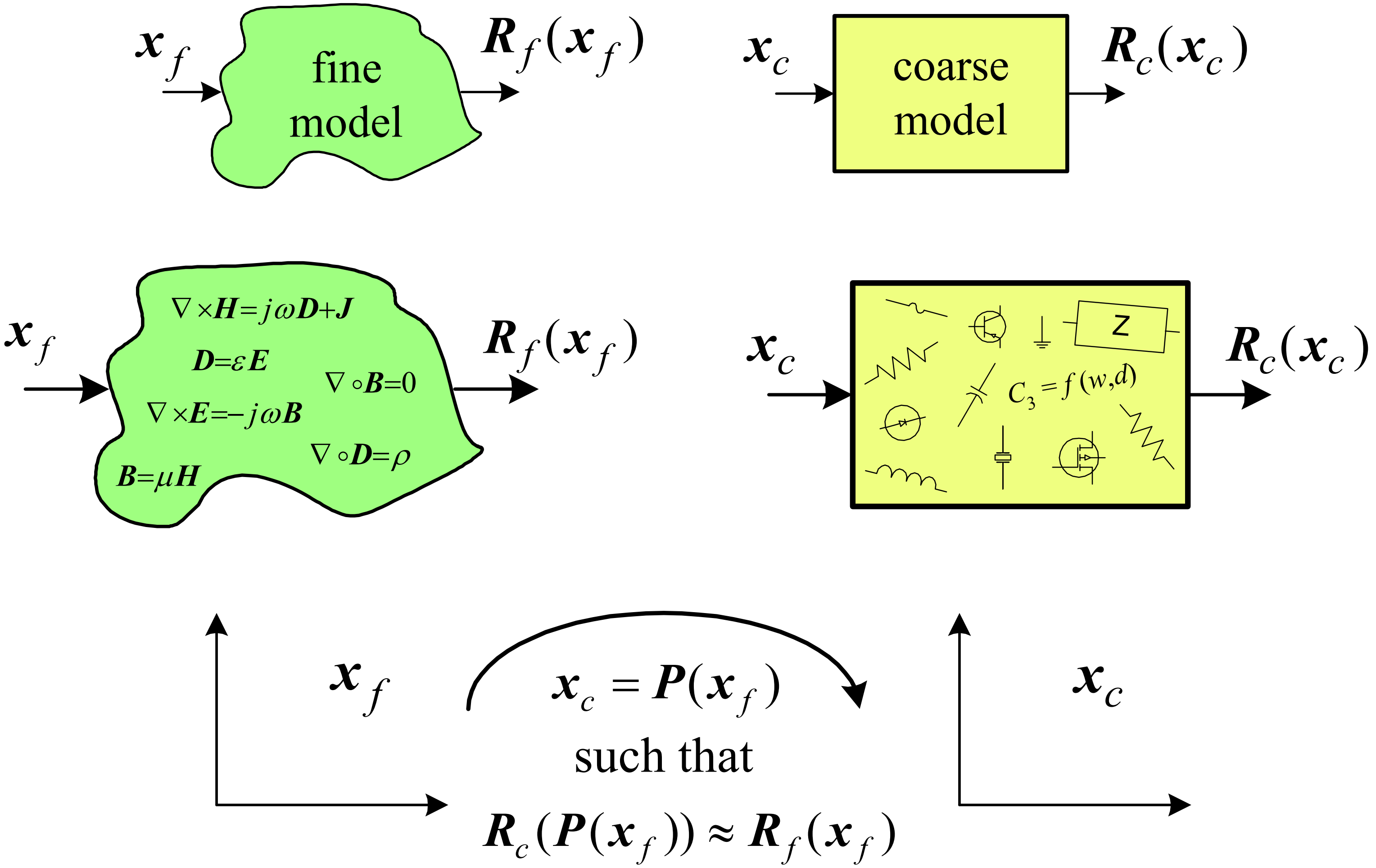
Parameter (input) Space Mapping	mapping, transformation or correction of design variables
Response (output) Space Mapping	mapping, transformation or correction of responses
Response Surface Approximation	linear/quadratic/polynomial approximation of responses w.r.t. design variables

Space Mapping: a Glossary of Terms

Neuro	implies use of artificial neural networks
Implicit Space Mapping	space mapping when the mapping is not obvious
Not Space Mapping	(usually) space mapping when not acknowledged
Parameter Transformation	space mapping
Predistortion	?

The Space Mapping Concept

(Bandler et al., 1994-)

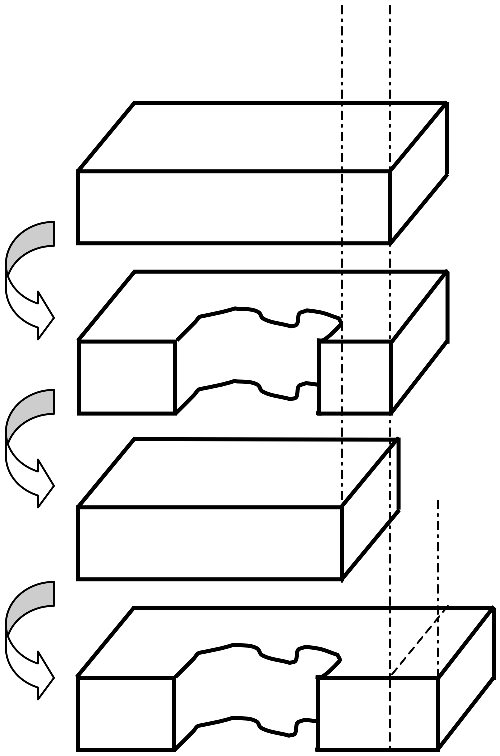


$$x_c = P(x_f)$$

such that

$$R_c(P(x_f)) \approx R_f(x_f)$$

Space Mapping Practice—Cheese Cutting Problem



optimal coarse model

initial guess

PE

prediction

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

$$x_f^{new} = x_f^{old} + x_c^* - x_c^{new}$$

The Brain’s Automatic Pilot

(Sandra Blakeslee, The New York Times,
International Herald Tribune, February 21, 2002, p.7)

[certain brain] circuits are used by the human brain
to assess social rewards …

…findings [by neuroscientists] …challenge the notion
that people always make conscious choices
about what they want and how to obtain it.

Gregory Berns (Emory University School of Medicine):
… most decisions are made subconsciously
with many gradations of awareness.

The Brain’s Automatic Pilot

(Sandra Blakeslee, The New York Times,
International Herald Tribune, February 21, 2002, p.7)

P. Read Montague (Baylor College of Medicine): … how did evolution create a brain that could make … distinctions … [about] …what it must pay conscious attention to?

… the brain has evolved to shape itself, starting in infancy, according to what it encounters in the external world.

… much of the world is predictable: buildings usually stay in one place, gravity makes objects fall …

The Brain’s Automatic Pilot

(Sandra Blakeslee, The New York Times,
International Herald Tribune, February 21, 2002, p.7)

As children grow, their brains build internal models of everything they encounter, gradually learning to identify objects …

… as new information flows into it … the brain automatically compares it with what it already knows.

… if there is a surprise …. the mismatch … instantly shifts the brain into a new state.

Drawing on past experience … a decision is made …

Current Space Mapping Milestones

yield driven EM optimization using Space Mapping-based neuromodels (2001)

EM-based optimization exploiting Partial Space Mapping (PSM) and exact sensitivities (2002)

Implicit Space Mapping (ISM) EM-based modeling and design (2002)

introduction of Space Mapping to mathematicians (2002)

Special Issue of *Optimization and Engineering* on Surrogate Modelling and Space Mapping for Engineering Optimization (2002)

Selected Space Mapping Contributors

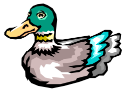
Kaj Madsen (Technical University of Denmark, 1993-)
mapping updates, trust region methods

Pavio (Motorola, 1994-)
companion model approach, filter design, LTCC circuits

Shen Ye (ComDev, 1997-)
circuit calibration technique

Mansour (Com Dev, University of Waterloo, 1998-)
Cauchy method and adaptive sampling

Stephane Bila (Limoges, France 1998-)
space mapping, waveguide devices



Selected Space Mapping Contributors

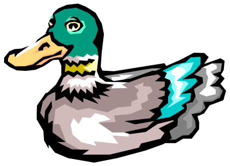
Rayas-Sánchez (McMaster University; ITESO, Mexico 1998-)
space mapping through artificial neural networks

Jacob Søndergaard (Technical University of Denmark, 1999-)
space mapping: theory and algorithms

Qi-jun Zhang (Carleton University, 1999-)
knowledge based neural networks, space mapping

Jan Snel (Philips Semiconductors, Netherlands, 2001)
RF component design, library model enhancement

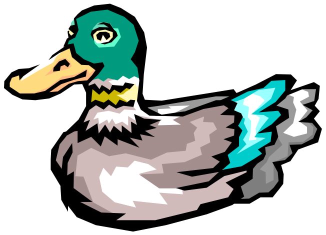
Dan Swanson (Bartley RF Systems, 2001)
combline filter design



Selected Space Mapping Contributors

Steven Leary (University of Southampton, England, 2000-)
constraint mapping, applications in civil engineering

Lehmensiek (University of Stellenbosch, South Africa, 2000, 2001)
filter design, coupling structures



Frank Pedersen (Technical University of Denmark, 2001-)
space mapping, neural networks

Ke-Li Wu (Chinese University of Hong Kong, 2001-)
knowledge embedded space mapping, LTCC circuits

Pablo Soto (Polytechnic University of Valencia, Spain, 2001)
aggressive space mapping, inductively coupled filters

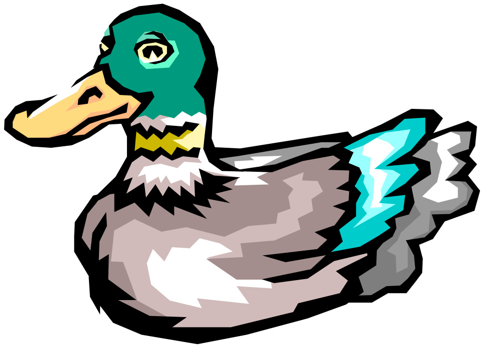
Hong-Soon Choi (Seoul National University, Korea, 2001)
aggressive space mapping, design of magnetic systems

Selected Space Mapping Contributors

Luis Vicente (University of Coimbra, Portugal, 2001-)
mathematics of space mapping: models, sensitivities and trust regions

Marcus Redhe (Linköping University, Sweden, 2001)
sheet metal forming and vehicle crashworthiness design

Dieter Peltz (Radio Frequency Systems, Australia, 2002)
difference matrix approach, coupled resonator filters



Safavi-Naeini (University of Waterloo, 2002)
multi-level generalized space mapping,
multi-cavity microwave structures

Jan-Willem Lobeek (Philips Semiconductors, Netherlands, 2002)
power amplifier design

Jacobian-Space Mapping Relationship

(Bakr et al., 1999)

through PE we match the responses

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

by differentiation

$$\left(\frac{\partial \boldsymbol{R}_f^T}{\partial \boldsymbol{x}_f}\right)^T \approx \left(\frac{\partial \boldsymbol{R}_c^T}{\partial \boldsymbol{x}_c}\right)^T \cdot \left(\frac{\partial \boldsymbol{x}_c^T}{\partial \boldsymbol{x}_f}\right)^T$$

Jacobian-Space Mapping Relationship

(Bakr et al., 1999)

given coarse model Jacobian $\boldsymbol{J}_c$ and space mapping matrix $\boldsymbol{B}$ we estimate

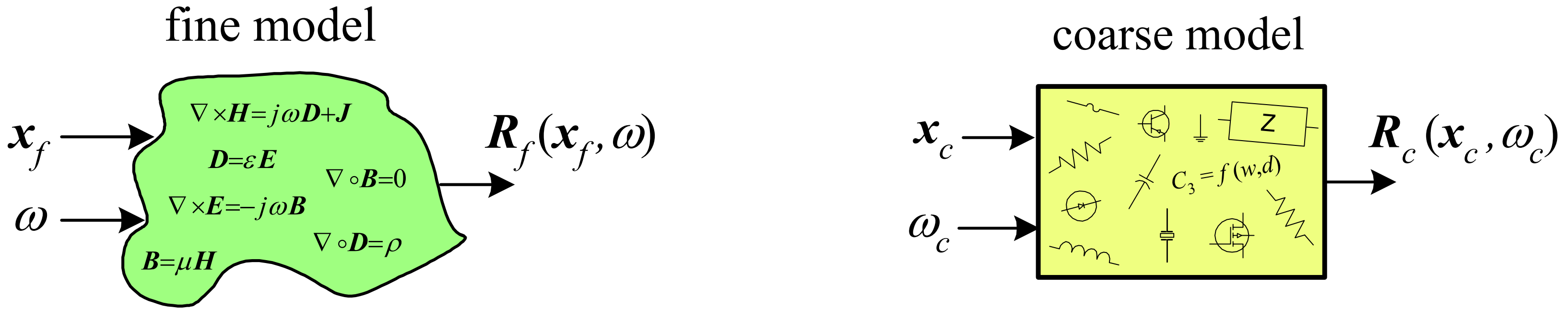
$$\boldsymbol{J}_f(\boldsymbol{x}_f) \approx \boldsymbol{J}_c(\boldsymbol{x}_c)\boldsymbol{B}$$

given $\boldsymbol{J}_c$ and $\boldsymbol{J}_f$ we estimate (least squares)

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

Conventional Space Mapping for Microwave Circuits

(Bandler et al., 1994)



find

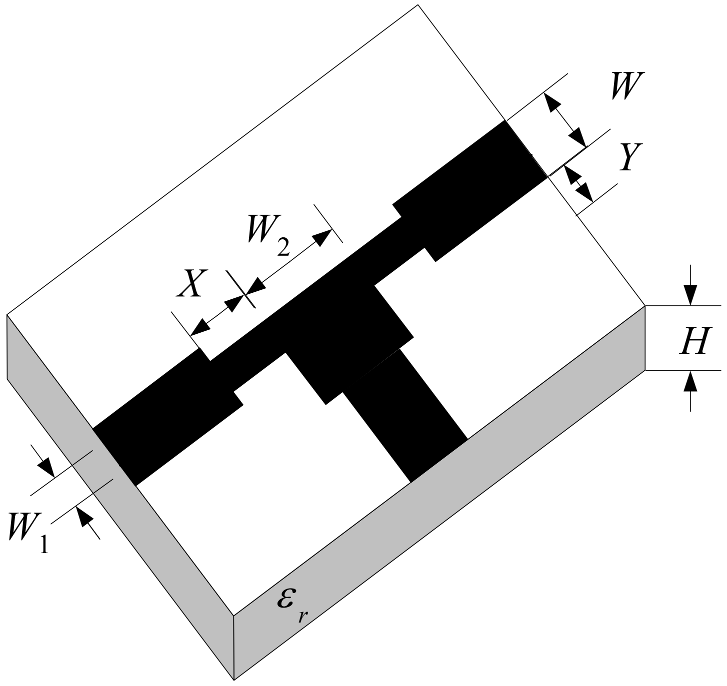
$$\begin{bmatrix}\boldsymbol{x}_c\\ \omega_c\end{bmatrix}=\boldsymbol{P}(\boldsymbol{x}_f,\omega)$$

such that

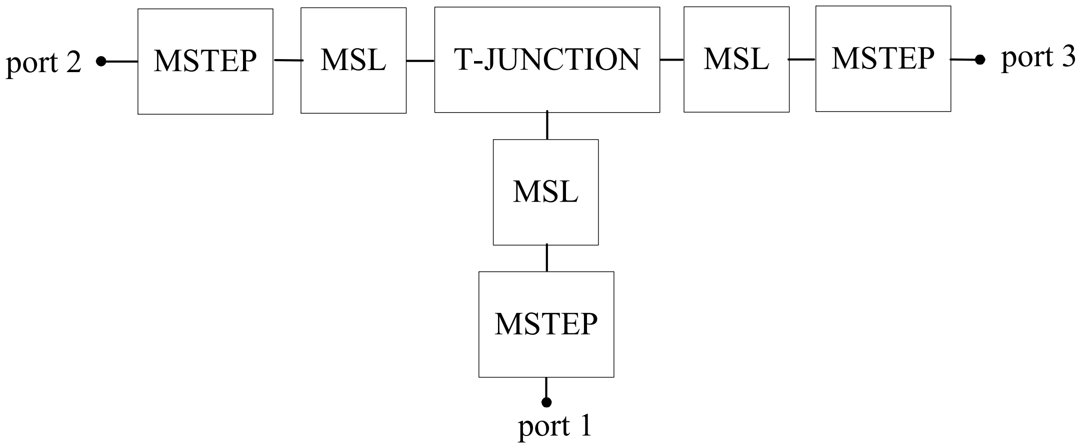
$$\boldsymbol{R}_c(\boldsymbol{x}_c,\omega_c)\approx\boldsymbol{R}_f(\boldsymbol{x}_f,\omega)$$

Microstrip Shaped T-Junction

fine model



coarse model



Microstrip Shaped T-Junction

the region of interest

$$15 \text{ mil} \le H \le 25 \text{ mil}$$
$$2 \text{ mil} \le X \le 10 \text{ mil}$$
$$15 \text{ mil} \le Y \le 25 \text{ mil}$$
$$8 \le \varepsilon_r \le 10$$

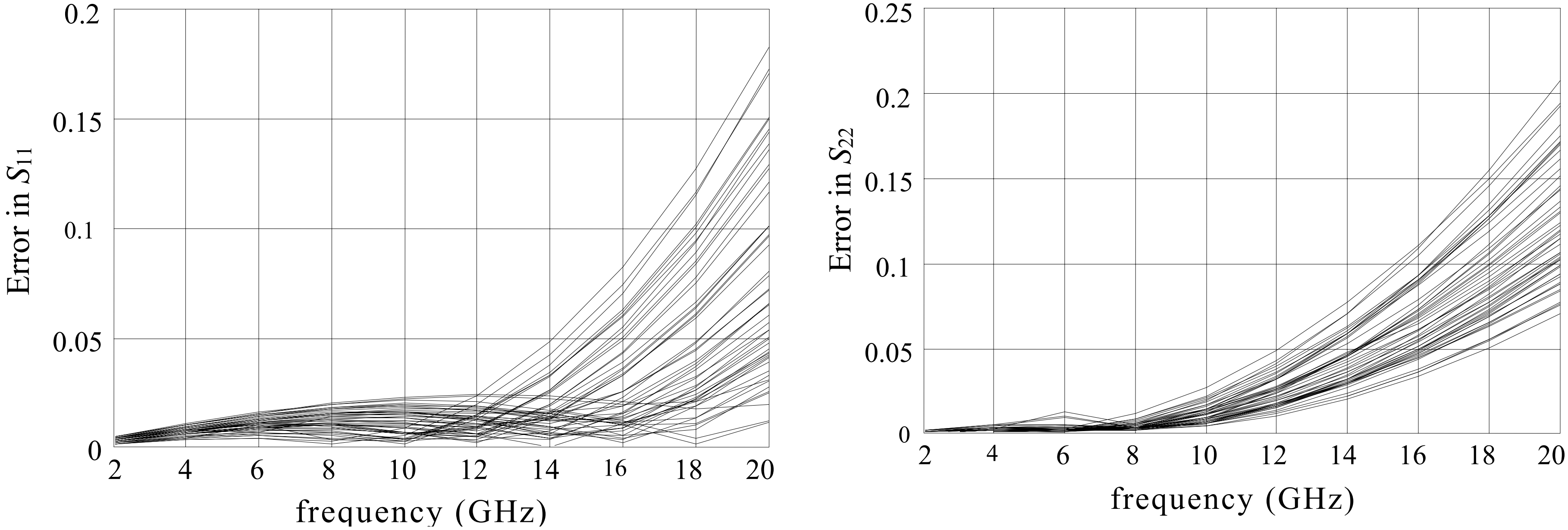
the frequency range is 2 GHz to 20 GHz with a step of 2 GHz
the number of base points is 9, the number of test points is 50

the widths W of the input lines track H so that their characteristic impedance is 50 ohm

$W_1 = W/3$, W_2 is suitably constrained

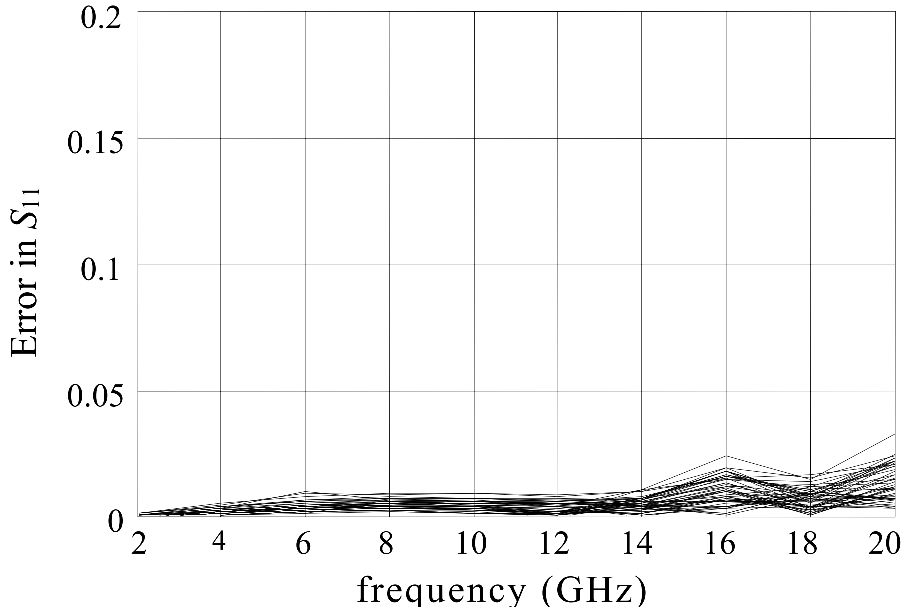
Microstrip Shaped T-Junction Coarse Model

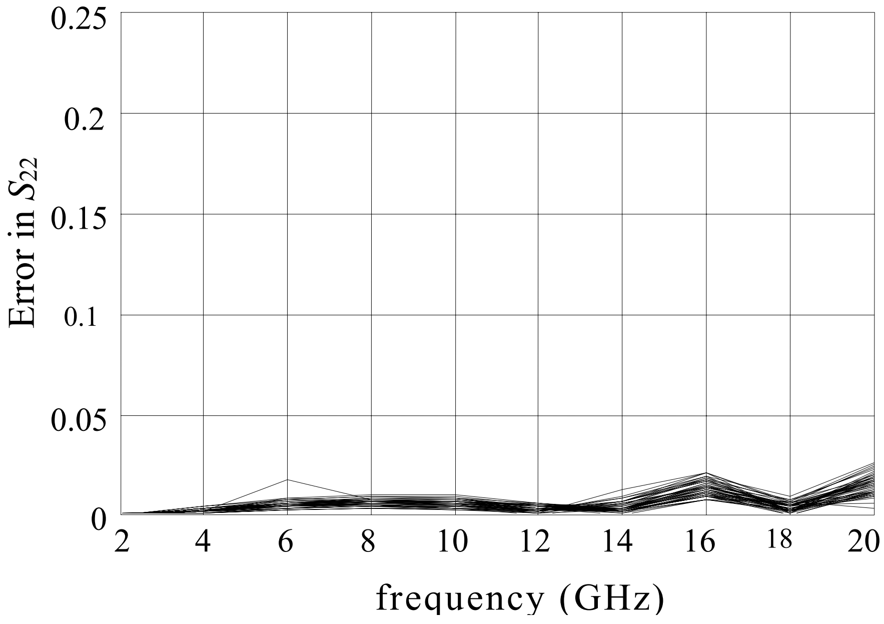
errors w.r.t. Sonnet’s ***em*** at the test points



Microstrip Shaped T-Junction Enhanced Coarse Model

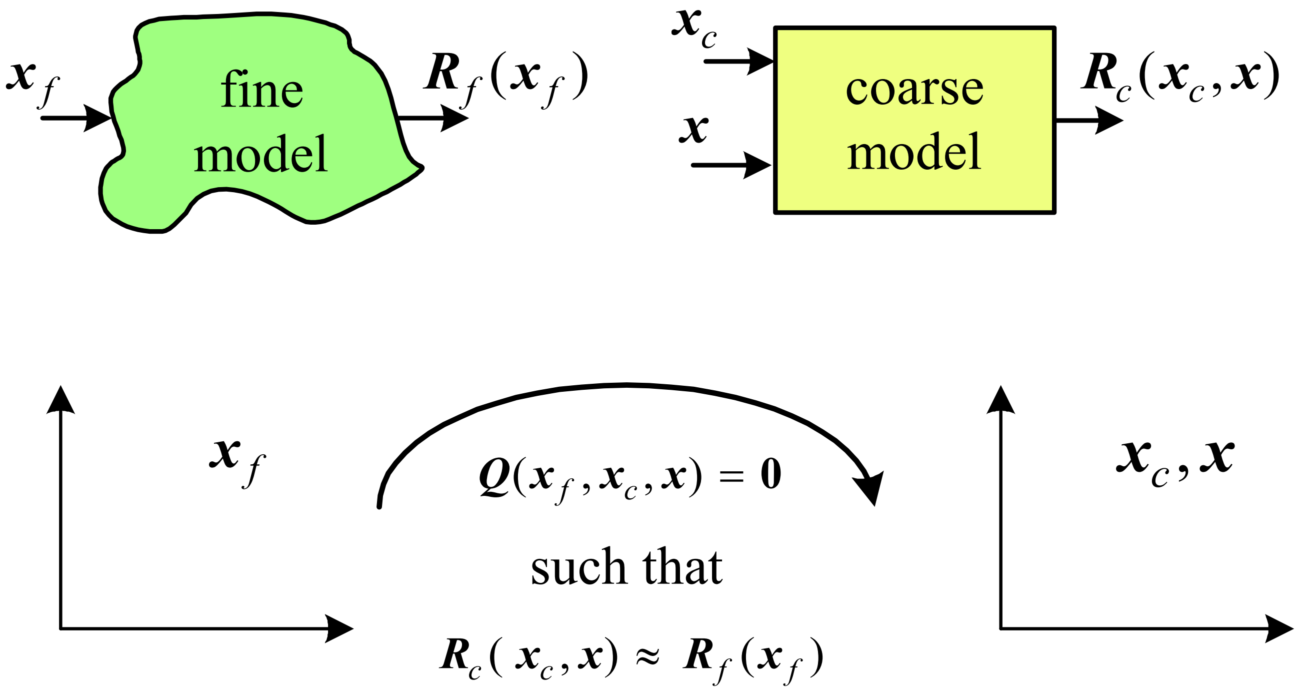
errors w.r.t. Sonnet's ***em*** at the test points





Implicit Space Mapping Theory

(Bandler et al., 2002)



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

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

$\boldsymbol{x}_f$ $\boldsymbol{x}_c, \boldsymbol{x}$

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

such that

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

Implicit Space Mapping Practice

(Bandler et al., 2002)

effective for EM-based microwave modeling and design

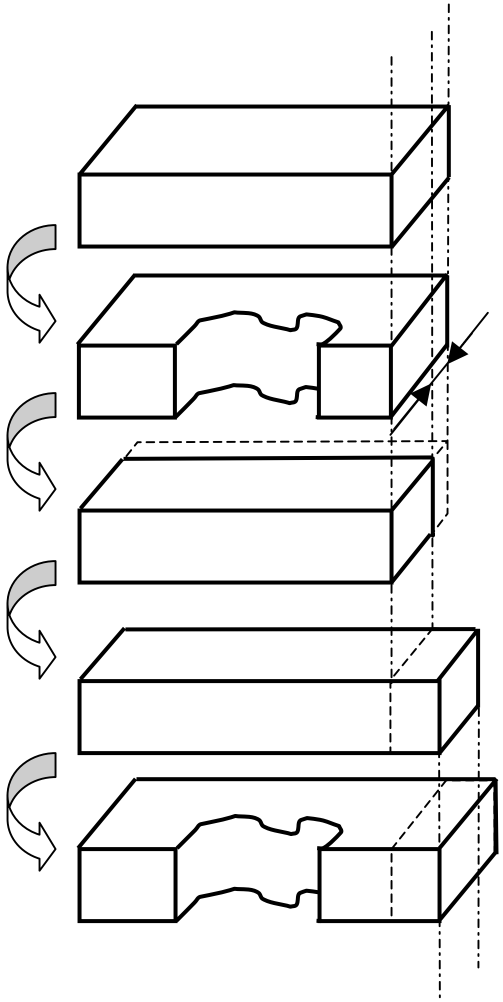
coarse model aligned with EM (fine) model
through preassigned parameters

easy implementation

no explicit mapping involved

no matrices to keep track of

Implicit Space Mapping Practice—Cheese Cutting Problem



optimal coarse model $x_c^{*(0)}$ $x^{(0)}$

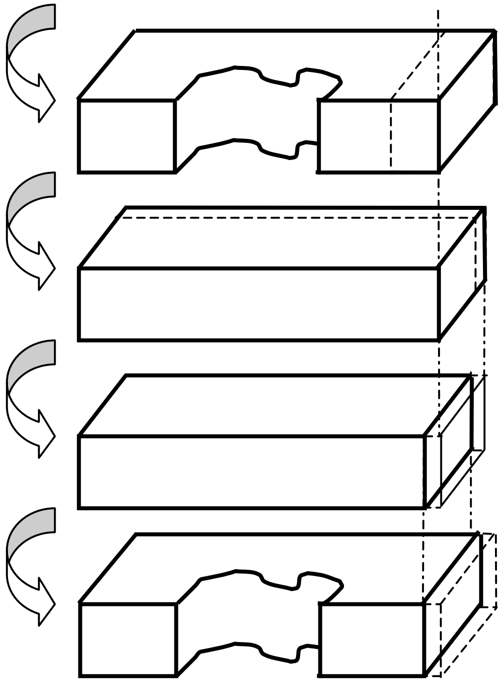
initial guess $x_f^{(0)} = x_c^{*(0)}$

PE $x_c^{*(0)}$ $x^{(1)}$

prediction $x_c^{*(1)}$ $x^{(1)}$

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

Implicit Space Mapping Practice—Cheese Cutting Problem



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

PE $x_c^{*(1)}$ $x^{(2)}$

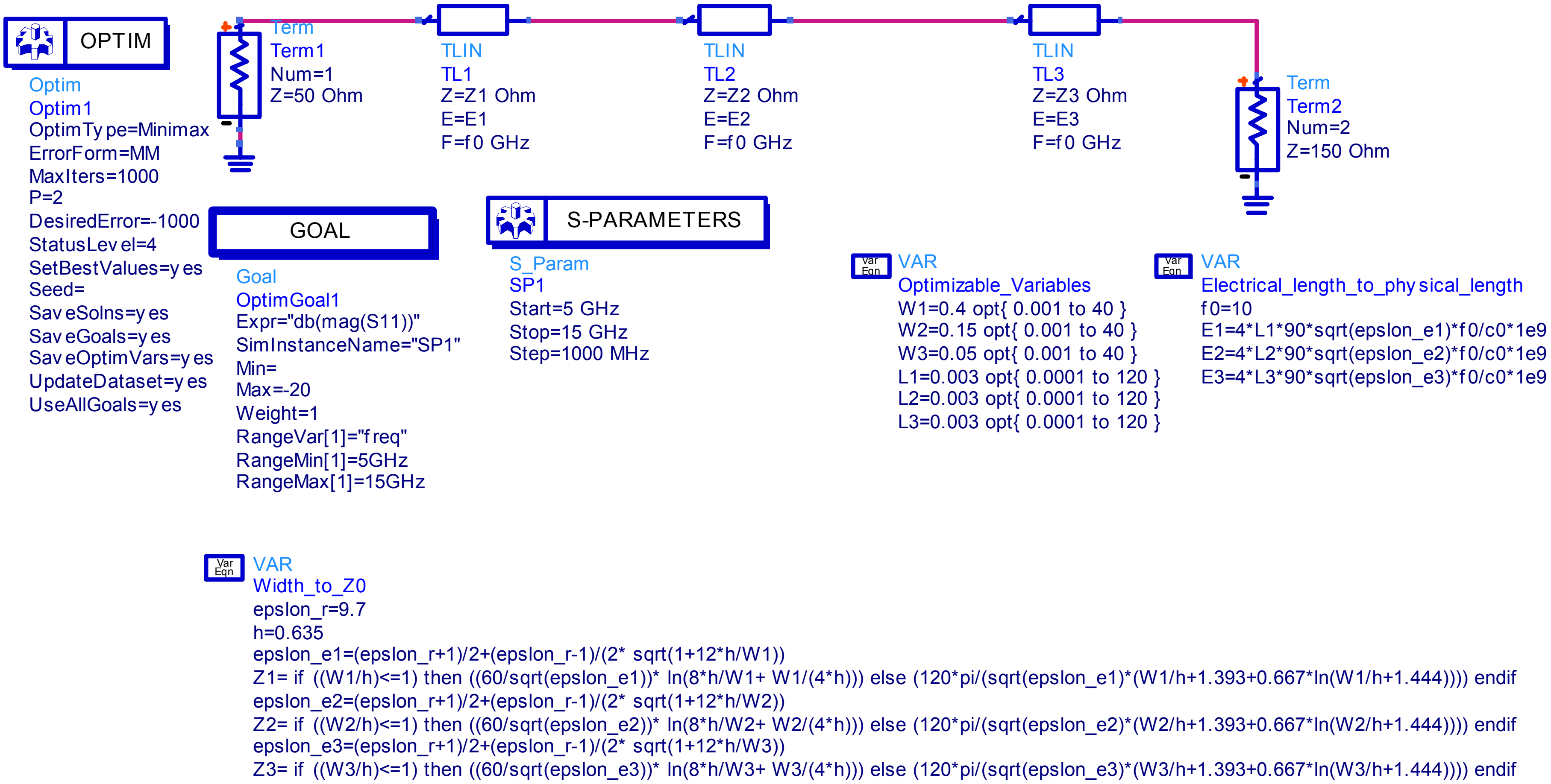
prediction $x_c^{*(2)}$ $x^{(2)}$

verification $x_f^{(2)} = x_c^{*(2)}$

⋮

Implicit Space Mapping: Steps 1-3

optimize coarse model



Optim
Optim1
OptimType=Minimax
ErrorForm=MM
MaxIters=1000
P=2
DesiredError=-1000
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
SaveOptimVars=yes
UpdateDataset=yes
UseAllGoals=yes

Term
Term1
Num=1
Z=50 Ohm

TLIN
TL1
Z=Z1 Ohm
E=E1
F=f0 GHz

TLIN
TL2
Z=Z2 Ohm
E=E2
F=f0 GHz

TLIN
TL3
Z=Z3 Ohm
E=E3
F=f0 GHz

Term
Term2
Num=2
Z=150 Ohm

Goal
OptimGoal1
Expr="db(mag(S11))"
SimInstanceName="SP1"
Min=
Max=-20
Weight=1
RangeVar[1]="freq"
RangeMin[1]=5GHz
RangeMax[1]=15GHz

S_Param
SP1
Start=5 GHz
Stop=15 GHz
Step=1000 MHz

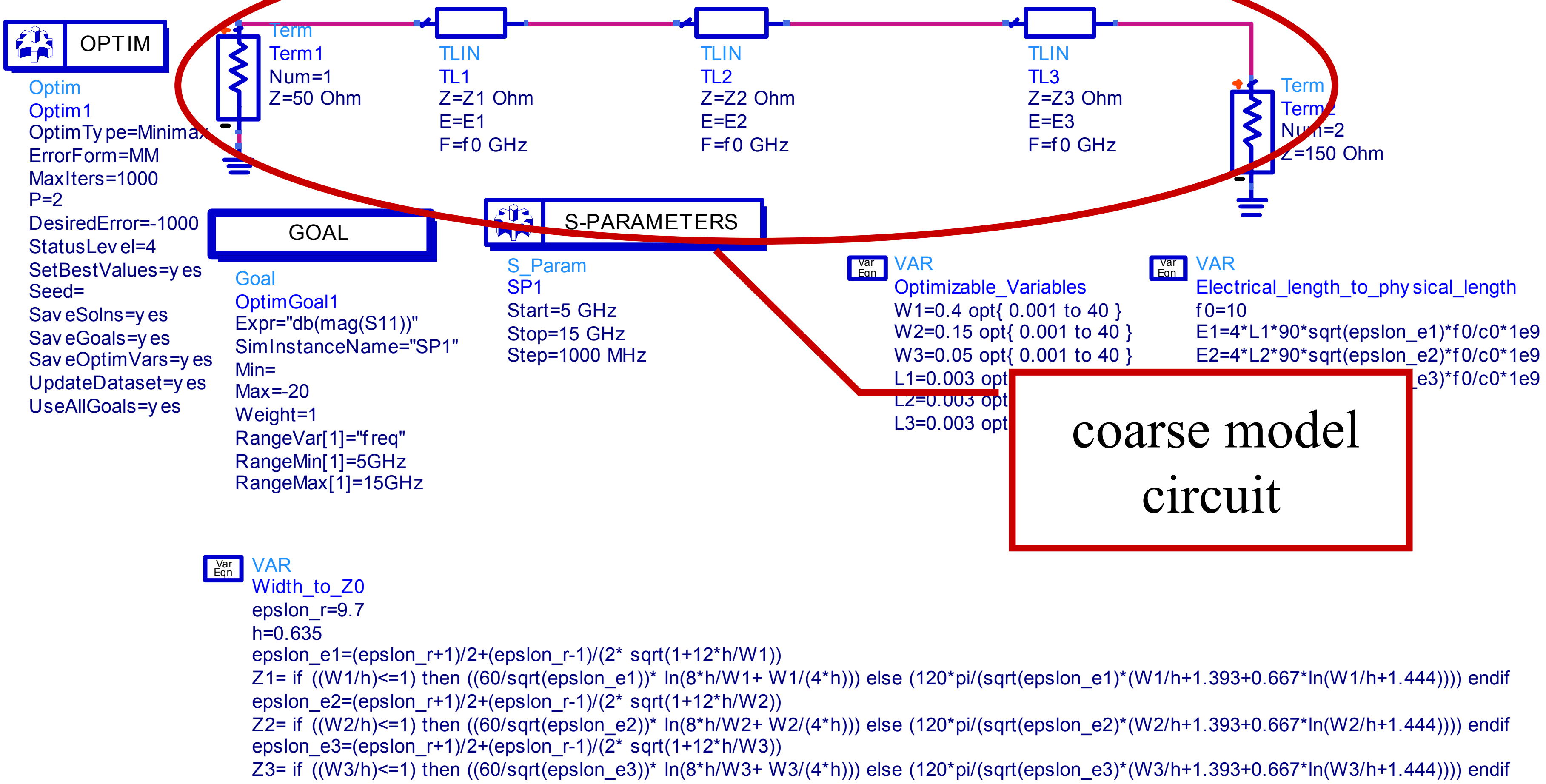
VAR
Optimizable_Variables
W1=0.4 opt{ 0.001 to 40 }
W2=0.15 opt{ 0.001 to 40 }
W3=0.05 opt{ 0.001 to 40 }
L1=0.003 opt{ 0.0001 to 120 }
L2=0.003 opt{ 0.0001 to 120 }
L3=0.003 opt{ 0.0001 to 120 }

VAR
Electrical_length_to_physical_length
f0=10
E1=4*L1*90*sqrt(epslon_e1)*f0/c0*1e9
E2=4*L2*90*sqrt(epslon_e2)*f0/c0*1e9
E3=4*L3*90*sqrt(epslon_e3)*f0/c0*1e9

VAR
Width_to_Z0
epslon_r=9.7
h=0.635
epslon_e1=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W1))
Z1= if ((W1/h)<=1) then ((60/sqrt(epslon_e1))* ln(8*h/W1+ W1/(4*h))) else (120*pi/(sqrt(epslon_e1)*(W1/h+1.393+0.667*ln(W1/h+1.444)))) endif
epslon_e2=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W2))
Z2= if ((W2/h)<=1) then ((60/sqrt(epslon_e2))* ln(8*h/W2+ W2/(4*h))) else (120*pi/(sqrt(epslon_e2)*(W2/h+1.393+0.667*ln(W2/h+1.444)))) endif
epslon_e3=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W3))
Z3= if ((W3/h)<=1) then ((60/sqrt(epslon_e3))* ln(8*h/W3+ W3/(4*h))) else (120*pi/(sqrt(epslon_e3)*(W3/h+1.393+0.667*ln(W3/h+1.444)))) endif

Implicit Space Mapping: Steps 1-3

optimize coarse model



OPTIM

Optim
Optim1
OptimType=Minimax
ErrorForm=MM
MaxIters=1000
P=2
DesiredError=-1000
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
SaveOptimVars=yes
UpdateDataset=yes
UseAllGoals=yes

Term
Term1
Num=1
Z=50 Ohm

TLIN
TL1
Z=Z1 Ohm
E=E1
F=f0 GHz

TLIN
TL2
Z=Z2 Ohm
E=E2
F=f0 GHz

TLIN
TL3
Z=Z3 Ohm
E=E3
F=f0 GHz

Term
Term2
Num=2
Z=150 Ohm

GOAL

Goal
OptimGoal1
Expr="db(mag(S11))"
SimInstanceName="SP1"
Min=
Max=-20
Weight=1
RangeVar[1]="freq"
RangeMin[1]=5GHz
RangeMax[1]=15GHz

S-PARAMETERS

S_Param
SP1
Start=5 GHz
Stop=15 GHz
Step=1000 MHz

VAR
Optimizable_Variables
W1=0.4 opt{ 0.001 to 40 }
W2=0.15 opt{ 0.001 to 40 }
W3=0.05 opt{ 0.001 to 40 }
L1=0.003 opt
L2=0.003 opt
L3=0.003 opt

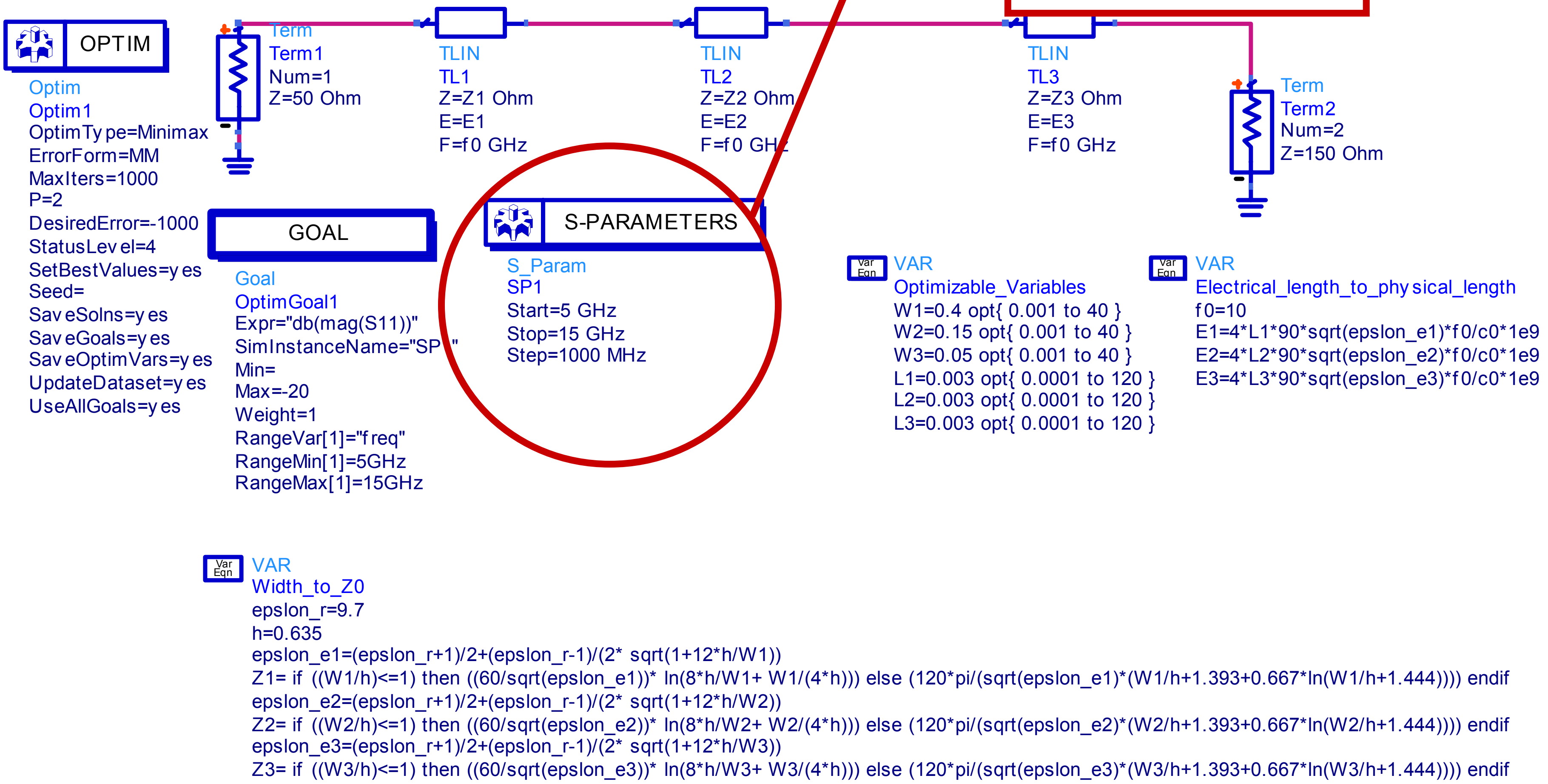
VAR
Electrical_length_to_physical_length
f0=10
E1=4*L1*90*sqrt(epslon_e1)*f0/c0*1e9
E2=4*L2*90*sqrt(epslon_e2)*f0/c0*1e9
_e3)*f0/c0*1e9

coarse model circuit

VAR
Width_to_Z0
epslon_r=9.7
h=0.635
epslon_e1=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W1))
Z1= if ((W1/h)<=1) then ((60/sqrt(epslon_e1))* ln(8*h/W1+ W1/(4*h))) else (120*pi/(sqrt(epslon_e1)*(W1/h+1.393+0.667*ln(W1/h+1.444)))) endif
epslon_e2=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W2))
Z2= if ((W2/h)<=1) then ((60/sqrt(epslon_e2))* ln(8*h/W2+ W2/(4*h))) else (120*pi/(sqrt(epslon_e2)*(W2/h+1.393+0.667*ln(W2/h+1.444)))) endif
epslon_e3=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W3))
Z3= if ((W3/h)<=1) then ((60/sqrt(epslon_e3))* ln(8*h/W3+ W3/(4*h))) else (120*pi/(sqrt(epslon_e3)*(W3/h+1.393+0.667*ln(W3/h+1.444)))) endif

Implicit Space Mapping: Steps 1-3

optimize coarse model



sweep range

OPTIM
Optim
Optim1
OptimType=Minimax
ErrorForm=MM
MaxIters=1000
P=2
DesiredError=-1000
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
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UseAllGoals=yes

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TLIN
TL2
Z=Z2 Ohm
E=E2
F=f0 GHz

TLIN
TL3
Z=Z3 Ohm
E=E3
F=f0 GHz

Term
Term2
Num=2
Z=150 Ohm

GOAL
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OptimGoal1
Expr="db(mag(S11))"
SimInstanceName="SP1"
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Max=-20
Weight=1
RangeVar[1]="freq"
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W1=0.4 opt{ 0.001 to 40 }
W2=0.15 opt{ 0.001 to 40 }
W3=0.05 opt{ 0.001 to 40 }
L1=0.003 opt{ 0.0001 to 120 }
L2=0.003 opt{ 0.0001 to 120 }
L3=0.003 opt{ 0.0001 to 120 }

VAR
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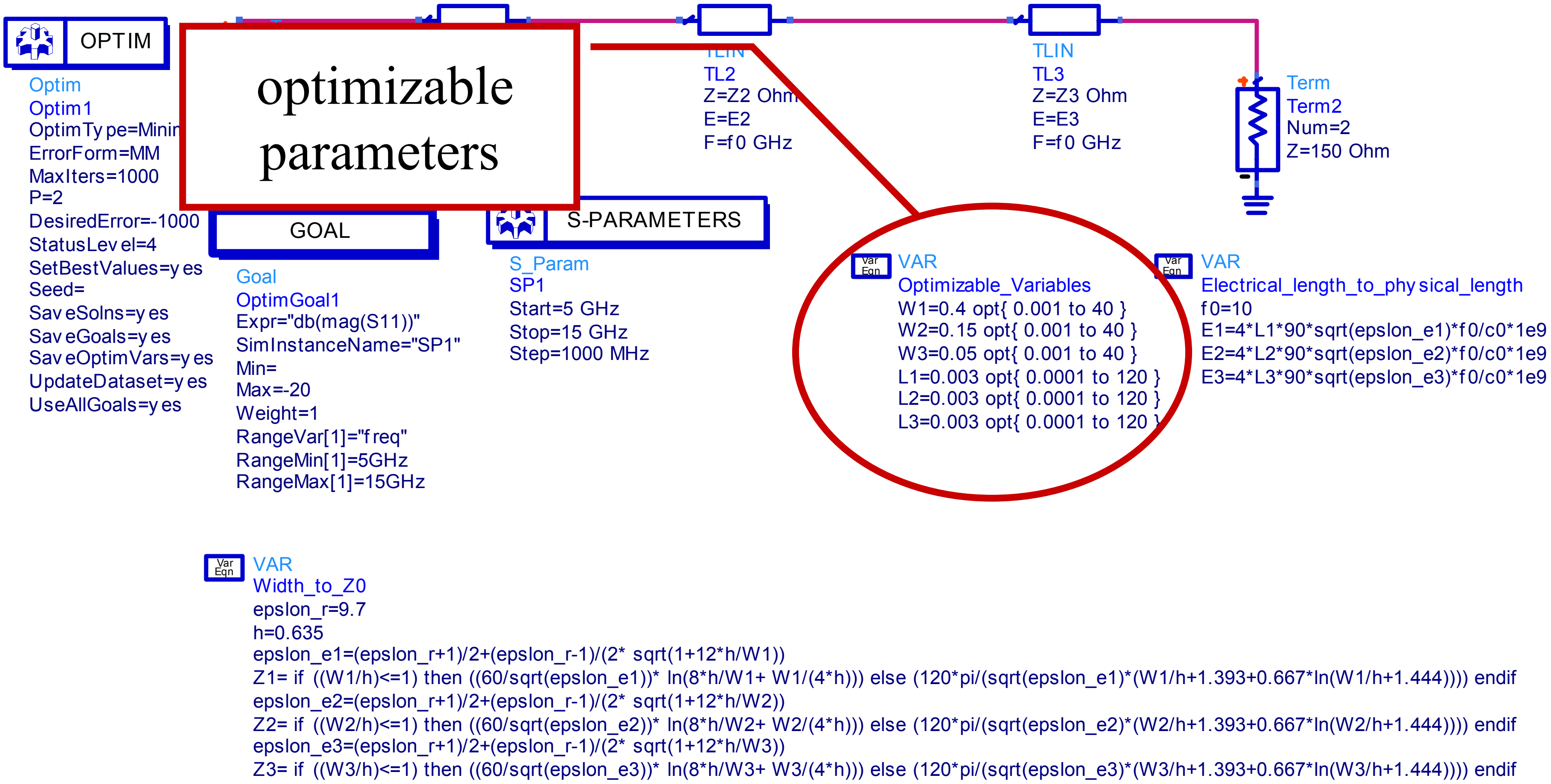
f0=10
E1=4*L1*90*sqrt(epslon_e1)*f0/c0*1e9
E2=4*L2*90*sqrt(epslon_e2)*f0/c0*1e9
E3=4*L3*90*sqrt(epslon_e3)*f0/c0*1e9

VAR
Width_to_Z0
epslon_r=9.7
h=0.635
epslon_e1=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W1))
Z1= if ((W1/h)<=1) then ((60/sqrt(epslon_e1))* ln(8*h/W1+ W1/(4*h))) else (120*pi/(sqrt(epslon_e1)*(W1/h+1.393+0.667*ln(W1/h+1.444)))) endif
epslon_e2=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W2))
Z2= if ((W2/h)<=1) then ((60/sqrt(epslon_e2))* ln(8*h/W2+ W2/(4*h))) else (120*pi/(sqrt(epslon_e2)*(W2/h+1.393+0.667*ln(W2/h+1.444)))) endif
epslon_e3=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W3))
Z3= if ((W3/h)<=1) then ((60/sqrt(epslon_e3))* ln(8*h/W3+ W3/(4*h))) else (120*pi/(sqrt(epslon_e3)*(W3/h+1.393+0.667*ln(W3/h+1.444)))) endif

Implicit Space Mapping: Steps 1-3

optimize coarse model



optimizable parameters

Optim
Optim1
OptimType=Minir
ErrorForm=MM
MaxIters=1000
P=2
DesiredError=-1000
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
SaveOptimVars=yes
UpdateDataset=yes
UseAllGoals=yes

Goal
OptimGoal1
Expr="db(mag(S11))"
SimInstanceName="SP1"
Min=
Max=-20
Weight=1
RangeVar[1]="freq"
RangeMin[1]=5GHz
RangeMax[1]=15GHz

S_Param
SP1
Start=5 GHz
Stop=15 GHz
Step=1000 MHz

TL2
Z=Z2 Ohm
E=E2
F=f0 GHz

TLIN
TL3
Z=Z3 Ohm
E=E3
F=f0 GHz

Term
Term2
Num=2
Z=150 Ohm

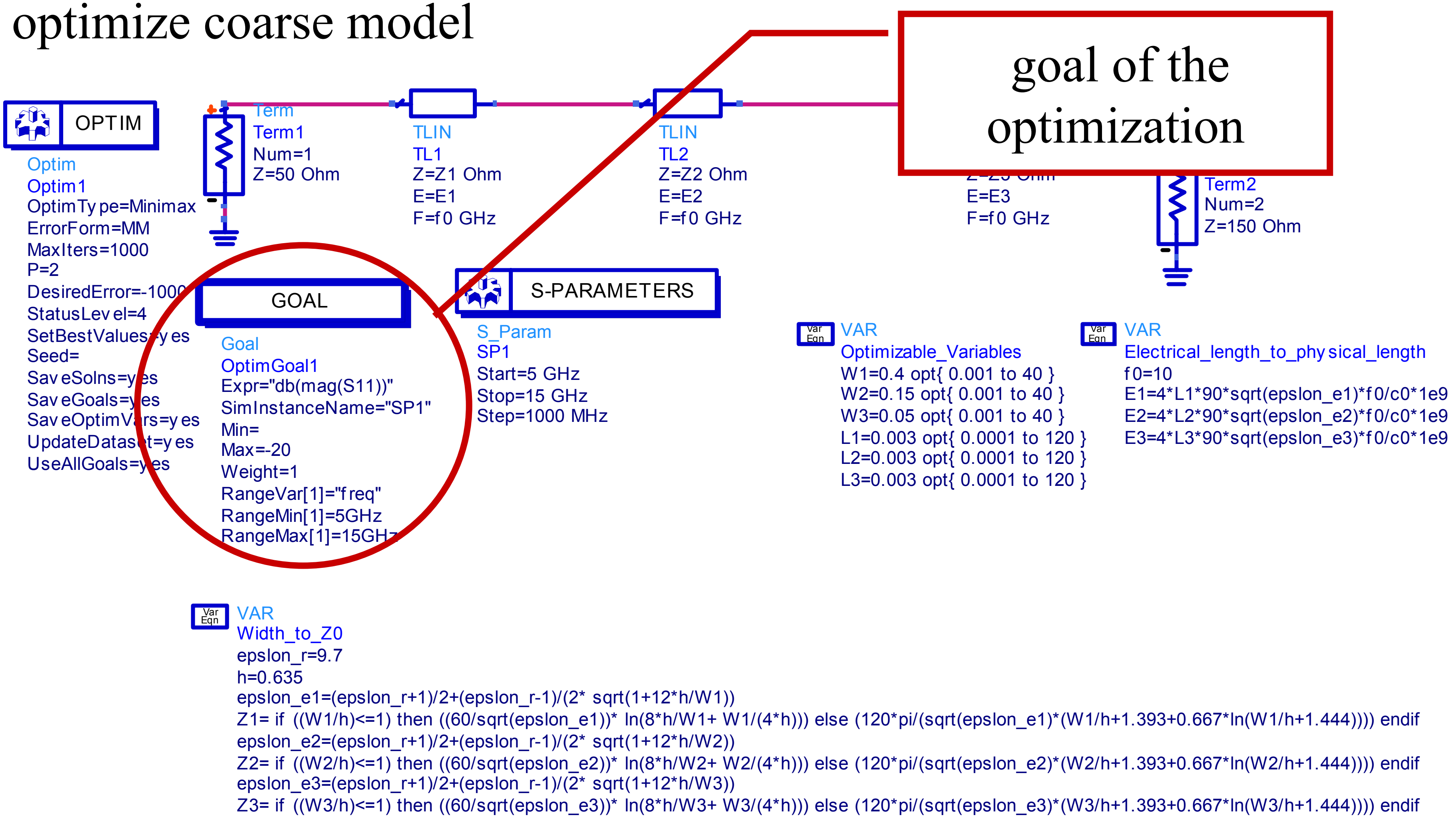
VAR
Optimizable_Variables
W1=0.4 opt{ 0.001 to 40 }
W2=0.15 opt{ 0.001 to 40 }
W3=0.05 opt{ 0.001 to 40 }
L1=0.003 opt{ 0.0001 to 120 }
L2=0.003 opt{ 0.0001 to 120 }
L3=0.003 opt{ 0.0001 to 120 }

VAR
Electrical_length_to_physical_length
f0=10
E1=4*L1*90*sqrt(epslon_e1)*f0/c0*1e9
E2=4*L2*90*sqrt(epslon_e2)*f0/c0*1e9
E3=4*L3*90*sqrt(epslon_e3)*f0/c0*1e9

VAR
Width_to_Z0
epslon_r=9.7
h=0.635
epslon_e1=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W1))
Z1= if ((W1/h)<=1) then ((60/sqrt(epslon_e1))* ln(8*h/W1+ W1/(4*h))) else (120*pi/(sqrt(epslon_e1)*(W1/h+1.393+0.667*ln(W1/h+1.444)))) endif
epslon_e2=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W2))
Z2= if ((W2/h)<=1) then ((60/sqrt(epslon_e2))* ln(8*h/W2+ W2/(4*h))) else (120*pi/(sqrt(epslon_e2)*(W2/h+1.393+0.667*ln(W2/h+1.444)))) endif
epslon_e3=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W3))
Z3= if ((W3/h)<=1) then ((60/sqrt(epslon_e3))* ln(8*h/W3+ W3/(4*h))) else (120*pi/(sqrt(epslon_e3)*(W3/h+1.393+0.667*ln(W3/h+1.444)))) endif

Implicit Space Mapping: Steps 1-3

optimize coarse model



goal of the optimization

OPTIM
Optim
Optim1
OptimType=Minimax
ErrorForm=MM
MaxIters=1000
P=2
DesiredError=-1000
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
SaveOptimVars=yes
UpdateDataset=yes
UseAllGoals=yes

Term
Term1
Num=1
Z=50 Ohm

TLIN
TL1
Z=Z1 Ohm
E=E1
F=f0 GHz

TLIN
TL2
Z=Z2 Ohm
E=E2
F=f0 GHz

E=E3
F=f0 GHz

Term2
Num=2
Z=150 Ohm

GOAL
Goal
OptimGoal1
Expr="db(mag(S11))"
SimInstanceName="SP1"
Min=
Max=-20
Weight=1
RangeVar[1]="freq"
RangeMin[1]=5GHz
RangeMax[1]=15GHz

S-PARAMETERS
S_Param
SP1
Start=5 GHz
Stop=15 GHz
Step=1000 MHz

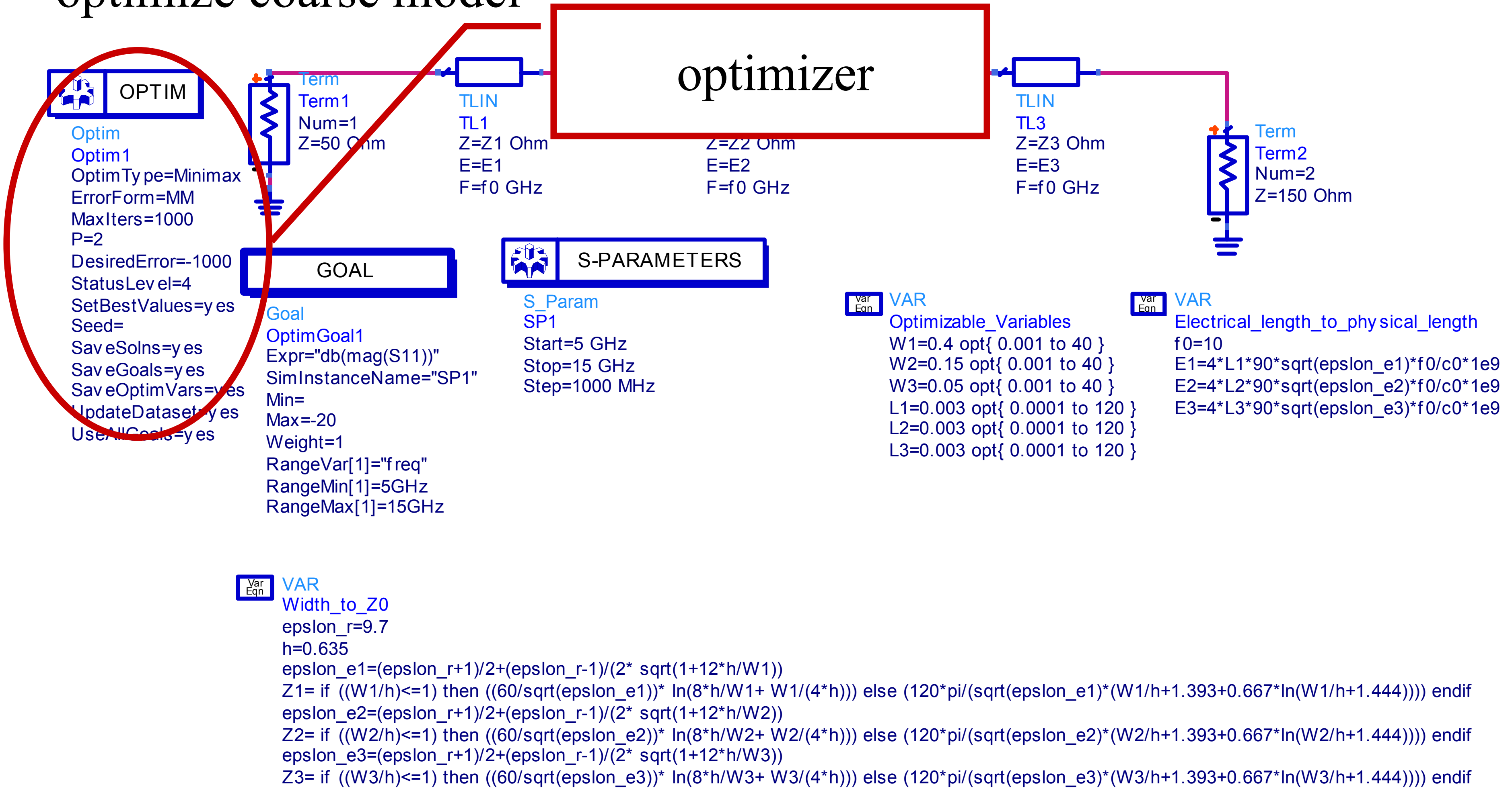
VAR
Optimizable_Variables
W1=0.4 opt{ 0.001 to 40 }
W2=0.15 opt{ 0.001 to 40 }
W3=0.05 opt{ 0.001 to 40 }
L1=0.003 opt{ 0.0001 to 120 }
L2=0.003 opt{ 0.0001 to 120 }
L3=0.003 opt{ 0.0001 to 120 }

VAR
Electrical_length_to_physical_length
f0=10
E1=4*L1*90*sqrt(epslon_e1)*f0/c0*1e9
E2=4*L2*90*sqrt(epslon_e2)*f0/c0*1e9
E3=4*L3*90*sqrt(epslon_e3)*f0/c0*1e9

VAR
Width_to_Z0
epslon_r=9.7
h=0.635
epslon_e1=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W1))
Z1= if ((W1/h)<=1) then ((60/sqrt(epslon_e1))* ln(8*h/W1+ W1/(4*h))) else (120*pi/(sqrt(epslon_e1)*(W1/h+1.393+0.667*ln(W1/h+1.444)))) endif
epslon_e2=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W2))
Z2= if ((W2/h)<=1) then ((60/sqrt(epslon_e2))* ln(8*h/W2+ W2/(4*h))) else (120*pi/(sqrt(epslon_e2)*(W2/h+1.393+0.667*ln(W2/h+1.444)))) endif
epslon_e3=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W3))
Z3= if ((W3/h)<=1) then ((60/sqrt(epslon_e3))* ln(8*h/W3+ W3/(4*h))) else (120*pi/(sqrt(epslon_e3)*(W3/h+1.393+0.667*ln(W3/h+1.444)))) endif

Implicit Space Mapping: Steps 1-3

optimize coarse model



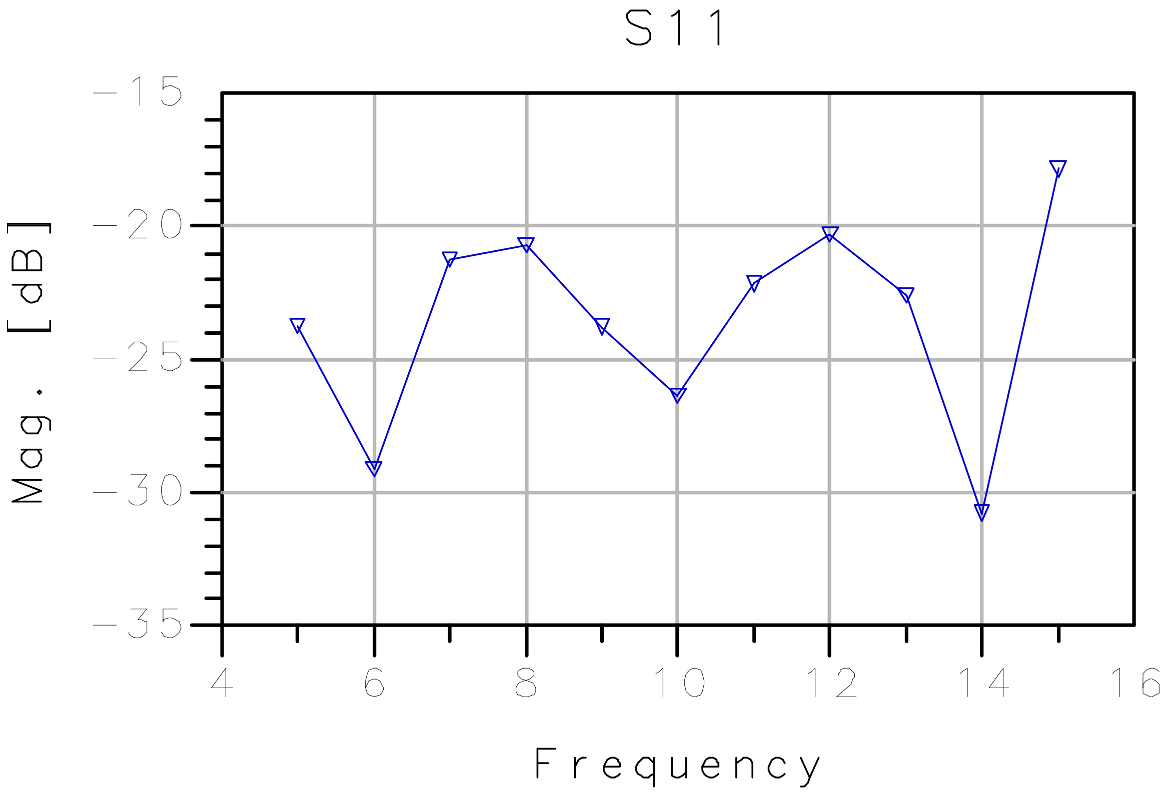
```
OPTIM
Optim
Optim1
OptimType=Minimax
ErrorForm=MM
MaxIters=1000
P=2
DesiredError=-1000
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
SaveOptimVars=yes
UpdateDataset=yes
UseAllGoals=yes

Term
Term1
Num=1
Z=50 Ohm

TLIN
TL1
Z=Z1 Ohm
E=E1
F=f0 GHz

Z=Z2 Ohm
E=E2
F=f0 GHz

TLIN
TL3
Z=Z3 Ohm
E=E3
F=f0 GHz

Term
Term2
Num=2
Z=150 Ohm

GOAL
Goal
OptimGoal1
Expr="db(mag(S11))"
SimInstanceName="SP1"
Min=
Max=-20
Weight=1
RangeVar[1]="freq"
RangeMin[1]=5GHz
RangeMax[1]=15GHz

S-PARAMETERS
S_Param
SP1
Start=5 GHz
Stop=15 GHz
Step=1000 MHz

VAR
Optimizable_Variables
W1=0.4 opt{ 0.001 to 40 }
W2=0.15 opt{ 0.001 to 40 }
W3=0.05 opt{ 0.001 to 40 }
L1=0.003 opt{ 0.0001 to 120 }
L2=0.003 opt{ 0.0001 to 120 }
L3=0.003 opt{ 0.0001 to 120 }

VAR
Electrical_length_to_physical_length
f0=10
E1=4*L1*90*sqrt(epslon_e1)*f0/c0*1e9
E2=4*L2*90*sqrt(epslon_e2)*f0/c0*1e9
E3=4*L3*90*sqrt(epslon_e3)*f0/c0*1e9

VAR
Width_to_Z0
epslon_r=9.7
h=0.635
epslon_e1=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W1))
Z1= if ((W1/h)<=1) then ((60/sqrt(epslon_e1))* ln(8*h/W1+ W1/(4*h))) else (120*pi/(sqrt(epslon_e1)*(W1/h+1.393+0.667*ln(W1/h+1.444)))) endif
epslon_e2=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W2))
Z2= if ((W2/h)<=1) then ((60/sqrt(epslon_e2))* ln(8*h/W2+ W2/(4*h))) else (120*pi/(sqrt(epslon_e2)*(W2/h+1.393+0.667*ln(W2/h+1.444)))) endif
epslon_e3=(epslon_r+1)/2+(epslon_r-1)/(2* sqrt(1+12*h/W3))
Z3= if ((W3/h)<=1) then ((60/sqrt(epslon_e3))* ln(8*h/W3+ W3/(4*h))) else (120*pi/(sqrt(epslon_e3)*(W3/h+1.393+0.667*ln(W3/h+1.444)))) endif
```

Implicit Space Mapping: Steps 4-5

simulate fine model using Momentum

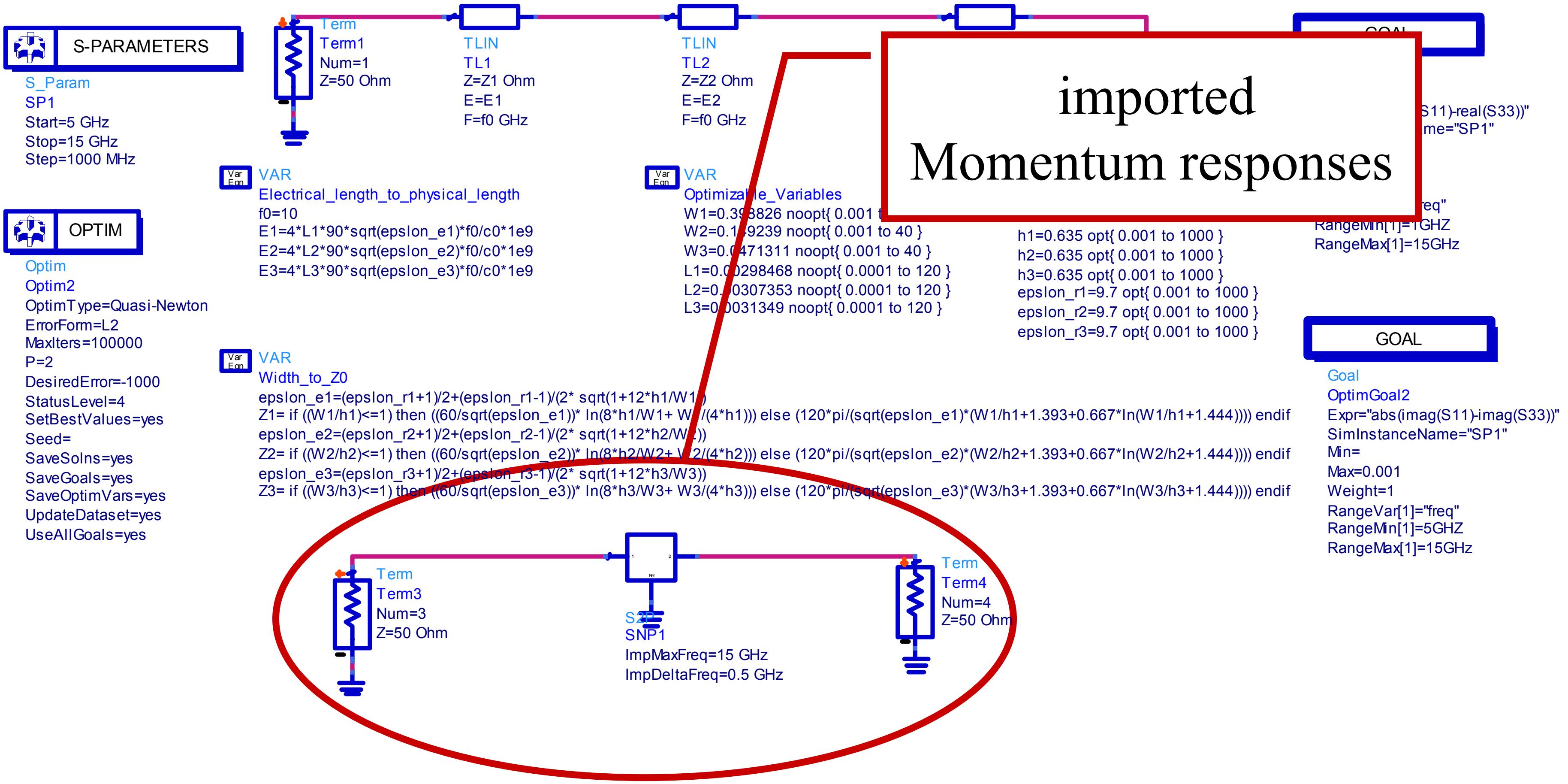
Implicit Space Mapping: Steps 5-6

obtain the fine model result and check stopping criteria



Implicit Space Mapping: Step 7

calibrate coarse model: extract preassigned parameters *x*



imported
Momentum responses

S-PARAMETERS
S_Param
SP1
Start=5 GHz
Stop=15 GHz
Step=1000 MHz

OPTIM
Optim
Optim2
OptimType=Quasi-Newton
ErrorForm=L2
MaxIters=100000
P=2
DesiredError=-1000
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
SaveOptimVars=yes
UpdateDataset=yes
UseAllGoals=yes

Term
Term1
Num=1
Z=50 Ohm

TLIN
TL1
Z=Z1 Ohm
E=E1
F=f0 GHz

TLIN
TL2
Z=Z2 Ohm
E=E2
F=f0 GHz

VAR
Electrical_length_to_physical_length
f0=10
E1=4*L1*90*sqrt(epslon_e1)*f0/c0*1e9
E2=4*L2*90*sqrt(epslon_e2)*f0/c0*1e9
E3=4*L3*90*sqrt(epslon_e3)*f0/c0*1e9

VAR
Optimiza[illegible]le_Variables
W1=0.39[illegible]3826 noopt{ 0.001 t
W2=0.1[illegible]9239 noopt{ 0.001 to 40 }
W3=0.[illegible]471311 noopt{ 0.001 to 40 }
L1=0.[illegible]0298468 noopt{ 0.0001 to 120 }
L2=0.[illegible]0307353 noopt{ 0.0001 to 120 }
L3=0.[illegible]0031349 noopt{ 0.0001 to 120 }

h1=0.635 opt{ 0.001 to 1000 }
h2=0.635 opt{ 0.001 to 1000 }
h3=0.635 opt{ 0.001 to 1000 }
epslon_r1=9.7 opt{ 0.001 to 1000 }
epslon_r2=9.7 opt{ 0.001 to 1000 }
epslon_r3=9.7 opt{ 0.001 to 1000 }

GOAL
S11)-real(S33))"
me="SP1"
req"
RangeMin[1]=1GHZ
RangeMax[1]=15GHz

VAR
Width_to_Z0
epslon_e1=(epslon_r1+1)/2+(epslon_r1-1)/(2* sqrt(1+12*h1/W1))
Z1= if ((W1/h1)<=1) then ((60/sqrt(epslon_e1))* ln(8*h1/W1+ W1/(4*h1))) else (120*pi/(sqrt(epslon_e1)*(W1/h1+1.393+0.667*ln(W1/h1+1.444)))) endif
epslon_e2=(epslon_r2+1)/2+(epslon_r2-1)/(2* sqrt(1+12*h2/W2))
Z2= if ((W2/h2)<=1) then ((60/sqrt(epslon_e2))* ln(8*h2/W2+ W2/(4*h2))) else (120*pi/(sqrt(epslon_e2)*(W2/h2+1.393+0.667*ln(W2/h2+1.444)))) endif
epslon_e3=(epslon_r3+1)/2+(epslon_r3-1)/(2* sqrt(1+12*h3/W3))
Z3= if ((W3/h3)<=1) then ((60/sqrt(epslon_e3))* ln(8*h3/W3+ W3/(4*h3))) else (120*pi/(sqrt(epslon_e3)*(W3/h3+1.393+0.667*ln(W3/h3+1.444)))) endif

GOAL
Goal
OptimGoal2
Expr="abs(imag(S11)-imag(S33))"
SimInstanceName="SP1"
Min=
Max=0.001
Weight=1
RangeVar[1]="freq"
RangeMin[1]=5GHZ
RangeMax[1]=15GHz

Term
Term3
Num=3
Z=50 Ohm

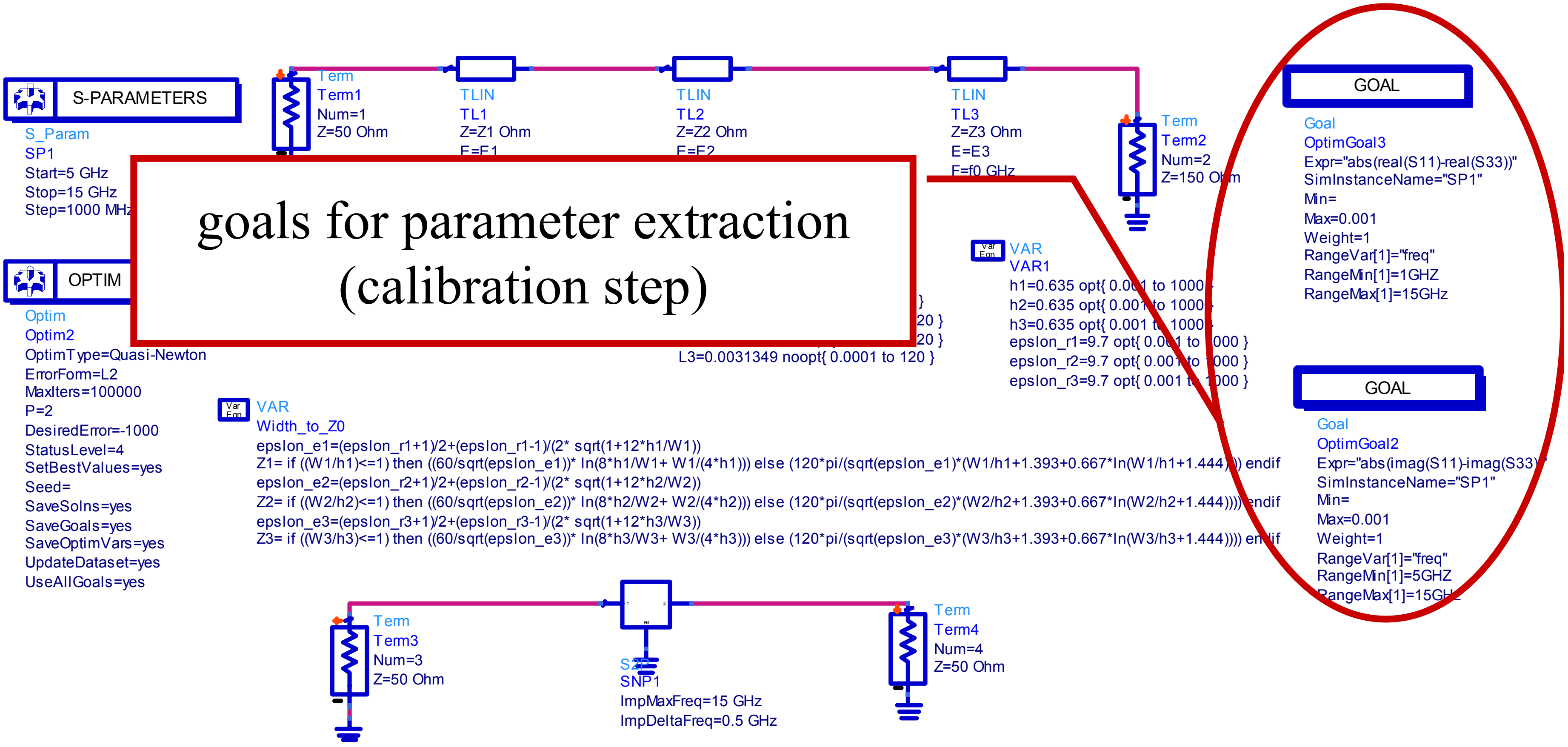
S2P
SNP1
ImpMaxFreq=15 GHz
ImpDeltaFreq=0.5 GHz

Term
Term4
Num=4
Z=50 Ohm

ADS/Momentum Implementation

Implicit Space Mapping: Step 7

calibrate coarse model: extract preassigned parameters *x*



goals for parameter extraction (calibration step)

S_Param
SP1
Start=5 GHz
Stop=15 GHz
Step=1000 MHz

Optim
Optim2
OptimType=Quasi-Newton
ErrorForm=L2
MaxIters=100000
P=2
DesiredError=-1000
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
SaveOptimVars=yes
UpdateDataset=yes
UseAllGoals=yes

Term
Term1
Num=1
Z=50 Ohm

TLIN
TL1
Z=Z1 Ohm
E=E1

TLIN
TL2
Z=Z2 Ohm
E=E2

TLIN
TL3
Z=Z3 Ohm
E=E3
F=f0 GHz

Term
Term2
Num=2
Z=150 Ohm

}
20 }
20 }
L3=0.0031349 noopt{ 0.0001 to 120 }

VAR
VAR1
h1=0.635 opt{ 0.001 to 1000 }
h2=0.635 opt{ 0.001 to 1000 }
h3=0.635 opt{ 0.001 to 1000 }
epslon_r1=9.7 opt{ 0.001 to 1000 }
epslon_r2=9.7 opt{ 0.001 to 1000 }
epslon_r3=9.7 opt{ 0.001 to 1000 }

VAR
Width_to_Z0
epslon_e1=(epslon_r1+1)/2+(epslon_r1-1)/(2* sqrt(1+12*h1/W1))
Z1= if ((W1/h1)<=1) then ((60/sqrt(epslon_e1))* ln(8*h1/W1+ W1/(4*h1))) else (120*pi/(sqrt(epslon_e1)*(W1/h1+1.393+0.667*ln(W1/h1+1.444)))) endif
epslon_e2=(epslon_r2+1)/2+(epslon_r2-1)/(2* sqrt(1+12*h2/W2))
Z2= if ((W2/h2)<=1) then ((60/sqrt(epslon_e2))* ln(8*h2/W2+ W2/(4*h2))) else (120*pi/(sqrt(epslon_e2)*(W2/h2+1.393+0.667*ln(W2/h2+1.444)))) endif
epslon_e3=(epslon_r3+1)/2+(epslon_r3-1)/(2* sqrt(1+12*h3/W3))
Z3= if ((W3/h3)<=1) then ((60/sqrt(epslon_e3))* ln(8*h3/W3+ W3/(4*h3))) else (120*pi/(sqrt(epslon_e3)*(W3/h3+1.393+0.667*ln(W3/h3+1.444)))) endif

GOAL
Goal
OptimGoal3
Expr="abs(real(S11)-real(S33))"
SimInstanceName="SP1"
Min=
Max=0.001
Weight=1
RangeVar[1]="freq"
RangeMin[1]=1GHZ
RangeMax[1]=15GHz

GOAL
Goal
OptimGoal2
Expr="abs(imag(S11)-imag(S33))"
SimInstanceName="SP1"
Min=
Max=0.001
Weight=1
RangeVar[1]="freq"
RangeMin[1]=5GHZ
RangeMax[1]=15GHz

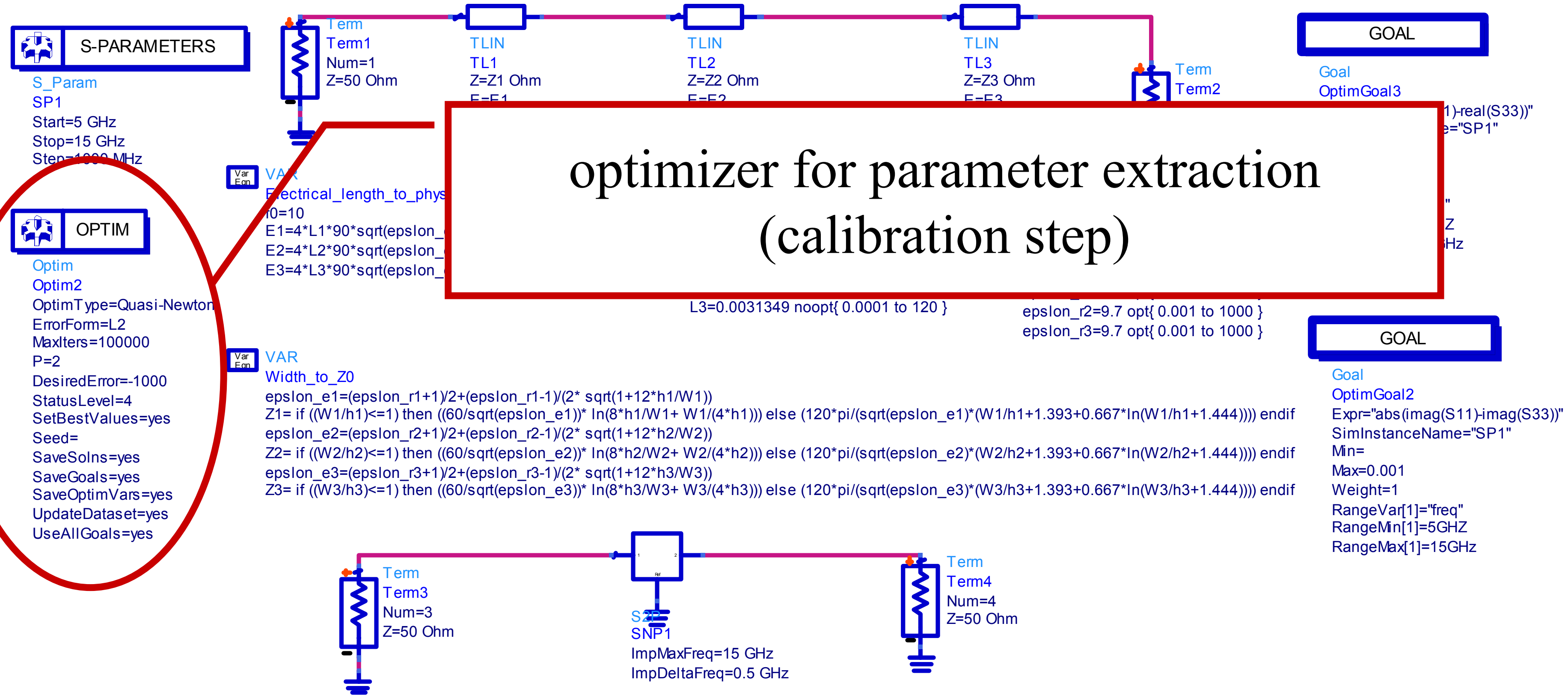
Term
Term3
Num=3
Z=50 Ohm

S2P
SNP1
ImpMaxFreq=15 GHz
ImpDeltaFreq=0.5 GHz

Term
Term4
Num=4
Z=50 Ohm

Implicit Space Mapping: Step 7

calibrate coarse model: extract preassigned parameters *x*

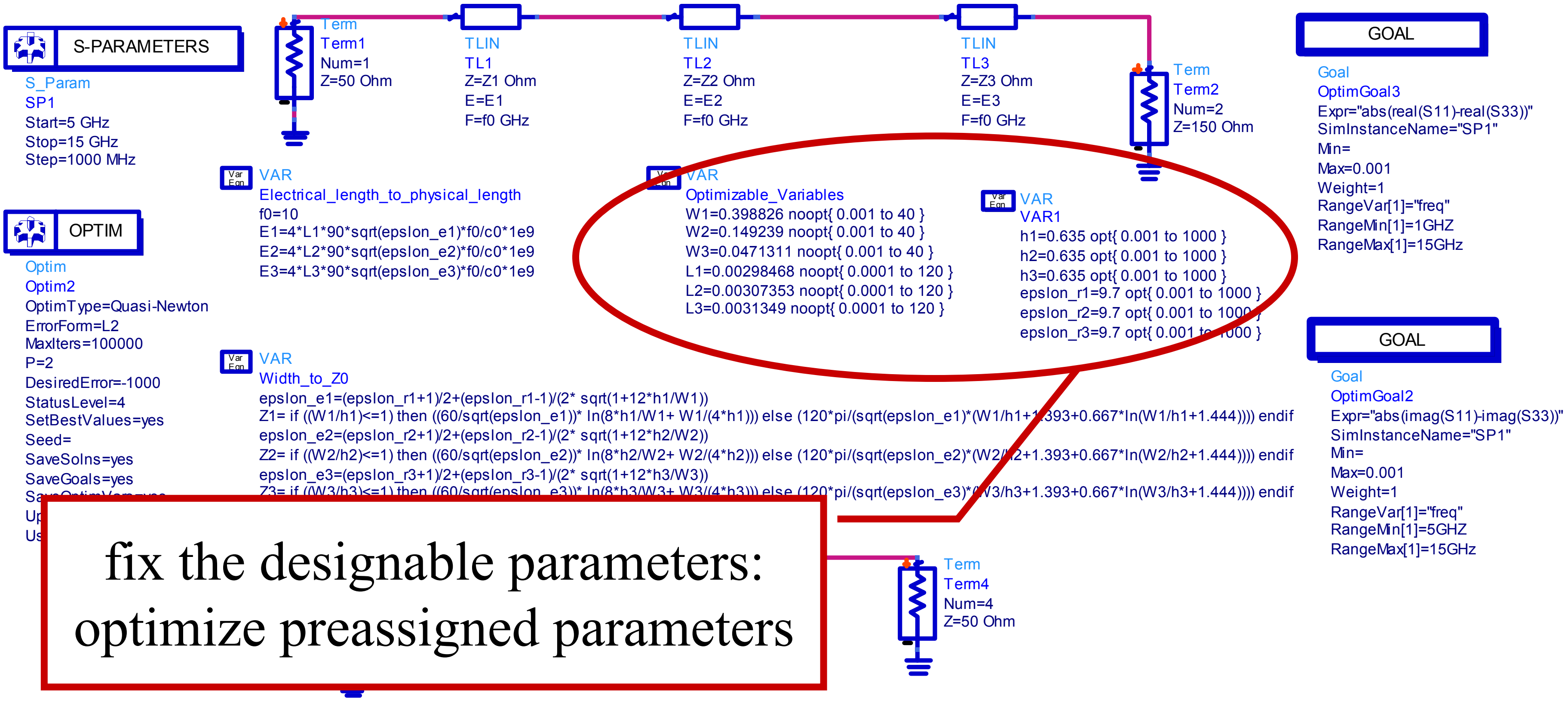


optimizer for parameter extraction
(calibration step)

```
S-PARAMETERS
S_Param
SP1
Start=5 GHz
Stop=15 GHz
Step=1000 MHz

OPTIM
Optim
Optim2
OptimType=Quasi-Newton
ErrorForm=L2
MaxIters=100000
P=2
DesiredError=-1000
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
SaveOptimVars=yes
UpdateDataset=yes
UseAllGoals=yes

Term
Term1
Num=1
Z=50 Ohm

TLIN
TL1
Z=Z1 Ohm
E=E1

TLIN
TL2
Z=Z2 Ohm
E=E2

TLIN
TL3
Z=Z3 Ohm
E=E3

Term
Term2

VAR
Electrical_length_to_phys
f0=10
E1=4*L1*90*sqrt(epslon_
E2=4*L2*90*sqrt(epslon_
E3=4*L3*90*sqrt(epslon_

L3=0.0031349 noopt{ 0.0001 to 120 }

epslon_r2=9.7 opt{ 0.001 to 1000 }
epslon_r3=9.7 opt{ 0.001 to 1000 }

GOAL
Goal
OptimGoal3
1)-real(S33))"
e="SP1"
"
Z
Hz

VAR
Width_to_Z0
epslon_e1=(epslon_r1+1)/2+(epslon_r1-1)/(2* sqrt(1+12*h1/W1))
Z1= if ((W1/h1)<=1) then ((60/sqrt(epslon_e1))* ln(8*h1/W1+ W1/(4*h1))) else (120*pi/(sqrt(epslon_e1)*(W1/h1+1.393+0.667*ln(W1/h1+1.444)))) endif
epslon_e2=(epslon_r2+1)/2+(epslon_r2-1)/(2* sqrt(1+12*h2/W2))
Z2= if ((W2/h2)<=1) then ((60/sqrt(epslon_e2))* ln(8*h2/W2+ W2/(4*h2))) else (120*pi/(sqrt(epslon_e2)*(W2/h2+1.393+0.667*ln(W2/h2+1.444)))) endif
epslon_e3=(epslon_r3+1)/2+(epslon_r3-1)/(2* sqrt(1+12*h3/W3))
Z3= if ((W3/h3)<=1) then ((60/sqrt(epslon_e3))* ln(8*h3/W3+ W3/(4*h3))) else (120*pi/(sqrt(epslon_e3)*(W3/h3+1.393+0.667*ln(W3/h3+1.444)))) endif

GOAL
Goal
OptimGoal2
Expr="abs(imag(S11)-imag(S33))"
SimInstanceName="SP1"
Min=
Max=0.001
Weight=1
RangeVar[1]="freq"
RangeMin[1]=5GHZ
RangeMax[1]=15GHz

Term
Term3
Num=3
Z=50 Ohm

S2P
SNP1
ImpMaxFreq=15 GHz
ImpDeltaFreq=0.5 GHz

Term
Term4
Num=4
Z=50 Ohm
```

Implicit Space Mapping: Step 7

calibrate coarse model: extract preassigned parameters *x*



S-PARAMETERS
S_Param
SP1
Start=5 GHz
Stop=15 GHz
Step=1000 MHz

OPTIM
Optim
Optim2
OptimType=Quasi-Newton
ErrorForm=L2
MaxIters=100000
P=2
DesiredError=-1000
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
Sa
Up
Us

Term
Term1
Num=1
Z=50 Ohm

TLIN
TL1
Z=Z1 Ohm
E=E1
F=f0 GHz

TLIN
TL2
Z=Z2 Ohm
E=E2
F=f0 GHz

TLIN
TL3
Z=Z3 Ohm
E=E3
F=f0 GHz

Term
Term2
Num=2
Z=150 Ohm

VAR
Electrical_length_to_physical_length
f0=10
E1=4*L1*90*sqrt(epslon_e1)*f0/c0*1e9
E2=4*L2*90*sqrt(epslon_e2)*f0/c0*1e9
E3=4*L3*90*sqrt(epslon_e3)*f0/c0*1e9

VAR
Optimizable_Variables
W1=0.398826 noopt{ 0.001 to 40 }
W2=0.149239 noopt{ 0.001 to 40 }
W3=0.0471311 noopt{ 0.001 to 40 }
L1=0.00298468 noopt{ 0.0001 to 120 }
L2=0.00307353 noopt{ 0.0001 to 120 }
L3=0.0031349 noopt{ 0.0001 to 120 }

VAR
VAR1
h1=0.635 opt{ 0.001 to 1000 }
h2=0.635 opt{ 0.001 to 1000 }
h3=0.635 opt{ 0.001 to 1000 }
epslon_r1=9.7 opt{ 0.001 to 1000 }
epslon_r2=9.7 opt{ 0.001 to 1000 }
epslon_r3=9.7 opt{ 0.001 to 1000 }

VAR
Width_to_Z0
epslon_e1=(epslon_r1+1)/2+(epslon_r1-1)/(2* sqrt(1+12*h1/W1))
Z1= if ((W1/h1)<=1) then ((60/sqrt(epslon_e1))* ln(8*h1/W1+ W1/(4*h1))) else (120*pi/(sqrt(epslon_e1)*(W1/h1+1.393+0.667*ln(W1/h1+1.444)))) endif
epslon_e2=(epslon_r2+1)/2+(epslon_r2-1)/(2* sqrt(1+12*h2/W2))
Z2= if ((W2/h2)<=1) then ((60/sqrt(epslon_e2))* ln(8*h2/W2+ W2/(4*h2))) else (120*pi/(sqrt(epslon_e2)*(W2/h2+1.393+0.667*ln(W2/h2+1.444)))) endif
epslon_e3=(epslon_r3+1)/2+(epslon_r3-1)/(2* sqrt(1+12*h3/W3))
Z3= if ((W3/h3)<=1) then ((60/sqrt(epslon_e3))* ln(8*h3/W3+ W3/(4*h3))) else (120*pi/(sqrt(epslon_e3)*(W3/h3+1.393+0.667*ln(W3/h3+1.444)))) endif

GOAL
Goal
OptimGoal3
Expr="abs(real(S11)-real(S33))"
SimInstanceName="SP1"
Min=
Max=0.001
Weight=1
RangeVar[1]="freq"
RangeMin[1]=1GHZ
RangeMax[1]=15GHz

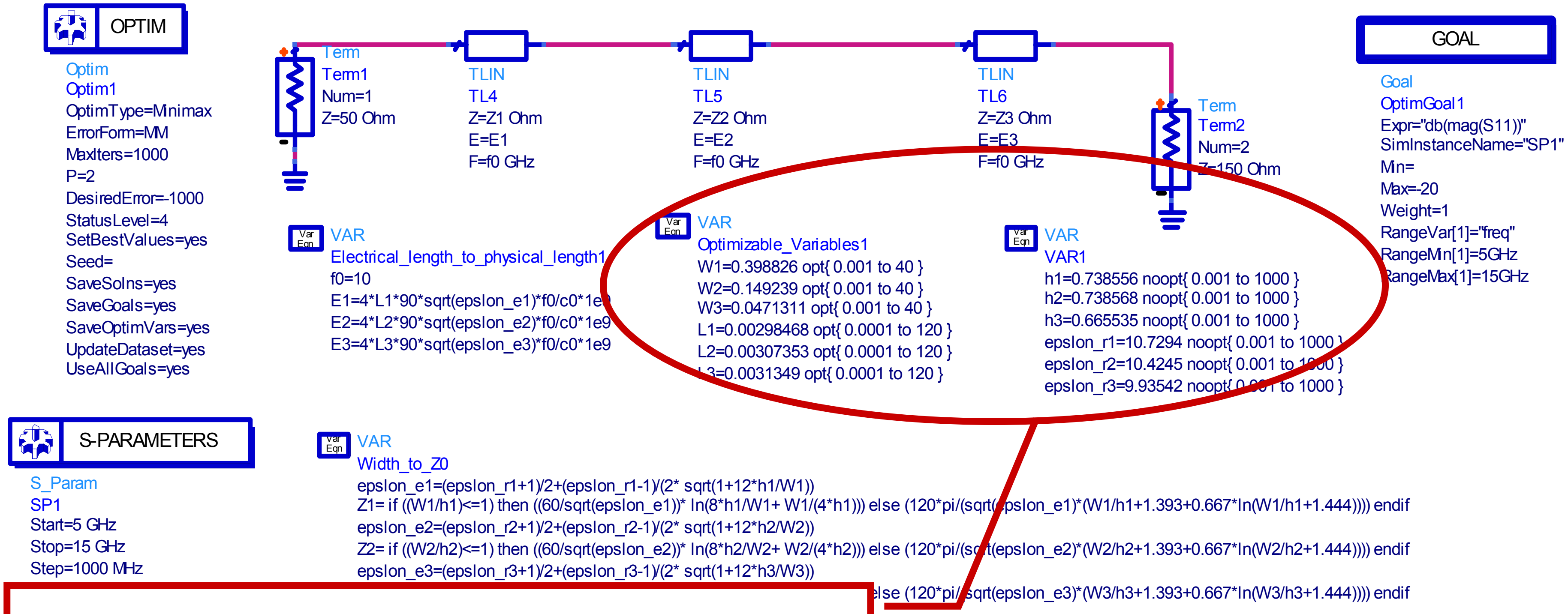
GOAL
Goal
OptimGoal2
Expr="abs(imag(S11)-imag(S33))"
SimInstanceName="SP1"
Min=
Max=0.001
Weight=1
RangeVar[1]="freq"
RangeMin[1]=5GHZ
RangeMax[1]=15GHz

Term
Term4
Num=4
Z=50 Ohm

fix the designable parameters:
optimize preassigned parameters

Implicit Space Mapping: Steps 8-3

fix preassigned parameters: reoptimize calibrated coarse model

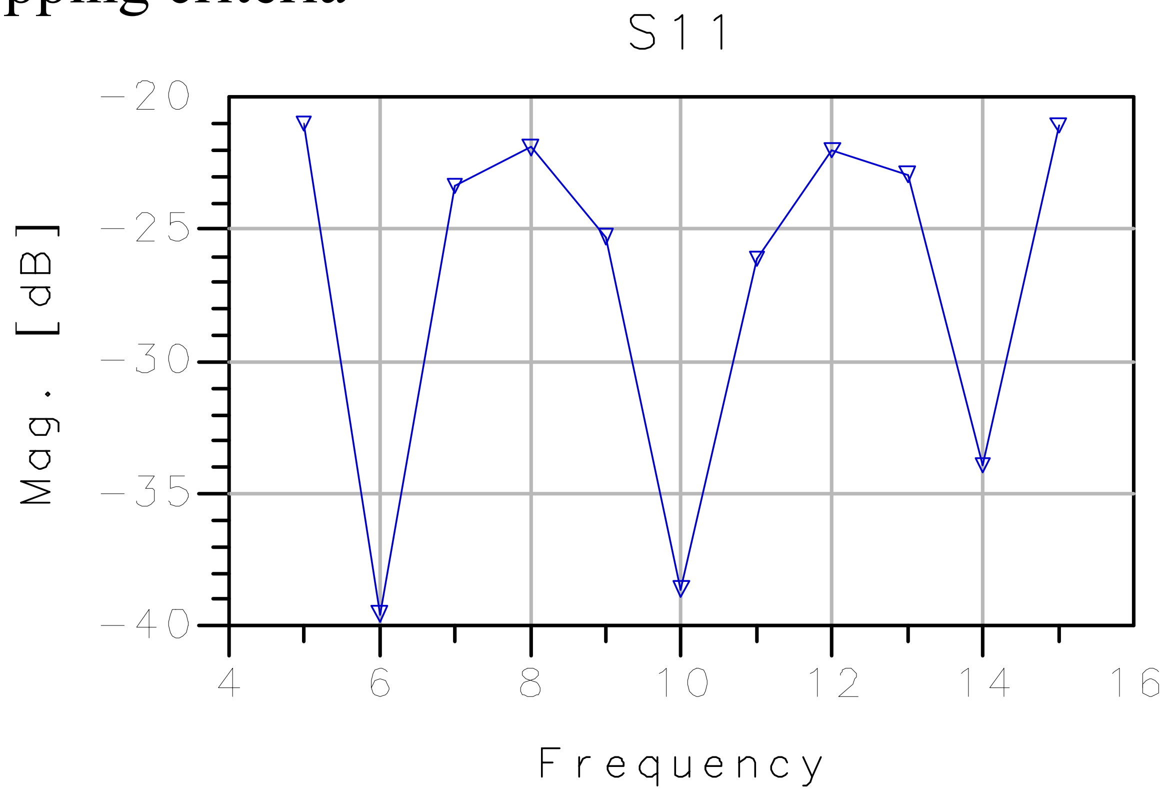


```
Optim
Optim1
OptimType=Minimax
ErrorForm=MM
MaxIters=1000
P=2
DesiredError=-1000
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=yes
SaveGoals=yes
SaveOptimVars=yes
UpdateDataset=yes
UseAllGoals=yes

Term1
Num=1
Z=50 Ohm

TL4
Z=Z1 Ohm
E=E1
F=f0 GHz

TL5
Z=Z2 Ohm
E=E2
F=f0 GHz

TL6
Z=Z3 Ohm
E=E3
F=f0 GHz

Term2
Num=2
Z=150 Ohm

Goal
OptimGoal1
Expr="db(mag(S11))"
SimInstanceName="SP1"
Min=
Max=-20
Weight=1
RangeVar[1]="freq"
RangeMin[1]=5GHz
RangeMax[1]=15GHz

VAR
Electrical_length_to_physical_length1
f0=10
E1=4*L1*90*sqrt(epslon_e1)*f0/c0*1e9
E2=4*L2*90*sqrt(epslon_e2)*f0/c0*1e9
E3=4*L3*90*sqrt(epslon_e3)*f0/c0*1e9

VAR
Optimizable_Variables1
W1=0.398826 opt{ 0.001 to 40 }
W2=0.149239 opt{ 0.001 to 40 }
W3=0.0471311 opt{ 0.001 to 40 }
L1=0.00298468 opt{ 0.0001 to 120 }
L2=0.00307353 opt{ 0.0001 to 120 }
L3=0.0031349 opt{ 0.0001 to 120 }

VAR
VAR1
h1=0.738556 noopt{ 0.001 to 1000 }
h2=0.738568 noopt{ 0.001 to 1000 }
h3=0.665535 noopt{ 0.001 to 1000 }
epslon_r1=10.7294 noopt{ 0.001 to 1000 }
epslon_r2=10.4245 noopt{ 0.001 to 1000 }
epslon_r3=9.93542 noopt{ 0.001 to 1000 }

S_Param
SP1
Start=5 GHz
Stop=15 GHz
Step=1000 MHz

VAR
Width_to_Z0
epslon_e1=(epslon_r1+1)/2+(epslon_r1-1)/(2* sqrt(1+12*h1/W1))
Z1= if ((W1/h1)<=1) then ((60/sqrt(epslon_e1))* ln(8*h1/W1+ W1/(4*h1))) else (120*pi/(sqrt(epslon_e1)*(W1/h1+1.393+0.667*ln(W1/h1+1.444)))) endif
epslon_e2=(epslon_r2+1)/2+(epslon_r2-1)/(2* sqrt(1+12*h2/W2))
Z2= if ((W2/h2)<=1) then ((60/sqrt(epslon_e2))* ln(8*h2/W2+ W2/(4*h2))) else (120*pi/(sqrt(epslon_e2)*(W2/h2+1.393+0.667*ln(W2/h2+1.444)))) endif
epslon_e3=(epslon_r3+1)/2+(epslon_r3-1)/(2* sqrt(1+12*h3/W3))
else (120*pi/(sqrt(epslon_e3)*(W3/h3+1.393+0.667*ln(W3/h3+1.444)))) endif
```

fix preassigned parameters:
reoptimize calibrated coarse model

Implicit Space Mapping: Steps 4-6

simulate fine model using Momentum,
satisfy stopping criteria



Conclusions

Space Mapping intelligently links companion “coarse” or “surrogate” models with “fine” models—physical, empirical, electromagnetic

Space Mapping optimization follows traditional experience of designers

researchers and practitioners attracted to Aggressive Space Mapping

Space Mapping already used in the RF industry
for enhanced (mapped) library (surrogate) models

Implicit Space Mapping (ISM), where preassigned parameters change in coarse model—novel approach

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