New Developments in Optimization Technology for RF, Wireless and Microwave Circuit Design, Integrating EM Simulations

J.W. Bandler

Simulation Optimization Systems Research Laboratory
McMaster University

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

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Outline

"Space Mapping" coined in 1993

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

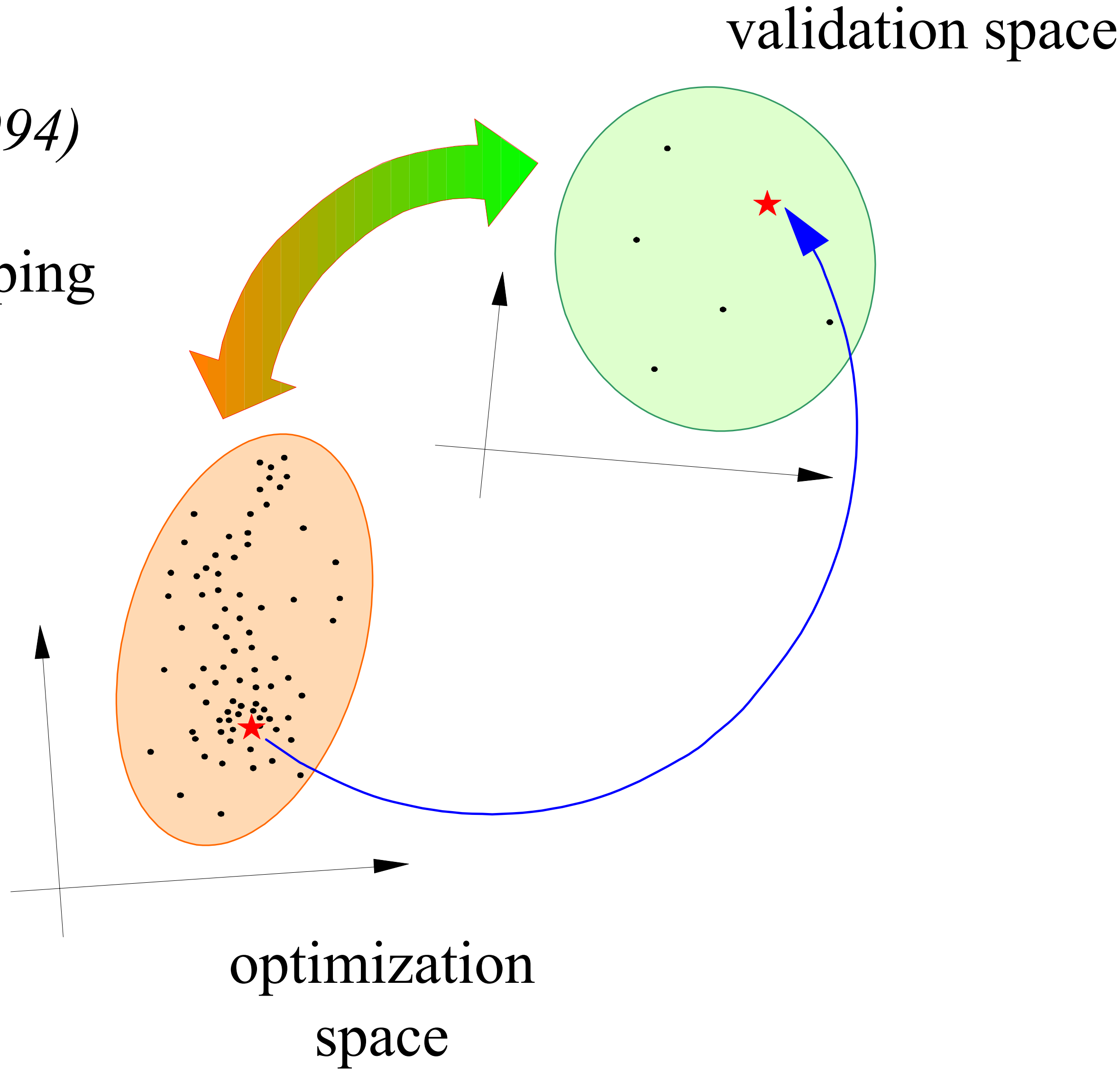
object oriented SMX system facilitates commercial simulators

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)



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
	mapped or enhanced coarse model
Surrogate Model	alternative expression for Surrogate
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/ Resolution	coarse
High Fidelity/ Resolution	fine
Empirical	coarse
Simplified Physics	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

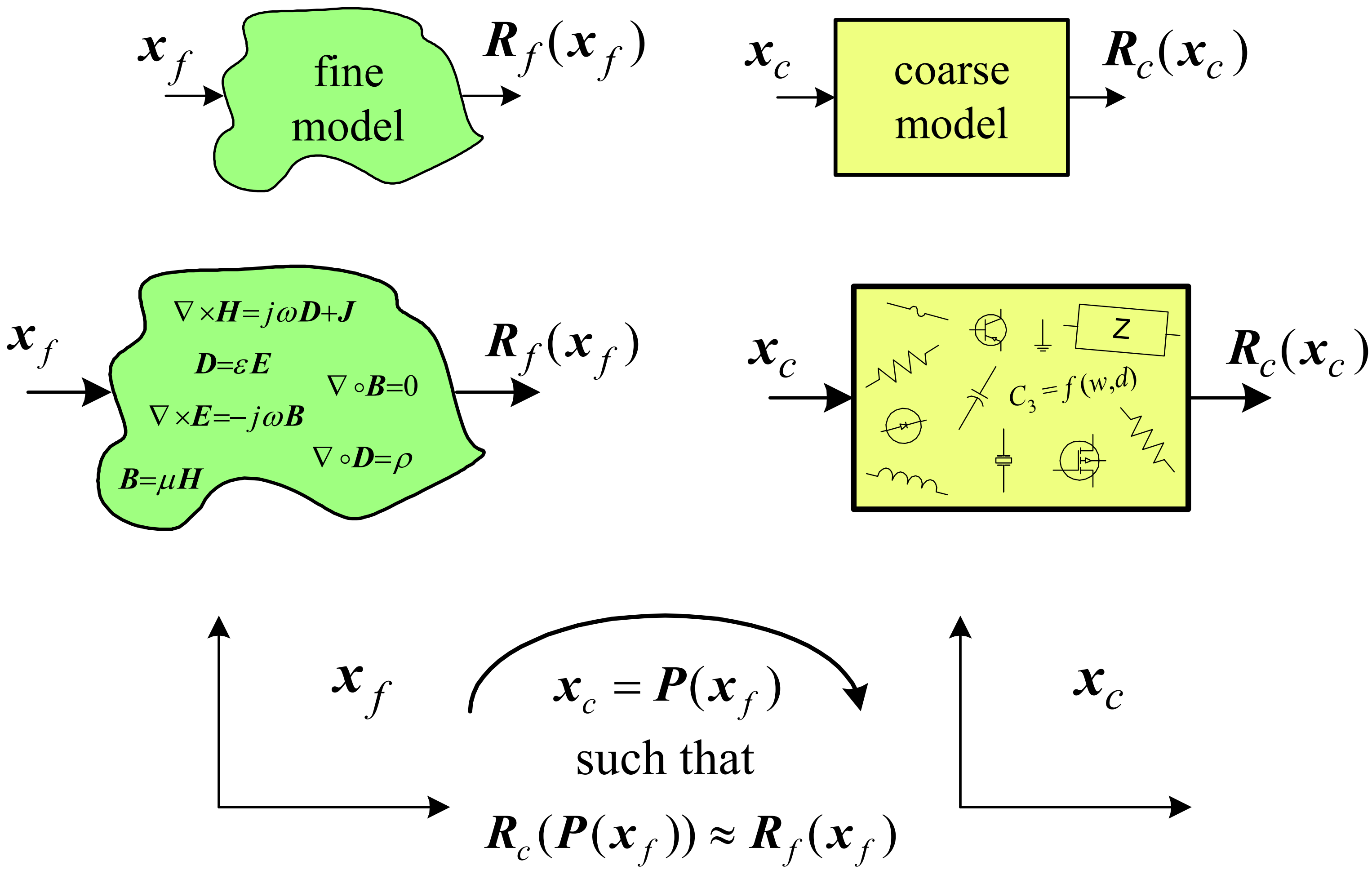
Parameter (input) Space Mapping	mapping, transformation or correction of design variables
Response (output) Space Mapping	mapping, transformation or correction of responses
Response Surface Approximation	linear/quadratic/polynomial approximation of responses w.r.t. design variables

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	?

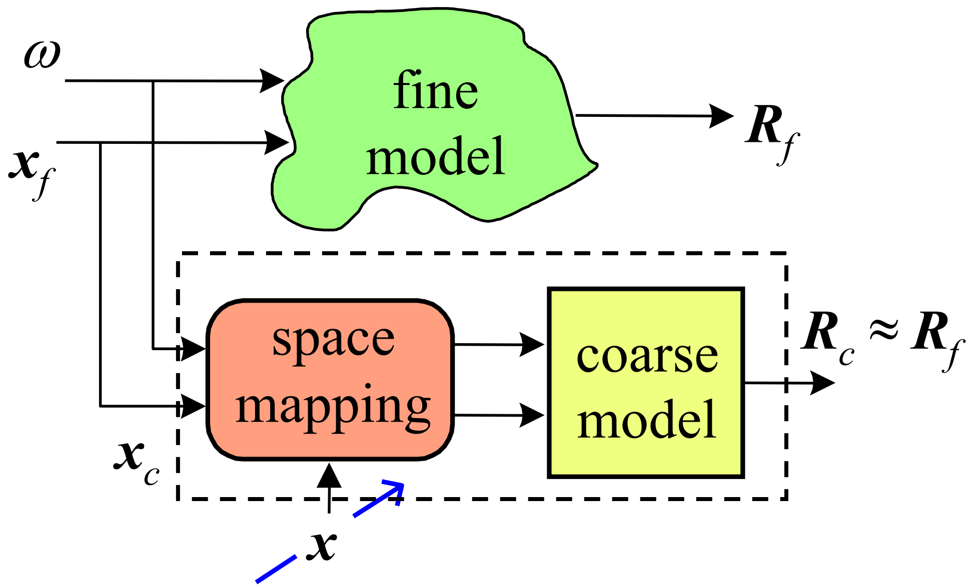
The Space Mapping Concept

(Bandler et al., 1994-)



General Space Mapping Technology (*Bandler et al., 1994-2002*)

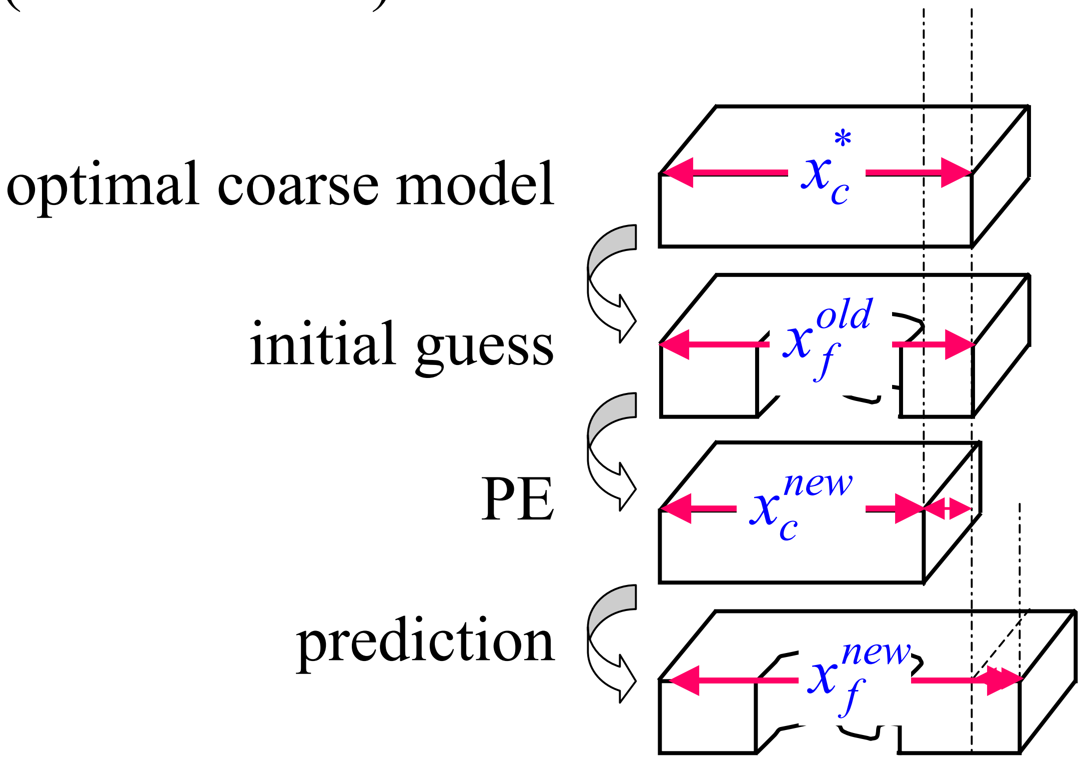
linearized: original and Aggressive Space Mapping
nonlinear: Neural Space Mapping, etc.
implicit: preassigned parameters (ISM)



parameters $\boldsymbol{x}$: coarse space parameters, neuron weights mapping tableau, KPP (ISM)

Space Mapping Practice—Cheese Cutting Problem

(*Bandler 2002*)



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

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

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

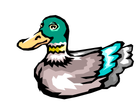
Kaj Madsen (Technical University of Denmark, 1993-)
mapping updates, trust region methods

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

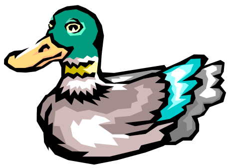
Rayas-Sánchez (McMaster University; ITESO, Mexico 1998-)
space mapping through artificial neural networks

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

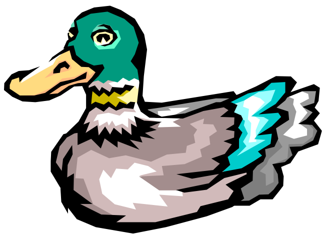


Selected Space Mapping Contributors

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

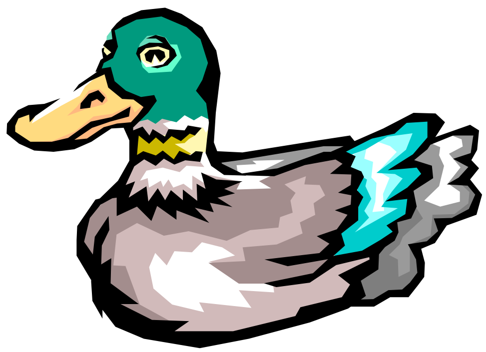
Selected Space Mapping Contributors

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

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

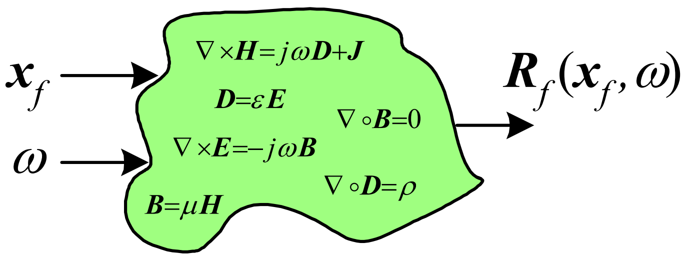
given $\boldsymbol{J}_c$ and $\boldsymbol{J}_f$ we estimate (least squares)

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

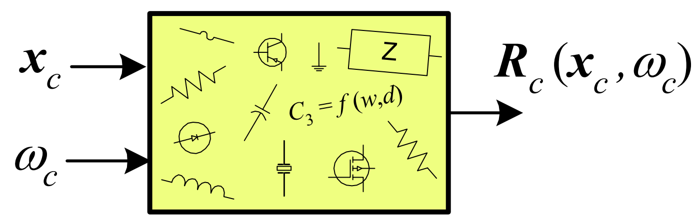
Conventional Space Mapping for Microwave Circuits

(Bandler et al., 1994)

fine model



coarse model



find

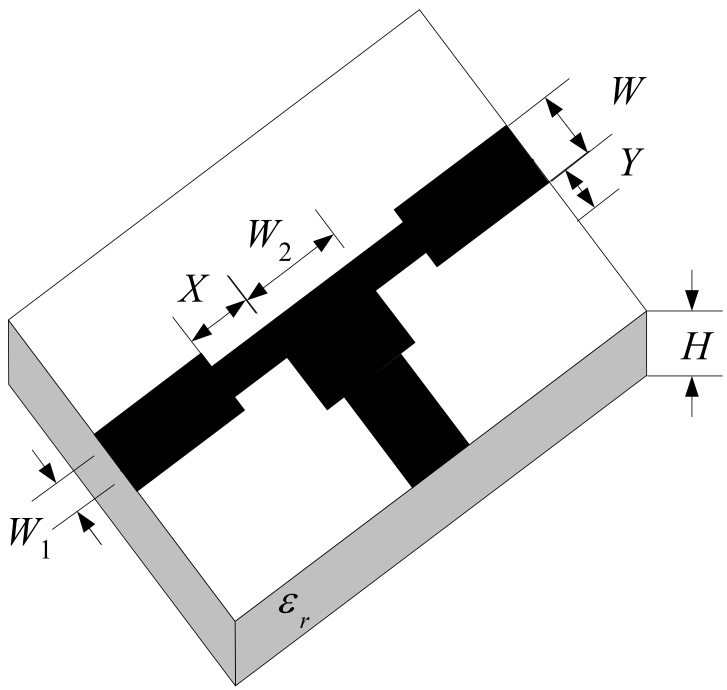
$$\begin{bmatrix}\boldsymbol{x}_c\\ \omega_c\end{bmatrix}=\boldsymbol{P}(\boldsymbol{x}_f,\omega)$$

such that

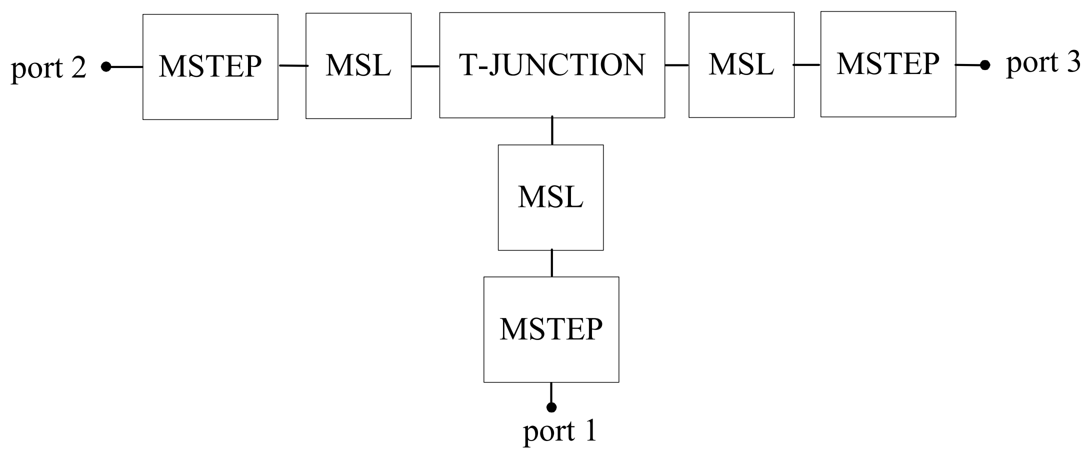
$$\boldsymbol{R}_c(\boldsymbol{x}_c,\omega_c)\approx\boldsymbol{R}_f(\boldsymbol{x}_f,\omega)$$

Microstrip Shaped T-Junction

fine model



coarse model



Microstrip Shaped T-Junction

the region of interest

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

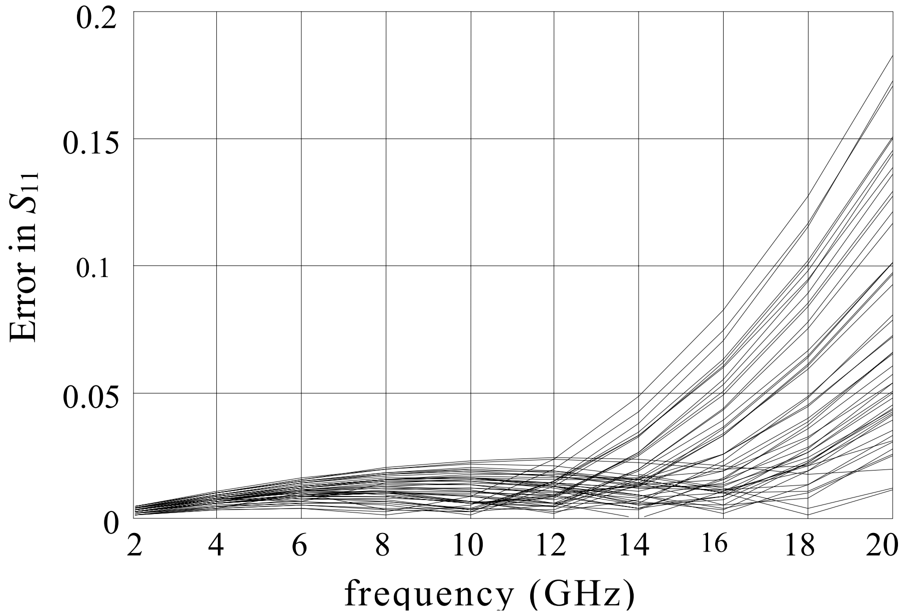
the frequency range is 2 GHz to 20 GHz with a step of 2 GHz
the number of base points is 9, the number of test points is 50

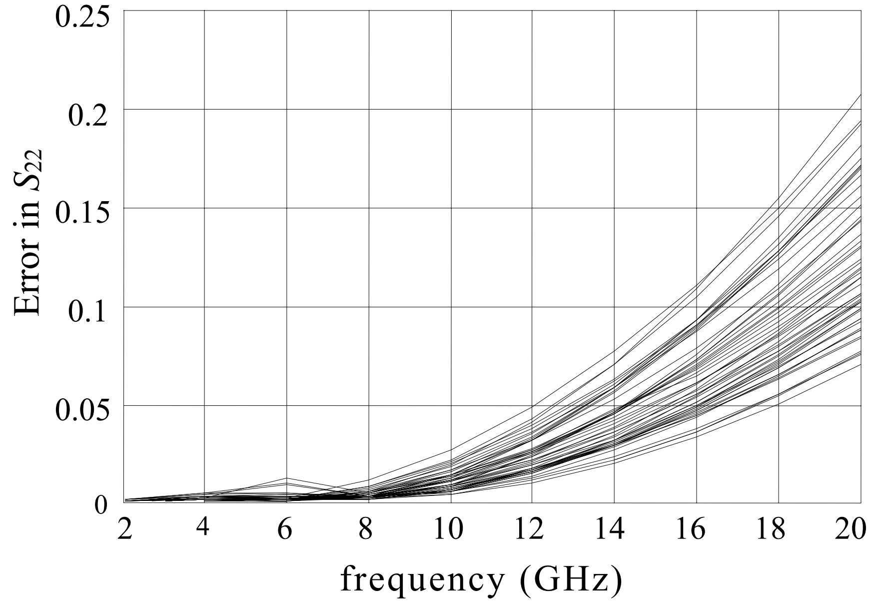
the widths W of the input lines track H so that their characteristic impedance is 50 ohm

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

Microstrip Shaped T-Junction Coarse Model

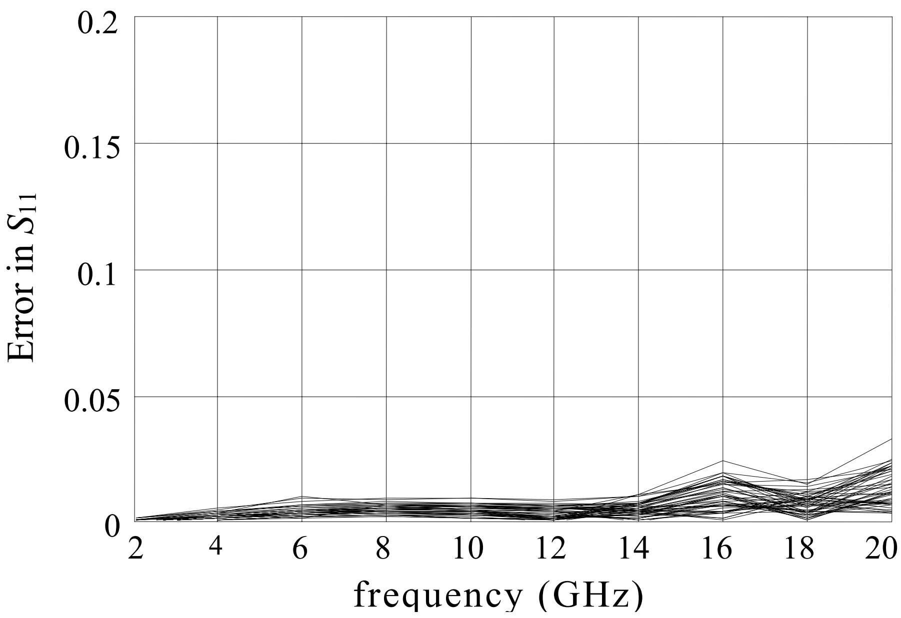
errors w.r.t. Sonnet's ***em*** at the test points

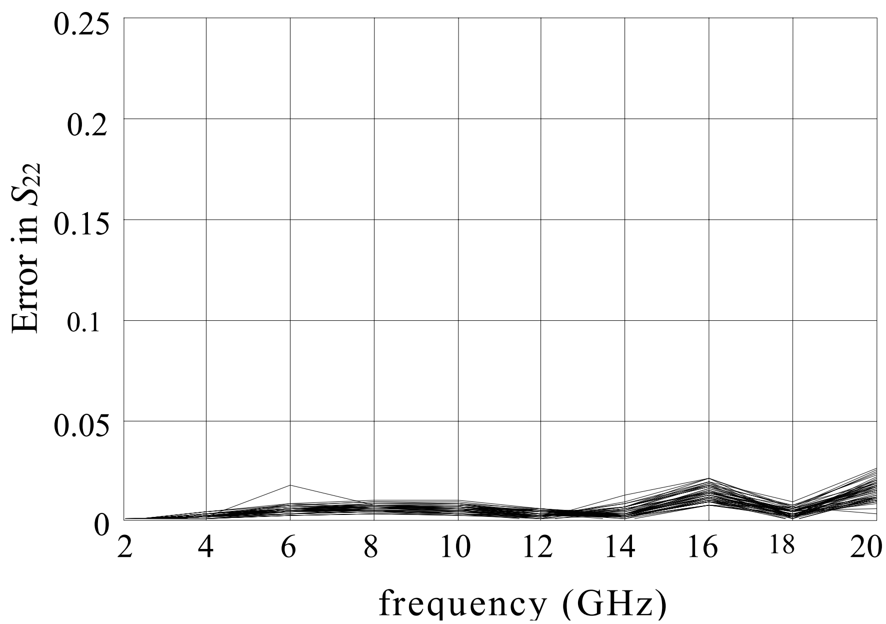




Microstrip Shaped T-Junction Enhanced Coarse Model

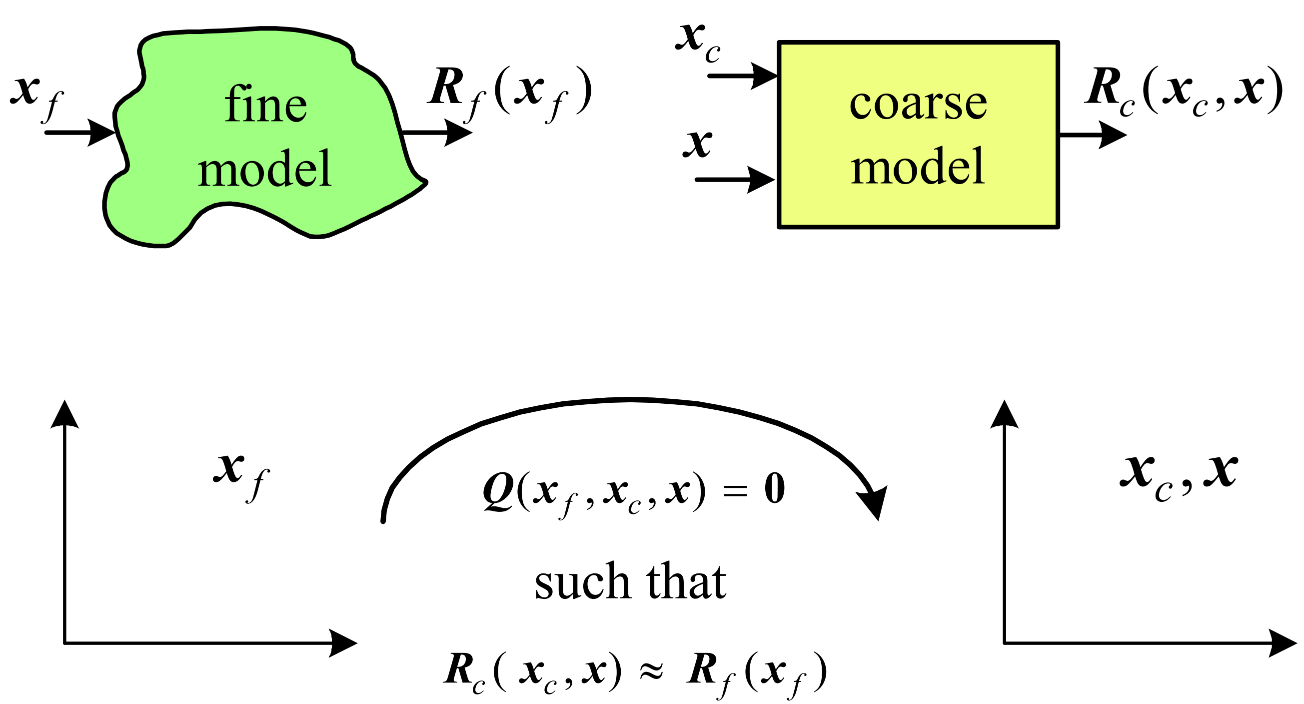
errors w.r.t. Sonnet's ***em*** at the test points





Implicit Space Mapping Theory

(Bandler et al., 2002)



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

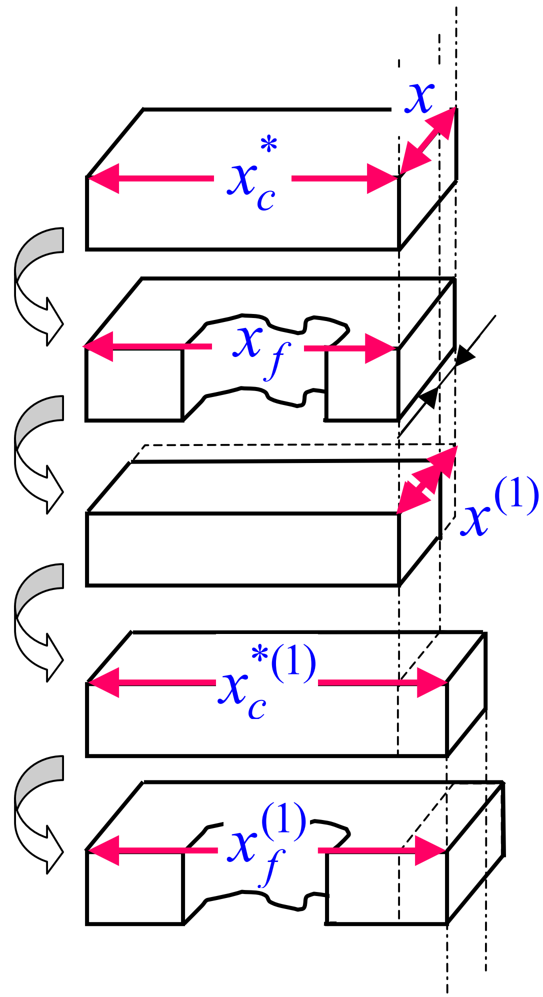
easy implementation

no explicit mapping involved

no matrices to keep track of

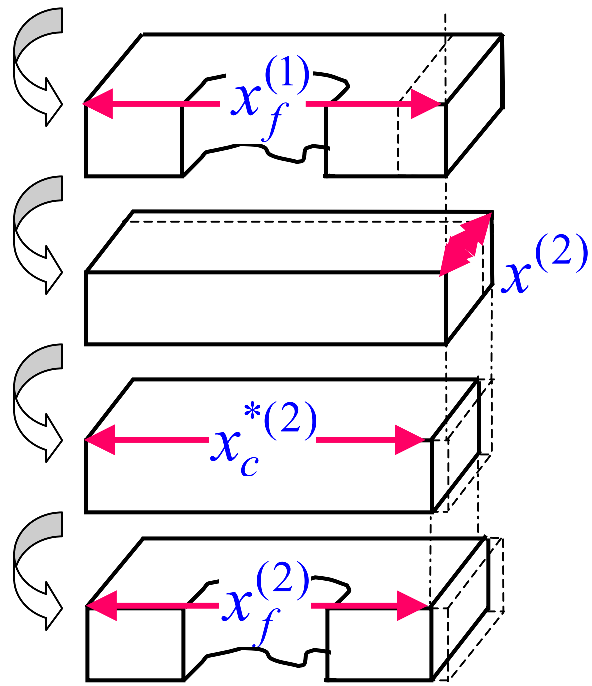
Implicit Space Mapping Practice—Cheese Cutting Problem

(*Bandler 2002*)



optimal coarse model	$x_c^{*(0)} \quad x^{(0)}$
initial guess	$x_f^{(0)} = x_c^{*(0)}$
PE	$x_c^{*(0)} \quad x^{(1)}$
prediction	$x_c^{*(1)} \quad x^{(1)}$
verification	$x_f^{(1)} = x_c^{*(1)}$

Implicit Space Mapping Practice—Cheese Cutting Problem
(*Bandler 2002*)



verification	$x_f^{(1)} = x_c^{*(1)}$
PE	$x_c^{*(1)} \quad x^{(2)}$
prediction	$x_c^{*(2)} \quad x^{(2)}$
verification	$x_f^{(2)} = x_c^{*(2)}$

⋮

Cheese Cutting Problem—A Numerical Example

(*Bandler 2002*)

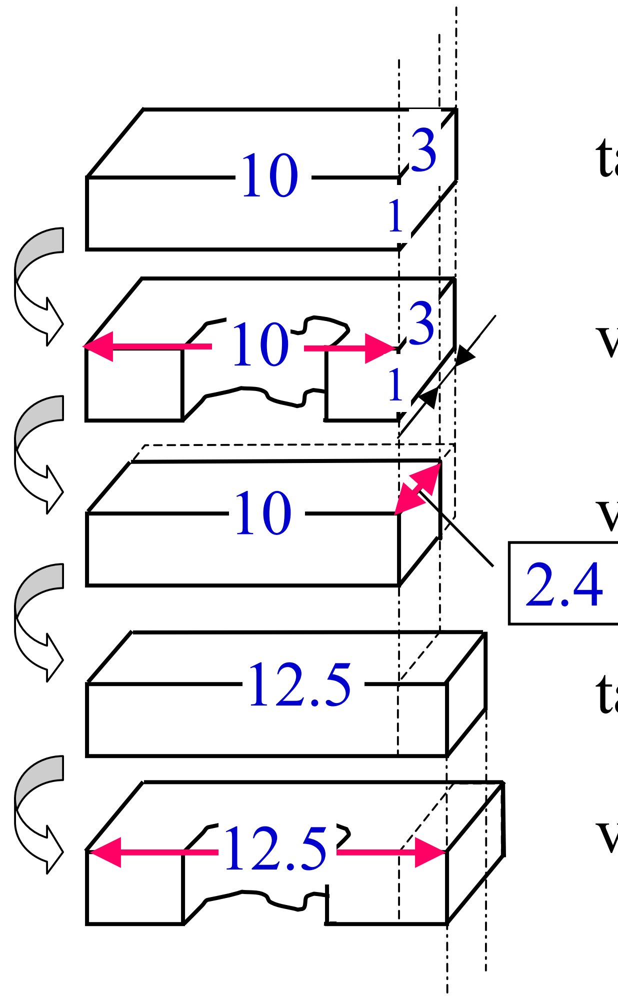
optimal coarse model — target volume =30

initial guess — volume =24

PE — volume =24

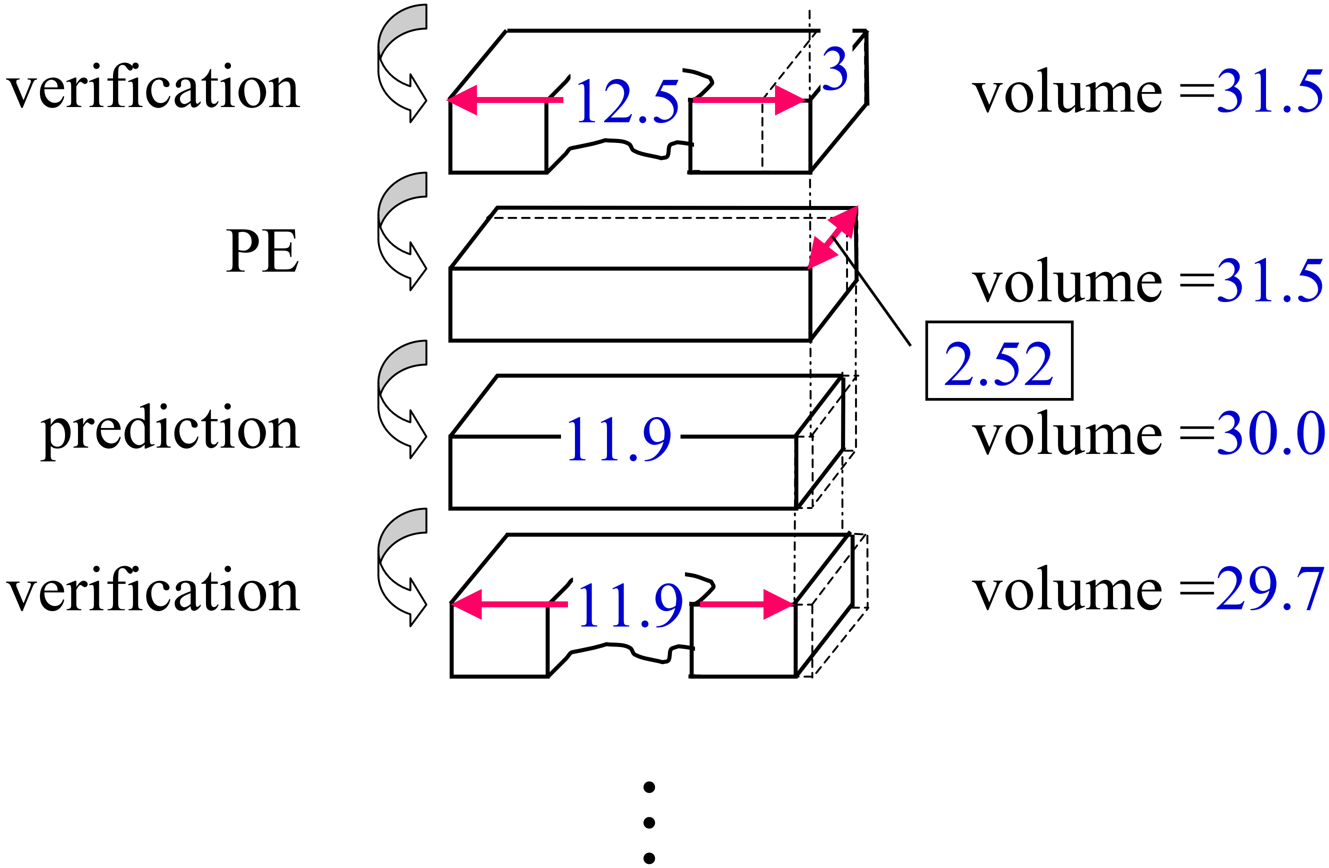
prediction — target volume =30

verification — volume =31.5



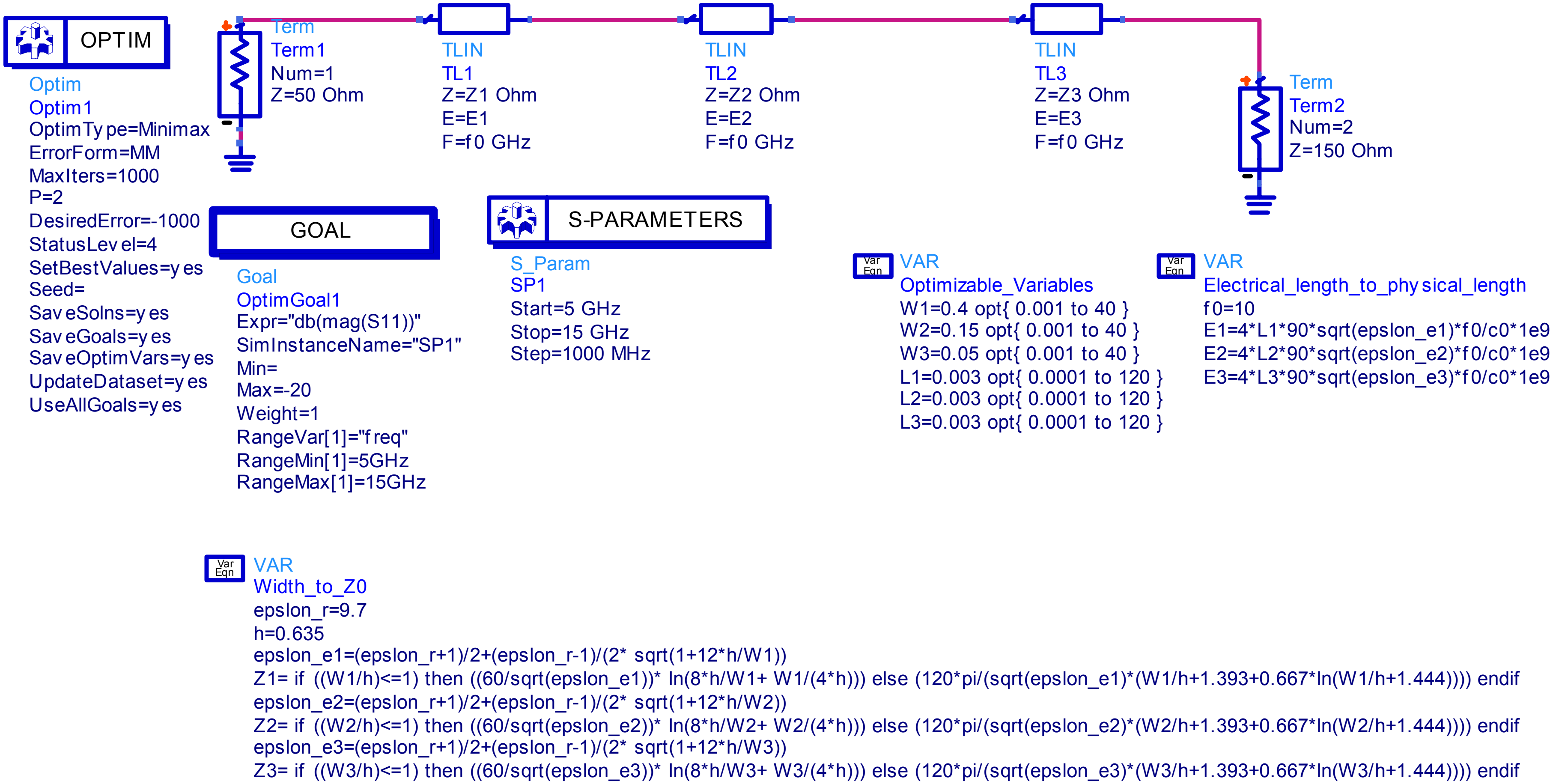
Cheese Cutting Problem—A Numerical Example

(*Bandler 2002*)



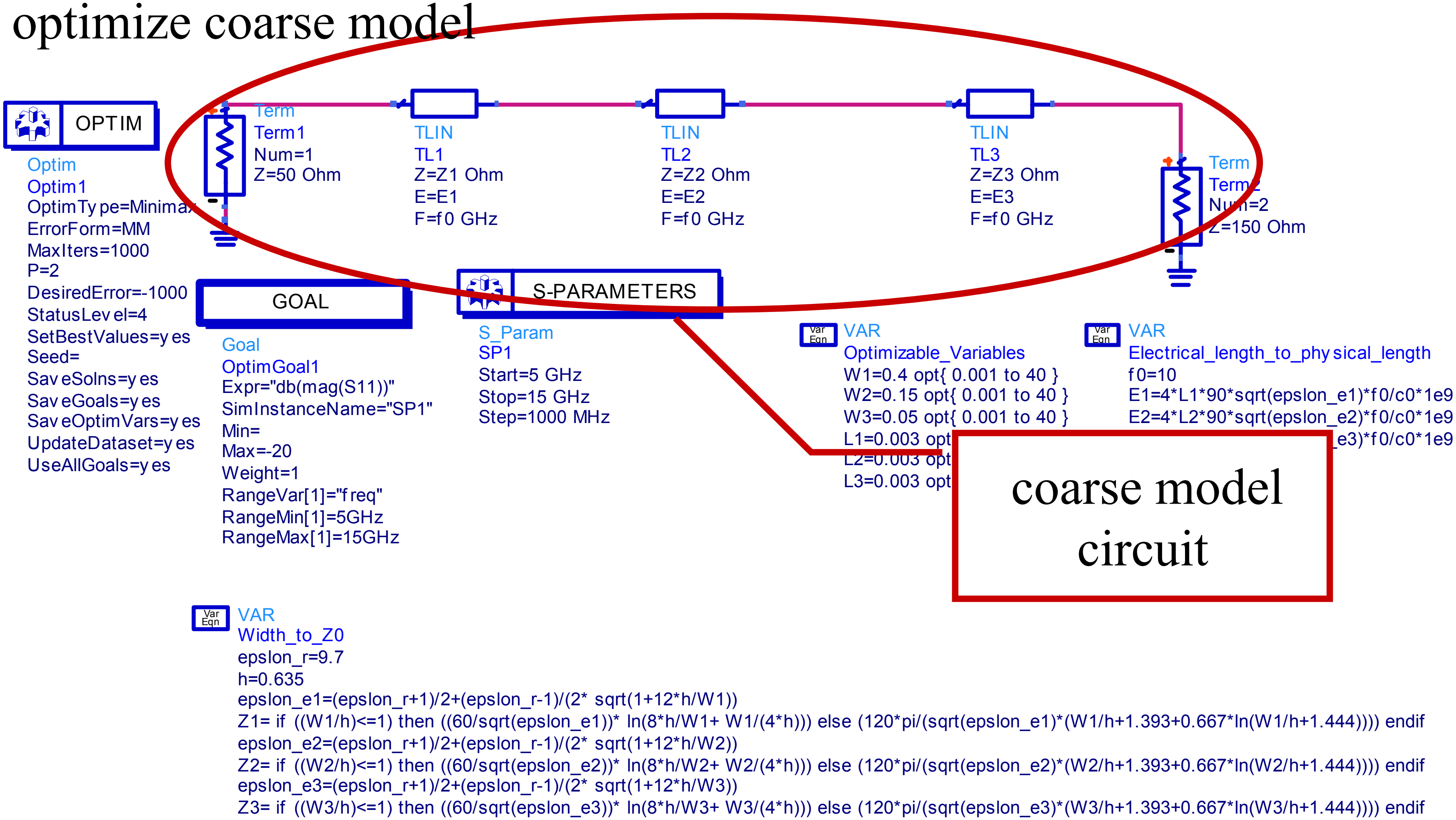
Implicit Space Mapping: Steps 1-3

optimize coarse model



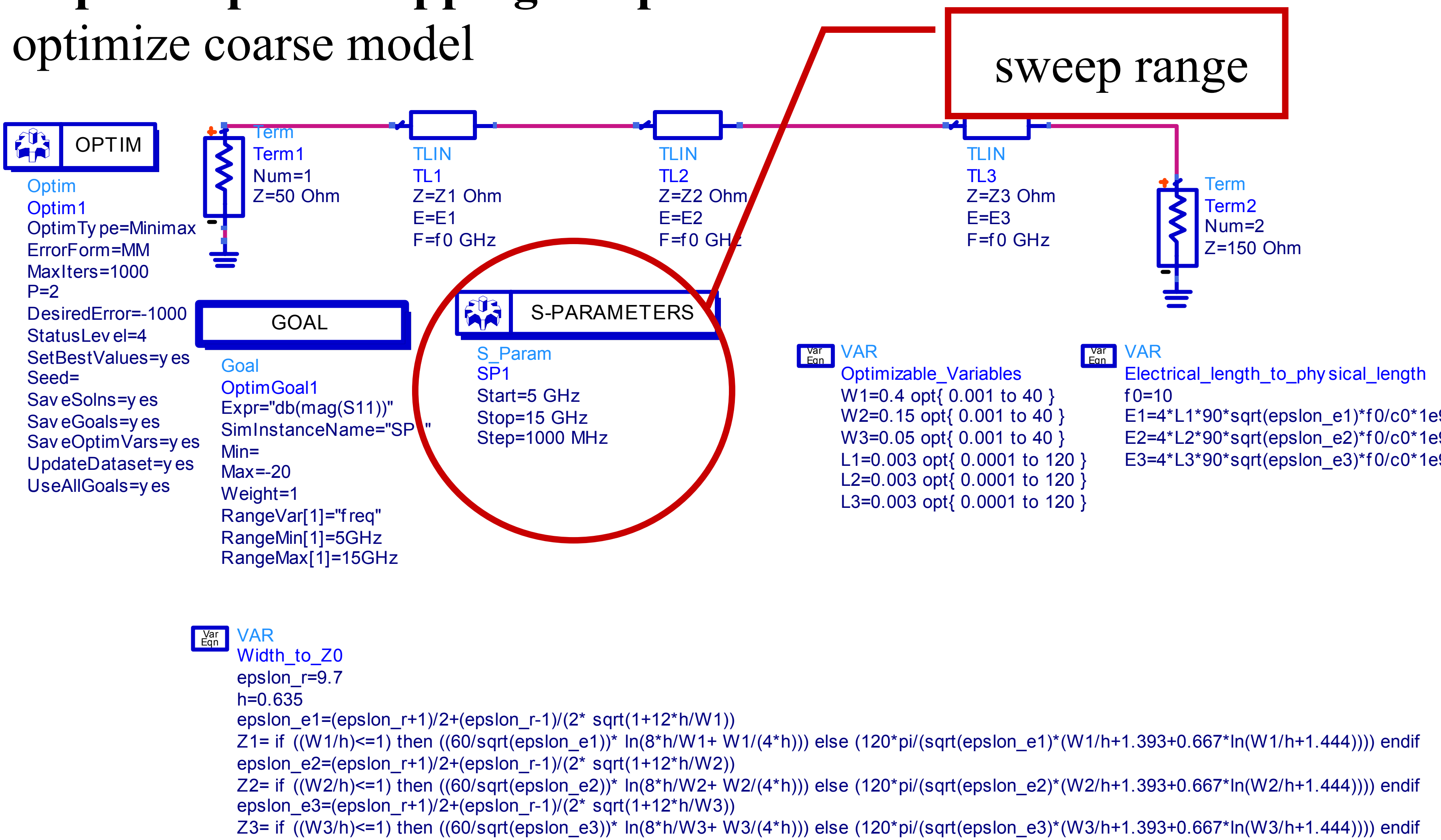
Implicit Space Mapping: Steps 1-3

optimize coarse model



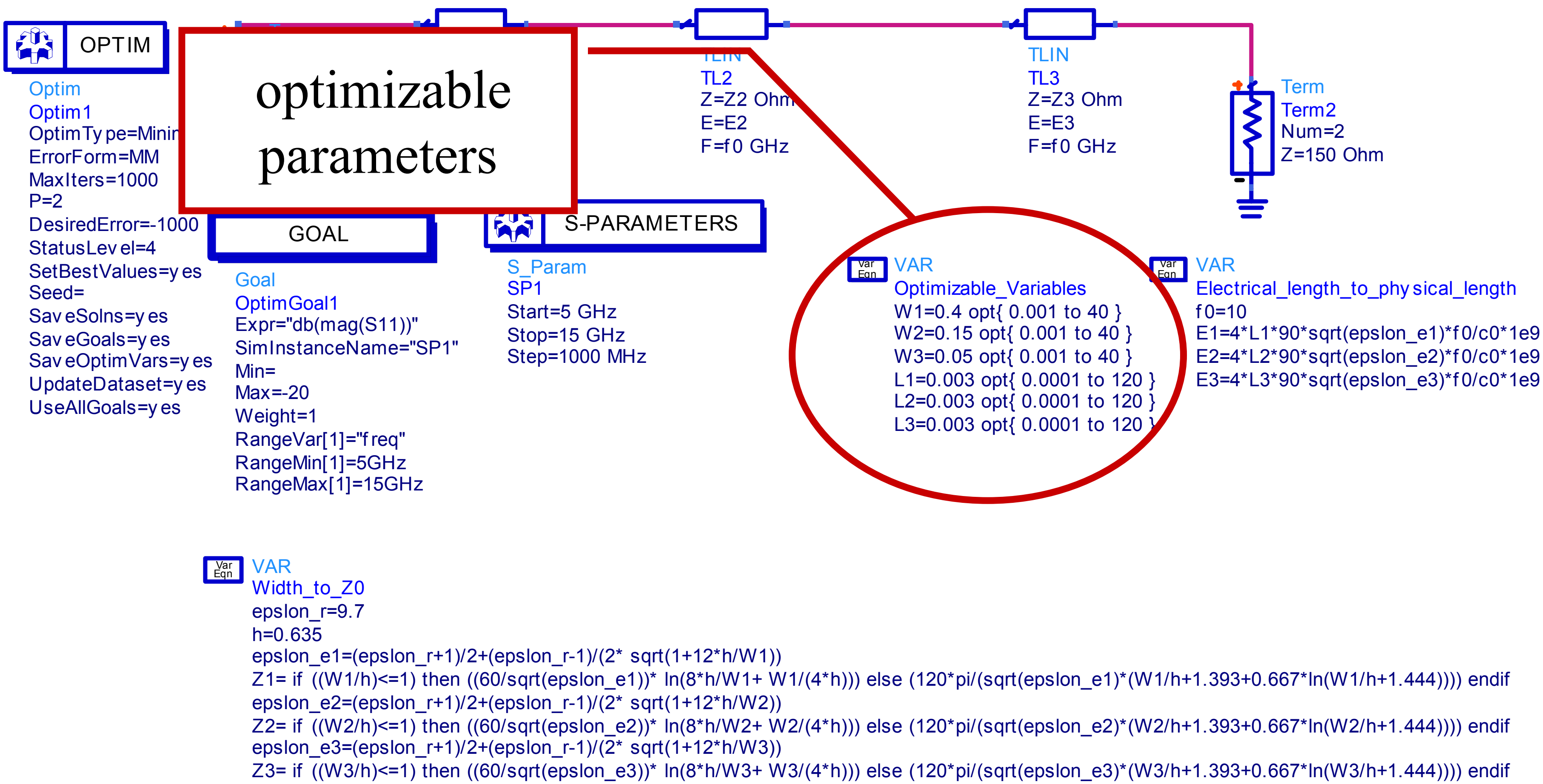
Implicit Space Mapping: Steps 1-3

optimize coarse model



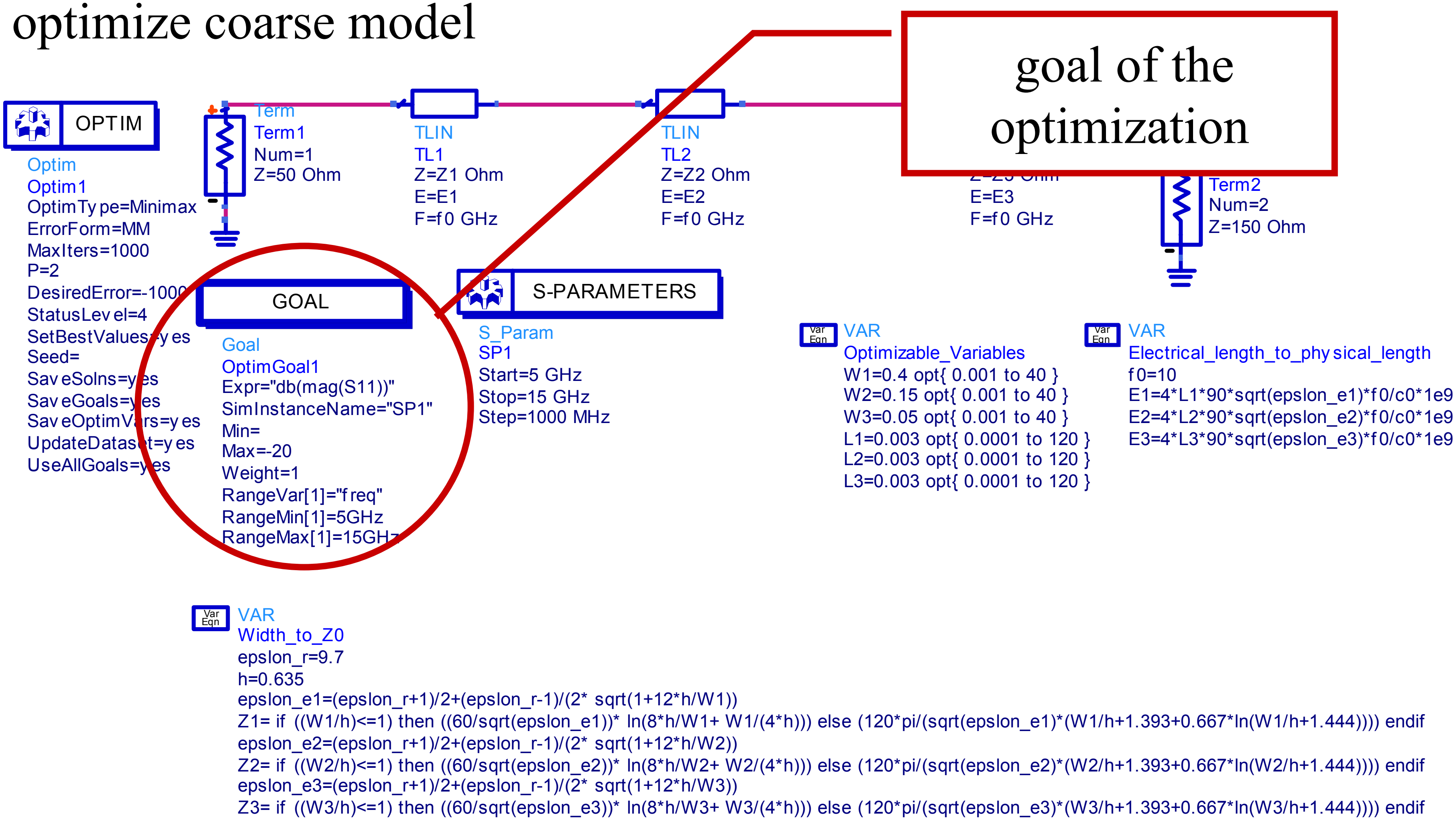
Implicit Space Mapping: Steps 1-3

optimize coarse model



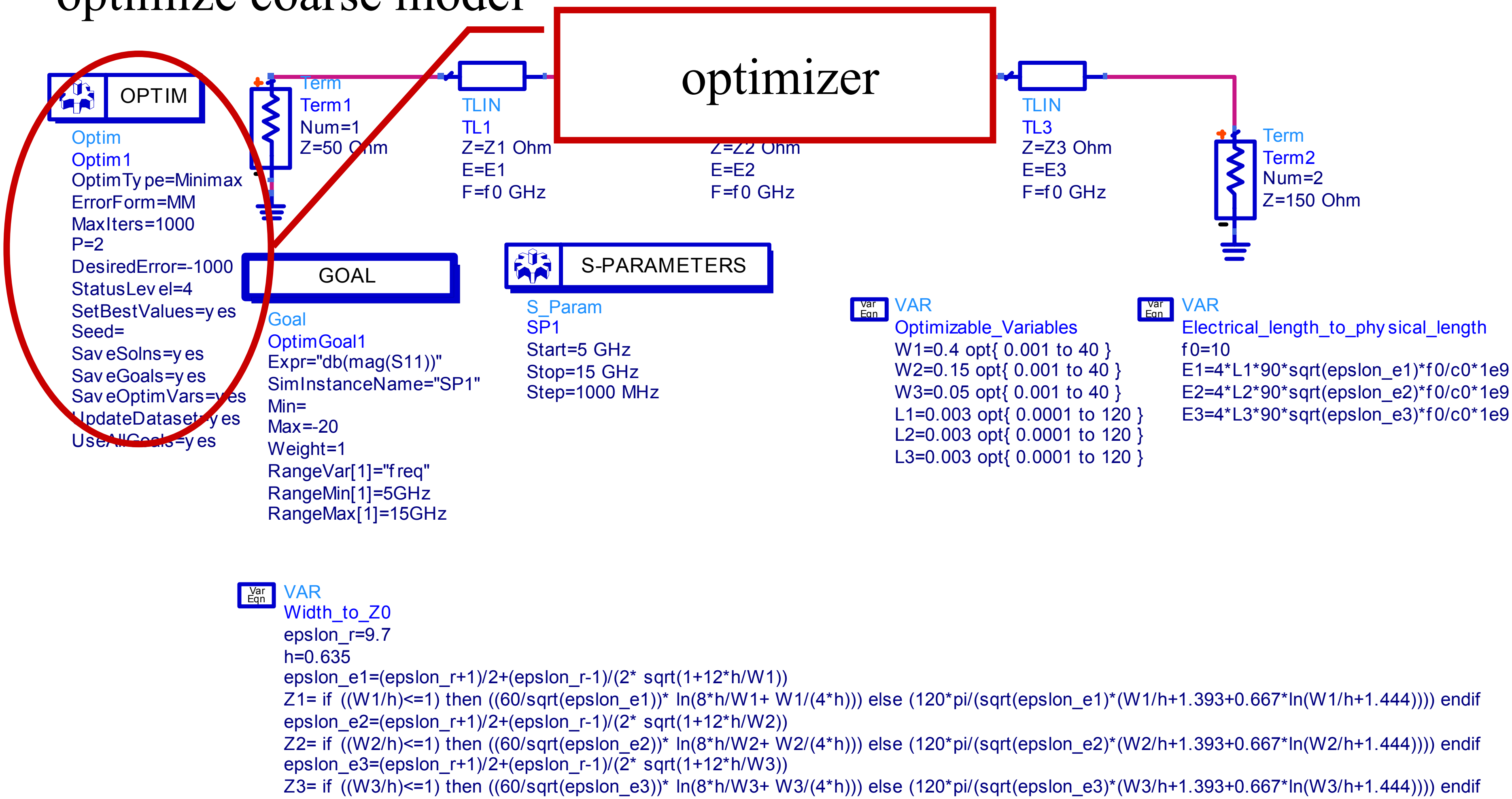
Implicit Space Mapping: Steps 1-3

optimize coarse model



Implicit Space Mapping: Steps 1-3

optimize coarse model

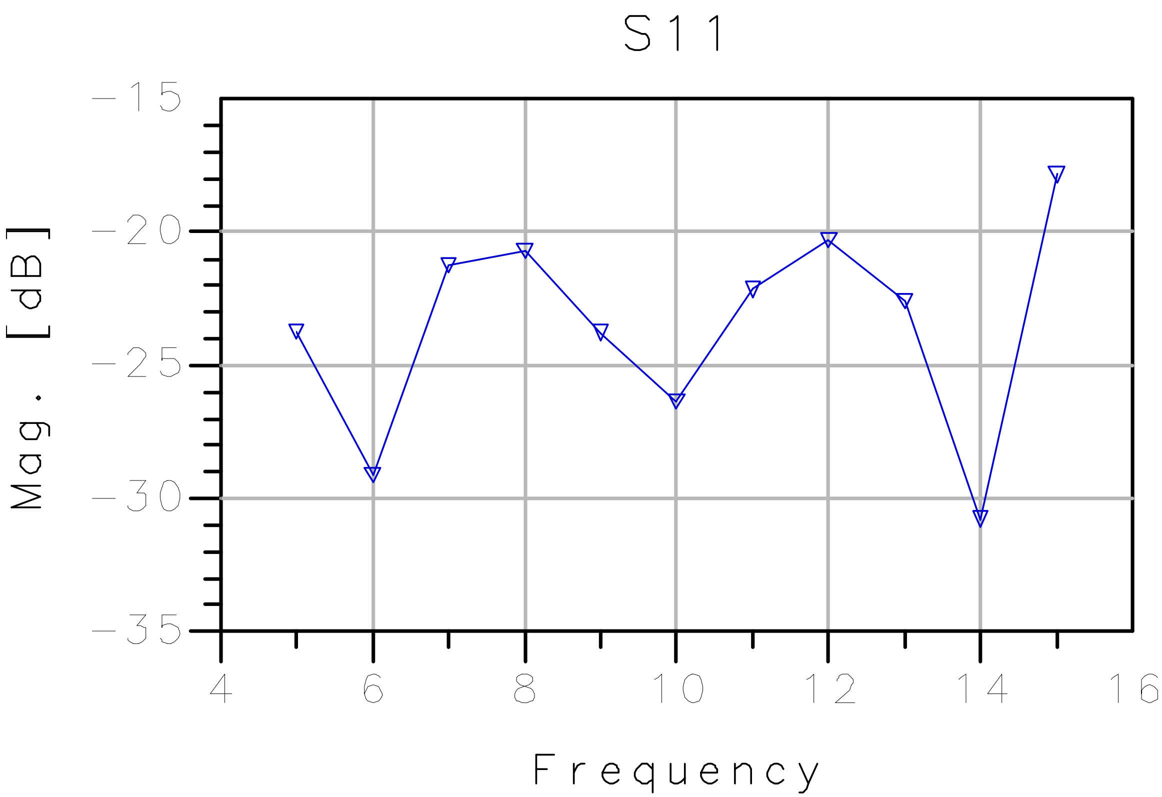


Implicit Space Mapping: Steps 4-5

simulate fine model using Momentum

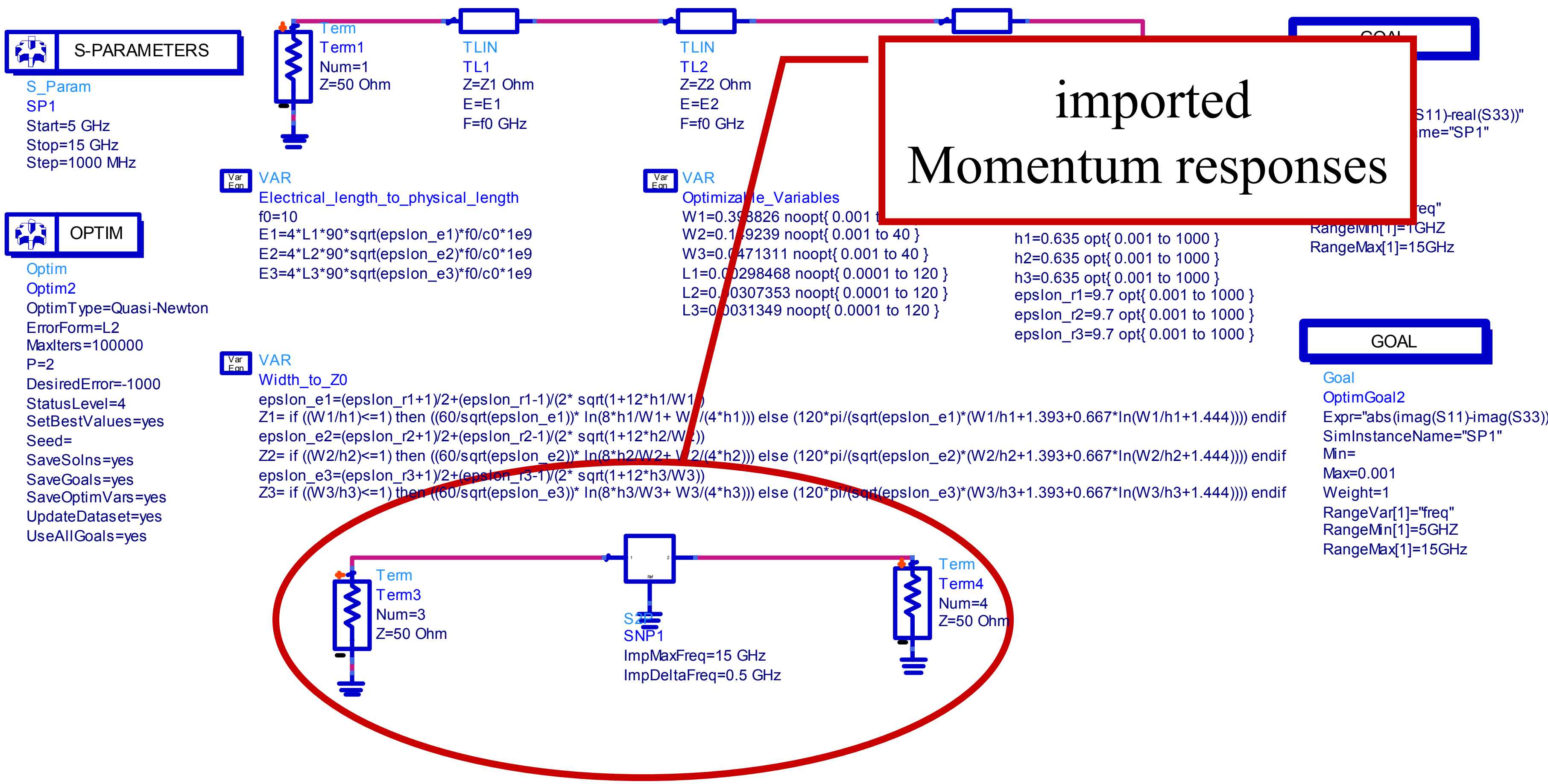
Implicit Space Mapping: Steps 5-6

obtain the fine model result and check stopping criteria



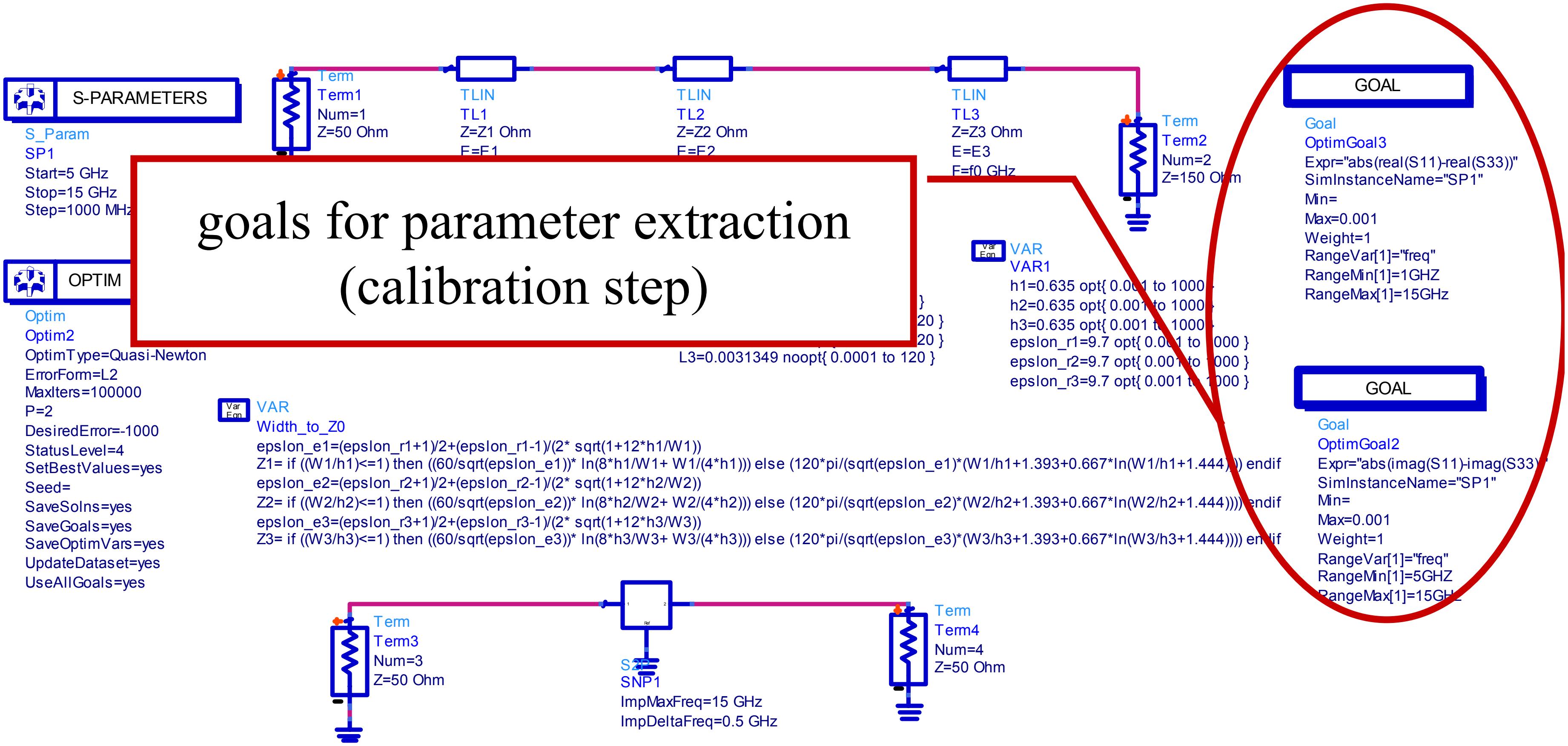
Implicit Space Mapping: Step 7

calibrate coarse model: extract preassigned parameters *x*



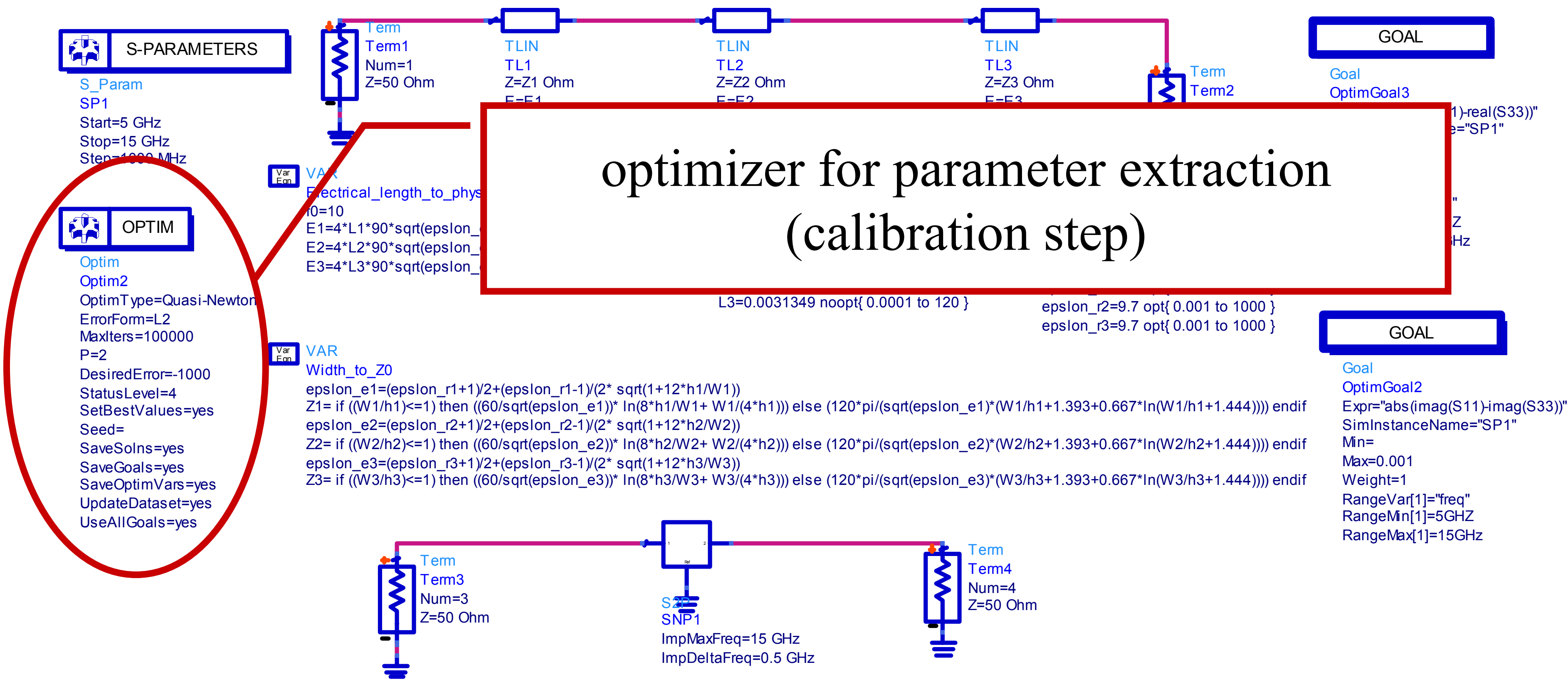
Implicit Space Mapping: Step 7

calibrate coarse model: extract preassigned parameters *x*



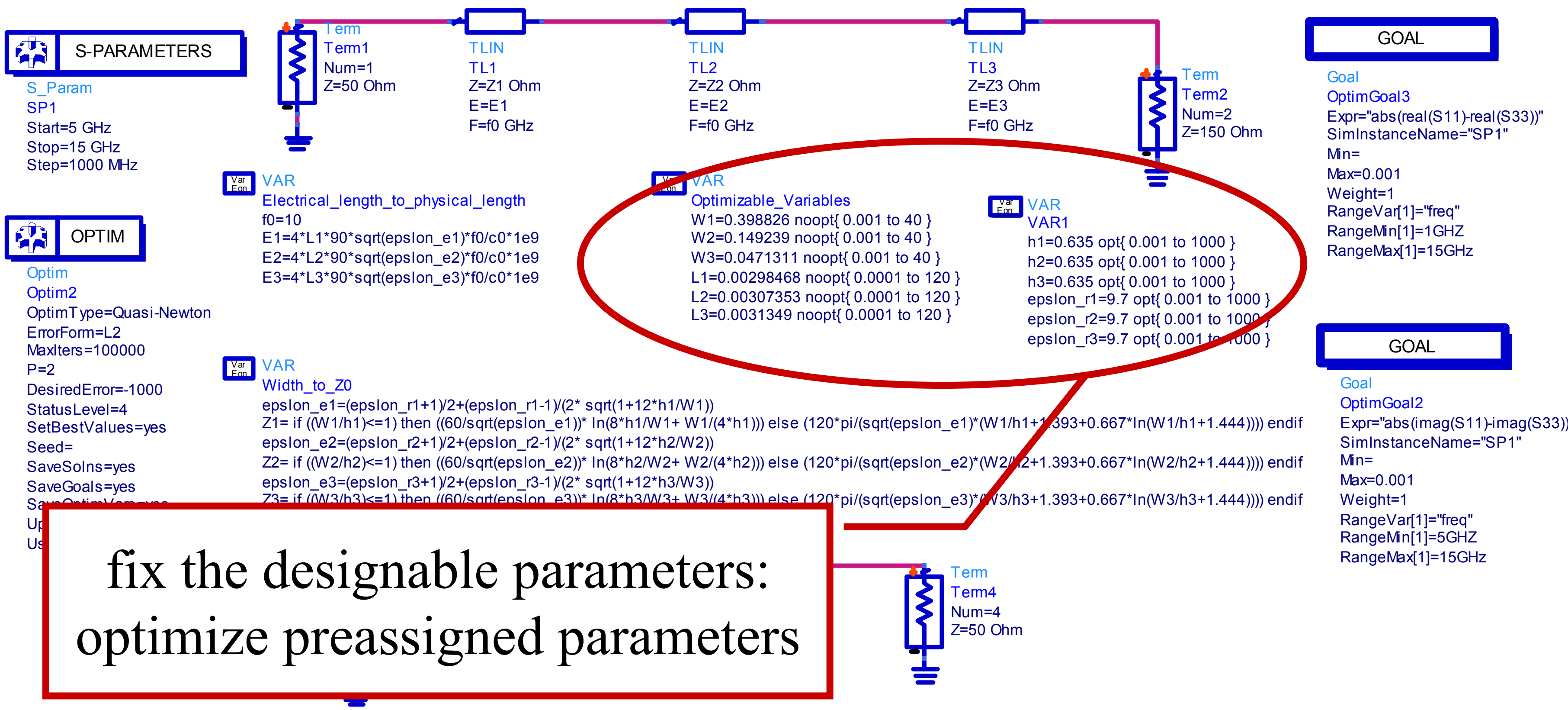
Implicit Space Mapping: Step 7

calibrate coarse model: extract preassigned parameters *x*



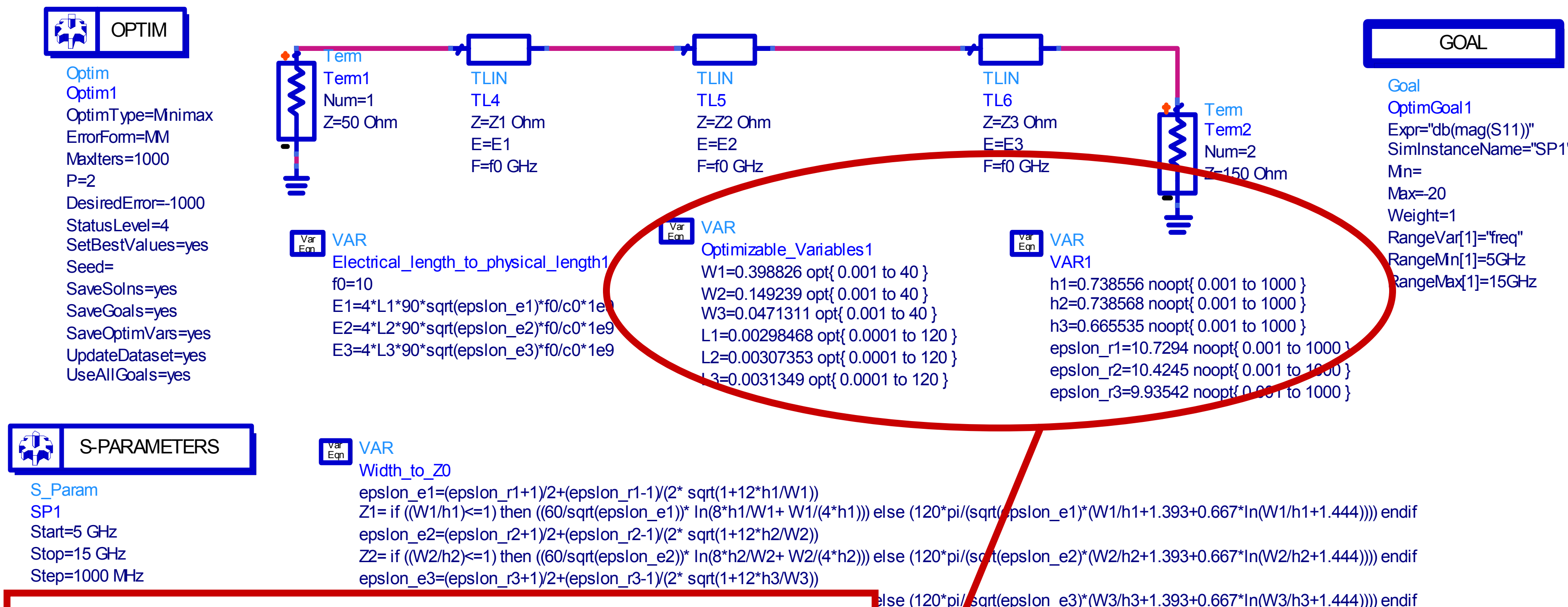
Implicit Space Mapping: Step 7

calibrate coarse model: extract preassigned parameters $\boldsymbol{x}$



Implicit Space Mapping: Steps 8-3

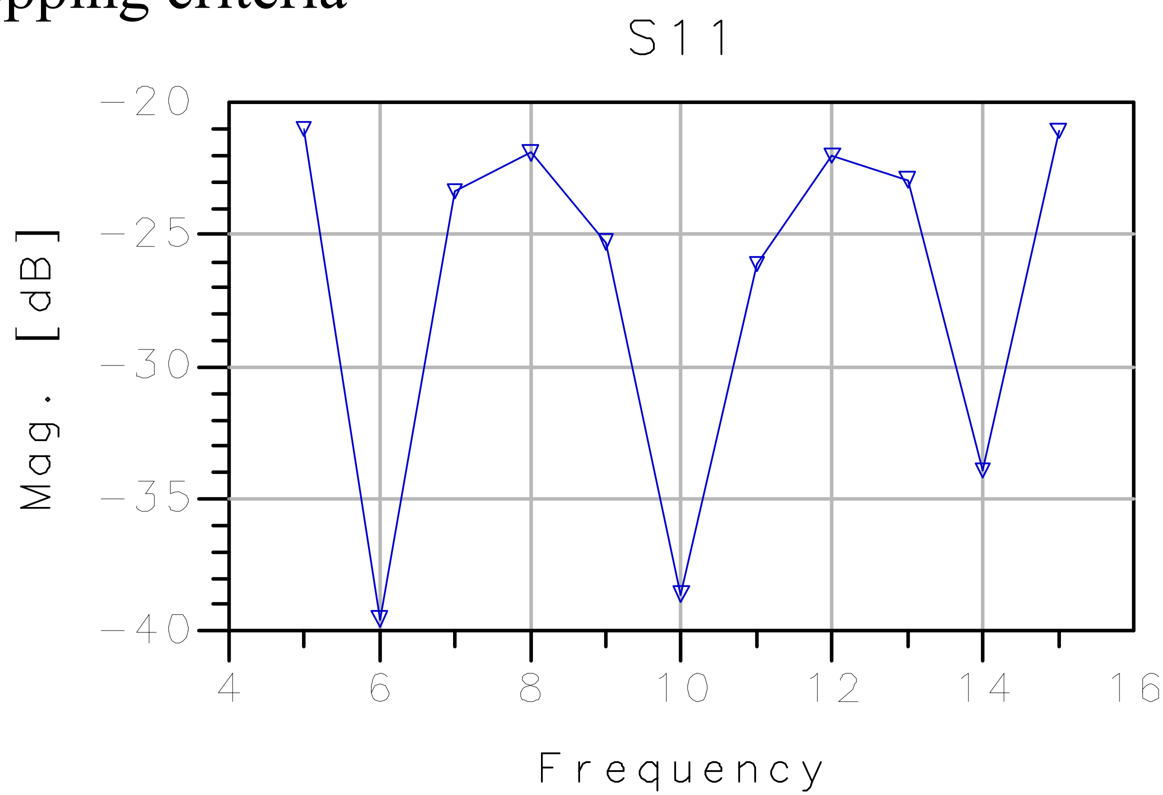
fix preassigned parameters: reoptimize calibrated coarse model



fix preassigned parameters:
reoptimize calibrated coarse model

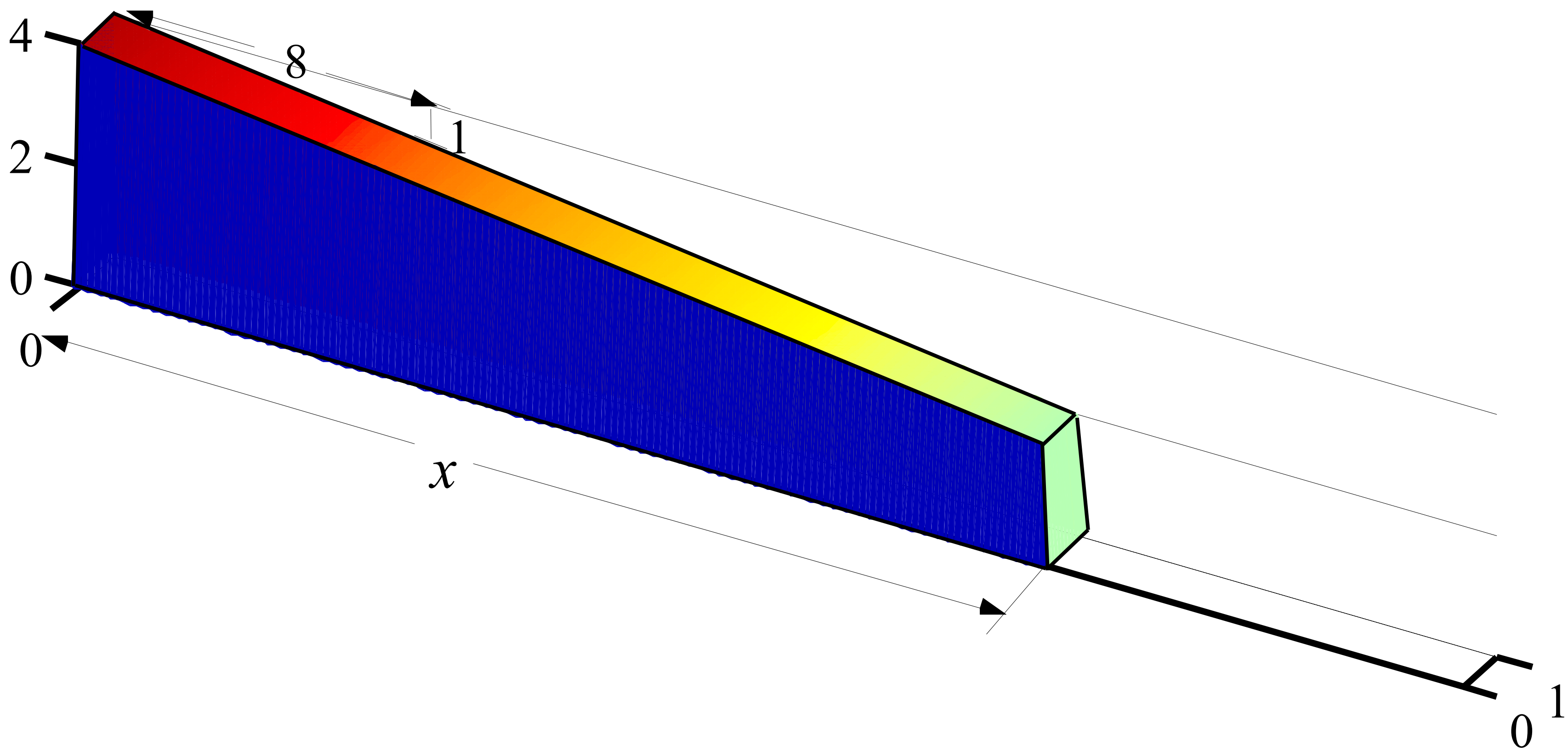
Implicit Space Mapping: Steps 4-6

simulate fine model using Momentum,
satisfy stopping criteria

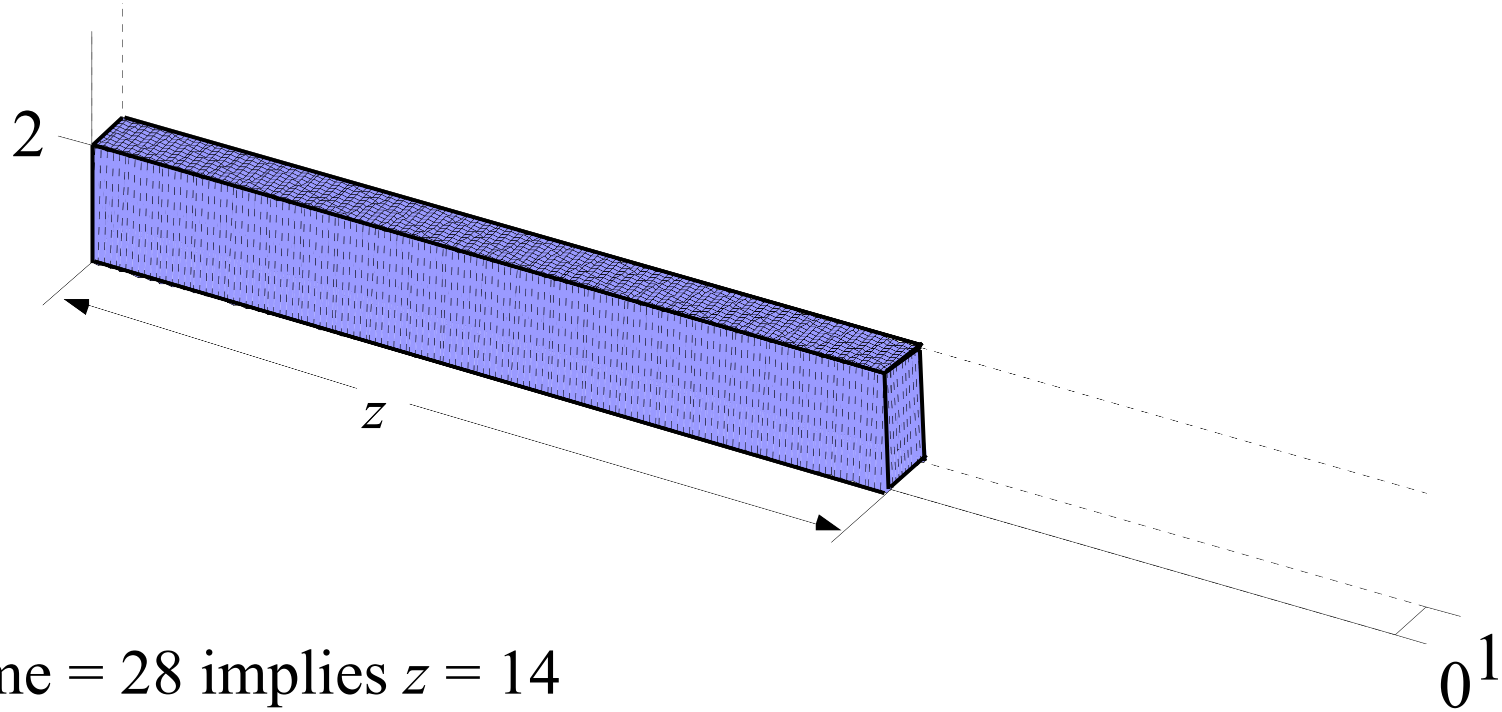


Wedge Cutting Problem (*Bandler, 2002*)

use space mapping to find the optimal position x of a cut such that the volume is equal to 28



Proposed Coarse Model



volume = 28 implies $z = 14$

Bandler's Conjecture No. 1

Space Mapping is a natural mechanism for the brain to relate objects or images with other objects, images, reality, or experience

Bandler's Conjecture No. 2

brains of "clever", experienced or intuitive individuals employ a Broyden-like update in the Space Mapping process

Bandler's Conjecture No. 3

"experienced" engineering designers, knowingly or not, routinely employ Space Mapping to achieve complex designs

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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