Task 2: Modeling and Simulation of Conducted and Radiated EMI from HPM and UWB Sources on PCBs and ICs

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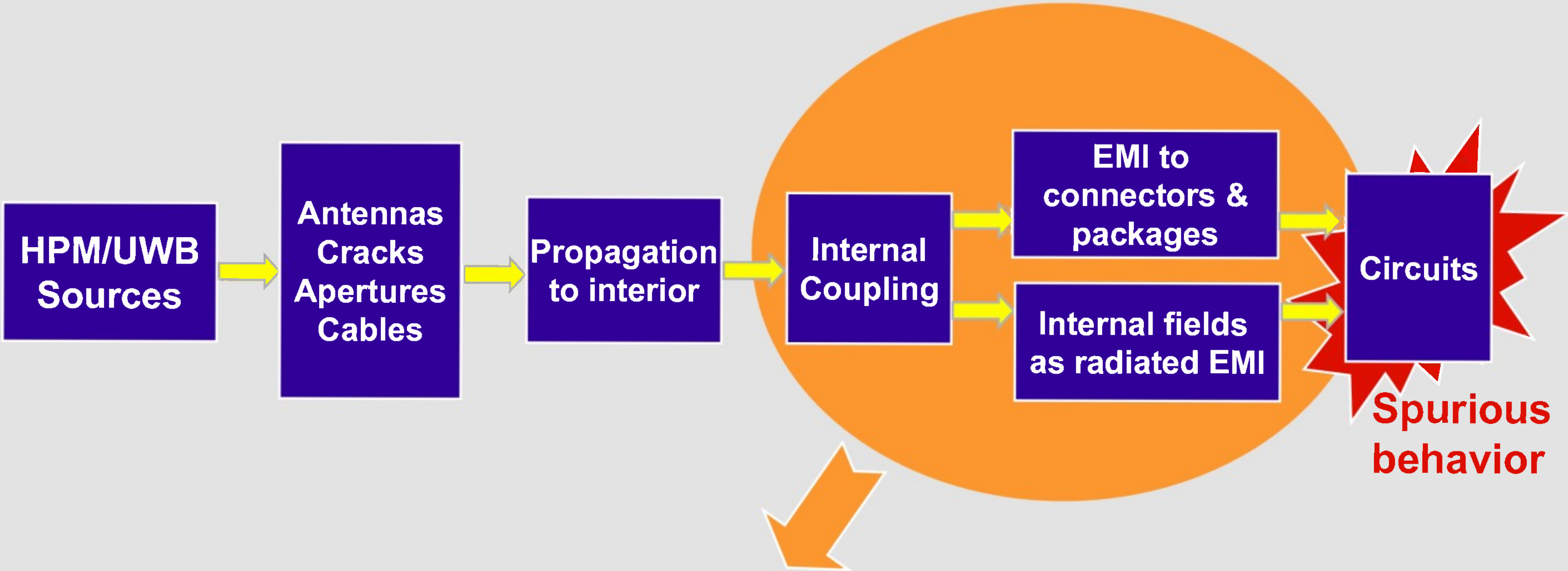
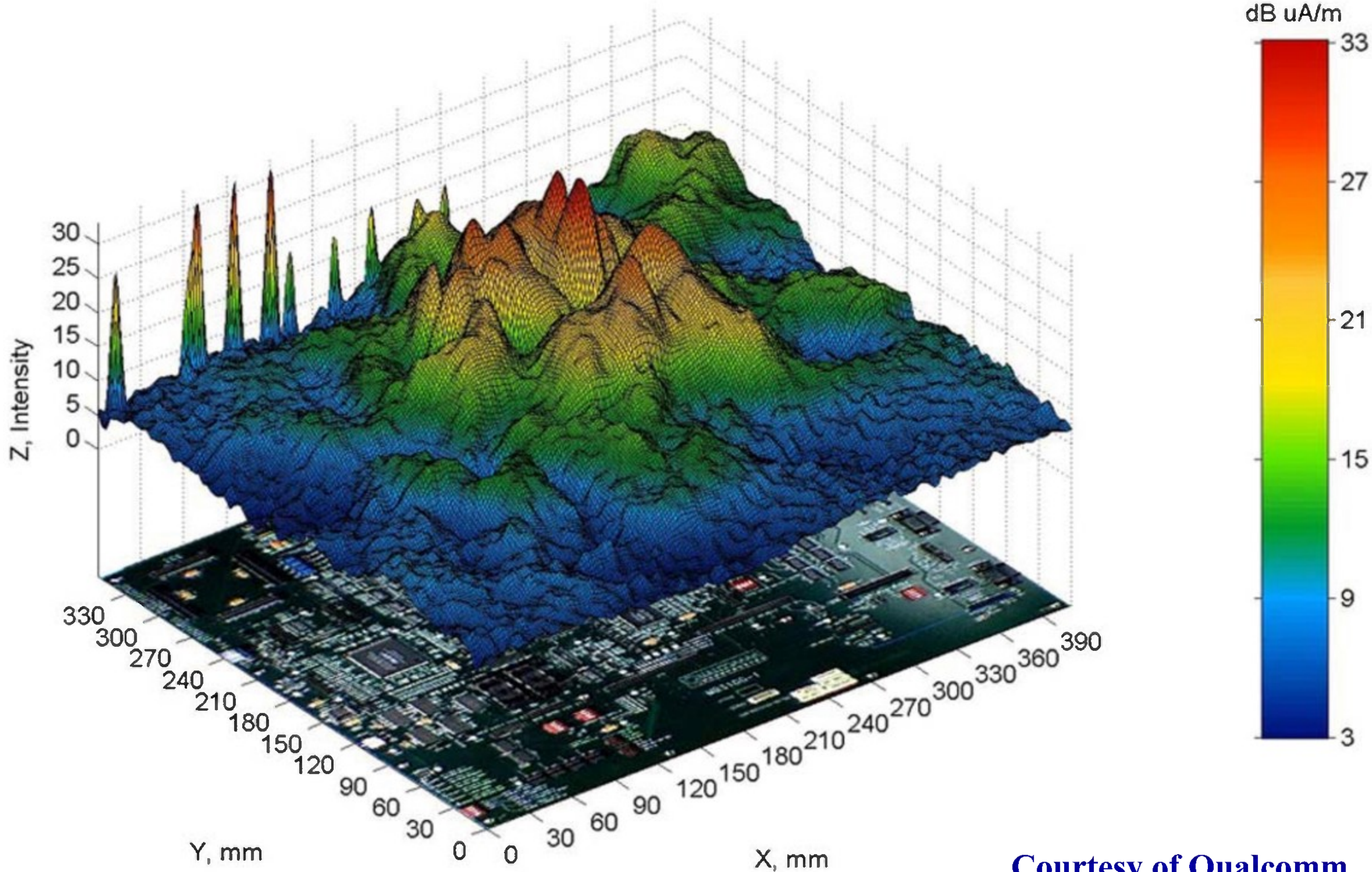
Objective



- Accurately “propagate” the spurious signals (noise) through the packaging hierarchy (printed circuit boards, cards, connectors, interposer, package…) to the die.

Major Obstacle: Tackling System Complexity



Courtesy of Qualcomm

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System Complexity translates to EM Complexity

- **EM Complexity**
  - Geometric complexity and distributed nature of the packaging hierarchy ("coupling path")
  - Broad frequency bandwidth of the interfering signal
  - Non-linearity of the terminations
- **Tackling Complexity**
  - Hierarchical approach to the modeling of electromagnetic interactions
    - From lumped models, to transmission-line models, to quasi-3D full-wave models, to 3D full-wave models
- **Abstracting Complexity**
  - Systematic order reduction of numerical models of the coupling path
  - Equivalent circuit representation of the coupling path for its seamless incorporation in network-oriented non-linear circuit simulators

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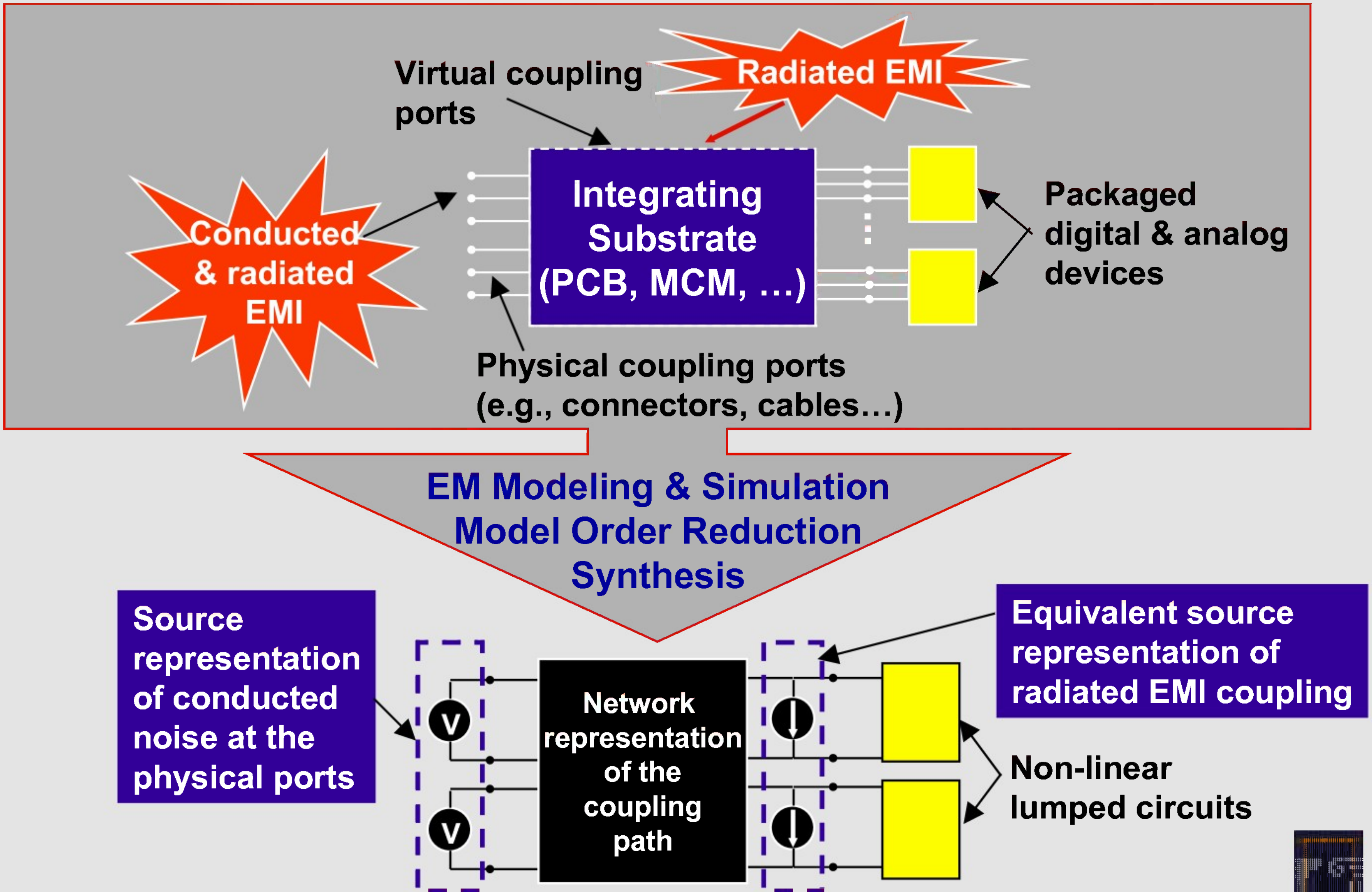
SUMMARY OF MODELING OBJECTIVE

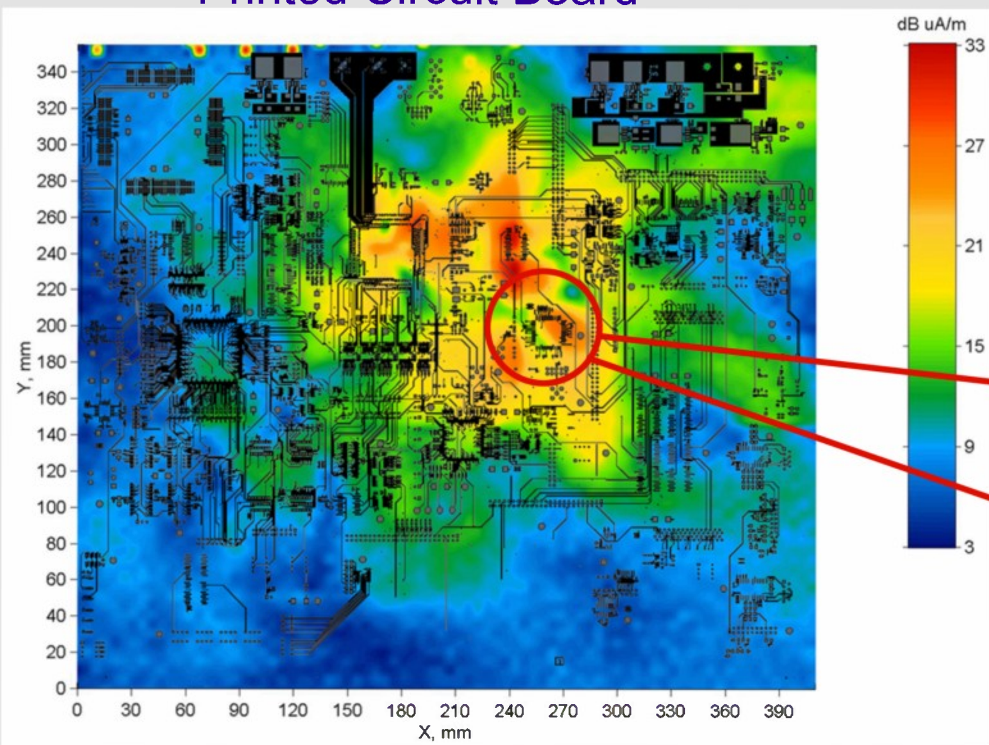


Specific Subtasks

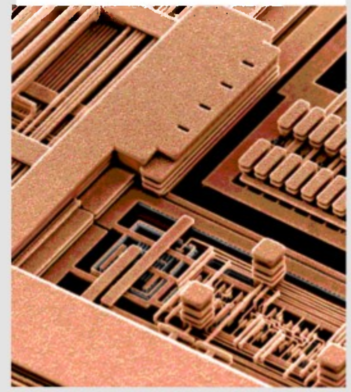
- Task 2.1 Development of a coupling path modeling methodology
- Task 2.2 Development of a (EMI) source modeling methodology
- Task 2.3 Non-linear Transient Simulation of the hybrid lumped-distributed non-linear network

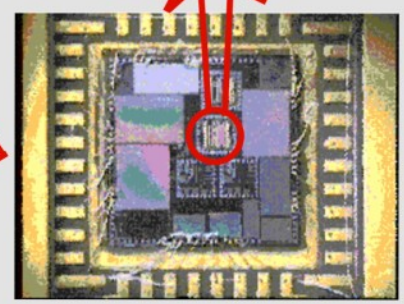
Subtask 1: Modeling of the Coupling Path

Printed Circuit Board



Chip





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Subtask 1: Modeling of the Coupling Path (Cont)

- Our modeling approach is hierarchical
  - EM-Physics driven "divide and conquer" approach
- Use suitable EM modeling approach for individual blocks
  - RLC models for short interconnect at chip & package level
  - Multi-conductor Transmission Lines (MTL)
    - Balanced interconnects at the board level
  - Quasi-3D EM Modeling for PCB power delivery network
  - Full-wave modeling
    - Unbalanced interconnects at the board level
    - Coupling through cables
    - RF/microwave packages & boards
- Reduction of EM models to non-linear network simulator (e.g. SPICE)
  - Direct model order reduction
  - Equivalent circuit synthesis

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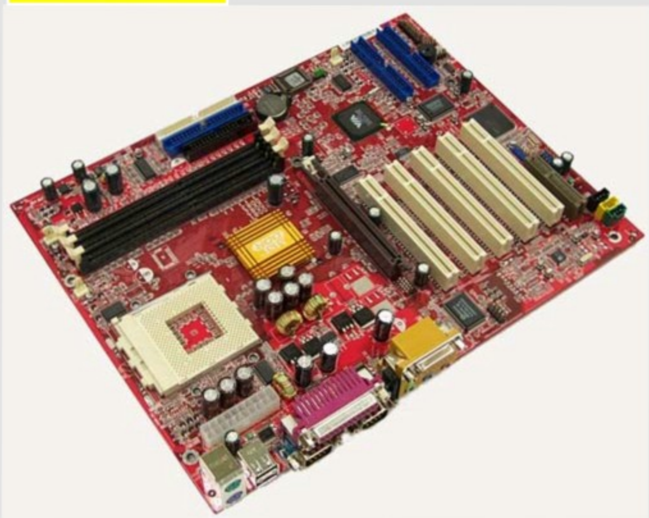
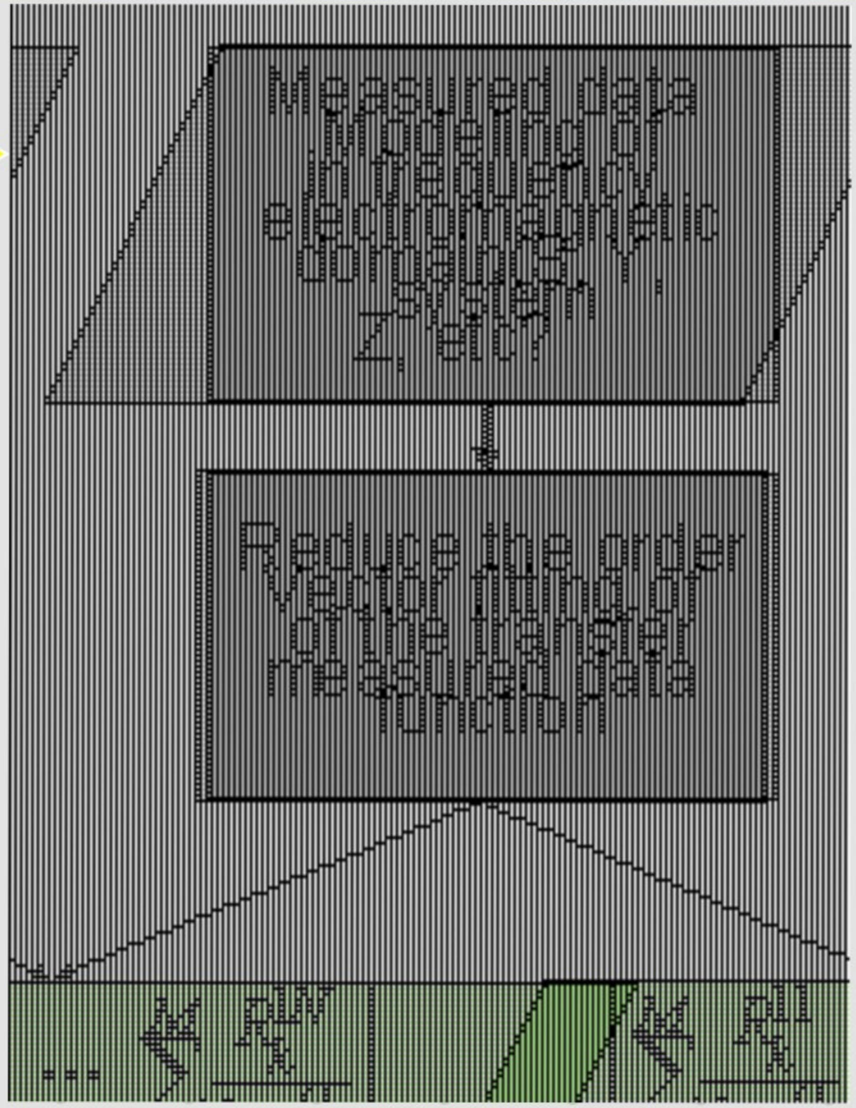
Block Diagram of EM Modeling Flow



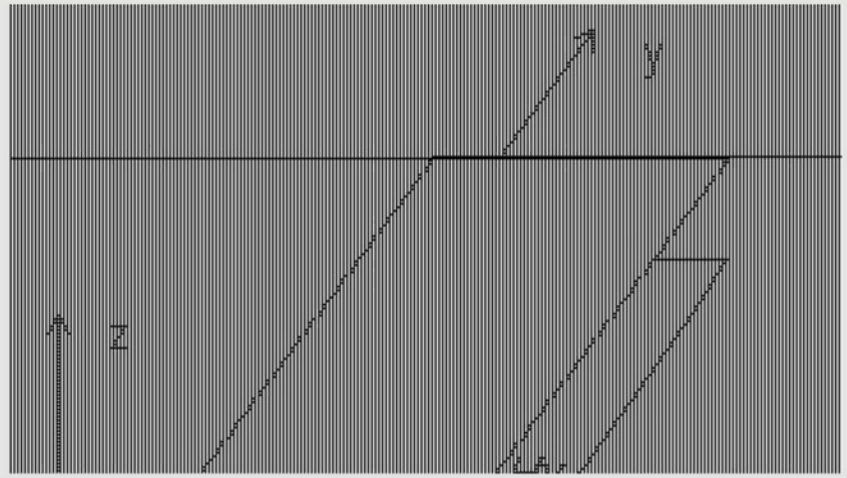


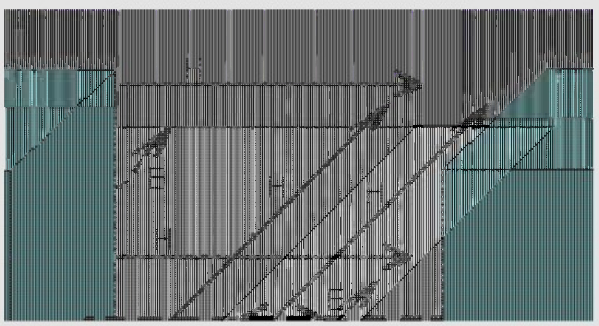
Quasi-3D Modeling of Power Delivery Network

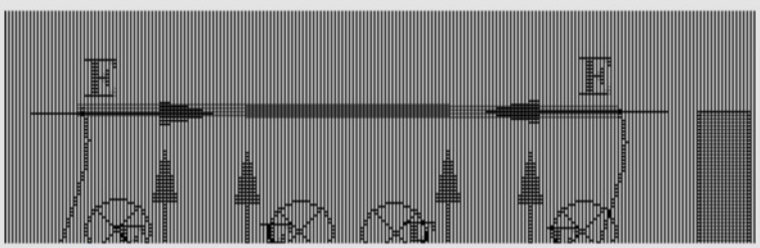
EM field between power/ground plane pairs exhibits, approximately, a two-dimensional variation

• Use simple 2D FDTD

Three-dimensional features (vias, pins, slots, voids, etc) require locally 3D models to capture the correct physics







$$j\omega\varepsilon E_z(i,j) = \Delta x^{-1}(H_y(i+1,j) - H_y(i,j)) - \Delta y^{-1}(H_x(i,j+1) - H_x(i,j))$$

$$-j\omega\mu\Delta y H_x(i,j) = E_z(i,j) - E_z(i,j-1)$$

$$j\omega\mu\Delta x H_y(i,j) = E_z(i,j) - E_z(i-1,j)$$

The resulting discrete EM model

$$\begin{bmatrix} \mathbf{G} & -\mathbf{D}_{\mathrm{I}} \\ -\mathbf{D}_{\mathrm{V}} & \mathbf{R} \end{bmatrix} \begin{bmatrix} \mathbf{E}(s) \\ \mathbf{H}(s) \end{bmatrix} + s \begin{bmatrix} \mathbf{C} & \mathbf{0} \\ \mathbf{0} & \mathbf{L} \end{bmatrix} \begin{bmatrix} \mathbf{E}(s) \\ \mathbf{H}(s) \end{bmatrix} = \mathbf{F}\mathbf{U}(s), \quad \mathbf{V} = \mathbf{F}^T \mathbf{X}$$

$$\mathbf{V}(s) = \mathbf{F}^T \left(\mathbf{A} + s\mathbf{B}\right)^{-1} \mathbf{F}\mathbf{U}(s) \quad \textit{where } \mathbf{A} = \begin{bmatrix} \mathbf{G} & \mathbf{-D}^{\mathrm{T}} \\ \mathbf{D} & \mathbf{R} \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \mathbf{C} & \mathbf{0} \\ \mathbf{0} & \mathbf{L} \end{bmatrix}$$

The multiport transfer function is: $\mathbf{Y}(s) = \mathbf{F}^T \left(\mathbf{A} + s\mathbf{B}\right)^{-1} \mathbf{F}$

- Direct time-domain simulation is possible if desired
  - Could be synchronized with time-domain IE solver
- Alternatively, model order reduction of the transfer function using an Arnoldi-based subspace iteration method (PRIMA) is used for the generation of a compact multiport

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Multi-port representation of the reduced-order model is in terms of rational functions

$$\mathbf{Y}(s) = \begin{bmatrix} \sum_{k=1}^{M} \frac{R_k^{11}}{s-P_k} & \cdots & \sum_{k=1}^{M} \frac{R_k^{1N}}{s-P_k} \\ \vdots & \cdot & \vdots \\ \sum_{k=1}^{M} \frac{R_k^{N1}}{s-P_k} & \cdots & \sum_{k=1}^{M} \frac{R_k^{NN}}{s-P_k} \end{bmatrix}$$

- Form compatible with circuit simulators that support rational function models (e.g. H-Spice, ADS)
- Equivalent circuit synthesis is possible also

Passive synthesis through Foster forms

For a passive, reciprocal multi-port, its admittance (or impedance) matrix may be cast in the following form:

$$\mathbf{H}(s) = \mathbf{G}_0 + s\mathbf{C}_0 + \sum_{q=1}^{Q}\left(\frac{a_q}{s-p_q} + \frac{\bar{a}_q}{s-\bar{p}_q}\right)\mathbf{G}_q$$

where it is:

- $\mathrm{Re}\{p_q\} \le 0, \quad q = 1, 2, \ldots Q$
- matrices $\mathbf{C}_0$ and $\mathbf{G}_q, \quad q = 0, 1, 2, \ldots, Q,$ are real and positive semi-definite
- $\mathrm{Re}\{a_q\} > 0, \quad q = 1, 2, \ldots Q$
- $0 < \mathrm{Im}\{a_q\}\,\mathrm{Im}\{p_q\} \le \left|\mathrm{Re}\{a_q\}\,\mathrm{Re}\{p_q\}\right|, \quad q = 1, 2, \ldots Q$

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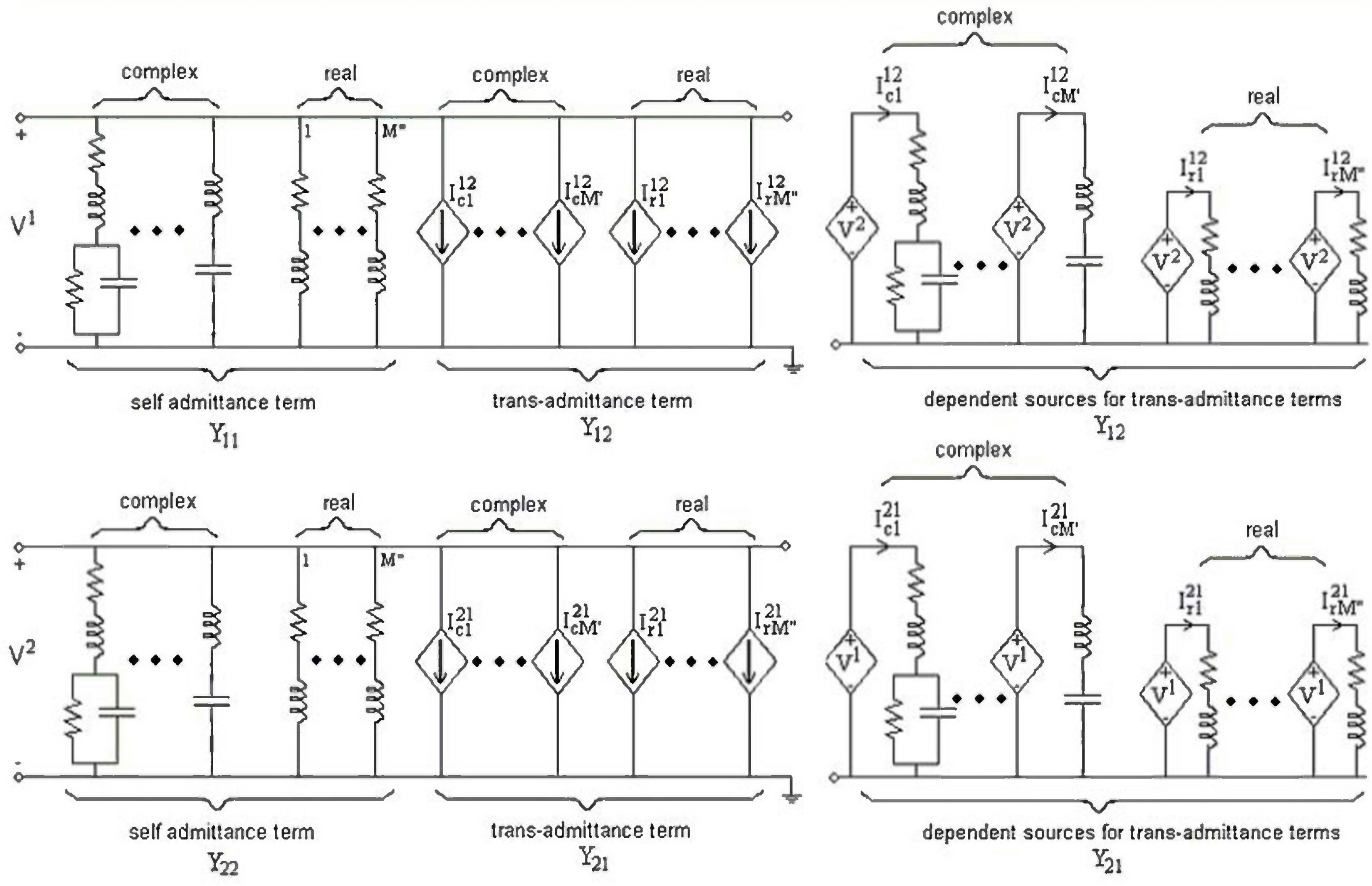
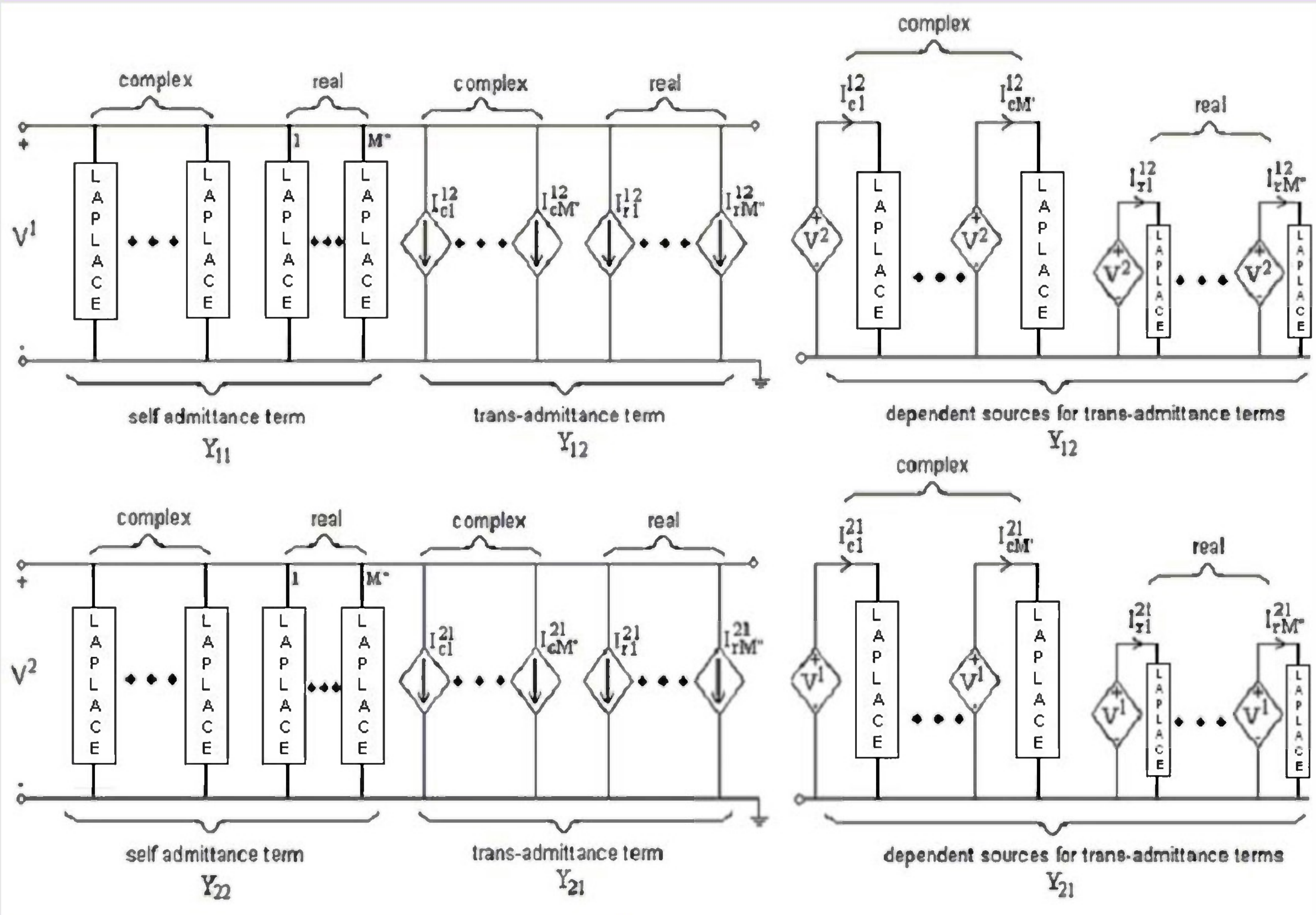
Equivalent circuit for a two-port



Two-port sub-circuit for use in H-SPICE



The advantages of the direct use of the rational function macro-model in the simulator

Elapsed Simulation Time

	3 ports	10 ports	36 ports
H-SPICE	0.7 sec	5.73 sec	21.2 min
Equivalent	2.3 sec	676.55 sec	>12 hours

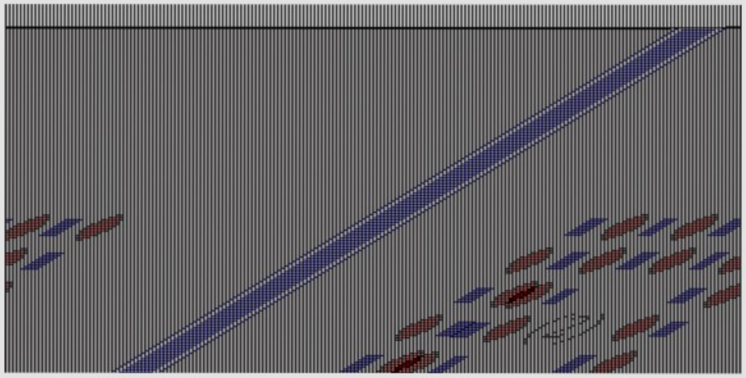
Transient Data File Size

	3 ports	10 ports	36 ports
H-SPICE	25.9 KB	53.4 KB	172 KB
Equivalent	308.2 KB	269 MB	>2 GB

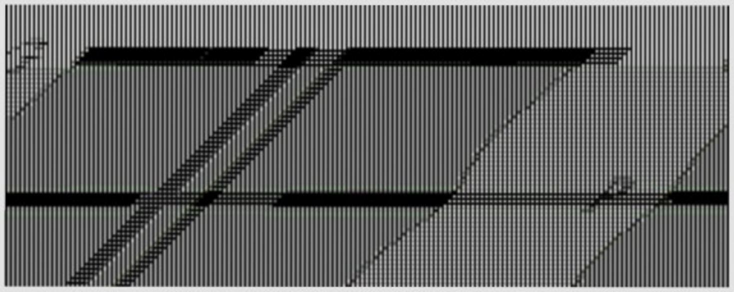
The secret is in the recursive convolution that is utilized for the interfacing of the macro-model with the rest of the circuit

Application to a 4-layer PCB

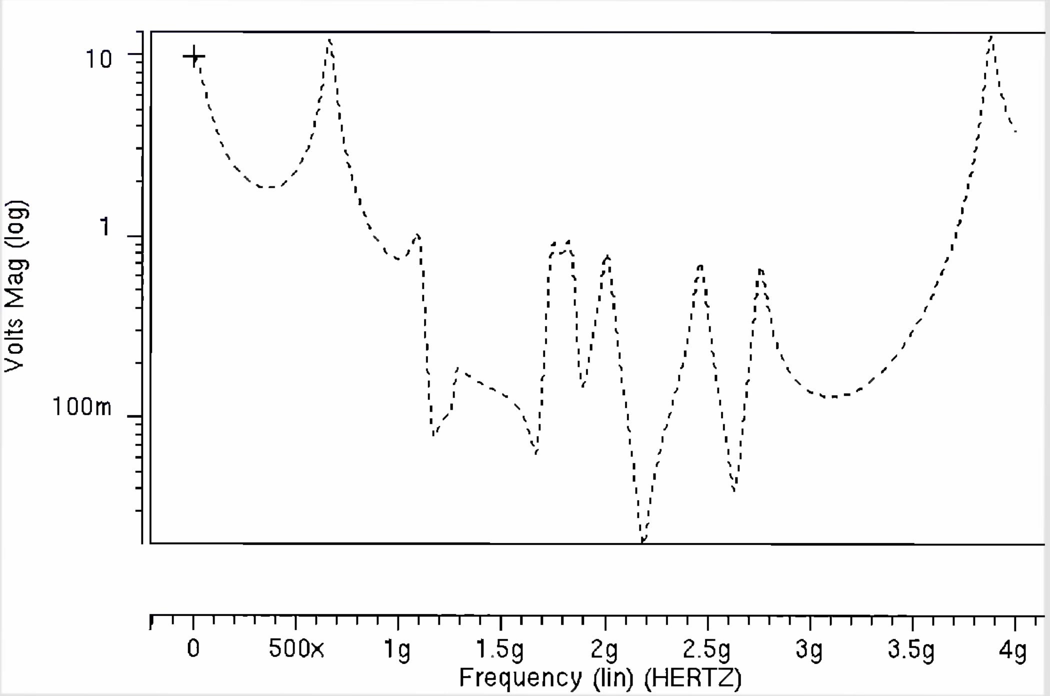
8 cm X 4 cm, 4 layer board. A 2mm gap is present all the way across the top ground plane. A total of 58 pins are used.



Top view



Cross-sectional view



|Z21| From H-SPICE

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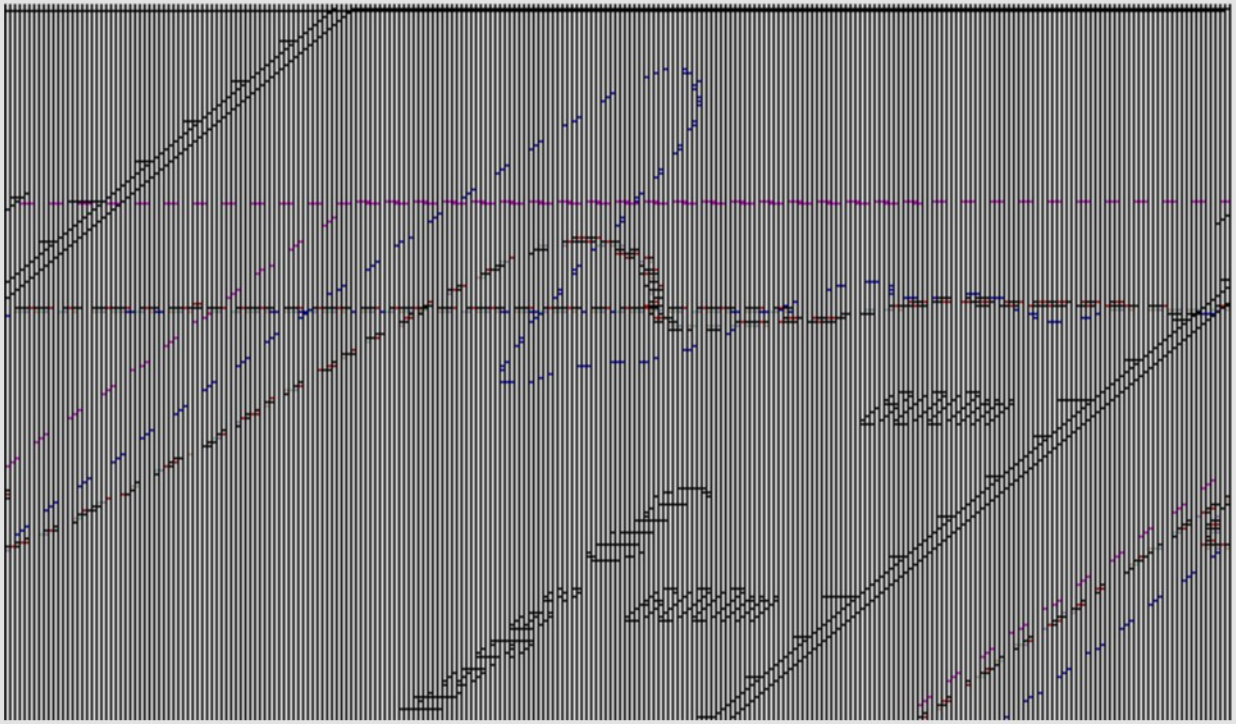
Application to a 4-layer PCB (cont'd)



H-SPICE calculation of the transient response.

Switching occurs at port 1 while port 2 is terminated with 50ohm.
Voltage at port 1 is depicted by the solid line.
Voltage at port 2 is depicted by the dotted line.

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Validation study in progress

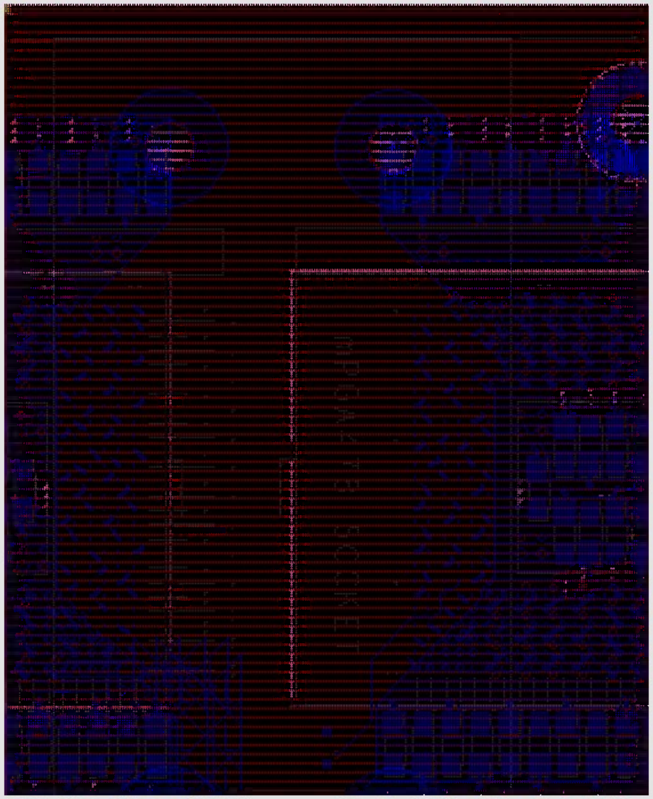
<u>Intel 4-layer test board</u>

1st layer: Power plane

2nd layer: Ground plane

3rd layer: Ground plane

4th layer: Power plane



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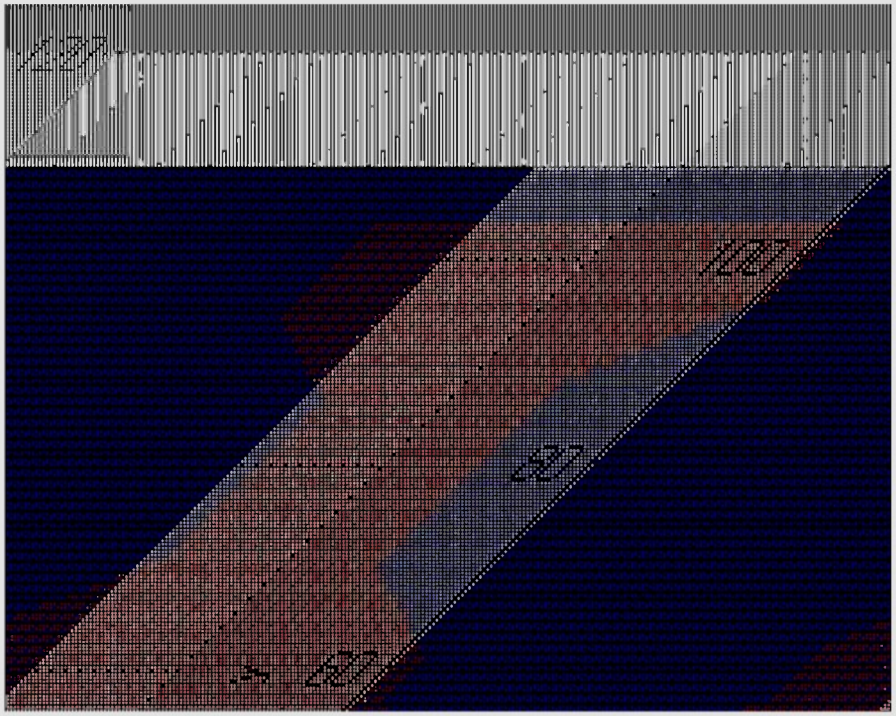
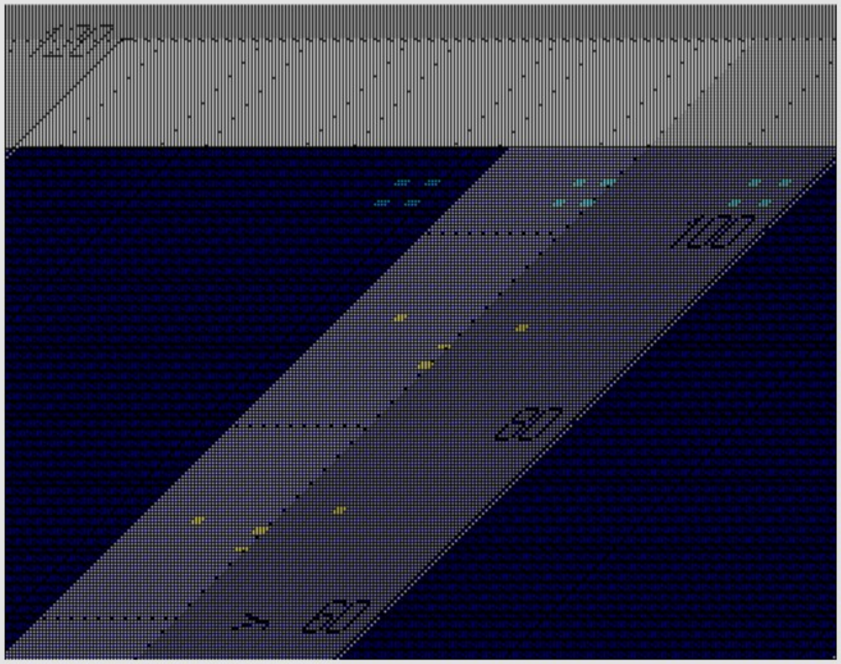
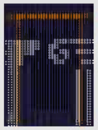
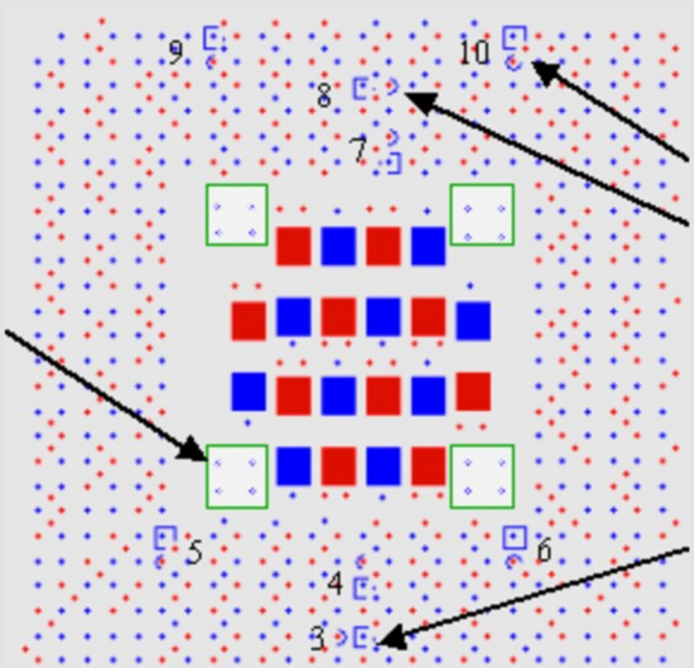
Samples of the generated mesh

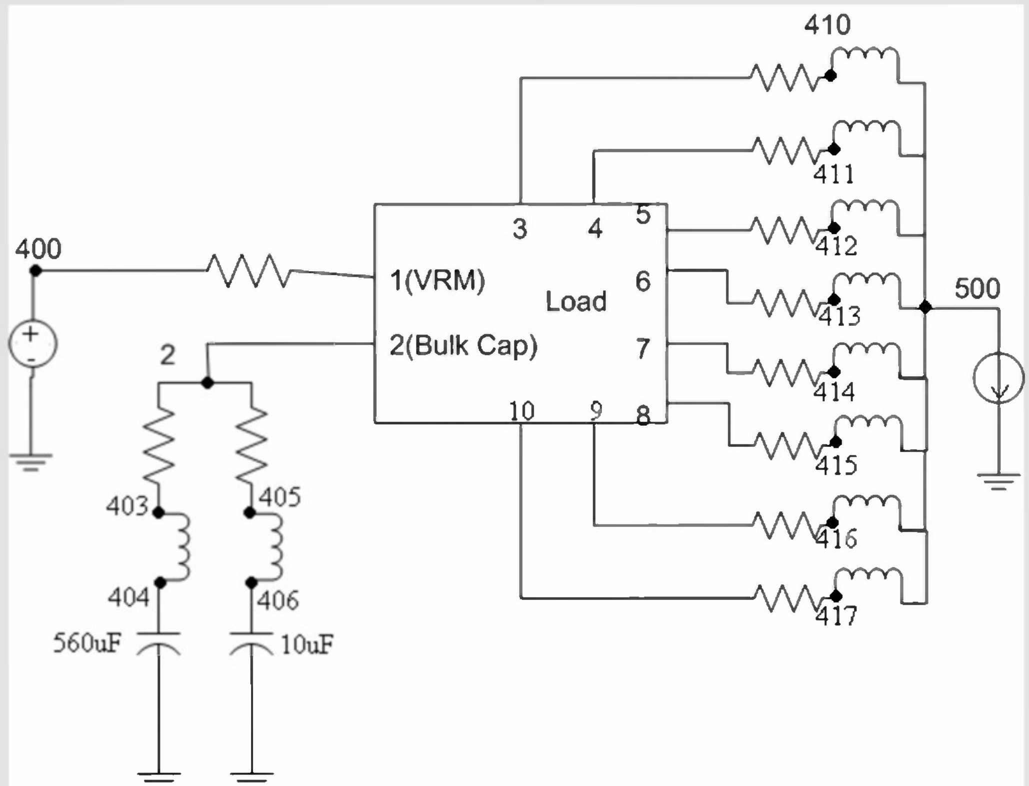






Generated multi-port for switching noise simulation in SPICE





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Rational function multi-port & equivalent circuit synthesis from raw data

- Data either from measurements or EM field solvers
- Step 1: Rational function fitting
  - Process guarantees stability but not passivity
  - Check fitted multi-port for passivity
    - If not passive, constrain fitting using Foster constraints
    - Repeat fitting

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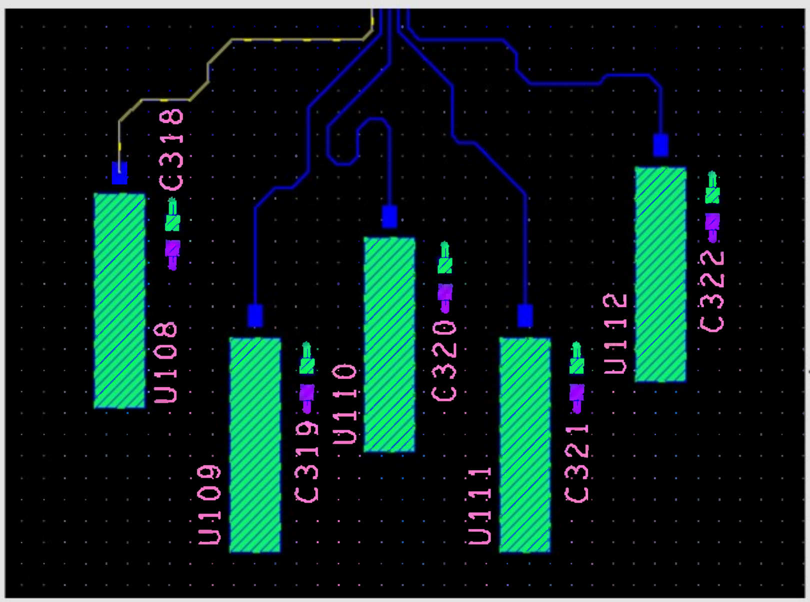
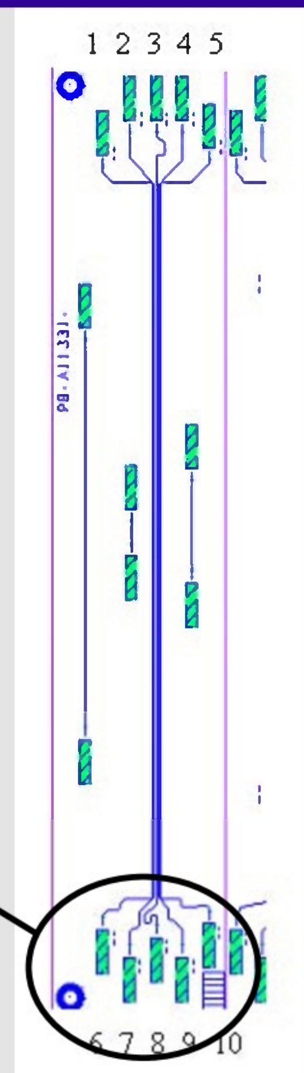
Validation of rational function fitting

PCB interconnect test structures courtesy of Intel





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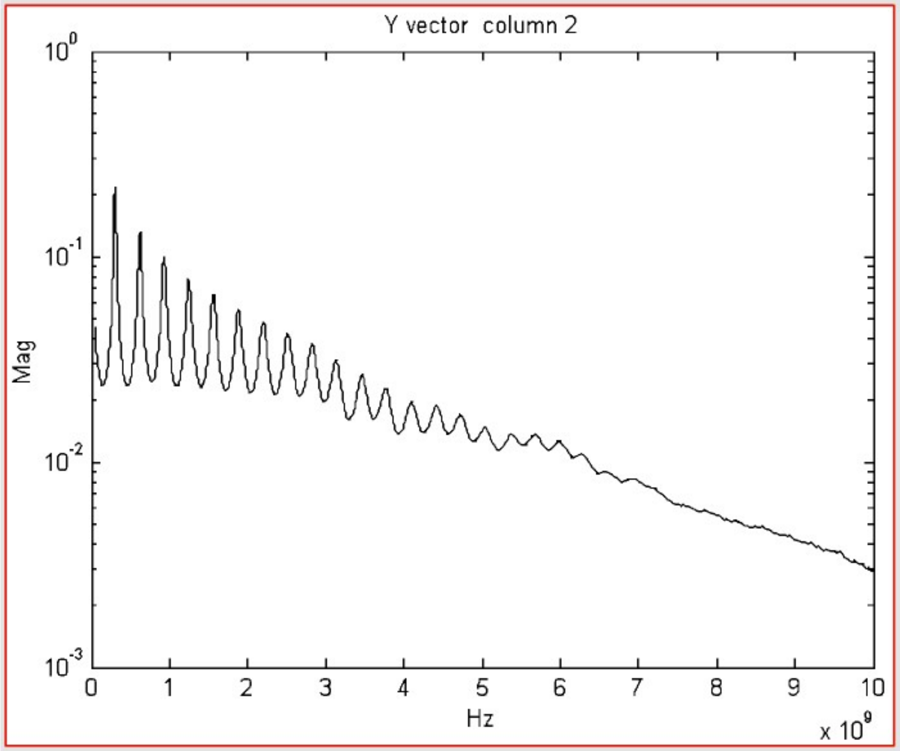
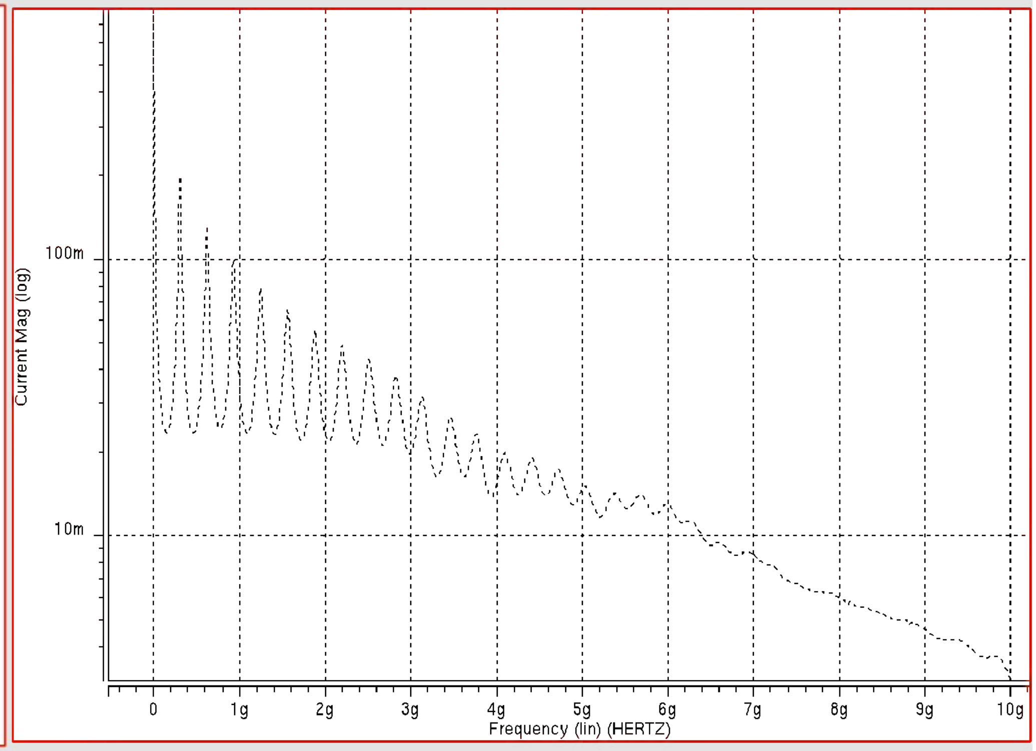
Validation of fitting (cont'd)





Measured $|Y_{61}|$*

Synthesized $|Y_{61}|$

(*) Measurements courtesy of Intel Corporation

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Task 2.1 Summary

- EM modeling flow for the coupling path established
- Quasi-3D EM Model for power delivery network completed
  - Validation in progress
  - Further enhancements include:
    - Incorporation of hooks for balanced MTLs
    - Incorporation of hooks for matrix transfer functions in Foster form
- Capability for SPICE-compatible broadband multi-port macro-model generation in place

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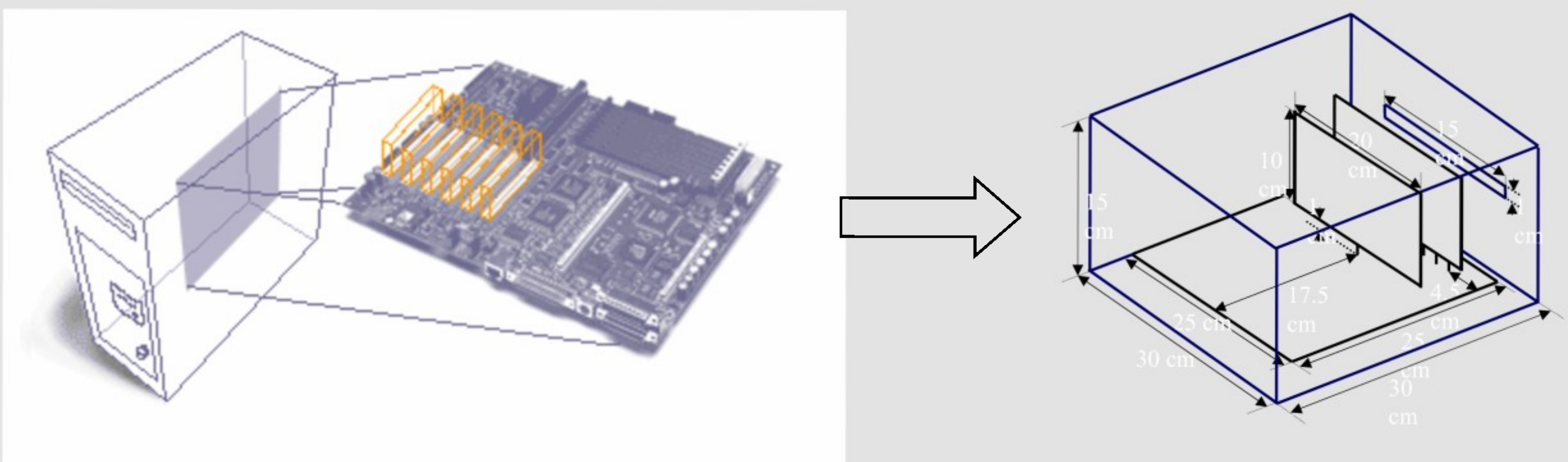
Subtask 2.3: Non-linear Transient Simulation

- ***Physics-oriented*** **nonlinear transient simulator**
  - Full wave modeling of printed circuit boards (PCBs) with fine geometric features, finite (and possibly inhomogeneous) dielectrics, and nonlinear loads and circuits
  - Interfaces with SPICE solvers and models



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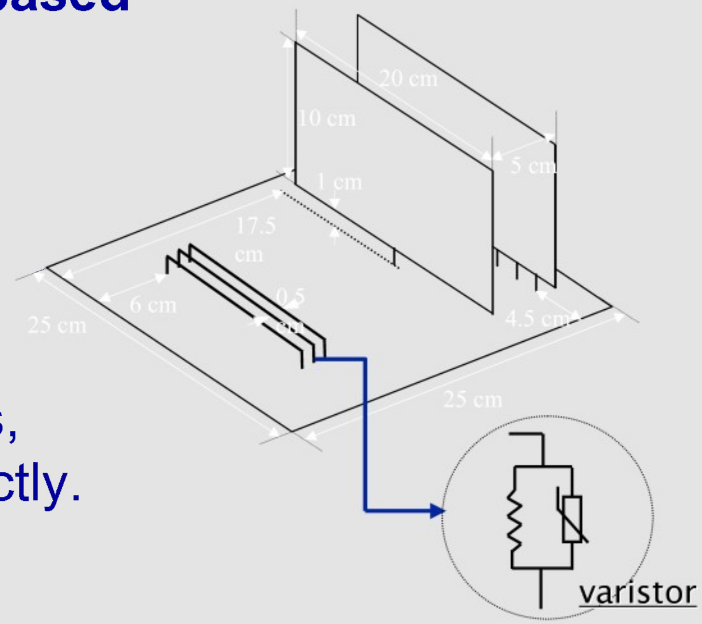
Introduction (cont.)

- **Time Domain Integral Equation (TDIE) based Marching-on-in-time (MOT) solvers**
  - Have been known to the acoustics and electromagnetics communities since the sixties.
  - Compared to frequency domain solvers, they can solve nonlinear problems directly.

    Liu and Tesche (1976),
    Landt and Miller (1983),
    Djordjevic and Sarkar (1985),
    Deiseroth and Singer (1995),
    Orlandi (1996)



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Introduction (cont.)

However TDIE - MOT solvers have long been conceived as

- Unstable: … But recently many proposals have surfaced for stabilizing these schemes (Davies, Rao and Sarkar, Walker, Smith, Rynne,…);
- Slow: … Computational complexity has prohibited application to analysis of large scale problems!

  … PWTD technology removes this computational bottleneck

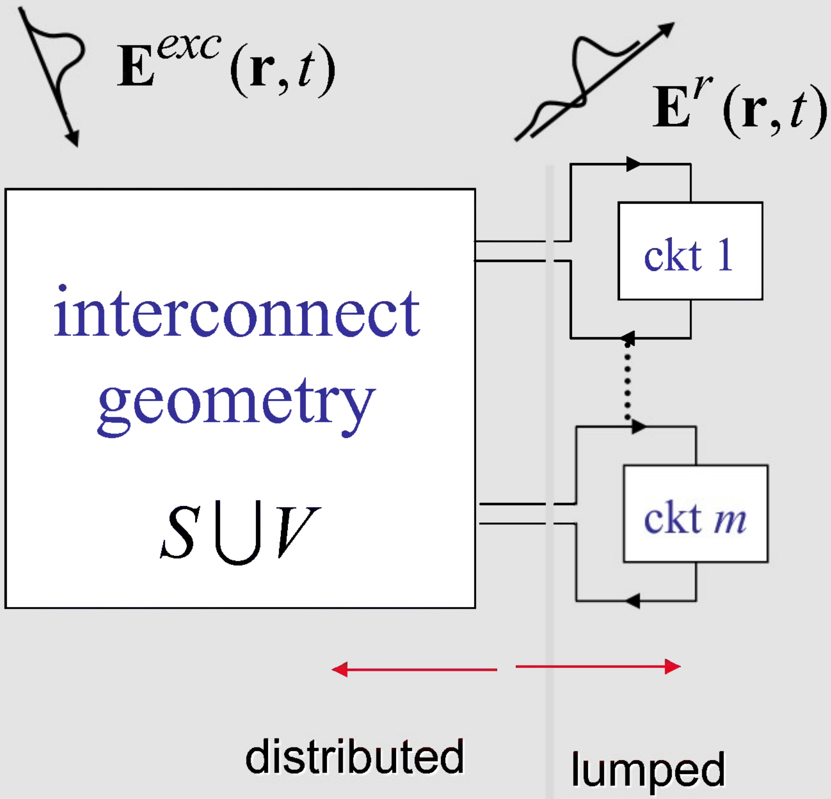
$$O(N_T N_S^2)$$

$$O(N_T N_S \log^2 N_S)$$

Now, we can / should be able to rapidly solve large -scale, nonlinear problems using the PWTD technology!!!

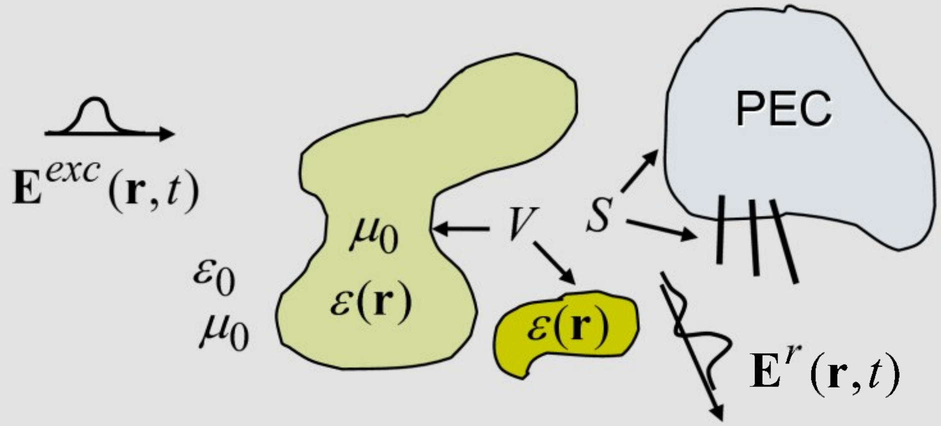
Formulation - Problem Definition

- **Given**
  - an of 3-D inhomogeneous dielectric bodies (V), and 3-D arbitrarily shaped PEC surfaces, wires, and surface-wire junctions (S),
  - Multiple linear / nonlinear lumped circuits connected to $S \cup V$
  - a temporally bandlimited excitation
- **Solve for**
  - all transient currents and voltages induced on the interconnect geometry $S \cup V$ and the the circuits (ckt 1, …, ckt m)
  - radiated electric and/or magnetic fields if required



Formulation – Time Domain Electric Field

- Assume spatially-variable, frequency independent permittivity and free-space permeability in *V*, and thin wires in *S* .
- Radiated electric field:



$$\mathbf{E}^{r}\left(\mathbf{r},t\right) = -\frac{\partial}{\partial t}\mathbf{A}\left(\mathbf{r},t\right) + c^2 \int_0^t dt' \nabla\nabla\cdot\mathbf{A}\left(\mathbf{r},t'\right) \qquad (1)$$

$$\mathbf{A}(\mathbf{r},t) = \frac{\mu_0}{4\pi}\left[\int_S ds' \frac{\delta(t-R/c)}{R} * \mathbf{J}_{PEC}(\mathbf{r}',t) + \int_V dv' \frac{\delta(t-R/c)}{R} * \mathbf{J}_{DIEL}(\mathbf{r}',t)\right], \qquad (2)$$

$$R = \left|\mathbf{r}-\mathbf{r}'\right|, \qquad \mathbf{J}_{DIEL}(\mathbf{r},t) = (\varepsilon(\mathbf{r})-\varepsilon_0)\frac{\partial}{\partial t}\mathbf{E}^{total}(\mathbf{r},t)$$

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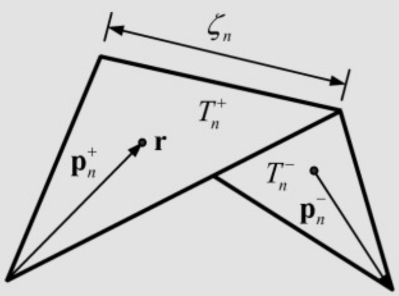
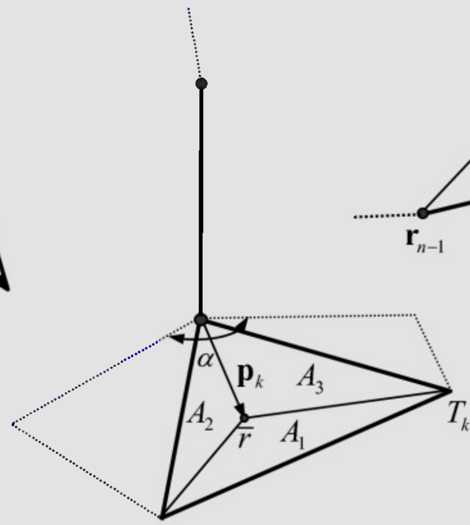
Formulation - MOT Algorithm

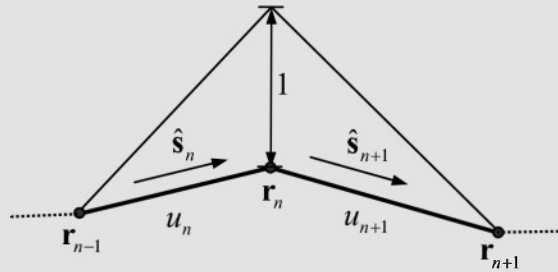
① Expand current as $$\mathbf{J}(\mathbf{r},t) \approx \sum_{n=1}^{N_S} \sum_{j=0}^{N_T} I_n^j \mathbf{f}_n^q(\mathbf{r}) T_j(t), \quad q = s, w, sw, d$$

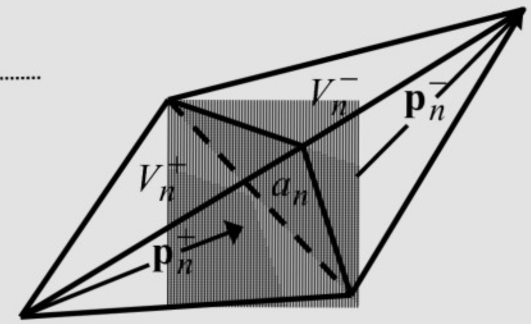
$$N_S = N_{PEC} + N_{DIEL}$$

- Surface and Volume Spatial Basis Functions









- The temporal basis functions are local cubic polynomials

Formulation - MOT Algorithm (cont.)

② Construct a system of equations by applying spatial Galerkin testing at each time step.

- for the *j'th* time step:

$$\bar{\mathbf{Z}}_0 \mathbf{I}_j = \mathbf{V}_j^{exc} - \sum_{l=1}^{j-1} \bar{\mathbf{Z}}_l \mathbf{I}_{j-l}$$

- $\bar{\mathbf{Z}}_0$: immediate interactions
- $\mathbf{I}_j$: unknowns
- $\mathbf{V}_j^{exc}$: tested incident field
- $\bar{\mathbf{Z}}_l$: delayed interactions
- $\mathbf{I}_{j-l}$: previously computed

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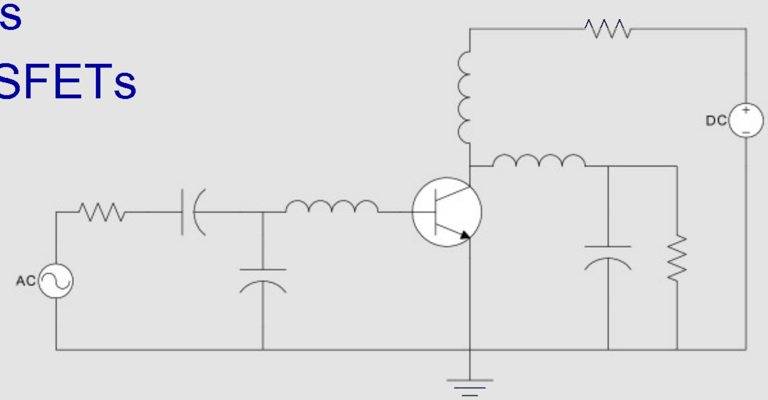
Formulation - Transient Circuit Simulator

- SPICE-like transient circuit simulator
  - Performs linear and nonlinear large-signal analysis using Modified nodal analysis
  - Nonlinear equations solved using multi-dimensional Newton
  - Incorporates the following circuit elements:
    - Independent/dependent voltage and current sources
    - Resistors, inductors, capacitors
    - Diodes, BJTs, MOSFETs, MESFETs



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Formulation - Transient Circuit Simulator (cont.)

- **Circuit behavior described by time-domain nodal equations (using trapezoidal rule for the *j*th time step)**

$$\mathbf{G}_0\left(\mathbf{V}_j\right) = \mathbf{I}_j^{exc} + \mathbf{G}_1\left(\mathbf{V}_{j-1}\right)$$

immediate interactions ($\mathbf{G}_0$) — unknowns ($\mathbf{V}_j$) — sources ($\mathbf{I}_j^{exc}$) — interactions from previous time step ($\mathbf{G}_1$) — previously computed ($\mathbf{V}_{j-1}$)

- **For *m* circuits, the nonlinear system of equations is**

$$\tilde{\mathbf{G}}_0\left(\tilde{\mathbf{V}}_j\right) = \begin{bmatrix} \mathbf{G}_0^1\left(\mathbf{V}_j^1\right) \\ \vdots \\ \mathbf{G}_0^m\left(\mathbf{V}_j^m\right) \end{bmatrix} = \begin{bmatrix} \mathbf{I}_j^{exc,1} \\ \vdots \\ \mathbf{I}_j^{exc,m} \end{bmatrix} + \begin{bmatrix} \mathbf{G}_1^1\left(\mathbf{V}_{j-1}^1\right) \\ \vdots \\ \mathbf{G}_1^m\left(\mathbf{V}_{j-1}^m\right) \end{bmatrix} = \tilde{\mathbf{I}}_j^{exc} + \tilde{\mathbf{G}}_1\left(\tilde{\mathbf{V}}_{j-1}\right)$$

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Formulation - Coupled EM / Circuit Equations

- **Combine the EM and circuit nodal equations** into a single consistent system to be solved for N_S EM and N_C circuit unknowns at each time step

$$\begin{bmatrix} \bar{\mathbf{Z}}_0 & \bar{\mathbf{C}}_v \\ \bar{\mathbf{C}}_i & 0 \end{bmatrix} \begin{bmatrix} \mathbf{I}_j \\ \tilde{\mathbf{V}}_j \end{bmatrix} + \begin{bmatrix} 0 \\ \tilde{\mathbf{G}}_0\left(\tilde{\mathbf{V}}_j\right) \end{bmatrix} = \begin{bmatrix} \mathbf{V}_j^{exc} - \sum_{l=1}^{j-1} \mathbf{Z}_l \mathbf{I}_{j-l} \\ \tilde{\mathbf{I}}_j^{exc} + \tilde{\mathbf{G}}_1\left(\tilde{\mathbf{V}}_{j-1}\right) \end{bmatrix}$$

- **Coupling between the circuits and the interconnect structure is accounted for by matrices** $\bar{\mathbf{C}}_v$ **and** $\bar{\mathbf{C}}_i$

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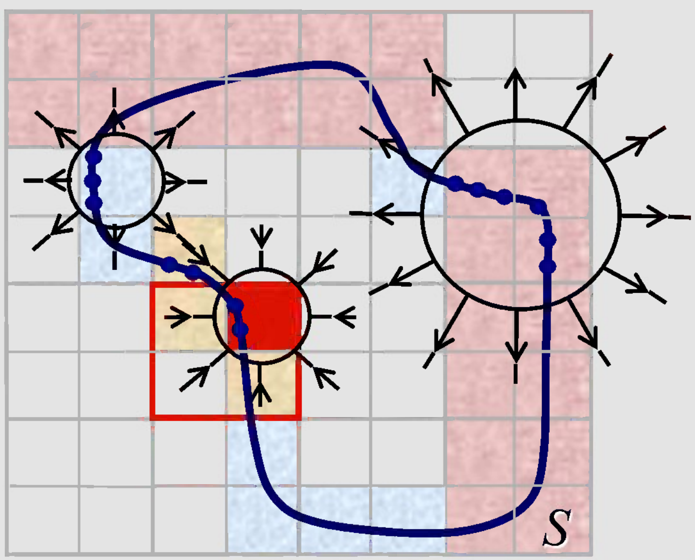
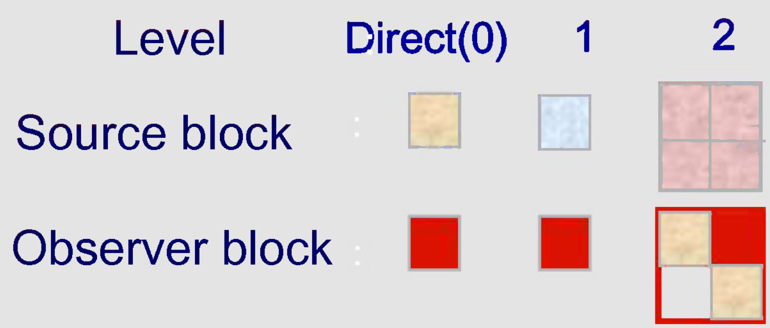
Formulation - the MLPWTD Algorithm

$$\bar{\mathbf{Z}}_0 \mathbf{I}_j = \mathbf{V}_j^{exc} - \boxed{\sum_{l=1}^{j-1} \bar{\mathbf{Z}}_l \, \mathbf{I}_{j-l}} \rightarrow \boxed{O(N_T N_S \log^2 N_S)}$$

↓

for typical PCB structures





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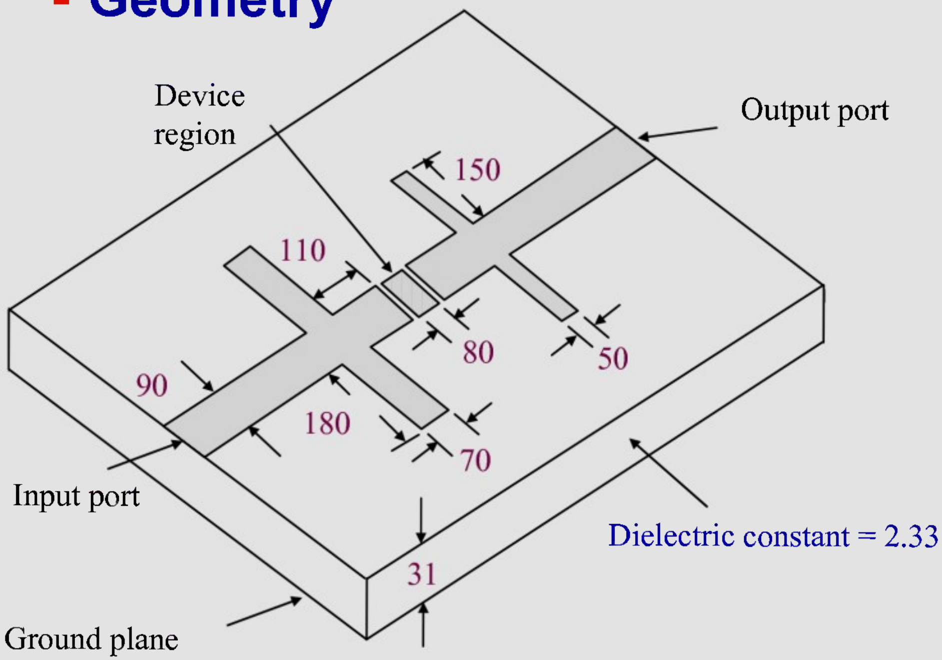
Analysis of Active Nonlinear Microwave Amplifier

- **Objective**

  Characterize structure from 2-10 GHz

- **Geometry**



- **Simulation Parameters**

$$N_s = 1468,\ N_v = 7096$$

$$N_s + N_v = 8564,\ N_t = 512$$

$$\Delta t = 5.0 \text{ ps}$$

- **Excitation pulse**

$$\mathbf{V}^{inc}(\mathbf{r},t) = V_0 \cos(\omega_0 t') e^{-t'^2/2\sigma^2}$$

$$\omega_0 = 2\pi \times 6 \times 10^9 \text{ rad/s}$$

$$t' = t - 6\sigma, \quad \sigma = 6.82 \times 10^{-11} \text{s}$$

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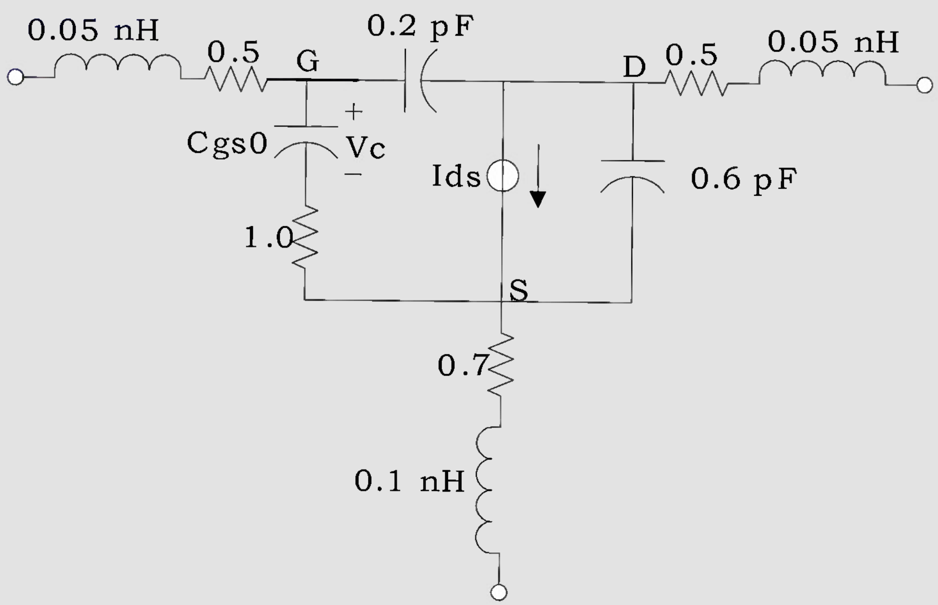
Amplifier : Nonlinear circuitry

- **MESFET Circuit Model**

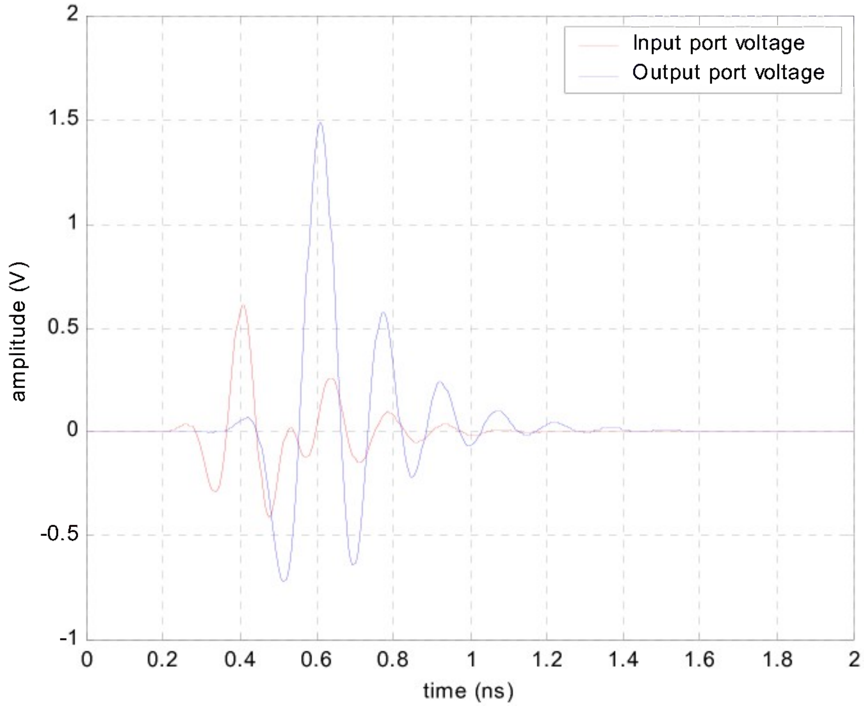


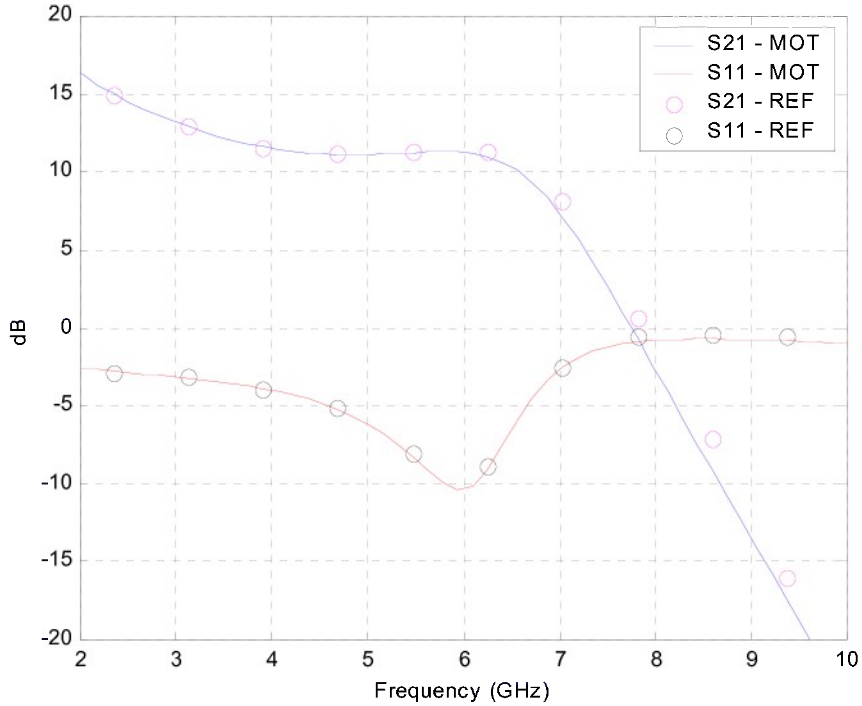
$$C_{gs}(v_c) = \frac{C_{gs0}}{\sqrt{1 - v_c / \phi_b}}$$

$$I_{ds}(v_{gs}, v_{ds}) = (A_0 + A_1 v_{gs} + A_2 v_{gs}^2 + A_3 v_{gs}^3)\tanh(\alpha v_{ds})$$

Amplifier: Plane Wave Interference

- Transient input/output waveforms
- MOT results*





* C. Kuo, B. Houshmand, and T. Itoh, “Full-wave analysis of packaged microwave circuits with active and nonlinear devices: an FDTD approach,” IEEE Trans. Microwave Theory Tech., vol. 45, pp. 819-826, May 1997.

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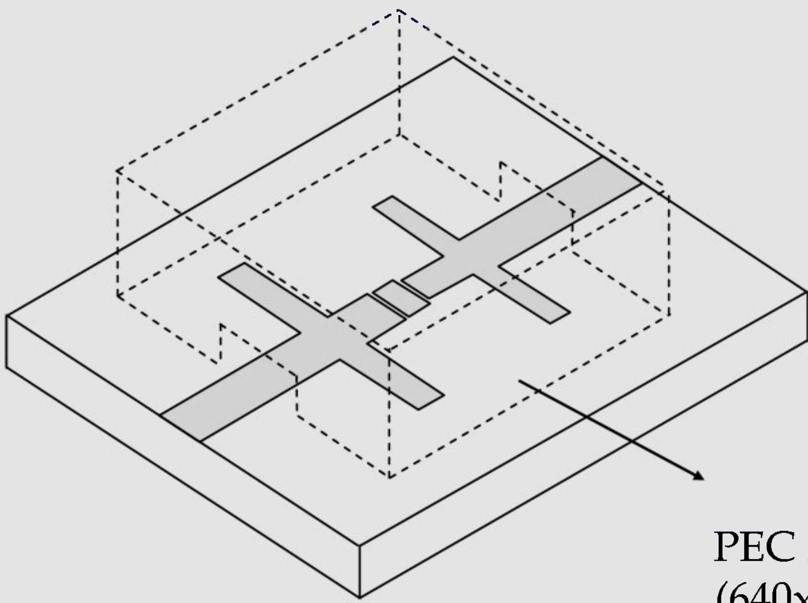
Amplifier + Shield: geometry

- **Objective**

Determine effect of shielding box on S-parameters

- **Geometry**



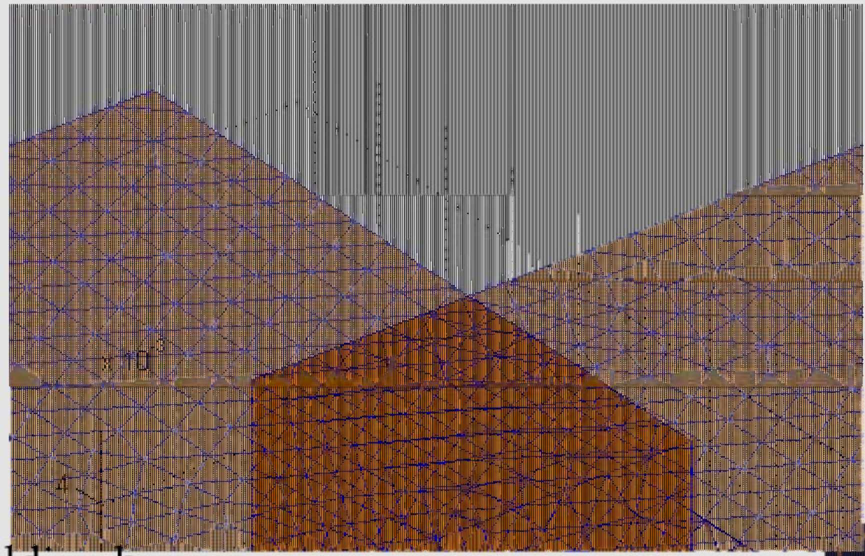
PEC shielding box
(640x186x690mils)

- **Simulation Parameters**

$$N_s = 3288,\ N_v = 7096$$

$$N_s + N_v = 10384,\ N_t = 700$$

$$\Delta t = 6.25 \text{ ps}$$



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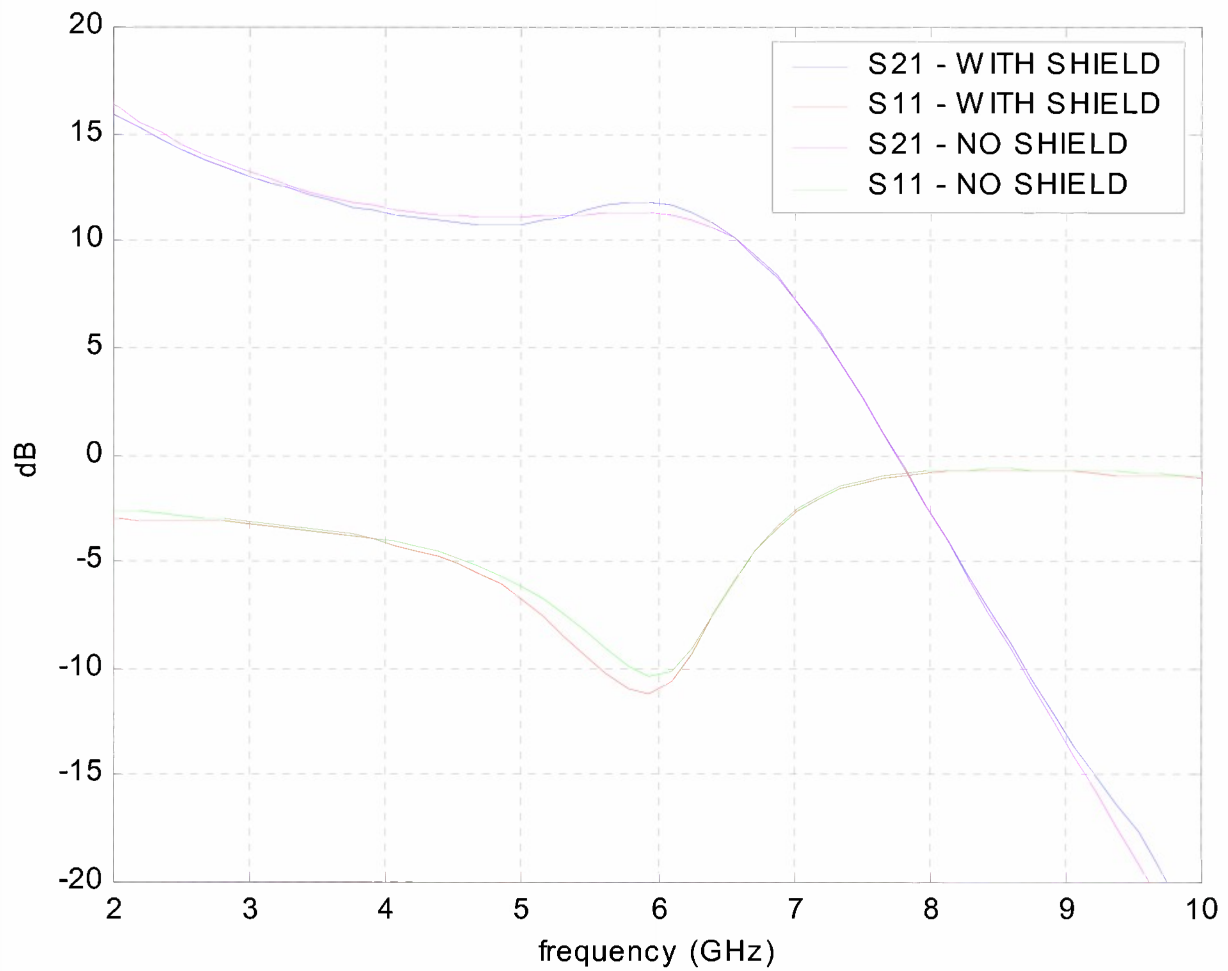
Amplifier + Shield: S-parameters



Amplifier + Shield: Plane Wave Interference

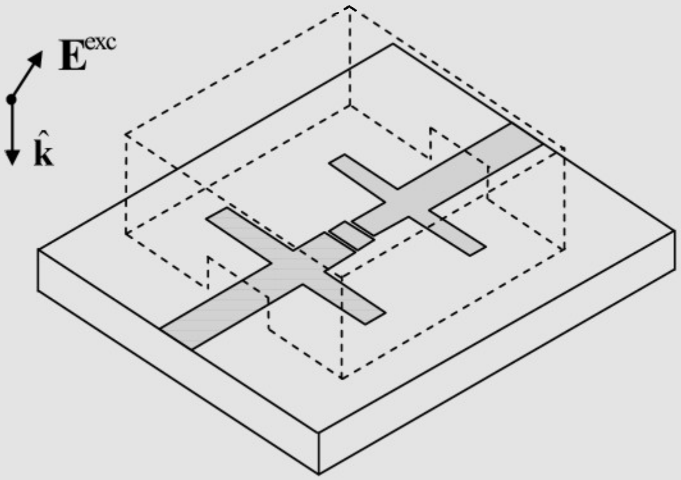
$$\mathbf{E}^{exc}(\mathbf{r},t) = \mathbf{E}_0 \cos(\omega_0 t') e^{-t'^2/2\sigma^2}$$

$$\mathbf{E}_0 = 500\hat{\mathbf{x}} + 500\hat{\mathbf{y}} \ \ V/m$$

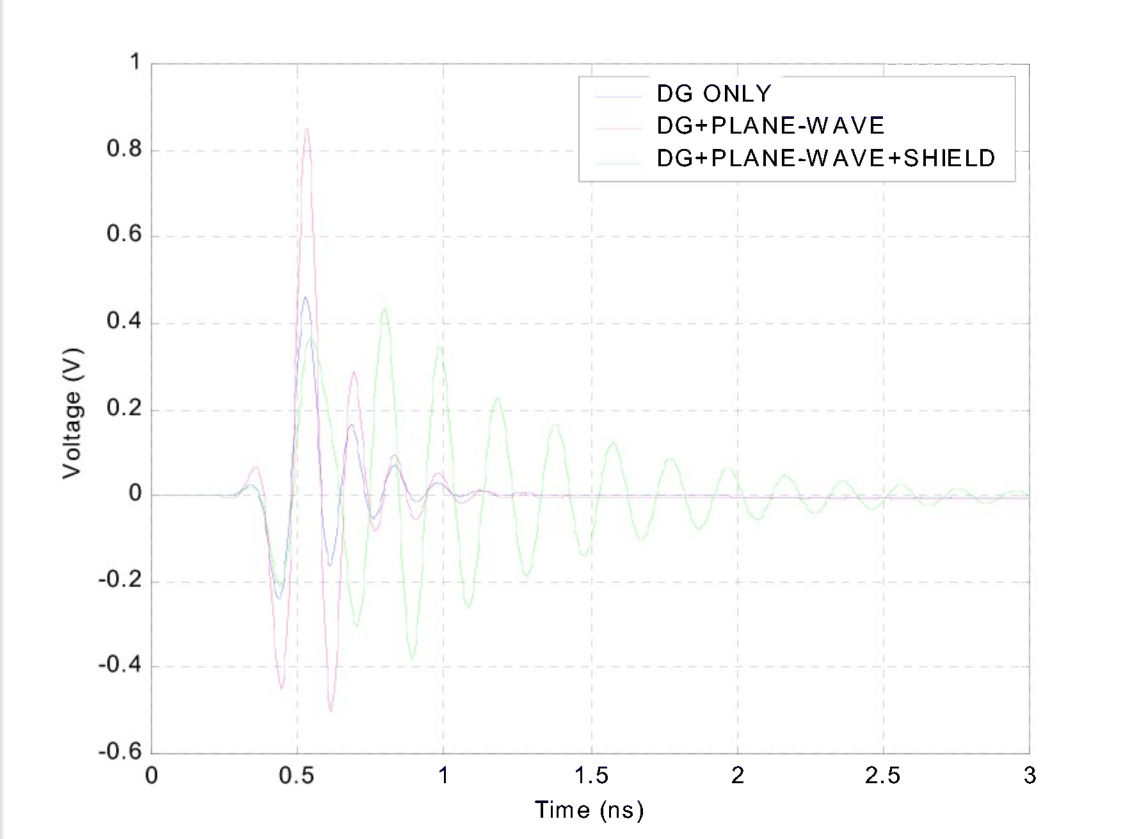
$$\omega_0 = 2\pi \times 6 \times 10^9 \ \text{rad/s}$$

$$t' = t - 6\sigma + (\hat{\mathbf{z}} \cdot \mathbf{r})/c$$

$$\sigma = 8.68 \times 10^{-11} \text{s}$$



Transient response at transistor output



Amplifier + Shield: Plane Wave Interference

$$\mathbf{E}^{exc}(\mathbf{r},t) = \mathbf{E}_0 \cos(\omega_0 t') e^{-t'^2/2\sigma^2}$$

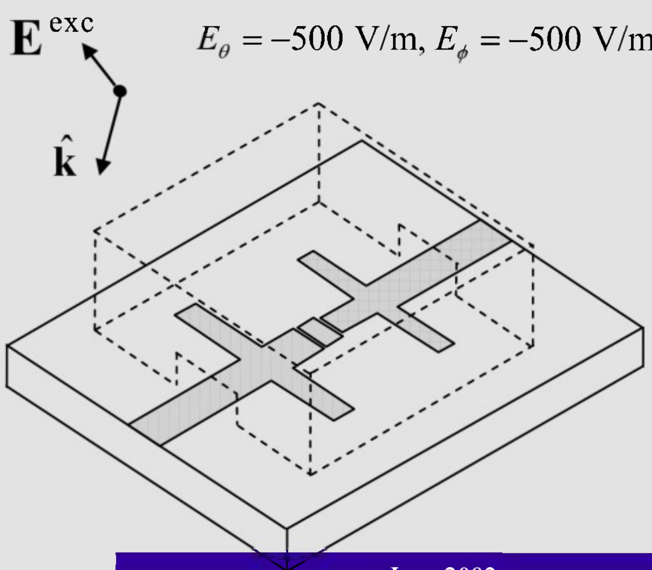
$$\omega_0 = 2\pi \times 4 \times 10^9 \text{ rad/s}$$

$$t' = t - 6\sigma - (\hat{\mathbf{k}} \cdot \mathbf{r})/c \qquad \sigma = 1/4\pi \text{ ns}$$

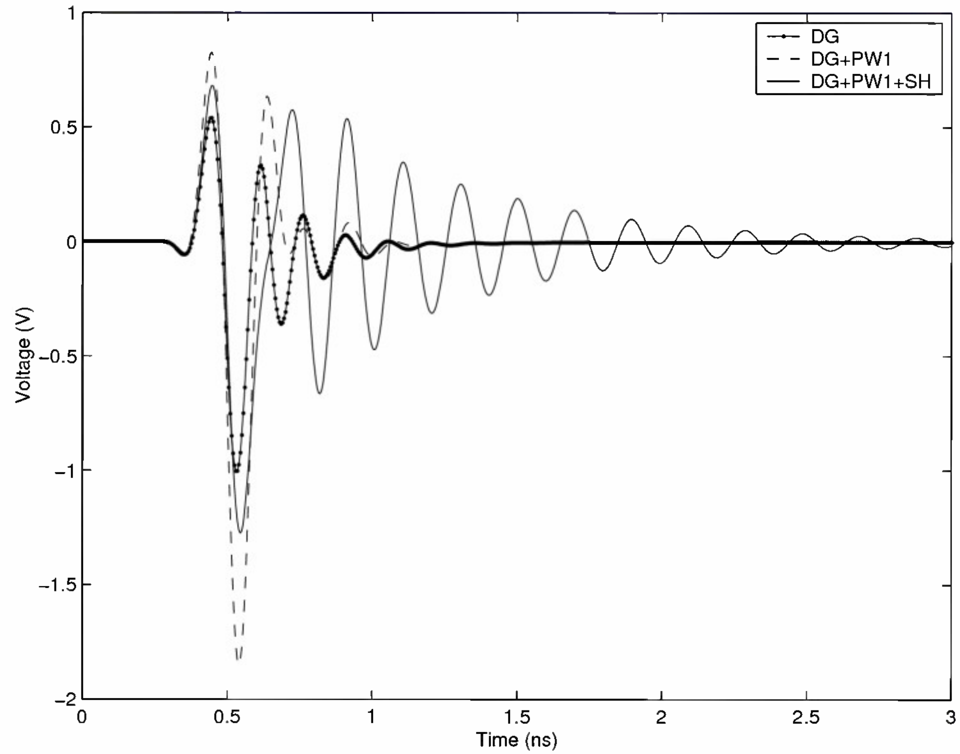
$$\theta_i = 145,\ \phi_i = 0$$

$$\hat{\mathbf{k}} = 0.5736\hat{\mathbf{x}} - 0.8192\hat{\mathbf{y}}$$

$$E_\theta = -500 \text{ V/m},\ E_\phi = -500 \text{ V/m}$$



Transient response at transistor output



Amplifier + Shield: Plane Wave Interference

$$\mathbf{E}^{exc}(\mathbf{r},t) = \mathbf{E}_0 \cos(\omega_0 t') e^{-t'^2/2\sigma^2}$$

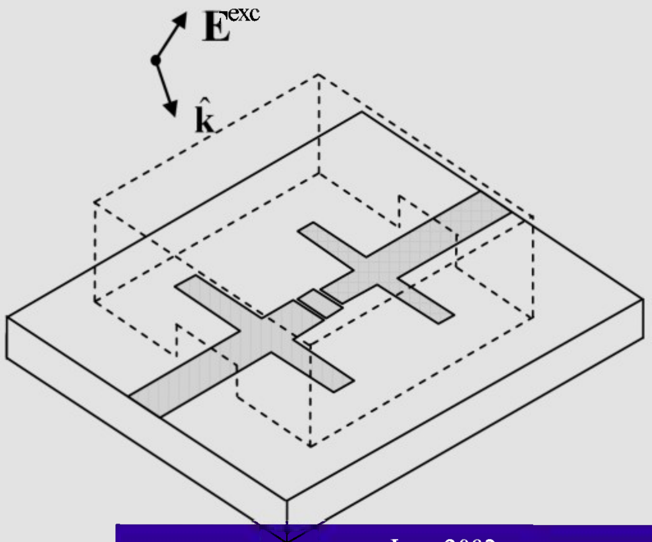
$$\omega_0 = 2\pi \times 3 \times 10^9 \text{ rad/s}$$

$$t' = t - 6\sigma - (\hat{\mathbf{k}} \cdot \mathbf{r})/c \qquad \sigma = 3/14\pi \text{ ns}$$

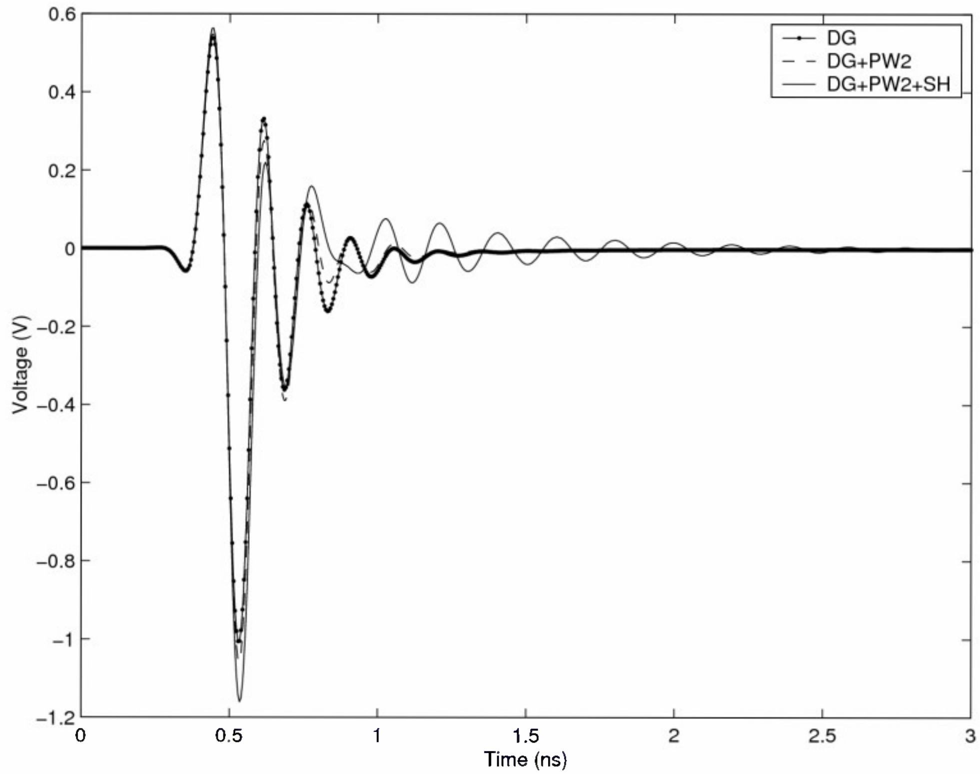
$$\theta_i = 115, \ \phi_i = 45$$

$$\hat{\mathbf{k}} = 0.6409(\hat{\mathbf{x}} + \hat{\mathbf{y}}) - 0.4226\hat{\mathbf{z}}$$

$$E_\theta = -500 \text{ V/m}, E_\phi = 500 \text{ V/m}$$



Transient response at transistor output



Amplifier + Shield: Plane Wave Interference

$$\mathbf{E}^{exc}(\mathbf{r},t) = \mathbf{E}_0 \cos(\omega_0 t')e^{-t'^2/2\sigma^2}$$

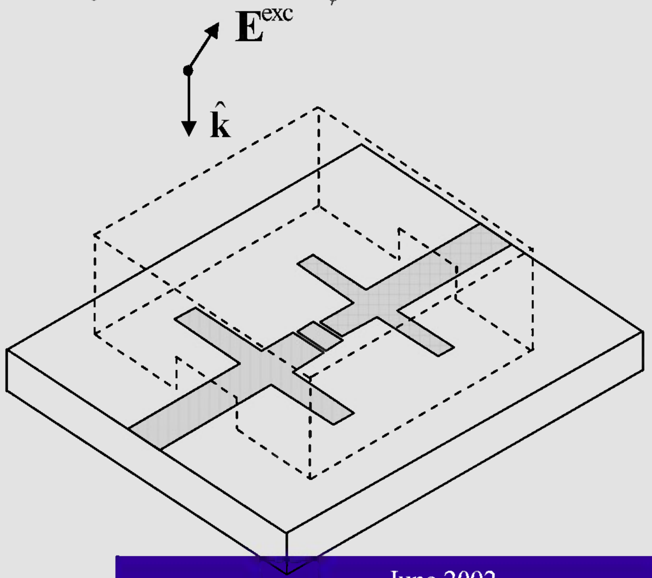
$\omega_0 = 2\pi \times 6 \times 10^9$ rad/s

$t' = t - 6\sigma - (\hat{\mathbf{k}} \cdot \mathbf{r})/c$ $\quad \sigma = 3/11\pi$ ns

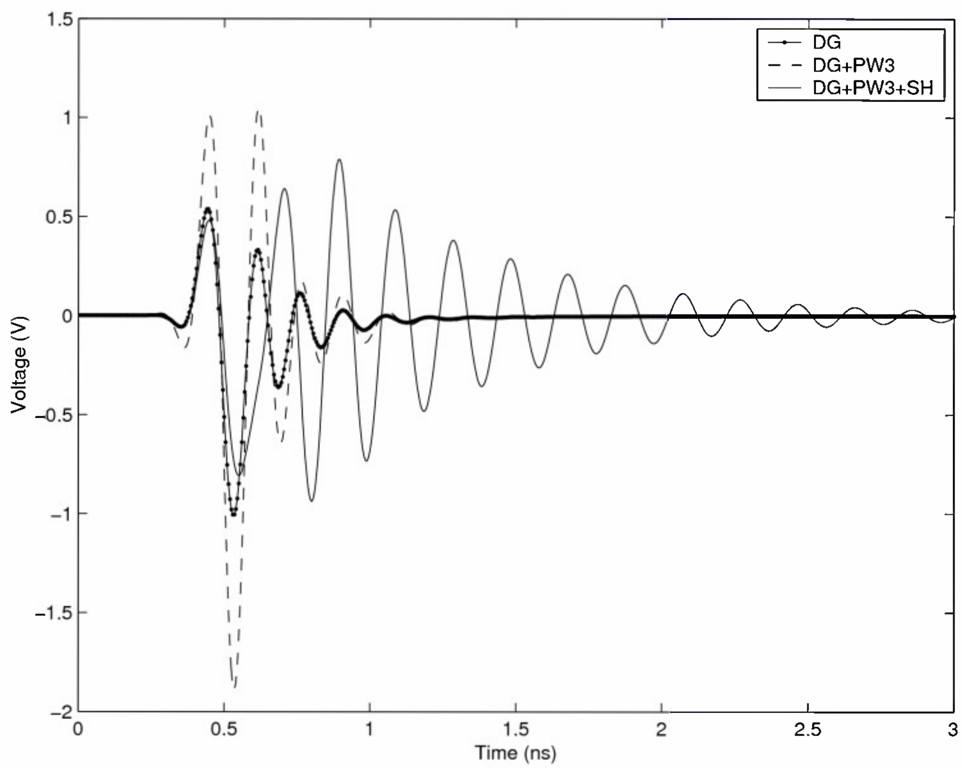
$\theta_i = 180,\ \phi_i = 0$

$\hat{\mathbf{k}} = -\hat{\mathbf{z}}$

$E_\theta = -500$ V/m, $E_\phi = 500$ V/m



Transient response at transistor output



Task 2.3: Summary

1) A MOT algorithm based on a hybrid surface/volume time domain integral equation has been developed for analysis of conducting/ inhomogeneous dielectric bodies,
2) This algorithm has been accelerated with the PWTD technology that rigorously reduces the $O(N_T N_S^2)$ computational complexity of the MOT solver to $O(N_T N_S \log^2 N_S)$ for typical PCB structures,
3) Linear/Nonlinear circuits in the system are modeled by coupling modified nodal analysis equations of circuits to MOT equations,
4) A nonlinear Newton-based solver is used at each time step to consistently solve for circuit and electromagnetic unknowns.
5) The proposed method can find extensive use in EMC/EMI and signal integrity analysis of PCB, interconnect and packaging structures with realistic complexity.

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