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February 06, 2001

Advances in Planar EM Simulation for RF Structures

Agilent Technologies
Innovating the HP Way

Overview

Part I Technology

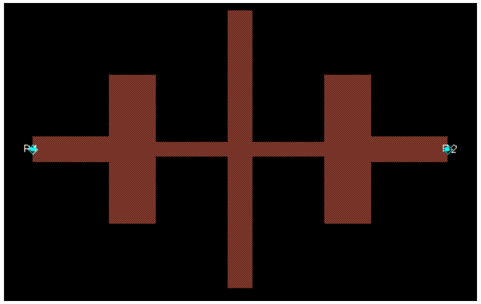
- Planar Electromagnetic Basics
- Quasi-Static Approximation
- Polygonal Mesh
- Star-Loop Transform

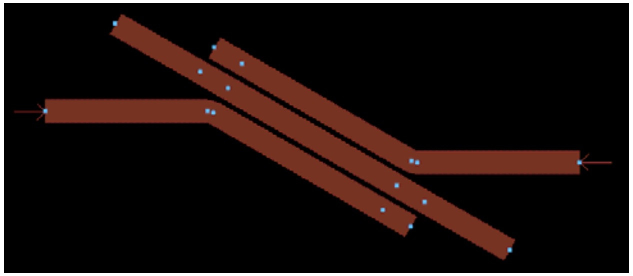
Part II Applications

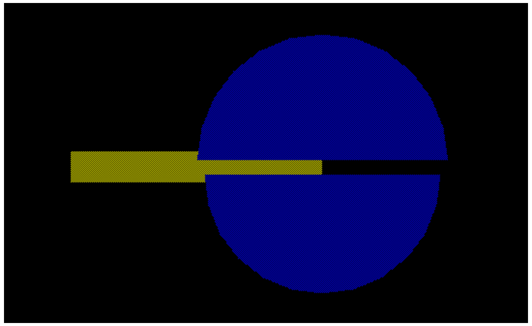
- RF Board Interconnect
- Digital Board Interconnect
- Ball Grid Array Package
- Microwave Lowpass Filter

Planar Electromagnetic Basics

Microwave Hybrid (Alumina)
Microwave MMIC (GaAs)
Planar Antennas
Antenna Arrays







- Electrically "large"
- Geometrically "simple"
- Microwave frequencies

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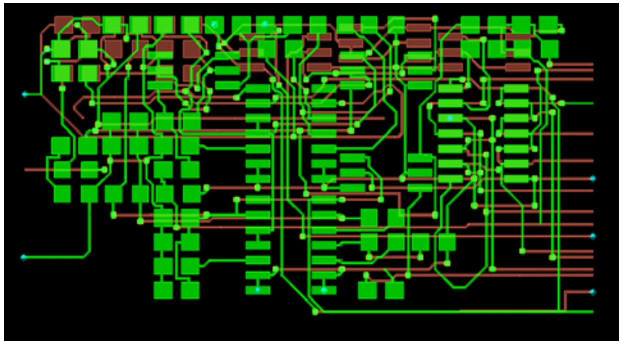
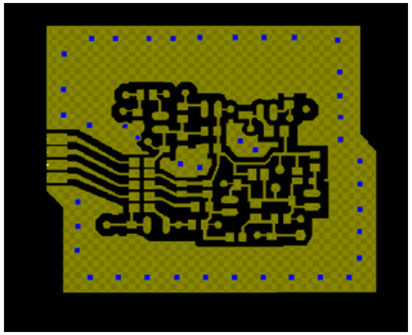
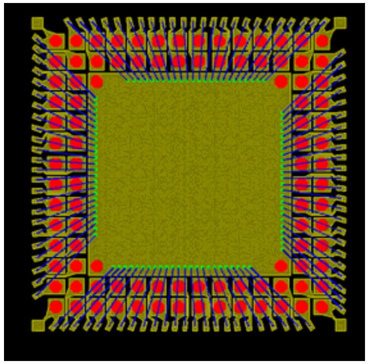
Planar Electromagnetic Basics

High-Speed Digital
RF Board (FR4, Duroid)
IC Package (BGA)
RF Module (MCM, LTCC)
RFIC (Silicon)

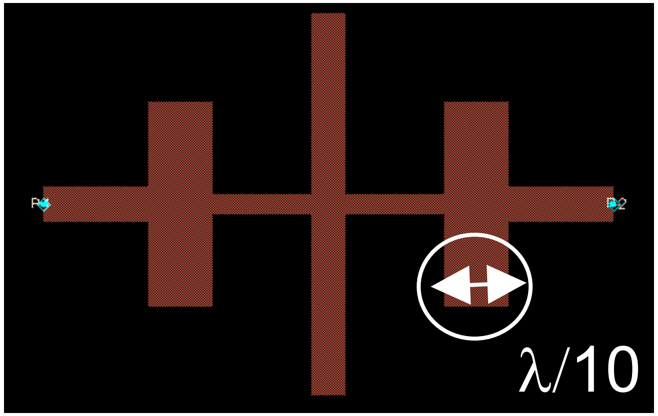




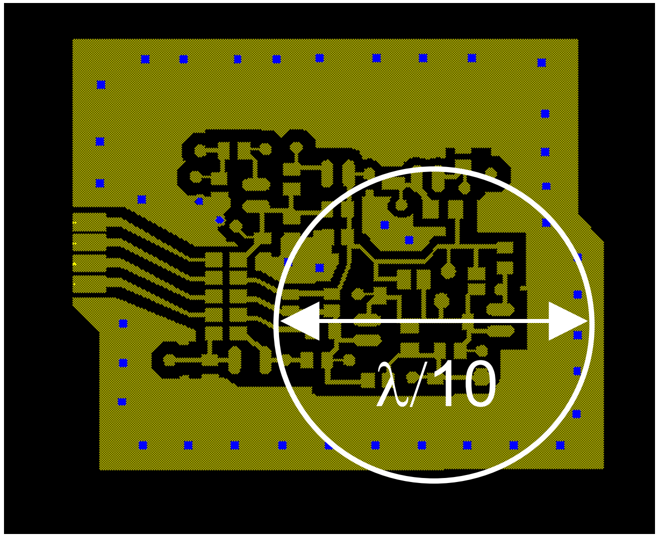


- Electrically "small"
- Geometrically "complex"
- DC to RF frequencies

Planar Electromagnetic Basics



Geometrically "simple"



Geometrically "complex"

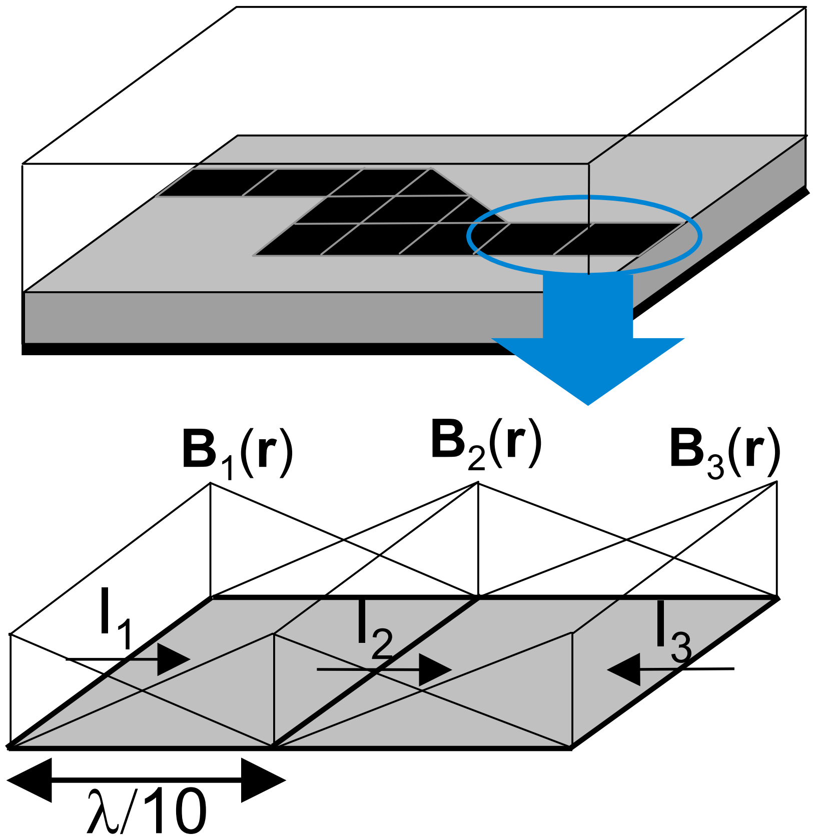
Planar Electromagnetic Basics

Physical Design

- Substrate
- Metallization
- Ports

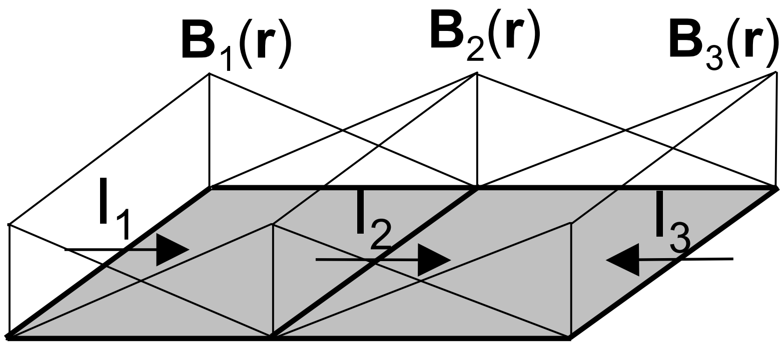
Method of Moments

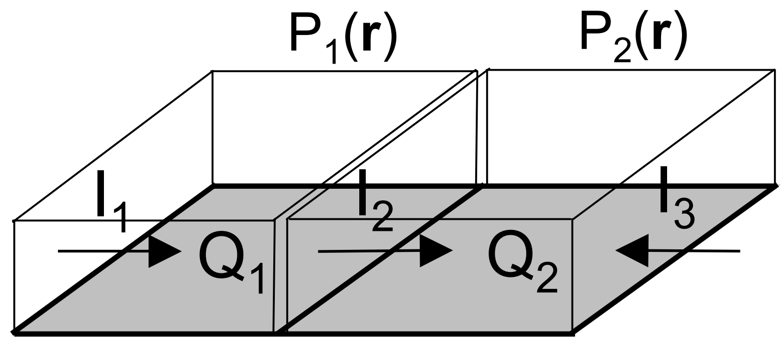
- Meshing
- Rooftop functions



$$J(\mathbf{r}) = I_1 B_1(\mathbf{r}) + I_2 B_2(\mathbf{r}) + I_3 B_3(\mathbf{r})$$

Planar Electromagnetic Basics





$$\mathbf{J}(\mathbf{r}) = I_1\mathbf{B}_1(\mathbf{r}) + I_2\mathbf{B}_2(\mathbf{r}) + I_3\mathbf{B}_3(\mathbf{r})$$

$$q(\mathbf{r}) = -\frac{1}{j\omega}\nabla \cdot J(\mathbf{r}) = Q_1P_1(\mathbf{r}) + Q_2P_2(\mathbf{r})$$

$$\nabla \cdot \mathbf{B}_1(\mathbf{r}) = -P_1(\mathbf{r})$$
$$\nabla \cdot \mathbf{B}_2(\mathbf{r}) = P_1(\mathbf{r}) - P_2(\mathbf{r})$$
$$\nabla \cdot \mathbf{B}_3(\mathbf{r}) = -P_2(\mathbf{r})$$

$$Q_1 = \frac{1}{j\omega}(I_1 - I_2)$$
$$Q_2 = \frac{1}{j\omega}(I_2 + I_3)$$

Current Continuity Relation is preserved in the discretization

Planar Electromagnetic Basics

Method of Moments

Maxwell's Equations

↓

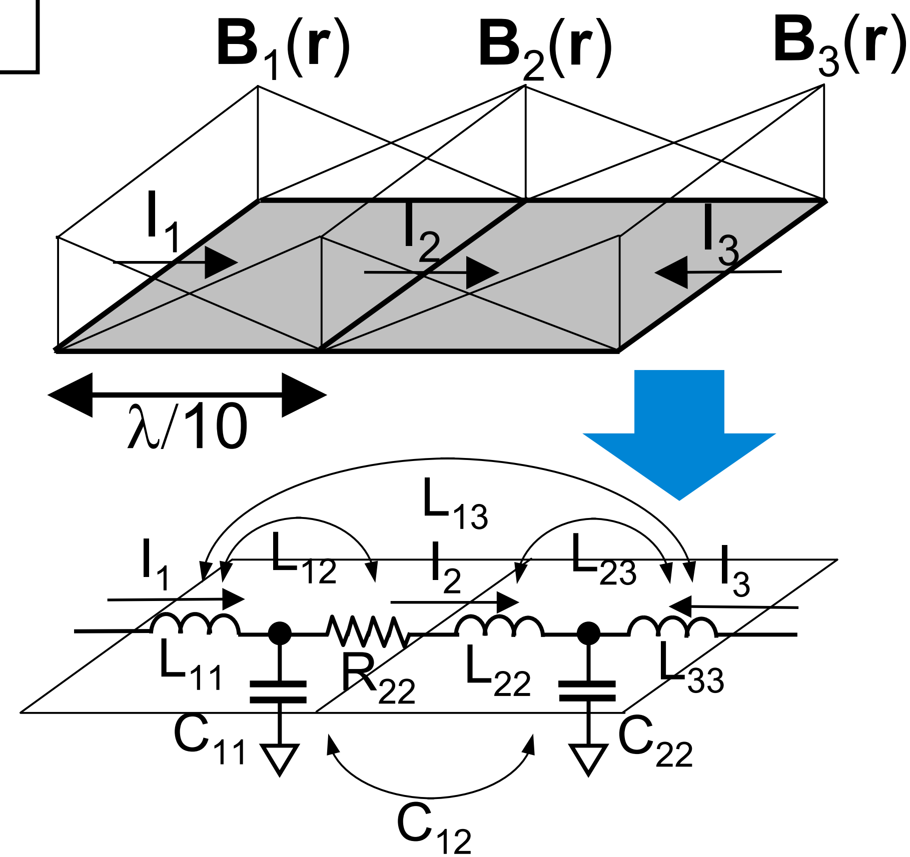
Matrix Equation

[Z].[I]=[V]

↕

Equivalent Circuit

$[Z] = [R] + j\omega[L] + 1/j\omega\ [C]^{-1}$



Fullwave versus Quasi-Static

Fullwave

Maxwell's Equations

⇓

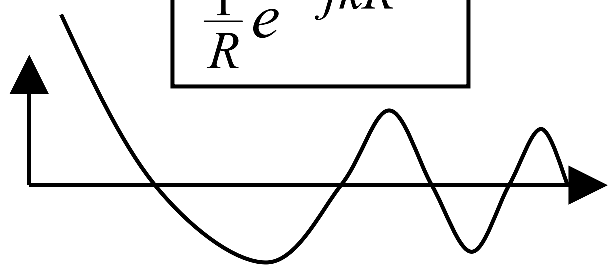
Matrix Equation

$[Z(\omega)].[I]=[V]$

⇕

Equivalent Circuit

$[Z] = [R(\omega)] + j\omega[L(\omega)] + 1/j\omega\ [C(\omega)]^{-1}$



$$\frac{1}{R}e^{-jkR}$$

- including coupling and radiation
- $[L(\omega)]$ & $[C(\omega)]$ frequency dependent
- $[Z(\omega)]$ matrix reload CPU intensive

Quasi-Static Approximation

Quasi-Static

Maxwell's Equations

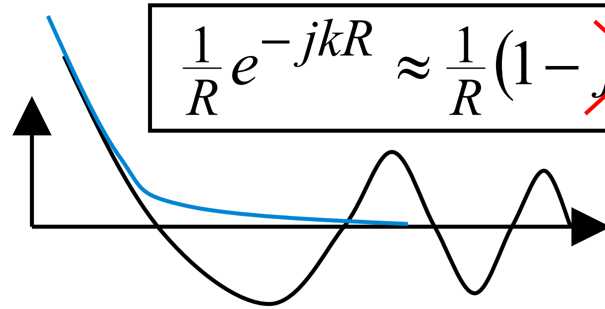
Matrix Equation

$[Z_0].[I]=[V]$

Equivalent Circuit

$[Z_0] = [R(\omega)] + j\omega[L_0] + 1/j\omega\,[C_0]^{-1}$

$$\frac{1}{R}e^{-jkR} \approx \frac{1}{R}(1 - jkR + \ldots)$$



- near field / low freq approximation

  $L(\omega) = L_0 + L_1\omega R + L_2(\omega R)^2 + \ldots$

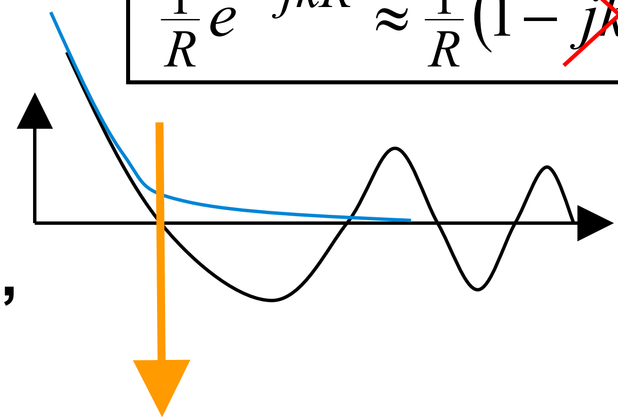
  $C(\omega) = C_0 + C_1\omega R + C_2(\omega R)^2 + \ldots$

- neglecting far field radiation
- $[L_0]$ & $[C_0]$ frequency independent
- $[Z_0]$ matrix reload very fast

Quasi-Static Approximation

Validity ??

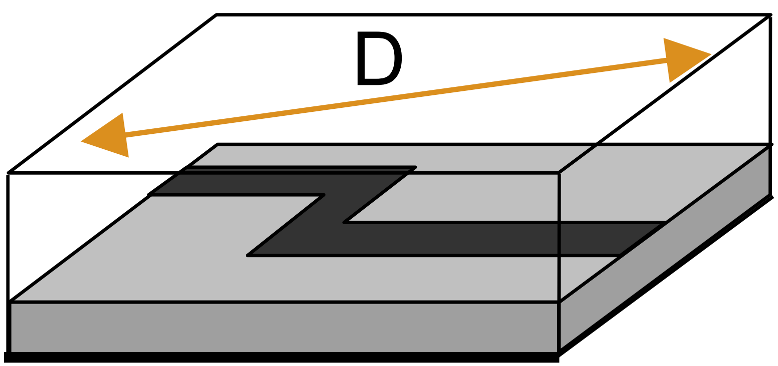
$$\frac{1}{R}e^{-jkR} \approx \frac{1}{R}(1 - \cancel{jkR} + \dots)$$



When the structure

- **does NOT radiate**
- **is electrically "small"**

Rule of thumb:



$$\text{Dimension} < \frac{\text{WaveLength}}{2} = \frac{C_{\text{light}}}{2\,\text{Freq}}$$

$$\Rightarrow \quad \text{Freq [GHz]} < \frac{150}{\text{D [mm]}}$$

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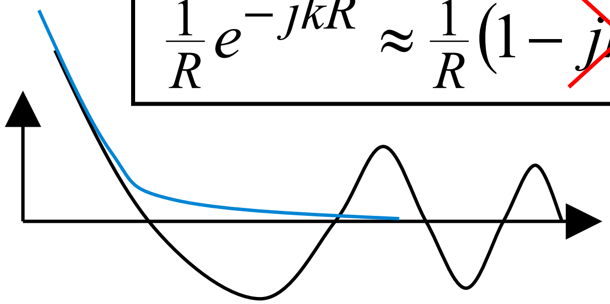
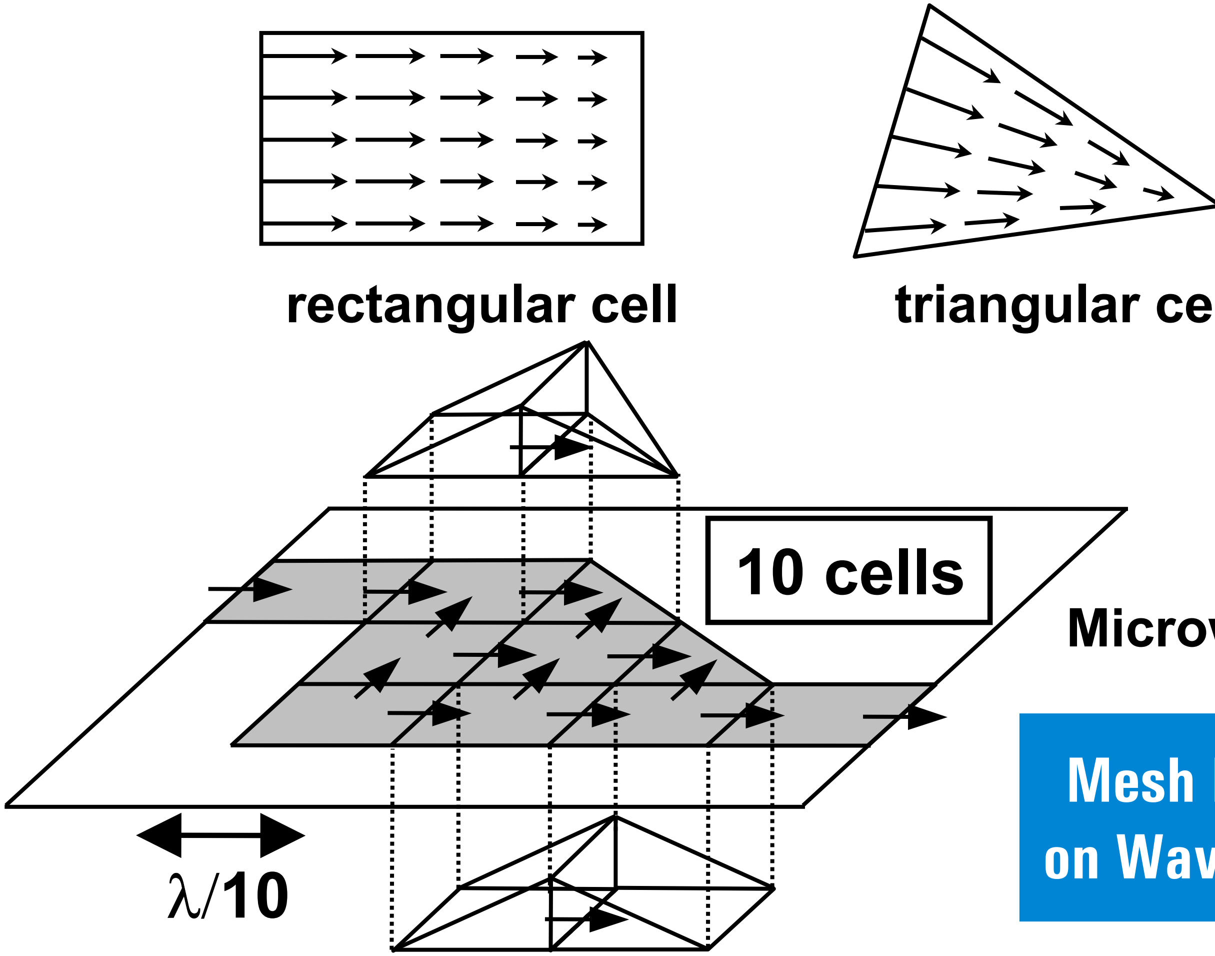
Quasi-Static Approximation

$$\frac{1}{R}e^{-jkR} \approx \frac{1}{R}\left(1 - \cancel{jkR} + \ldots\right)$$



- Near Field / Low Freq approximation
- Neglecting Far Field Radiation Terms
- Good for electrically “small” structures
- Strongly reduced computation time

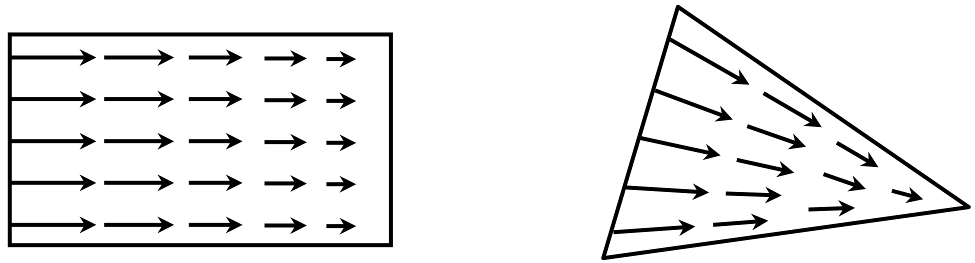
Rectangular-Triangular Mesh



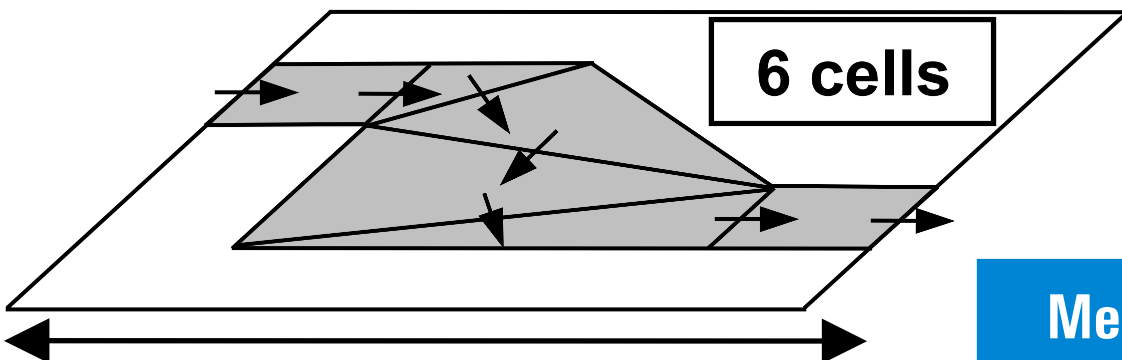
Microwave Frequency

Mesh Density depends on Wavelength Criterium

Rectangular-Triangular Mesh



rectangular cell   triangular cell



$\lambda/10$

RF Frequency

Mesh Density depends on Geometrical Complexity

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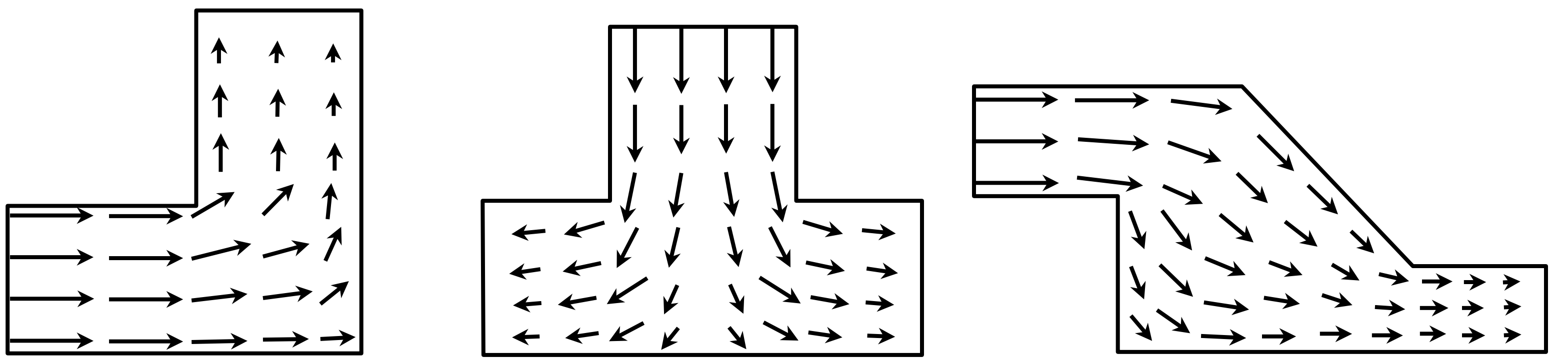
Polygonal Mesh

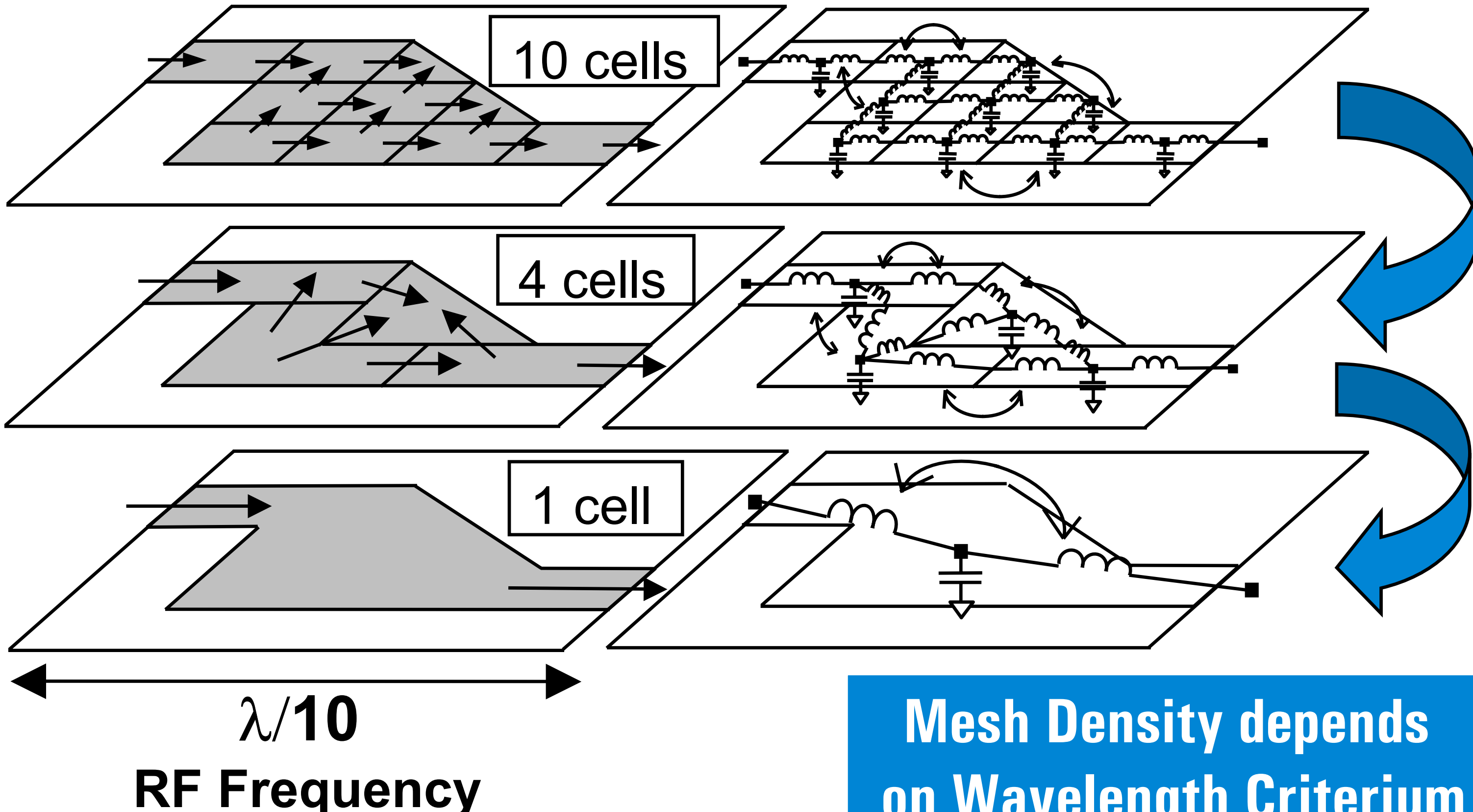


L-shaped cell T-shaped cell polygonal cell

- Arbitrary Polygonal cells
- Generalized Current functions
- Generalized L & C interactions

Polygonal Mesh

Mesh Density depends on Geometrical Complexity



Mesh Density depends on Wavelength Criterium

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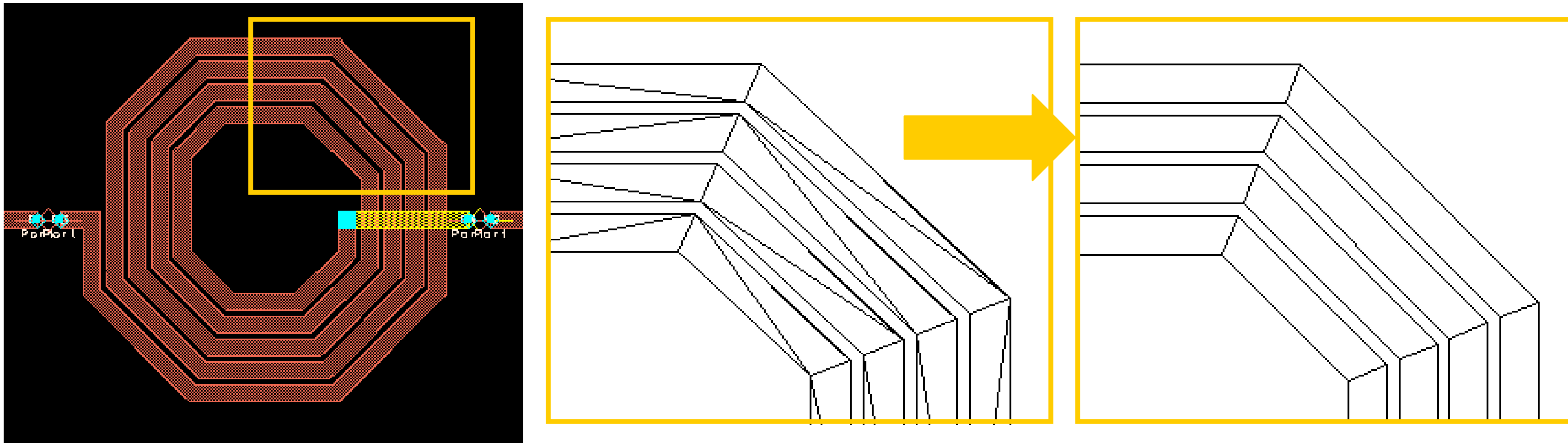
Polygonal Mesh



- Meshing complex geometries with POLYGONAL cells
- Eliminating slivery triangles
- Uncompromised accuracy for RF frequencies
- Strongly reduced computer memory
- Strongly reduced computation time

Star-Loop Transform

Low Frequency Breakdown

$$[Z].[I]=[V]$$

$$[Z] = j\omega[L] + 1/j\omega\,[C]^{-1}$$

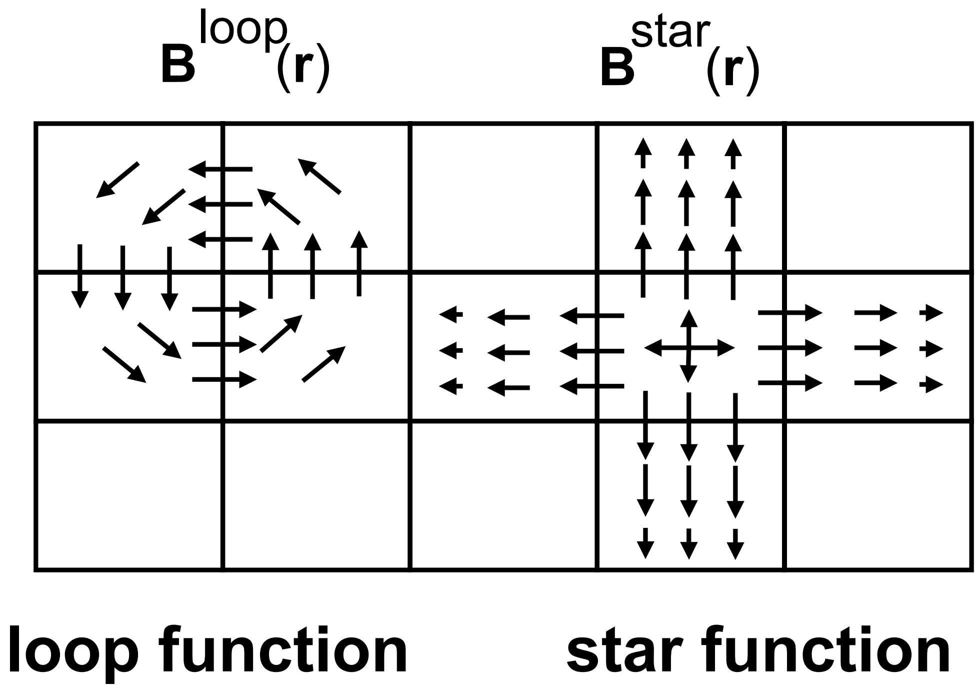
$j\omega[L]$ → zero $1/j\omega\,[C]^{-1}$ → infinity

[Z] is ill-conditioned for low frequencies

numerical solution breaks down

Star-Loop Transform

Rooftop functions are transformed into Star and Loop functions



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Star-Loop Transform

Loop functions are solenoidal

$$\nabla \cdot \mathbf{B}^{\text{loop}}(\mathbf{r}) = 0$$

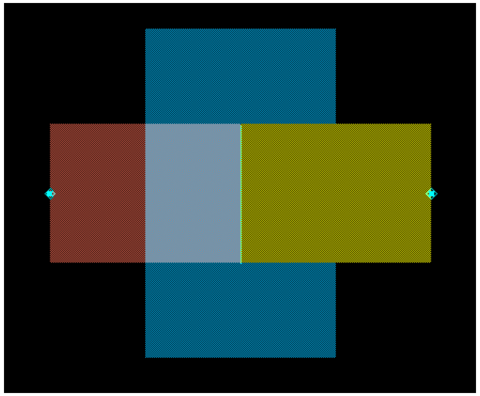
Loop Currents have no capacitive interactions ⟶ NO LF problem

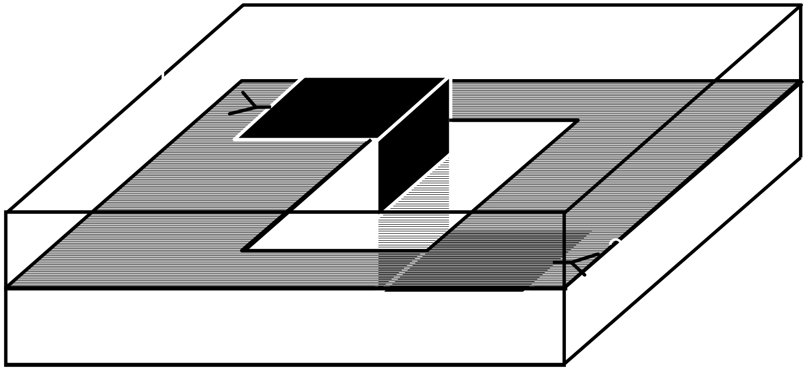
$$\frac{1}{j\omega}\begin{bmatrix} [C^{\text{star,star}}] & [0] \\ [0] & [0] \end{bmatrix}^{-1}$$

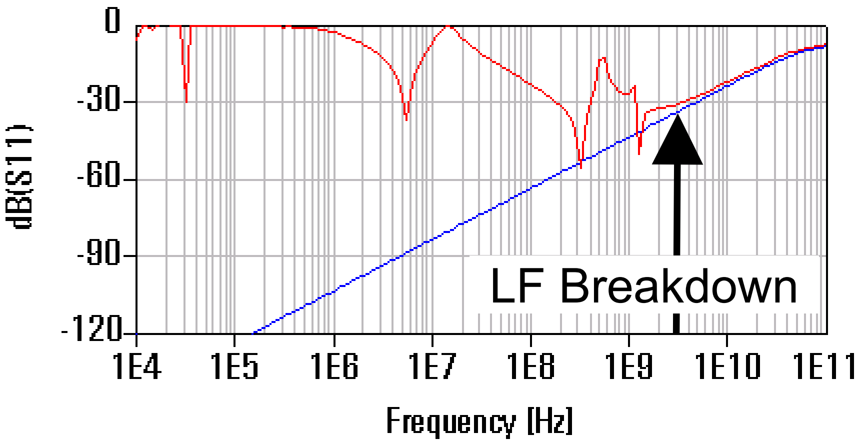
Loop functions ⟶ Magnetostatic Solution
Star Functions ⟶ Electrostatic Solution

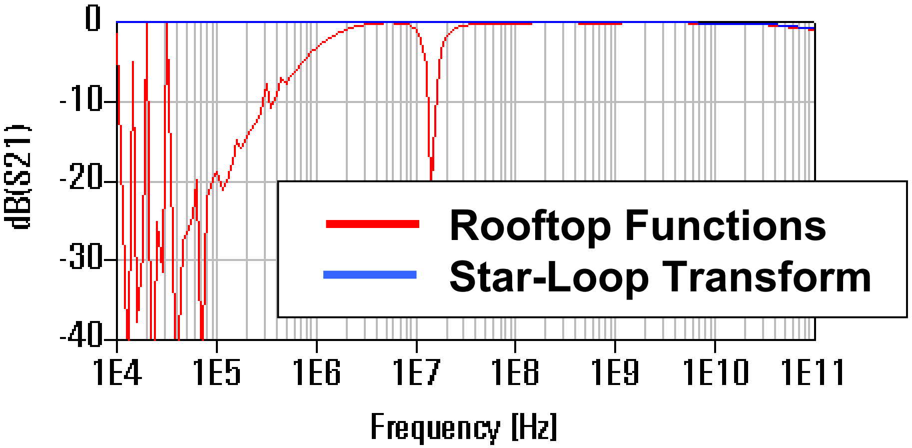
Star-Loop Transform

Microstrip through GroundPlane Transition









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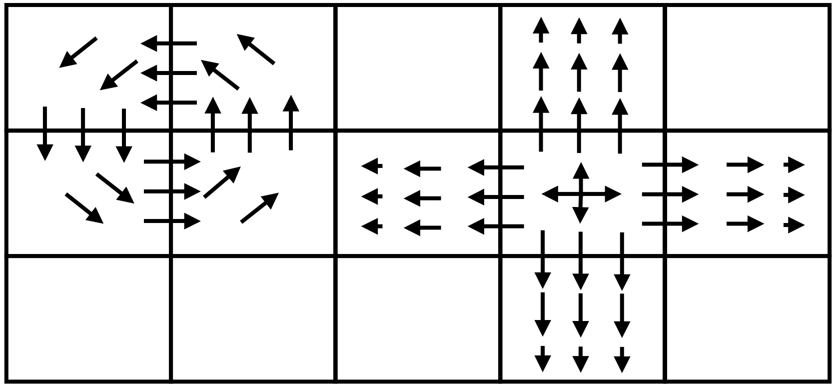
Star-Loop Transform



- gives stable solutions down to DC
- needed for circuit simulator

Part I Technology - Summary

New Planar Electromagnetic Technology

Addressing Speed, Capacity & Accuracy needs for High Speed Digital and Analog RF applications

Electrical Small	↔	Quasi-Static Model
Geometrical Complex	↔	Polygonal Mesh
DC to RF frequency	↔	Star-Loop Transform

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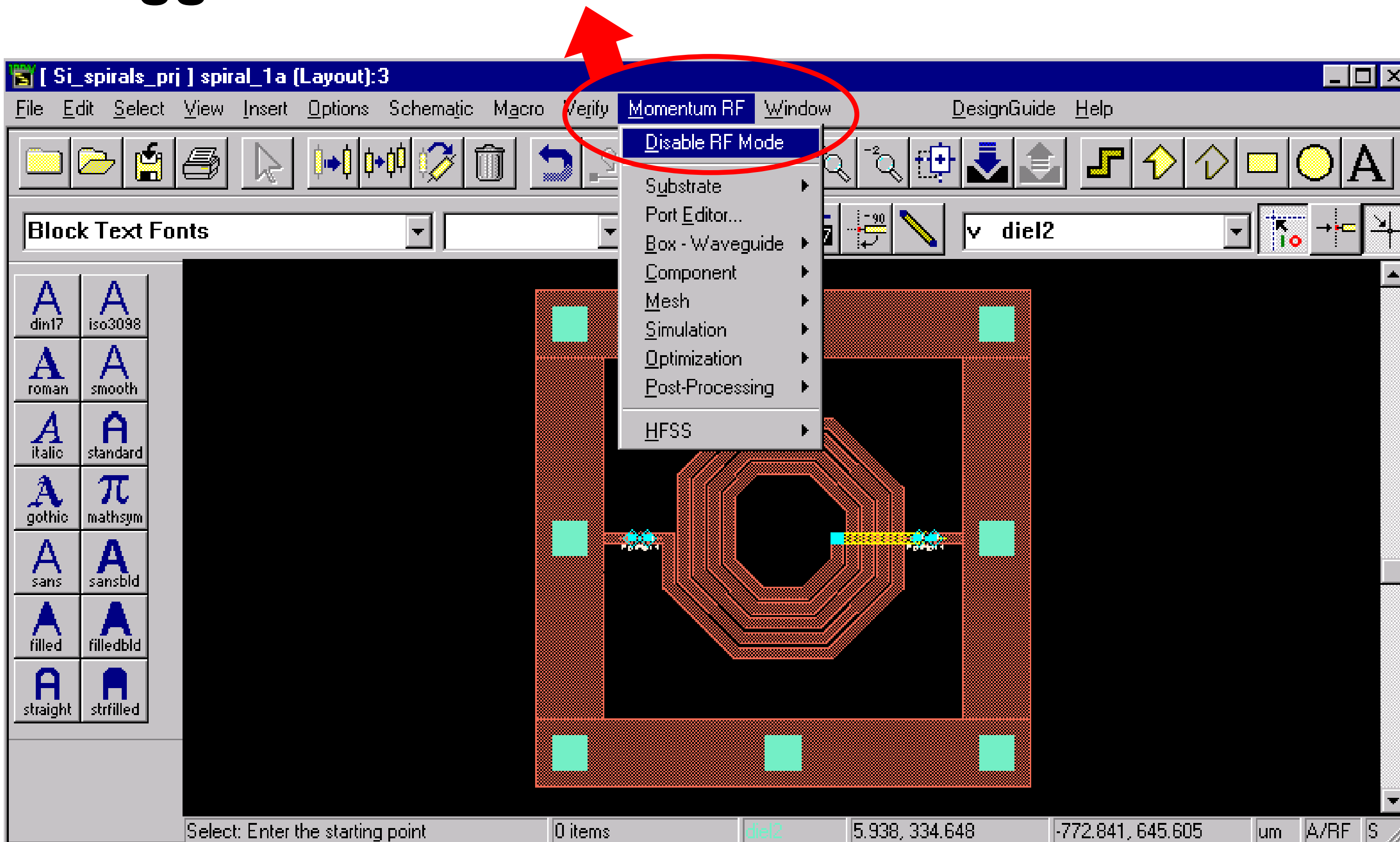
Momentum RF

Integrated in ADS 1.50 as new option in Momentum, user toggle allows to “enable/disable” RF mode



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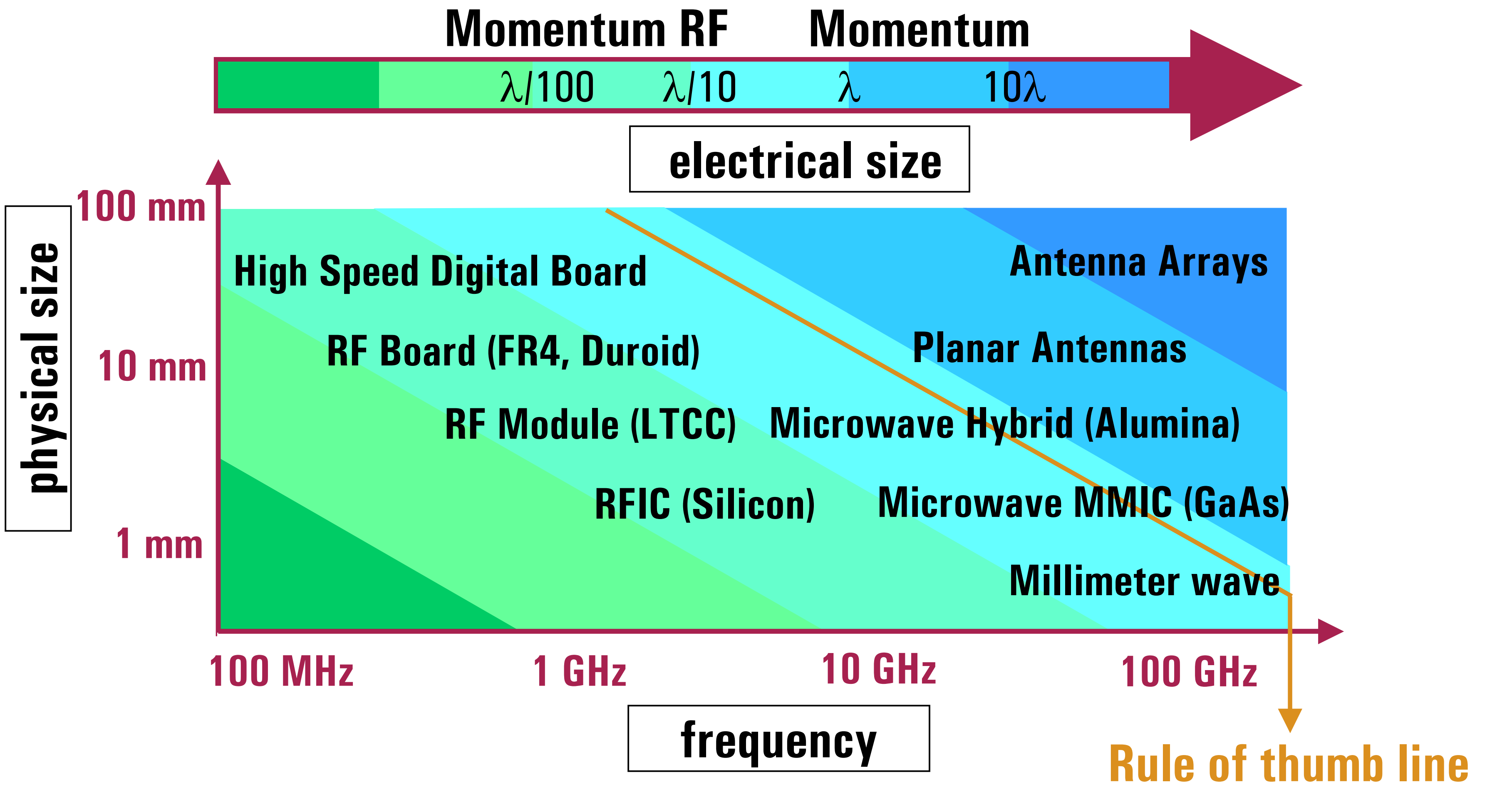
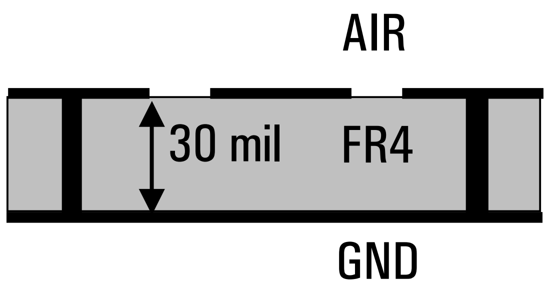
Momentum RF

	Momentum	Momentum RF	Benefit
Substrate			
Database	✓	✓	
Functions	fullwave	**QUASI-STATIC**	**Speed**
Ports			
Port Types	✓	✓	
Calibration	✓	☐	
Box - Waveguide	✓	☐	
Mesh			
Mesh Options	✓	✓	
Cells	rectangle/triangle	**POLYGONAL**	**Speed & Capacity**
Simulation			
Sweep types	✓	✓	
Basis functions	rooftop	**STAR/LOOP**	**LF stability**
Optimization	✓	✓	
Post-Processing			
Visualization	✓	✓	
Radiation Pattern	✓	☐	

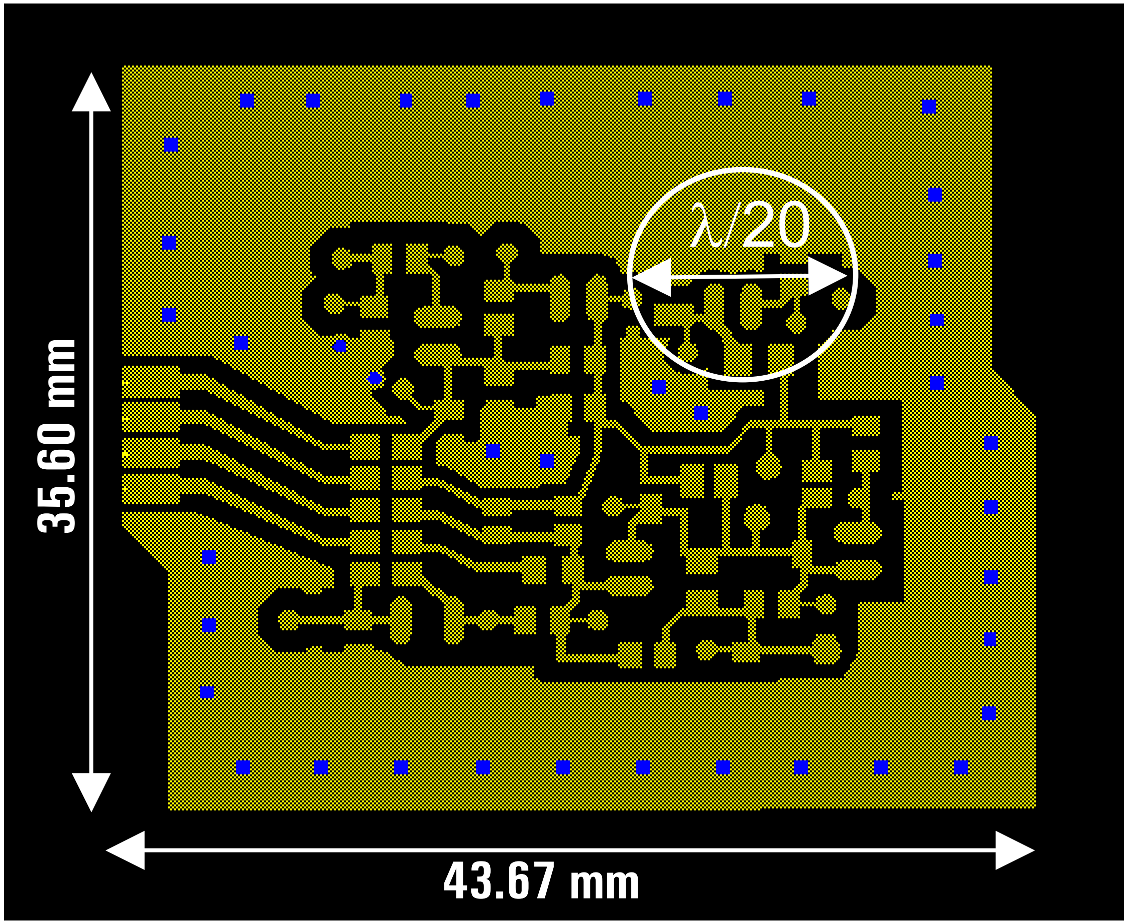
Part II Applications



RF Board Interconnect



Mesh Density
20 cells/λ [1GHz]



Rule of thumb: freq < 2.66 GHz

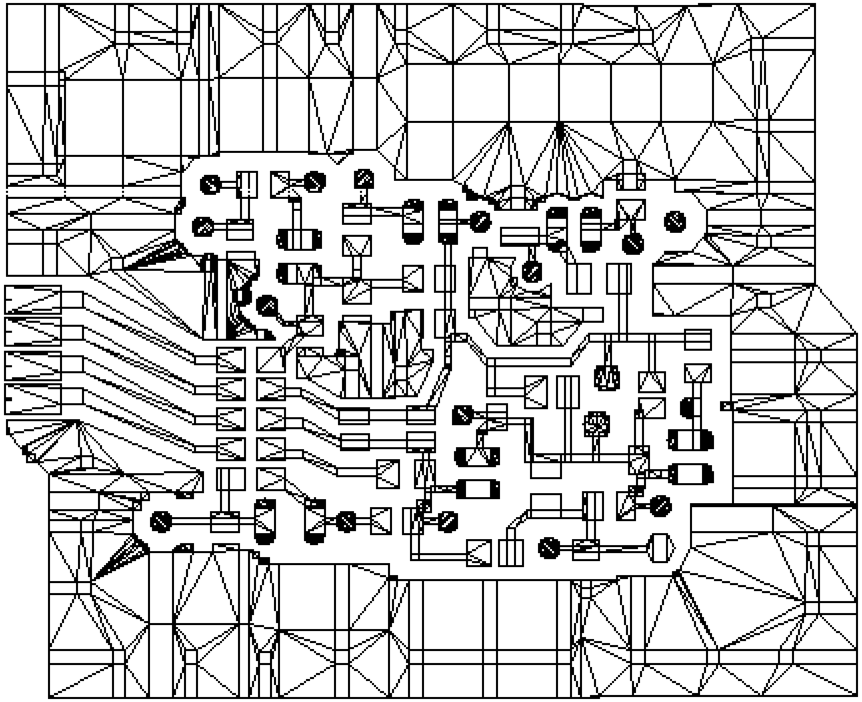
RF Board Interconnect

Momentum

Mesh: 20 cells/λ, 1 GHz

Matrix size : **3428**
Process size : **152.48 MB**
User time : **3h 14m 51s**

rectangular & triangular mesh



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RF Board Interconnect

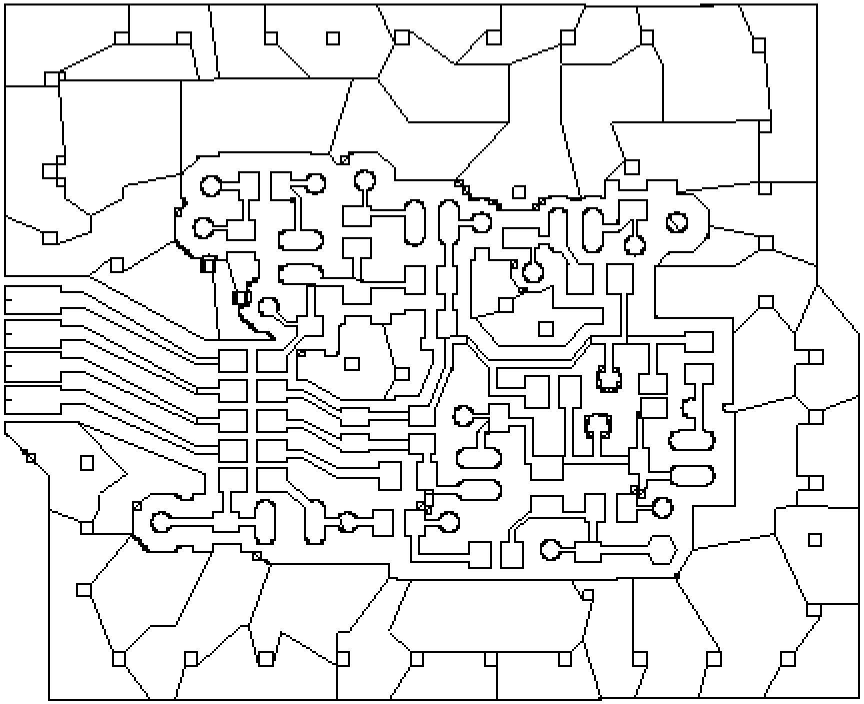
Momentum RF

Mesh: 20 cells/λ, 1 GHz

Matrix size : **733**
Process size : **59.35 MB**
User time : **14m 24s**

memory: 3 x
speed: 14 x

polygonal mesh



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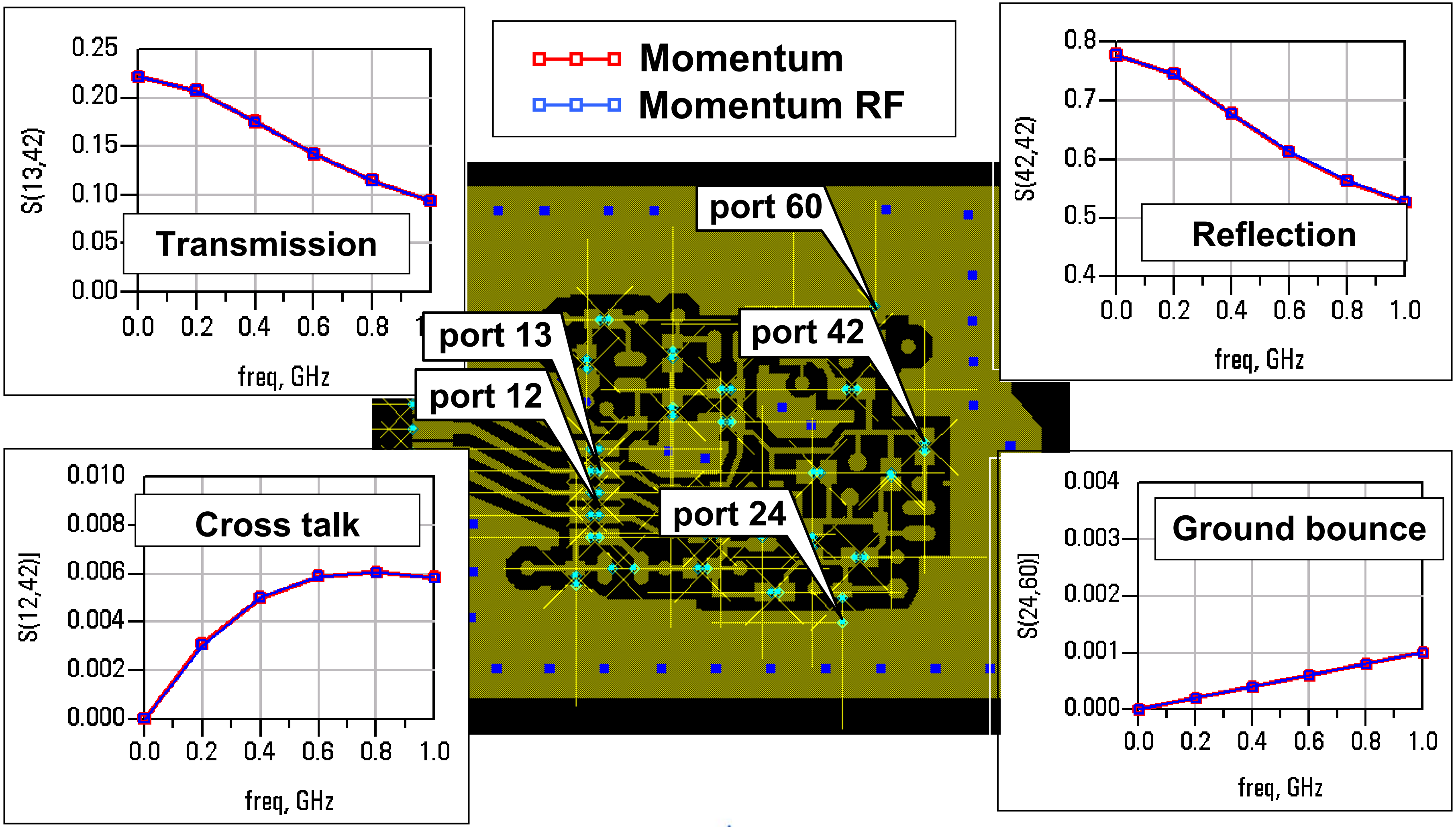
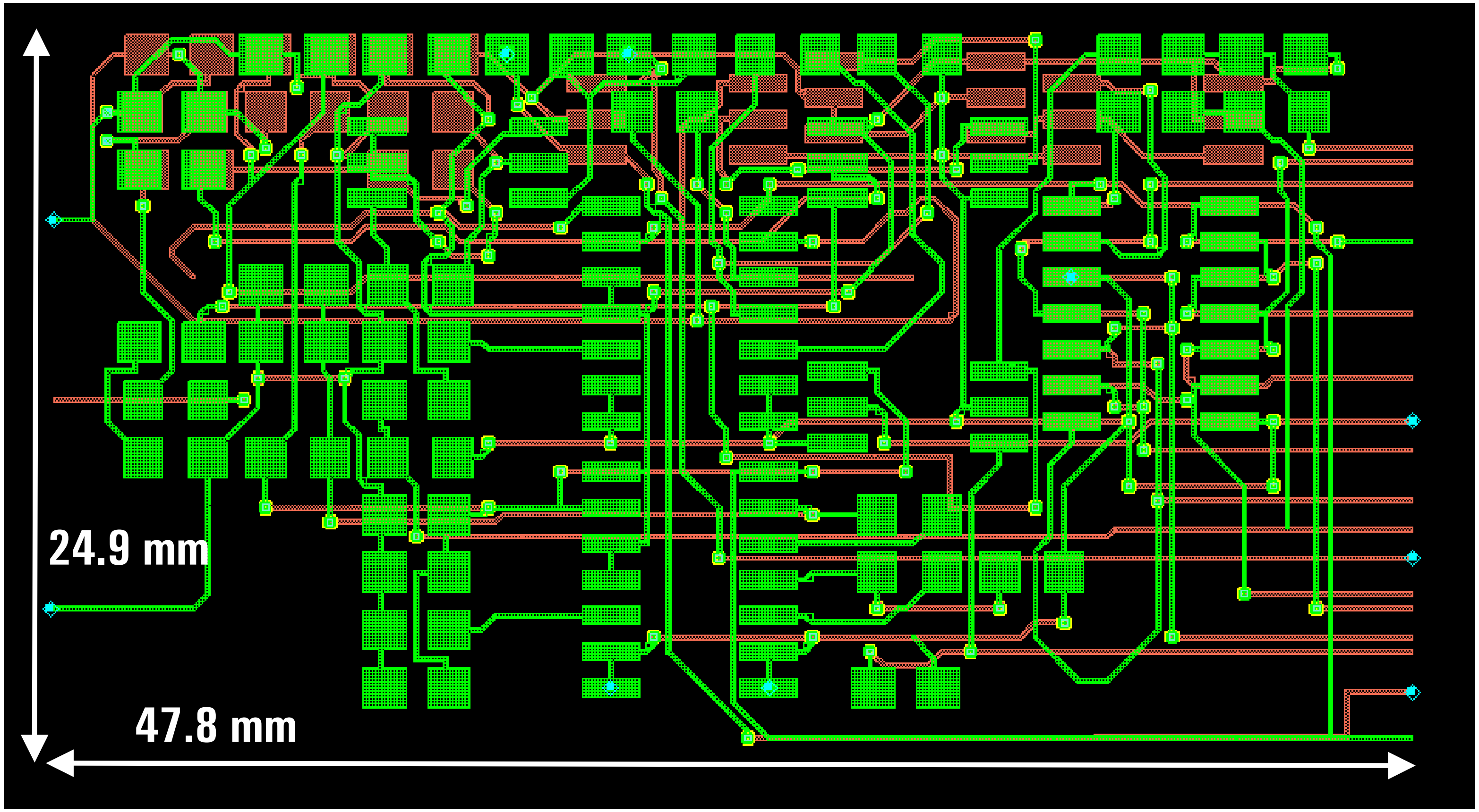
RF Board Interconnect



Digital Board Interconnect



Rule of thumb: freq < 2.77 GHz

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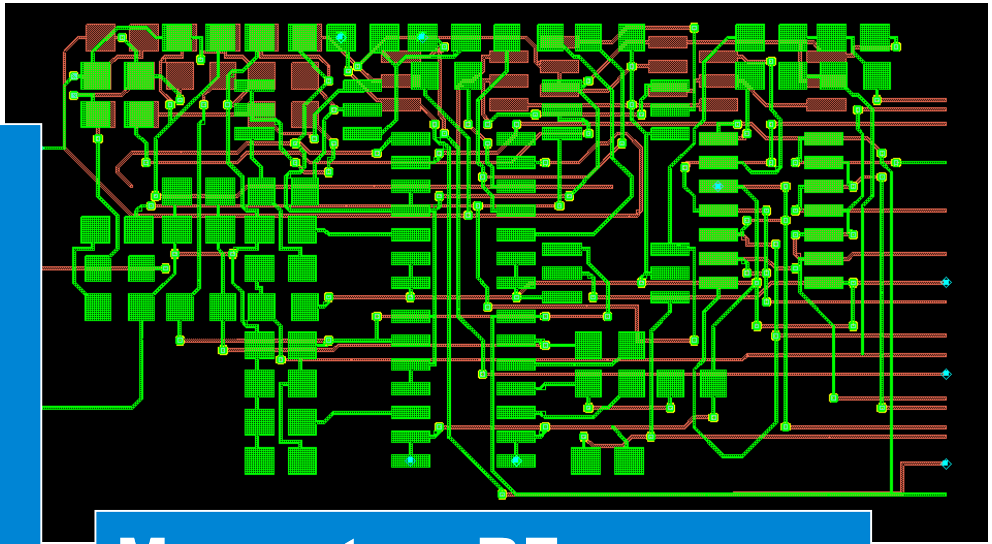
Digital Board Interconnect



Momentum

Mesh: 10 cells/λ, 3 GHz

Matrix size : **8124**
Process size : **> 1 GB**
User time : **> 1 day**

Momentum RF

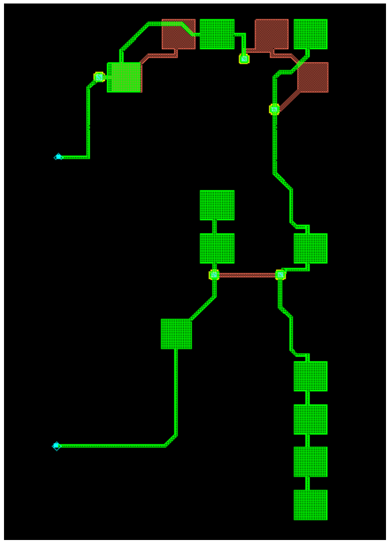
Mesh: 10 cells/λ, 3 GHz

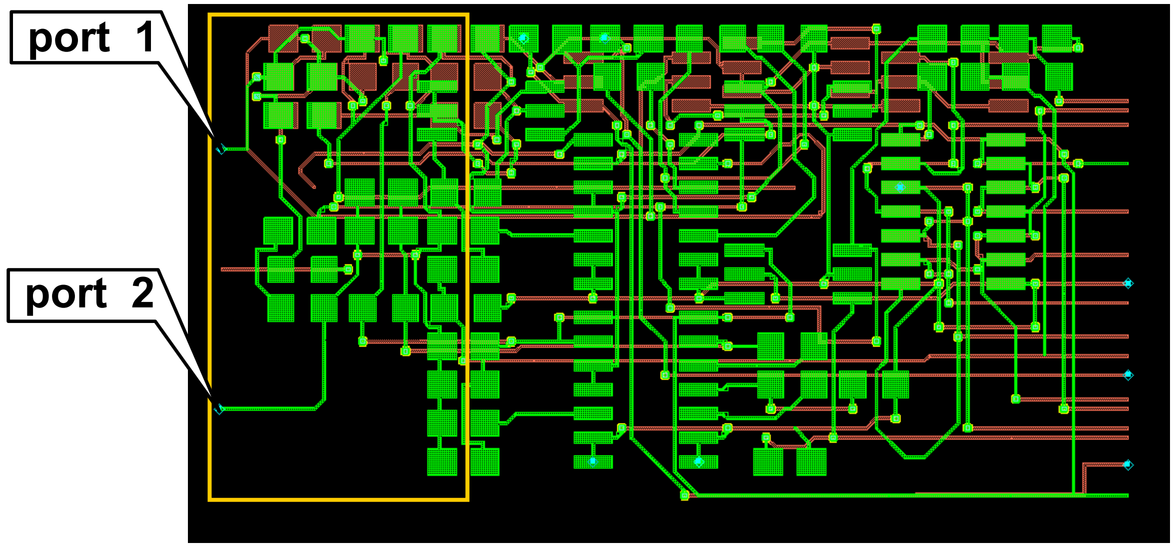
Matrix size : **722**
Process size : **150.41 MB**
User time : **1h 37m 07s**

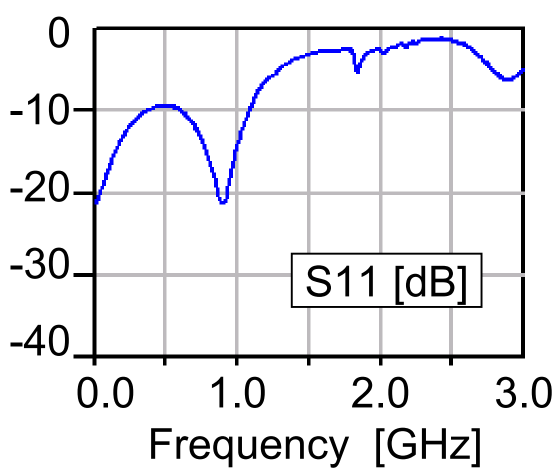
memory: 10 x
speed: 20 x

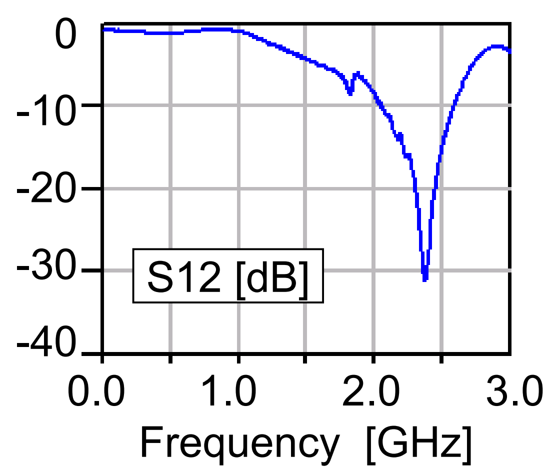
Digital Board Interconnect

reflection & transmission of single trace

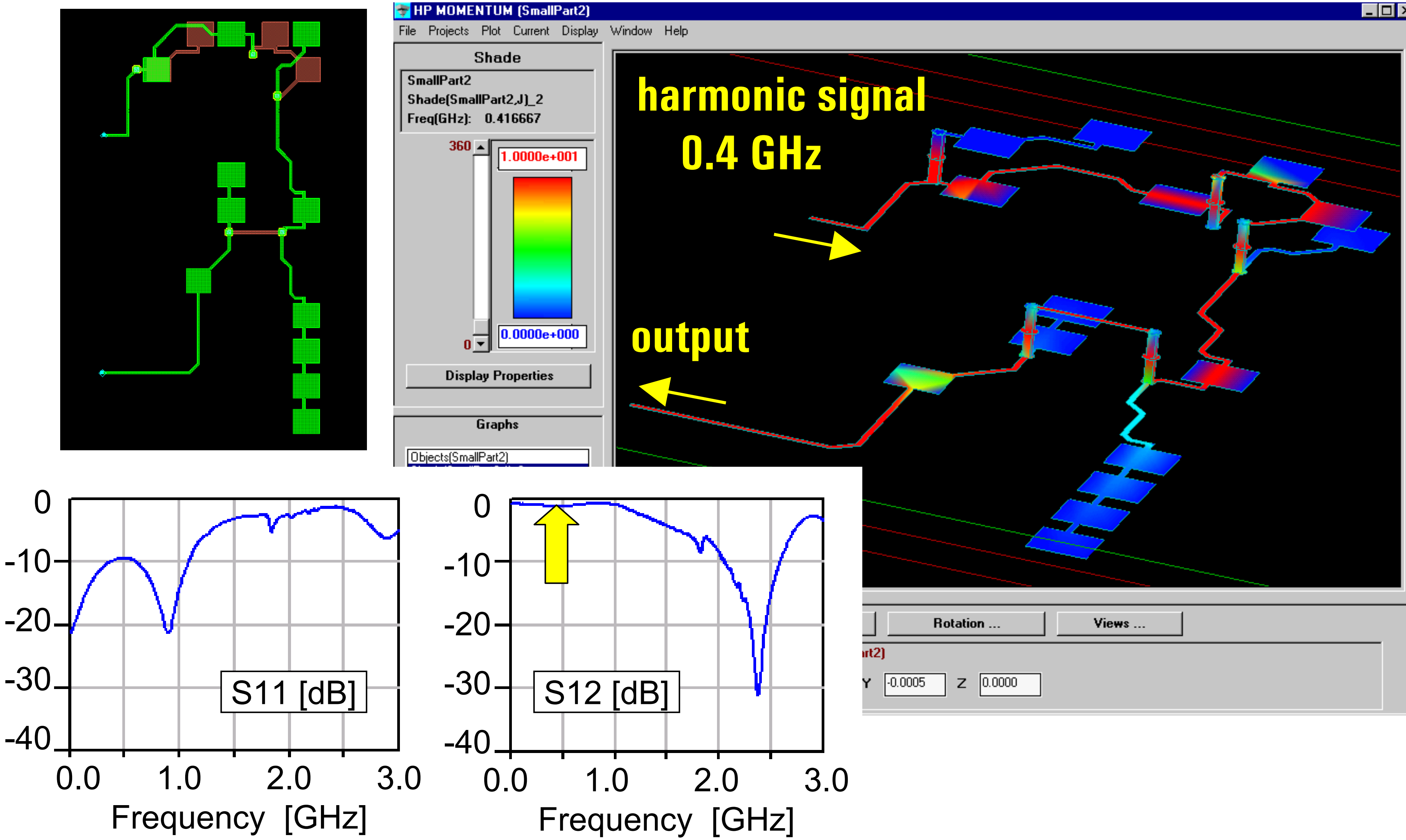




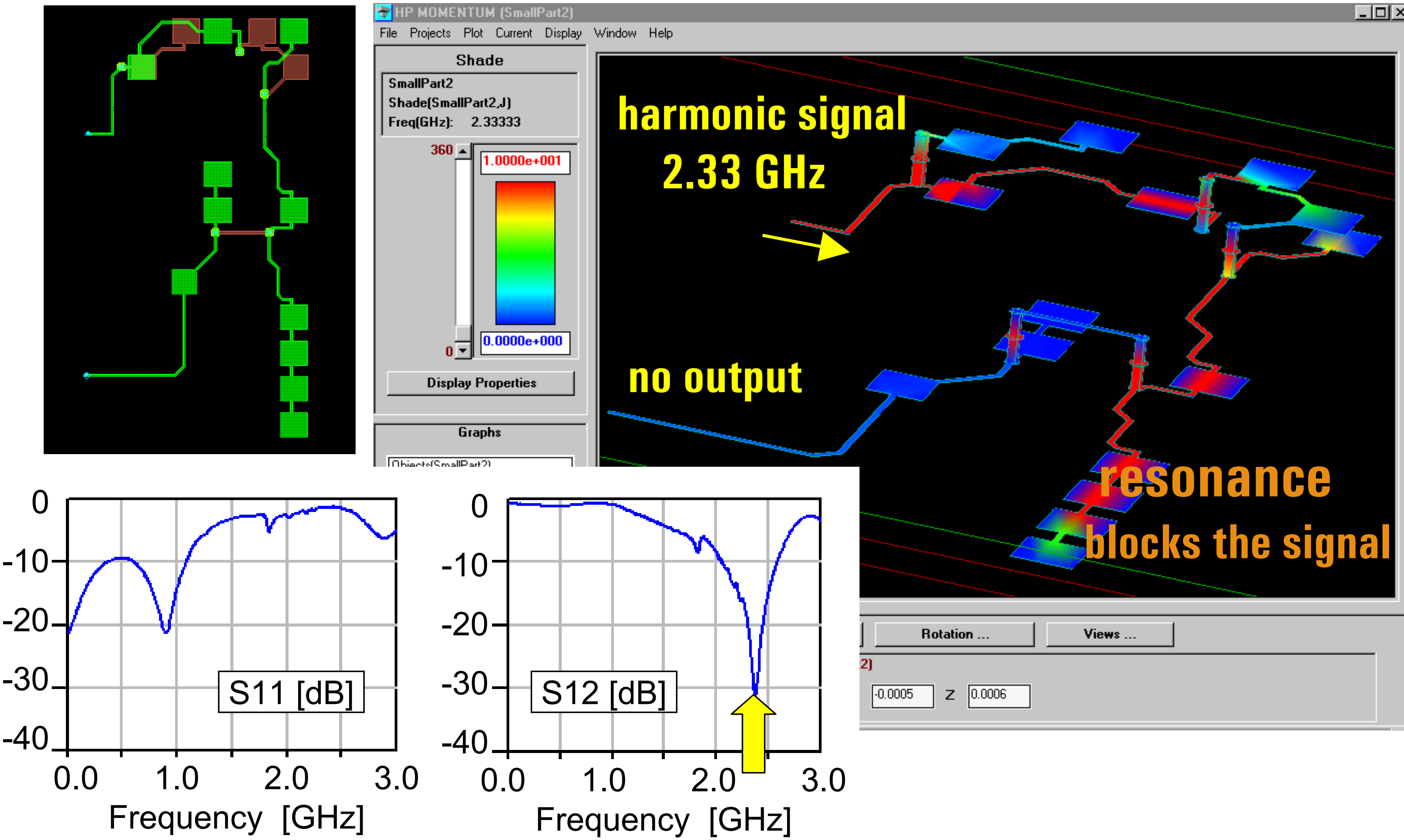




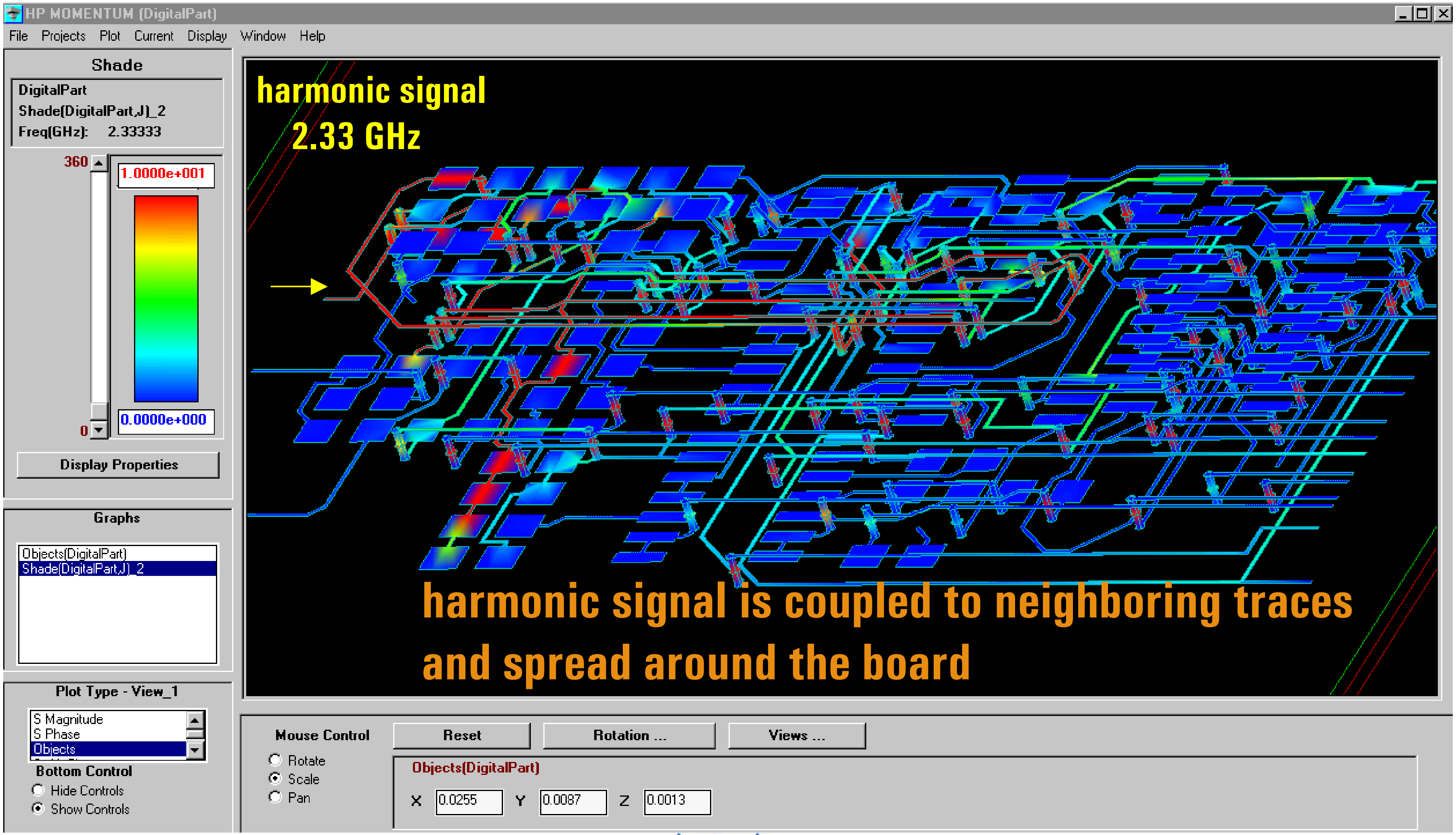
Digital Board Interconnect



Digital Board Interconnect



Digital Board Interconnect



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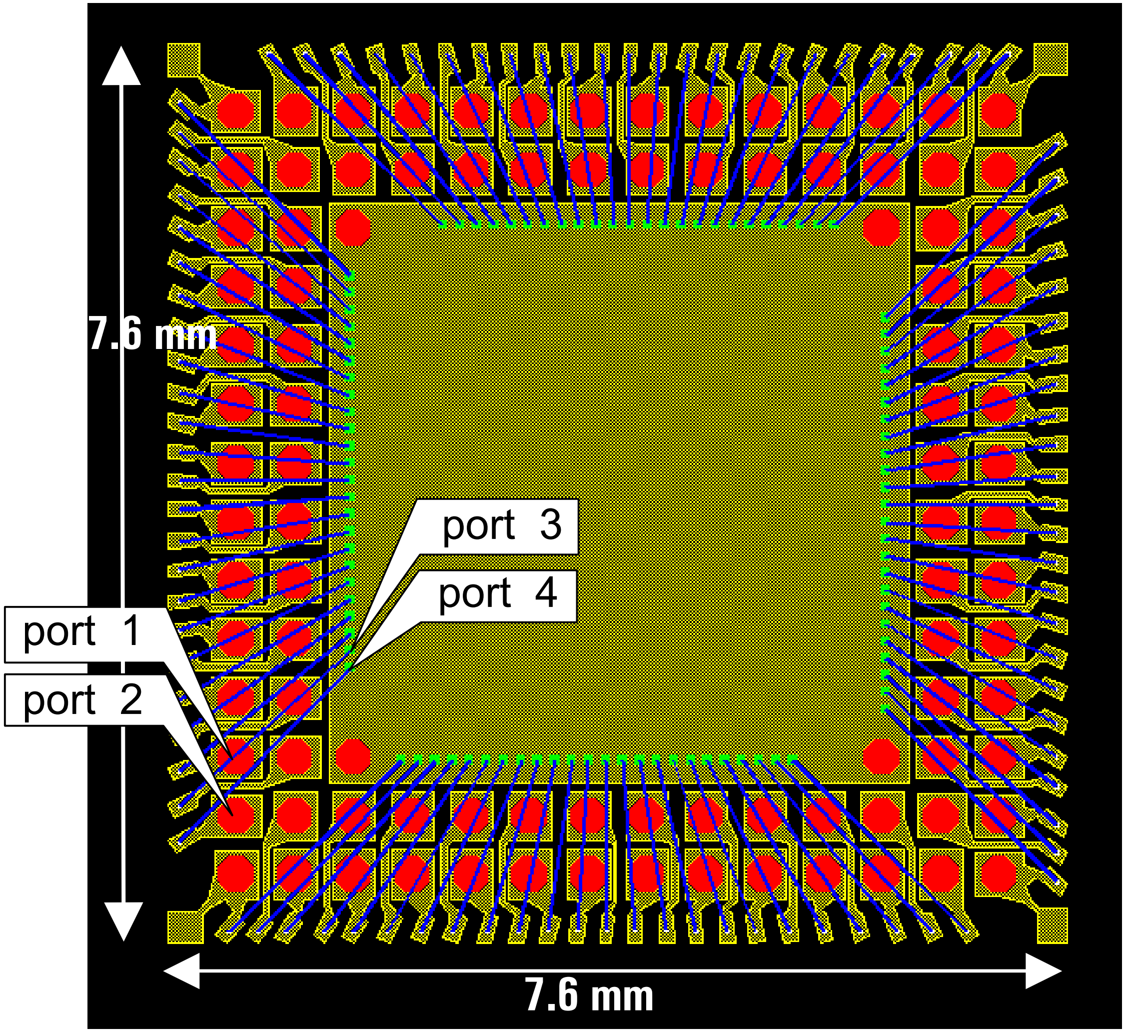
Ball Grid Array Package



Rule of thumb:
freq < 13.8 GHz

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Ball Grid Array Package

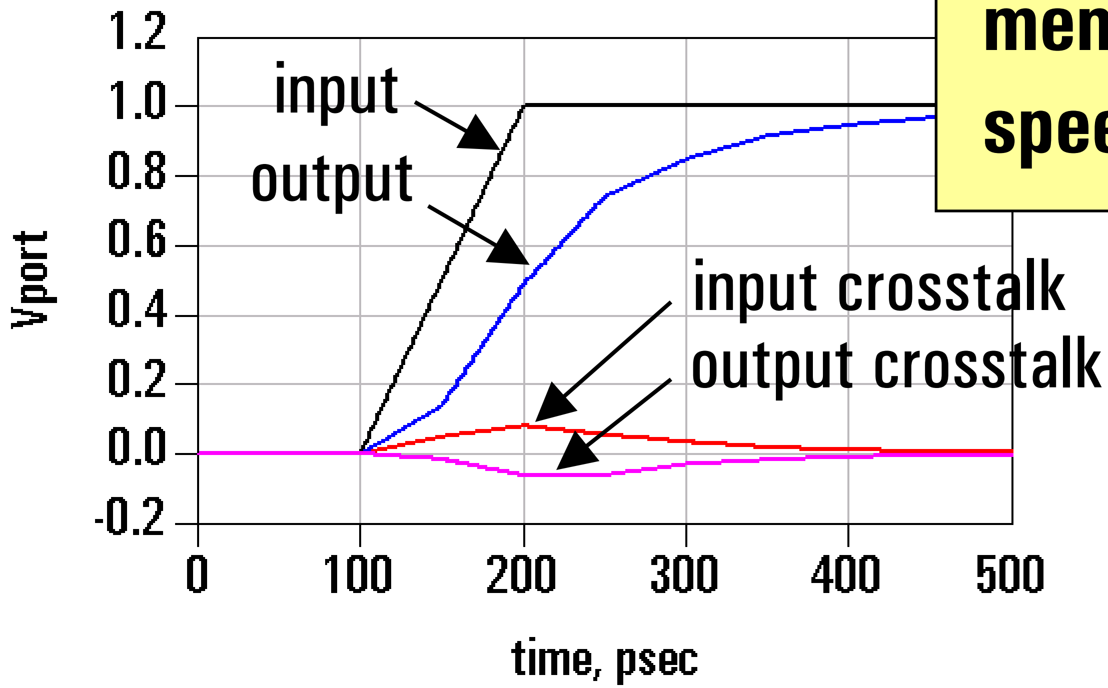
Momentum

Matrix size	:	**8244**
Process size	:	**> 1 GB**
User time	:	**> 1 day**

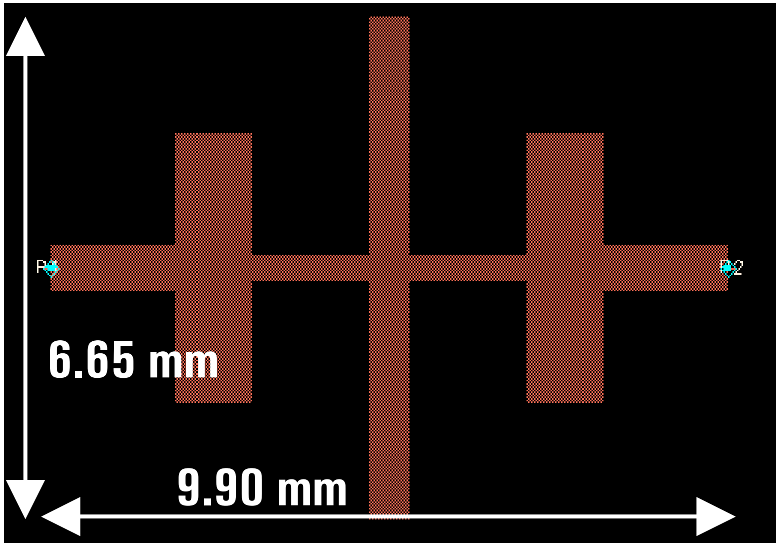
Momentum RF

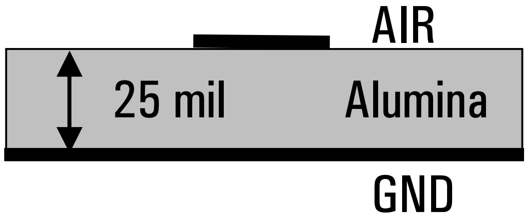
Matrix size	:	**1354**
Process size	:	**106.57 MB**
User time	:	**1h 47m 53s**

memory: 10 x
speed: 20 x



Microwave Lowpass Filter

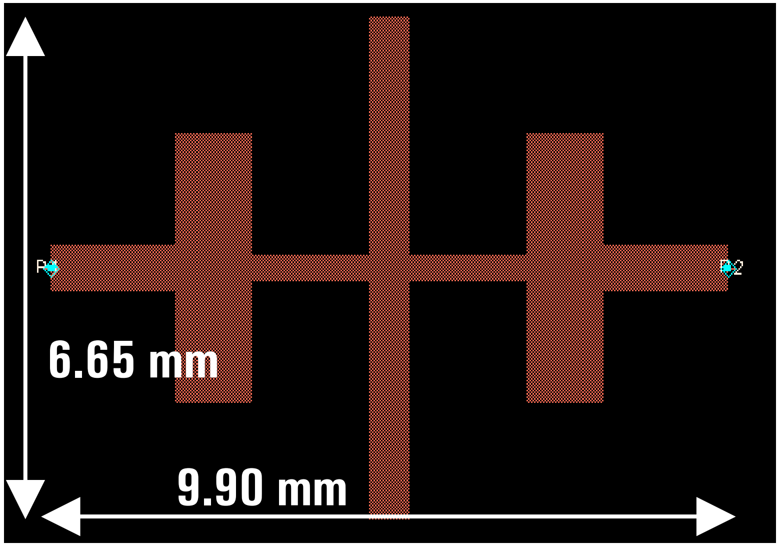


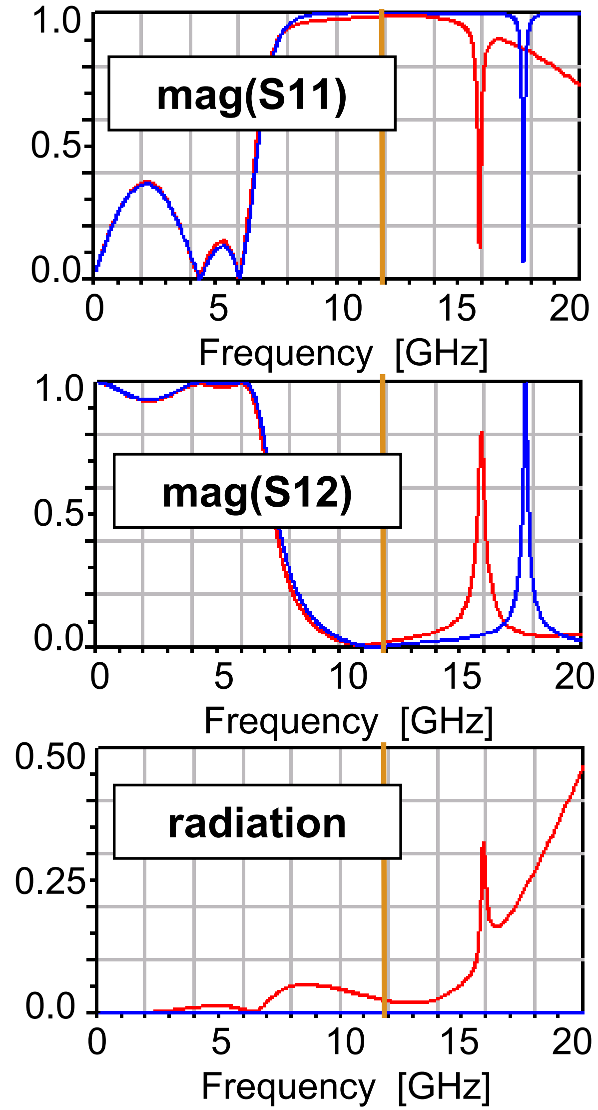


Momentum		
Mesh: 10 cells/λ, 20 GHz		
Matrix size	:	**181**
Process size	:	**2.92 MB**
User time	:	**1 m 02 s**

Momentum RF		
Mesh: 10 cells/λ, 20 GHz		
Matrix size	:	**122**
Process size	:	**2.13 MB**
User time	:	**0 m 09 s**

Microwave Lowpass Filter





Momentum
Momentum RF

Rule of thumb: freq < 12.5 GHz

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