Space Mapping for Modeling Microwave Circuits

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Outline

Space Mapping concept

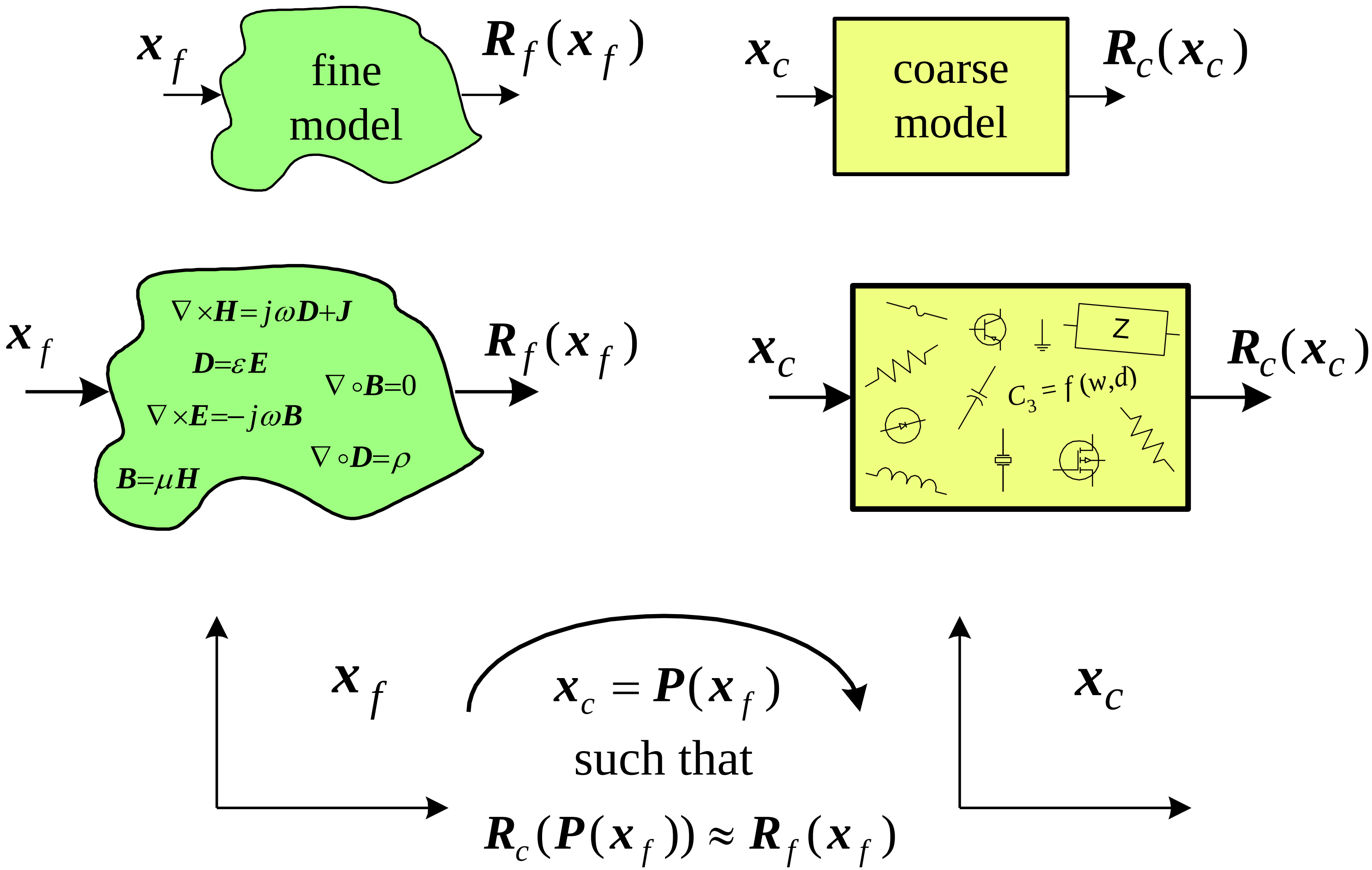
Generalized Space Mapping (GSM) tableau approach to modeling

Neural Space Mapping modeling

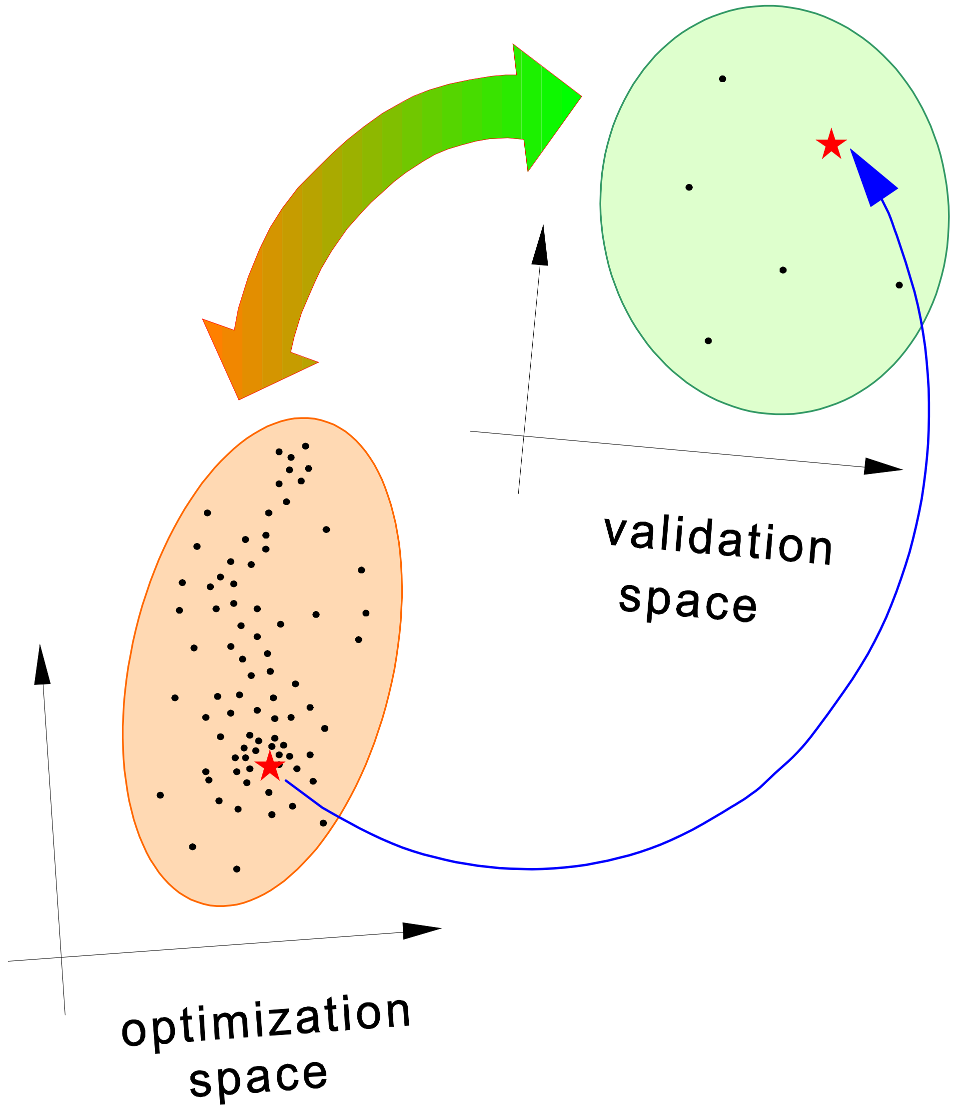
conclusions

The Space Mapping Concept

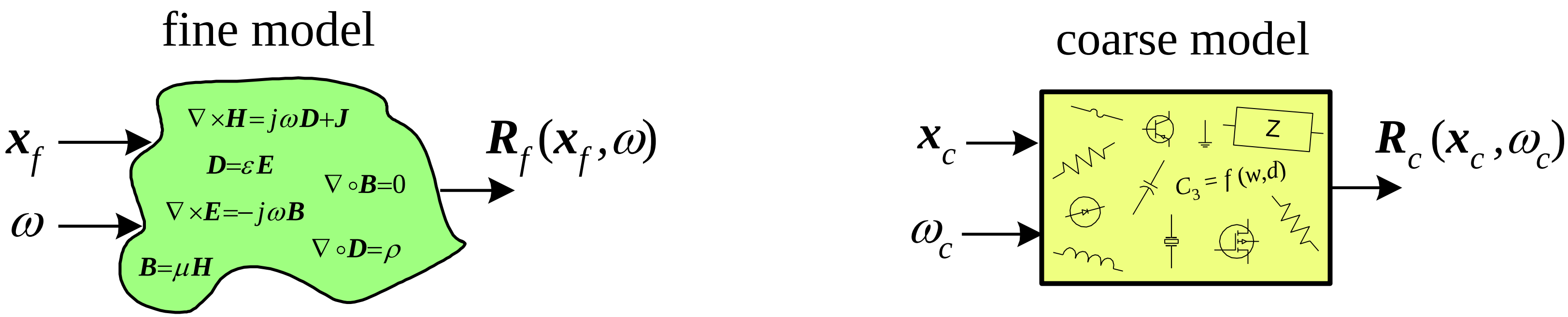
(Bandler et al., 1994-)



The Space Mapping Concept (continued)



Frequency Space Mapping Concept
(Bandler et. al., 1995)



find

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

such that

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

Mathematical Formulation for GSM

the kth mapping is given by

$$(\boldsymbol{x}_{ck}, \omega_{ck}) = \boldsymbol{P}_k(\boldsymbol{x}_f, \omega)$$

in matrix form, assuming a linear mapping

$$\begin{bmatrix} \boldsymbol{x}_{ck} \\ \omega_{ck} \end{bmatrix} = \begin{bmatrix} \boldsymbol{c}_k \\ \delta_k \end{bmatrix} + \begin{bmatrix} \boldsymbol{B}_k & \boldsymbol{s}_k \\ \boldsymbol{t}_k^T & \sigma_k \end{bmatrix} \begin{bmatrix} \boldsymbol{x}_f \\ \omega \end{bmatrix}$$

the mapping parameters $\{\boldsymbol{c}_k, \boldsymbol{B}_k, \boldsymbol{s}_k, \boldsymbol{t}_k, \sigma_k, \delta_k\}$ can be evaluated by solving the optimization problem

$$\min_{\boldsymbol{c}_k, \boldsymbol{B}_k, \boldsymbol{s}_k, \boldsymbol{t}_k, \sigma_k, \delta_k} \left\| \begin{bmatrix} \boldsymbol{e}_{k1}^T & \boldsymbol{e}_{k2}^T & \cdots & \boldsymbol{e}_{km}^T \end{bmatrix}^T \right\|$$

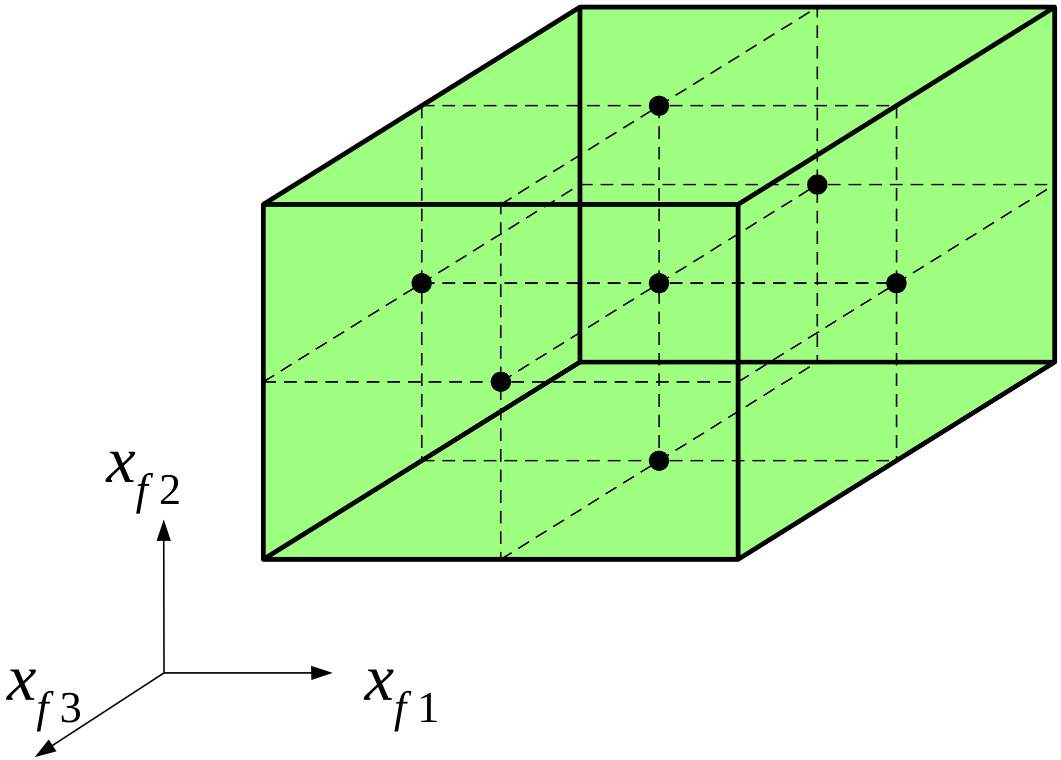
where m is the number of base points selected in the fine model space and $\boldsymbol{e}_{kj}$ is an error vector given by

$$\boldsymbol{e}_{kj} = \boldsymbol{R}_f(\boldsymbol{x}_f^{(j)}, \omega) - \boldsymbol{R}_c(\boldsymbol{x}_{ck}^{(j)}, \omega_{ck}), \quad j = 1,2,\ldots,m$$

Starting Point and Learning Samples

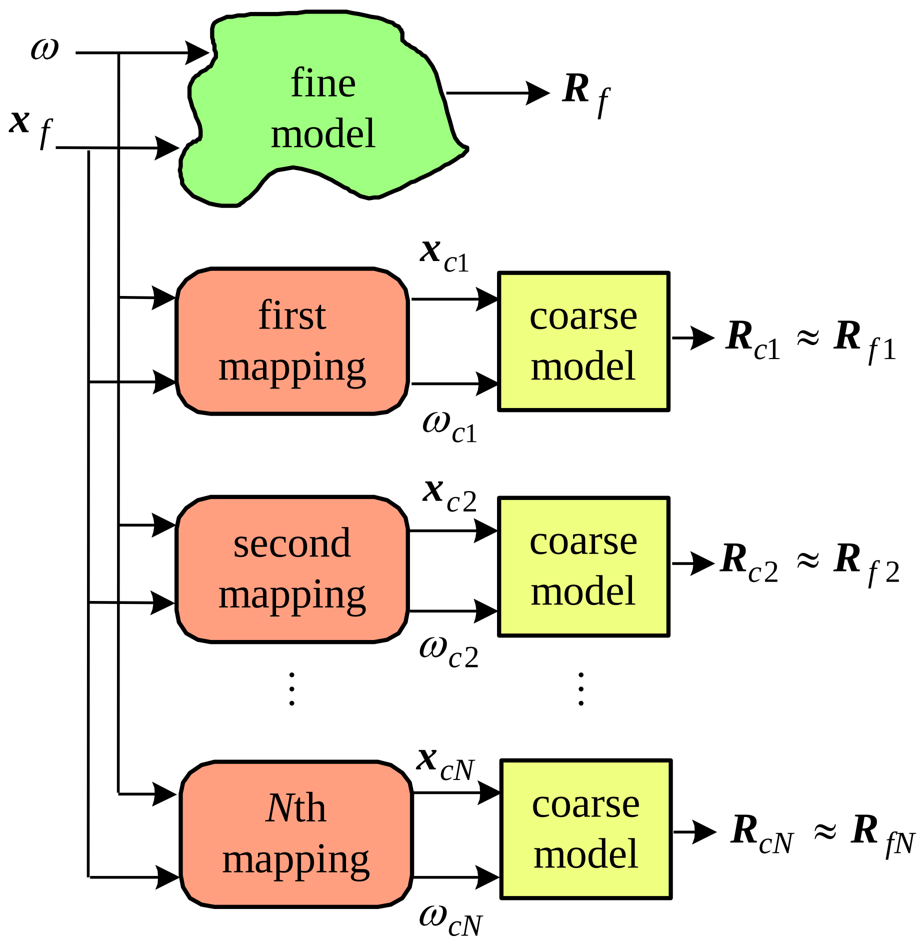
we chose a unit mapping ($\boldsymbol{x}_c \approx \boldsymbol{x}_f$ and $\omega_c \approx \omega$) as the starting point for the optimization problem

$2n+1$ points are used for a microwave circuit with n design parameters



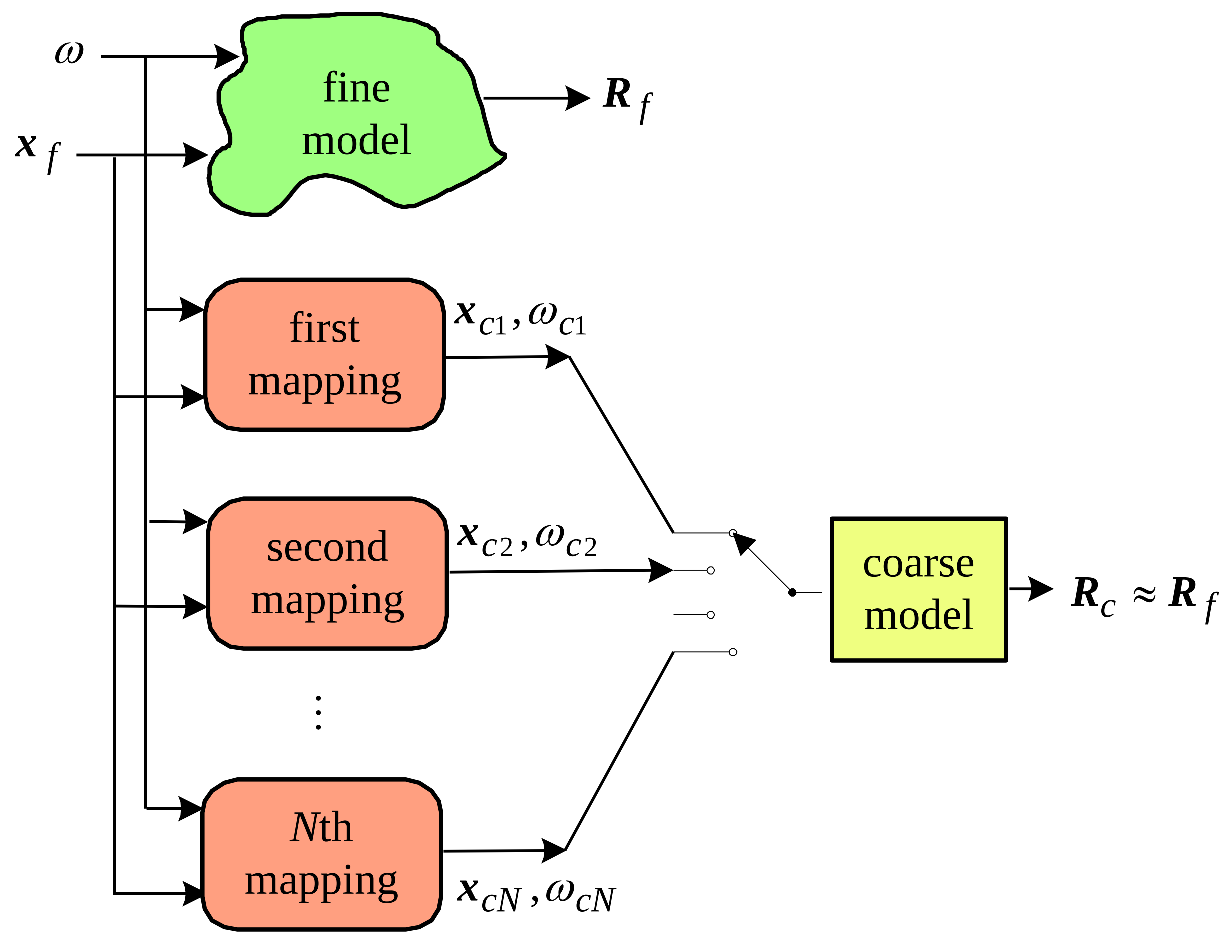
Multiple Space Mapping (MSM) Concept

MSM for Device Responses (MSMDR)



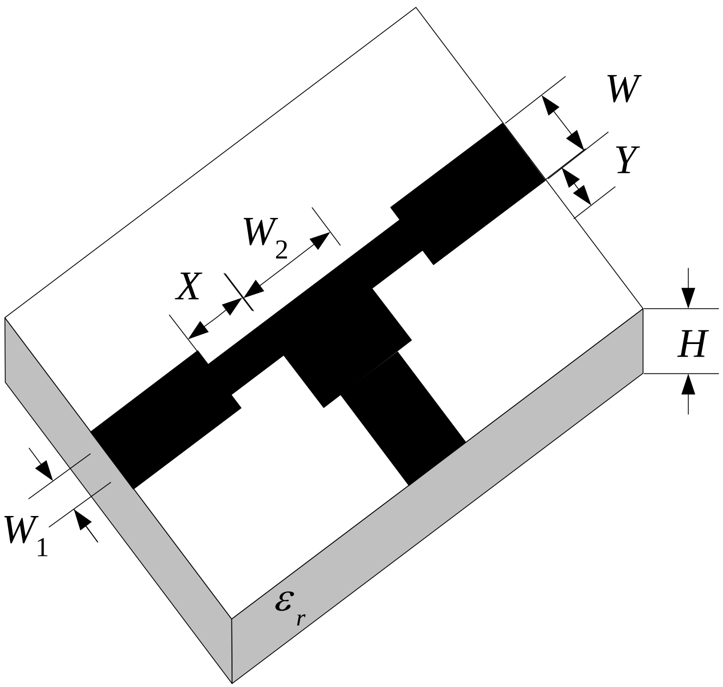
Multiple Space Mapping (MSM) Concept

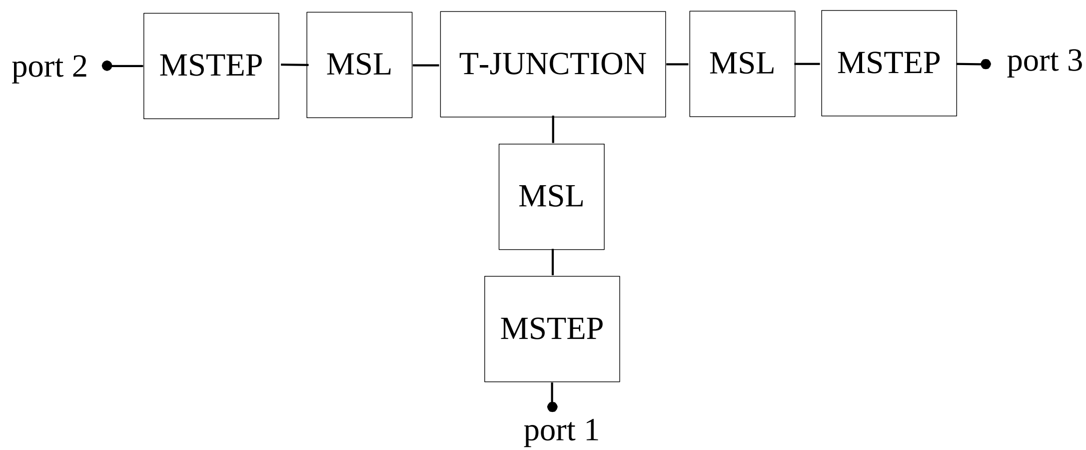
MSM for Frequency Intervals (MSMFI)



Microstrip Shaped T-Junction

the fine and coarse models





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

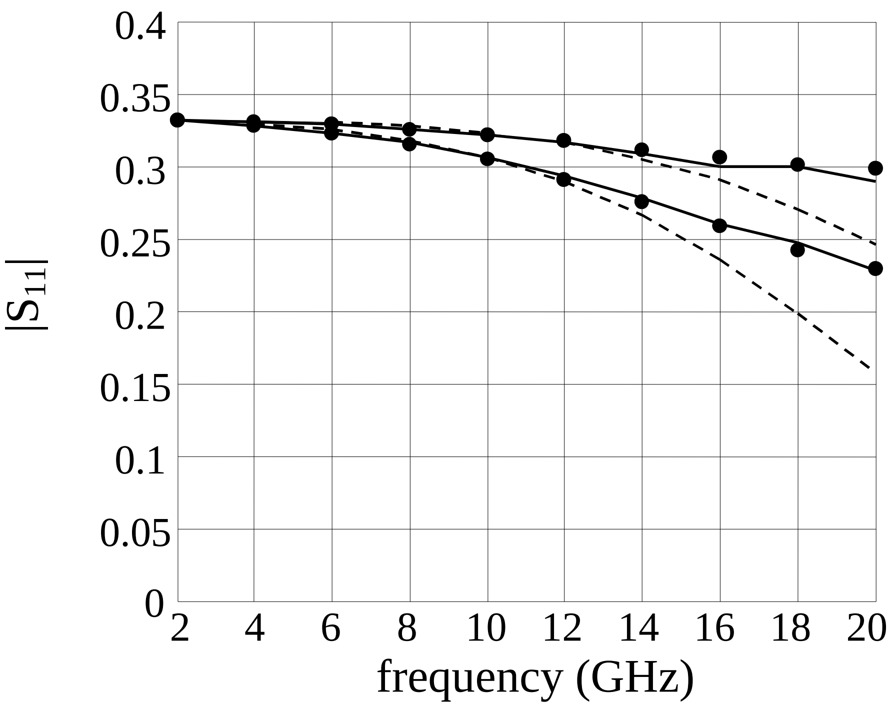
MSMFI is developed to enhance the accuracy of the coarse model

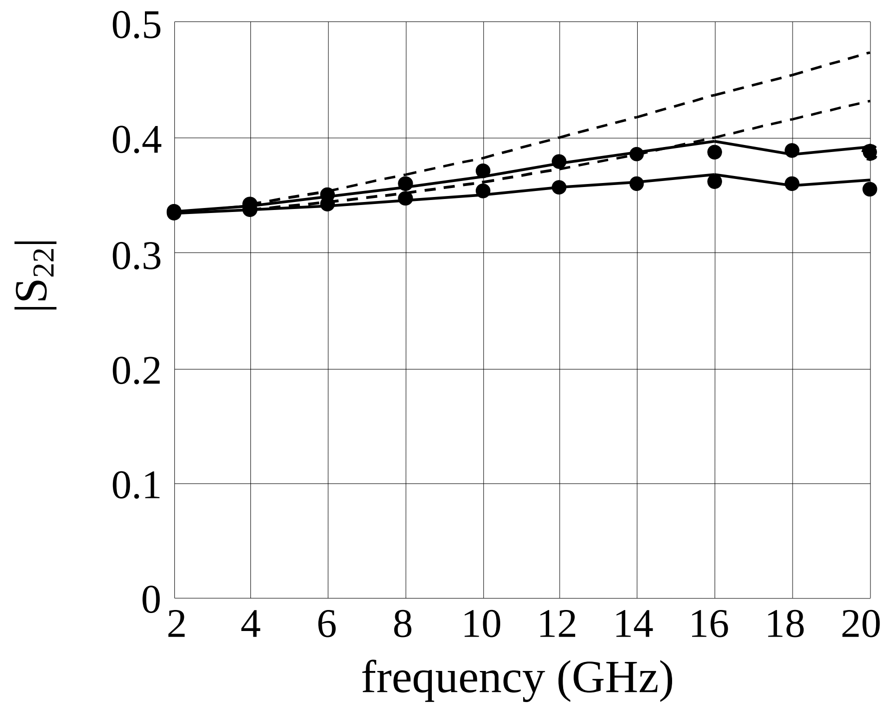
our algorithm determined two intervals: 2-16 GHz and 16-20 GHz

	2 GHz to 16 GHz	16 GHz to 20 GHz
$\boldsymbol{B}$	$\begin{bmatrix} 1.04 & 0.07 & 0.01 & 0.08 & -0.06 & 0.00 & 0.22 \\ 0.00 & 0.89 & 0.00 & -0.07 & -0.20 & 0.06 & -0.03 \\ -0.00 & 0.07 & 0.99 & 0.04 & -0.12 & 0.01 & -0.06 \\ -0.04 & 0.00 & -0.01 & 0.97 & 0.10 & -0.06 & -0.27 \\ 0.01 & 0.04 & 0.00 & 0.03 & 0.99 & -0.05 & -0.03 \\ -0.13 & -0.05 & -0.04 & -0.16 & 0.12 & 0.99 & 0.62 \\ -0.08 & 0.12 & -0.03 & 0.00 & -0.07 & 0.03 & 0.83 \end{bmatrix}$	$\begin{bmatrix} 0.99 & 0.02 & -0.00 & 0.01 & -0.09 & -0.01 & 0.13 \\ 0.05 & 0.85 & 0.01 & -0.07 & -0.28 & 0.01 & -0.01 \\ -0.06 & 0.15 & 0.98 & 0.04 & -0.25 & 0.00 & 0.02 \\ -0.10 & -0.06 & -0.03 & 0.88 & 0.13 & -0.09 & -0.27 \\ 0.08 & 0.04 & 0.03 & 0.11 & 1.07 & -0.04 & -0.12 \\ -0.14 & -0.02 & -0.05 & -0.15 & 0.23 & 1.03 & 0.51 \\ -0.13 & 0.22 & -0.04 & 0.02 & -0.07 & 0.03 & 0.87 \end{bmatrix}$
$\boldsymbol{c}$	$[0.02\ \ 0.01\ \ -0.01\ \ -0.03\ \ -0.01\ \ 0.07\ \ -0.03]^T$	$[0.01\ \ 0.01\ \ -0.01\ \ -0.03\ \ -0.01\ \ 0.05\ \ -0.03]^T$
$\boldsymbol{s}$	$[-0.01\ \ 0.09\ \ -0.10\ \ -0.02\ \ 0.00\ \ -0.02\ \ -0.20]^T$	$[0.00\ \ 0.01\ \ -0.01\ \ 0.00\ \ 0.00\ \ 0.00\ \ -0.02]^T$
$\boldsymbol{t}$	$\mathbf{0}$	$[0.01\ \ 0.00\ \ -0.02\ \ 0.00\ \ 0.00\ \ 0.00\ \ 0.00]^T$
σ	0.851	0.957
δ	–0.003	0.008

Microstrip Shaped T-Junction

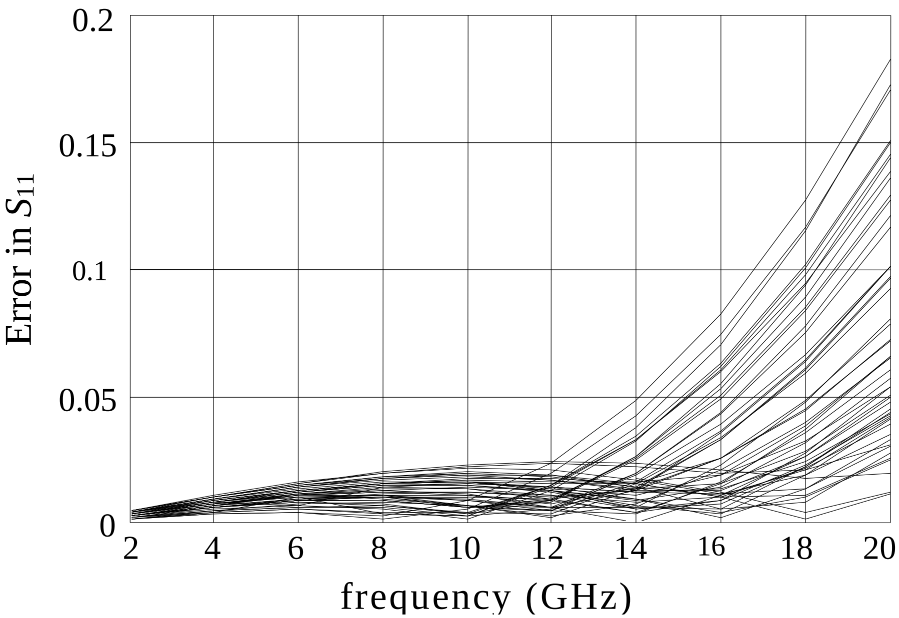
the responses at two test points in the region of interest by Sonnet's ***em*** (•):
the coarse model (---), the enhanced coarse model (—)

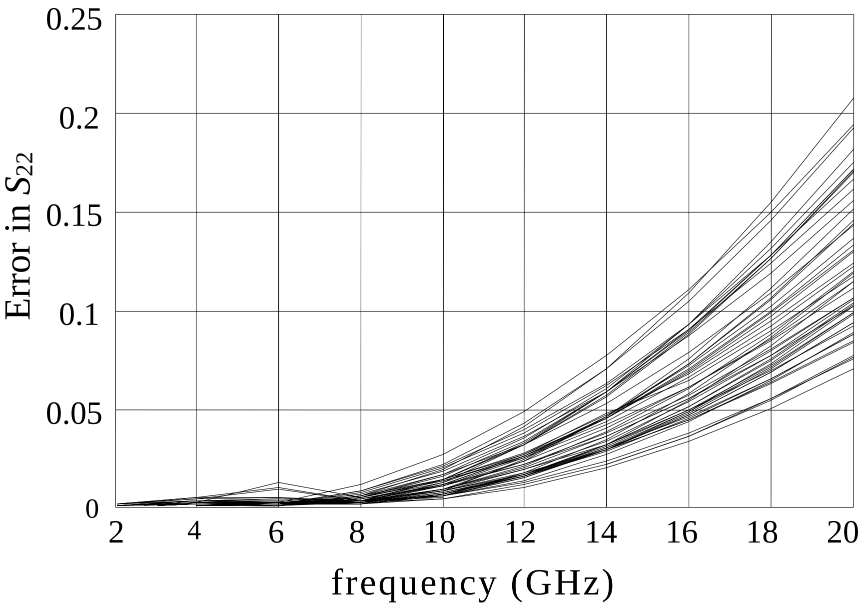




Microstrip Shaped T-Junction

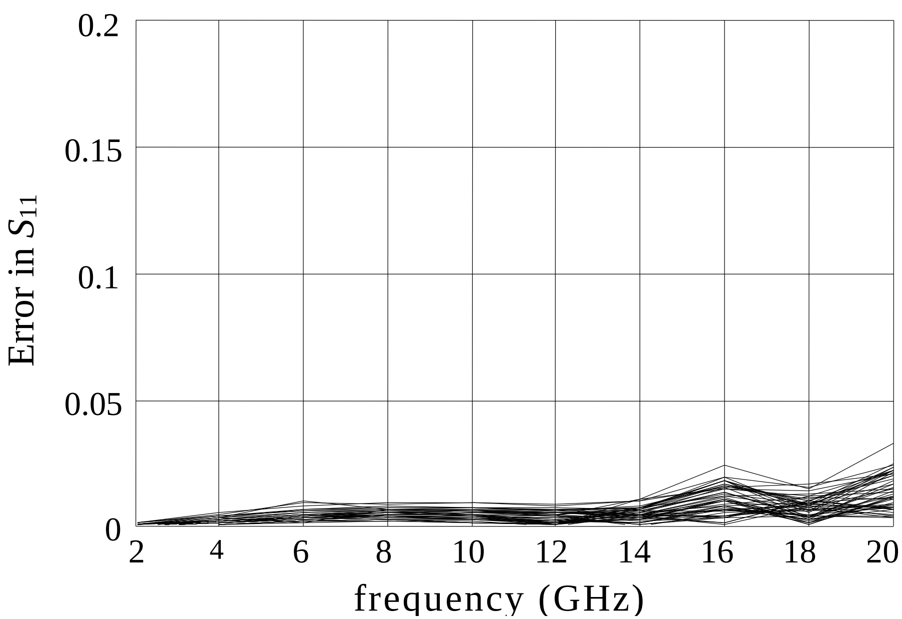
the errors of the coarse model responses at the test points

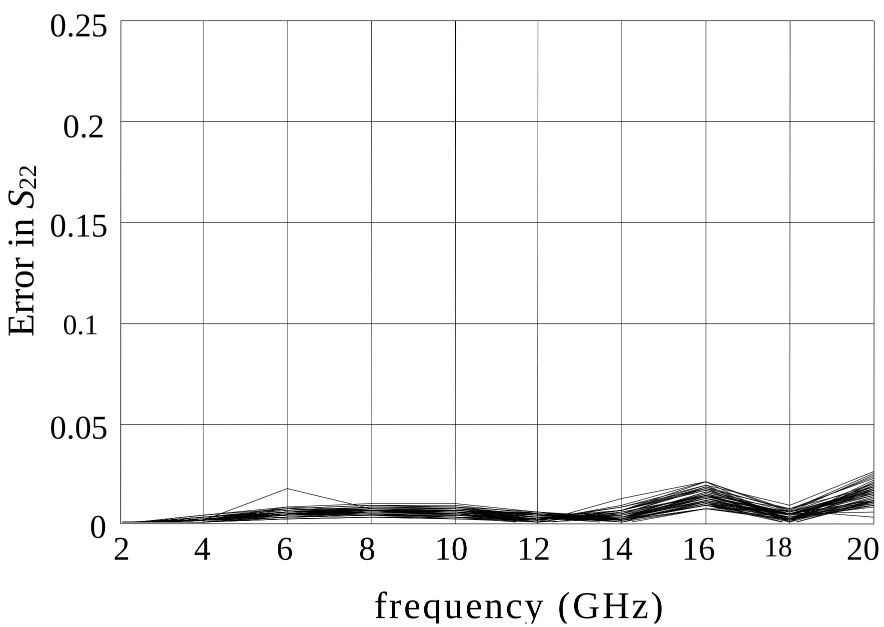




Microstrip Shaped T-Junction

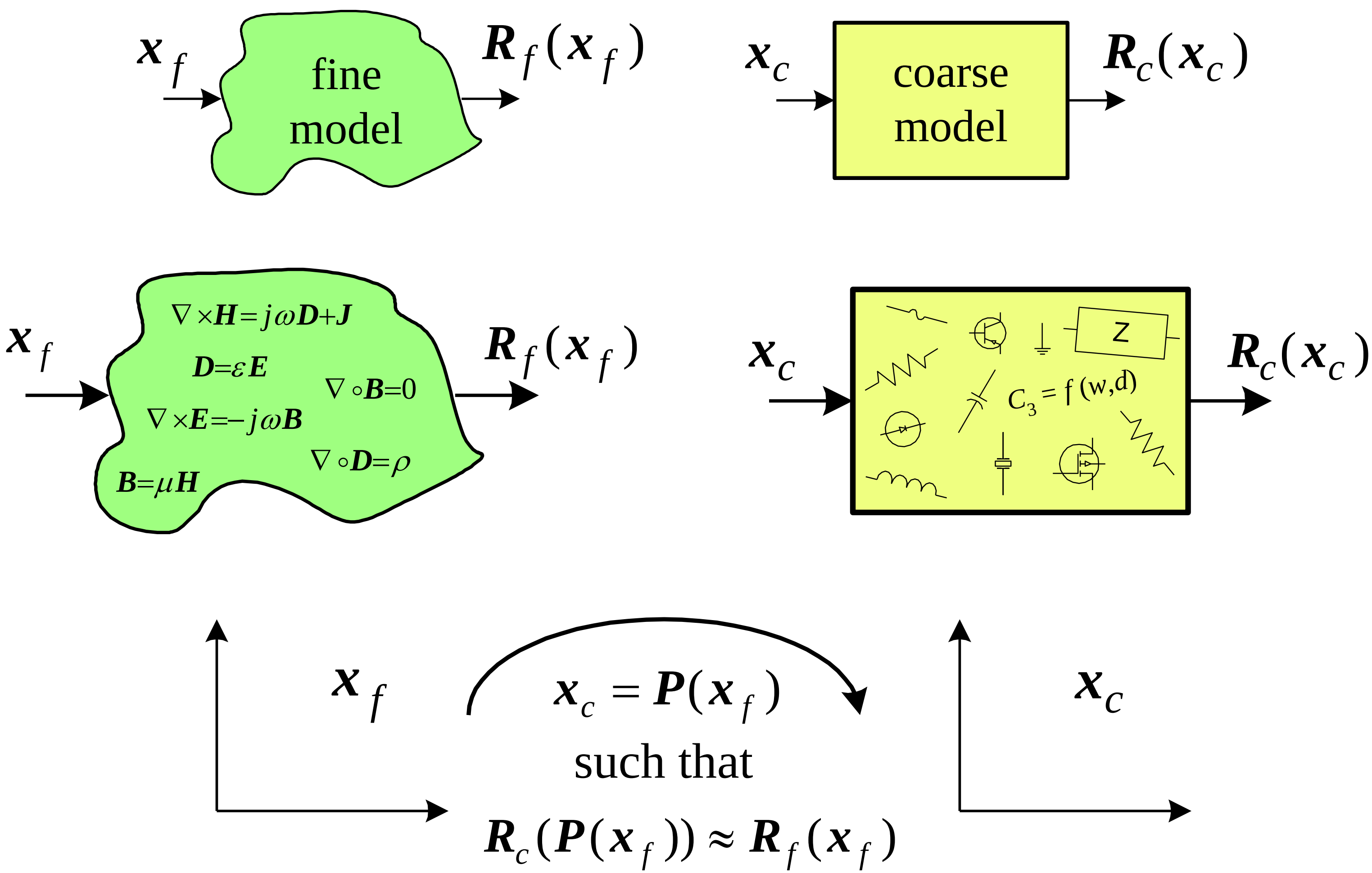
the errors of the enhanced coarse model responses at the test points





The Space Mapping Concept

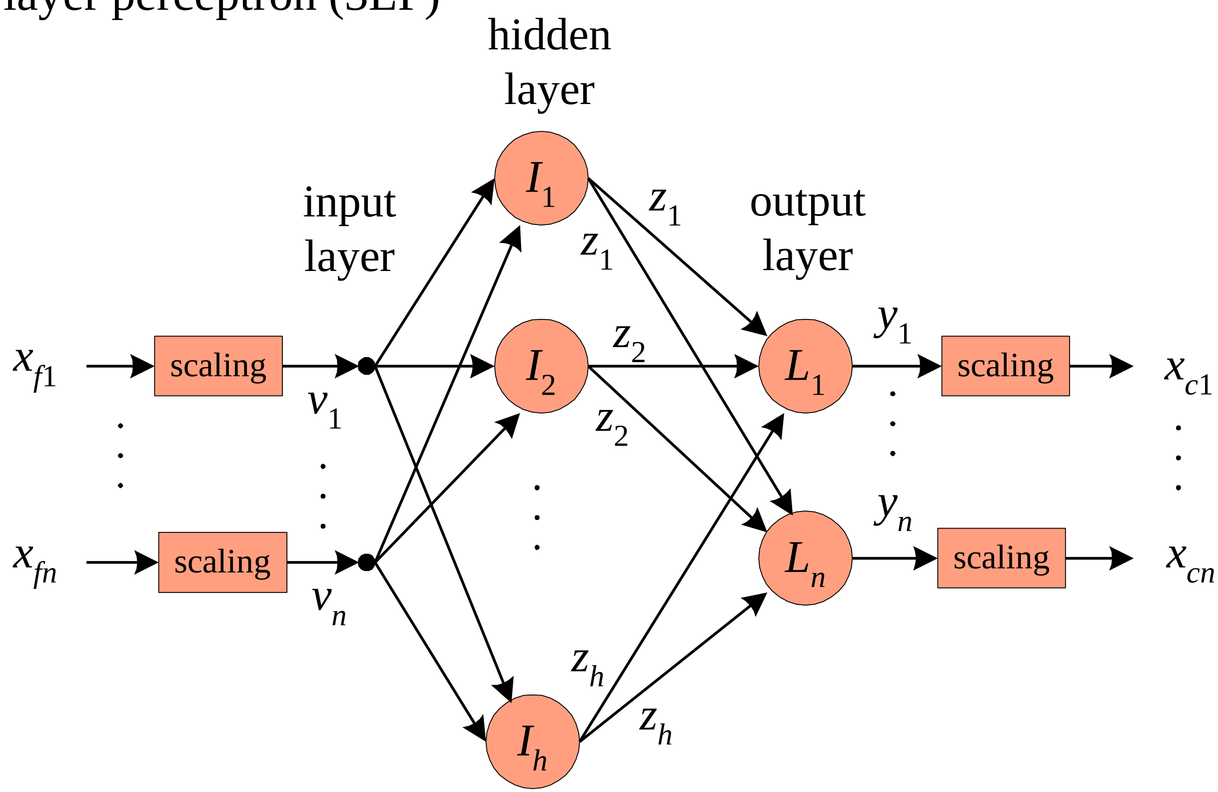
(Bandler et al., 1994-)



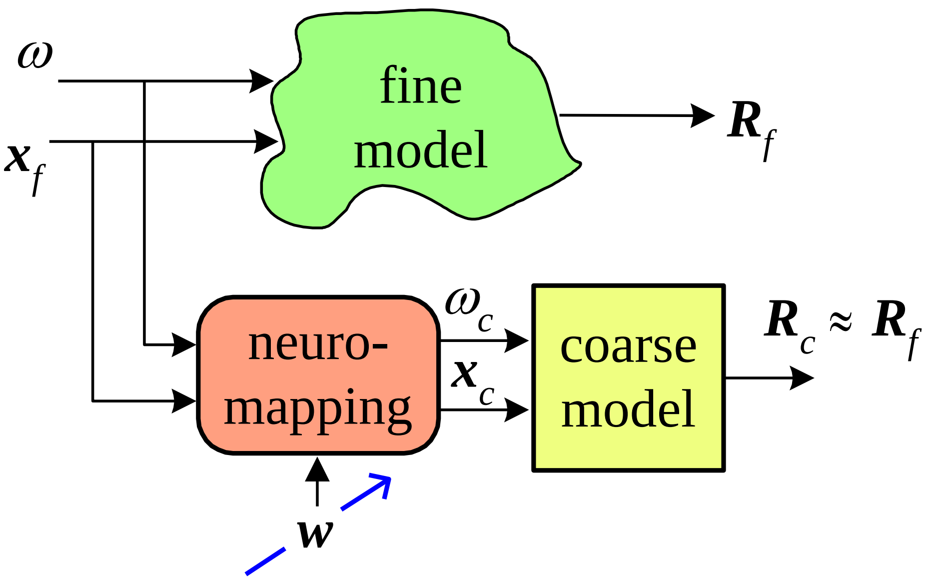
Neural Space Mapping

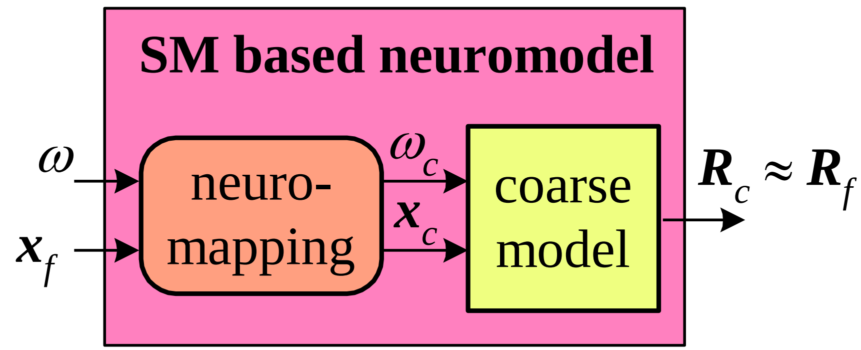
(Bandler et al., 1999)

using a three layer perceptron (3LP)



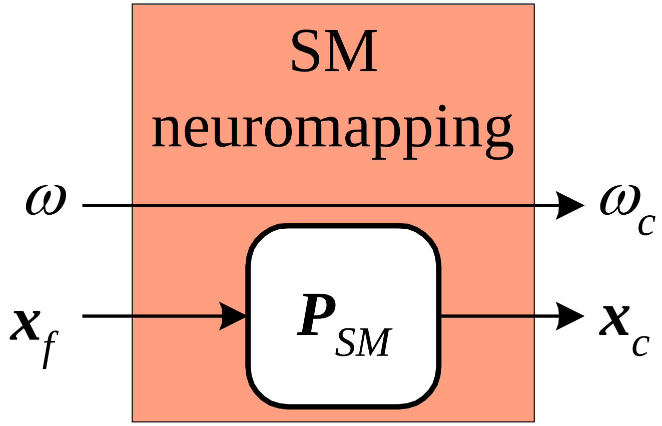
Space Mapping Based Neuromodeling
(Bandler et. al., 1999)



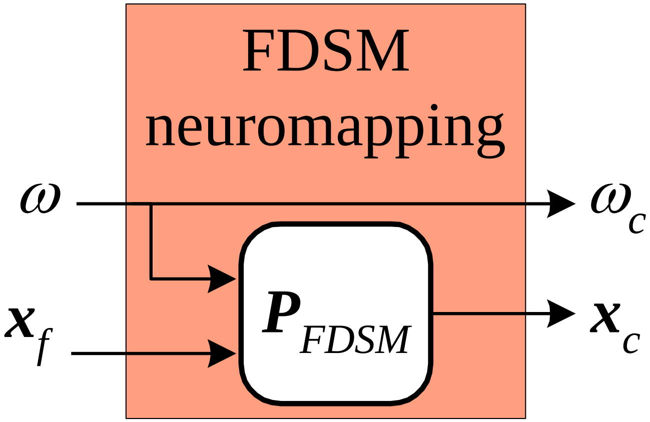


Neuromappings

Space Mapped neuromapping

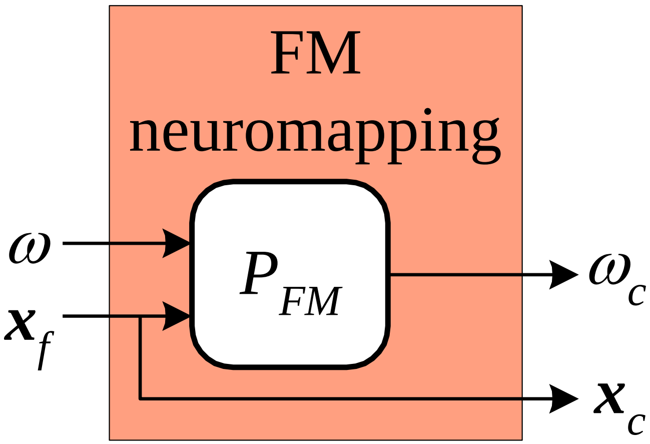


Frequency-Dependent Space Mapped neuromapping

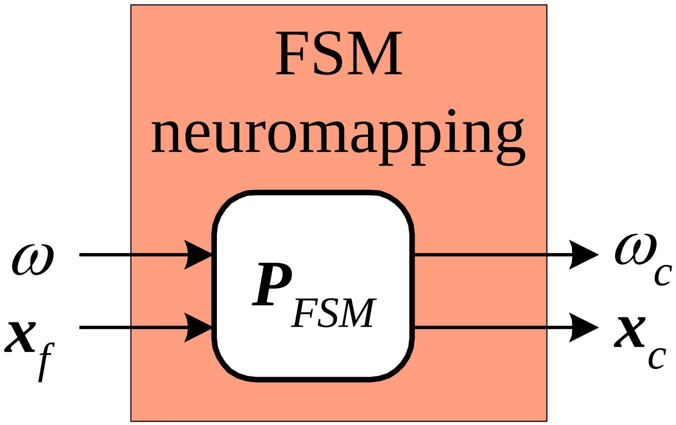


Neuromappings (continued)

Frequency Mapped neuromapping

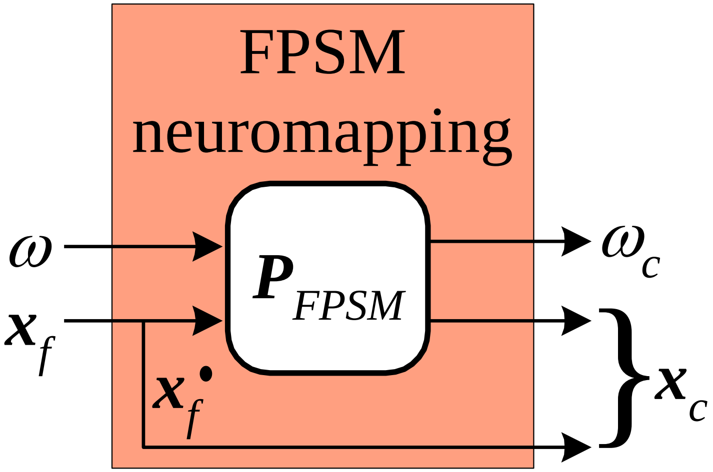


Frequency Space
Mapped neuromapping



Neuromappings (continued)

Frequency Partial-Space
Mapped neuromapping



it is not always necessary to map the whole set of design parameters

coarse model sensitivities can be used to select the mapped parameters

Training the SM-Based Neuromodel

$$\boldsymbol{w}^* = \arg\min_{\boldsymbol{w}} \left\| [\cdots \quad \boldsymbol{e}_s^T \quad \cdots]^T \right\|$$

$$\boldsymbol{e}_s = \boldsymbol{R}_f(\boldsymbol{x}_f^{(l)}, \omega_j) - \boldsymbol{R}_c(\boldsymbol{x}_{c_j}^{(l)}, \omega_{c_j}) \qquad \boldsymbol{e}_s \in \Re^r$$

$$\begin{bmatrix} \boldsymbol{x}_{c_j}^{(l)} \\ \omega_{c_j} \end{bmatrix} = \boldsymbol{P}(\boldsymbol{x}_f^{(l)}, \omega_j, \boldsymbol{w})$$

$$j = 1, \ldots, F_p \qquad l = 1, \ldots, 2n+1 \qquad s = j + F_p(l-1)$$

r is the number of responses in the model

$\boldsymbol{P}$ is the neuromapping function and $\boldsymbol{w}$ contains the free parameters of the ANN

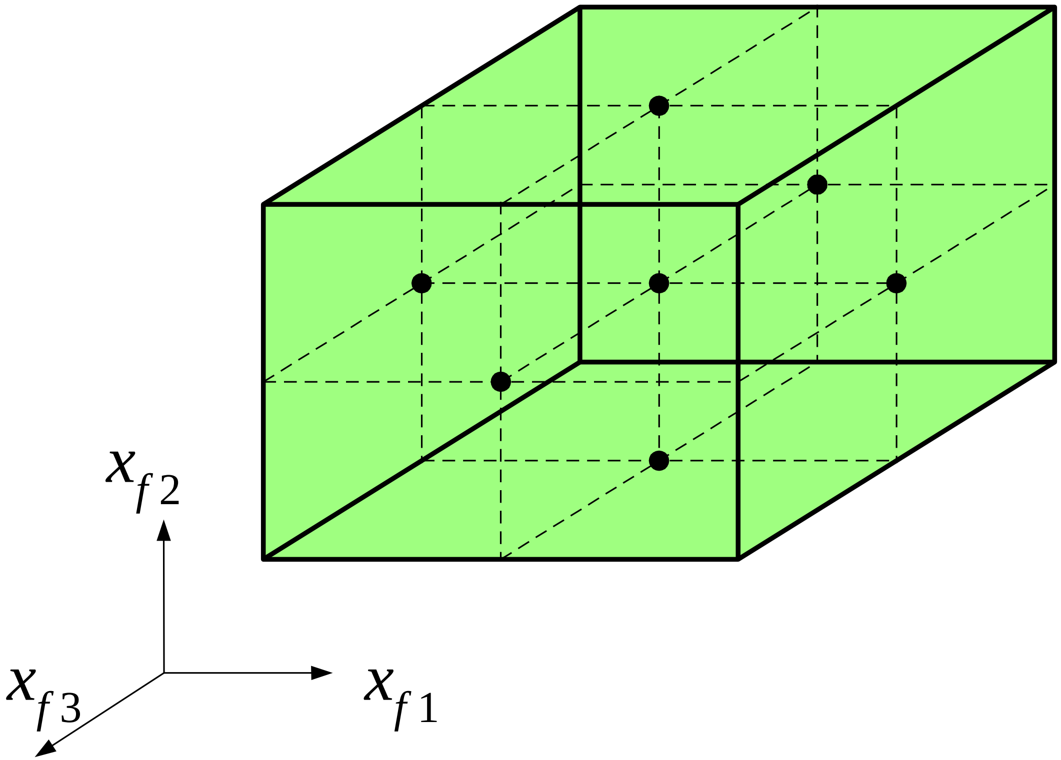
$2n+1$ is the number of training base points and F_p is the number of frequency points

Huber optimization is used to solve this problem

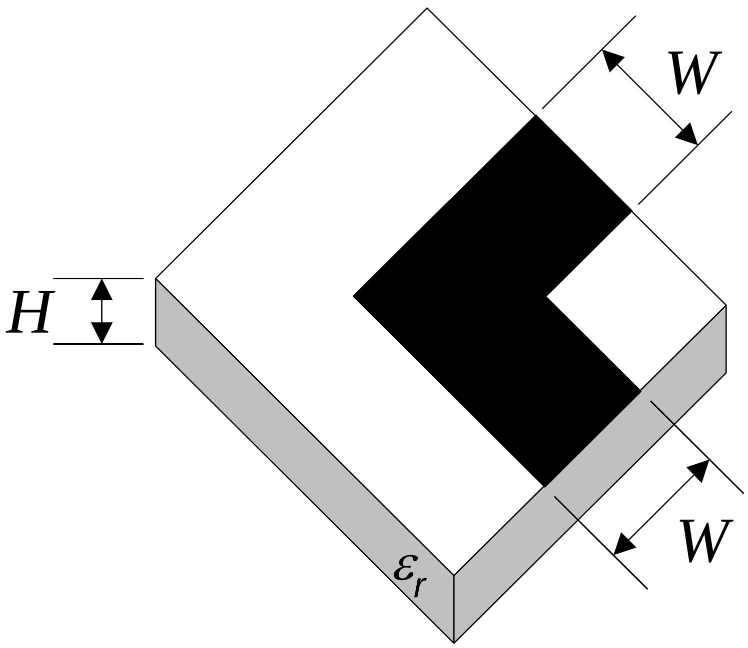
Starting Point and Learning Samples

we chose a unit mapping ($\boldsymbol{x}_c \approx \boldsymbol{x}_f$ and $\omega_c \approx \omega$) as the starting point for the optimization problem

$2n+1$ points are used for a microwave circuit with n design parameters



Microstrip Right Angle Bend



region of interest

$$20\text{mil} \le W \le 30\text{mil}$$
$$8\text{mil} \le H \le 16\text{mil}$$
$$8 \le \varepsilon_r \le 10$$
$$1\text{GHz} \le \omega \le 41\text{GHz}$$

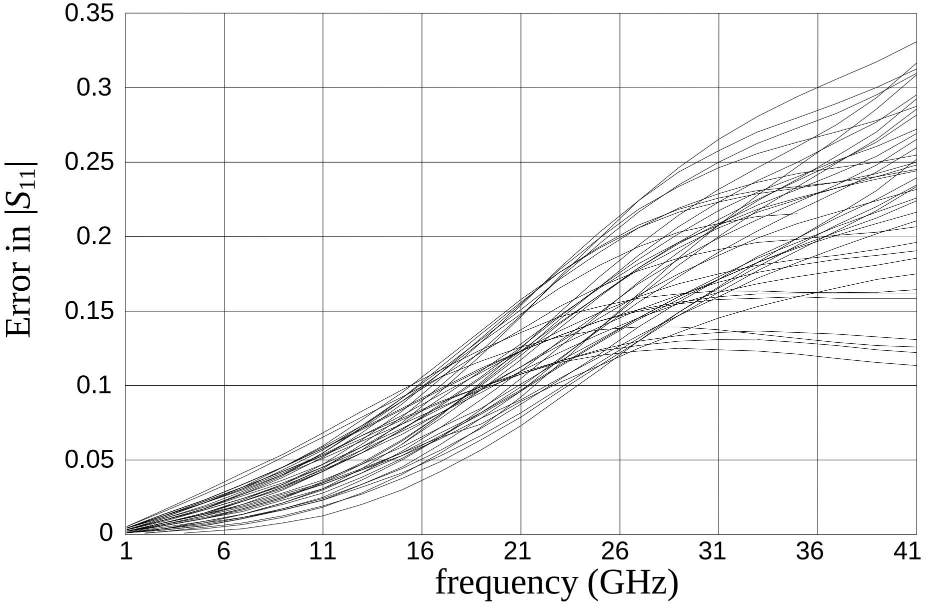
“coarse” model: equivalent circuit model *(Gupta, Garg and Bahl, 1979)*

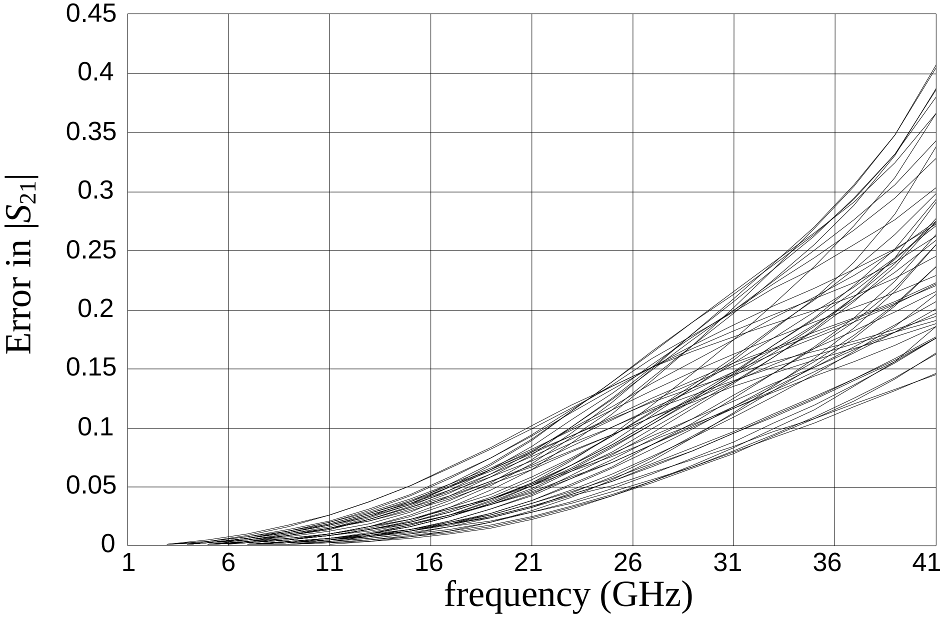
“fine” model: Sonnet’s ***em***™

learning set: 7 base points with “star” distribution

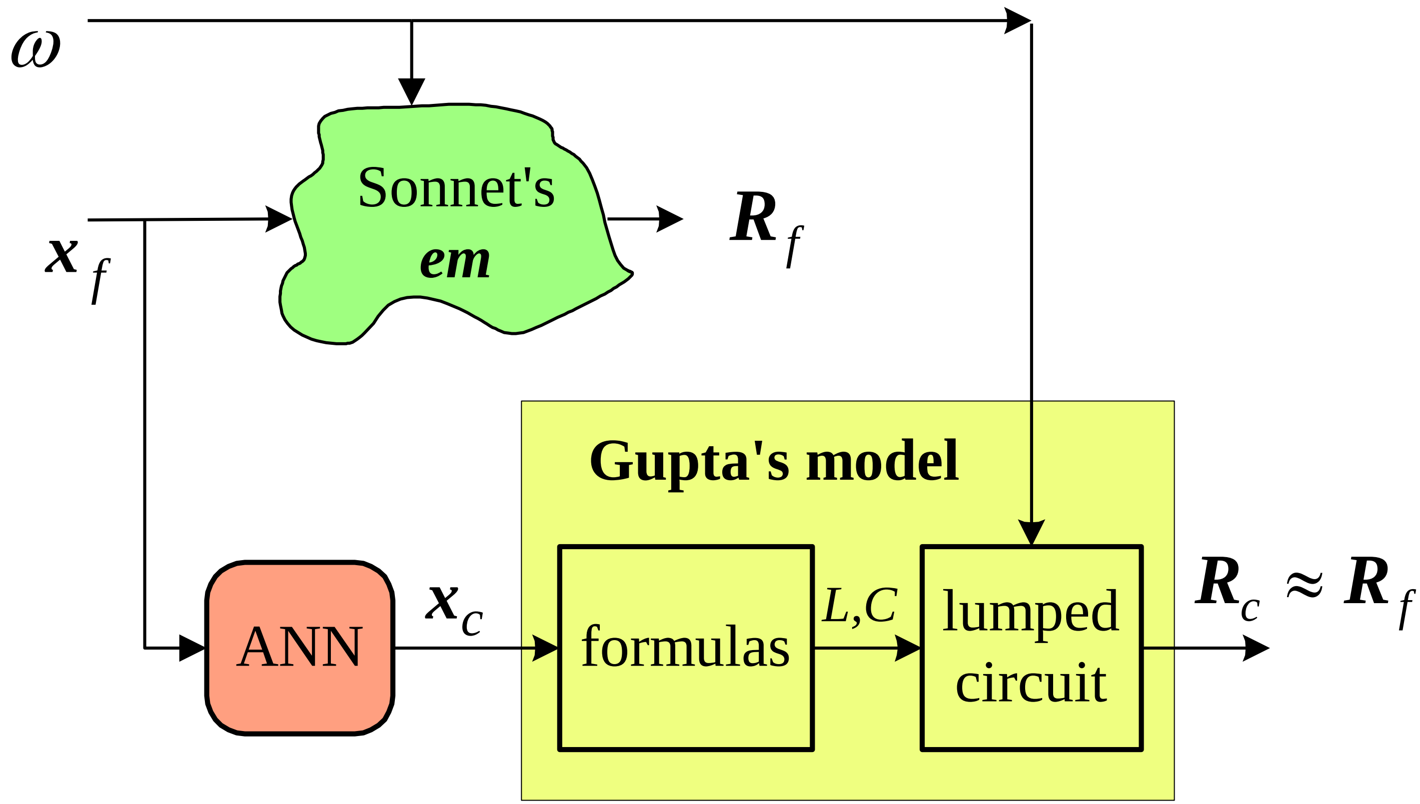
Microstrip Right Angle Bend Coarse Model Errors

comparison between ***em***™ and coarse model at 50 random test points





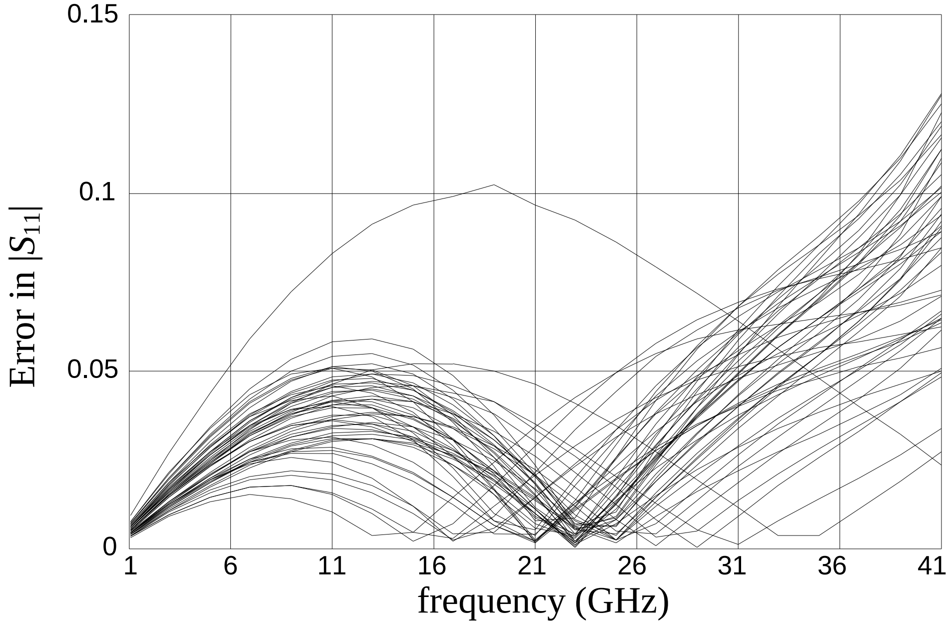
SM Neuromodel for the Right Angle Bend (3LP:3-6-3)

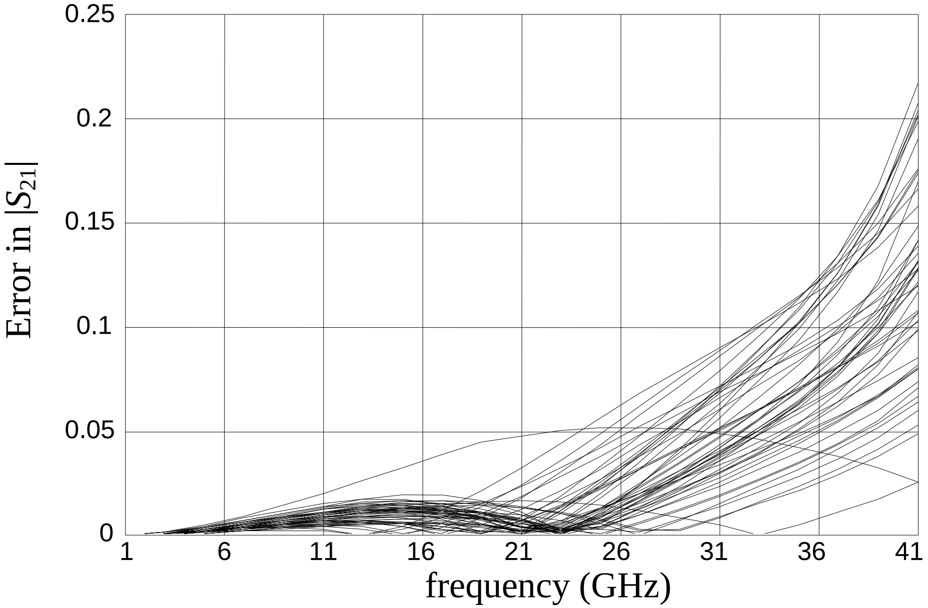


$$\boldsymbol{x}_f = [W \;\; H \;\; \varepsilon_r]^T$$

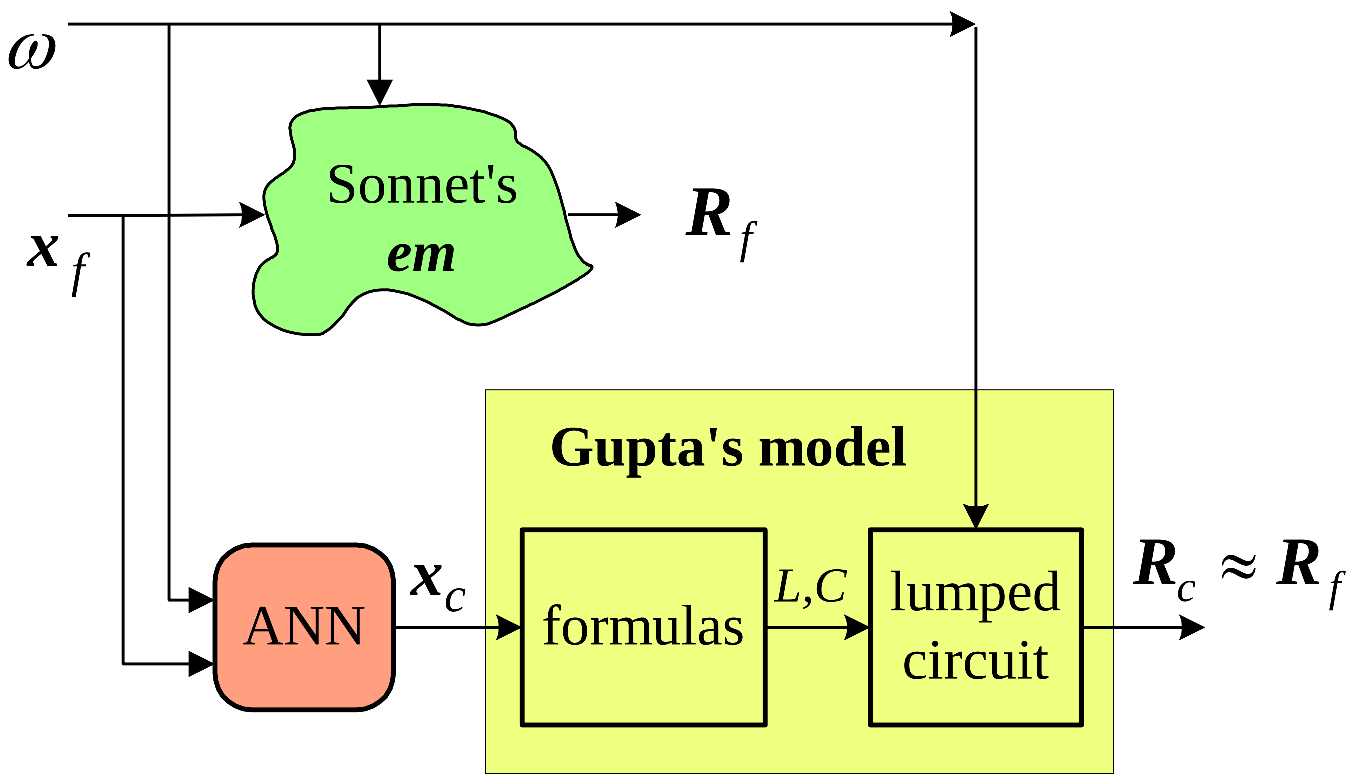
SM Neuromodel Results for the Right Angle Bend

comparison between ***em***™ and the SM neuromodel





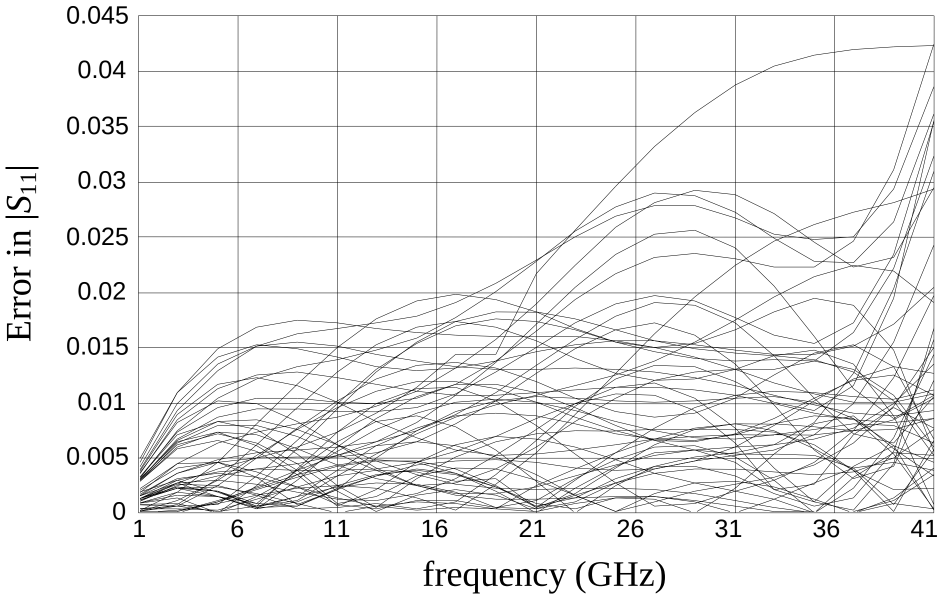
FDSM Neuromodel for the Right Angle Bend (3LP:4-7-3)

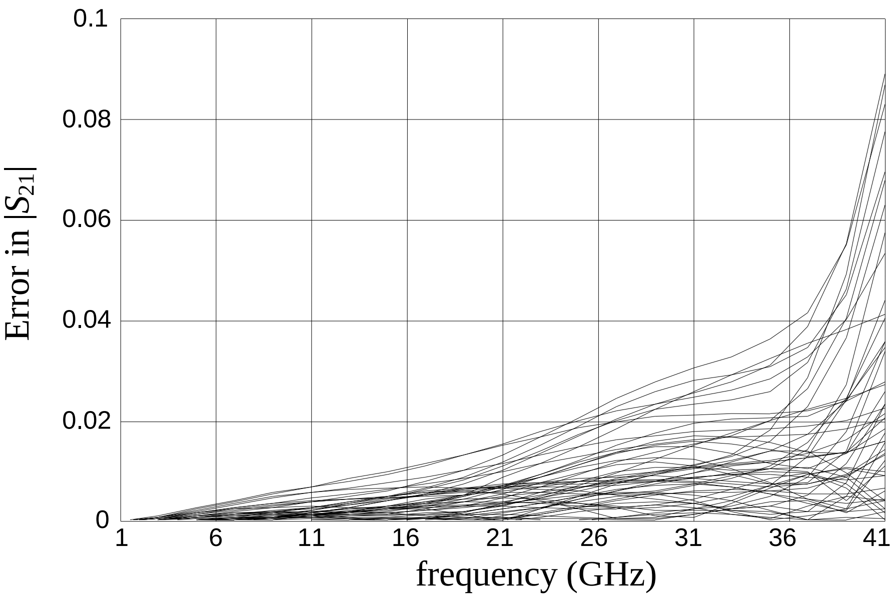


$\boldsymbol{x}_f = [W \;\; H \;\; \varepsilon_r]^T$

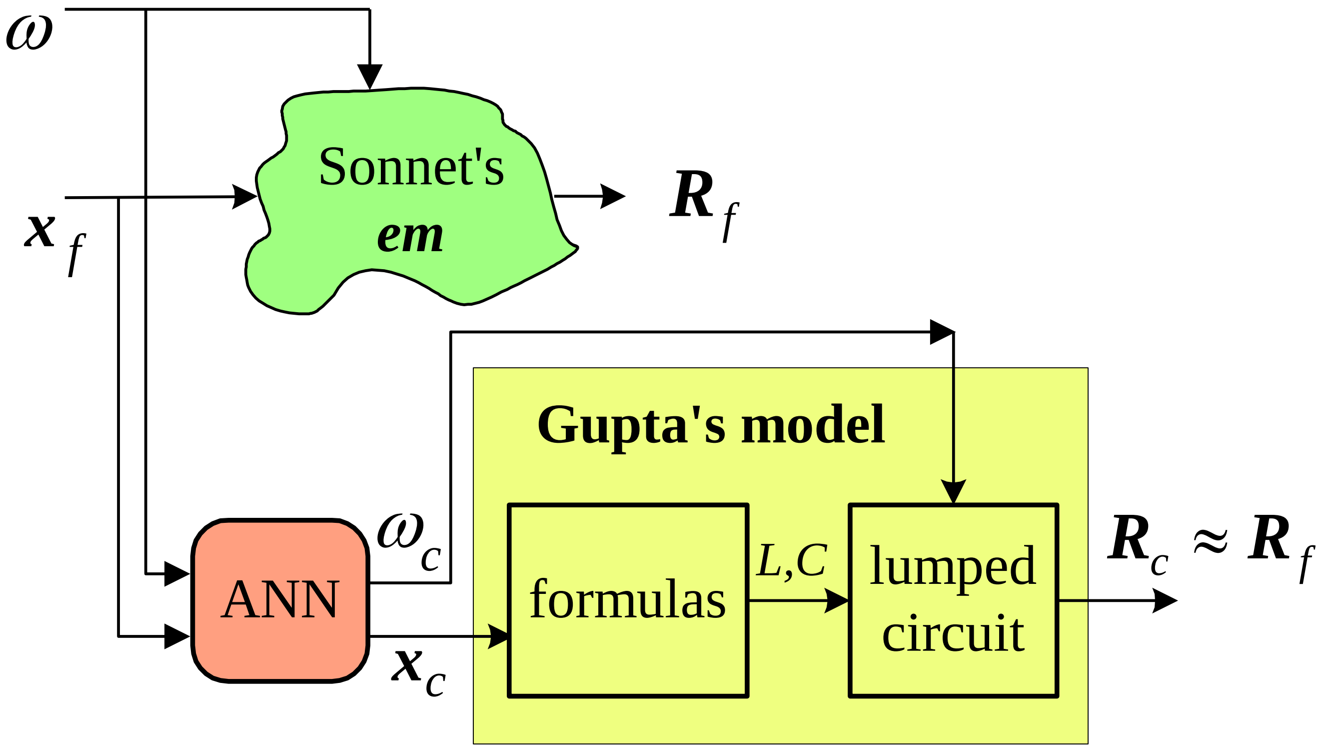
FDSM Neuromodel Results for the Right Angle Bend

comparison between ***em***™ and the FDSM neuromodel





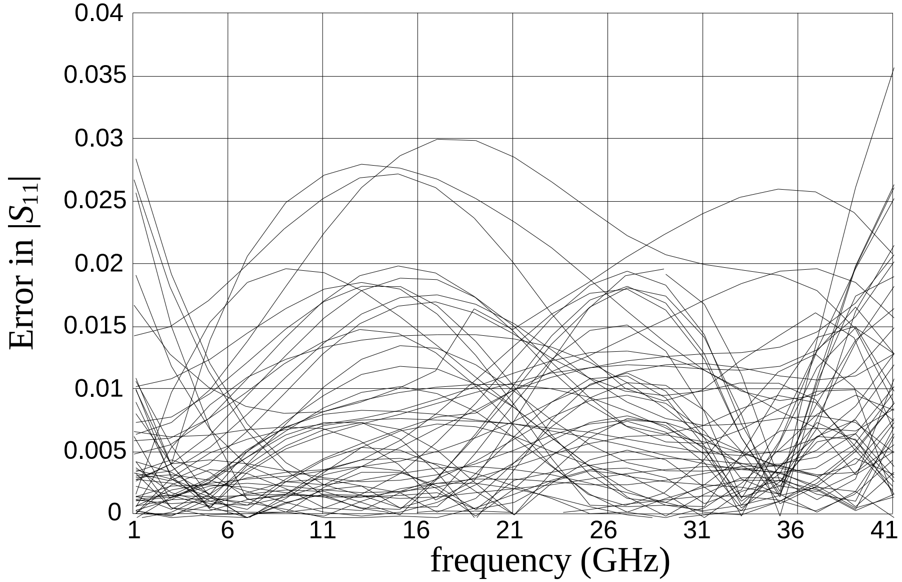
FSM Neuromodel for the Right Angle Bend (3LP:4-8-4)

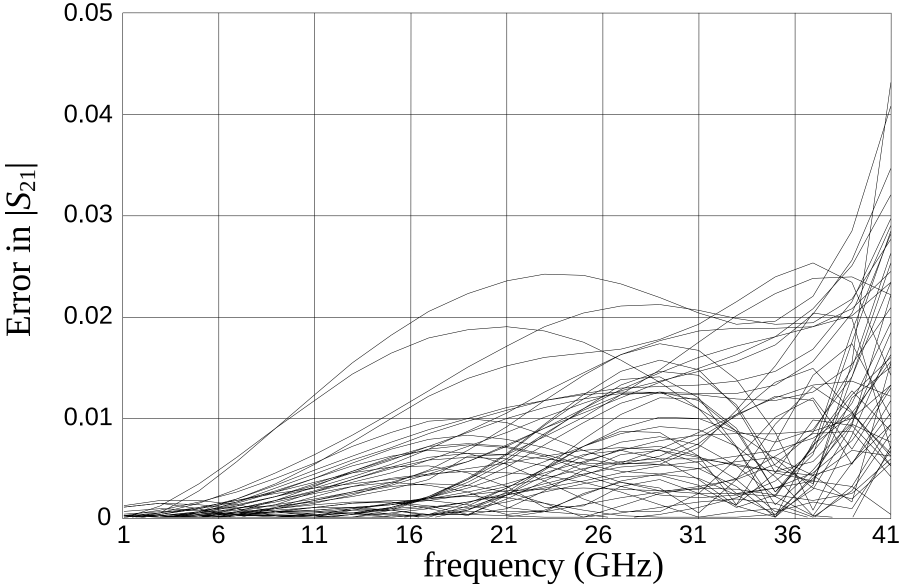


$\boldsymbol{x}_f = [W \;\; H \;\; \varepsilon_r]^T$

FSM Neuromodel Results for the Right Angle Bend

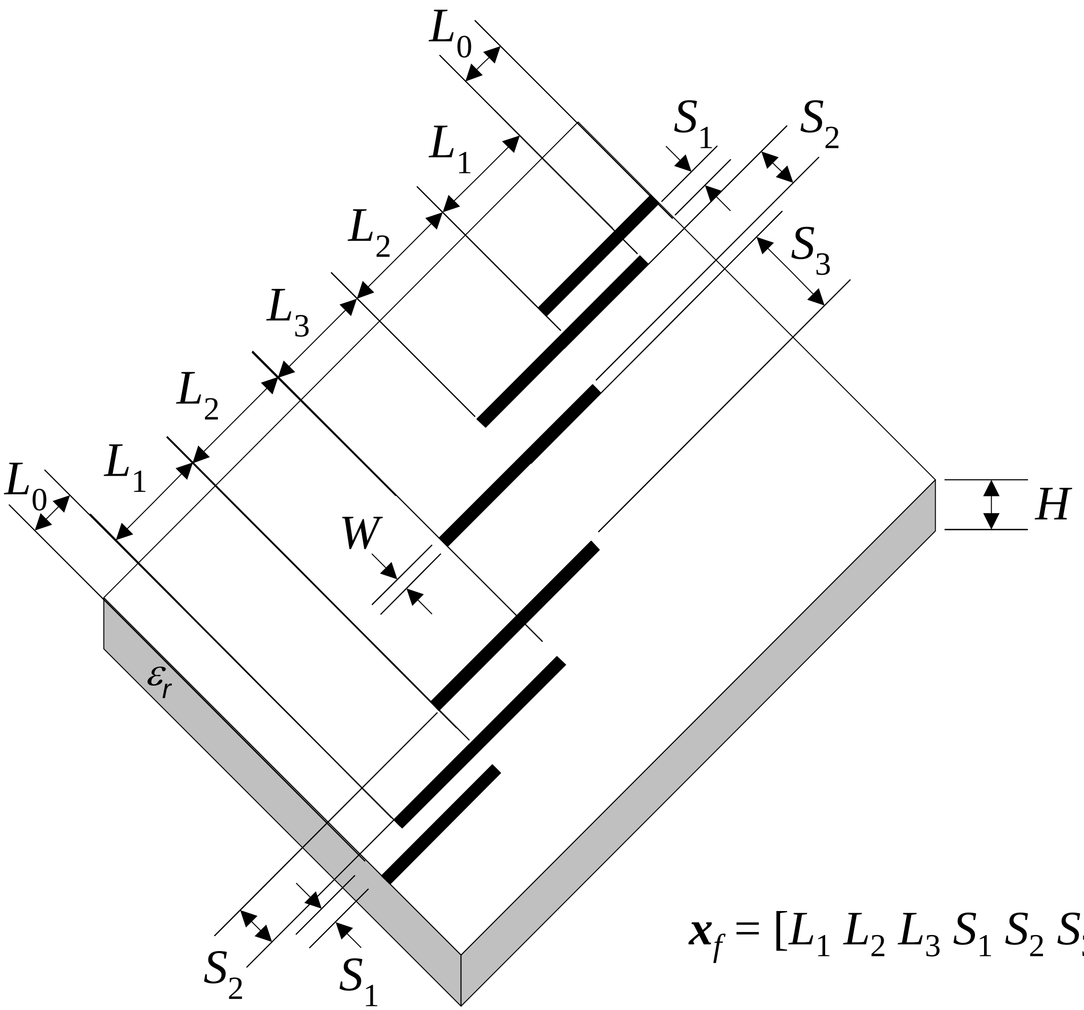
comparison between ***em***™ and the FSM neuromodel





HTS Quarter-Wave Parallel Coupled-Line Microstrip Filter

(Westinghouse, 1993)



region of interest

$$175\text{mil} \le L_1 \le 185\text{mil}$$
$$190\text{mil} \le L_2 \le 210\text{mil}$$
$$175\text{mil} \le L_3 \le 185\text{mil}$$
$$18\text{mil} \le S_1 \le 22\text{mil}$$
$$75\text{mil} \le S_2 \le 85\text{mil}$$
$$70\text{mil} \le S_3 \le 90\text{mil}$$
$$3.901\text{GHz} \le \omega \le 4.161\text{GHz}$$

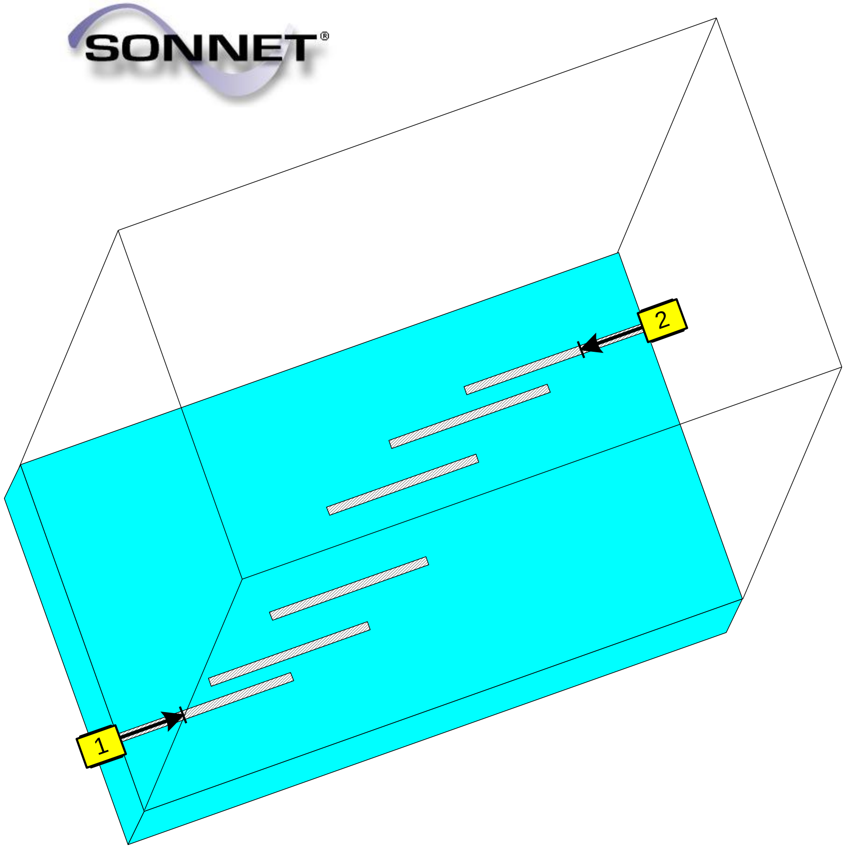
$$L_0 = 50\text{mil}$$
$$H = 20\text{mil}$$
$$W = 7\text{mil}$$
$$\varepsilon_r = 23.425$$
$$\text{loss tangent} = 3\times10^{-5}$$

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

HTS Microstrip Filter: Fine and Coarse Models

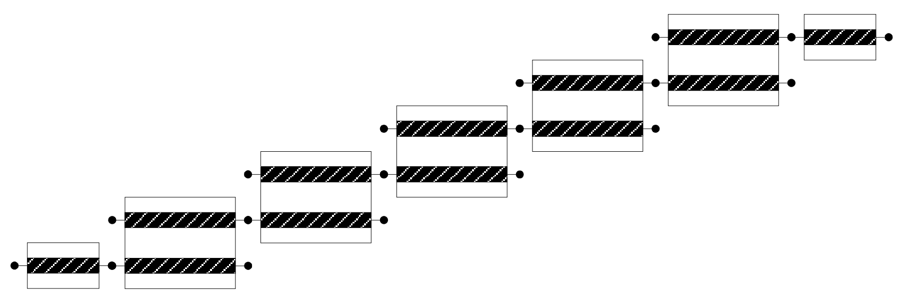
fine model:

Sonnet's ***em***™ with high resolution grid



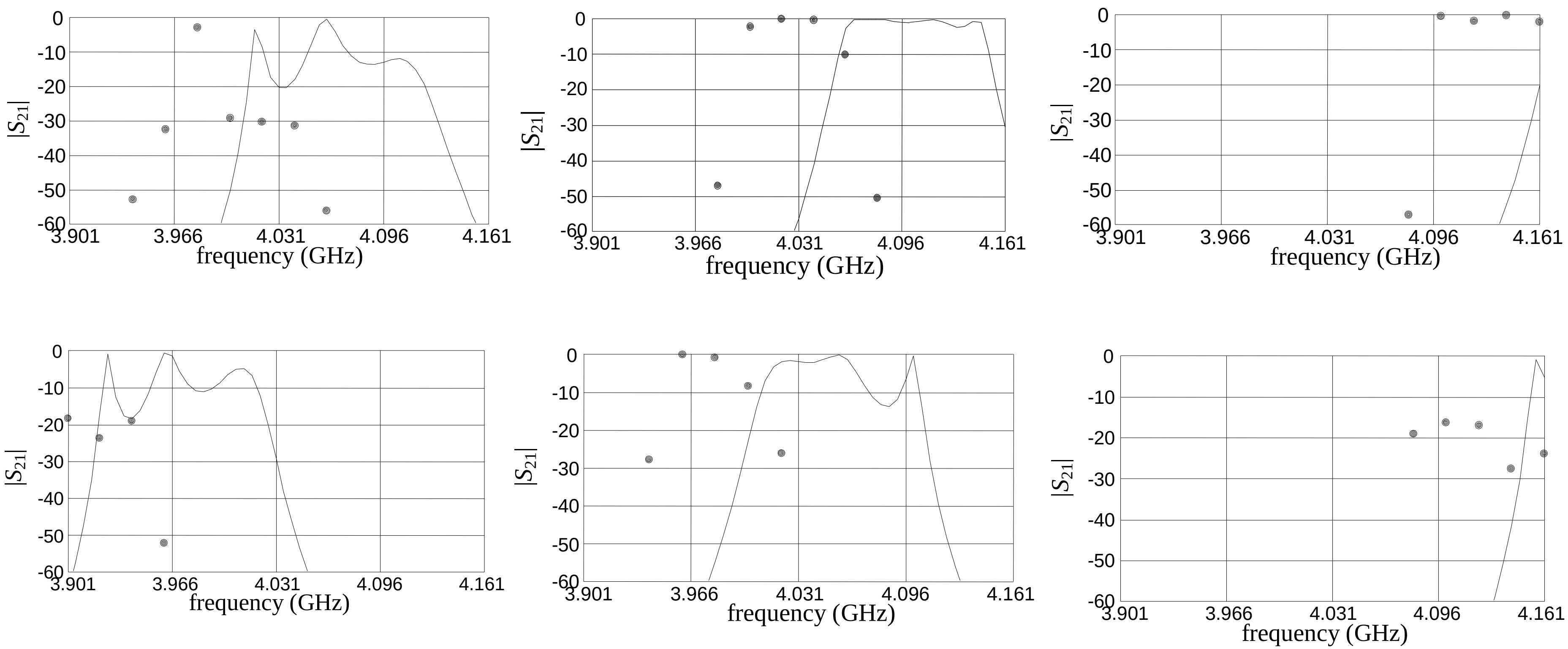
coarse model:

OSA90/hope™ built-in models of open circuits, microstrip lines and coupled microstrip lines

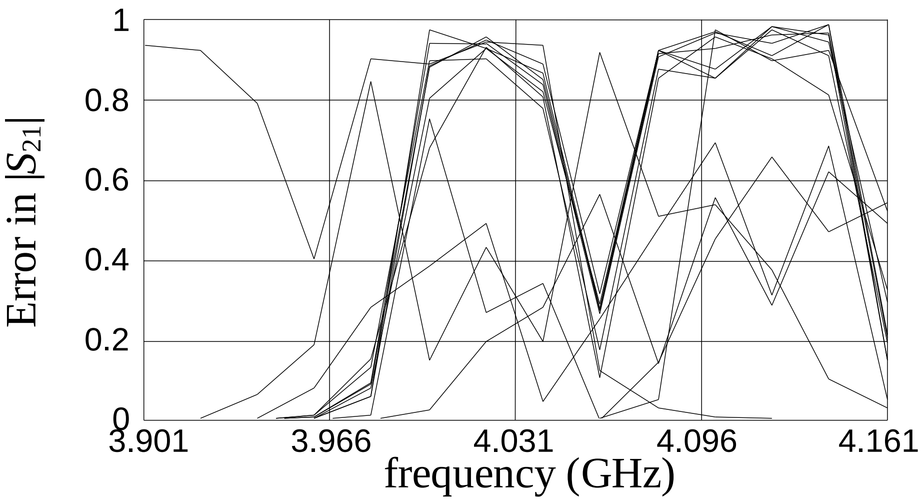


HTS Filter Responses Before Neuromodeling

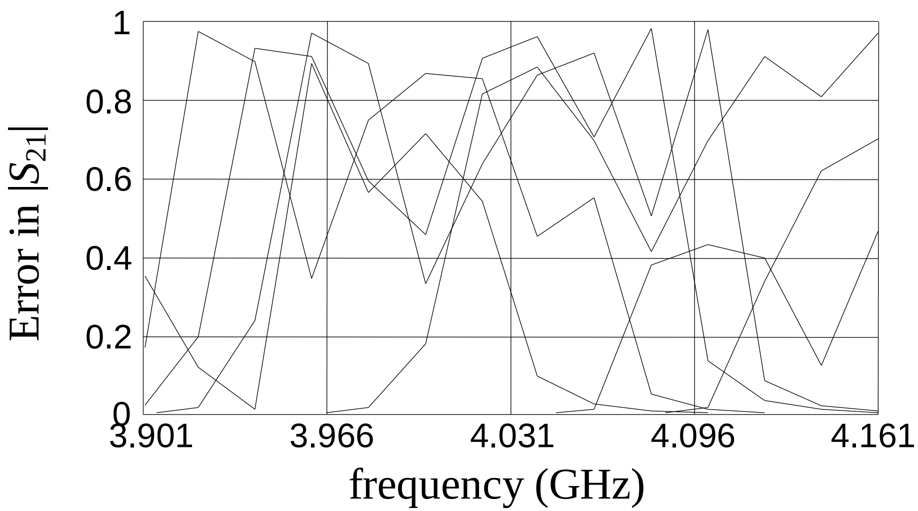
responses using ***em***™ (•) and OSA90/hope™ (–) at three learning and three test points



HTS Coarse Model Error w.r.t. *em*™ before any Neuromodeling



in the learning set

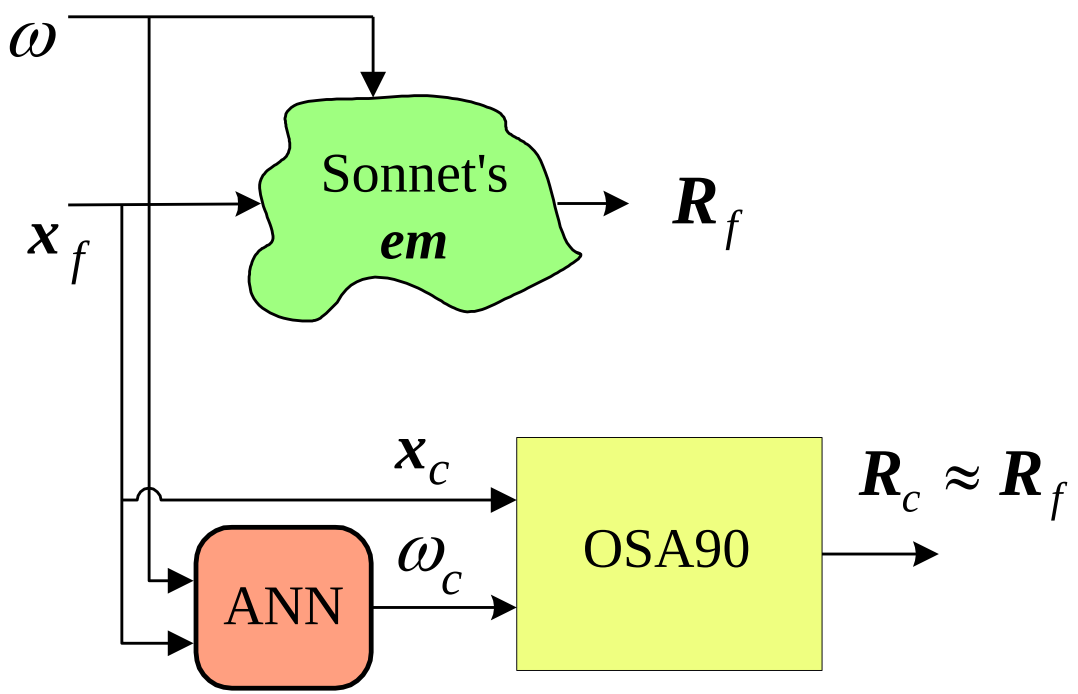


in the testing set

learning set: 13 base points with "star" distribution

testing set: 7 random base points in the region of interest
(not seen in the learning set)

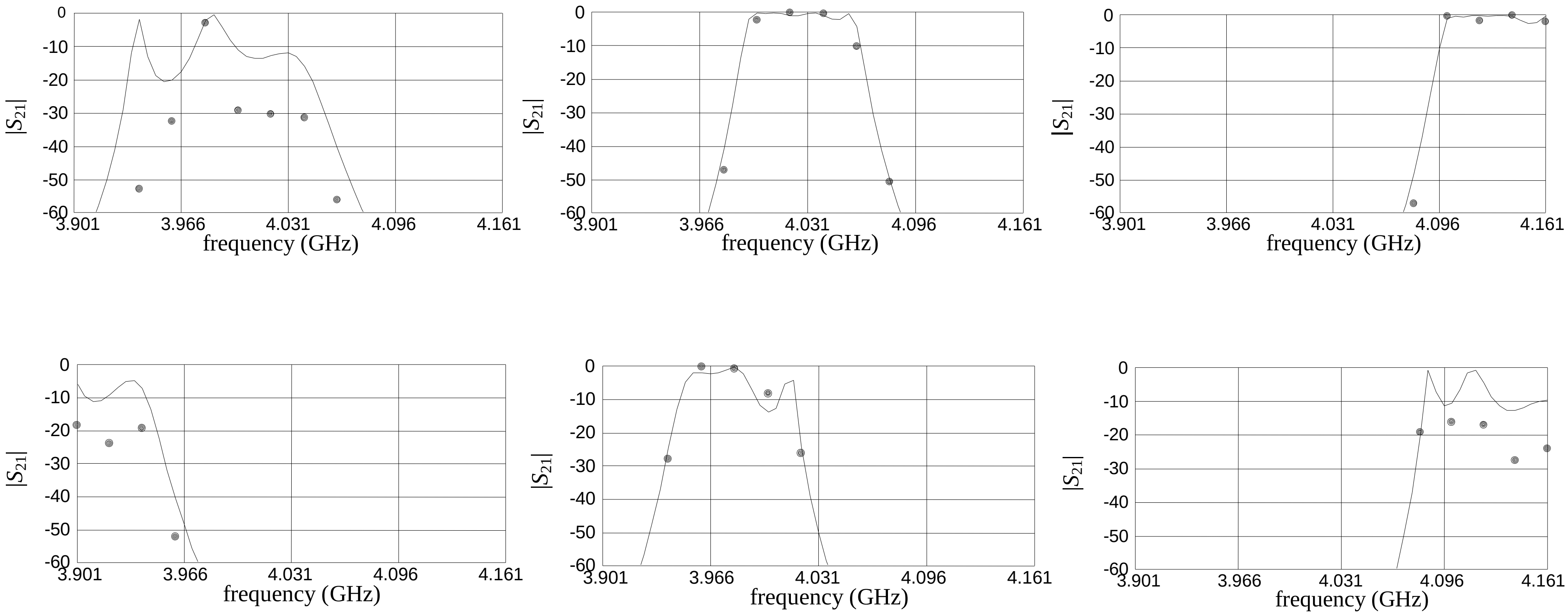
FM Neuromodel for the HTS Filter (3LP:7-5-1)



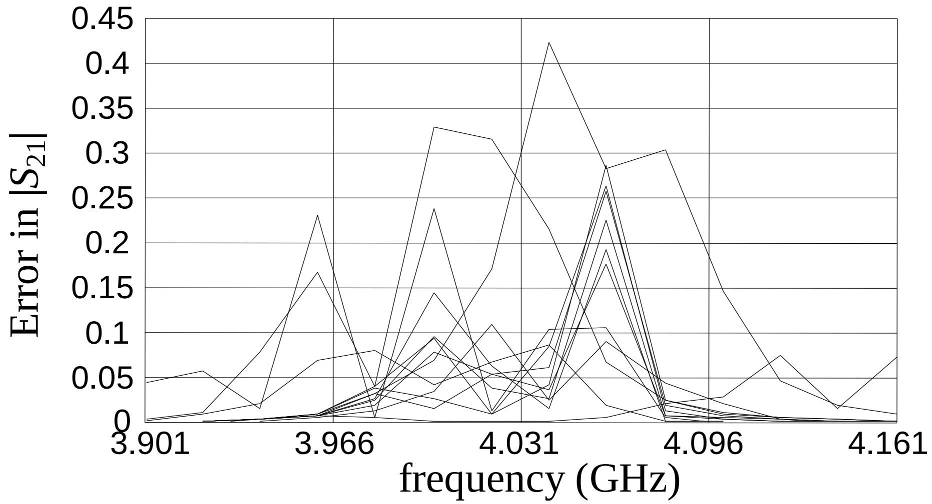
$$\boldsymbol{x}_f = [L_1\ L_2\ L_3\ S_1\ S_2\ S_3]^T$$

FM Neuromodel for the HTS Filter (3LP:7-5-1)

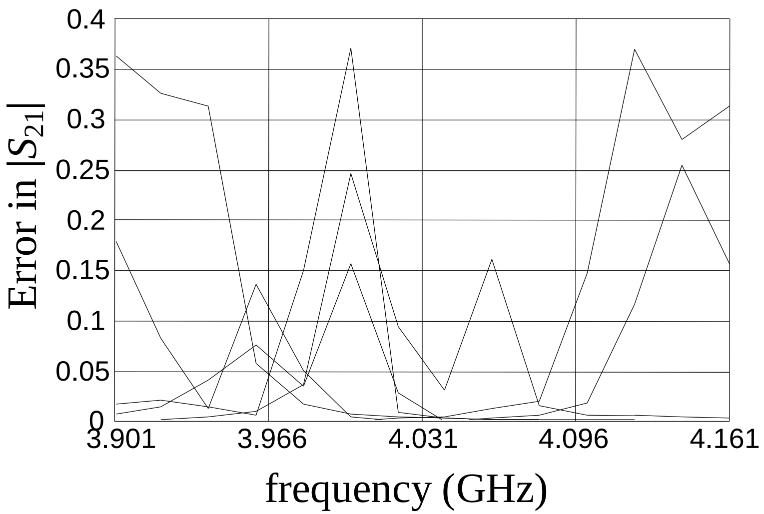
responses using ***em***™ (•) and FMN model (–) at the three learning and three testing points



HTS FM Neuromodel Error w.r.t. *em*™

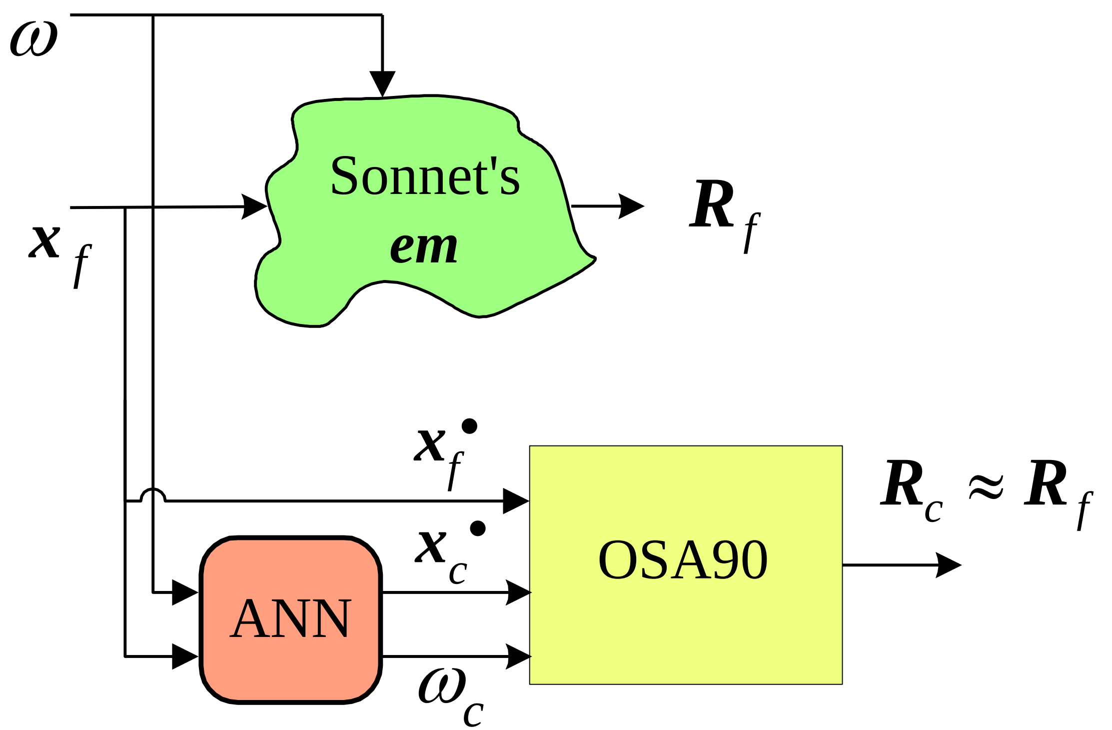


in the learning set



in the testing set

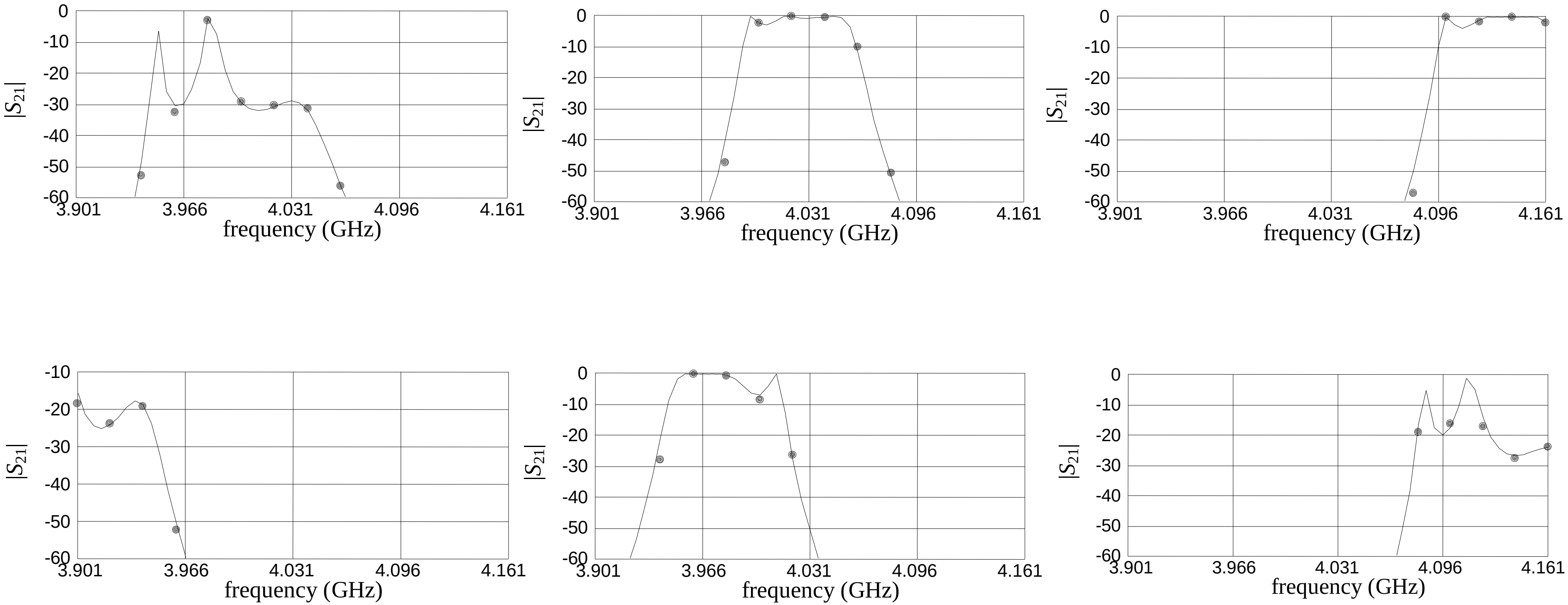
FPSM Neuromodel for the HTS Filter (3LP:7-7-3)



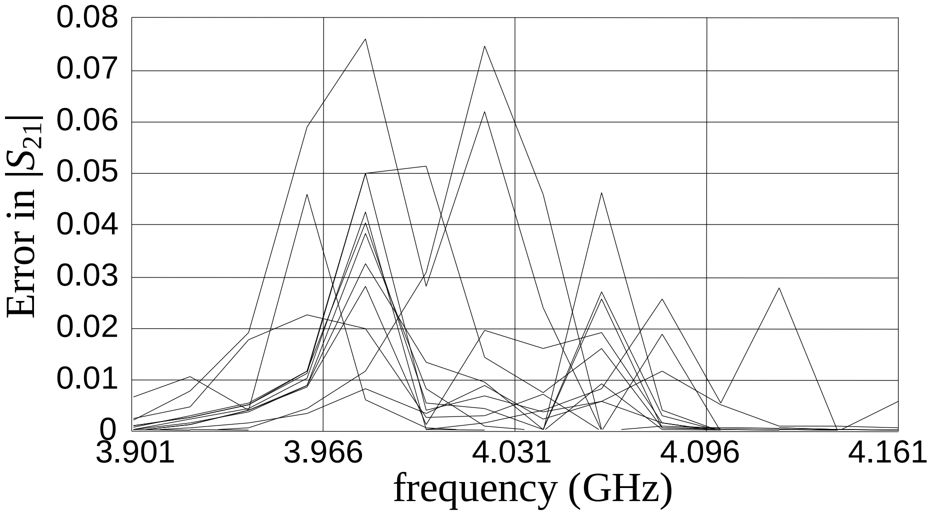
$$\boldsymbol{x}_f = [L_1\ L_2\ L_3\ S_1\ S_2\ S_3]^T \qquad \boldsymbol{x}_f^\bullet = [L_2\ L_3\ S_2\ S_3]^T \qquad \boldsymbol{x}_c^\bullet = [L_{1c}\ S_{1c}]^T$$

FPSM Neuromodel for the HTS Filter (3LP:7-7-3)

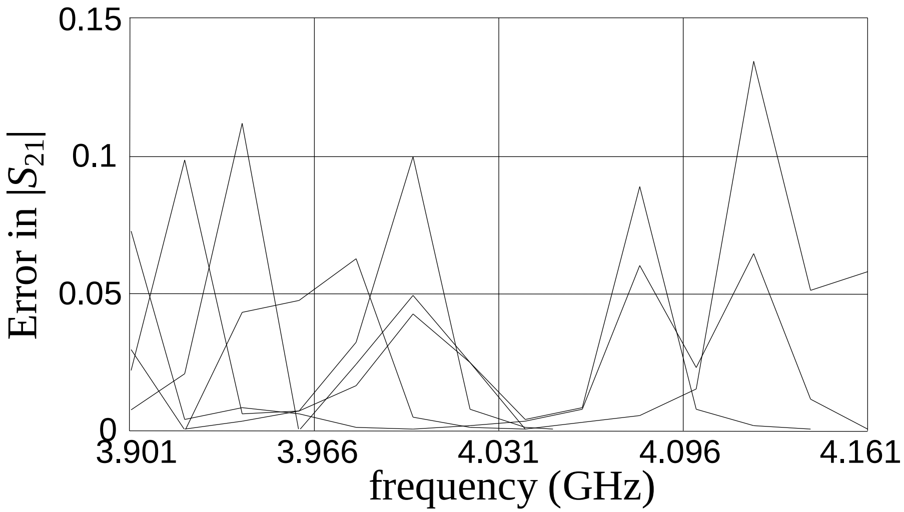
responses using ***em***™ (•) and FPSMN model (–) at the three learning and three testing points



HTS FPSM Neuromodel Error w.r.t. *em*™



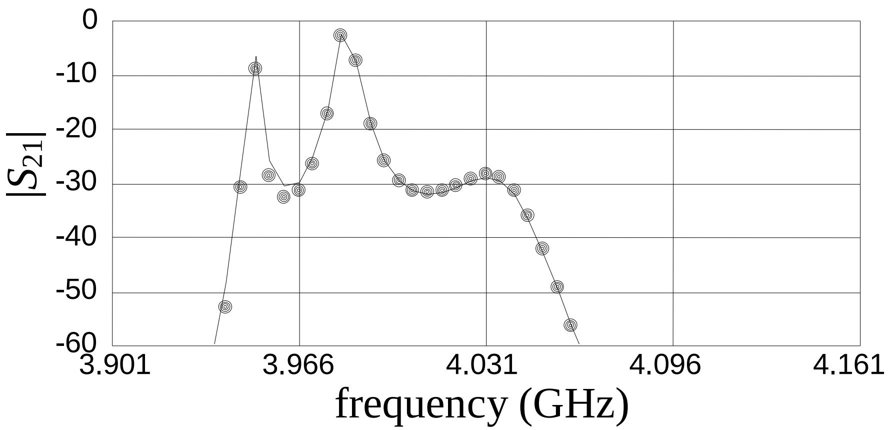
in the learning set

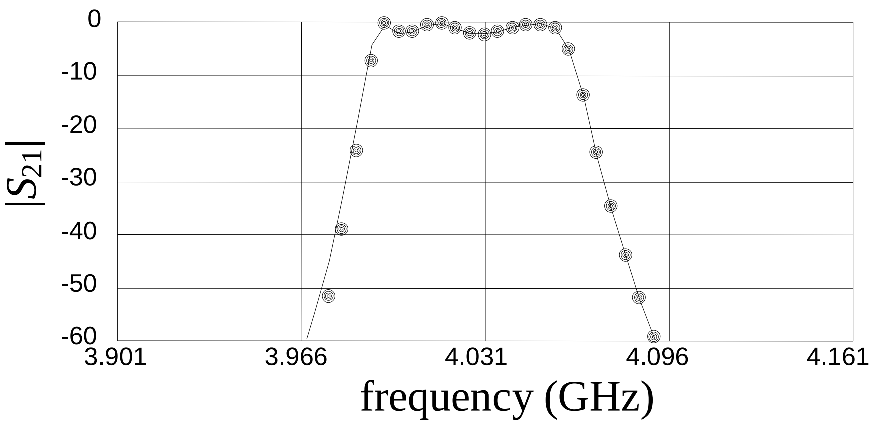


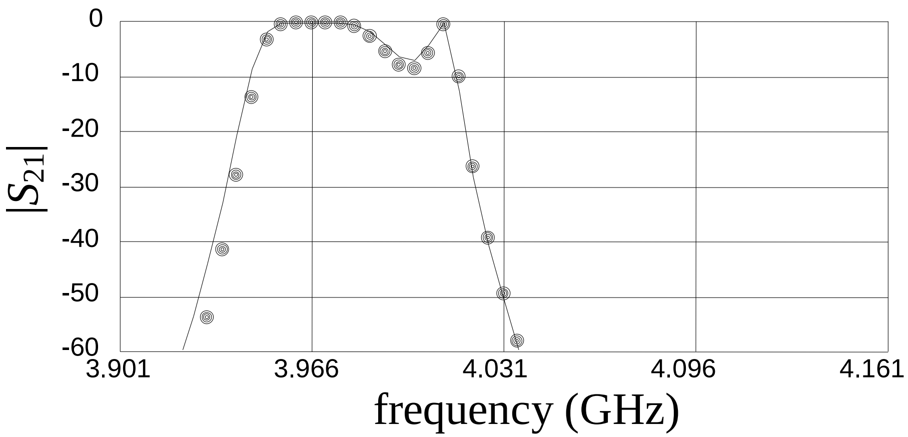
in the testing set

FPSM Neuromodel for the HTS Filter: Fine Frequency Sweep Results

comparison between ***em***™ (●) and FPSMN model (–) at two learning and one testing points







Other Applications of SM based Neuromodels
(Bandler et al., 2000, 2001)

Neural Space Mapping (NSM) Optimization

EM-based Statistical Analysis

EM-based Yield Optimization

Neural Inverse Space Mapping (NISM) Optimization

Conclusions

we describe applications of Space Mapping technology to modeling

we review Generalized Space Mapping (GSM) as an engineering device modeling framework

SM based neuromodeling techniques are also reviewed

frequency-sensitive neuromappings expand the usefulness of empirical quasi-static models

Space Mapping based models can be exploited for efficient EM optimization, statistical analysis and yield optimization

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