**A GENERALIZED SPACE MAPPING TABLEAU APPROACH TO DEVICE MODELING**

J.W. Bandler, N. Georgieva, M.A. Ismail, J.E. Rayas-Sánchez and Q.J. Zhang

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# A GENERALIZED SPACE MAPPING TABLEAU APPROACH TO DEVICE MODELING

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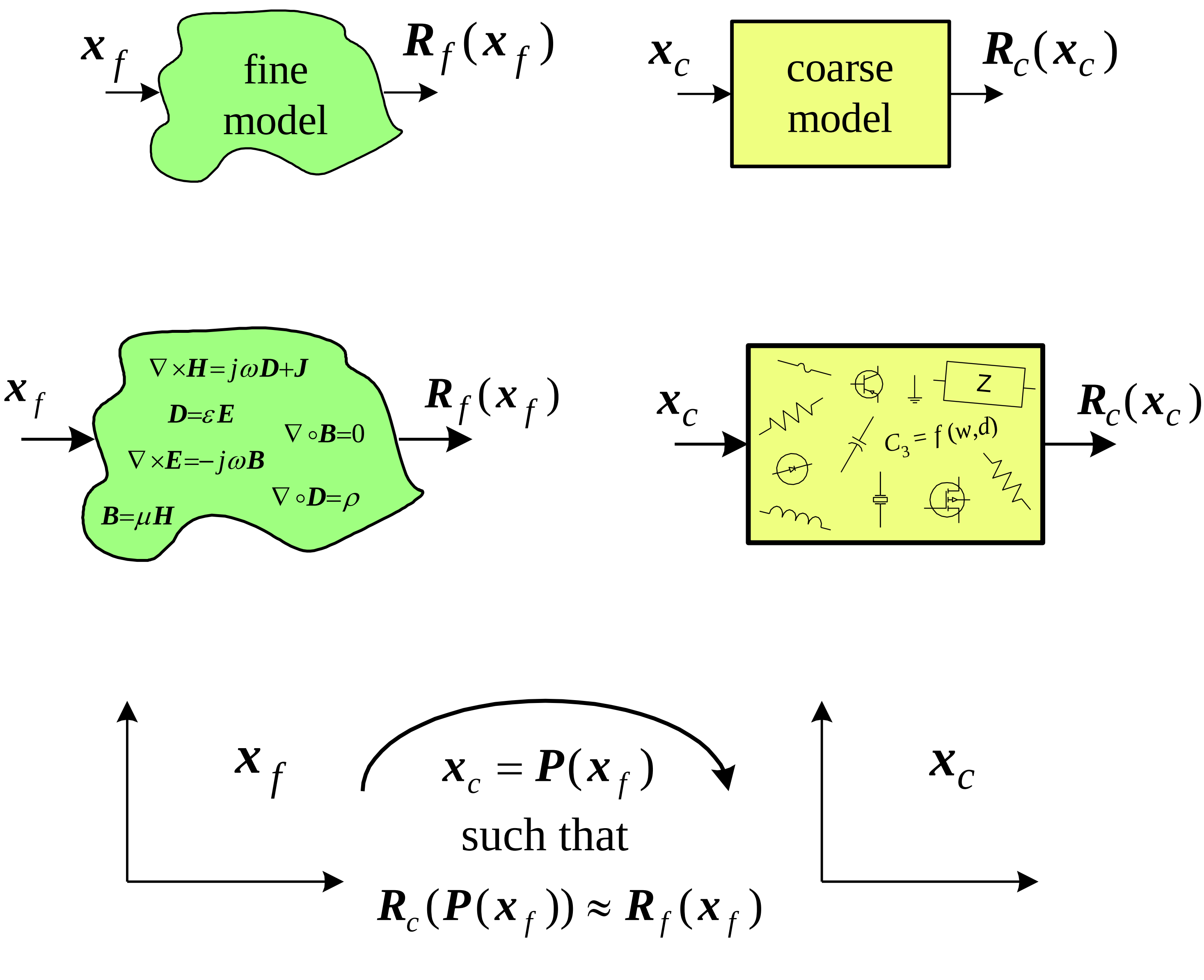
## Space Mapping Concept
*(Bandler et al., 1994-)*



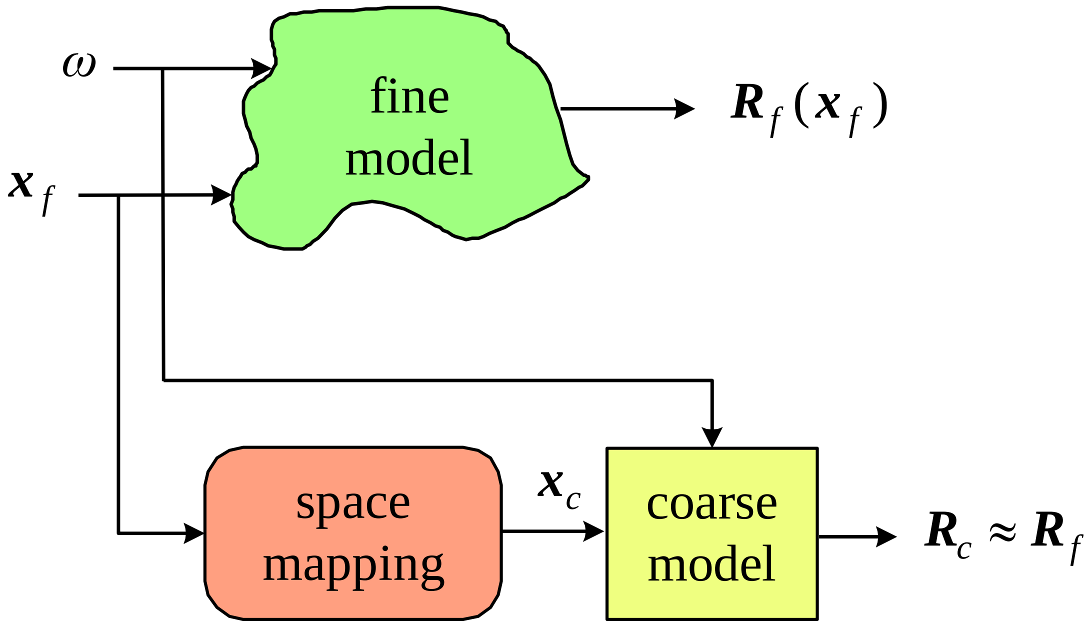
## Generalized Space Mapping (GSM)

GSM is a comprehensive framework to engineering device modeling

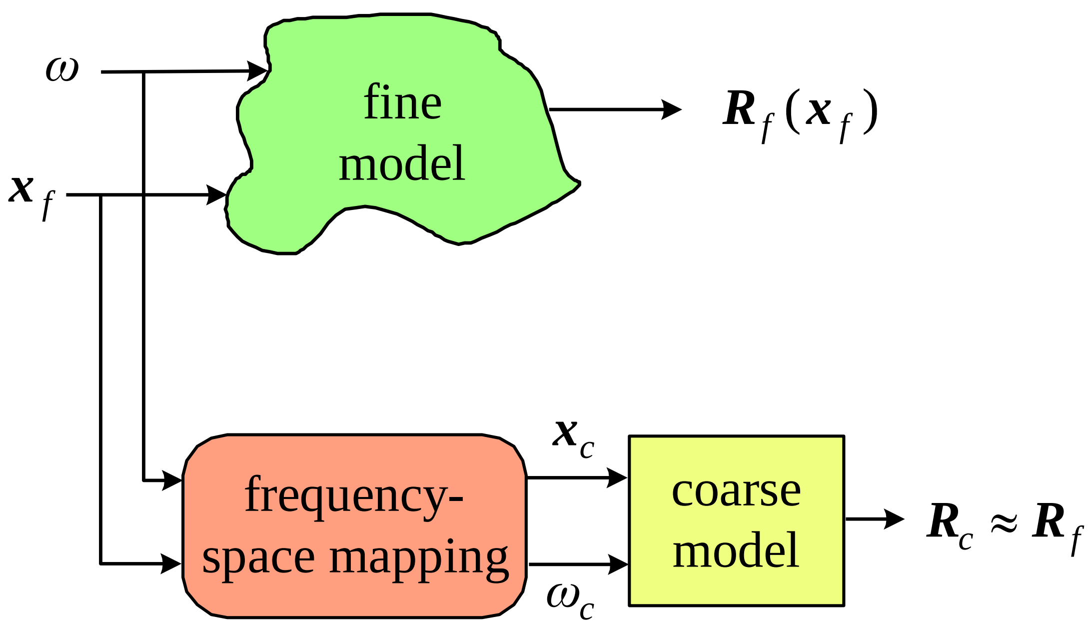
GSM exploits the Space Mapping (SM), the Frequency Space Mapping (FSM) *(Bandler et al., 1994)* and the Multiple Space Mapping (MSM) *(Bandler et al., 1998)* concepts to build a new engineering device modeling framework

two cases are considered: the basic Space Mapping Super Model (SMSM) concept and the Frequency-Space Mapping Super Model (FSMSM) concept

## Space Mapping Super Model (SMSM)

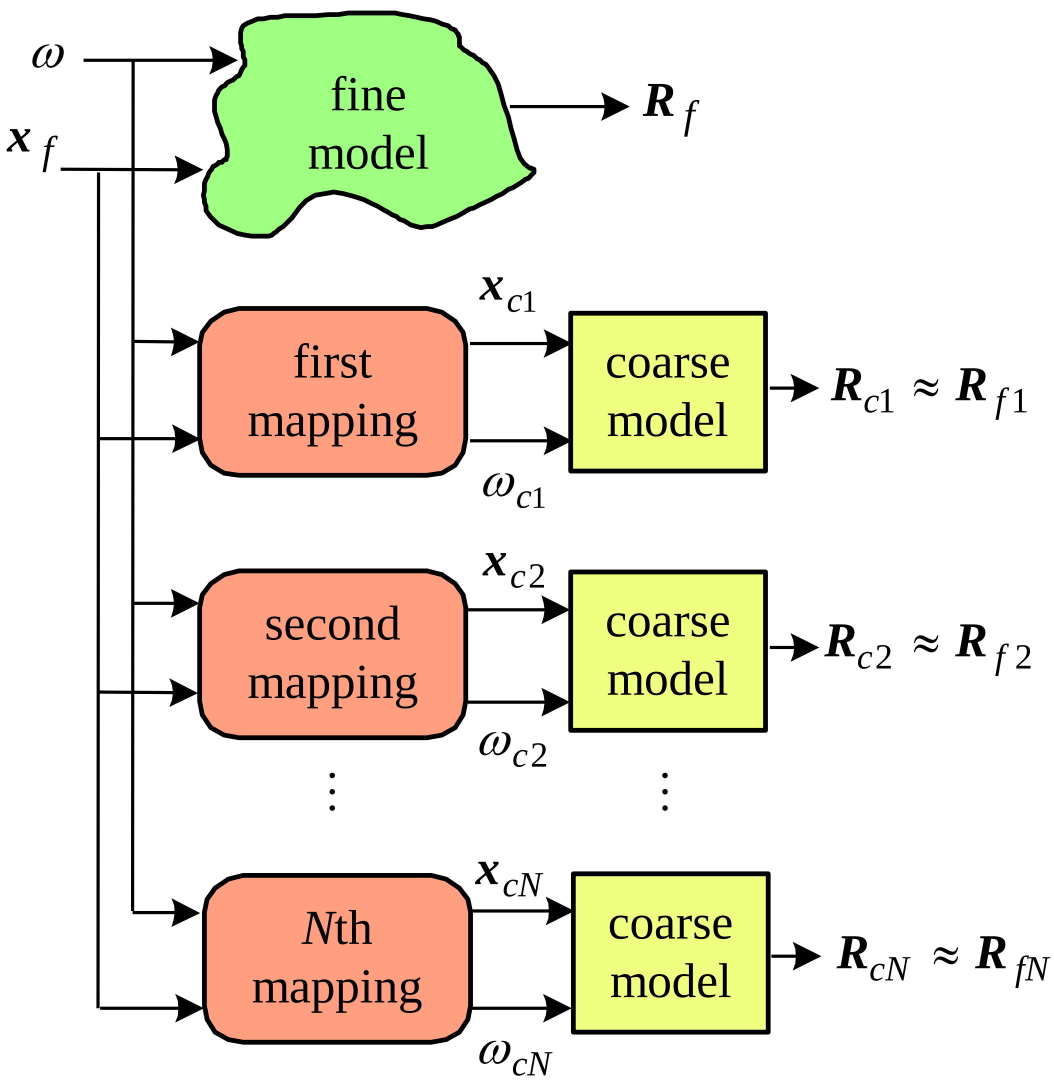



## Frequency-Space Mapping Super Model (FSMSM)



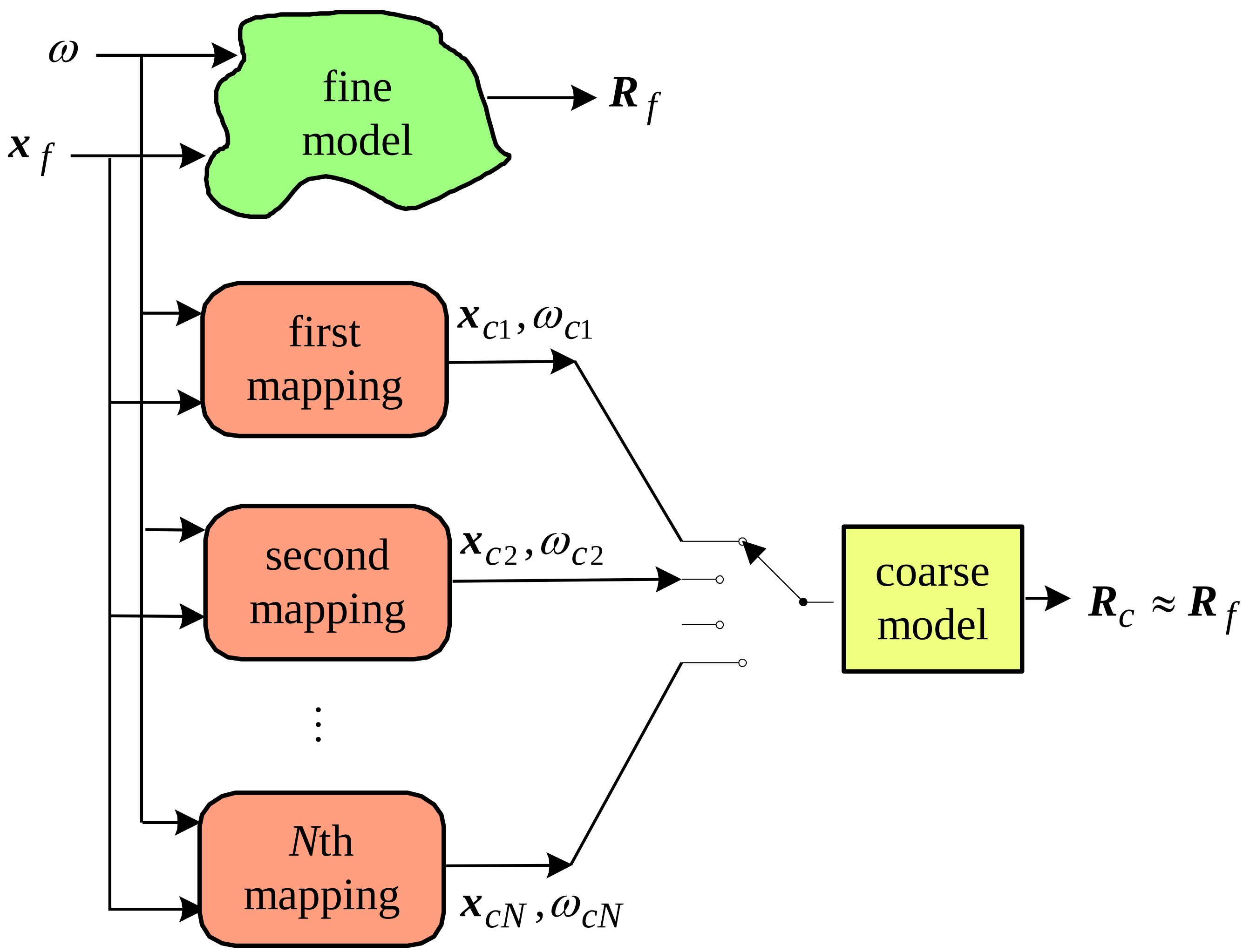
## Multiple Space Mapping (MSM) Concept

MSM for Device Responses (MSMDR)



## Multiple Space Mapping (MSM) Concept

MSM for Frequency Intervals (MSMFI)



## Mathematical Formulation for GSM

the $k$th mapping targeting the sub-response $\boldsymbol{R}_k$ or the response $\boldsymbol{R}$ in the $k$th frequency sub-range is given by

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

or, 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, directly or indirectly, 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

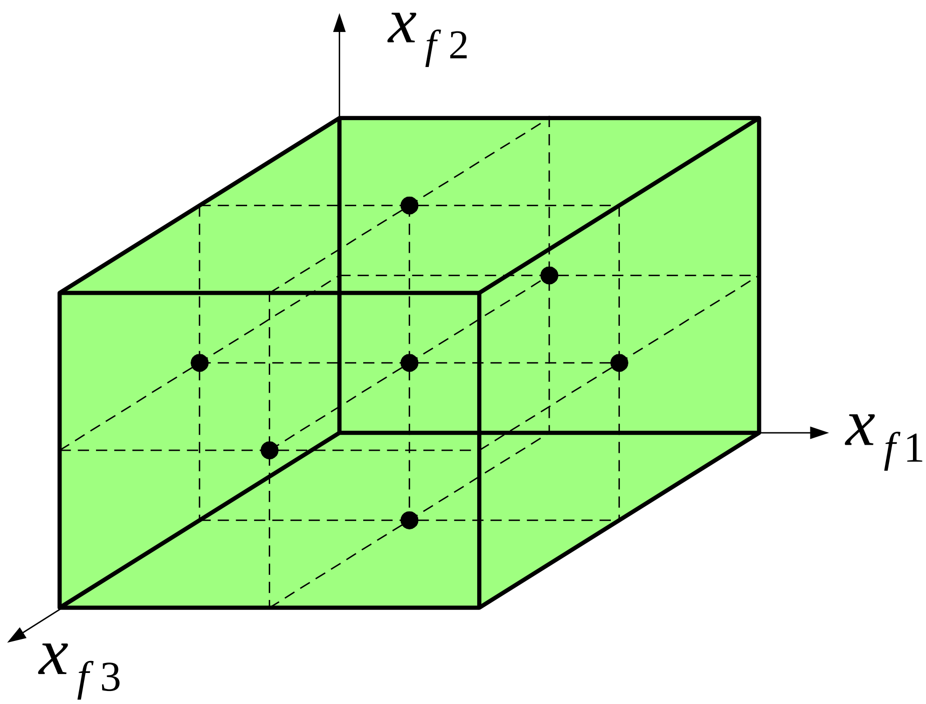
$$\boldsymbol{e}_{kj} = \boldsymbol{R}_f(\boldsymbol{x}_f^{(j)}, \omega) - \boldsymbol{R}_c(\boldsymbol{x}_{ck}^{(j)}, \omega_{ck}), \quad j = 1,2,\ldots,m$$

an important variation of the mapping is to use the inverse of the frequency variable (which is proportional to the wavelength) instead of the frequency itself

## Selection of the Base Points

the selection of the base points in the region of interest follows the star distribution *(Bandler et al., 1989)*

according to this distribution the number of base points for a microwave circuit with $n$ design parameters is $m = 2n + 1$



## An Implementation of SMSM and FSMSM

the SMSM or the FSMSM for the *k*th mapping can be evaluated through the following steps

select a set of *m* base points $\{\boldsymbol{x}_f^{(j)},\ j=1,2,\ldots,m\}$ in the region of interest (star distribution)

the mapping parameters in the SMSM are obtained by applying direct optimization to solve

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

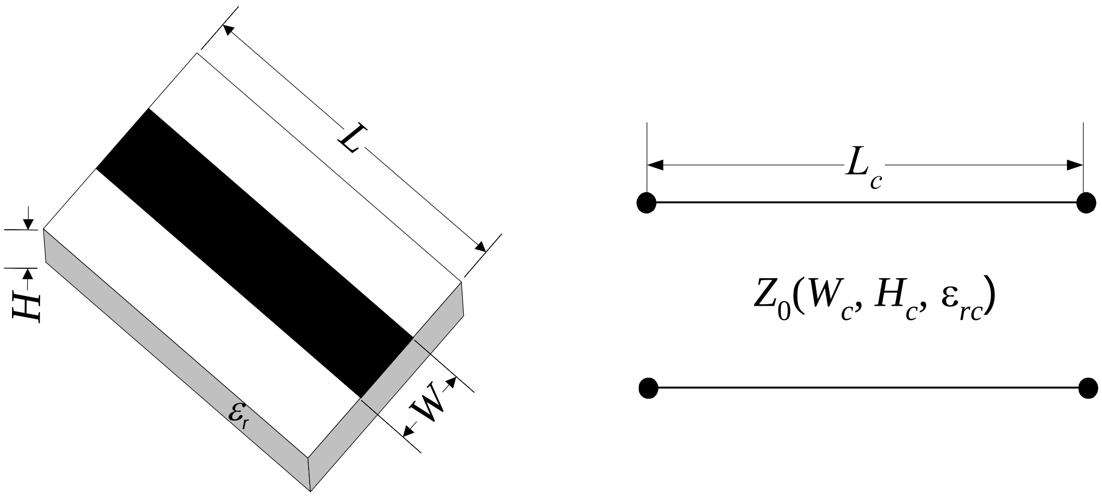
considering $\boldsymbol{s}_k = \boldsymbol{0},\quad \boldsymbol{t}_k = \boldsymbol{0},\quad \sigma_k = 1,\quad \delta_k = 0$

the mapping parameters in the FSMSM are obtained by applying direct optimization to solve

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

## Comparison between SMSM and FSMSM

## Microstrip Transmission Line




| Parameter | Minimum value | Maximum value |
|---|---|---|
| $W$ | 10 mil | 30 mil |
| $L$ | 40 mil | 60 mil |
| $H$ | 10 mil | 20 mil |
| $\varepsilon_r$ | 8 | 10 |

the frequency range is 20 GHz to 30 GHz

the number of base points is 9 and the number of test points is 50

## Microstrip Transmission Line

SMSM and FSMSM mapping parameters for the microstrip transmission line

| | SMSM | FSMSM |
|---|---|---|
| $\boldsymbol{B}$ | $\begin{bmatrix} 1.015 & -0.002 & -0.007 & -0.022 \\ -0.001 & 0.992 & 0.020 & 0.023 \\ -0.008 & 0.001 & 0.985 & 0.027 \\ 0.009 & -0.004 & 0.044 & 1.028 \end{bmatrix}$ | $\begin{bmatrix} 1.026 & -0.005 & 0.006 & -0.021 \\ -0.009 & 0.965 & -0.011 & 0.017 \\ -0.002 & 0.004 & 0.979 & 0.022 \\ 0.019 & -0.001 & 0.020 & 1.025 \end{bmatrix}$ |
| $\boldsymbol{c}$ | $[-0.011 \;\; -0.008 \;\; 0.012 \;\; -0.036]^T$ | $[-0.013 \;\; 0.001 \;\; 0.011 \;\; -0.010]^T$ |
| $\boldsymbol{s}$ | **0** (fixed) | $[-0.006 \;\; 0 \;\; 0.002 \;\; -0.002]^T$ |
| $\boldsymbol{t}$ | **0** (fixed) | **0** |
| $\sigma$ | 1 (fixed) | 1.035 |
| $\delta$ | 0 (fixed) | 0.001 |

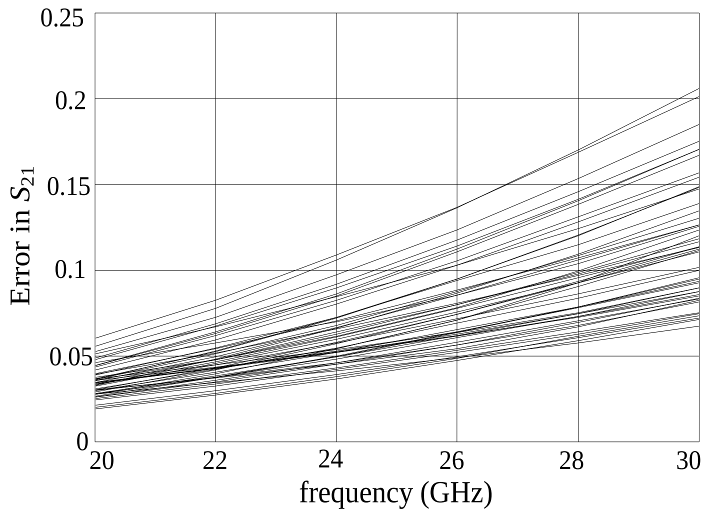
to display the results in a compact way we define the error in the scattering parameter $S_{ij}$ as the modulus of the difference between the scattering parameter $S_{ij}^f$ computed by the fine model and $S_{ij}^c$ computed by the coarse model

$$\text{error in } S_{ij} = \left| S_{ij}^f - S_{ij}^c \right|$$

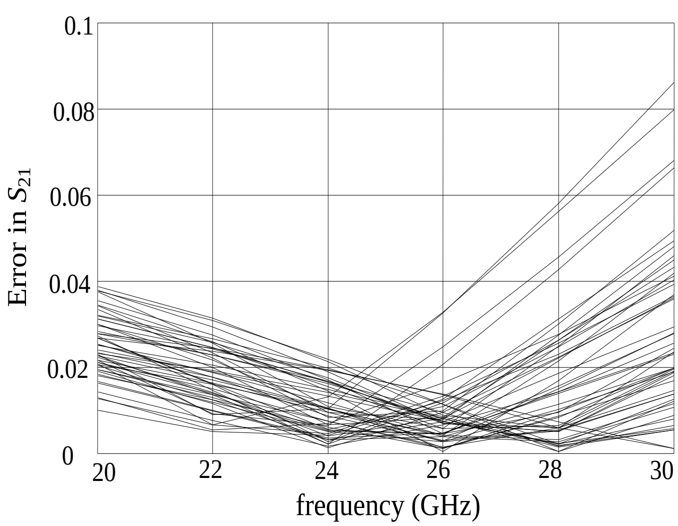
$$= \sqrt{(\text{Re}[S_{ij}^f] - \text{Re}[S_{ij}^c])^2 + (\text{Im}[S_{ij}^f] - \text{Im}[S_{ij}^c])^2}$$

# Microstrip Transmission Line

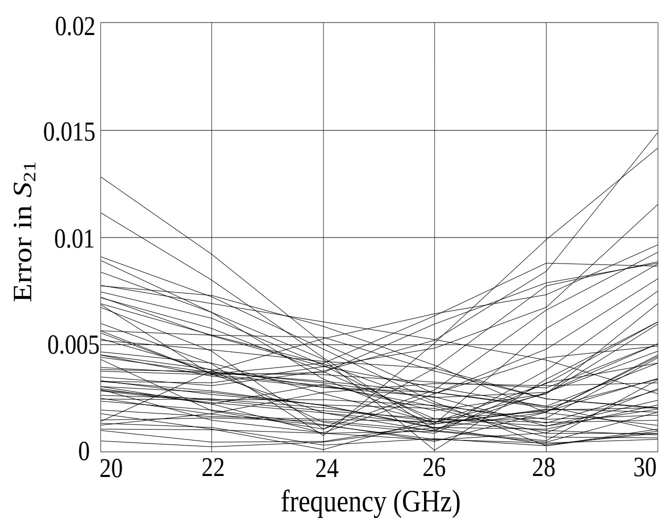
the error in $S_{21}$ at the test points




before applying any modeling technique

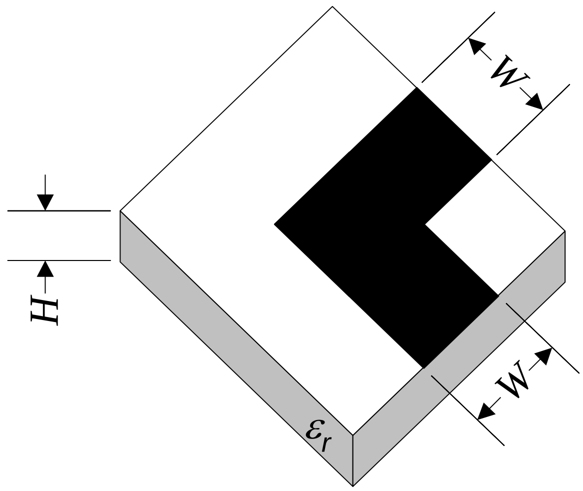



after applying SMSM




after applying FSMSM

## Microstrip Right Angle Bend




| Parameter | Minimum value | Maximum value |
|---|---|---|
| $W$ | 20 mil | 30 mil |
| $H$ | 8 mil | 16 mil |
| $\varepsilon_r$ | 8 | 10 |

the frequency range is 1 GHz to 41 GHz

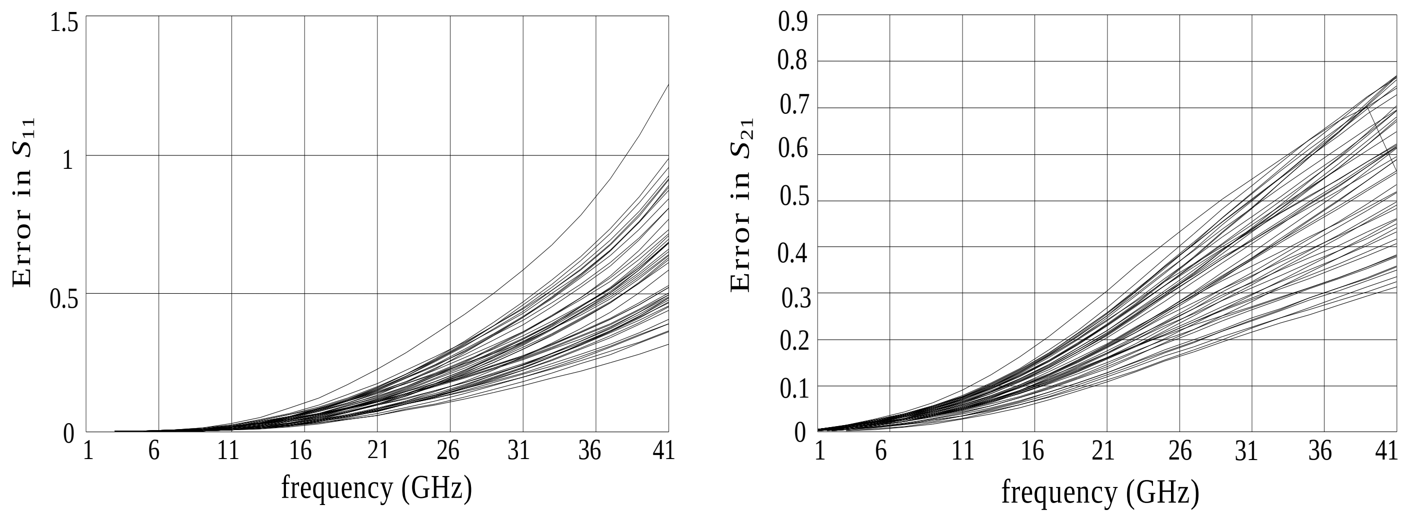
the number of base points is 7 and the number of test points is 50

the fine model is analyzed by Sonnet's ***em*** and the "coarse" model is a Jansen empirical model *(Jansen et al., 1983)*

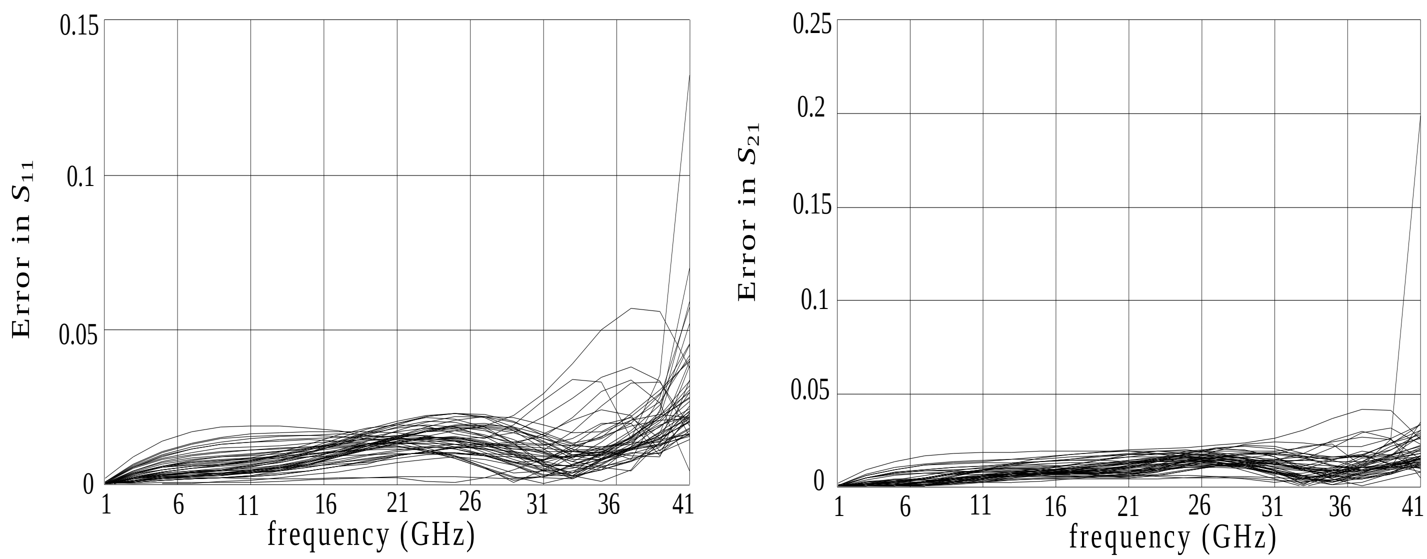
the FSMSM was developed to enhance the coarse model of the microstrip right angle bend

# Microstrip Right Angle Bend

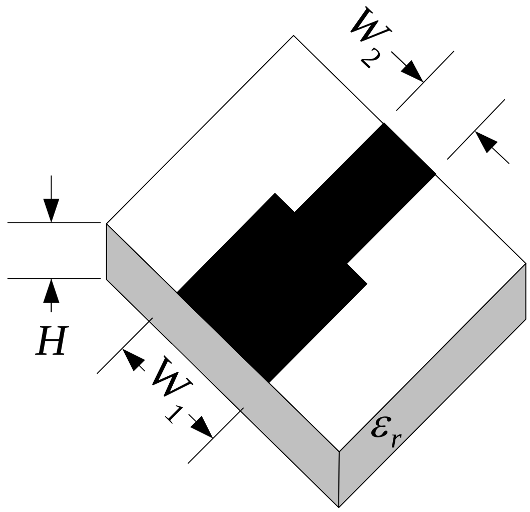
the error in $S_{11}$ and $S_{21}$ at the test points before applying FSMSM




the errors in $S_{11}$ and $S_{21}$ at the test points after applying FSMSM (mapping the inverse of the frequency variable)



## Microstrip Step Junction




| Parameter | Minimum value | Maximum value |
|---|---|---|
| $W_1$ | 20 mil | 40 mil |
| $W_2$ | 10 mil | 20 mil |
| $H$ | 10 mil | 20 mil |
| $\varepsilon_r$ | 8 | 10 |

the frequency range is 2 GHz to 40 GHz

the number of base points is 9 and the number of test points is 50

the fine model is analyzed by Sonnet's ***em*** and the coarse model is an element of OSA90/hope

## Microstrip Step Junction

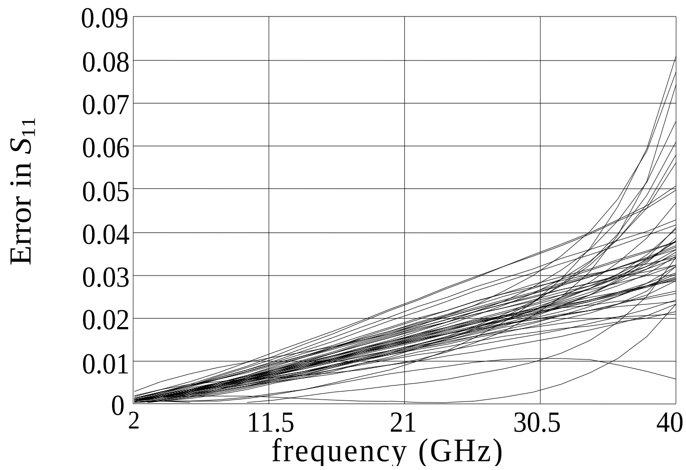
MSM for Device Responses (MSMDR) was developed to enhance the coarse model of the microstrip step junction

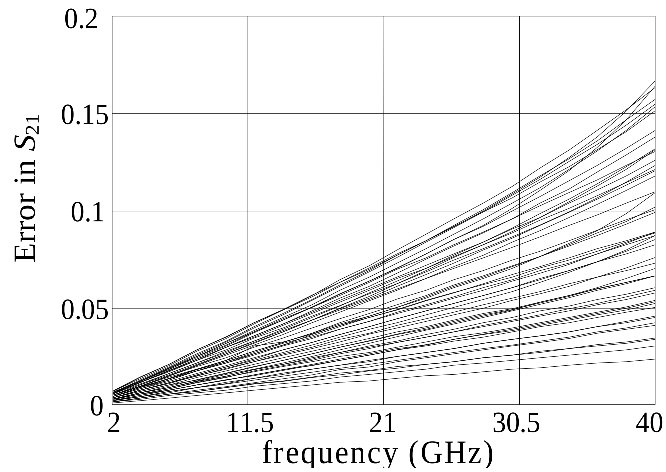
the mapping parameters for the microstrip step junction

| | Target responses are {Im[$S_{11}$], Im[$S_{21}$], Im[$S_{22}$], Re[$S_{21}$])} | Target responses are {Re[$S_{11}$], Re[$S_{22}$]} |
|---|---|---|
| $\boldsymbol{B}$ | $\begin{bmatrix} 0.764 & 0.033 & -0.062 & 0.074 \\ 0.191 & 0.632 & 0.255 & -0.502 \\ -0.023 & 0.116 & 1.485 & 0.018 \\ 0.676 & -0.365 & -0.111 & 0.177 \end{bmatrix}$ | $\begin{bmatrix} 3.071 & -0.008 & -0.010 & -0.004 \\ 0.008 & 0.202 & 0.032 & 0.004 \\ -0.001 & 0.001 & 1.152 & 0.000 \\ -0.077 & -0.118 & -0.002 & 1.241 \end{bmatrix}$ |
| $\boldsymbol{c}$ | $[\,0.002 \quad -0.002 \quad 0.002 \quad -0.006\,]^T$ | $[\,-0.001 \quad 0.001 \quad 0.000 \quad -0.003\,]^T$ |
| $\boldsymbol{s}$ | $[\,-0.003 \quad 0.004 \quad -0.001 \quad -0.002\,]^T$ | $\mathbf{0}$ |
| $\boldsymbol{t}$ | $[\,-0.001 \quad 0.000 \quad -0.005 \quad 0.000\,]^T$ | $[\,-0.001 \quad 0.000 \quad -0.007 \quad 0.003\,]^T$ |
| $\sigma$ | 1.546 | 5.729 |
| $\delta$ | 0.113 | 0.065 |

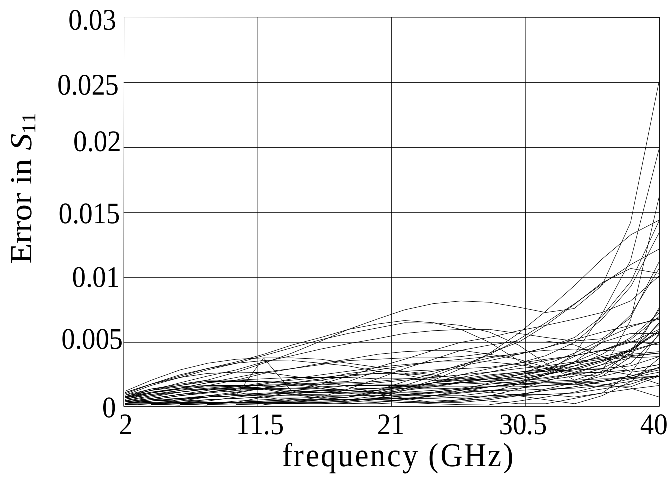
# Microstrip Step Junction

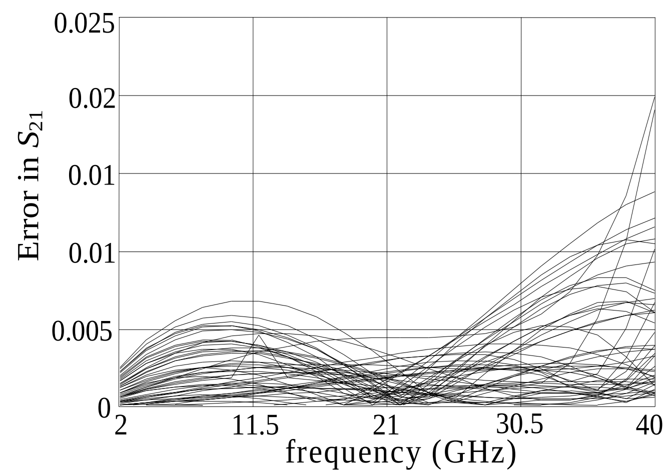
the error in $S_{11}$ and $S_{21}$ at the test points before applying (MSMDR)




the error in $S_{11}$ and $S_{21}$ at the test points after applying (MSMDR) (mapping the inverse of the frequency variable)

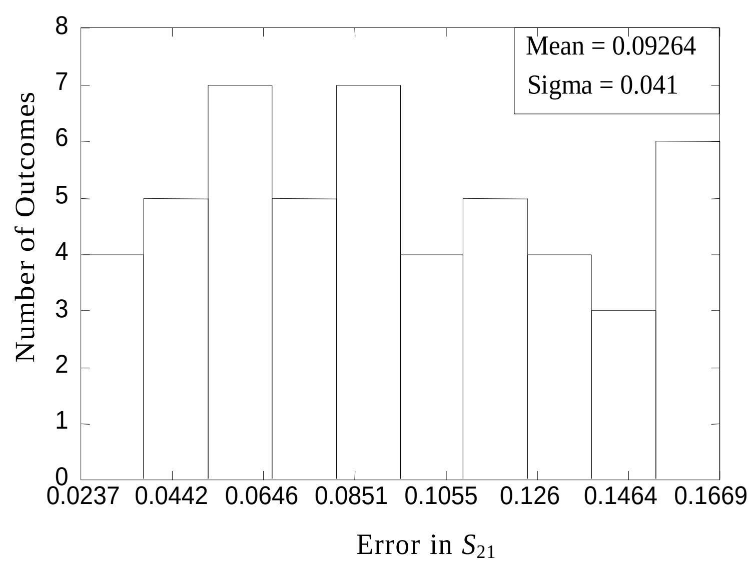


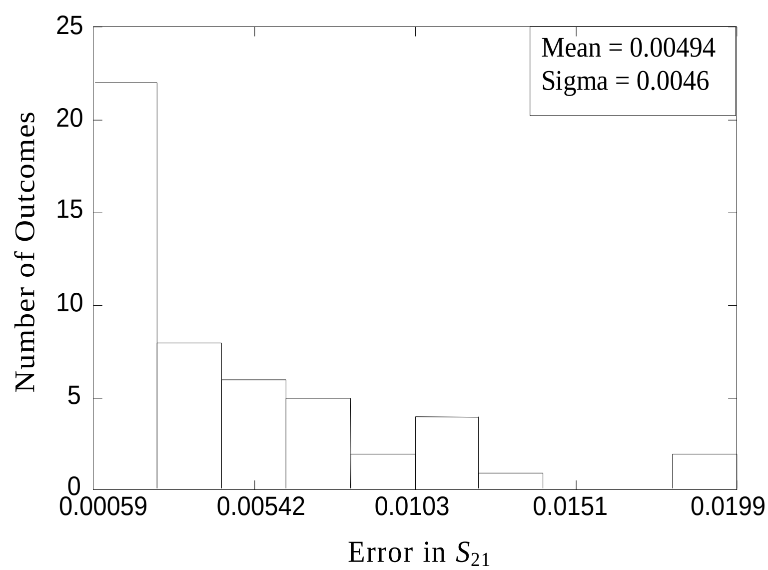
# Microstrip Step Junction

the histogram of the error in $S_{21}$ of the microstrip step junction for 50 points in the region of interest at 40 GHz

by the coarse model

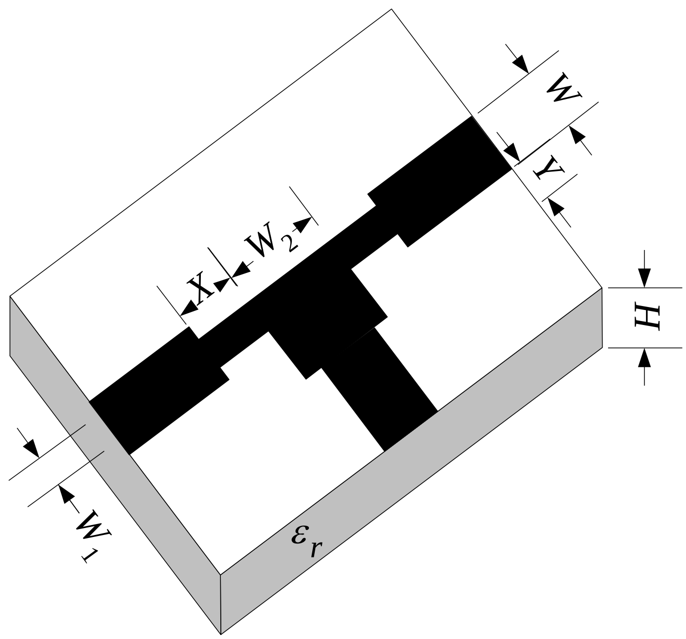


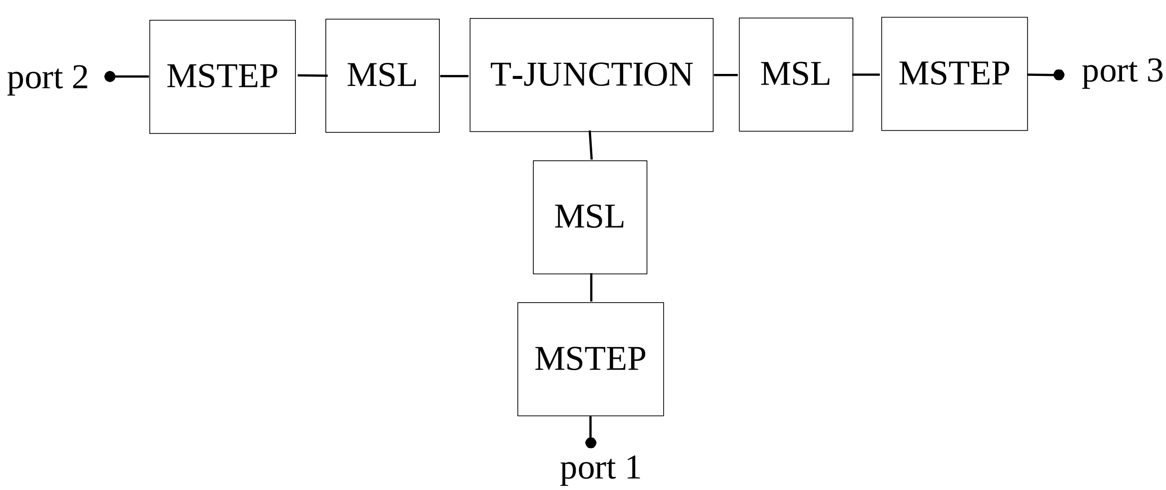

by the enhanced coarse model



# Microstrip Shaped T-Junction

the fine and coarse models



## Microstrip Shaped T-Junction

the region of interest

| Parameter | Minimum value | Maximum value |
|---|---|---|
| $H$ | 15 mil | 25 mil |
| $X$ | 5 mil | 15 mil |
| $Y$ | 5 mil | 15 mil |
| $\varepsilon_r$ | 8 | 10 |

the frequency range is 2 GHz to 20 GHz with a step of 2 GHz

the number of base points is 9 and the number of test points is 50

the width $W$ of the input lines is determined in terms of $H$ and $\varepsilon_r$ so that the characteristic impedance of the input lines is 50 ohm

the width $W_1$ is taken as 1/3 of the width $W$

the width $W_2$ is obtained so that the characteristic impedance of the microstrip line after the step connected to port 2 is twice that of the microstrip line after the step connected to port 1

# Microstrip Shaped T-Junction

MSM for Frequency Intervals (MSMFI) was developed to enhance the accuracy of the T-Junction coarse model

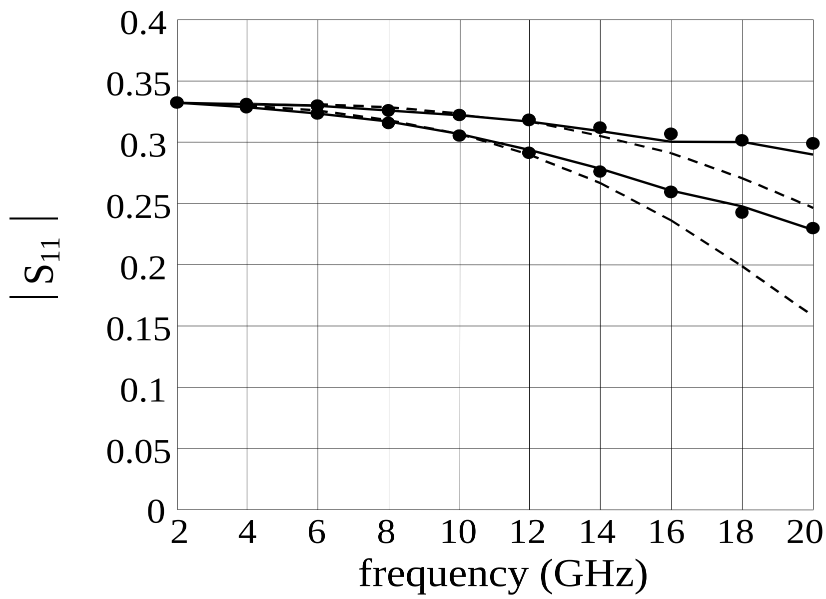
the total frequency range was divided into two intervals: 2 GHz to 16 GHz and 16 GHz to 20 GHz

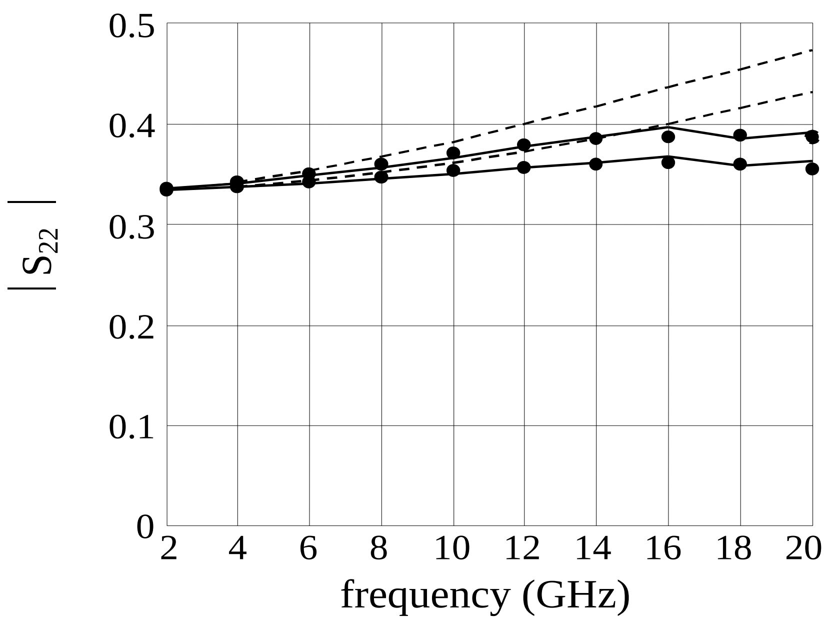
the mapping parameters are

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

## Microstrip Shaped T-Junction

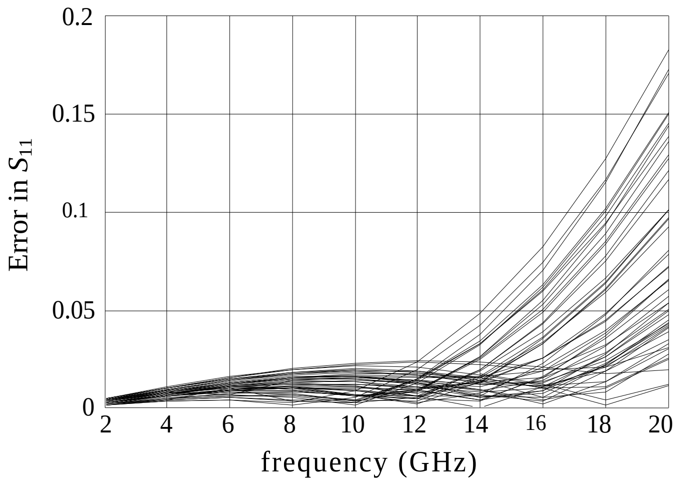
the responses of the shaped T-Junction at two test points in the region of interest by Sonnet's ***em*** (●), by the coarse model (---) and by the enhanced coarse model (—)

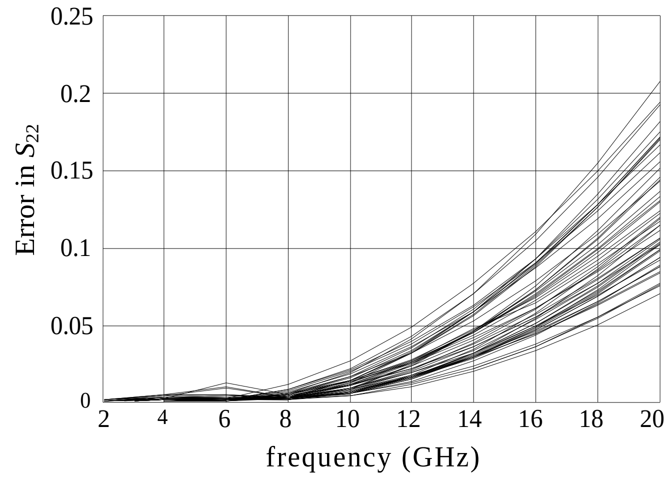


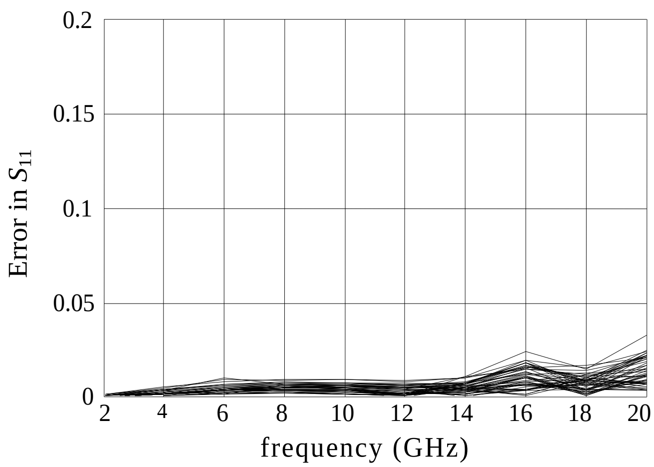
# Microstrip Shaped T-Junction

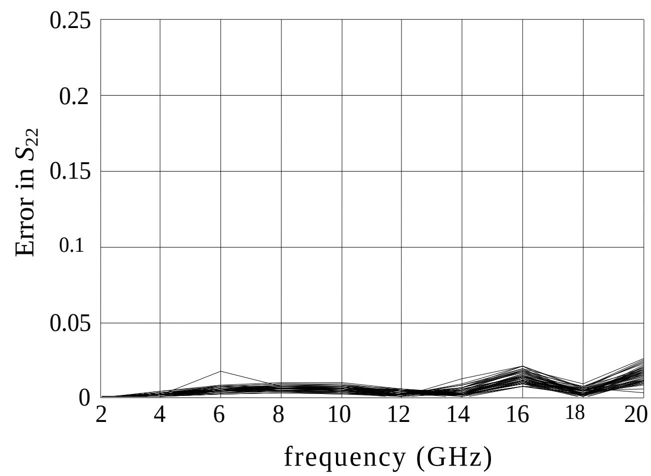
the error in $S_{11}$ and in $S_{22}$ of the shaped T-Junction coarse model at the test points




the error in $S_{11}$ and in $S_{22}$ of the shaped T-Junction enhanced coarse model at the test points



## Microstrip Shaped T-Junction

the enhanced coarse model for the shaped T-Junction can be utilized in optimization

the optimization variables are $X$ and $Y$

the other parameters are kept fixed ($W$ = 24 mil, $H$ = 25 mil and $\varepsilon_r = 9.9$)

the design specifications are

$$|S_{11}| \le 1/3, \quad |S_{22}| \le 1/3$$

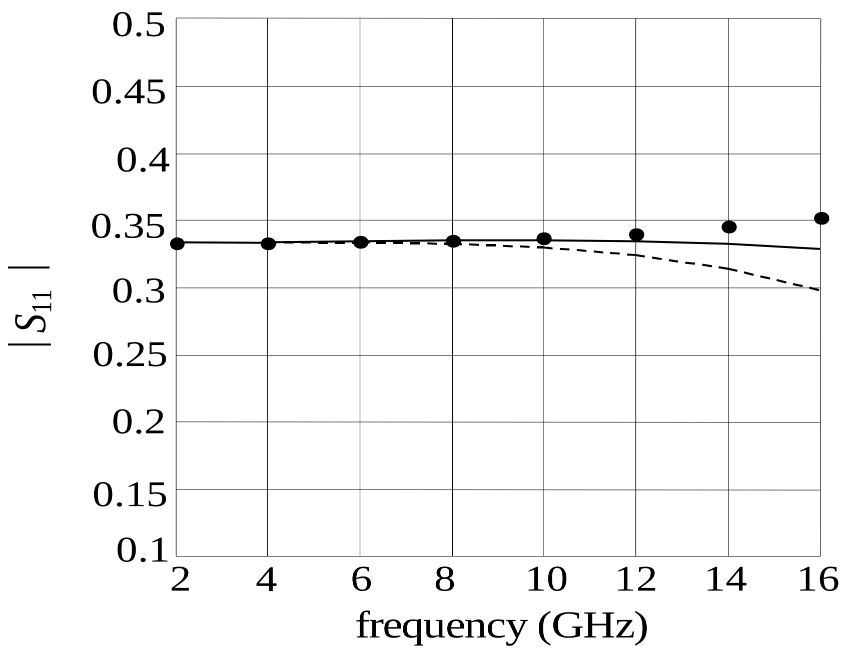
in the frequency range 2 GHz to 16 GHz

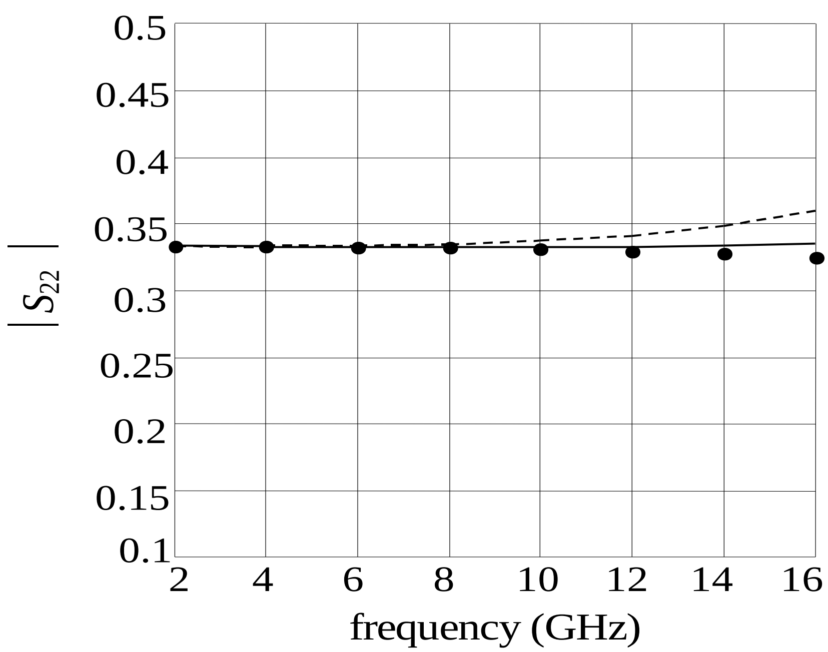
the minimax optimizer in OSA90/hope reached the solution

$$X = 2.1 \text{ mil and } Y = 21.1 \text{ mil}$$

## Microstrip Shaped T-Junction

responses of the optimum shaped T-Junction by Sonnet's ***em*** (●), by the coarse model (---) and by the enhanced coarse model (—)



## Conclusions

we introduce a comprehensive framework called Generalized Space mapping (GSM) to engineering device modeling

in GSM we utilize a few relevant full-wave EM simulations to match the responses of the fine model and the coarse model over a designable region of parameters and frequency

GSM generalizes the Space Mapping (SM), the Frequency Space Mapping (FSM) and the Multiple Space Mapping (MSM) concepts to build a new engineering device modeling framework

two fundamental concepts are presented: one is a basic Space Mapping Super Model (SMSM) and the other is a basic Frequency-Space Mapping Super Model (FSMSM)

MSM can be combined with SMSM and FSMSM to provide a powerful and reliable modeling tool for microwave devices

## Recent Work

J.W. Bandler, R.M. Biernacki, S.H. Chen and Q.H. Wang, "Multiple space mapping EM optimization of signal integrity in high-speed digital circuits," *Proc. 5th Int. Workshop on Integrated Nonlinear Microwave and Millimeterwave Circuits* (Duisburg, Germany), 1998, pp. 138-140.

J.W. Bandler, M.A. Ismail, J.E. Rayas-Sánchez and Q.J. Zhang, "Neuromodeling of microwave circuits exploiting space mapping technology," *IEEE MTT-S Int. Microwave Symp. Digest* (Anaheim, CA), 1999, pp. 149-152.

J.W. Bandler, M.A. Ismail, J.E. Rayas-Sánchez and Q.J. Zhang, "Neuromodeling of microwave circuits exploiting space mapping technology," *IEEE Trans. Microwave Theory Tech.*, vol. 47, 1999.

J.W. Bandler and J.E. Rayas-Sánchez, "Circuit CAD and modeling through space mapping," *IEEE MTT-S Int. Microwave Symp.*, Workshop WSFD (Anaheim, CA), 1999.

J.W. Bandler, M.A. Ismail, J.E. Rayas-Sánchez and Q.J. Zhang, "New directions in model development for RF/microwave components utilizing artificial neural networks and space mapping," *IEEE AP-S Int. Symp. Digest* (Orlando, FL), 1999, pp. 2572-2575.