Recent Via Modeling Methods for Multi-Vias in a Shared Anti-pad

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Signal Link Path

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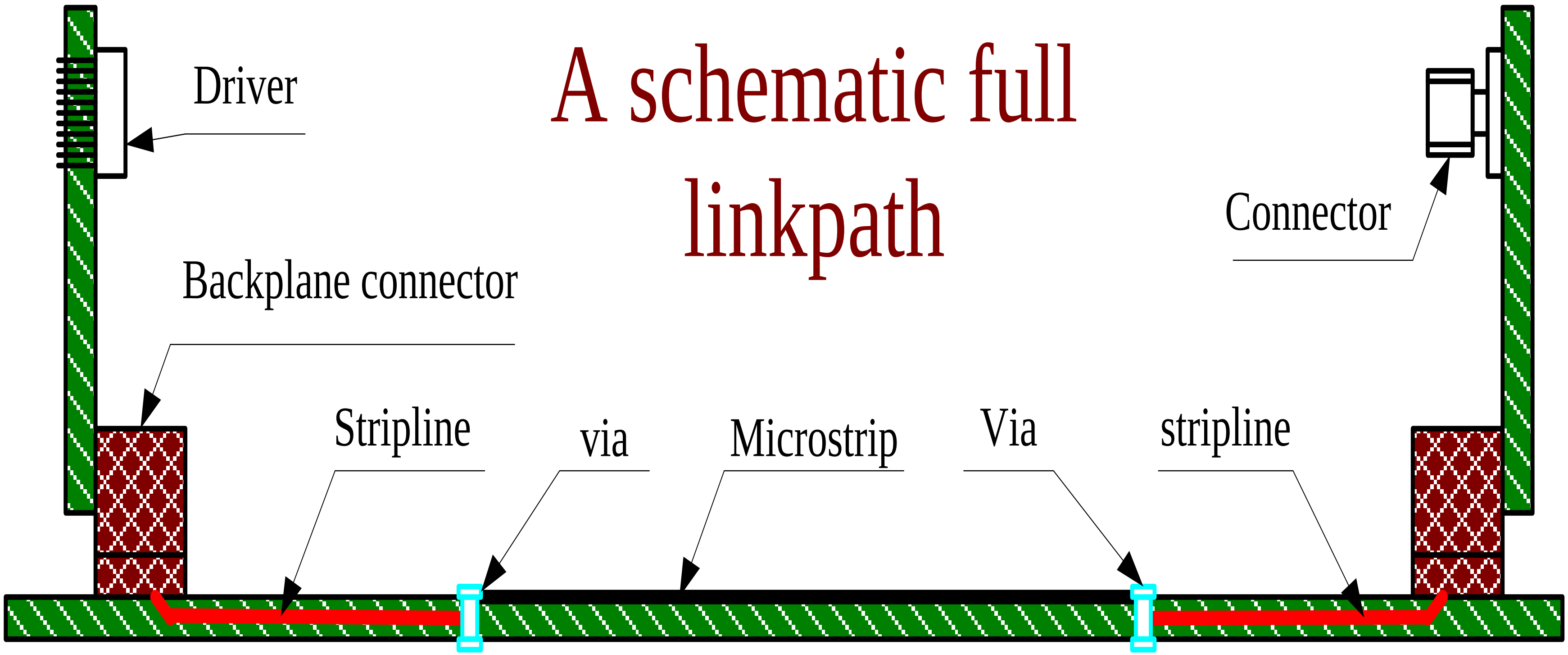
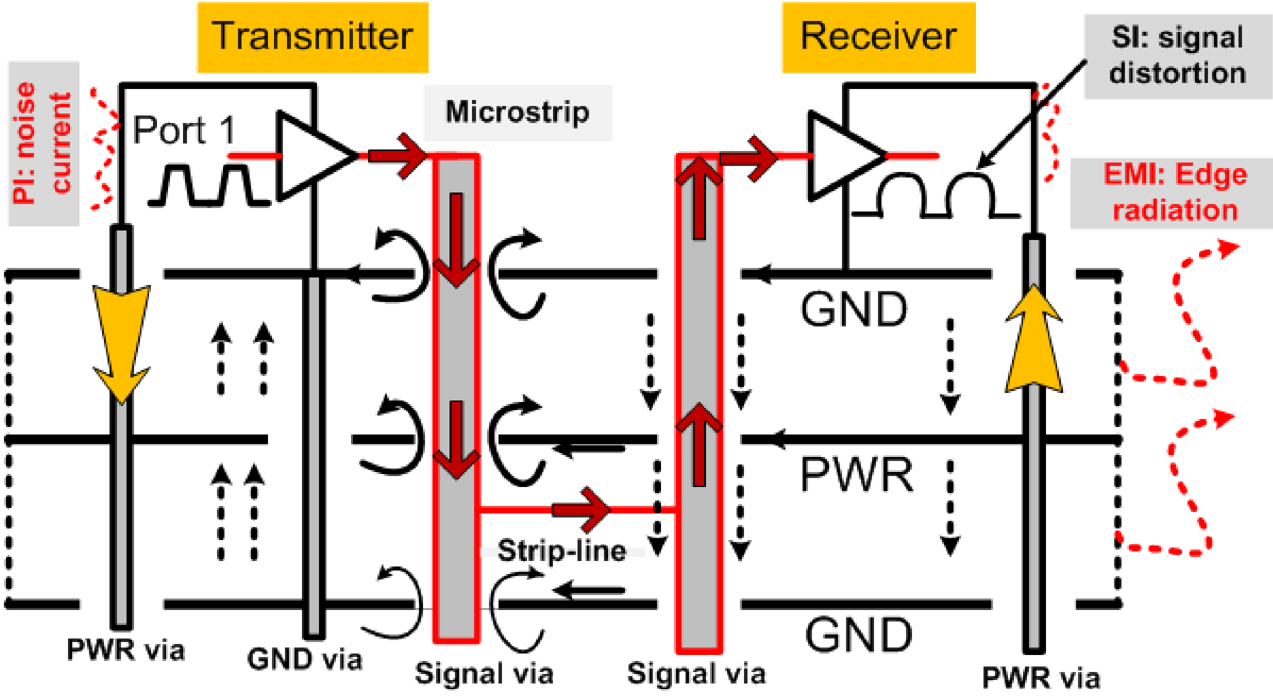
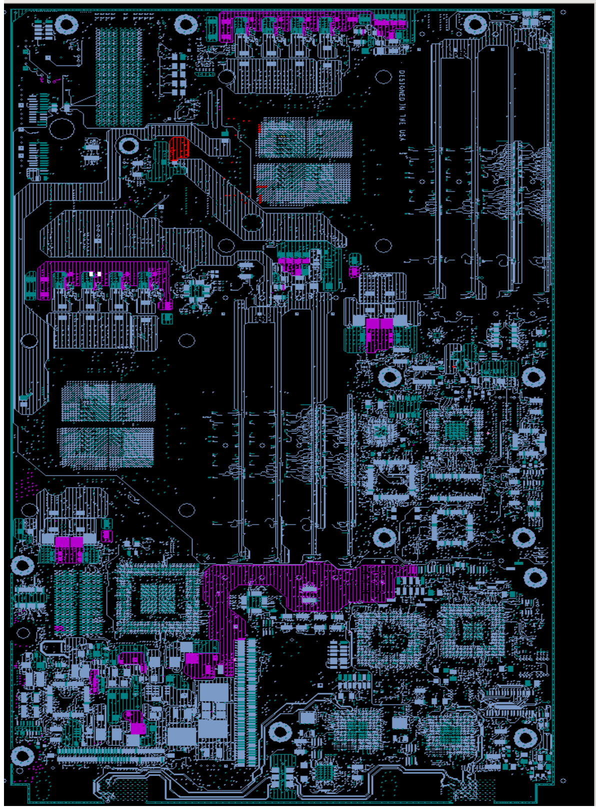


Outline

- Vias modeling in signal/power integrity and EMI
- Modeling conventional via structures by hybrid field-circuit via models
  - Physics-based via model
  - Intrinsic via circuit model
- Modeling multi-vias in a shared anti-pad
  - Hybrid 3D/2D finite element methods (FEM)
  - Hybrid FEM and boundary integral equations (BIE)
- Future work

Via modeling: critical roles in SI, PI & EMI

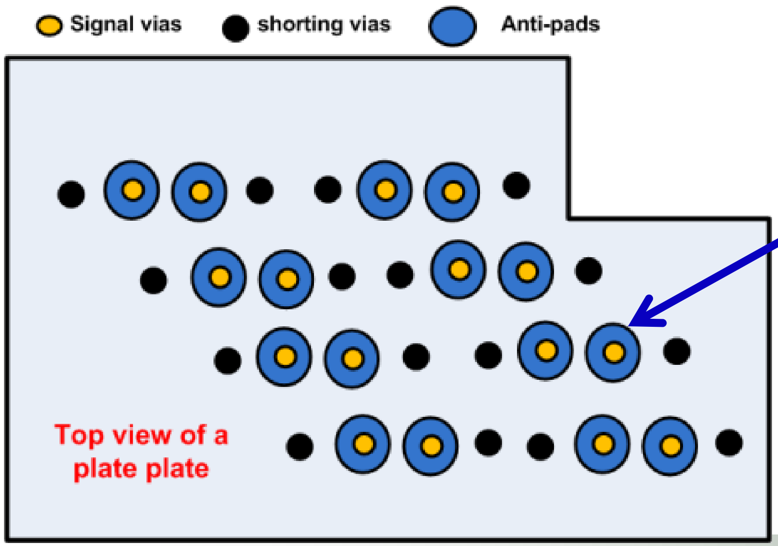




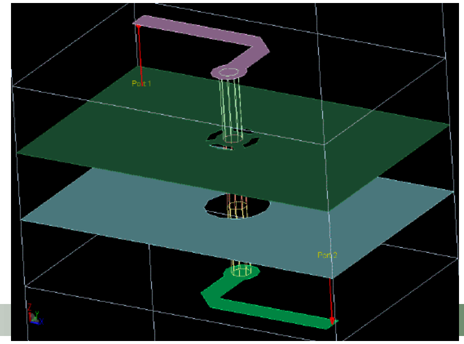
•**SI:** vias are discontinuities for microstrip and strip lines, causing mismatching.
•**PI:** vias excites propagating waves between plate pair, causing noise currents on PWR/GND vias and thus result in voltage fluctuations for I/O buffers.
•**EMI:** propagating waves may lead to plate pair resonances and cause strong edge radiations.

Overview of via models: a single via in a round anti-pad

- Hybrid field-circuit models
  - o Physics-based via model (Prof. Schuster Christian, TUHH);
  - o Intrinsic via circuit model (EMC Lab/MST);
- Multiple scattering methods (semi-analytical full-wave method)
  - o Conventional multiple scattering method (Prof. Leung Tsang, Univ. Washington);
  - o Generalized multiple scattering method (EMC Lab/MST);



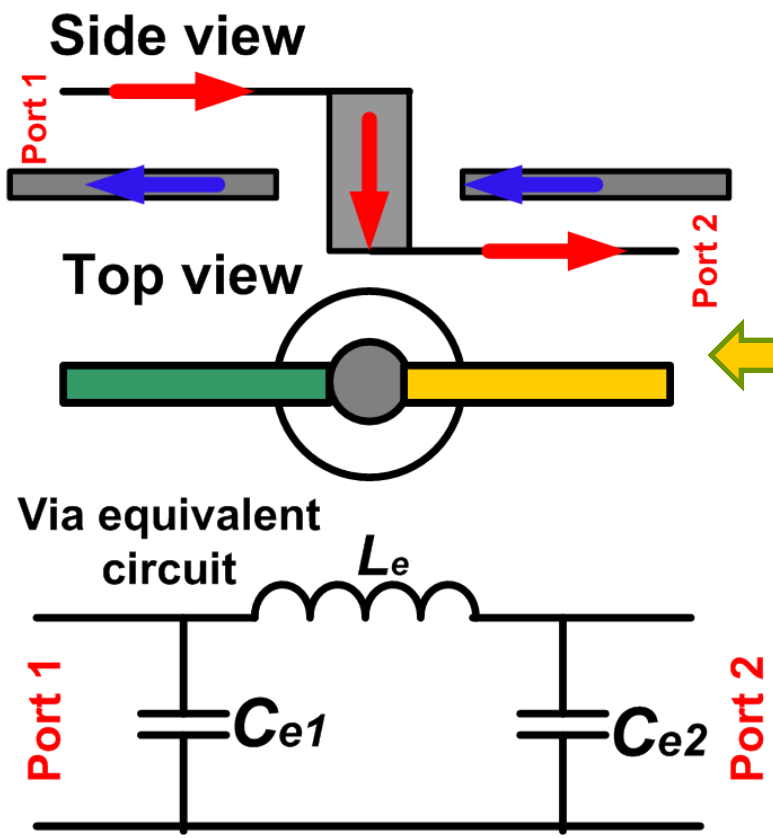
All above methods have an assumption of coaxial TEM mode in anti-pads in all of via models

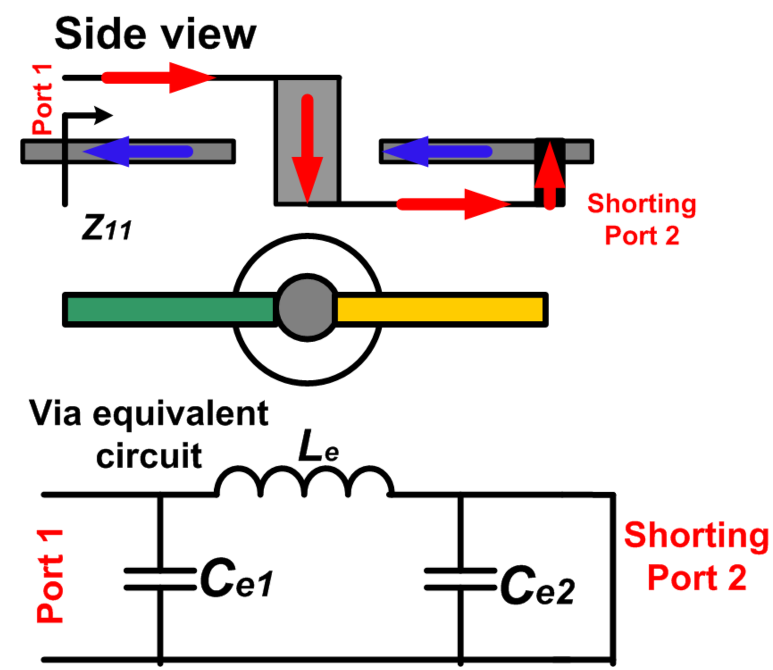


A via crossing a single plate

- Full-wave methods (FDTD, MoM)

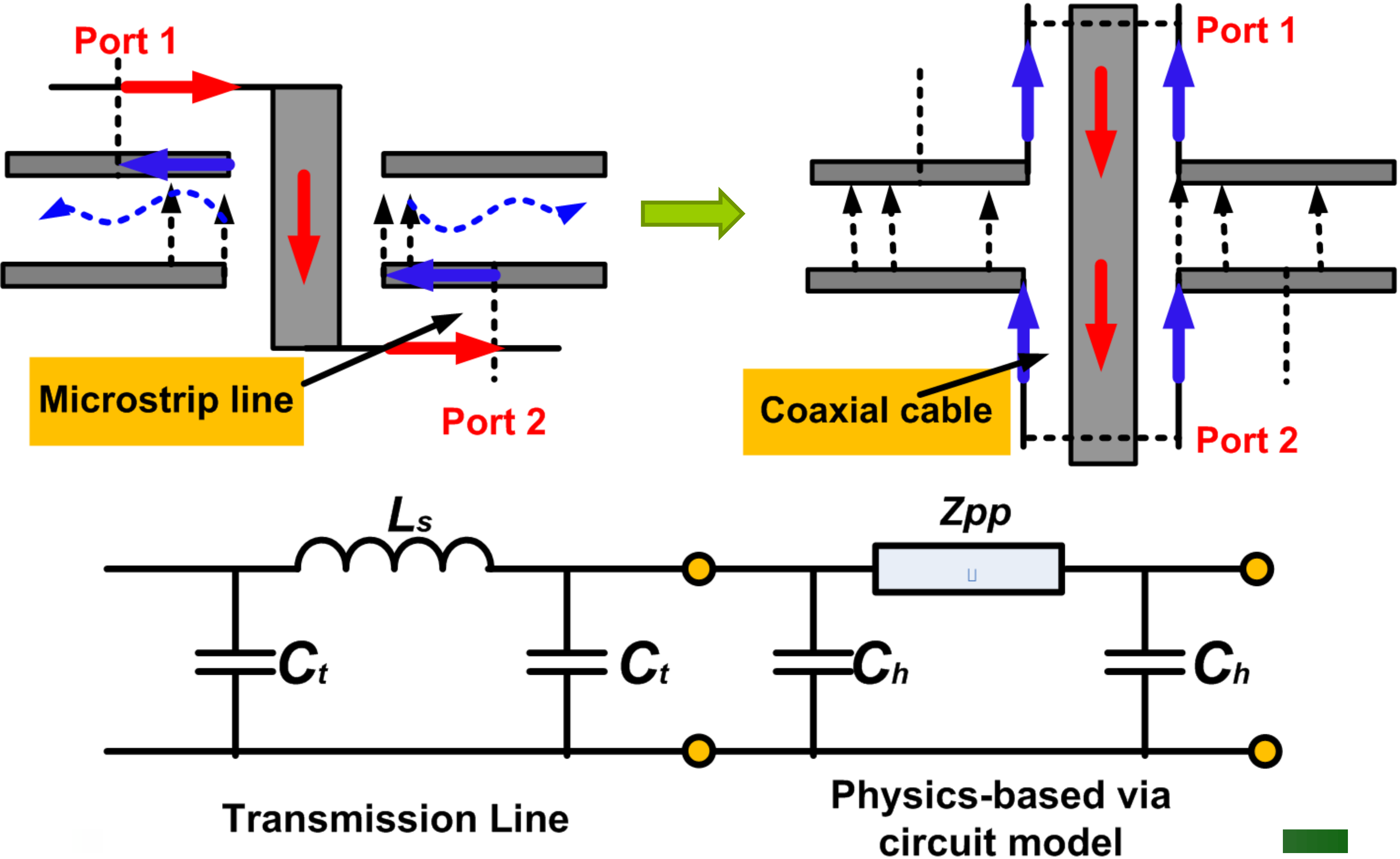
Quasi-static integral equation method to extract he excess capacitances



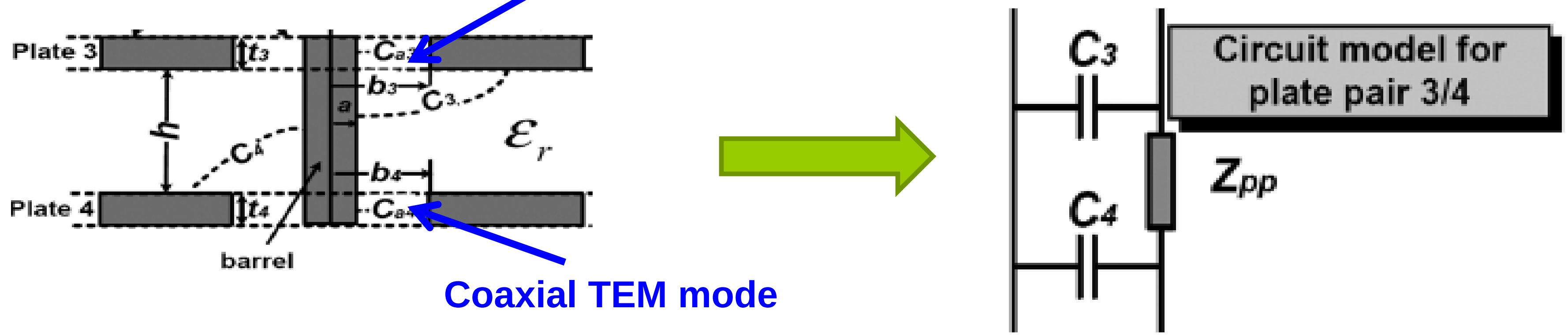


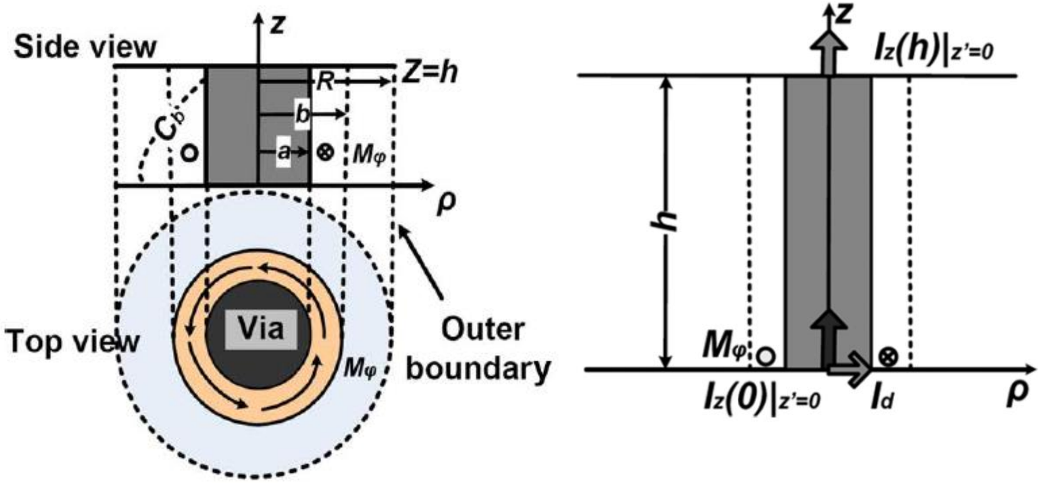
By open and shorting ports, we can "guess" a circuit model based on our physics intuition.

A via crossing a plate pair



Physics-based via model: via-plate capacitance





Magnetic frill current

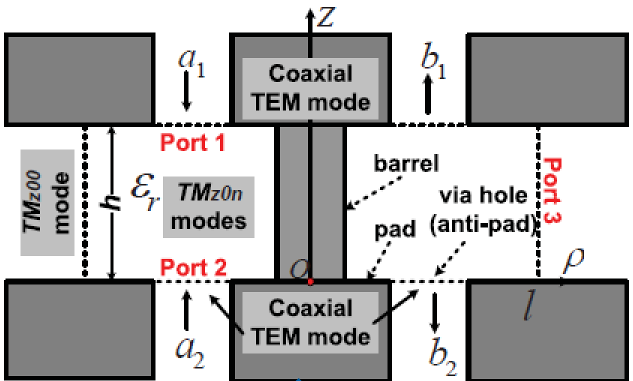
Analytical formula

$$C_b = \frac{8\pi\varepsilon}{h\ln(b/a)} \sum_{n=1,3,5\ldots}^{2N-1} \frac{\left(1-\Gamma_a^{(n)}\Gamma_R^{(n)}\right)^{-1}}{k_n^2 H_0^{(2)}(k_n a)} \cdot \left\{ \left[H_0^{(2)}(k_n b) - H_0^{(2)}(k_n a) \right] + \Gamma_R^{(n)} \left[J_0(k_n b) - J_0(k_n a) \right] \right\}$$

Question: what contribution from the even-number parallel plate waveguide modes?

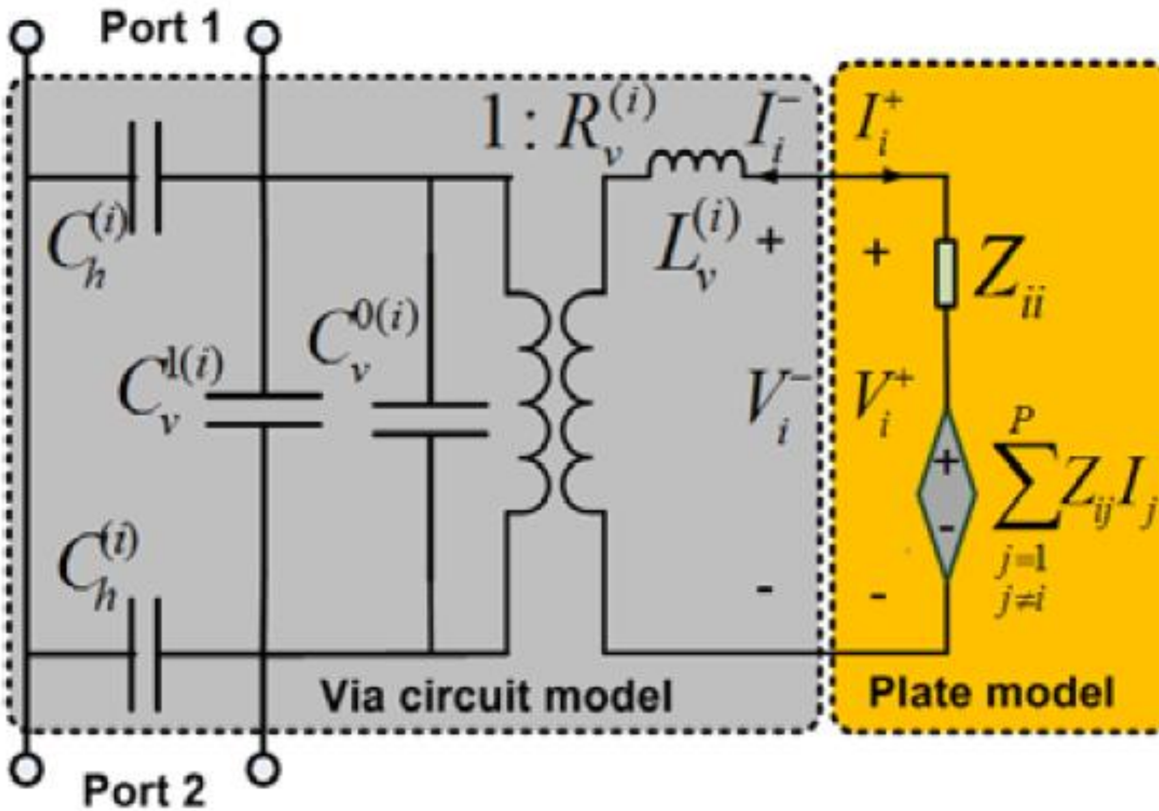
Y. Zhang, J. Fan, G. Selli, M. Cocchini, F. D. Paulis, "Analytical evaluation of via-plate capacitance for multilayer printed circuit boards and packages, " *IEEE Trans. Microwave Theory Tech.*, vol. 56, no. 9, pp. 2118-2128, Sep 2008.

Intrinsic via circuit model



Localized geometric parameters

Circuit model which satisfies via boundary conditions



All parasitic parameters are extracted by analytical expression in a fraction of seconds!!

Y. -J. Zhang, and J. Fan, "An intrinsic circuit model for multiple vias in an irregular plate pair through rigorous electromagnetic analysis," *IEEE Trans. Microwave Theory Tech.*, vol. 58, no. 8, pp. 2251-2265, Aug 2010.

Y. -J. Zhang, G. Feng, J. Fan, "A novel impedance definition of a parallel plate pair for an intrinsic via circuit model", *IEEE Trans. Microwave Theory Tech.*, vol. 58, no. 12, pp. 3780-3789, Dec 2010.

Intrinsic via circuit model for SI/PI analysis

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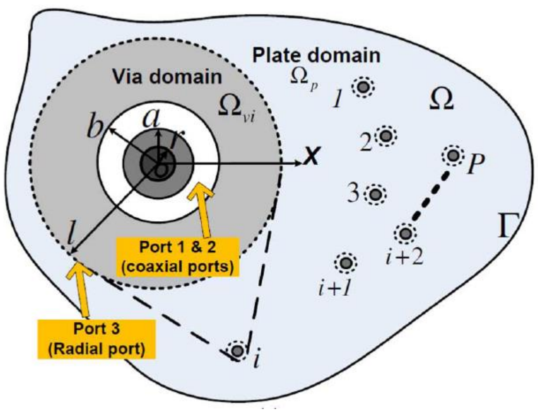
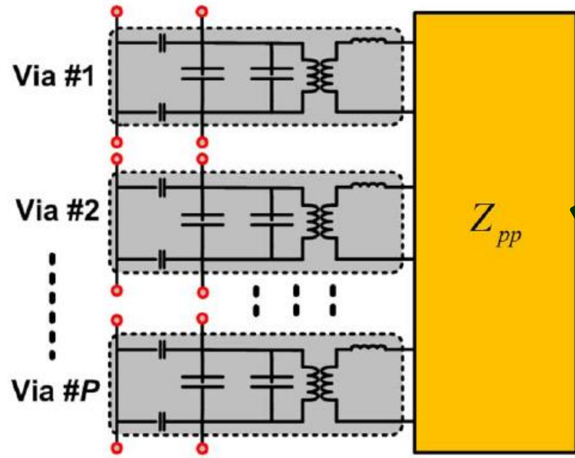
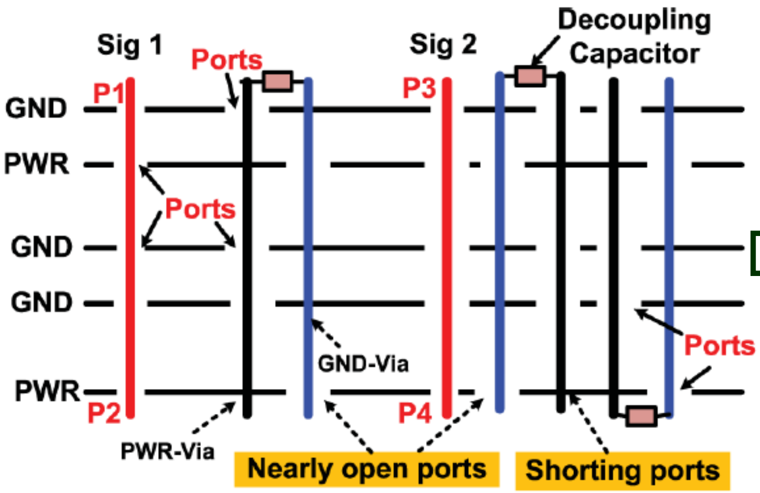
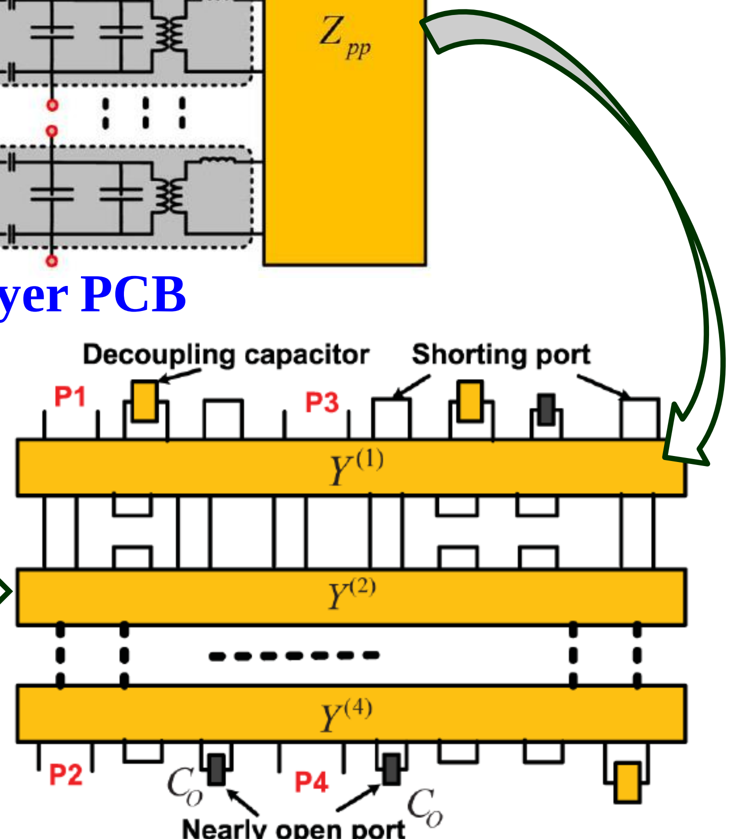
Hybrid field- circuit model for a plate pair





Systematic modeling multilayer PCB

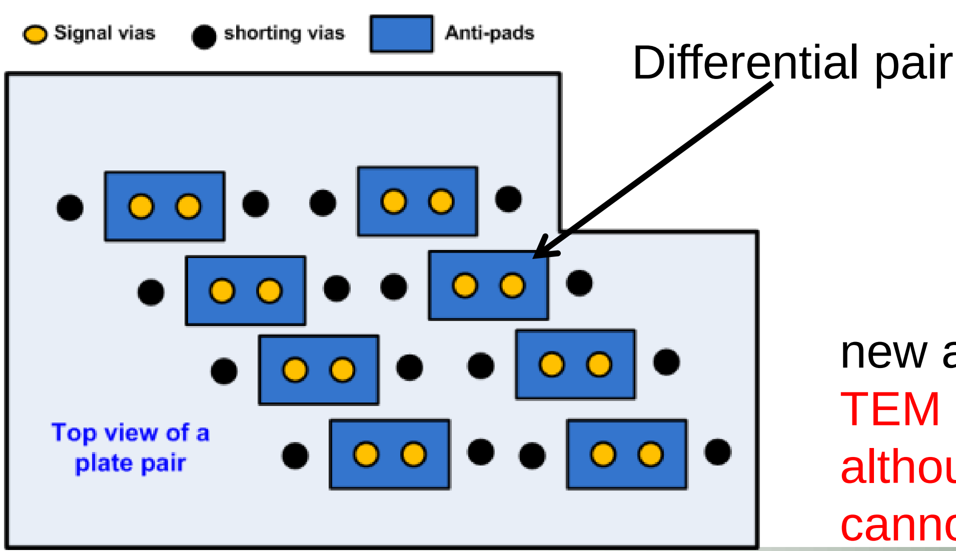




Multiple vias in a shared anti-pad

- Hybrid full-wave solvers
  - Hybrid 3D/2D finite element method (EMC Lab/MST)
  - Hybrid FEM and Boundary integral equations (EMC Lab/MST)
  - (Generalized) multiple scattering method

By Prof. Leung Tsang, Univ. of Washington



Challenges for via modeling:

- No analytical field distribution in anti-pads;
- Circuit models difficult to extract.

new assumption:
TEM mode in anti-pads
although analytical expressions
cannot be obtained.

Domain decomposition: via- and plate-domains

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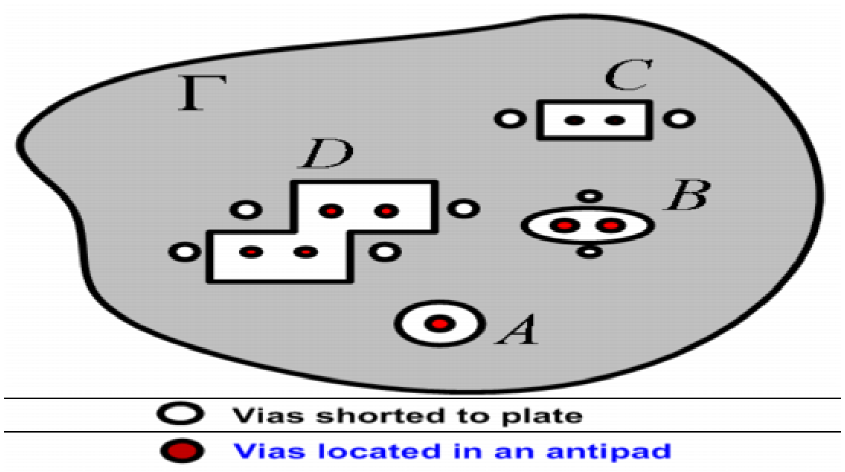
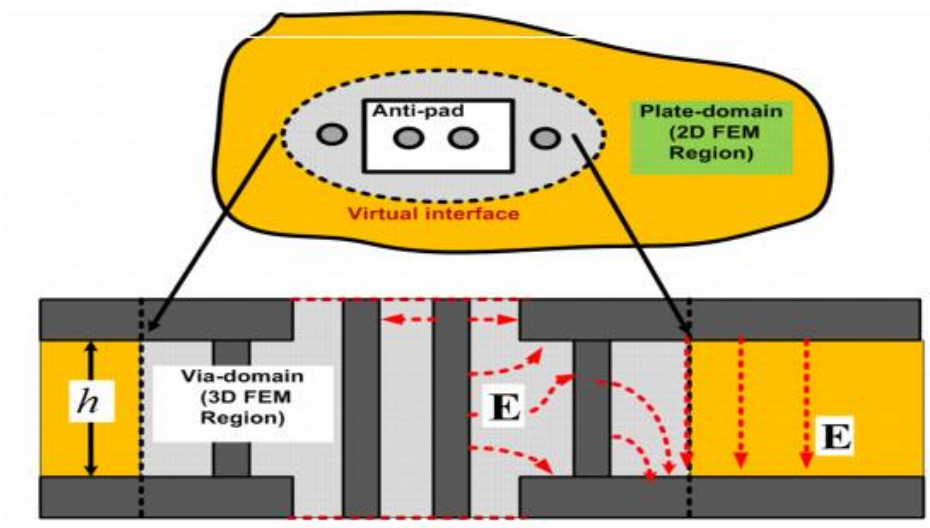




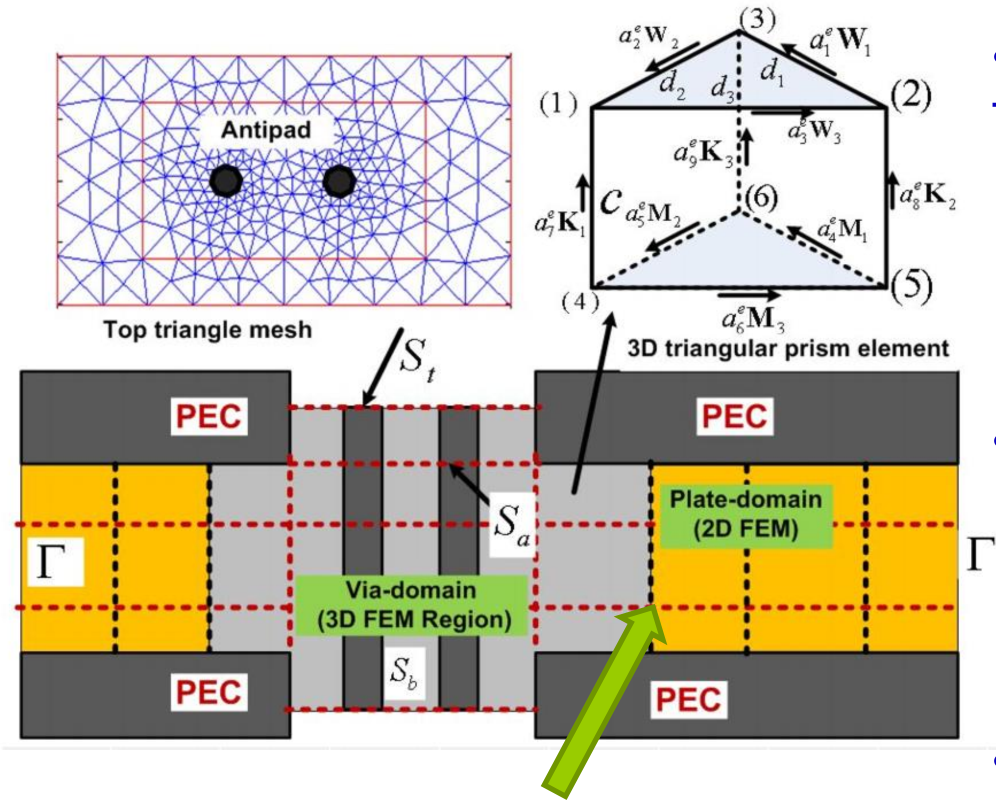
$$k_\rho = \sqrt{k_0^2 \varepsilon_r - (n\pi/h)^2}. \qquad k_0^2 \varepsilon_r \ll (\pi/h)^2$$

For n is not zero, waves will decay exponentially.

Note:

1. A plate pair can be divided by into via-domains and plate-domain(s)
2. via-domains have three-dimensional, complicated field distributions
3. Plate-domain has only TEM mode of parallel plate waveguide (Zero-order parallel plate waveguides)

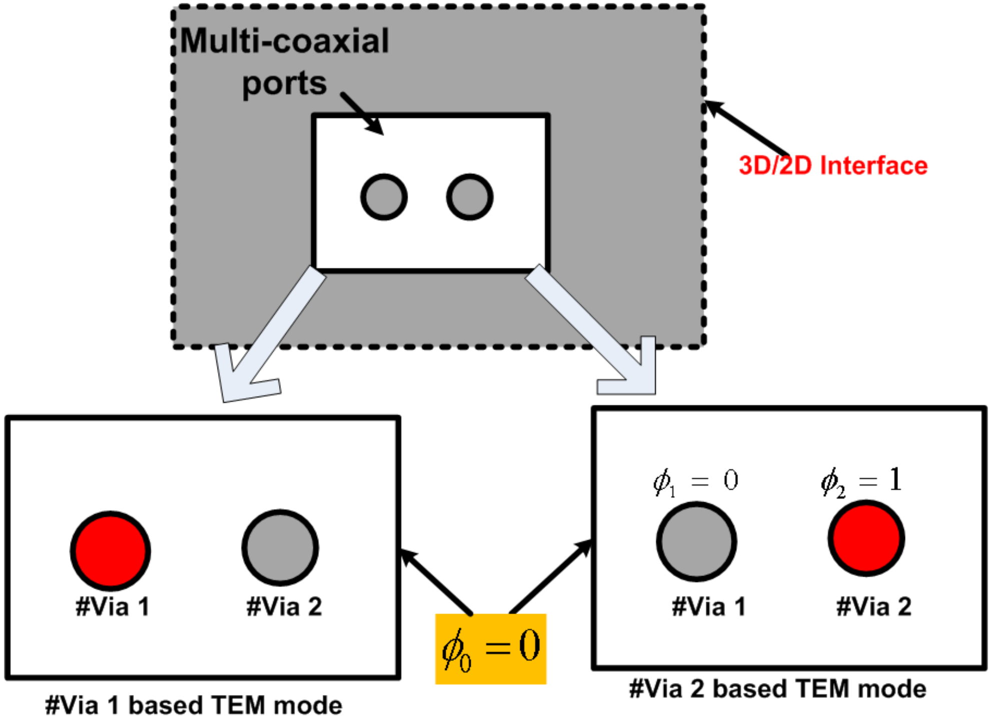
Hybrid 3D/2D FEM for a plate pair



How to satisfy the boundary condition at the interface of 3D and 2D FEM regions?

- 2D electro-static FEM calculation of TEM port modes;
  - A reasonable assumption(?)
  - Used as sources to excite the parallel plate structure Cascaded layer-by-layer
- 3D full-wave FEM for via-domains
  - Higher-order parallel plate modes included
  - Capacitive and inductive coupling among vias
- 2D full-wave FEM for plate-domains
  - Zero-order parallel plate mode
  - Reduced the number of unknowns

2D FEM for TEM modes in an Anti-pad



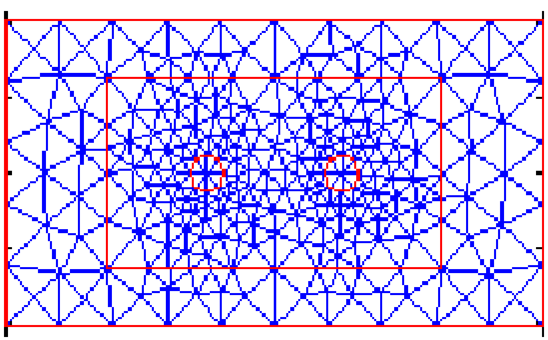
Functional for potential distribution in an antipad

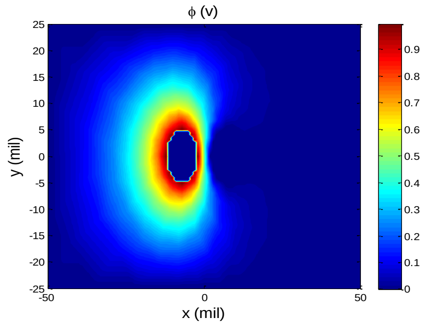
$$F(\phi) = \frac{1}{2}\iint_S \nabla\phi \bullet \varepsilon\nabla\phi ds = 0$$

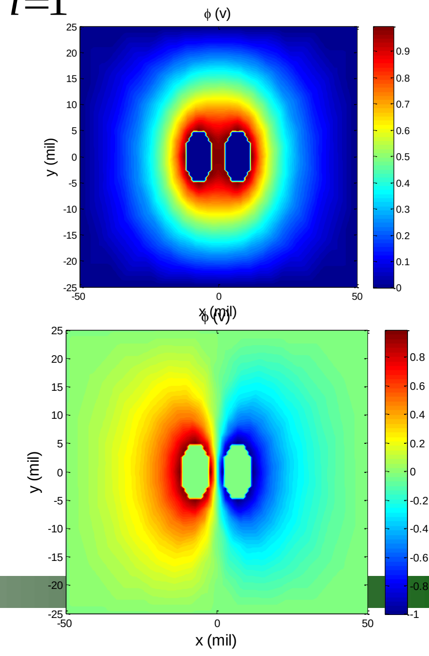
Node-based FEM

$$\phi = \sum_{e=1}^{N_e}\sum_{i=1}^{3} a_i^e N_i^e(x,y)$$

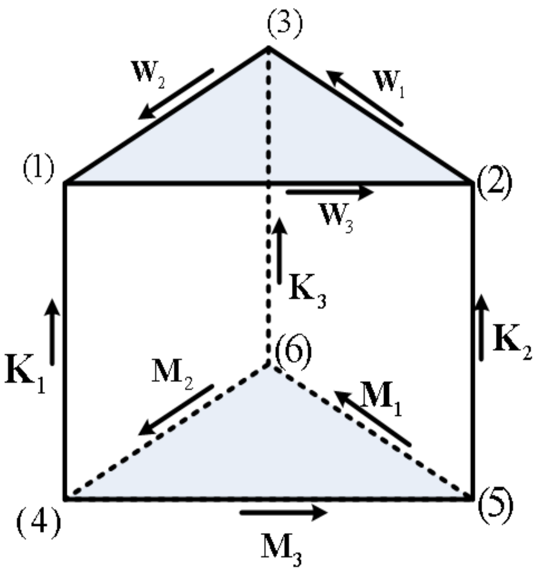
Triangular meshes







Functional of the magnetic fields in 3D FEM



$$F(\mathbf{H}) = \frac{1}{2}\int_V \left(\nabla \times \mathbf{H} \cdot \varepsilon_r^{-1} \nabla \times \mathbf{H} - k_0^2 \mathbf{H} \cdot \mathbf{H}\right) dV + j\omega\varepsilon_0 \oint_S \mathbf{H} \cdot \mathbf{E} \times \mathbf{n} dS$$

$$\mathbf{E} = -\nabla \phi$$

TEM modes in anti-pads as sources

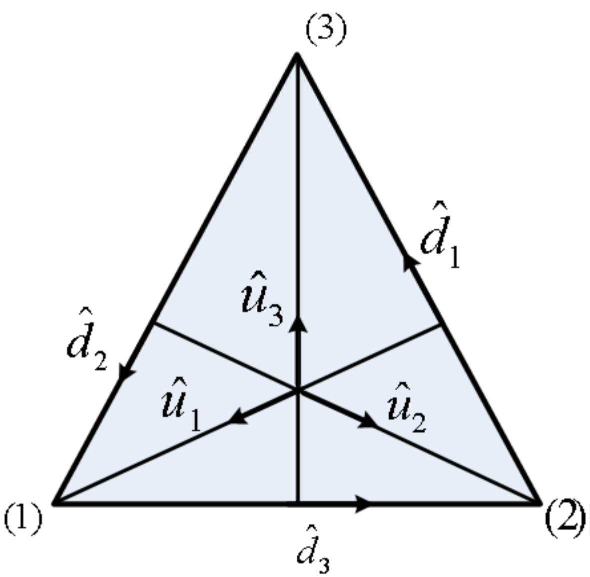
$$\mathbf{H} = \sum_{e=1}^{N_e} \sum_{i=1}^{9} a_i^e \mathbf{B}_i^e(x,y,z)$$

$$\mathbf{B}_i^e(x,y,z) = \begin{cases} \mathbf{W}_i(x,y,z) & i = 1,2,3 \\ \mathbf{M}_{i-3}(x,y,z) & i = 4,5,6 \\ \mathbf{K}_{i-6}(x,y,z) & i = 7,8,9 \end{cases}$$

$$\begin{aligned} \mathbf{W}_i &= \mathbf{N}_i(x,y) z/c \\ \mathbf{M}_i &= \mathbf{N}_i(x,y)(1 - z/c) \\ \mathbf{K}_i &= L_i(x,y)\mathbf{e}_z \end{aligned}$$

Edge elements

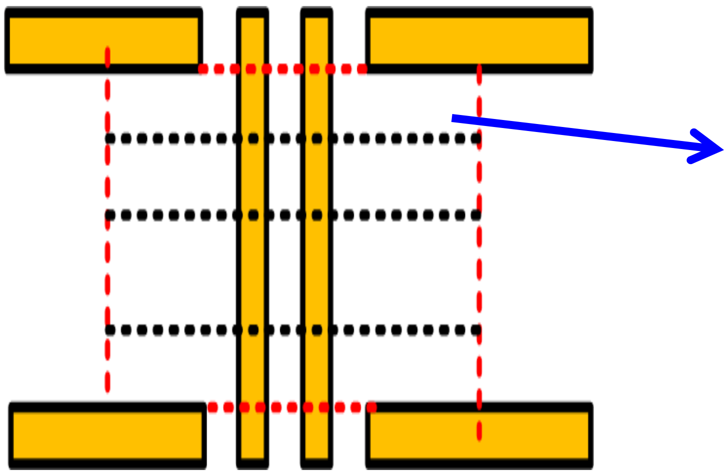
Node elements

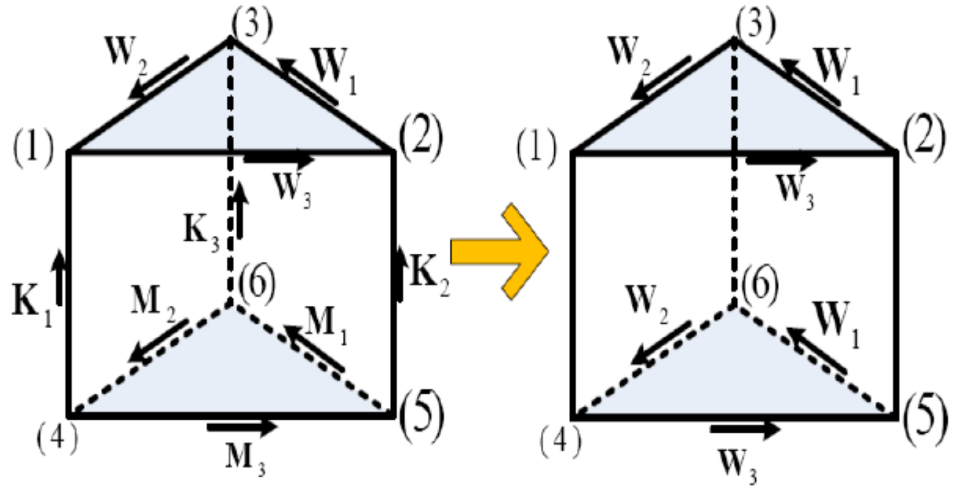


Edge elements

$$\mathbf{N}_i(x,y) = d_i\left(L_{i+1}\nabla L_{i+2} - L_{i+2}\nabla L_{i+1}\right)$$

Triangular Prism Element: 3D → 2D (1)





3D Triangular prism element

2D Triangular prism element

using $a_1^e = a_4^e \quad a_7^e = 0$
$a_2^e = a_5^e \quad a_8^e = 0$
$a_3^e = a_6^e \quad a_9^e = 0$

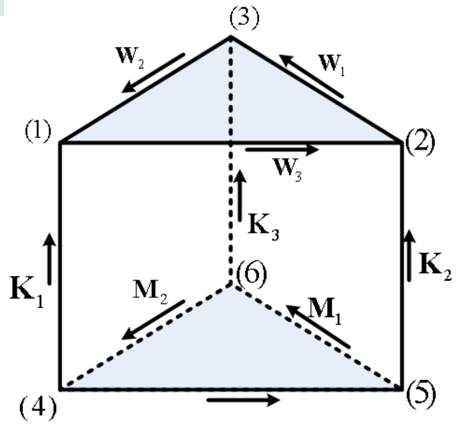
→ a 2D triangular prism element !

Note: In coding, these conditions can be automatically satisfied if top and bottom edges in a prism are numbered as same edge numbering index and side-edges are not accounted at all.

3D FEM can be converted into 2D FEM easily and boundary conditions along 2D and 3D domains are satisfied automatically.

Triangular Prism Element: 3D → 2D (2)

$$\mathbf{K}_{ij}^e = \int_{V_e} \left[\varepsilon_r^{-1}\nabla \times \mathbf{B}_i^e \cdot \nabla \times \mathbf{B}_j^e - k_0^2 \mathbf{B}_i^e \cdot \mathbf{B}_j^e\right] dV_e$$



Add them together.

3D FEM 9-by-9 element matrix

$$\mathbf{K}^e = \varepsilon_r^{-1}\begin{bmatrix} \frac{c}{3}\mathbf{N}_\nabla + \frac{1}{c}\mathbf{N} & \frac{c}{6}\mathbf{N}_\nabla - \frac{1}{c}\mathbf{N} & -\mathbf{N}_{\nabla L} \\ \frac{c}{6}\mathbf{N}_\nabla - \frac{1}{c}\mathbf{N} & \frac{c}{3}\mathbf{N}_\nabla + \frac{1}{c}\mathbf{N} & \mathbf{N}_{\nabla L} \\ -\mathbf{N}_{\nabla L}^T & \mathbf{N}_{\nabla L}^T & c\mathbf{F} \end{bmatrix} - k_0^2 \begin{bmatrix} \frac{c}{3}\mathbf{N} & \frac{c}{6}\mathbf{N} & \mathbf{0} \\ \frac{c}{6}\mathbf{N} & \frac{c}{3}\mathbf{N} & \mathbf{0} \\ -\mathbf{0} & \mathbf{0} & c\mathbf{E} \end{bmatrix}$$

$$a_1^e = a_4^e \qquad a_7^e = 0$$
$$a_2^e = a_5^e \qquad a_8^e = 0$$
$$a_3^e = a_6^e \qquad a_9^e = 0$$

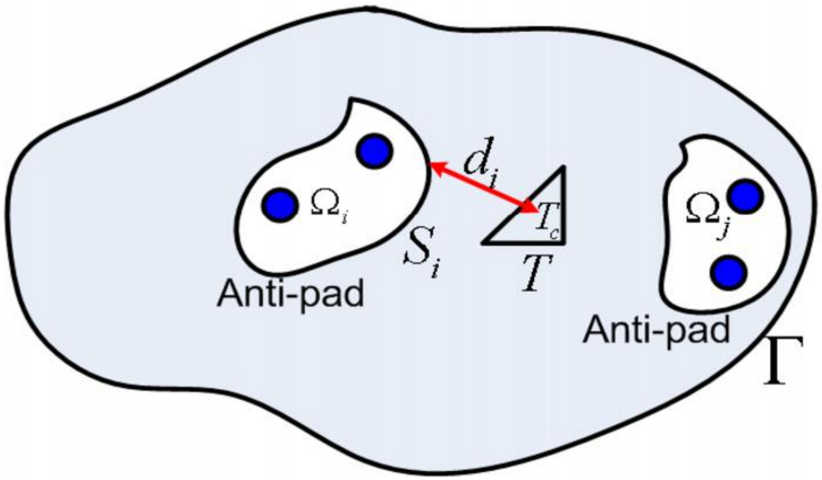
Delete the third column and raw.

2D FEM 3-by-3 element matrix

$$\mathbf{K}^e = \varepsilon_r^{-1} c\mathbf{N}_\nabla - k_0^2 c\mathbf{N}$$

9 unknowns have been reduced to 3 unknowns!

Interface between via-domains and plate-domain



the anti-pad Ω_i's outer contour S_i

The distances between the triangle T and the anti-pads' outer contour.

$$d_i,\ i = 1, 2, ..., P$$

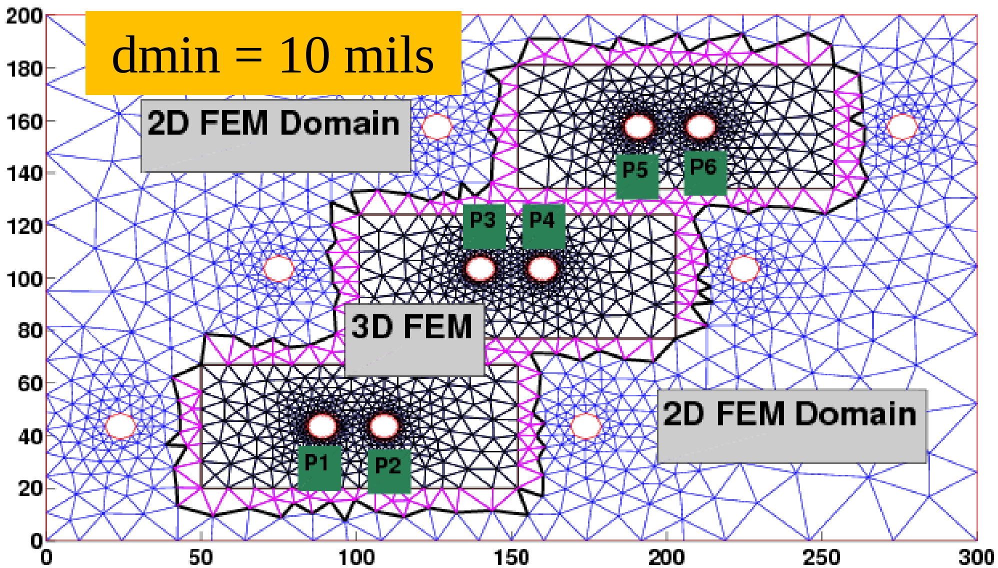
The criterion distance, d_{min}, depends mainly on the operating frequency, the dielectric constant of the material between the two plates and the plate separation, h, as the horizontal wave number of the parallel plate mode is

Transverse Wavenumber Parallel-plate modes

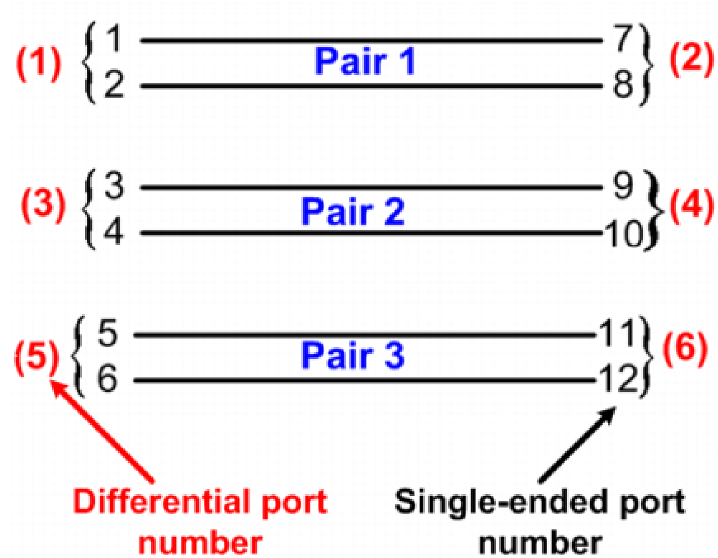
$$k_\rho = \sqrt{k_0^2 \varepsilon_r - (n\pi/h)^2}. \Longrightarrow e^{-\pi\rho/h} \quad \text{for n=1}$$

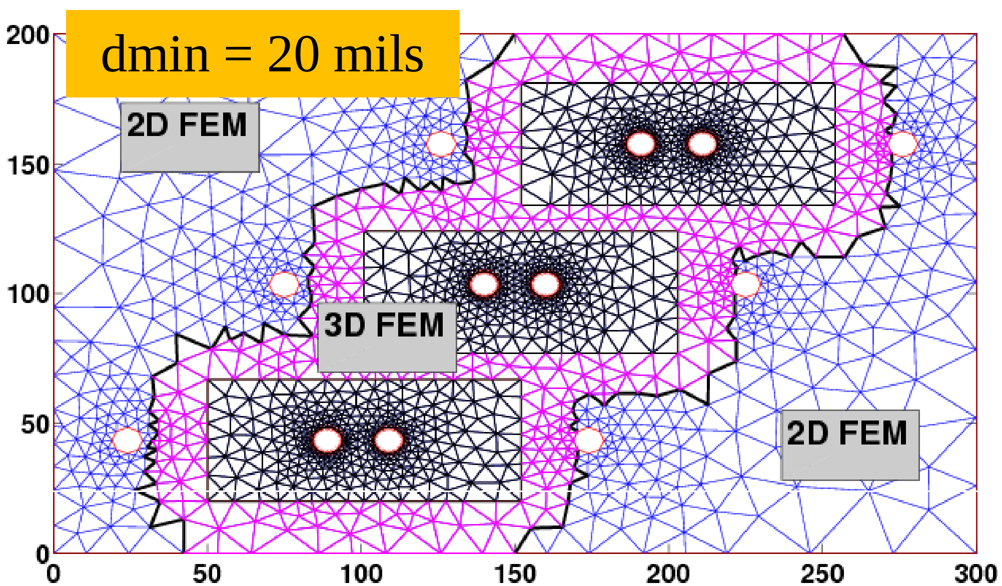
First higher-order mode decays away from the anti-pad.

Different criterion distance



Unit: mil = 0.0254 mm
h = 10 mils, t = 1 mil
Epsr = 4.0, tanLoss = 0.02

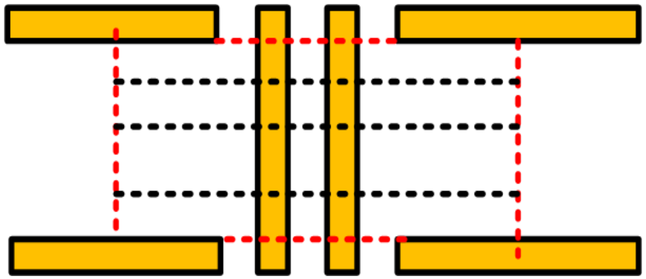


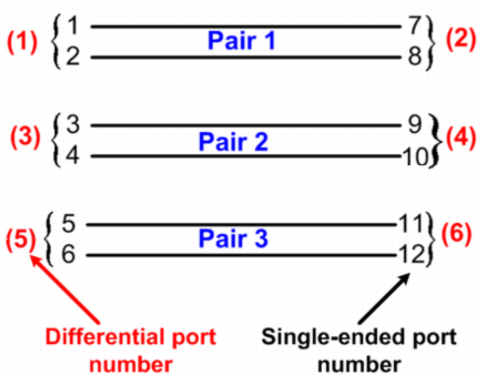


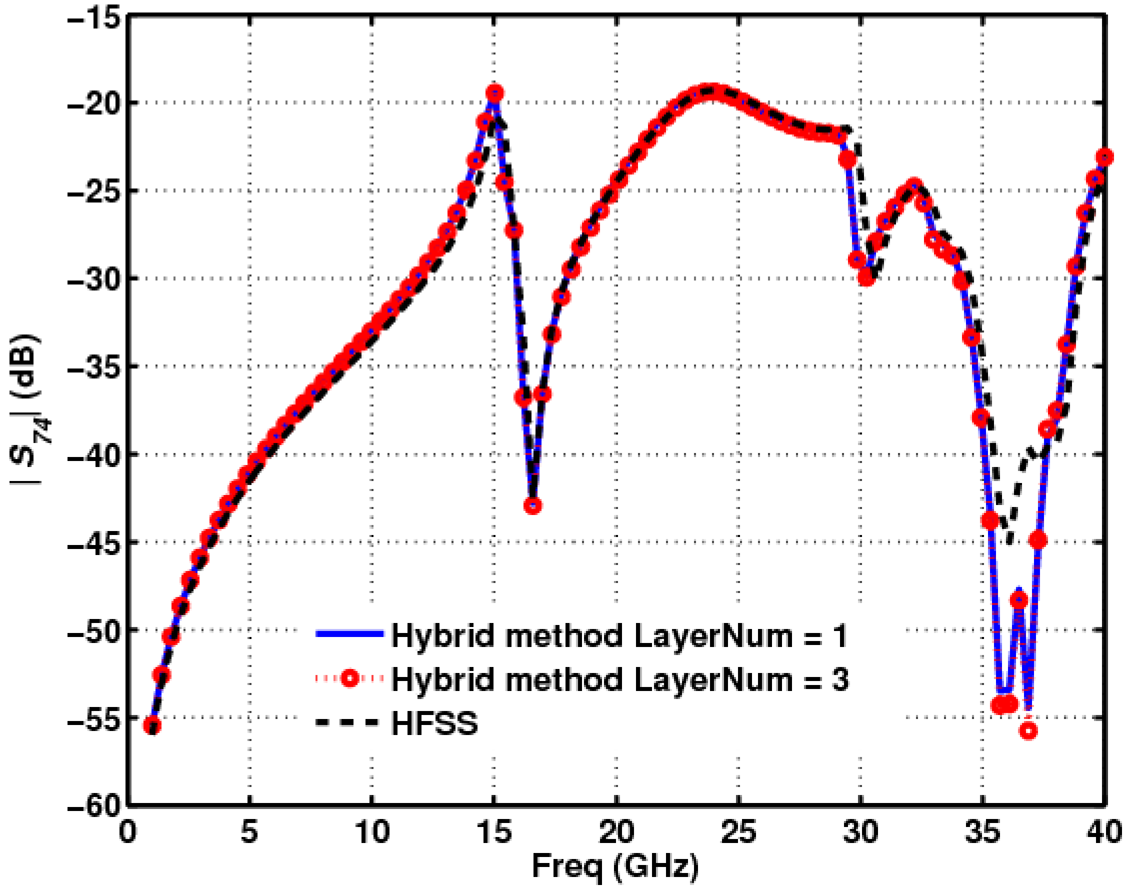
Note:

Our experience indicates dmin =1~3 h is accurate enough.

Layer number of triangular prisms

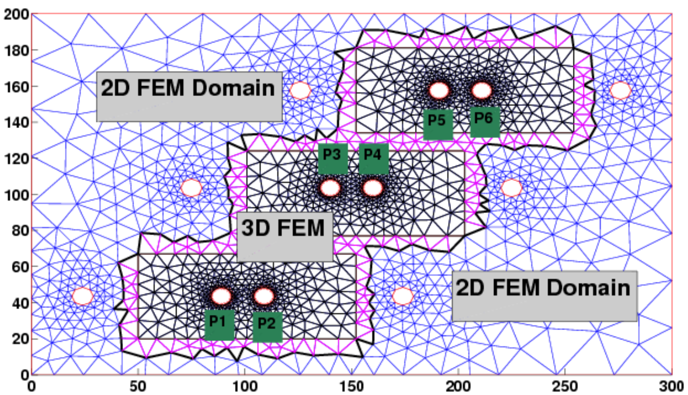


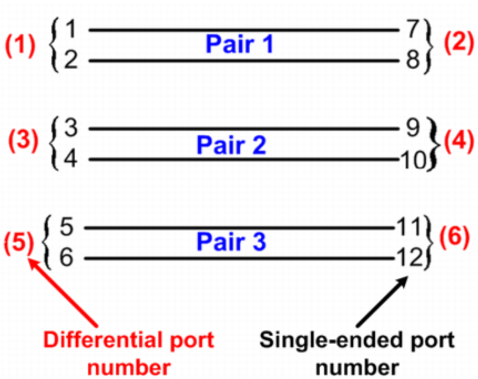


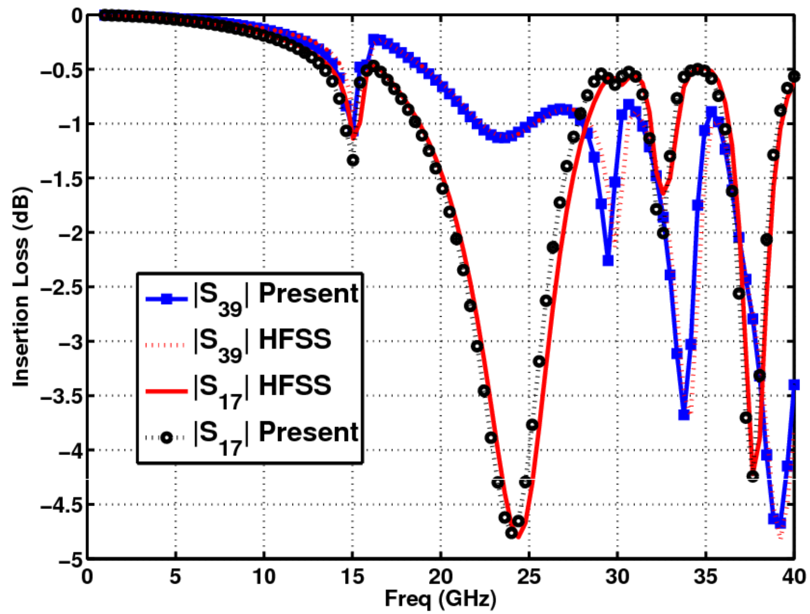


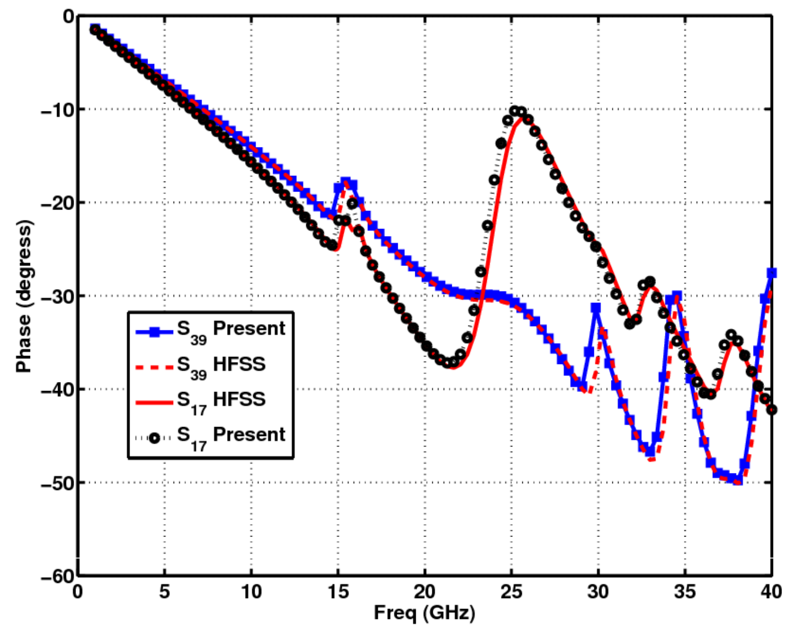
1. The hybrid method has been validated by comparing with HFSS
2. Surprisingly, only one layer of prisms is good enough.

Single-ended insertion loss



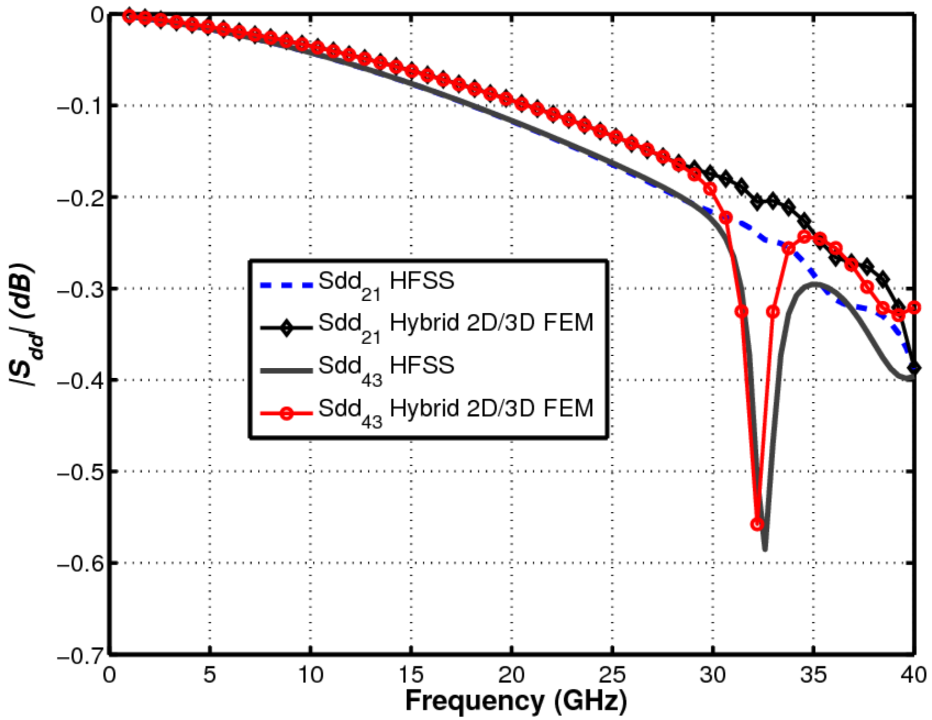


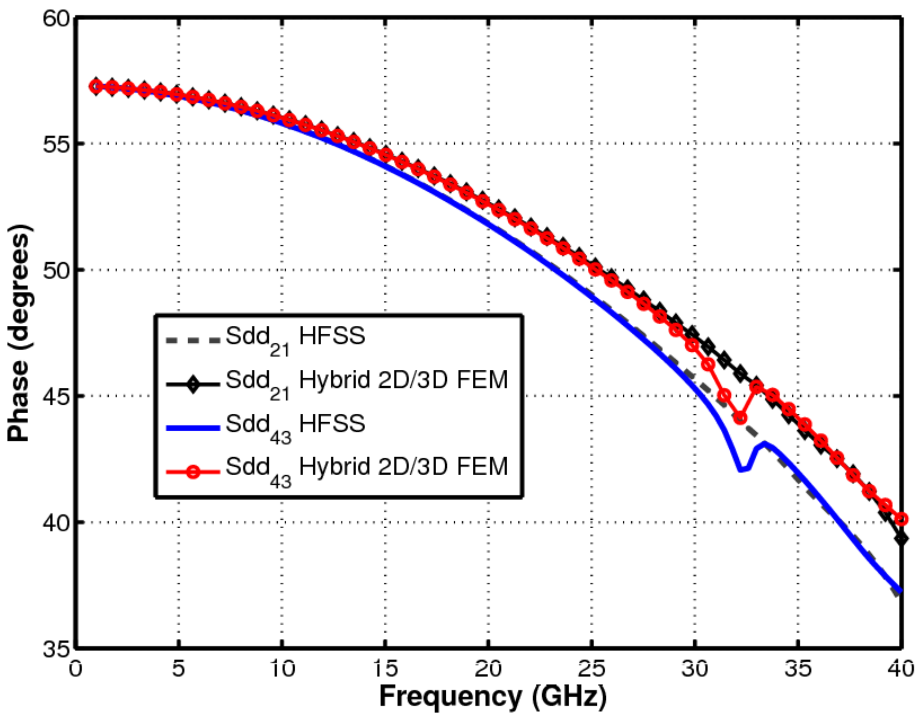


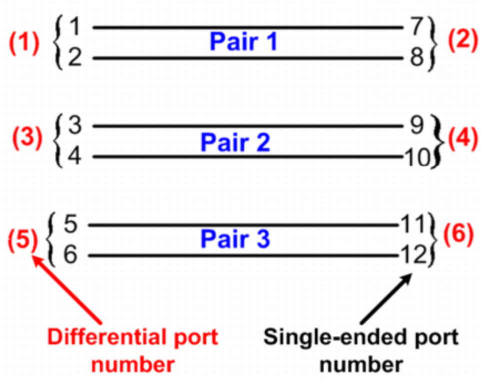


Again, the hybrid method is validated.

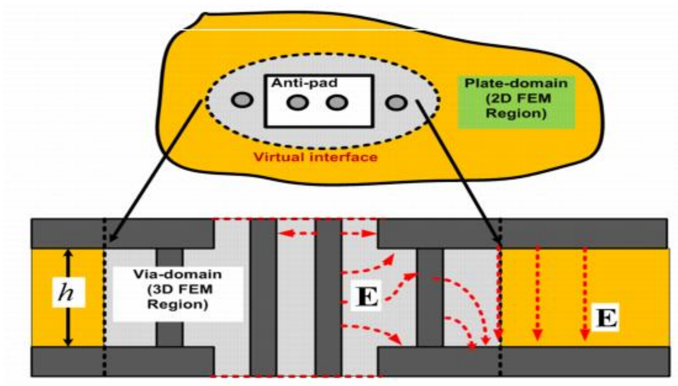
Differential mode insertion loss

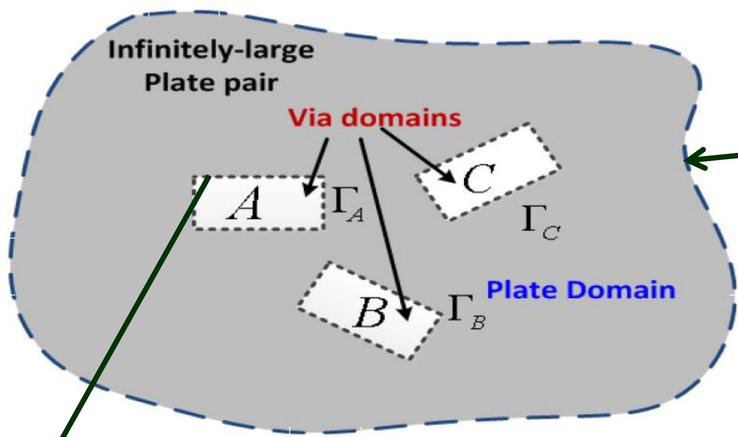




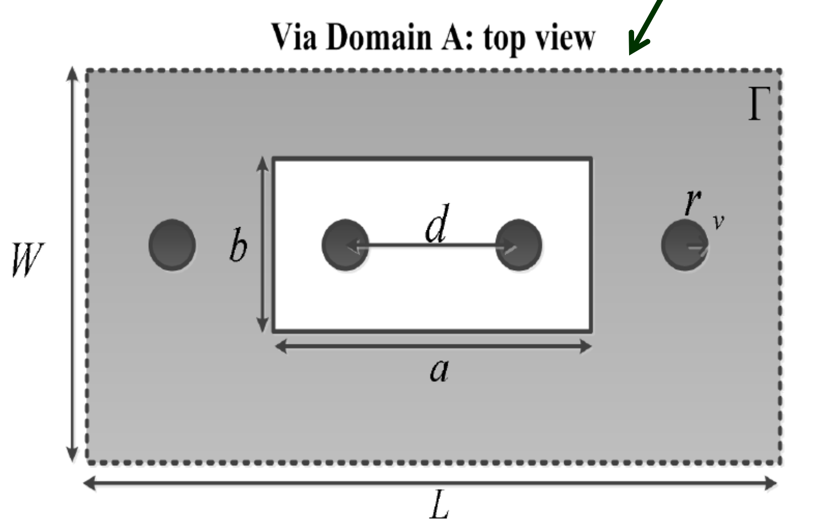


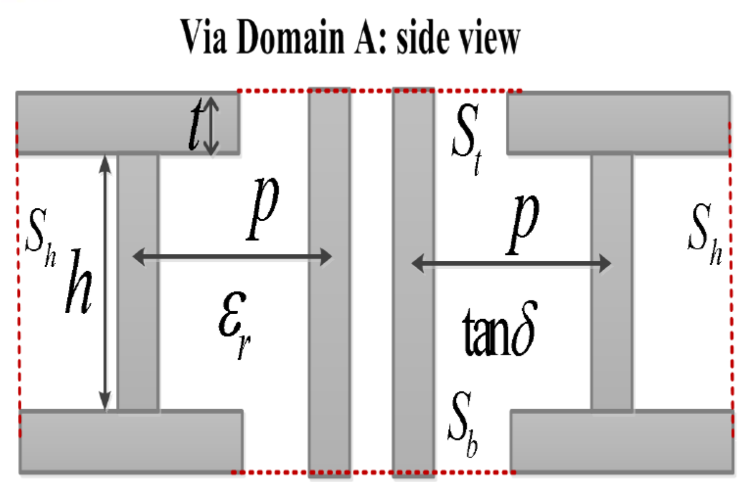
Hybrid FEM and boundary integral equations





Also PMC or PEC





Via-domains: 3D FEM + Plate-domain: 2D BIE

3D FEM analysis for via-domains

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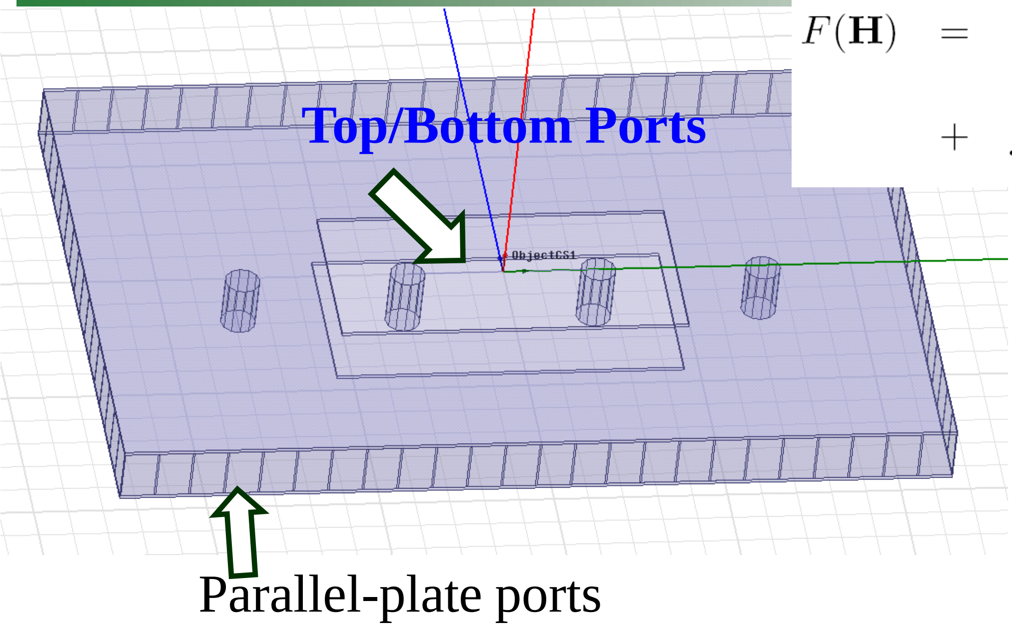


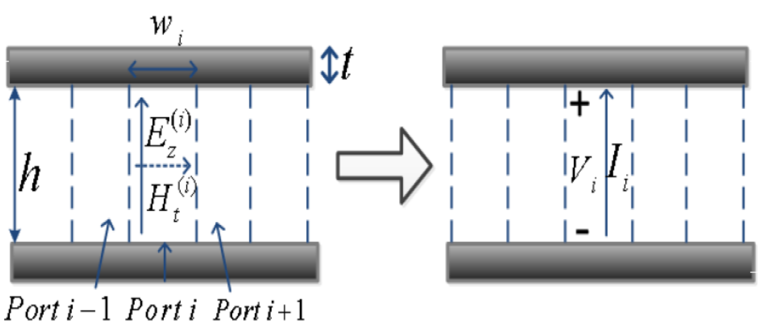
$$F(\mathbf{H}) = \frac{1}{2}\int\int\int_V \left(\nabla\times\mathbf{H}\cdot\varepsilon_r^{-1}\nabla\times\mathbf{H} - k_0^2\mathbf{H}\cdot\mathbf{H}\right)dV + j\omega\varepsilon_0\int\int_S \mathbf{n}\times\mathbf{H}\cdot\mathbf{E}_s dS \quad (1)$$

$$\mathbf{n}\times\mathbf{H} = J_z\mathbf{e}_z$$

$$\mathbf{E}_s = E_z\mathbf{e}_z$$

$$V_i = -E_z^{(i)}h$$

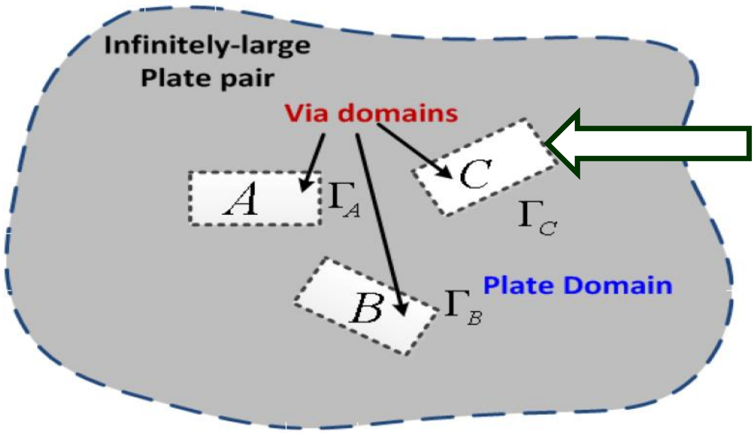
$$I_i = w_i J_z^{(i)}$$



S-parameter for a via domain

$$\begin{bmatrix}\mathbf{b}_t^v\\ \mathbf{b}_b^v\\ \mathbf{b}_h^v\end{bmatrix} = \begin{bmatrix}\mathbf{S}_{tt}^v & \mathbf{S}_{tb}^v & \mathbf{S}_{th}^v\\ \mathbf{S}_{bt}^v & \mathbf{S}_{bb}^v & \mathbf{S}_{bh}^v\\ \mathbf{S}_{ht}^v & \mathbf{S}_{hb}^v & \mathbf{S}_{hh}^v\end{bmatrix}\begin{bmatrix}\mathbf{a}_t^v\\ \mathbf{a}_b^v\\ \mathbf{a}_h^v\end{bmatrix}$$

Boundary integral equation for plate-domains



Parallel-plate ports

$$V_i = -E_z^{(i)} h$$
$$I_i = w_i J_z^{(i)}$$

Radiated E-fields by electric currents J

$$E_z^J(\mathbf{r}) = -\frac{k\eta}{4} \int_\Gamma J_z(\mathbf{r}') H_0^{(2)}(k|\mathbf{r}-\mathbf{r}'|) d\Gamma.$$

Radiated E-fields by magnetic currents M (Ez here)

$$E_z^M(\mathbf{r}) = \frac{j}{4} \int_\Gamma E_z(\mathbf{r}') \nabla \left[H_0^{(2)}(k|\mathbf{r}-\mathbf{r}'|) \right] \cdot \mathbf{n}' d\Gamma,$$

Boundary integral equations on virtual interfaces and plate edges

$$E_z(\mathbf{r}) = E_z^M(\mathbf{r}) + E_z^J(\mathbf{r})$$

$$\begin{aligned} & - \frac{k\eta}{4} \int_\Gamma J_z(\mathbf{r}') H_0^{(2)}(k|\mathbf{r}-\mathbf{r}'|) d\Gamma \\ & = E_z(\mathbf{r}) - \frac{j}{4} \int_\Gamma E_z(\mathbf{r}') \nabla \left[H_0^{(2)}(k|\mathbf{r}-\mathbf{r}'|) \right] \cdot \mathbf{n}' d\Gamma \end{aligned}$$

Plate-domain model: Zpp

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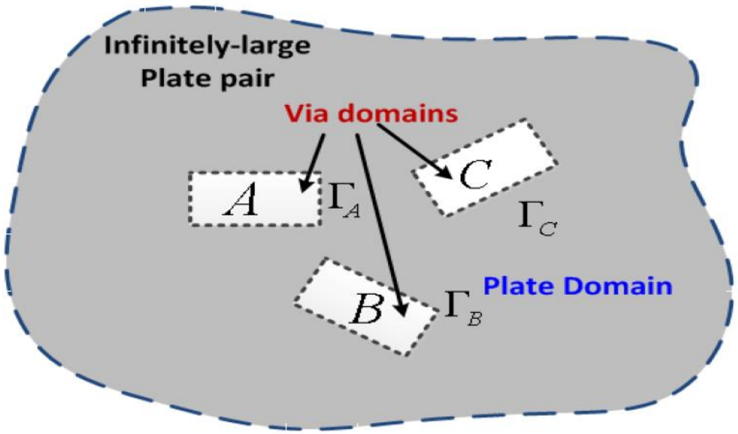
$$
\begin{aligned}
& - \quad \frac{k\eta}{4} \int_{\Gamma} J_z(\mathbf{r}') H_0^{(2)}(k|\mathbf{r}-\mathbf{r}'|) d\Gamma \\
& = \quad E_z(\mathbf{r}) - \frac{j}{4} \int_{\Gamma} E_z(\mathbf{r}') \nabla \left[H_0^{(2)}(k|\mathbf{r}-\mathbf{r}'|) \right] \cdot \mathbf{n}' d\Gamma
\end{aligned}
$$



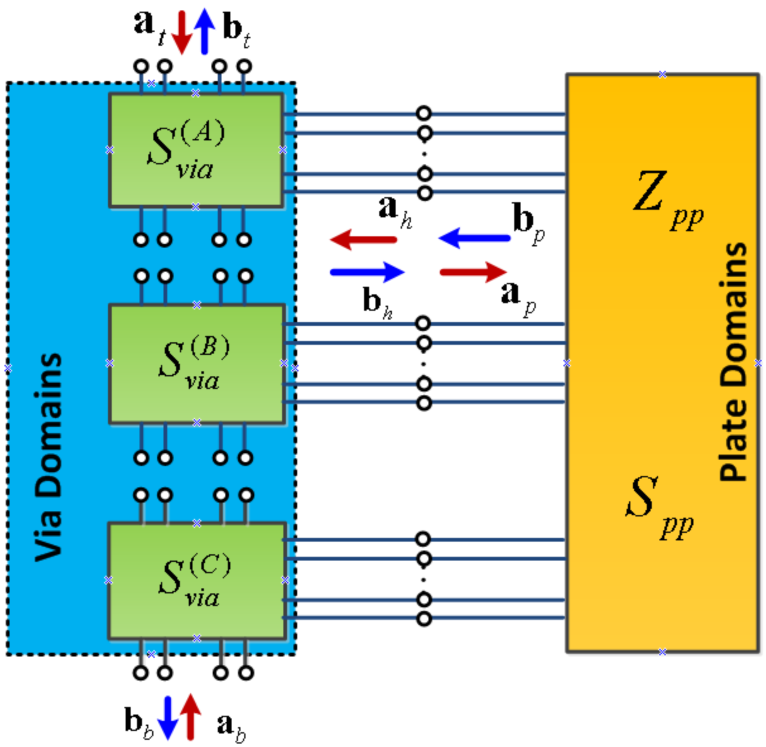
$$
\begin{aligned}
V_i &= -E_z^{(i)} h \\
I_i &= w_i J_z^{(i)}
\end{aligned}
$$

Integral equation solved by the method of moments

$$\mathbf{V}_p = \mathbf{Z}_{pp} \mathbf{I}_p$$

Zpp related tangential H-fields and E-fields on the virtual interfaces between 3D FEM via domains and the plate domain.

Integrated via domains and plate domain



Combined S-parameters of via domains

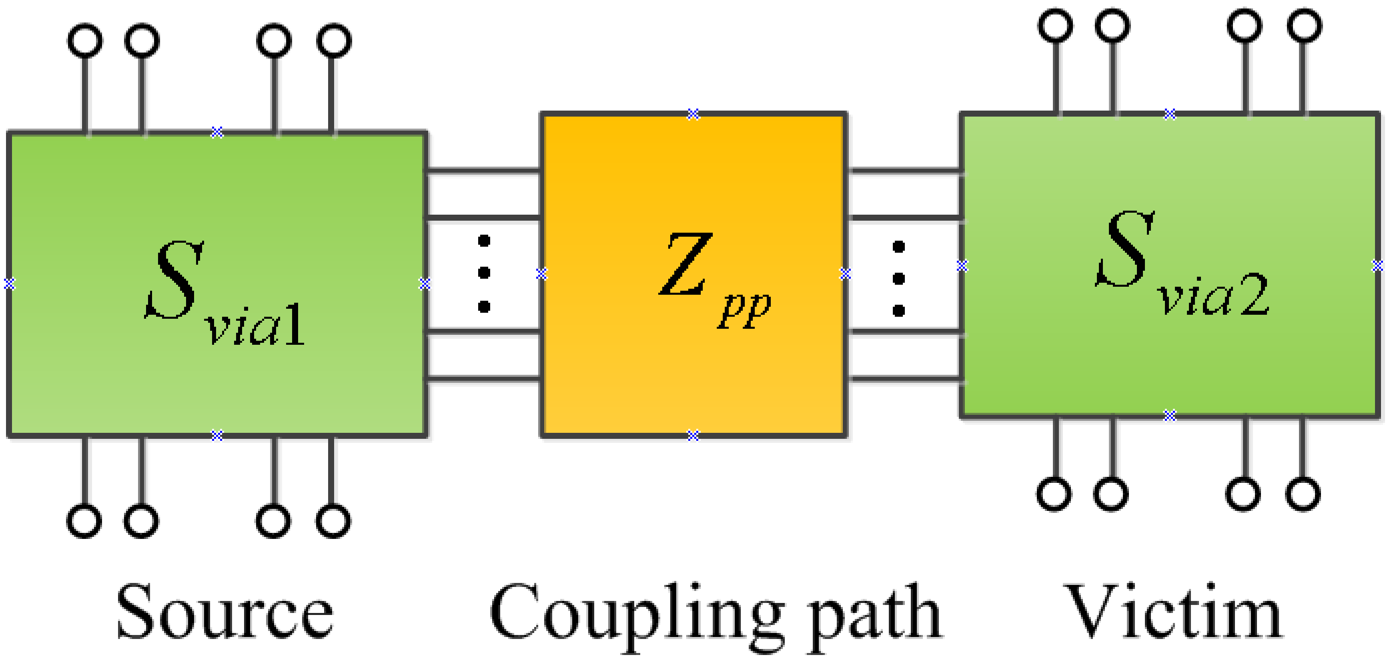
$$\begin{bmatrix} \mathbf{b}_t \\ \mathbf{b}_b \\ \mathbf{b}_h \end{bmatrix} = \begin{bmatrix} \mathbf{S}_{tt} & \mathbf{S}_{tb} & \mathbf{S}_{th} \\ \mathbf{S}_{bt} & \mathbf{S}_{bb} & \mathbf{S}_{bh} \\ \mathbf{S}_{ht} & \mathbf{S}_{hb} & \mathbf{S}_{hh} \end{bmatrix} \begin{bmatrix} \mathbf{a}_t \\ \mathbf{a}_b \\ \mathbf{a}_h \end{bmatrix}$$

Connection of S-parameters of via domains and plat domain

$$\begin{bmatrix} \mathbf{b}_t \\ \mathbf{b}_b \end{bmatrix} = \begin{bmatrix} \mathbf{S}_{tt}^{(l)} & \mathbf{S}_{tb}^{(l)} \\ \mathbf{S}_{bt}^{(l)} & \mathbf{S}_{bb}^{(l)} \end{bmatrix} \begin{bmatrix} \mathbf{a}_t \\ \mathbf{a}_b \end{bmatrix}$$

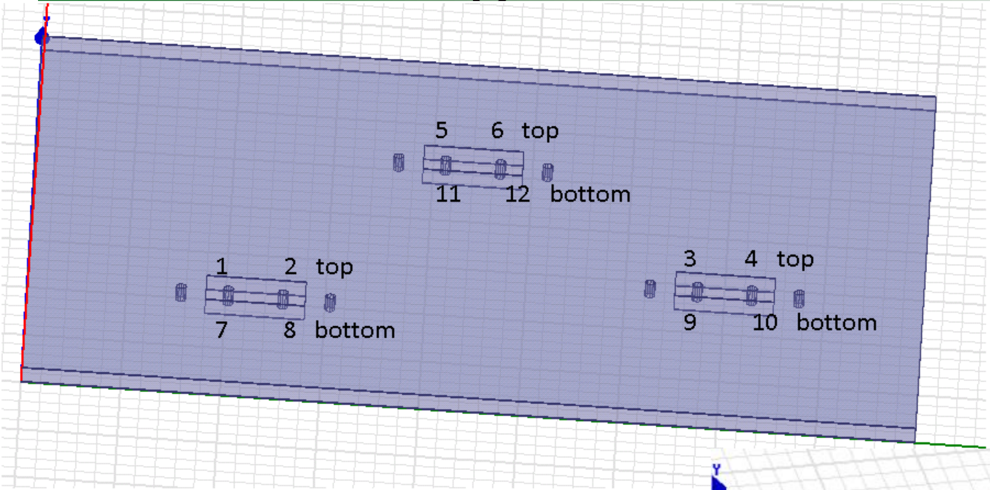
$$\begin{aligned}
\mathbf{S}_{tt}^{(l)} &= \mathbf{S}_{tt} + \mathbf{S}_{th}\mathbf{S}_{pp}\left(\mathbf{I} - \mathbf{S}_{hh}\mathbf{S}_{pp}\right)^{-1}\mathbf{S}_{ht} \\
\mathbf{S}_{tb}^{(l)} &= \mathbf{S}_{tb} + \mathbf{S}_{th}\mathbf{S}_{pp}\left(\mathbf{I} - \mathbf{S}_{hh}\mathbf{S}_{pp}\right)^{-1}\mathbf{S}_{hb} \\
\mathbf{S}_{bt}^{(l)} &= \mathbf{S}_{bt} + \mathbf{S}_{bh}\mathbf{S}_{pp}\left(\mathbf{I} - \mathbf{S}_{hh}\mathbf{S}_{pp}\right)^{-1}\mathbf{S}_{ht} \\
\mathbf{S}_{bb}^{(l)} &= \mathbf{S}_{bb} + \mathbf{S}_{bh}\mathbf{S}_{pp}\left(\mathbf{I} - \mathbf{S}_{hh}\mathbf{S}_{pp}\right)^{-1}\mathbf{S}_{hb}
\end{aligned}$$

Benefits of hybrid 3D FEM and BIE



1. S-parameter of each via domain can be regarded as intrinsic properties of the via structure as it does not change with surrounding environment.
2. S-parameter of the plate domain characterizes the coupling path among via domains.

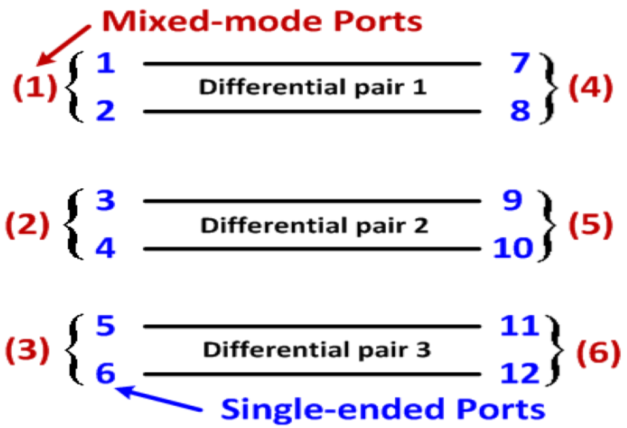
Three via structures in a plate pair with PML and PMC edges

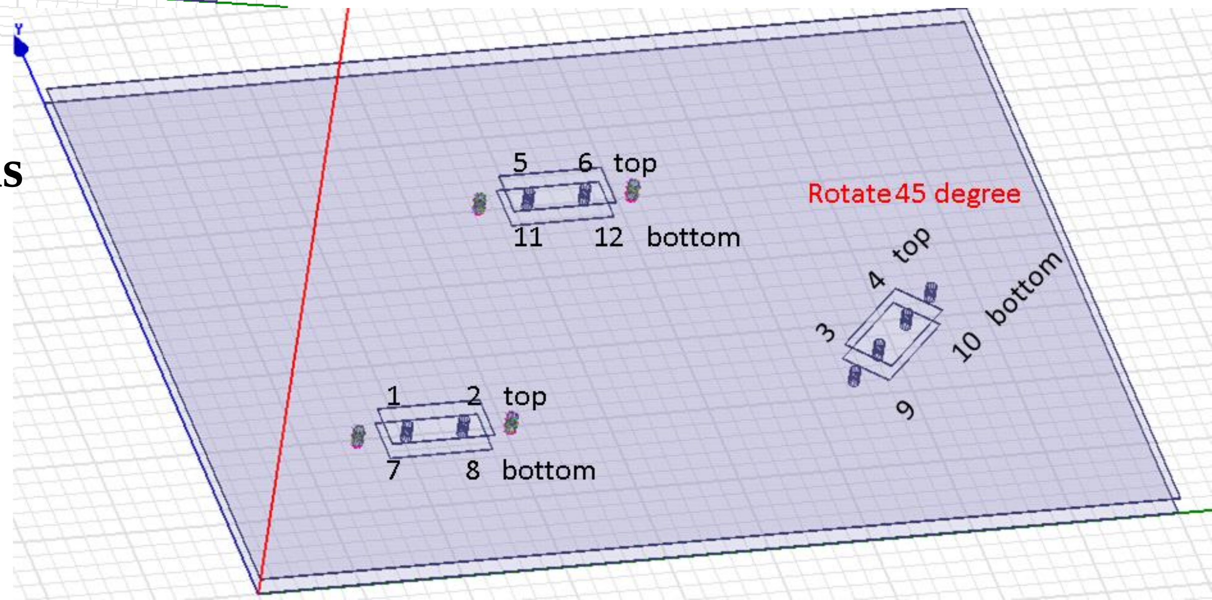


Case 1: three parallel via domains

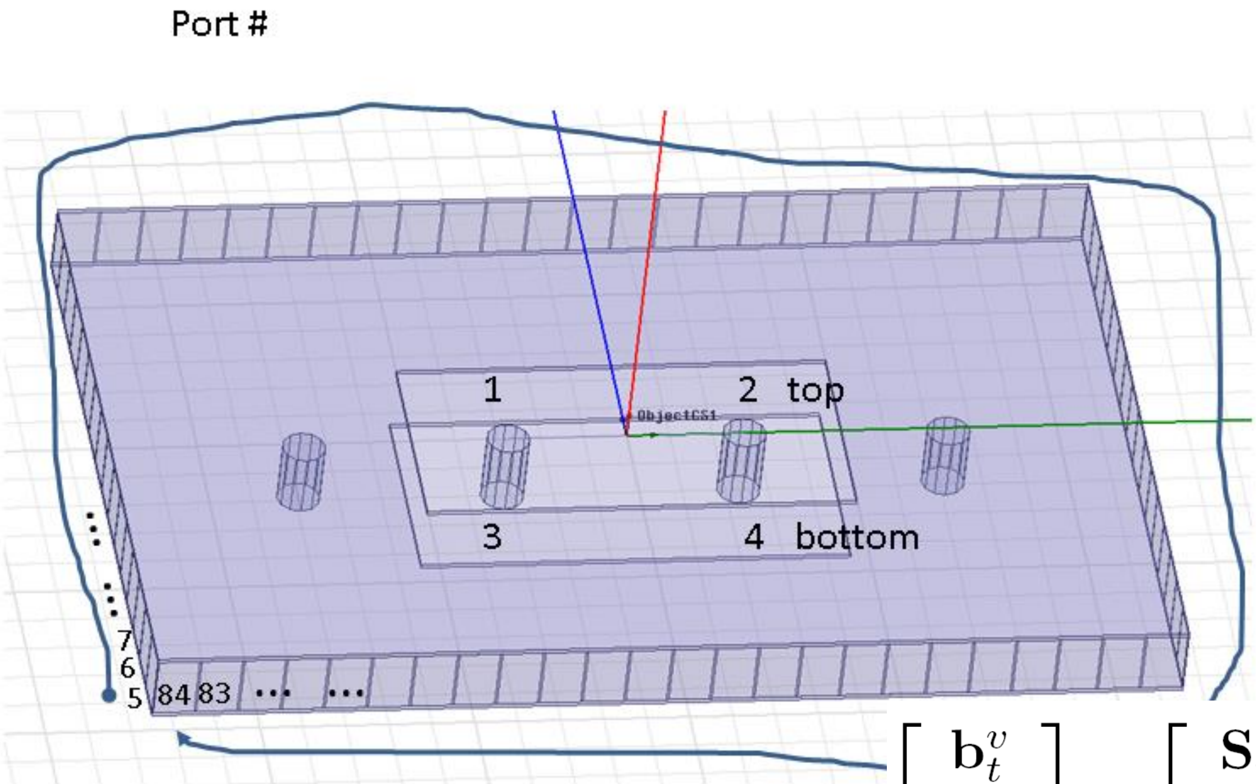
Radiation boundary condition and perfectly magnetic boundaries are used for 4 edges in HFSS simulation.

Case 2: three via domains





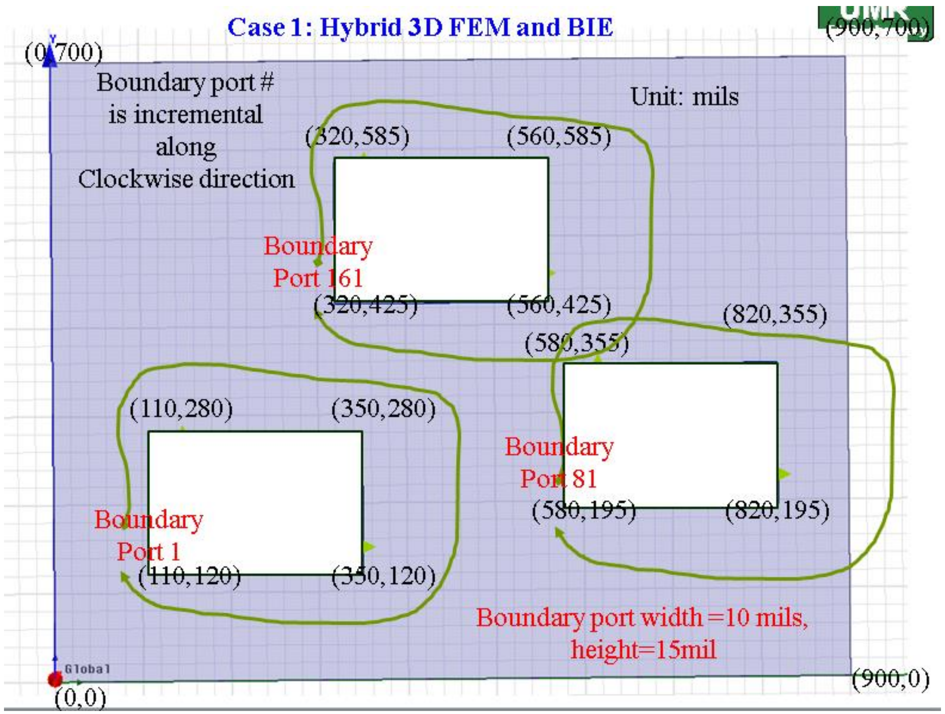
Hybrid 3D FEM and BIE: via domain



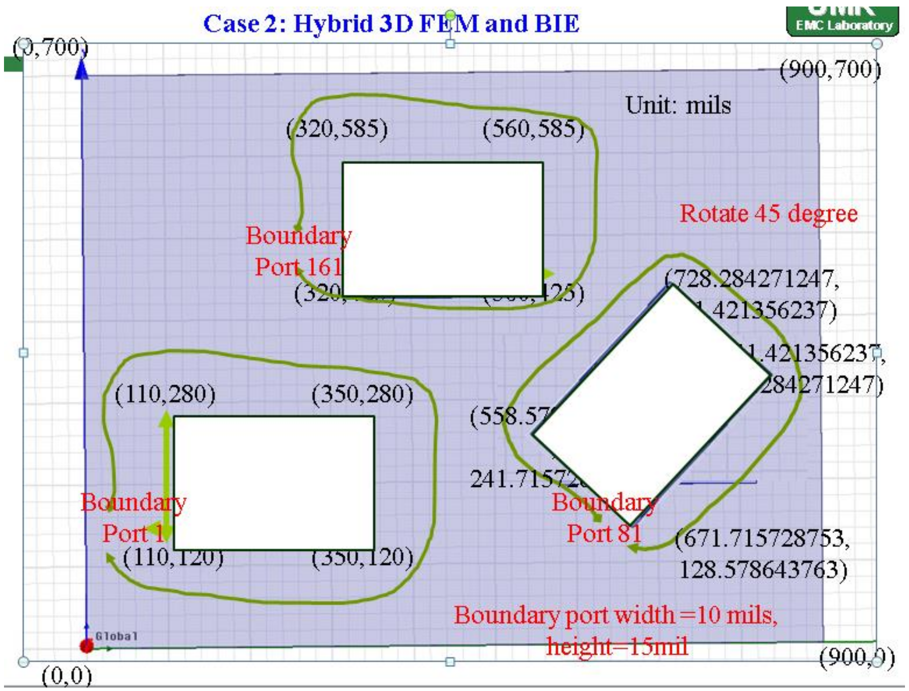
$$\begin{bmatrix} \mathbf{b}_t^v \\ \mathbf{b}_b^v \\ \mathbf{b}_h^v \end{bmatrix} = \begin{bmatrix} \mathbf{S}_{tt}^v & \mathbf{S}_{tb}^v & \mathbf{S}_{th}^v \\ \mathbf{S}_{bt}^v & \mathbf{S}_{bb}^v & \mathbf{S}_{bh}^v \\ \mathbf{S}_{ht}^v & \mathbf{S}_{hb}^v & \mathbf{S}_{hh}^v \end{bmatrix} \begin{bmatrix} \mathbf{a}_t^v \\ \mathbf{a}_b^v \\ \mathbf{a}_h^v \end{bmatrix}$$

84-by-84 S-parameter matrix for a single via domain.

Plate domain in hybrid 3D FEM and BIE

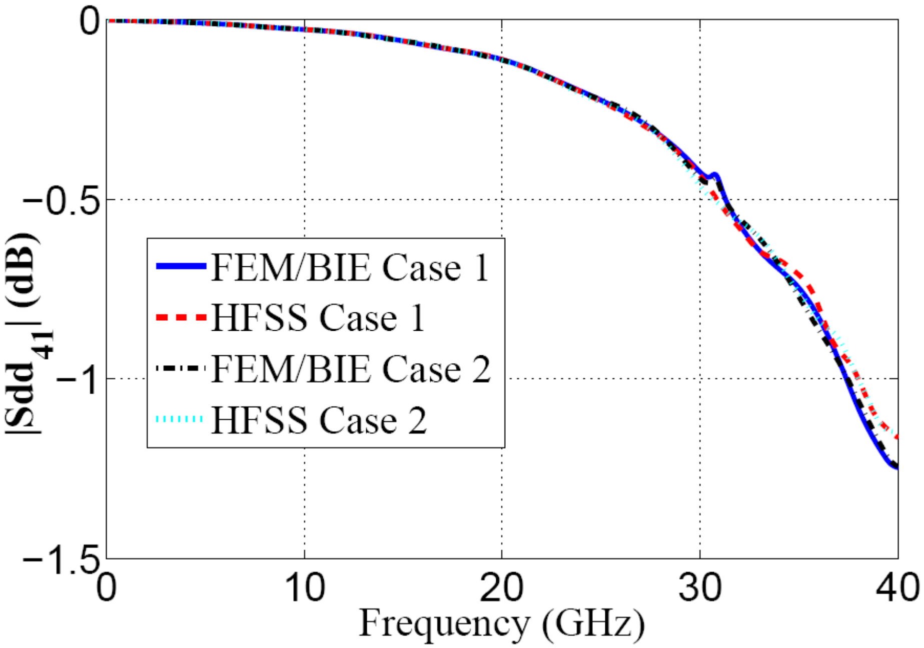


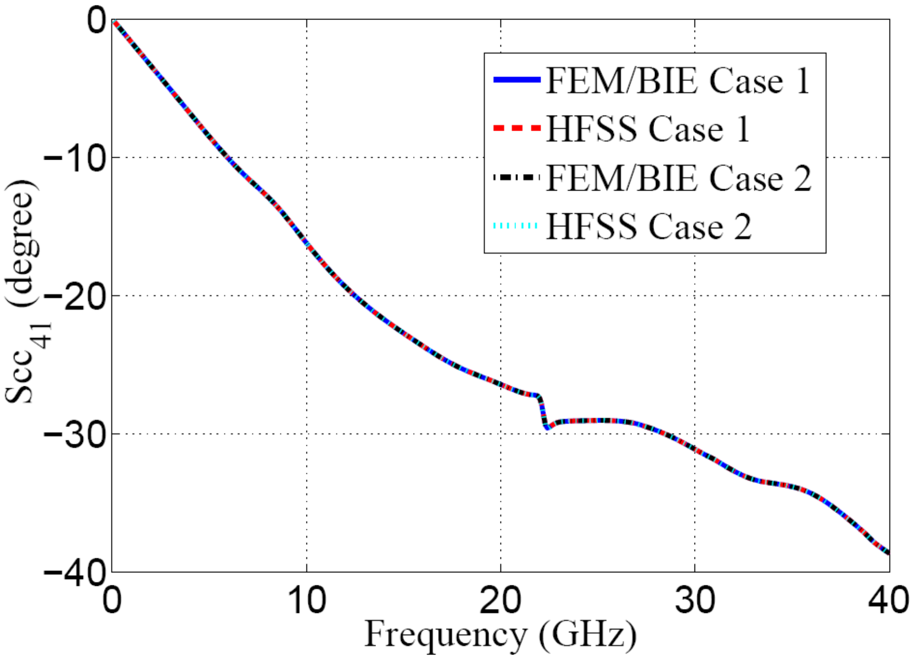
Case 1



Case 2

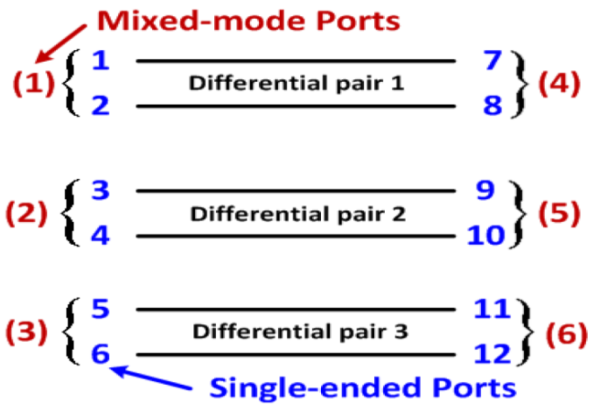
Insertion loss: infinitely-large plate pair



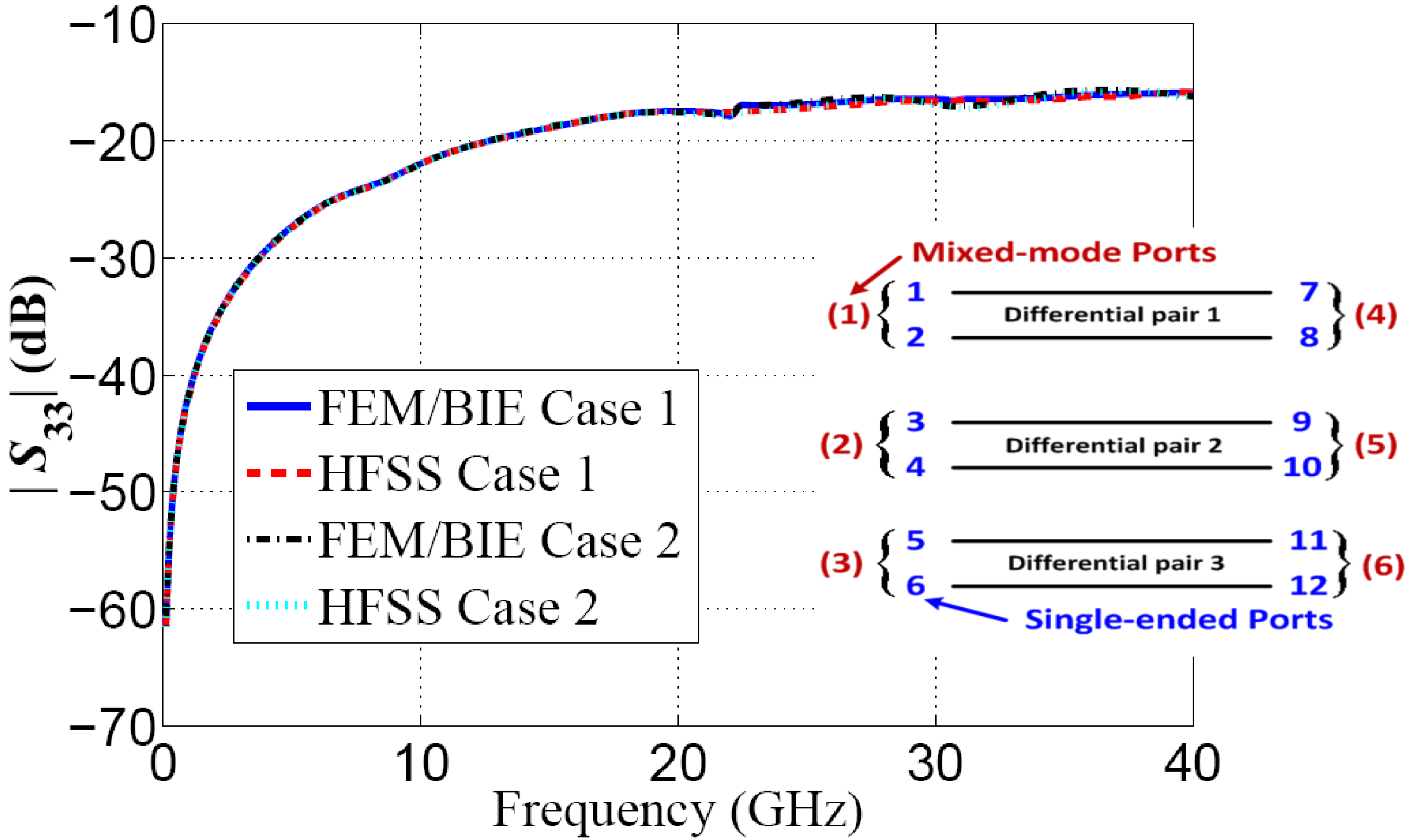


Differential mode

Common mode



Single-ended return loss



Insertion loss: finite plate pair with PMC edges

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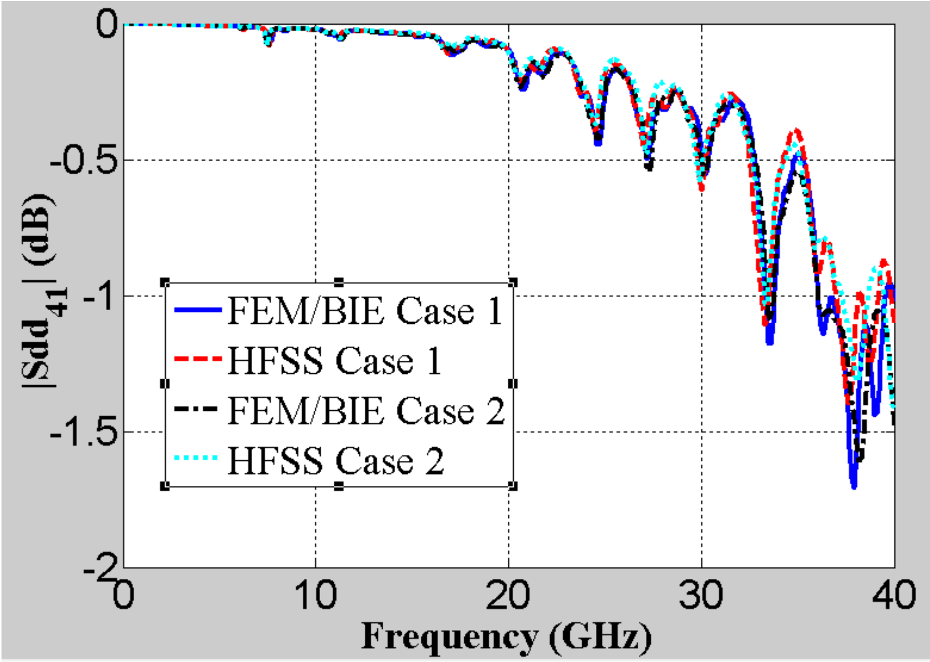
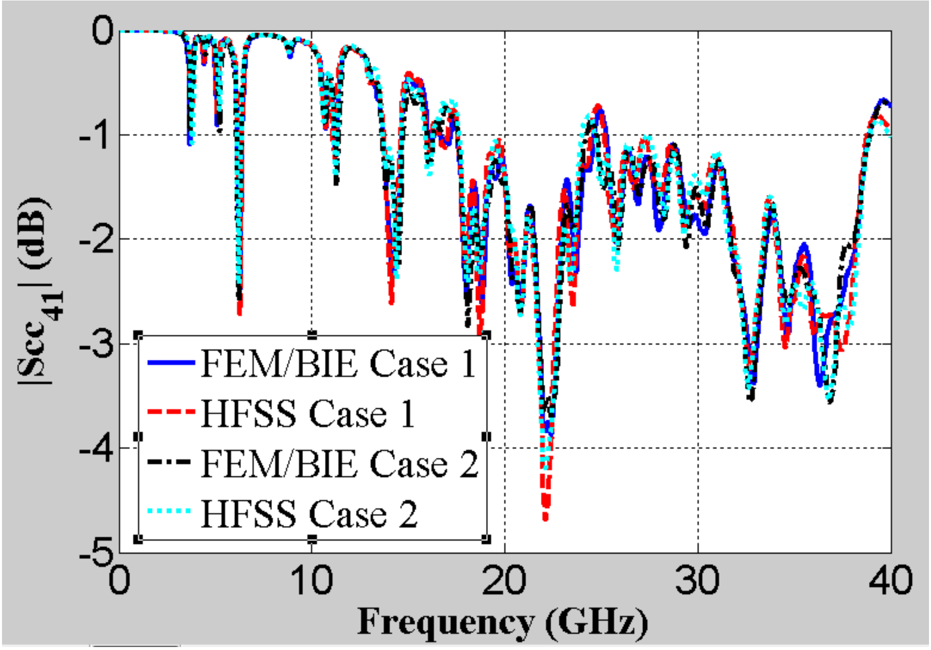
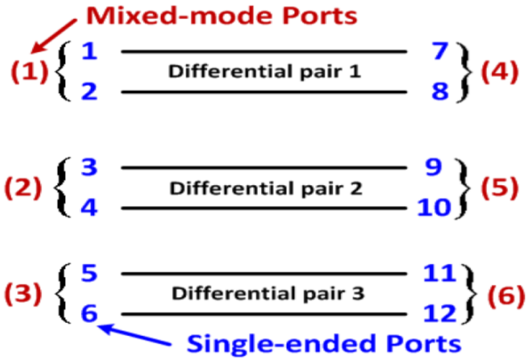


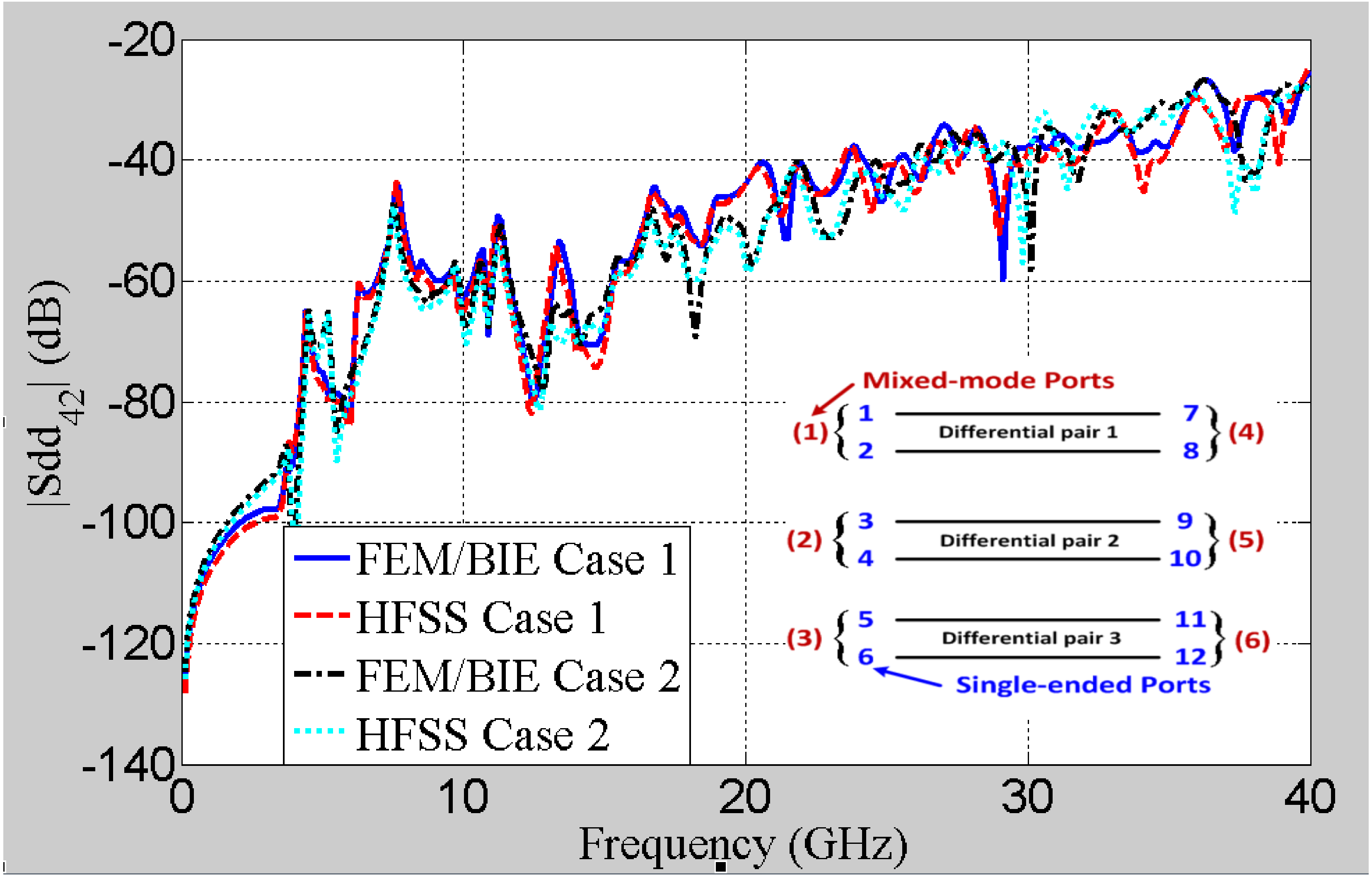


Differential mode



Common mode

Forward Cross Talk



Mixed-mode cross-talk

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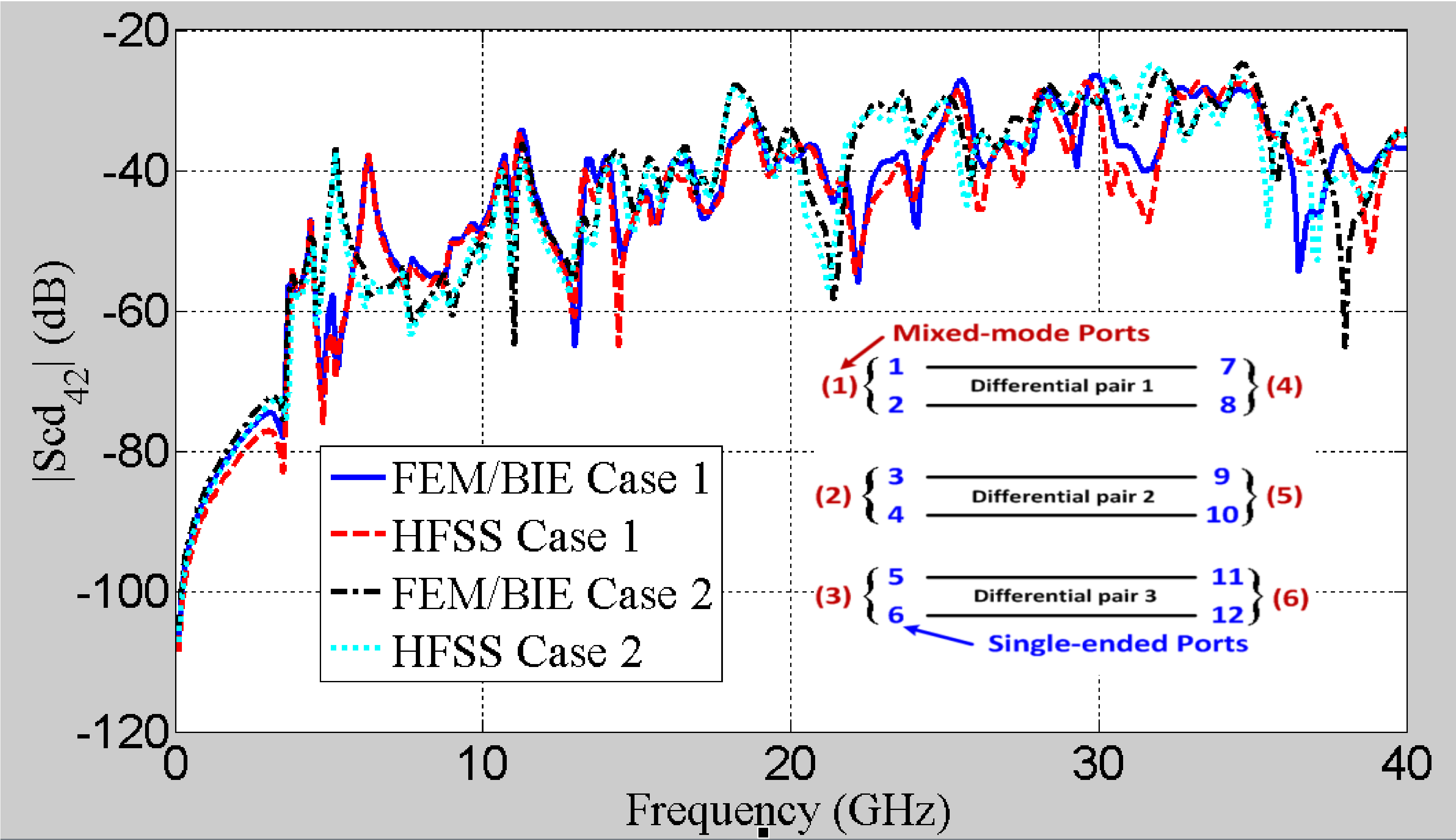

Future work: higher-order modes in anti-pads

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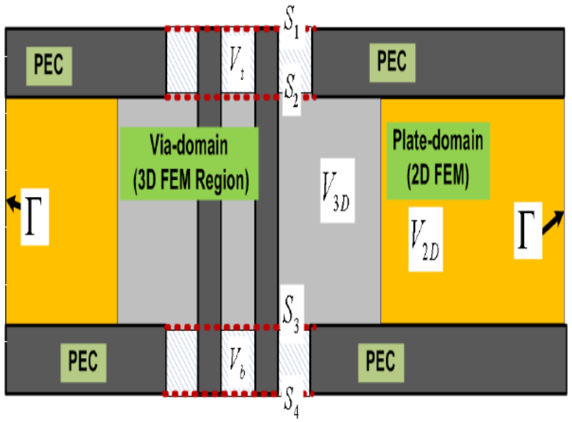
Test TEM assumption in via holes on S1 and S2

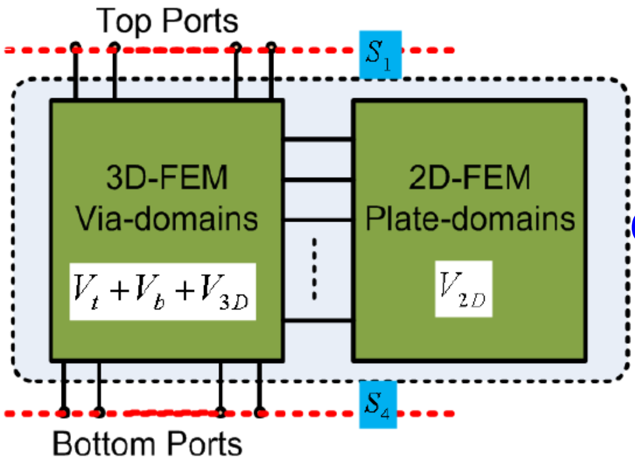


Hybrid 3D/2D FEM

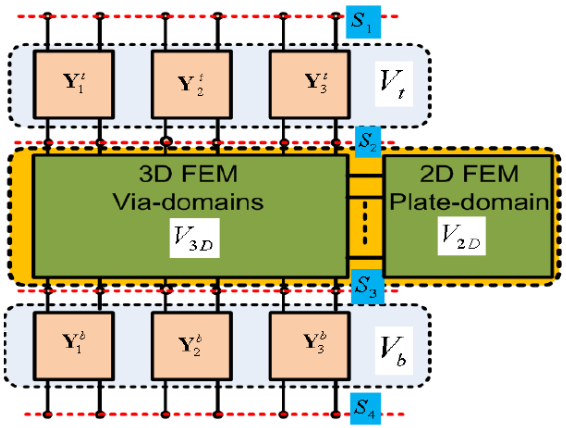
Combined admittance matrix (CAM)

Higher-order modes considered

Higher-order modes not considered



Comparison



If TEM mode assumptions on S2 and S3 are good enough, two approaches should get similar results.

Comparisons: different plate thickness

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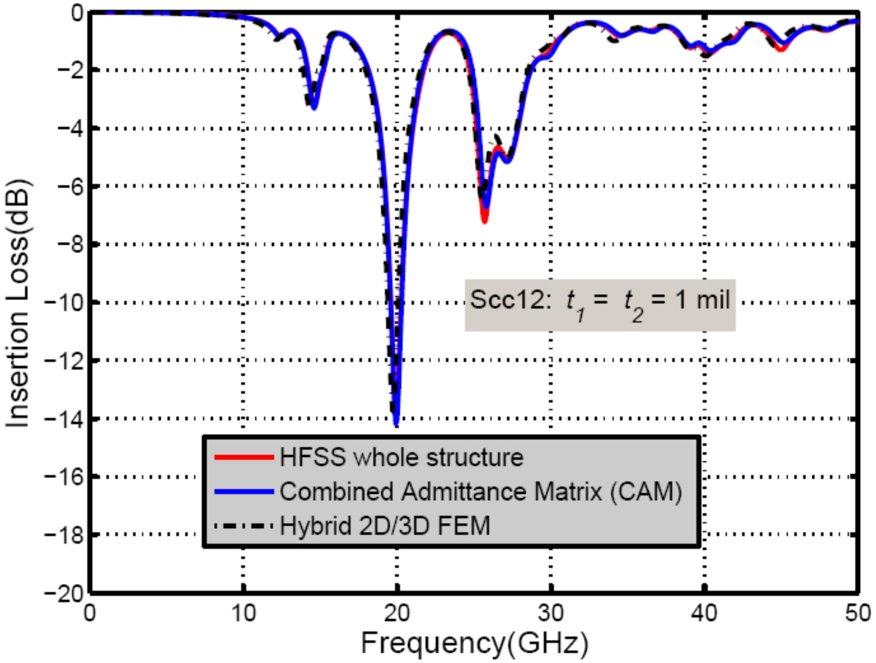


Plate thickness: 1 mils

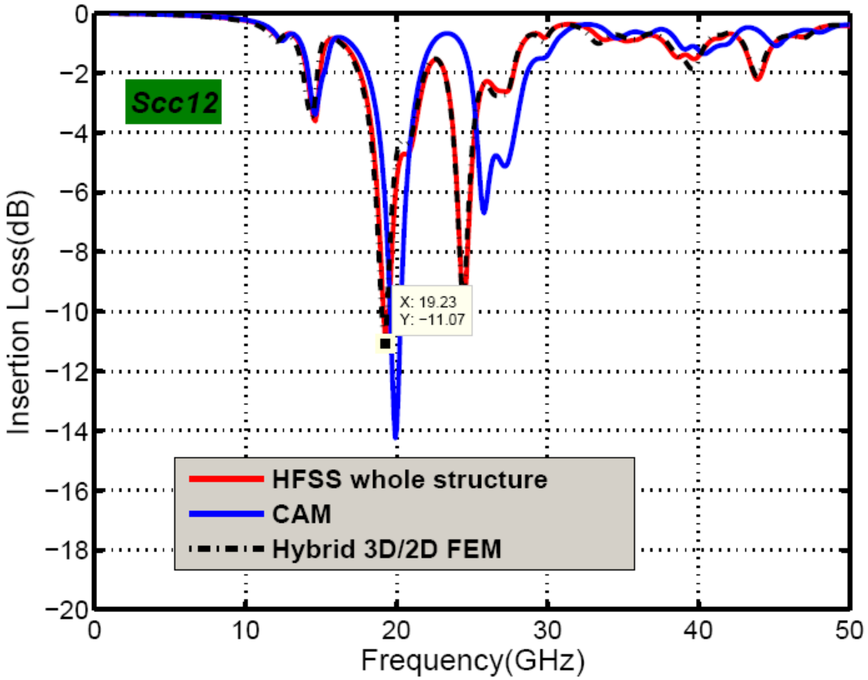
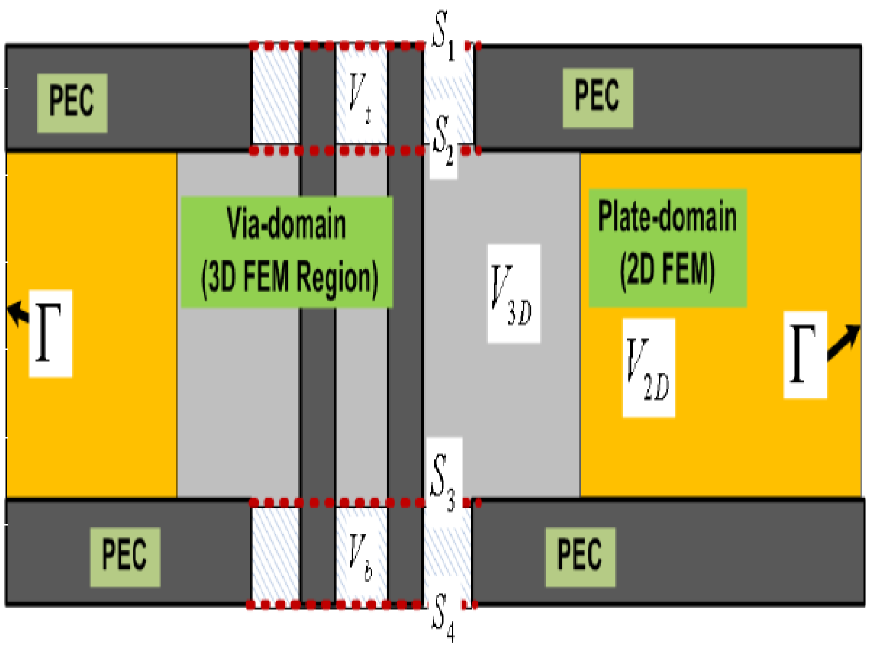


Plate thickness: 10 mils

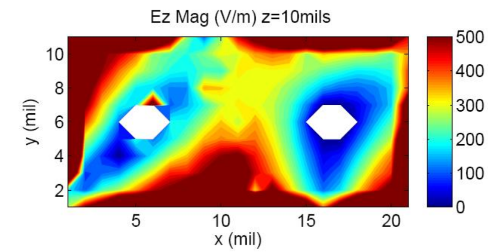
Question: why smaller plate thickness leads to smaller differences between two approaches?

Explanation: plate thickness 10 mils

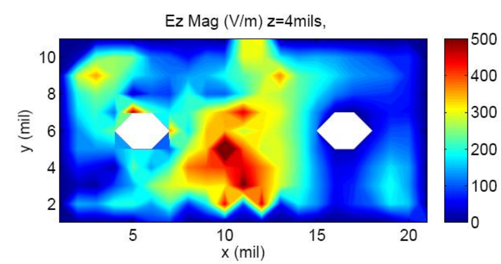


TEM modes as sources on S1

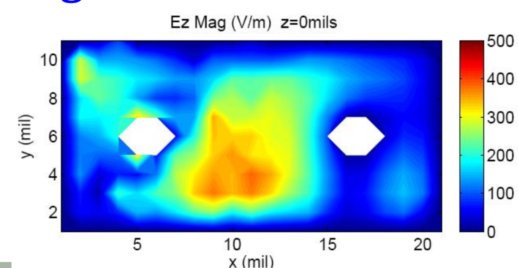
Higher-order E-modes on S2



Higher-order E-modes on a cross-section between S1 and S2



Higher-order E-modes on S1



Note:

1. Strictly speaking, TEM assumption on S2 or S3 is not correct but perhaps an acceptable approximation.
2. More rigorous method will include the higher-order modes as they can couple from one layer of plate pair to another layer.

Summary

- Critical roles of via modeling in SI/PI and EMI analysis
- Review of hybrid field-circuit models of vias for conventional via structures.
- Two recently developed hybrid methods, hybrid 3D/2D FEM and hybrid 3D FEM and 2D BIE, are introduced.

Comments and Questions?

Suggestion for future work?