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EM-based Design Optimization of RF and Microwave Circuits using Functional Surrogate Models

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Abstract

An effective CAD methodology to perform efficient EM-based design optimization of microwave circuits using surrogate models based on polynomial functional interpolants is described. This surrogate-driven design procedure is especially suitable for cases where a continuous coarse model is not available. The corresponding surrogate models are formulated as low-order functions of the design variables, and are used to interpolate highly accurate electromagnetic responses in a region of interest around a selected reference design. Global optimal values for the surrogate model weighting factors are efficiently obtained in closed form, using compact formulas. Exhaustive evaluation of the generalization performance of this surrogate modeling approach is addressed. The proposed CAD methodology is illustrated using commercially available EM simulators Sonnet and CST Microwave Studio for the design optimization of several high-speed PCB interconnect structures.

Outline

- Surrogate modeling
- Surrogate modeling using polynomial interpolants
- Generalization performance of polynomial surrogates
- Surrogate-driven optimization of an SIW-CPW transition
- Surrogate-driven optimization of microstrip traces with via fences
- Conclusions

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Surrogate Modeling

- Design optimization of microwave circuits requires accurate and inexpensive models
- Surrogate models were proposed for efficient and accurate optimization of expensive functions (fine models)
- Surrogate modeling refers to the iterative construction of functional relationships based on a limited amount of fine model data with no derivatives information

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Surrogate Modeling using Polynomials

- It takes as a basis a "zero-order" model:
  - Fixed fine model response, or
  - Input-mapped coarse model
- Multidimensional polynomials enhance the zero-order model around a reference design
- Closed-form expression are used to calculate the functional weighting factors (globally optimal)
- It uses a limited amount fine model data

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Fine, Coarse and Surrogate Models

- $\boldsymbol{R}_{\mathrm{f}} \in \Re^p$: fine model response sampled at p independent-variable points; evaluating $\boldsymbol{R}_{\mathrm{f}}(\boldsymbol{x})$ is expensive
- $\boldsymbol{x} \in \Re^n$: design variables
- $\boldsymbol{R}_{\mathrm{c}} \in \Re^p$: coarse model response; evaluating $\boldsymbol{R}_{\mathrm{c}}(\boldsymbol{x})$ is inexpensive
- We want a surrogate model $\boldsymbol{R}_{\mathrm{s}}(\boldsymbol{x}) : X_{\mathrm{s}} \rightarrow \Re^p$ such that $\boldsymbol{R}_{\mathrm{s}}(\boldsymbol{x}) \approx \boldsymbol{R}_{\mathrm{f}}(\boldsymbol{x})$ in a region X_{s} around $\boldsymbol{x}^{(0)}$
- To "train" the surrogate model, we use L learning points, denoted as $\boldsymbol{x}^{(1)}, \boldsymbol{x}^{(2)}, \ldots, \boldsymbol{x}^{(L)}$
- To test the surrogate model we use T testing points

(*Bandler et al., 2000*)

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"Zero-Order" Models

- Fixed fine model response

$$\boldsymbol{R}_s^{(0)}(\boldsymbol{x}) = \boldsymbol{R}_f(\boldsymbol{x}^{(0)}) \quad \text{for all } \boldsymbol{x} \in X_s$$

- Linearly input mapped coarse model

$$\boldsymbol{R}_s^{(0)}(\boldsymbol{x}) = \boldsymbol{R}_c(\boldsymbol{B}\boldsymbol{x} + \boldsymbol{c}) \quad \text{for all } \boldsymbol{x} \in X_s$$

where $\boldsymbol{B} \in \Re^{n\times n}$ and $\boldsymbol{c} \in \Re^n$

- Linear input mapped coarse model with local output correction

$$\boldsymbol{R}_s^{(0)}(\boldsymbol{x}) = \boldsymbol{R}_c(\boldsymbol{B}\boldsymbol{x} + \boldsymbol{c}) + \boldsymbol{d} \quad \text{for all } \boldsymbol{x} \in X_s$$

where $\boldsymbol{d} \in \Re^p$

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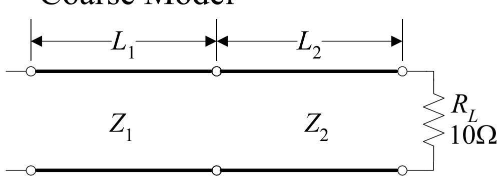
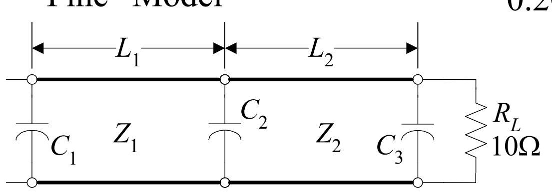
"Zero-Order" Models – Example

Coarse Model



"Fine" Model



$C_1 = C_2 = C_3 = 10\text{pF}$
$Z_1 = 2.23615\Omega$, $Z_2 = 4.47230\Omega$

$\boldsymbol{x} = [L_1 \;\; L_2]^T$
(electrical lengths at 1GHz, in degrees)
$\boldsymbol{x}^{(0)} = [74.14 \quad 79.64]^T$

$\boldsymbol{R}_f \in \Re^p$ is $|S_{11}|$ for $0.2\text{GHz} \le f \le 1.8\text{GHz}$, $p = 300$

Two cases:
$\boldsymbol{R}_s^{(0)}(\boldsymbol{x}) = \boldsymbol{R}_f(\boldsymbol{x}^{(0)})$
$\boldsymbol{R}_s^{(0)}(\boldsymbol{x}) = \boldsymbol{R}_c(\boldsymbol{B}\boldsymbol{x} + \boldsymbol{c}) + \boldsymbol{d}$
($\boldsymbol{B}$ and $\boldsymbol{c}$ obtained after a BBSM)

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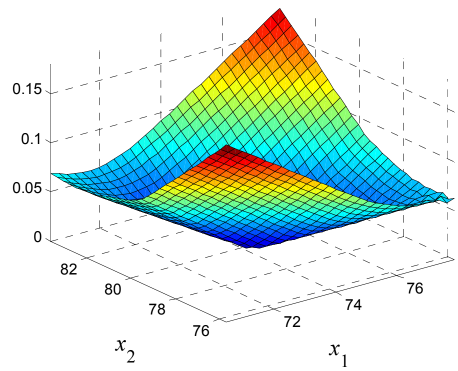
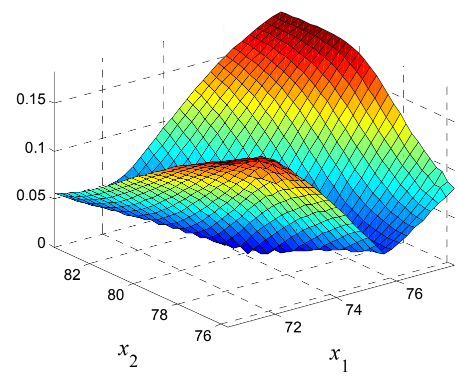
"Zero-Order" Models – Example (cont)

Region of interest around $\boldsymbol{x}^{(0)}$: ±5% deviation for L_1 and L_2

Maximum absolute errors for $\boldsymbol{R}_s^{(0)}(\boldsymbol{x})$





$$\boldsymbol{R}_s^{(0)}(\boldsymbol{x}) = \boldsymbol{R}_f(\boldsymbol{x}^{(0)}) \qquad \boldsymbol{R}_s^{(0)}(\boldsymbol{x}) = \boldsymbol{R}_c(\boldsymbol{B}\boldsymbol{x} + \boldsymbol{c}) + \boldsymbol{d}$$

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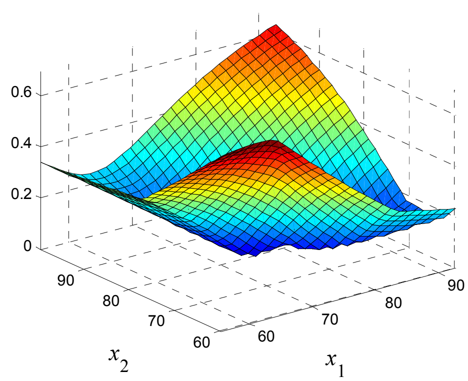
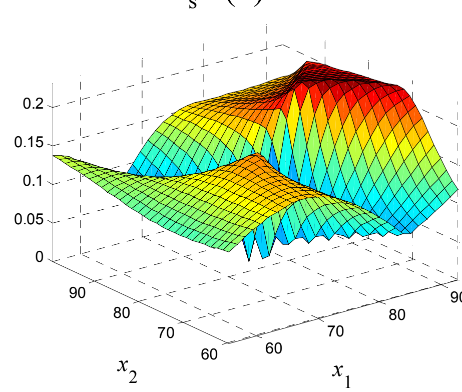
"Zero-Order" Models – Example (cont)

Region of interest around $\boldsymbol{x}^{(0)}$: ±25% deviation for L_1 and L_2

Maximum absolute errors for $\boldsymbol{R}_s^{(0)}(\boldsymbol{x})$





$$\boldsymbol{R}_s^{(0)}(\boldsymbol{x}) = \boldsymbol{R}_f(\boldsymbol{x}^{(0)}) \qquad \boldsymbol{R}_s^{(0)}(\boldsymbol{x}) = \boldsymbol{R}_c(\boldsymbol{B}\boldsymbol{x} + \boldsymbol{c}) + \boldsymbol{d}$$

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First-Order Surrogate Model

$$\boldsymbol{R}_{\mathrm{s}}^{(1)}(\boldsymbol{x}) = \boldsymbol{R}_{\mathrm{s}}^{(0)}(\boldsymbol{x}) + \boldsymbol{W}^{(1)}(\boldsymbol{x} - \boldsymbol{x}^{(0)}) \qquad \text{for all } \boldsymbol{x} \in X_{\mathrm{s}}$$

where $\boldsymbol{W}^{(1)} \in \Re^{p \times n}$ contains all the weighting factors,

$$\boldsymbol{W}^{(1)} = \boldsymbol{\Delta R}^{(0)} (\boldsymbol{\Delta x}^{(1)})^{+}$$

where $(\cdot)^{+}$ denotes the pseudo-inverse, and $\boldsymbol{\Delta x}^{(1)} \in \Re^{n \times L}$ and $\boldsymbol{\Delta R}^{(0)} \in \Re^{p \times L}$ are

$$\boldsymbol{\Delta x}^{(1)} = \begin{bmatrix} (\boldsymbol{x}^{(1)} - \boldsymbol{x}^{(0)}) \\ (\boldsymbol{x}^{(2)} - \boldsymbol{x}^{(0)}) \\ \vdots \\ (\boldsymbol{x}^{(L)} - \boldsymbol{x}^{(0)}) \end{bmatrix}^{\mathrm{T}}, \quad \boldsymbol{\Delta R}^{(0)} = \begin{bmatrix} \boldsymbol{R}_{\mathrm{f}}(\boldsymbol{x}^{(1)}) - \boldsymbol{R}_{\mathrm{s}}^{(0)}(\boldsymbol{x}^{(1)}) \\ \boldsymbol{R}_{\mathrm{f}}(\boldsymbol{x}^{(2)}) - \boldsymbol{R}_{\mathrm{s}}^{(0)}(\boldsymbol{x}^{(2)}) \\ \vdots \\ \boldsymbol{R}_{\mathrm{f}}(\boldsymbol{x}^{(L)}) - \boldsymbol{R}_{\mathrm{s}}^{(0)}(\boldsymbol{x}^{(L)}) \end{bmatrix}^{\mathrm{T}}$$

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Second-Order Surrogate Model

$$\boldsymbol{R}_{\mathrm{s}}^{(2)}(\boldsymbol{x}) = \boldsymbol{R}_{\mathrm{s}}^{(0)}(\boldsymbol{x}) + \boldsymbol{W}^{(1)}(\boldsymbol{x} - \boldsymbol{x}^{(0)}) + \begin{bmatrix} \vdots \\ (\boldsymbol{x} - \boldsymbol{x}^{(0)})^{\mathrm{T}} \boldsymbol{W}_k^{(2)} (\boldsymbol{x} - \boldsymbol{x}^{(0)}) \\ \vdots \end{bmatrix}$$

$\boldsymbol{W}_k^{(2)} \in \Re^{n \times n}$ has the weighting factors for the k-th independent variable sample

$$\boldsymbol{w}_k = (\boldsymbol{\Delta X})^{+} \boldsymbol{\Delta R}_k^{(0)} \qquad \text{for } k = 1 \ldots p$$

where vector $\boldsymbol{w}_k$ contains the rows of $\boldsymbol{W}^{(1)}$ and all the columns of $\boldsymbol{W}_k^{(2)}$,

$$\boldsymbol{w}_k = [\boldsymbol{w}_k^{(1)} \quad \boldsymbol{w}_{k1}^{(2)} \quad \boldsymbol{w}_{k2}^{(2)} \quad \ldots \quad \boldsymbol{w}_{kn}^{(2)}]^{\mathrm{T}} \in \Re^{(n^2+n)}$$

and

$$\boldsymbol{\Delta X} = [\boldsymbol{\Delta x}^{(1)^{\mathrm{T}}} \quad \boldsymbol{\Delta X}^{(2)}] \in \Re^{L \times (n^2+n)}$$

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Second-Order Surrogate Model (cont.)

$$\boldsymbol{\Delta X}^{(2)} = \begin{bmatrix} (x_1^{(1)} - x_1^{(0)})(\boldsymbol{x}^{(1)} - \boldsymbol{x}^{(0)})^{\mathrm{T}} & \cdots & (x_n^{(1)} - x_n^{(0)})(\boldsymbol{x}^{(1)} - \boldsymbol{x}^{(0)})^{\mathrm{T}} \\ \vdots & \ddots & \vdots \\ (x_1^{(L)} - x_1^{(0)})(\boldsymbol{x}^{(L)} - \boldsymbol{x}^{(0)})^{\mathrm{T}} & \cdots & (x_n^{(L)} - x_n^{(0)})(\boldsymbol{x}^{(L)} - \boldsymbol{x}^{(0)})^{\mathrm{T}} \end{bmatrix}$$

$$\boldsymbol{\Delta X}^{(2)} \in \Re^{L \times n^2}$$

$$\boldsymbol{\Delta R}_k^{(0)} = \begin{bmatrix} R_{\mathrm{f}k}(\boldsymbol{x}^{(1)}) - R_{\mathrm{s}k}^{(0)}(\boldsymbol{x}^{(1)}) \\ R_{\mathrm{f}k}(\boldsymbol{x}^{(2)}) - R_{\mathrm{s}k}^{(0)}(\boldsymbol{x}^{(2)}) \\ \vdots \\ R_{\mathrm{f}k}(\boldsymbol{x}^{(L)}) - R_{\mathrm{s}k}^{(0)}(\boldsymbol{x}^{(L)}) \end{bmatrix} \in \Re^{L}$$

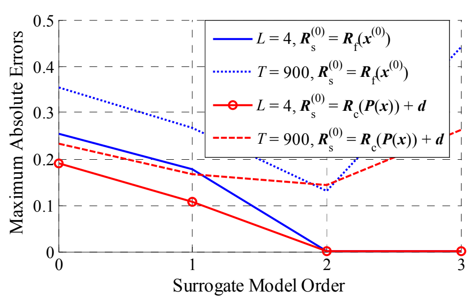
We have generalized this formulation for an N-th order surrogate model

Impedance Transformer Example

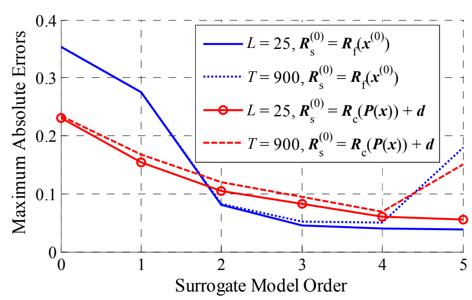
Errors in learning and testing sets for the surrogate models

Region of interest around $\boldsymbol{x}^{(0)}$: ±10% deviation for L_1 and L_2

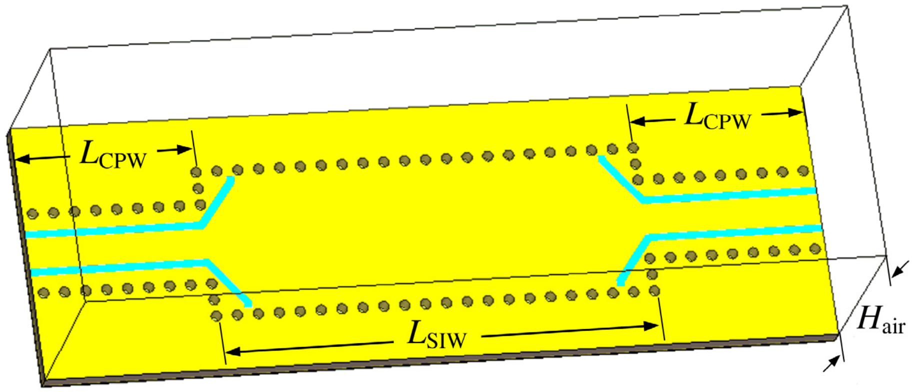
Small learning set



Large learning set



SIW Interconnect with CBCPW Transitions

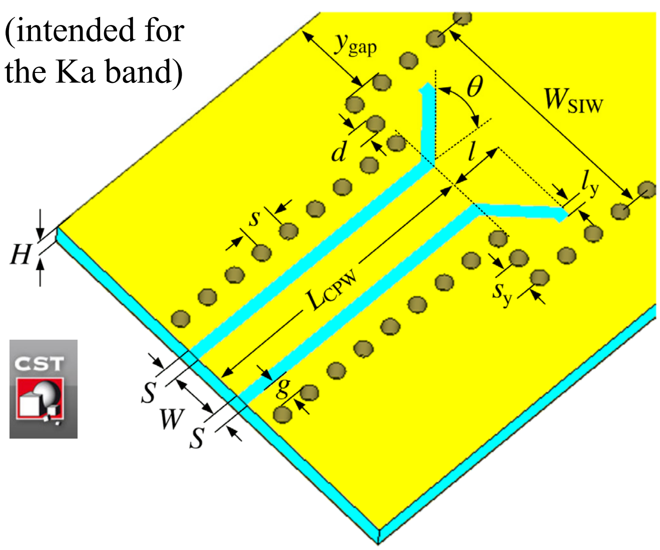


L_{SIW} = 12.6 mm, L_{CPW} = 5.1 mm
H = 20 mil, ε_r = 2.94, tan δ = 0.0012 at 10 GHz
$\sigma_{Cu} = 5.8 \times 10^7$ S/m, t = 0.65 mil

(*Chen and Wu, 2009*)

SIW to CBCPW Transition – Detailed View

(intended for the Ka band)

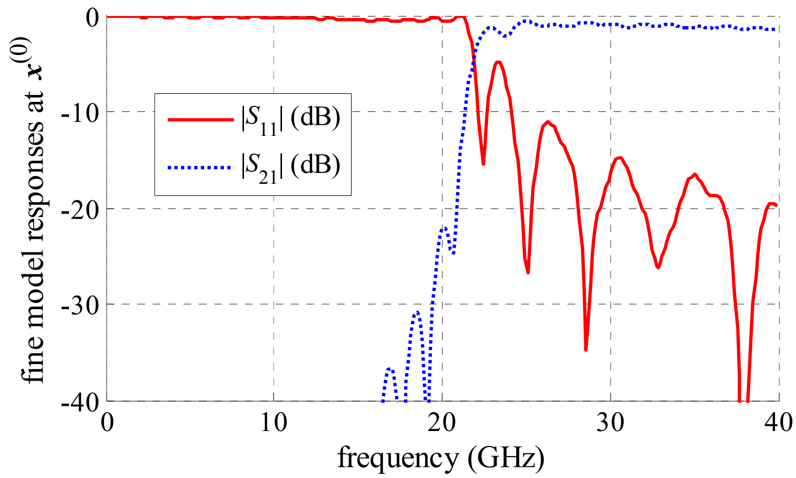


W_{SIW} = 4.3 mm
W = 0.9 mm
S = 0.2262 mm
g = 0.358 mm
d = 0.3 mm
s = 2d
s_y = 0.4085 mm
l_y = 0.2 mm
y_{gap} = 1.66 mm

Initially,
θ = 45°
l = 1 mm

(*Chen and Wu, 2009*)

Initial Fine Model Responses



Simulation time: 34.2 min
(Dual core Xeon 5160 at 3GHz and 4GB RAM)

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Surrogate Model of the SIW-CBCPW

- We select $\boldsymbol{x} = [\theta\,(\text{degrees}) \quad l\,(\text{mm})]^T$
- $\boldsymbol{x}^{(0)} = [45 \quad 1]^T$
- $\boldsymbol{R}_s^{(0)}(\boldsymbol{x}) = \boldsymbol{R}_f(\boldsymbol{x}^{(0)})$
- Region of interest around $\boldsymbol{x}^{(0)}$: ±15% deviation for θ and ±5% deviation for l
- We use 8 learning base points
- We use 10 random test points

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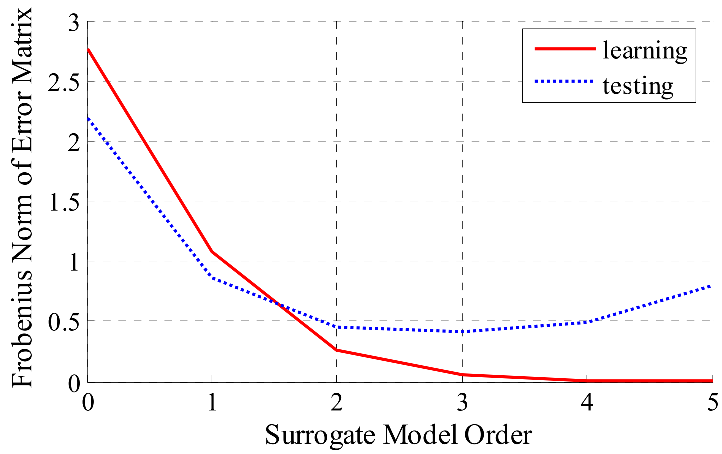
Surrogate Model of the SIW-CBCPW (cont)

Errors in learning and testing sets for the surrogate models of $|S_{11}|$



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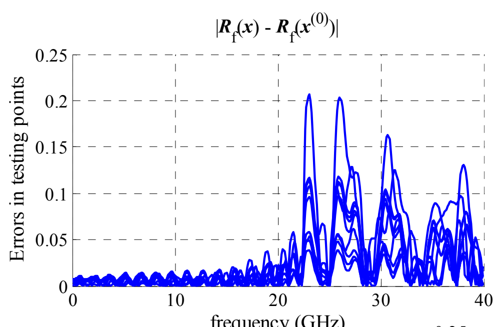
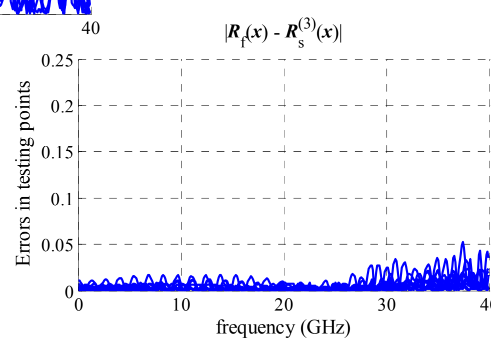
Surrogate Model of the SIW-CBCPW (cont)



Absolute errors in $|S_{11}|$ at testing base points



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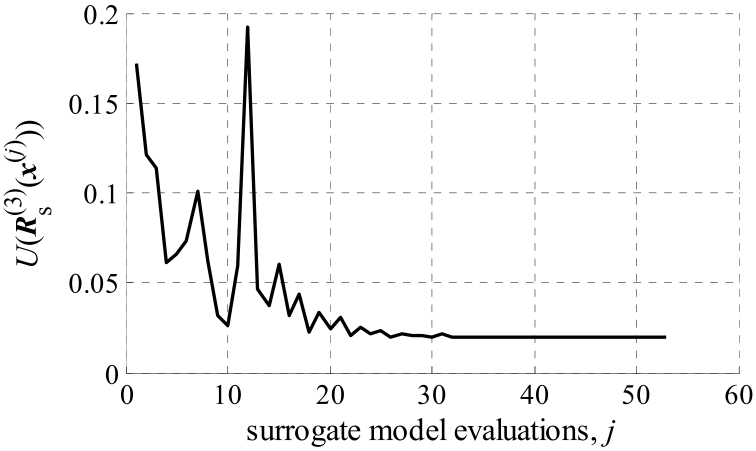
Optimizing the SIW-CBCPW Surrogate

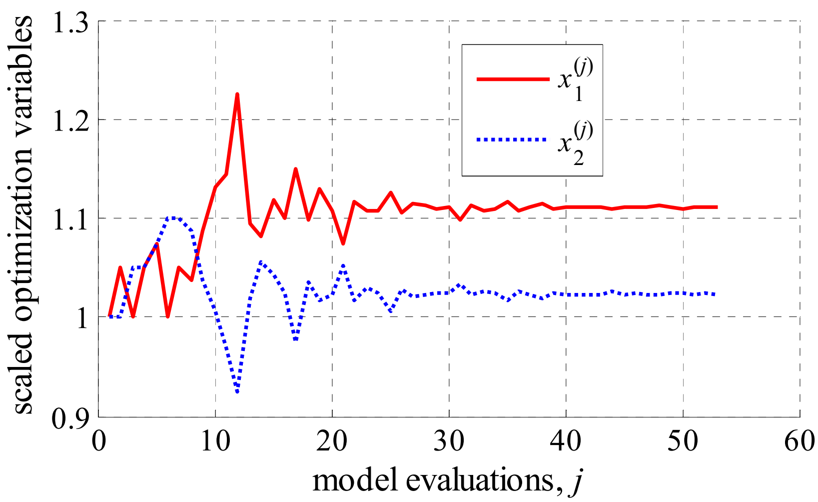
We optimize $\boldsymbol{R}_s^{(3)}(\boldsymbol{x})$ to minimize $|S_{11}|$ in the Ka band



Optimization time: 2.9 seconds; Model evaluations: 53

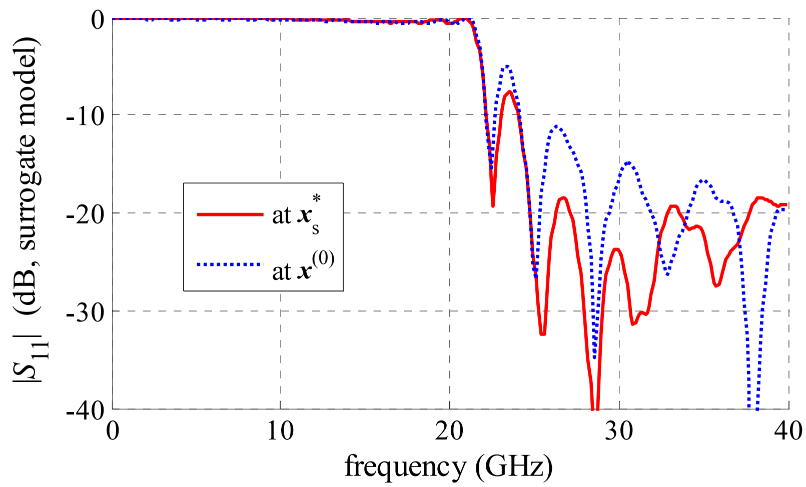
Optimizing the SIW-CBCPW Surrogate (cont)

$$\boldsymbol{x}_s^* = [49.994 \quad 1.023]^T$$



Optimizing the SIW-CBCPW Surrogate (cont)

$x^{(0)} = [45 \quad 1]^T \qquad x_s^* = [49.994 \quad 1.023]^T$



(Ka band: 26.5-40 GHz)

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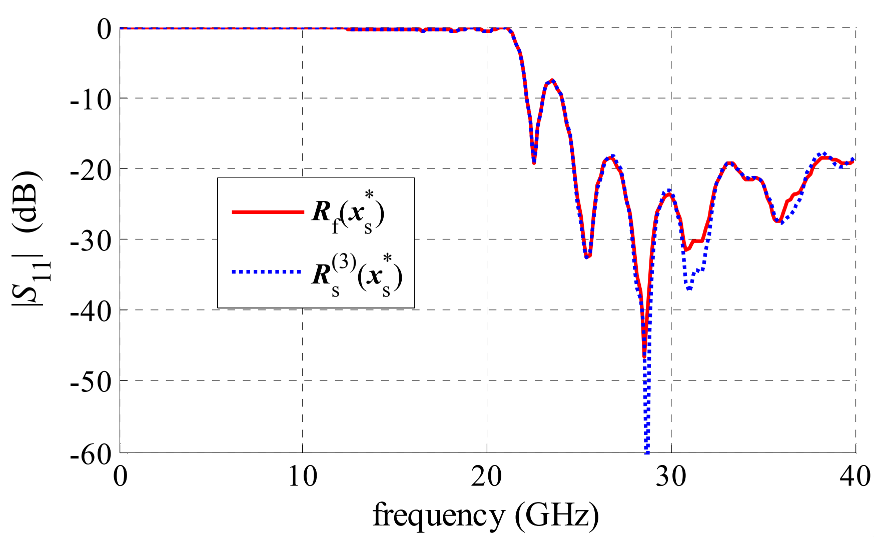
Surrogate *vs* Fine Model at x_s^*



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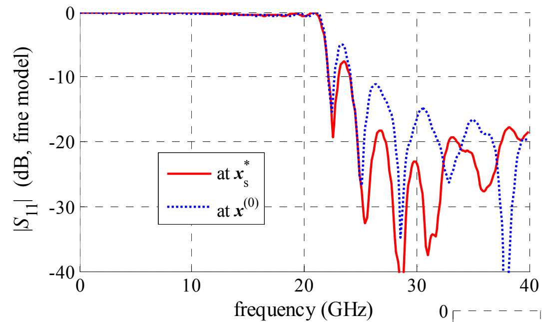
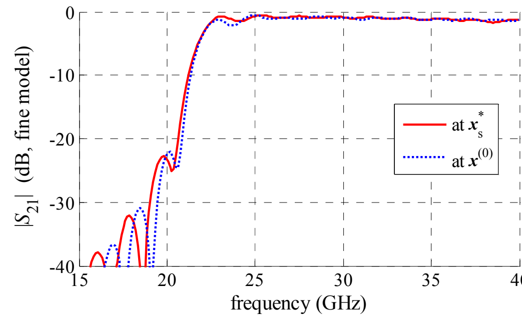
Fine Model Responses, Initial *vs* Final

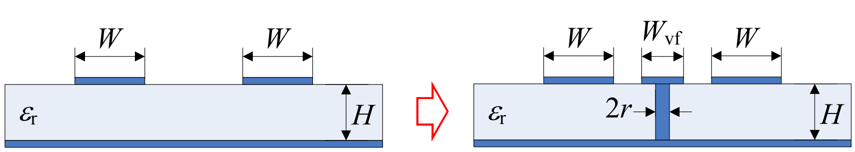




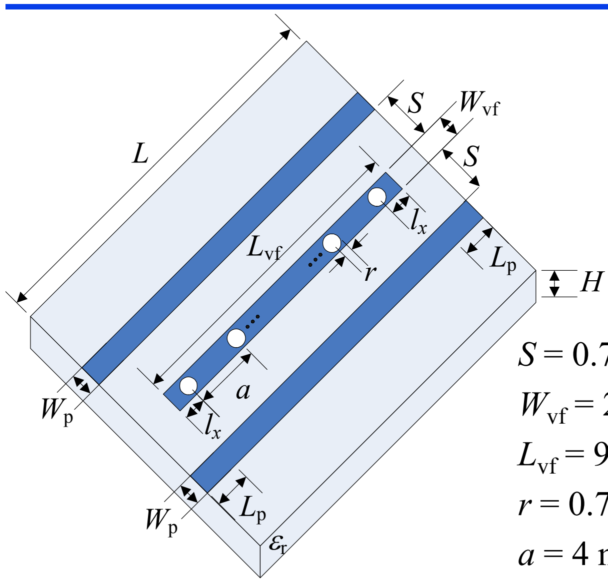
(Ka band: 26.5-40 GHz)

Crosstalk Reduction by Guard Traces

- Crosstalk is a major concern in high-speed interconnect design
- A traditional technique to minimize crosstalk consists of using via fences or guard traces
- Inserting via fences between microstrip lines effectively reduces crosstalk and transmission losses
- However, via fences deteriorate impedance matching



Microstrip Traces with Via Fence



(*Suntives et al., 2006*)

ε_r = 4.4 (FR4)
tan δ = 0.02 at 10 GHz
H = 1.575 mm

W_p = 2.9 mm
L_p = 5W_p

S = 0.75 mm
W_{vf} = 2 mm
L_{vf} = 98.5 mm
r = 0.762 mm
a = 4 mm
l_x = 1.25 mm

} 25 vias

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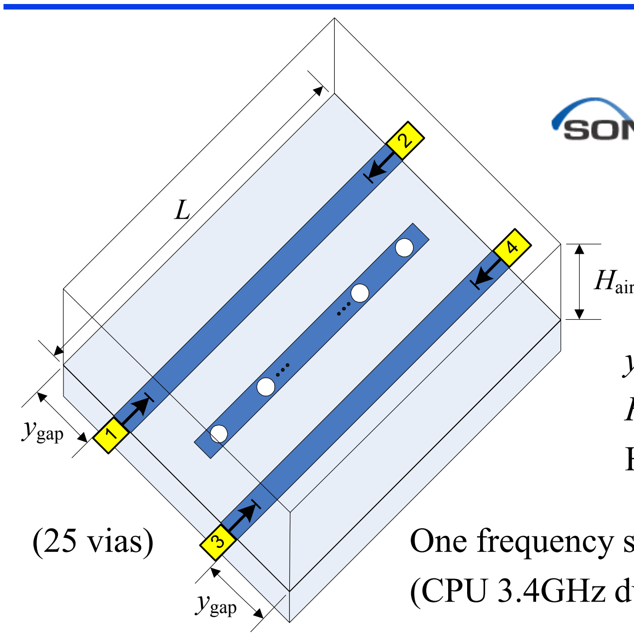
Microstrips with Via Fence – EM Model

SONNET®



(25 vias)

y_{gap} = 0.75W_{vf}
H_{air} = 6H
High-resolution grid

One frequency sweep: 46 min
(CPU 3.4GHz dual, 2GB RAM)

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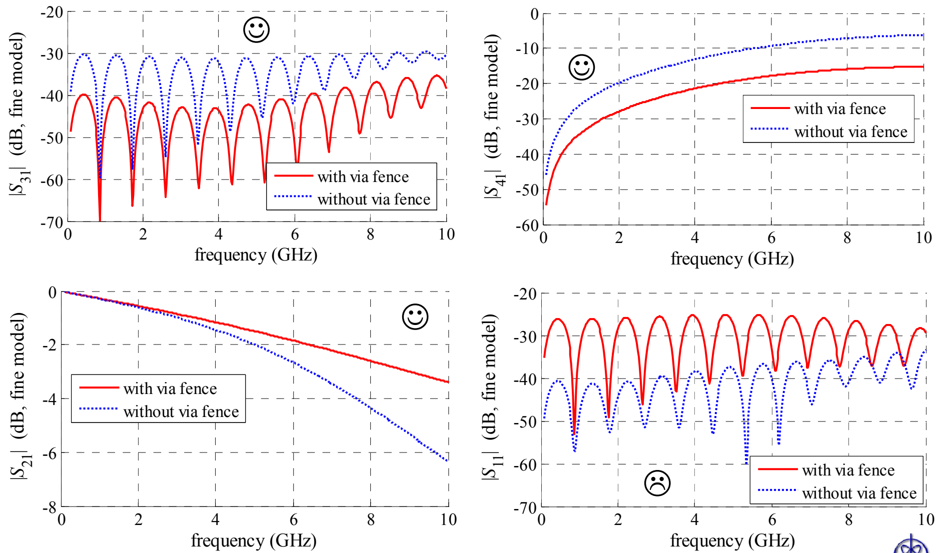
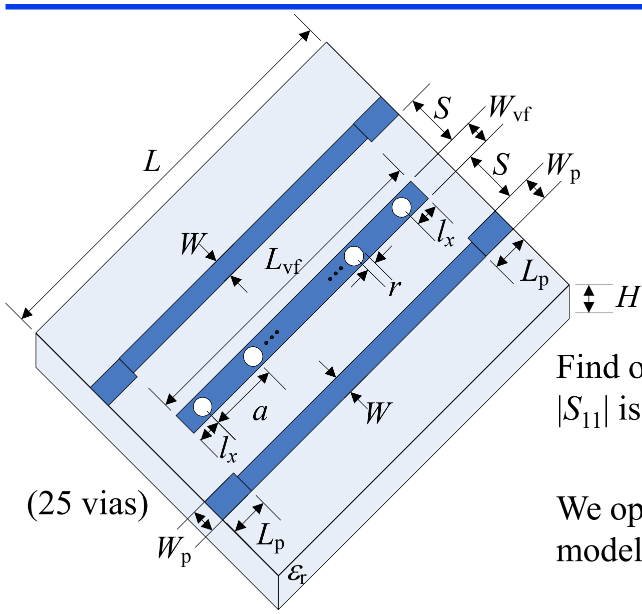
Microstrips with Via Fence – EM Responses



Improving Impedance Matching

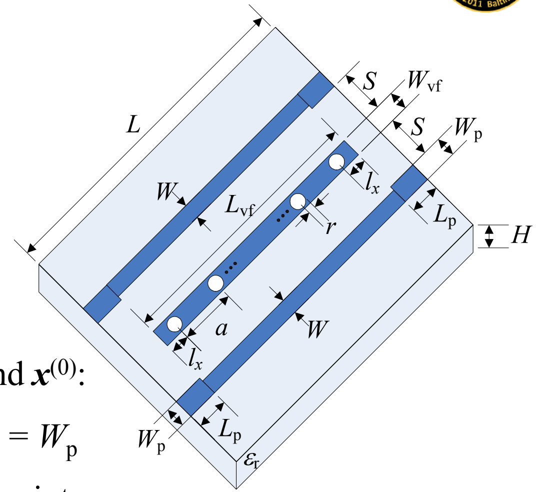


Find optimal W such that $|S_{11}|$ is minimized

We optimize a surrogate model

Surrogate Model of the Interconnect

- We select $\boldsymbol{x} = W$
- $\boldsymbol{x}^{(0)} = W_p = 2.9$ mm

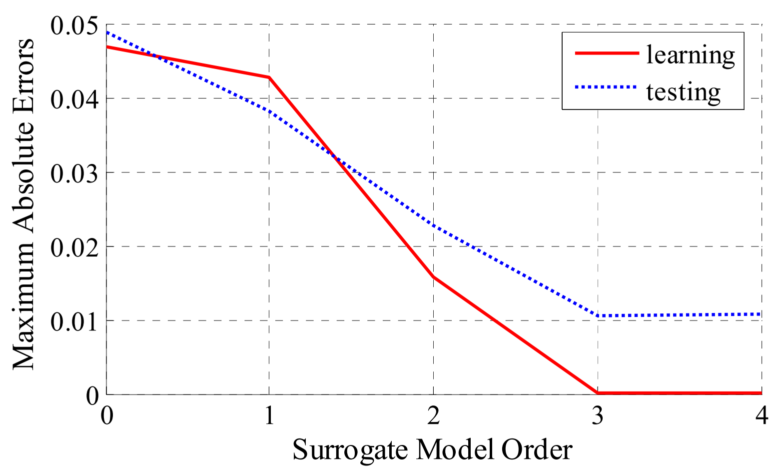


- Region of interest around $\boldsymbol{x}^{(0)}$:

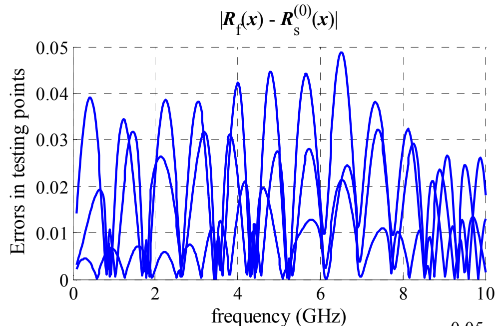
  2.5 mm ≤ W ≤ 2.9 mm = W_p
- We use 3 learning base points
- We use 3 test base points

Surrogate Model of the Interconnect (cont)

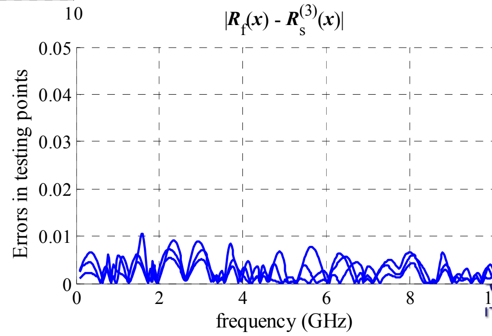
Maximum errors in learning and testing sets for the surrogate models of $|S_{11}|$



Surrogate Model of the Interconnect (cont)

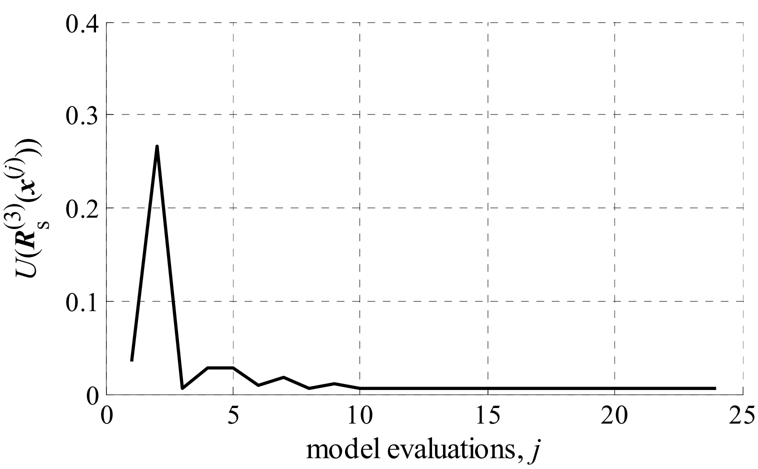


Absolute errors in $|S_{11}|$
at testing base points



Optimizing the Surrogate

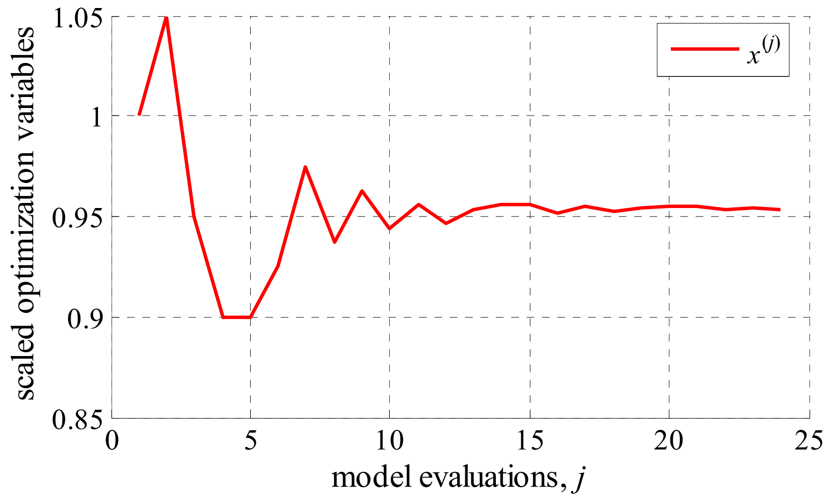
We optimize $\boldsymbol{R}_s^{(3)}(\boldsymbol{x})$ to minimize $|S_{11}|$



Optimization time: 2.05 seconds; Model evaluations: 24

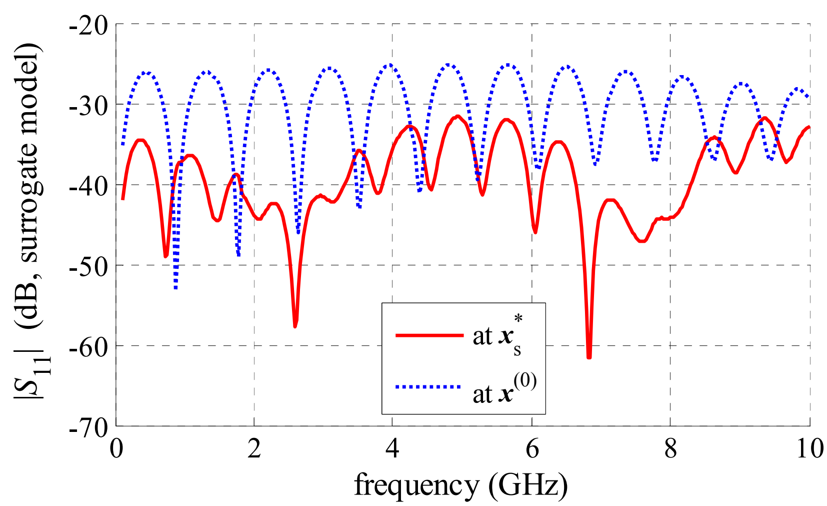
Optimizing the Surrogate (cont)

$x_s^* = W^* = 2.7663$ mm

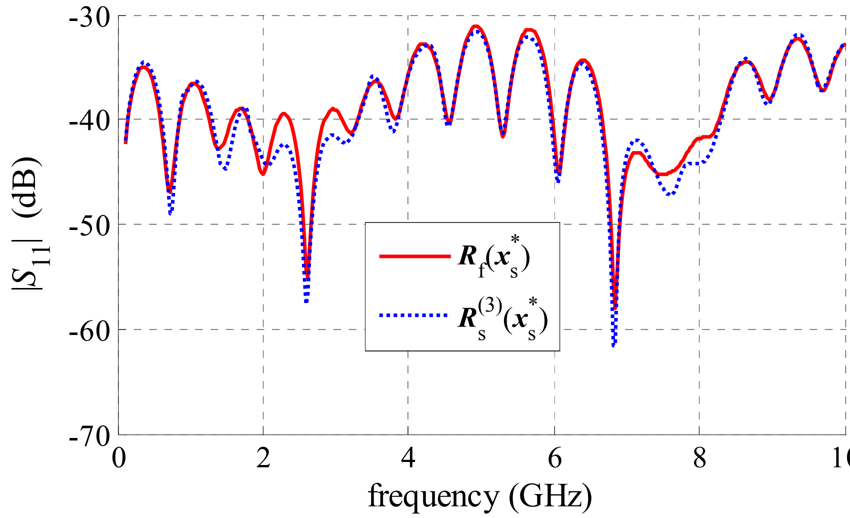


Optimizing the Surrogate (cont)

$x^{(0)} = 2.9$mm $x_s^* = 2.76$ mm



Surrogate *vs* Fine Model at $\boldsymbol{x}_s^*$



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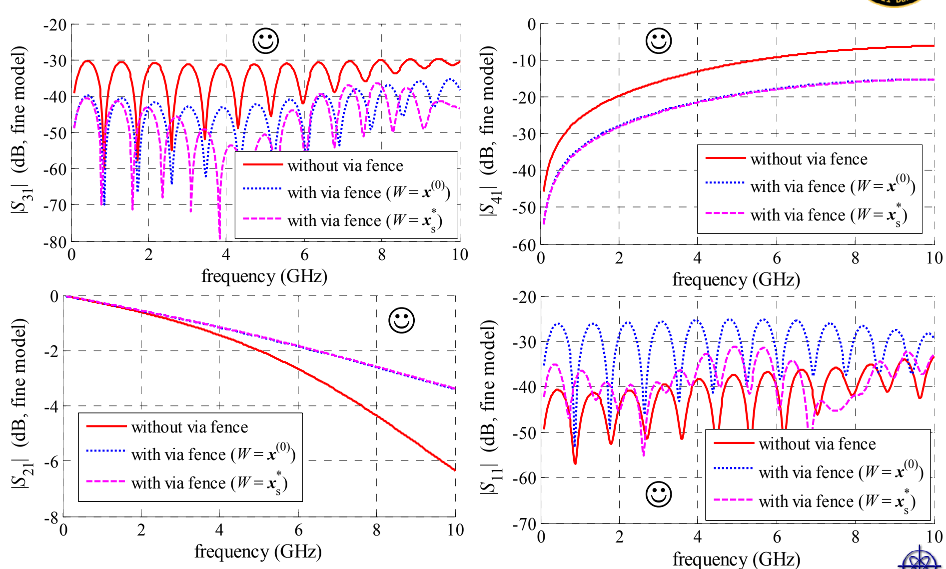
Fine Model Responses – Final Results



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Conclusions

- EM-based design optimization of microwave circuits using multidimensional polynomial surrogate models was described
- This formulation can be applied when no coarse model is available
- Global optimal weighting factors are obtained in closed form
- Generalization performance of polynomial interpolants was illustrated
- The design optimization of two high-speed PCB interconnect structures was presented

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Selected References

1. J. E. Rayas-Sánchez and N. Vargas-Chávez, "Design optimization of microstrip lines with via fences through surrogate modeling based on polynomial functional interpolants," in *IEEE Conf. Electrical Performance of Electronic Packaging and Systems (EPEPS-2010)*, Austin, TX, Oct. 2010, pp. 125-128.
2. J. E. Rayas-Sánchez, J. Aguilar-Torrentera and J. A. Jasso-Urzúa, "Surrogate modeling of microwave circuits using polynomial functional interpolants," in *IEEE MTT-S Int. Microwave Symp. Dig*., Anaheim, CA, May 2010, pp. 197-200.
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