EM Analysis of High Frequency Printed Circuit Boards

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Agenda

- EM tools overview
- When to use EM analysis
- Application examples: Filters
- The importance of meshing
- Including discrete components in the EM model
- Output from EM analysis: S-params and extracted models
- More application examples
- Framework integration

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What can we do with High Frequency Electromagnetic Software?

- Analyze and optimize critical layouts
- Virtual prototyping, fast and cost efficient
- More accurate and more flexible than traditional circuit simulator models
- "See" the high frequency currents & fields
- Simulate layouts that are difficult to measure, with any number of ports
- What-if studies for geometries & materials

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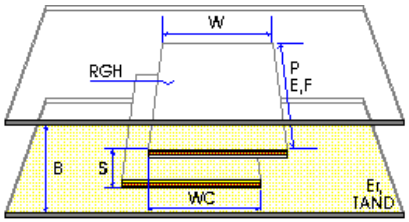
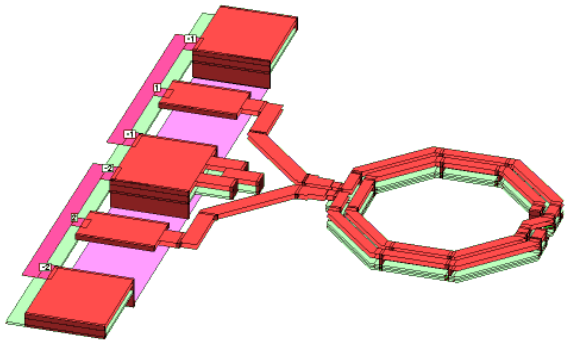
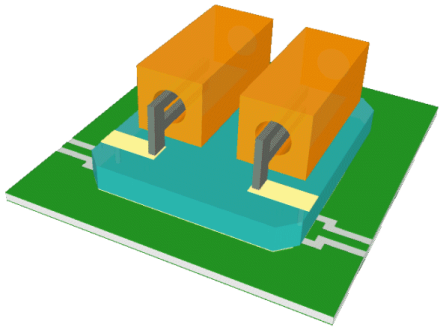
EM Analysis Approaches







2D Cross Section EM

Very fast.
Easy to use.
Easy to automate.
Constant cross section only.

3D Planar EM

sometimes called "2.5D"

Complete EM solution**,**
specialized for planar models.
Very accurate method.
Accurate wideband loss models.
Medium complexity, easy to learn.
User interface optimized for
planar work (PCB, RFIC).
Very good integration into
design frameworks.

3D Arbitrary Analysis

sometimes called "Full 3D"

Very general EM solution for
arbitrary geometries.
Nice 3D editors, but user interface
not optimized for planar work.
Solver method and ports not
optimized for planar work.
Much experience needed to get
highly accuracy results.
Very limited integration into
design frameworks

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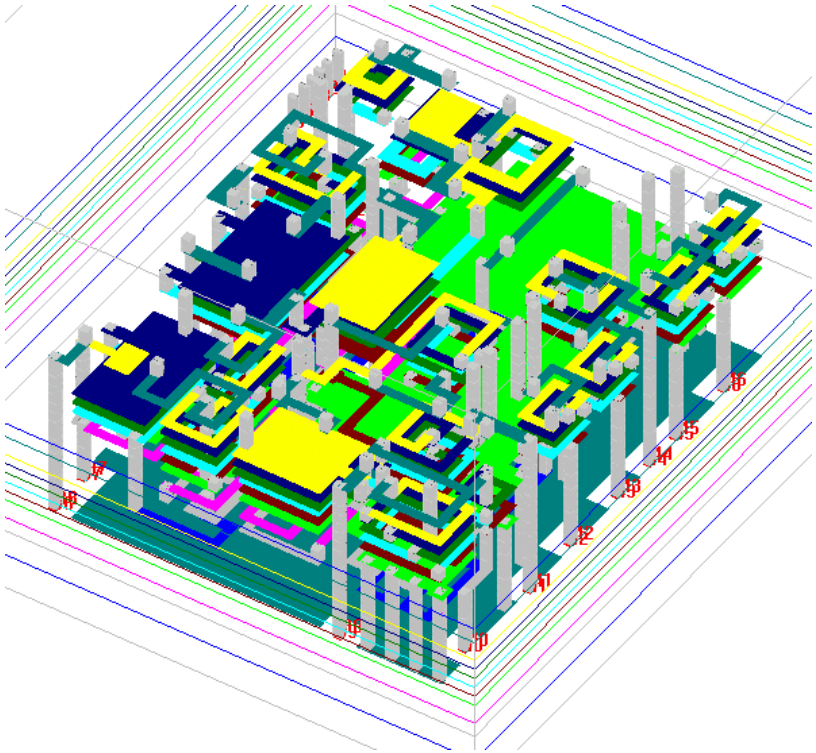
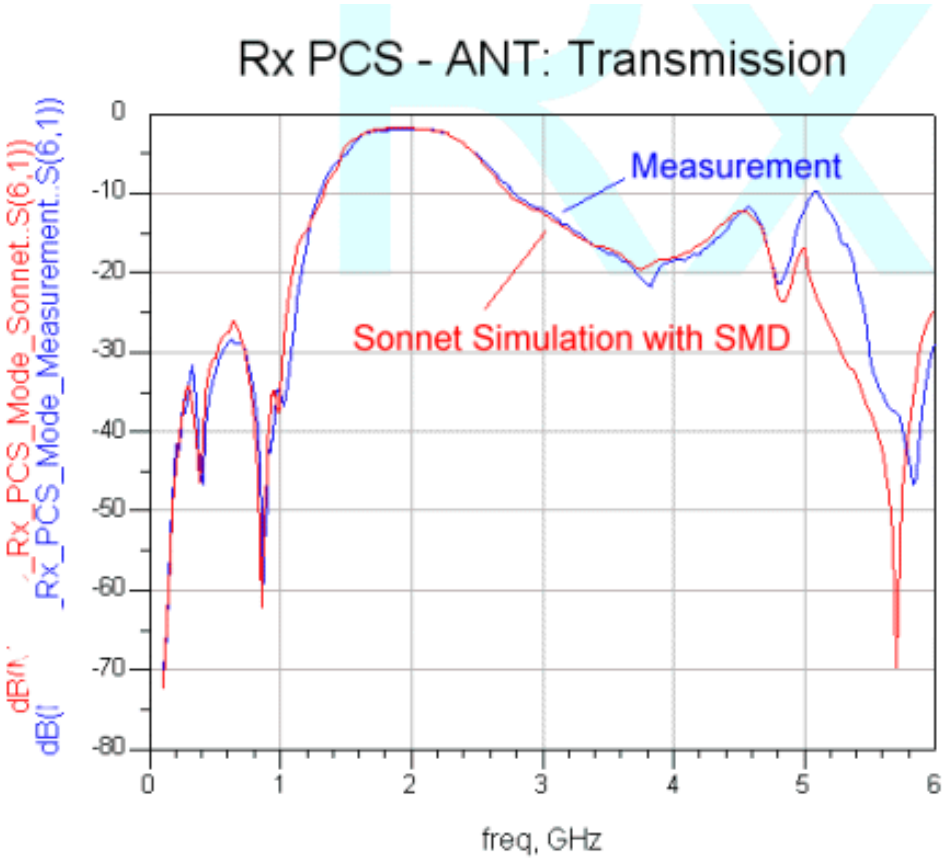
Typical EM Application:
Dense layouts, parasitic coupling





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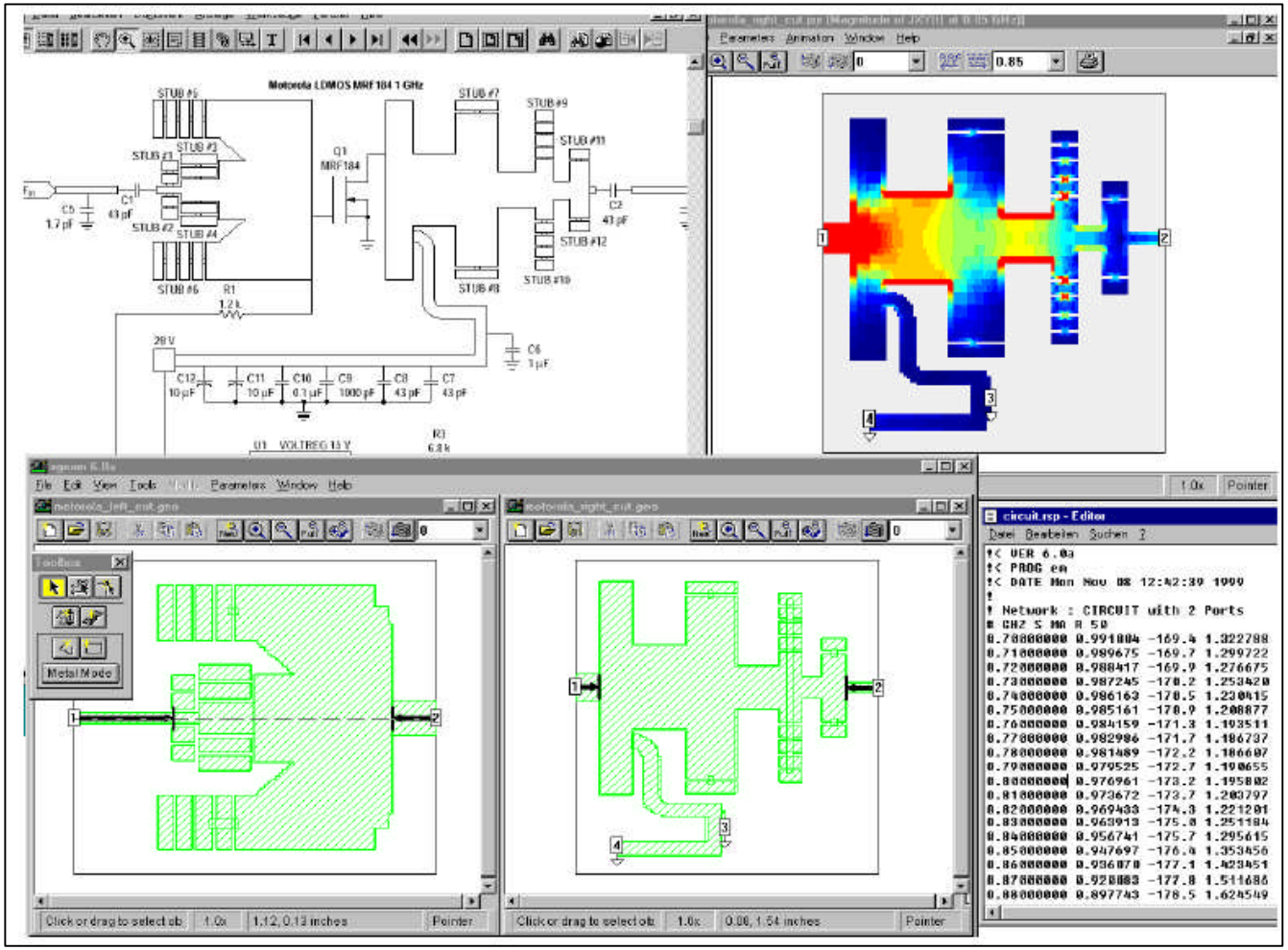
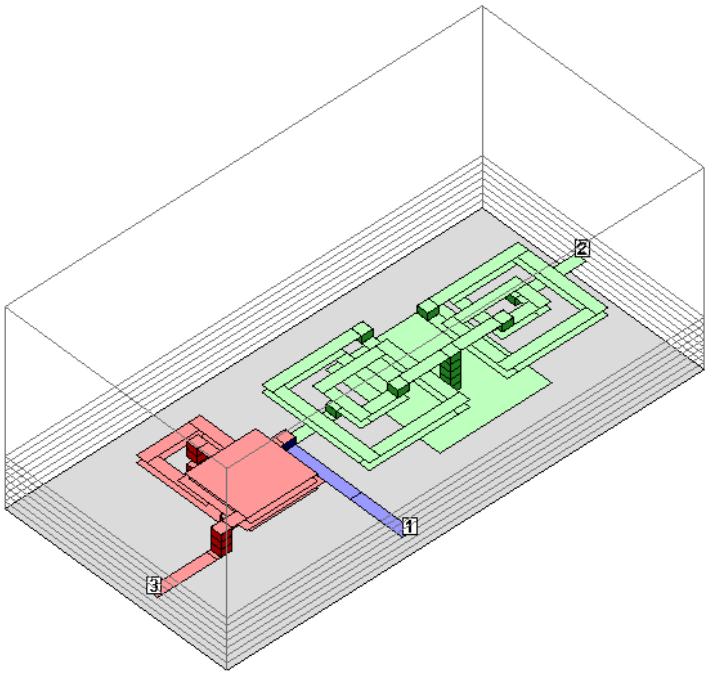
Typical EM Application:
No simple models available



The Sonnet Analysis Topology



- Arbitrary, predominantly planar circuit in a metal box
- Metal box walls provide good ground reference for accurate de-embedding
- Circuit is embedded in layered (planar) dielectric materials
- 3D current is allowed (vias between layers and to ground)
- Box cover (or floor) may be removed to allow radiation

All electromagnetic effects are included – parasitics, cross-coupling, package resonances, etc.

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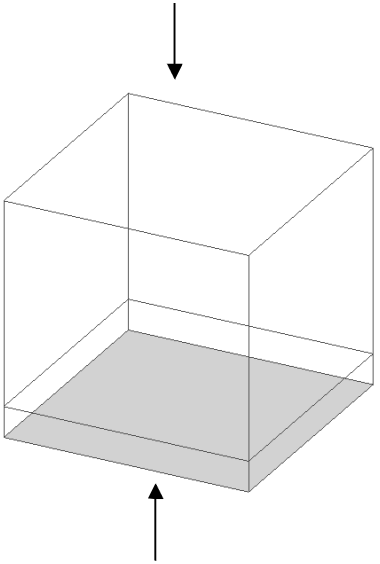
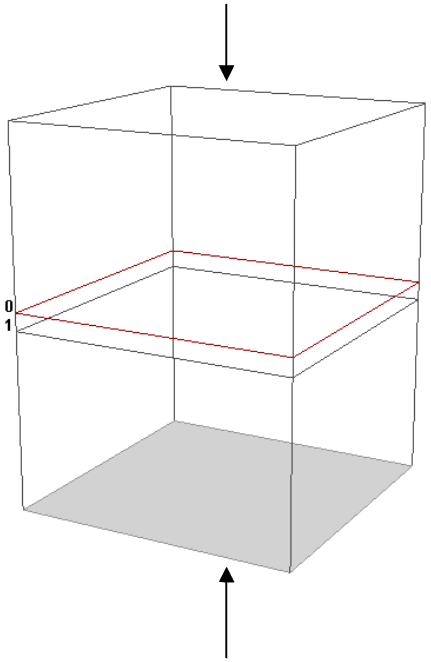
Metal for Sonnet Analysis Box

Free Space = absorbing boundary



Use bottom for microstrip ground

Free Space = absorbing boundary



Free Space = absorbing boundary

- Top and bottom material can be set by user, default is Lossless
- Can change to any metal that we have defined
- Efficient: use bottom of box for backside metalization
- If circuit radiates:
  use Free Space boundary,
  which means absorbing boundary
  (377 Ω/□)
- Air layer required between circuit and Free Space
- We can also have Free Space above <u>and</u> below if needed

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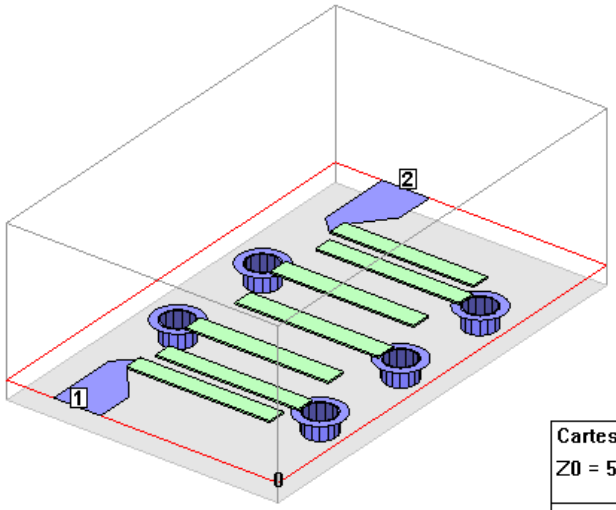
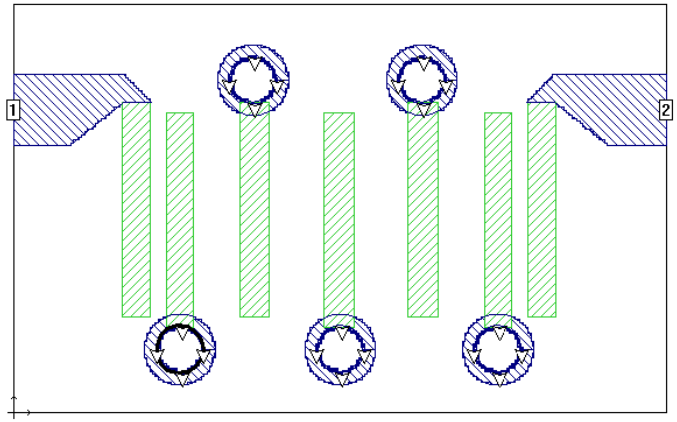
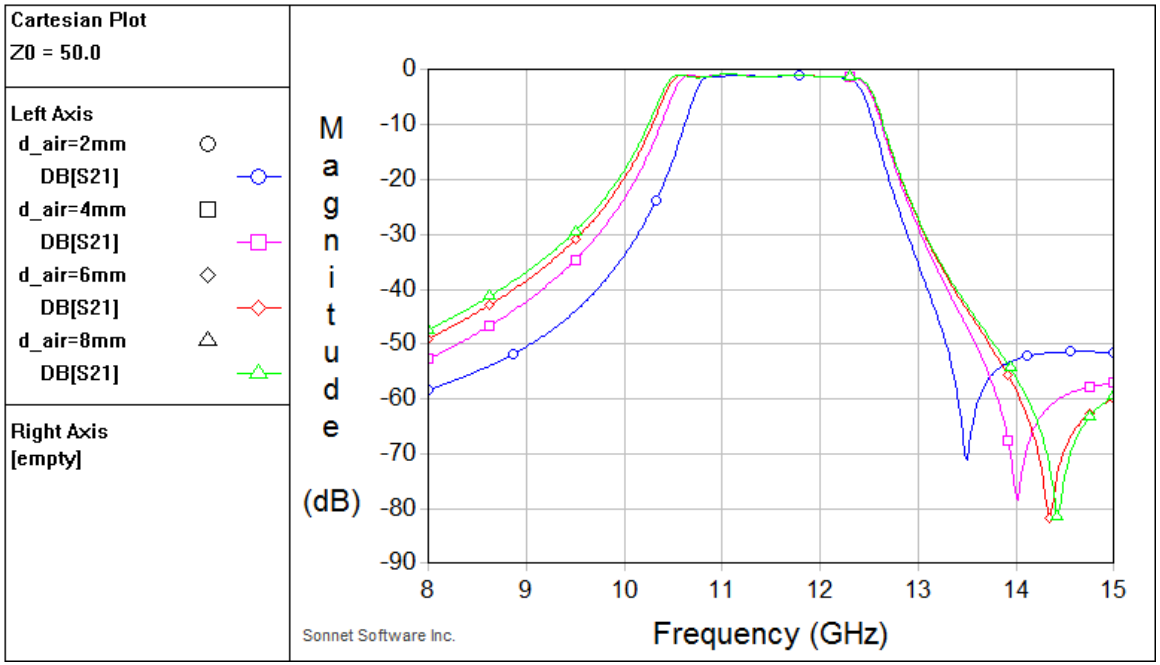
Packaged Filter



sweep d_air



Study influence of package on filter



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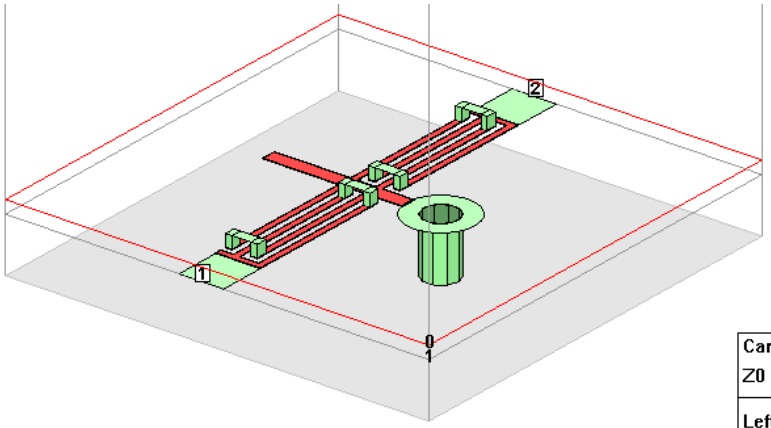
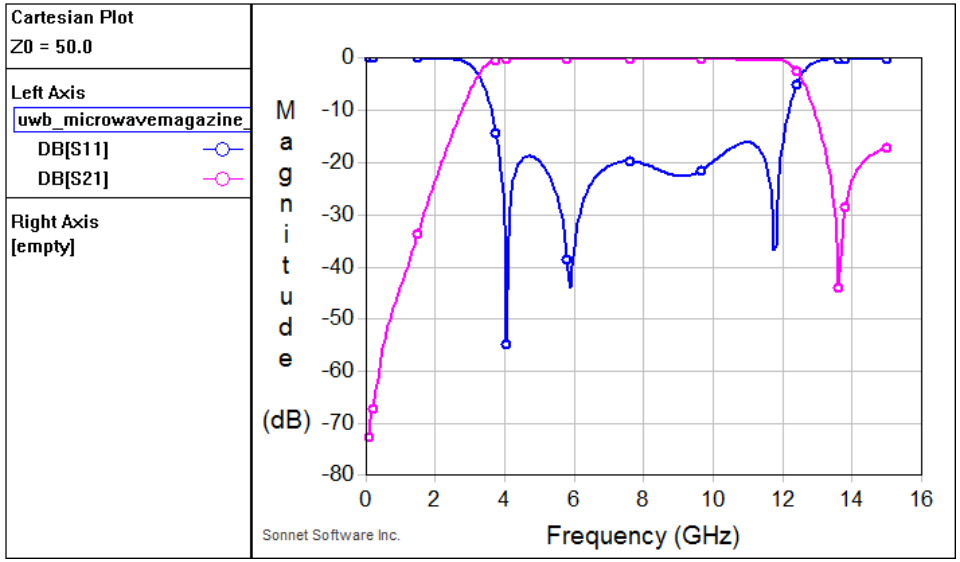
UWB Filter with Vias



- **Accurate 3D modelling of the via is required here**
- **Simple sheet via or wire models are not approriate**



Based on:
IEEE Microwave Magazine, June2010, page 59

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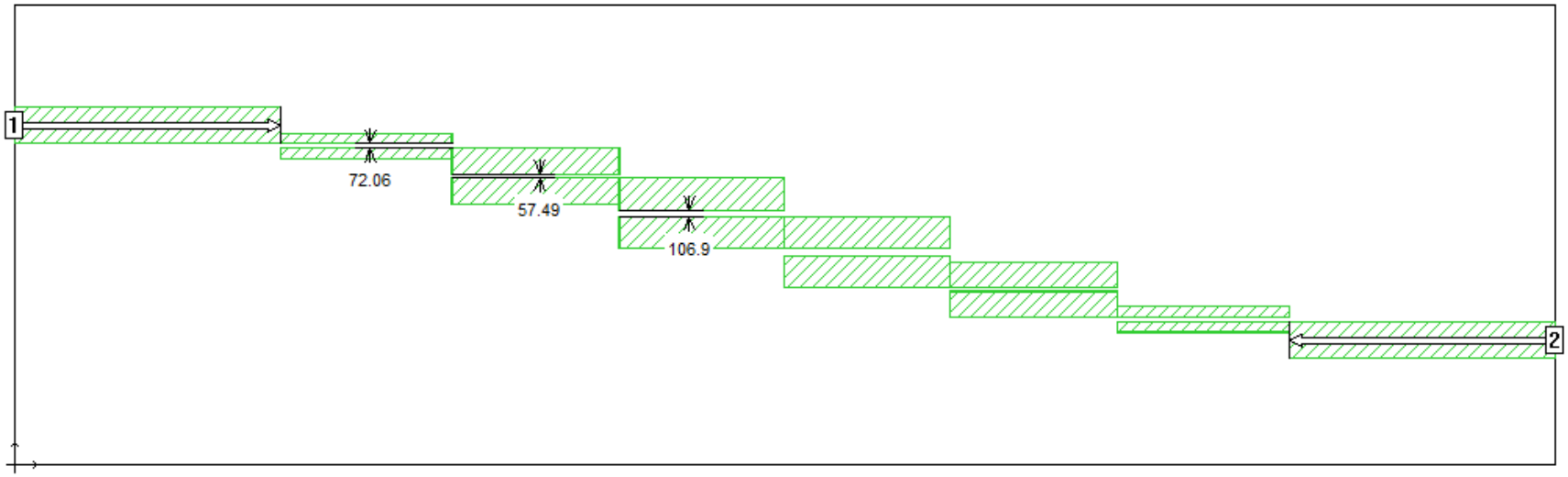
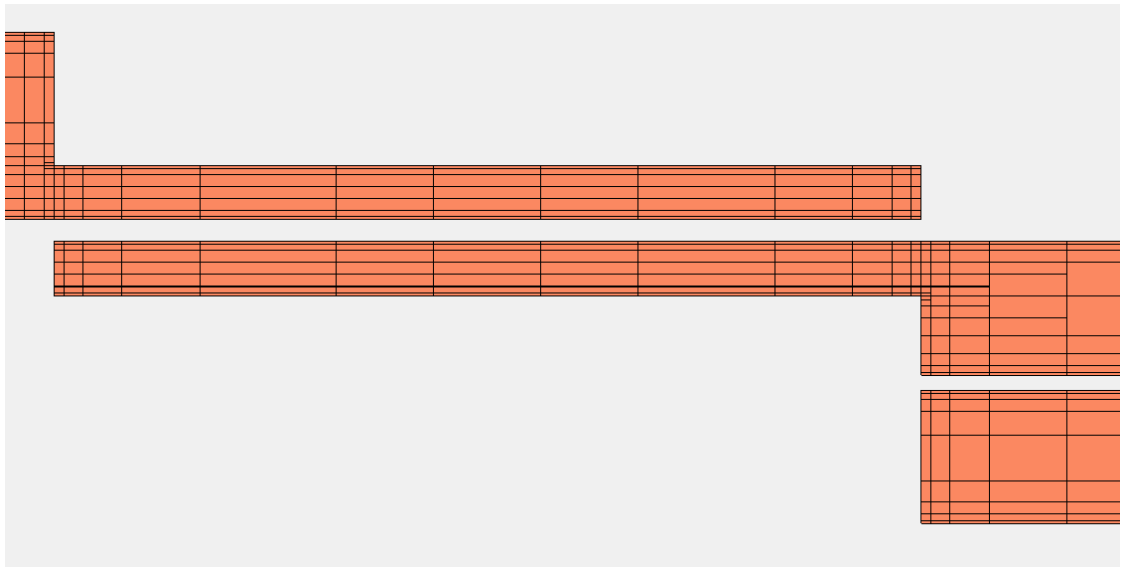
Coupled Line Filter



- **Fine mesh with accurate representation of the edge coupling is required**
- **It is not sufficient to sample the exact gap size, we also need fine mesh at the gap**



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Meshing

Why we do we care?

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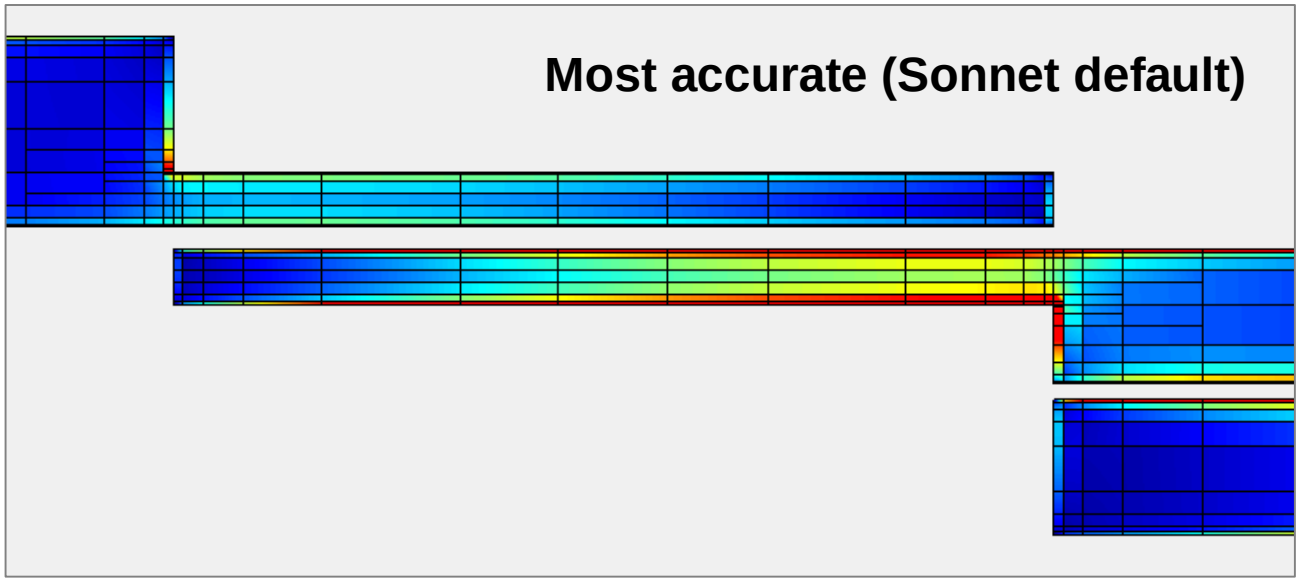
The Mesh Matters!



Current and charge at the edge has not enough detail because of the coarse mesh

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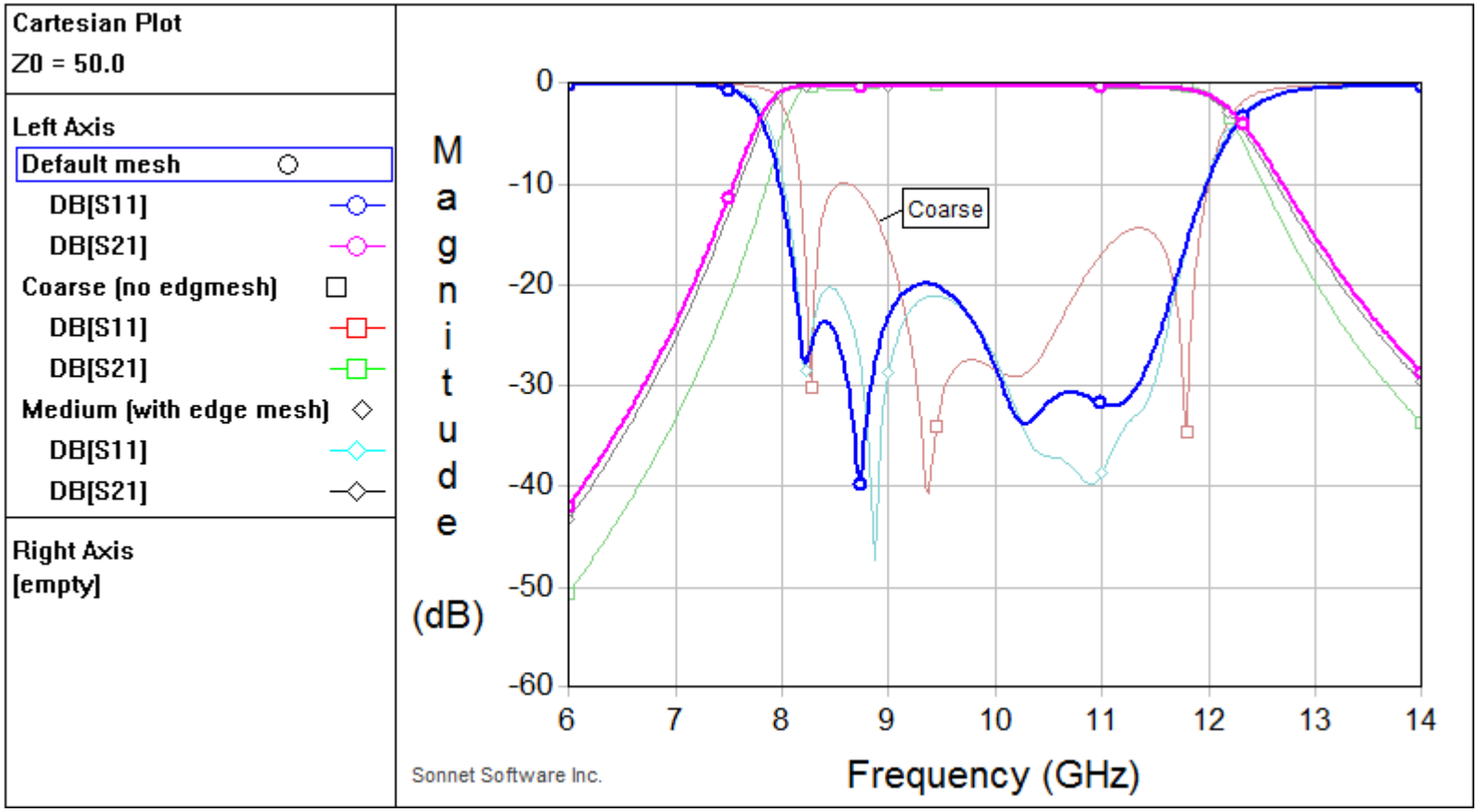
The Mesh Matters!



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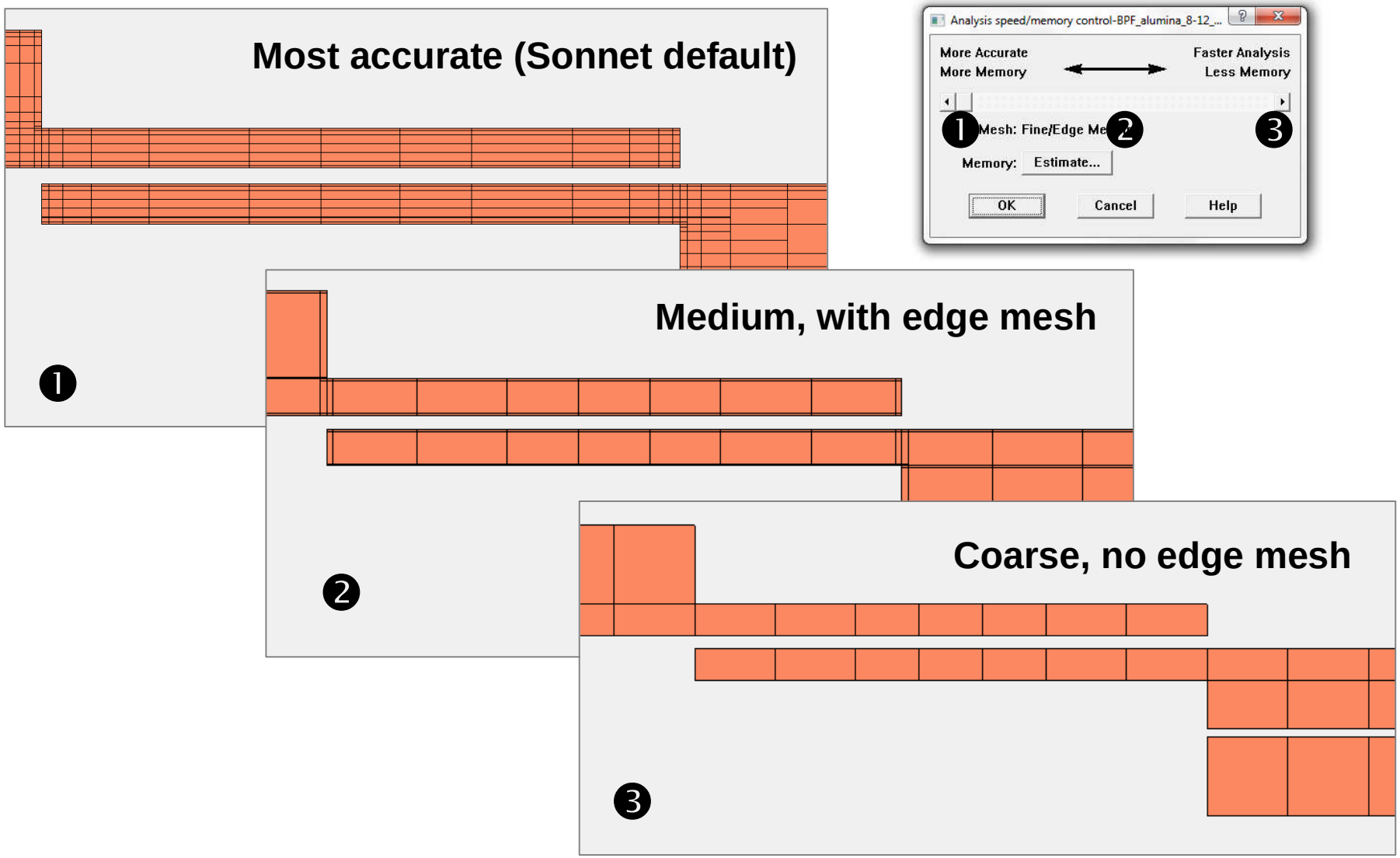
Global Mesh Density



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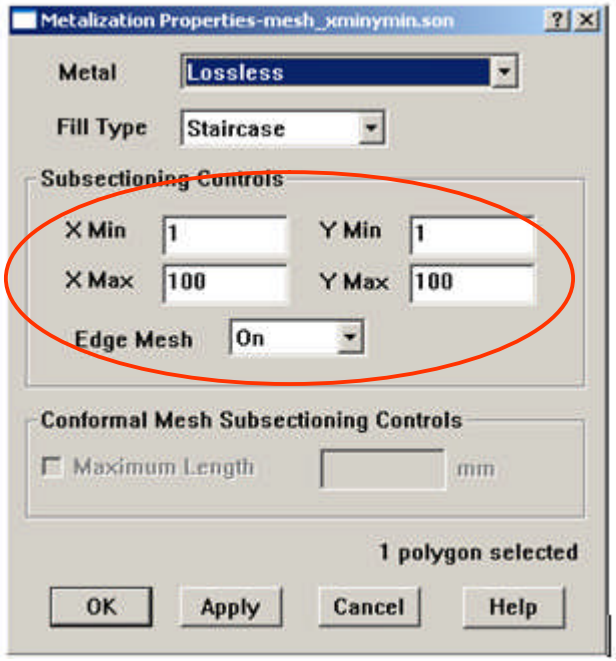
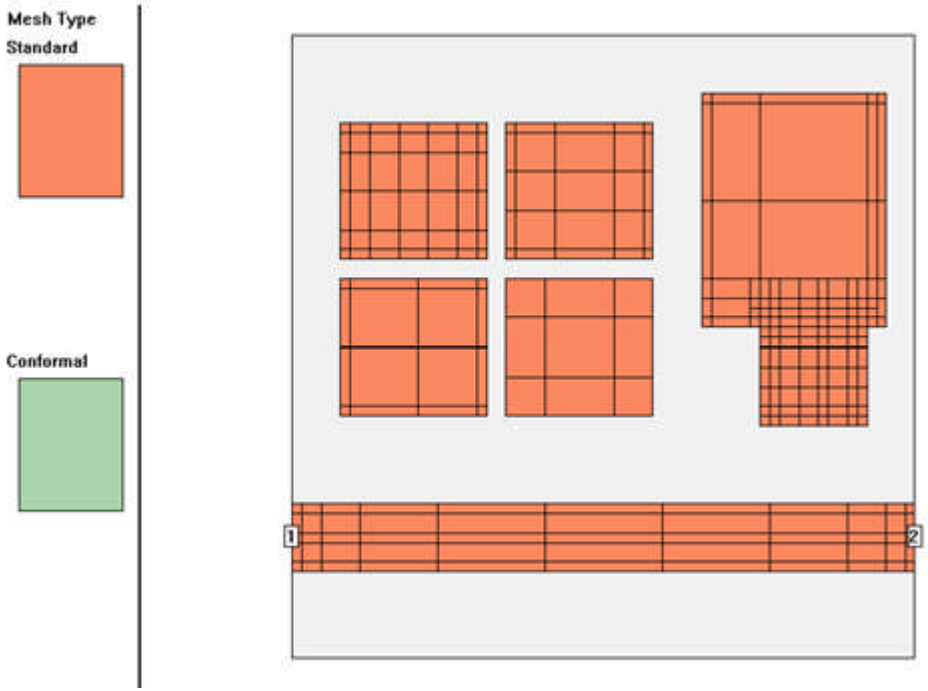
Mesh Density per Polygon



The Speed/Memory setting is global for the complete model.
If needed, we can also set the mesh density **individually** in the polygon properties.



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Sonnet Mesh Summary

- The mesh is extremely important to get accurate results
- Sonnet meshing default puts fine mesh at edges and discontinuities, and bigger subsections inside
- User can switch to reduced mesh density if needed.
- For maximum flexibility, mesh can also be set individually per polygon
- This can be useful for ground planes or layout areas known as not important

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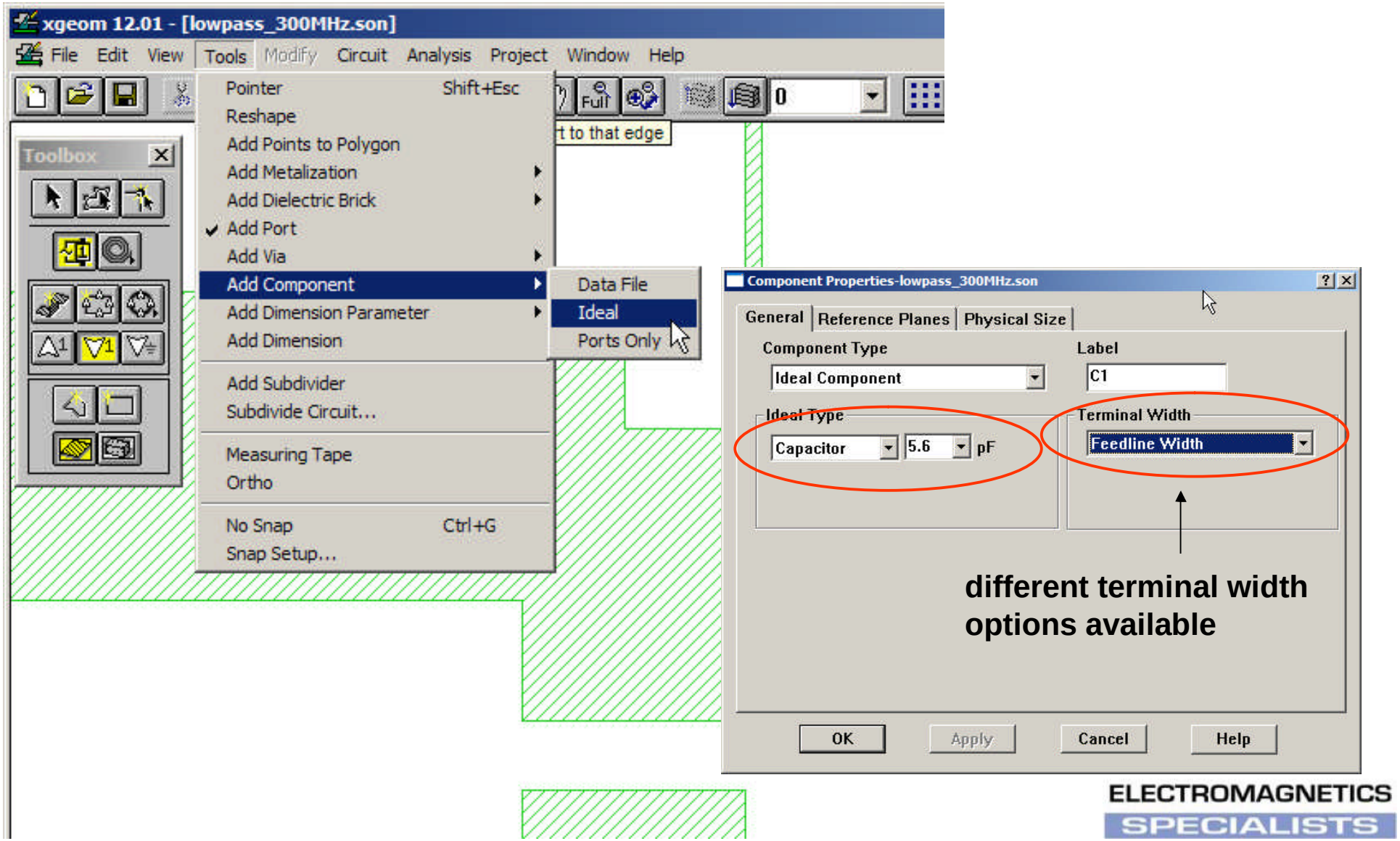
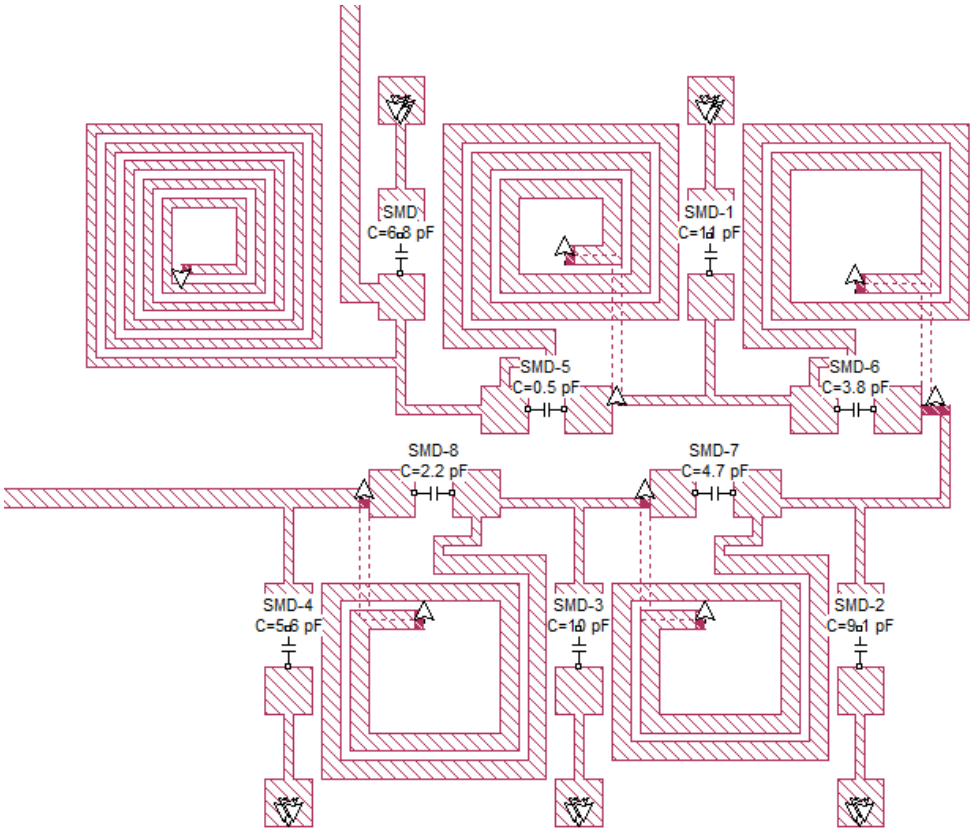
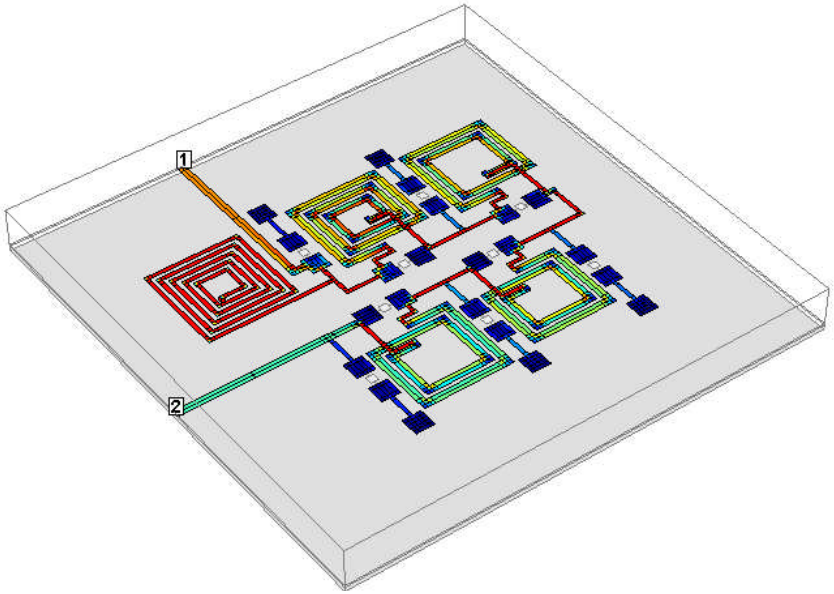
Discrete Components in Sonnet



Mixed Design: Layout and SMD





- **Current density with components included**
- **This requires components included in the EM model**

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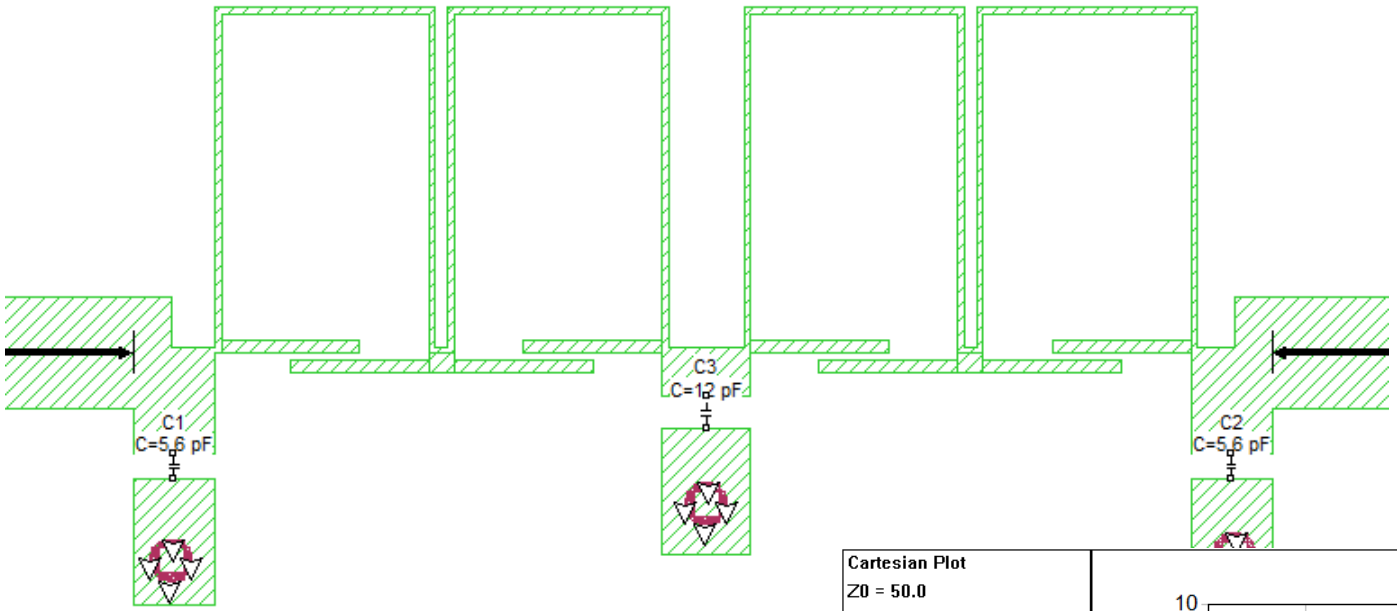
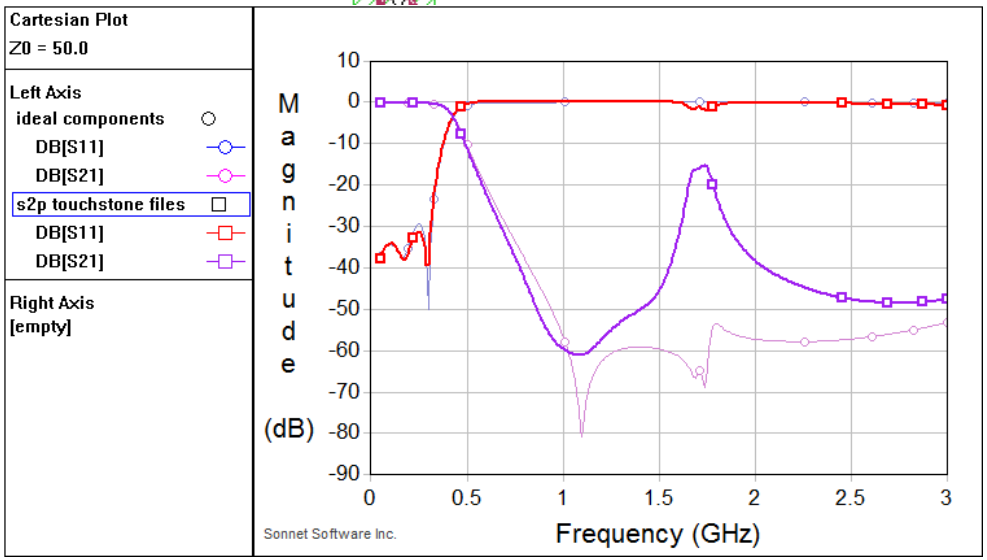
Mixed Design: Layout and SMD





Include measured data instead of ideal components, for more realistic results

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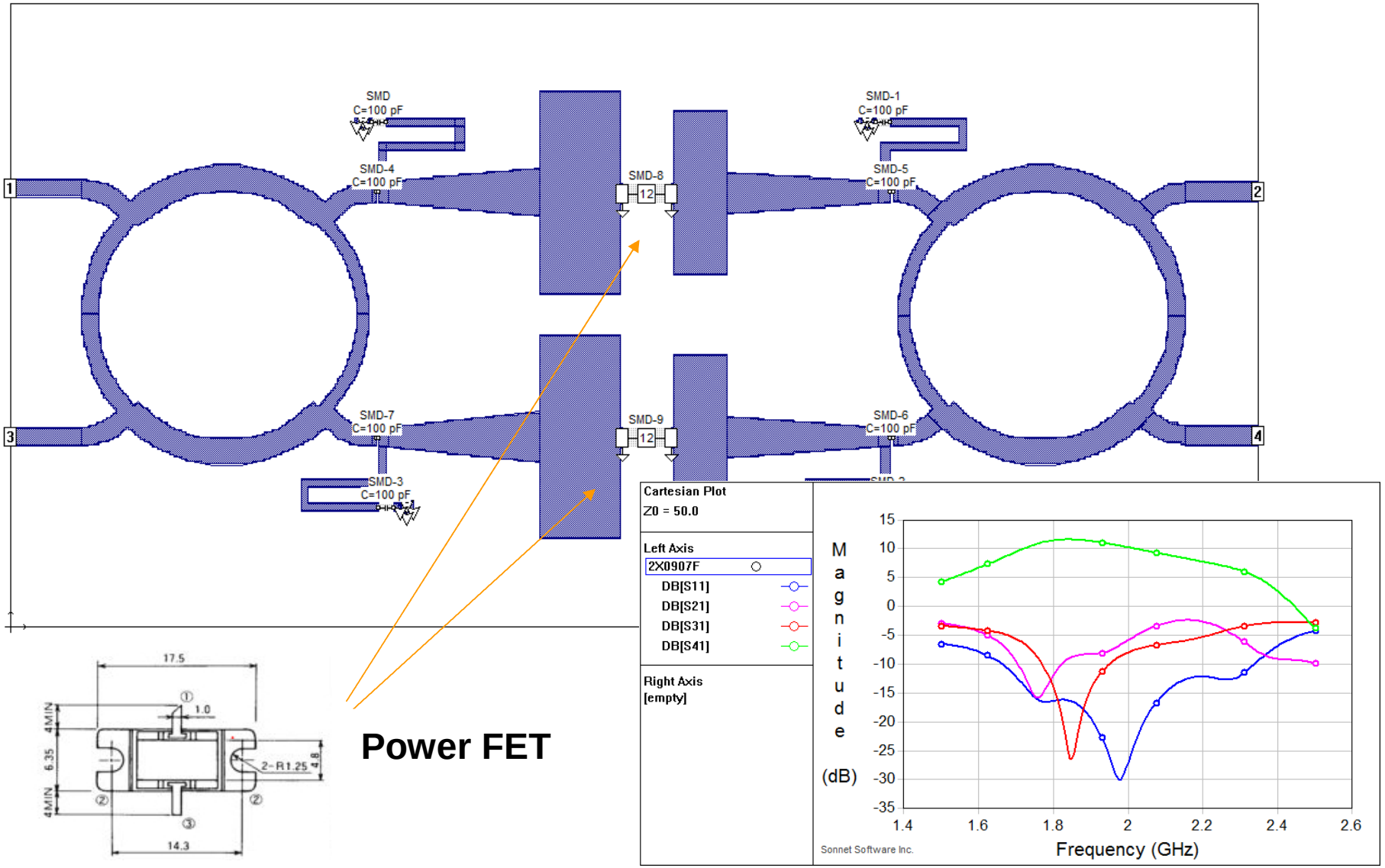
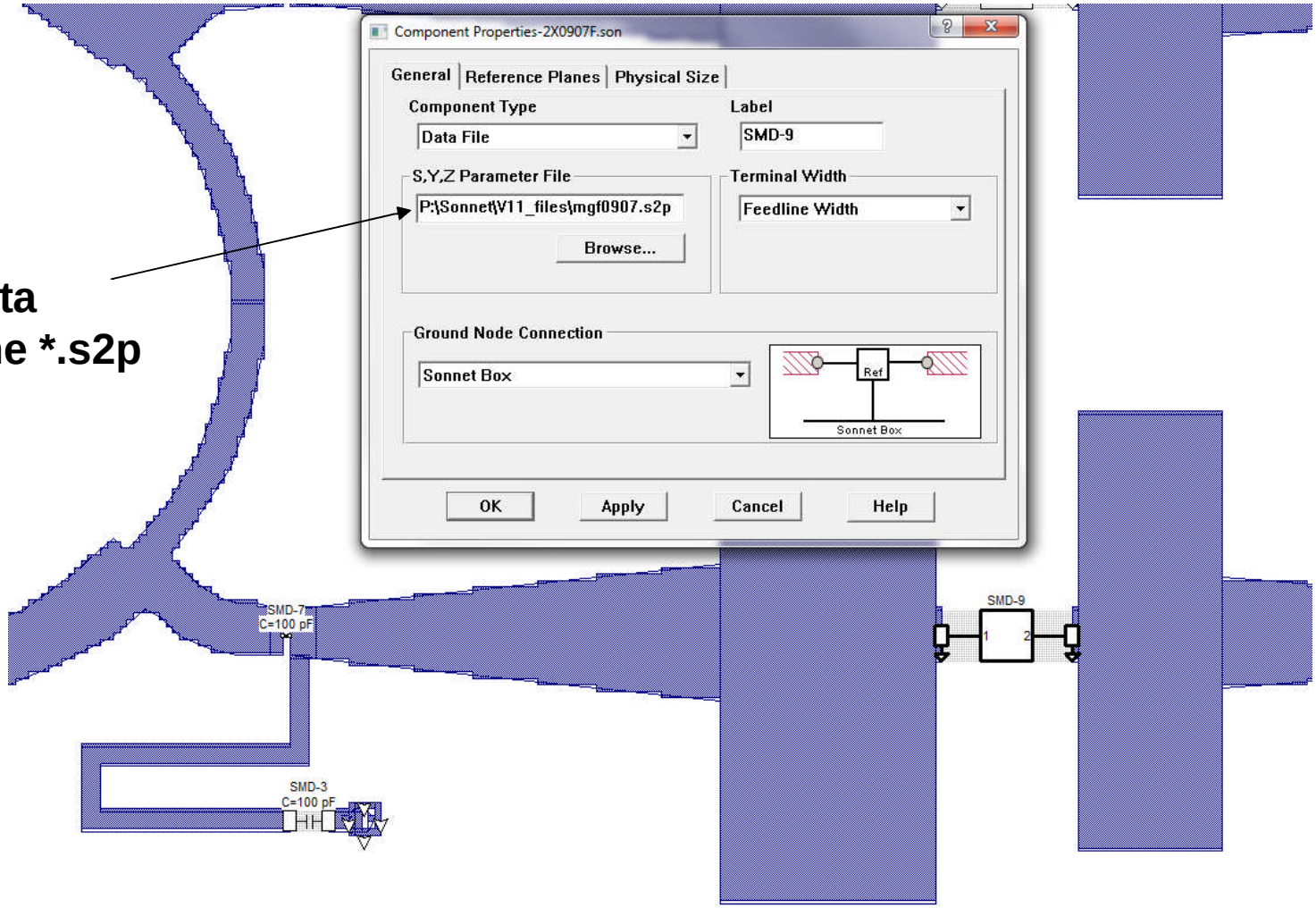
Amplifier with Components



Power FET

Amplifier with Components

measured data in Touchstone *.s2p format



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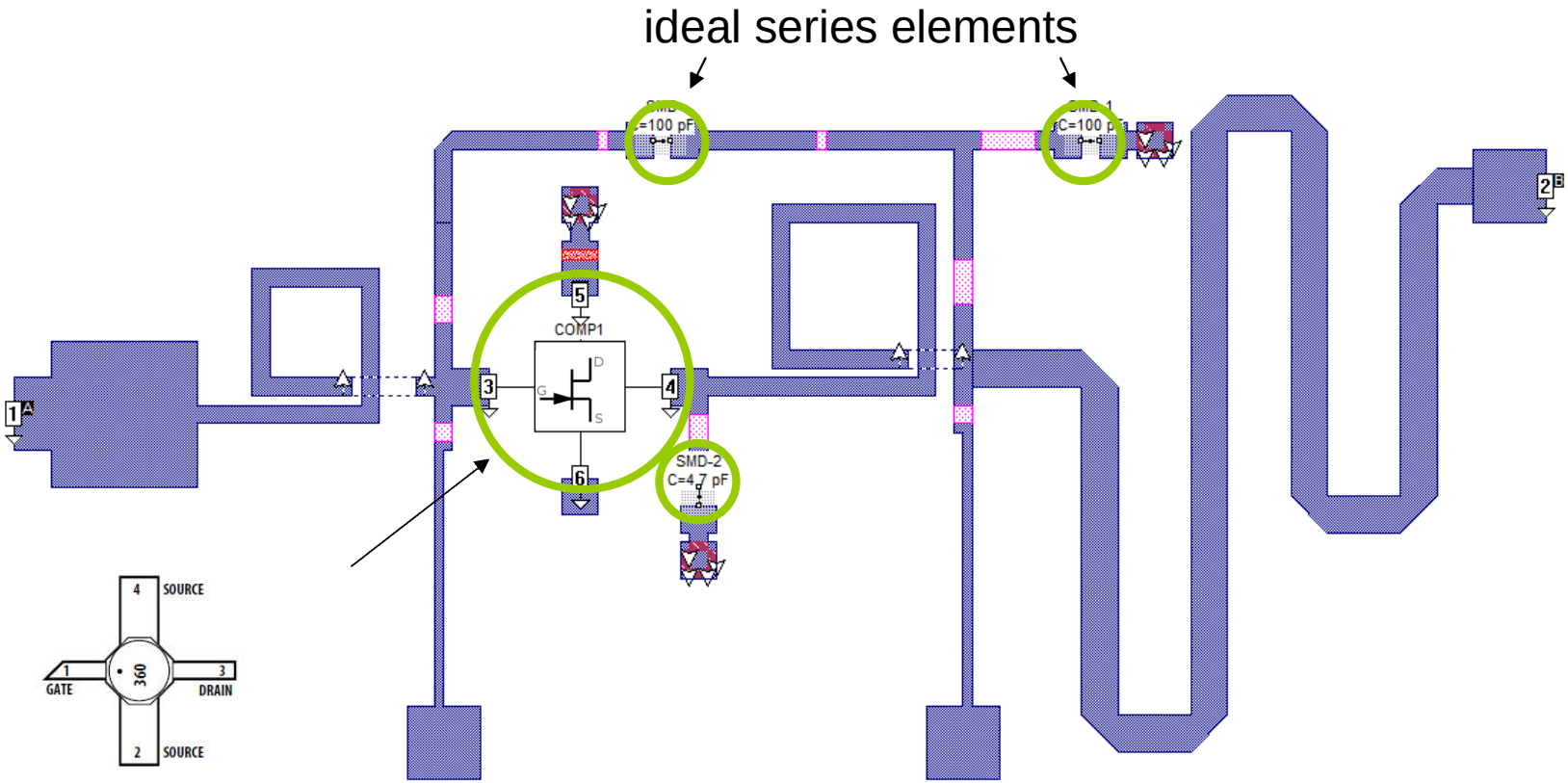
Ports with Global or Local Ground



FET pins are all connected to polygons ("floating source"), there is no direct path to global ground.

These ports can have global or local ground reference.

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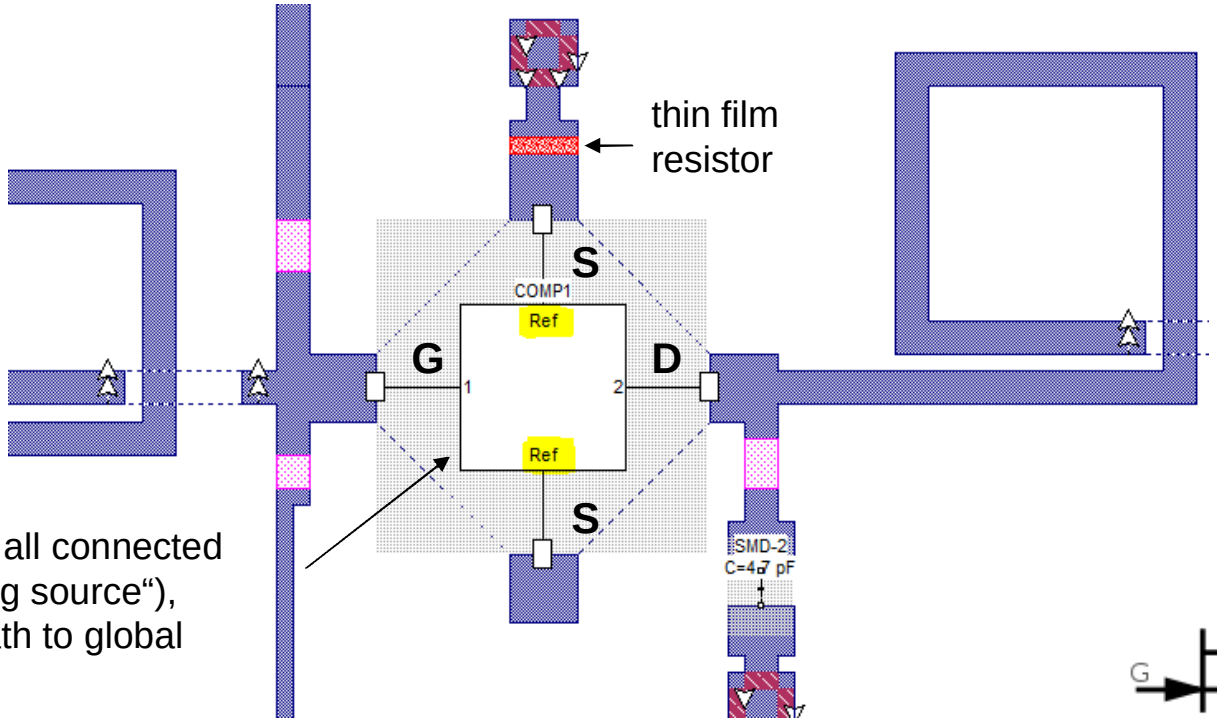
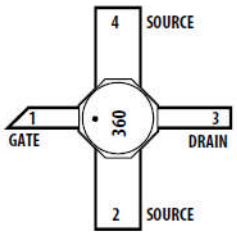
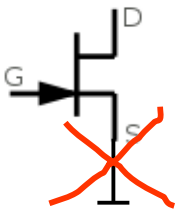
Components with Local Ground Node

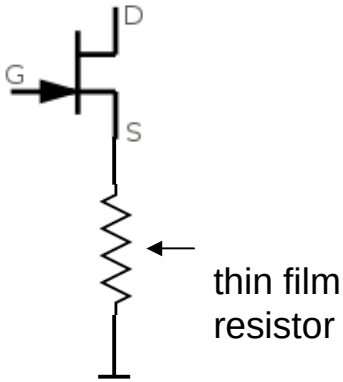


FET pins which are all connected to polygons ("floating source"), there is no direct path to global ground.

To insert a *.s2p data block, the ground pins are explicitely connected to the polygons.







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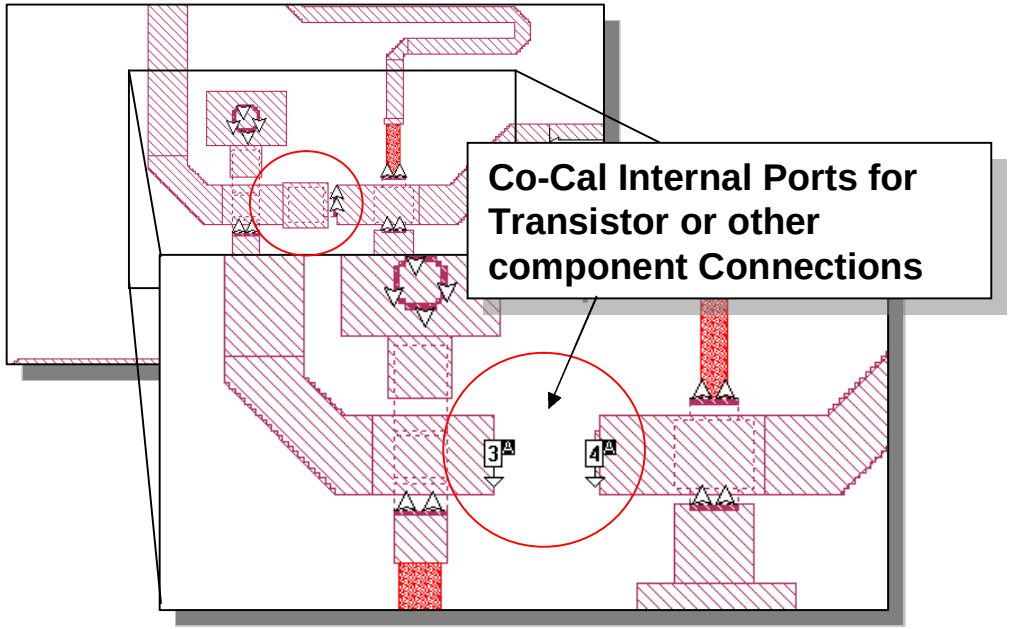
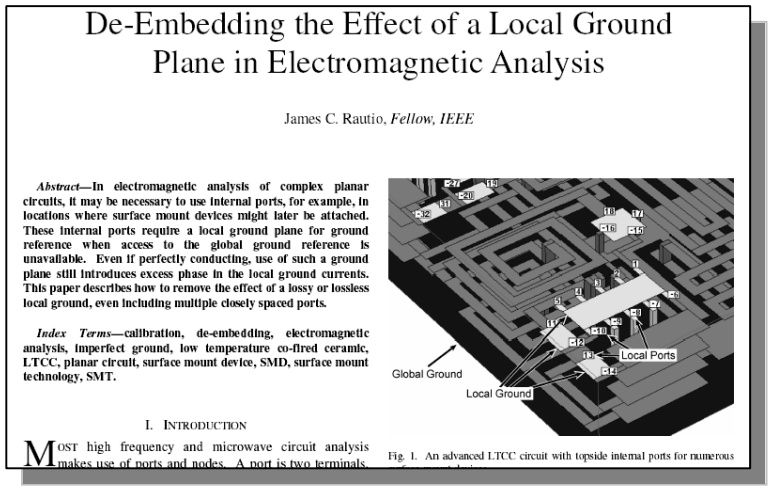
Co-calibrated™ Internal Ports





De-Embedding the Effect of a Local Ground Plane in Electromagnetic Analysis

James C. Rautio, *Fellow, IEEE*

***Abstract*—In electromagnetic analysis of complex planar circuits, it may be necessary to use internal ports, for example, in locations where surface mount devices might later be attached. These internal ports require a local ground plane for ground reference when access to the global ground reference is unavailable. Even if perfectly conducting, use of such a ground plane still introduces excess phase in the local ground currents. This paper describes how to remove the effect of a lossy or lossless local ground, even including multiple closely spaced ports.**

***Index Terms*—calibration, de-embedding, electromagnetic analysis, imperfect ground, low temperature co-fired ceramic, LTCC, planar circuit, surface mount device, SMD, surface mount technology, SMT.**

I. Introduction

Most high frequency and microwave circuit analysis makes use of ports and nodes. A port is two terminals.

Global Ground
Local Ground
Local Ports

Fig. 1. An advanced LTCC circuit with topside internal ports for numerous

- All ports introduce discontinuities
- De-embedding removes port discontinuities from our simulation models (and measurements!)
- Internal ports have traditionally been difficult to de-embed with high dynamic range
- New Co-Calibrated Internal Port technology introduces <u>>100 dB of dynamic range for internal ports</u>—an industry first
- Multiple Co-Calibrated Ports may be placed very close together and port cross-coupling is removed
- Theory is fully published

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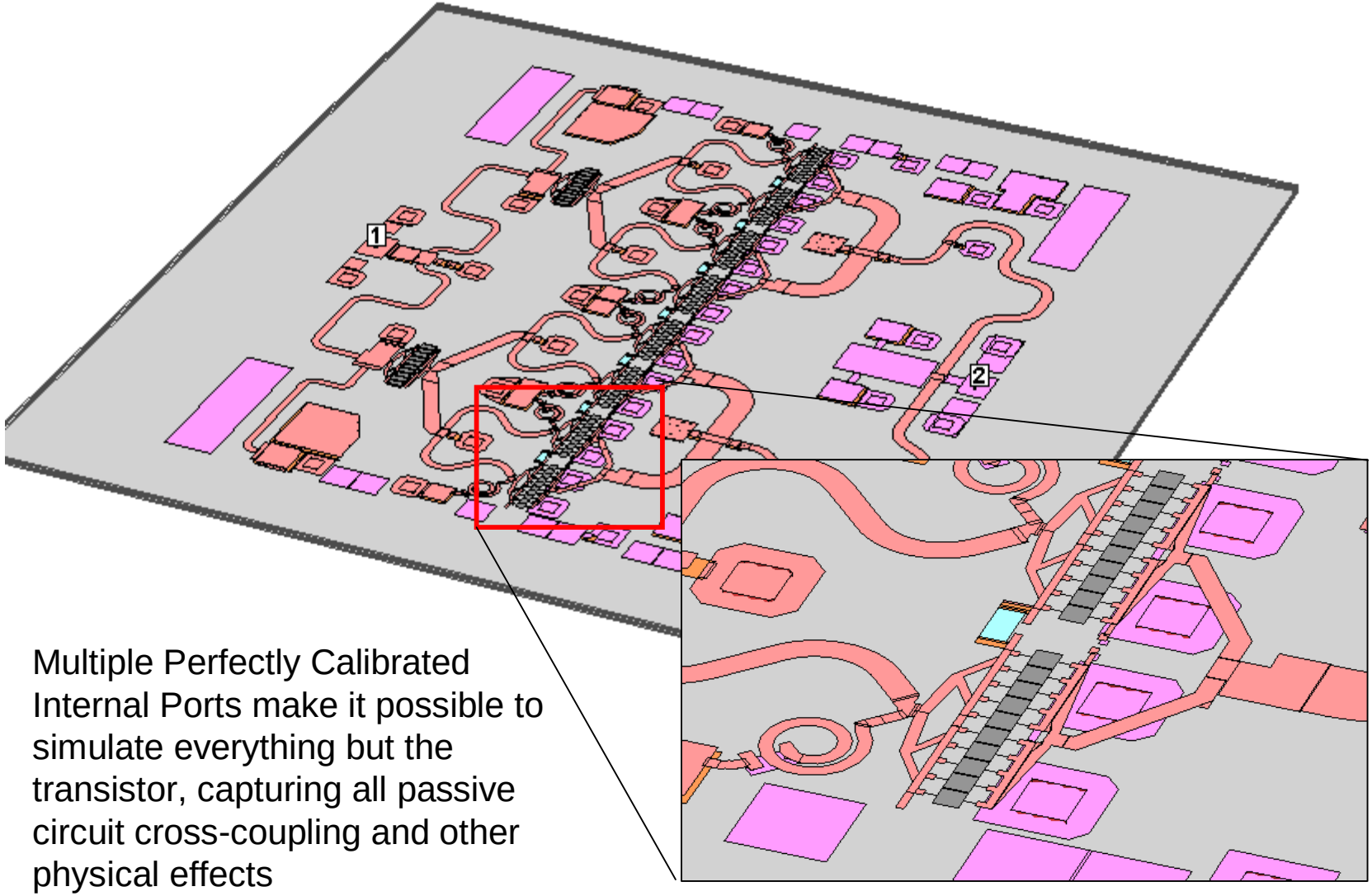
Co-calibrated Internal Ports



Multiple Perfectly Calibrated Internal Ports make it possible to simulate everything but the transistor, capturing all passive circuit cross-coupling and other physical effects

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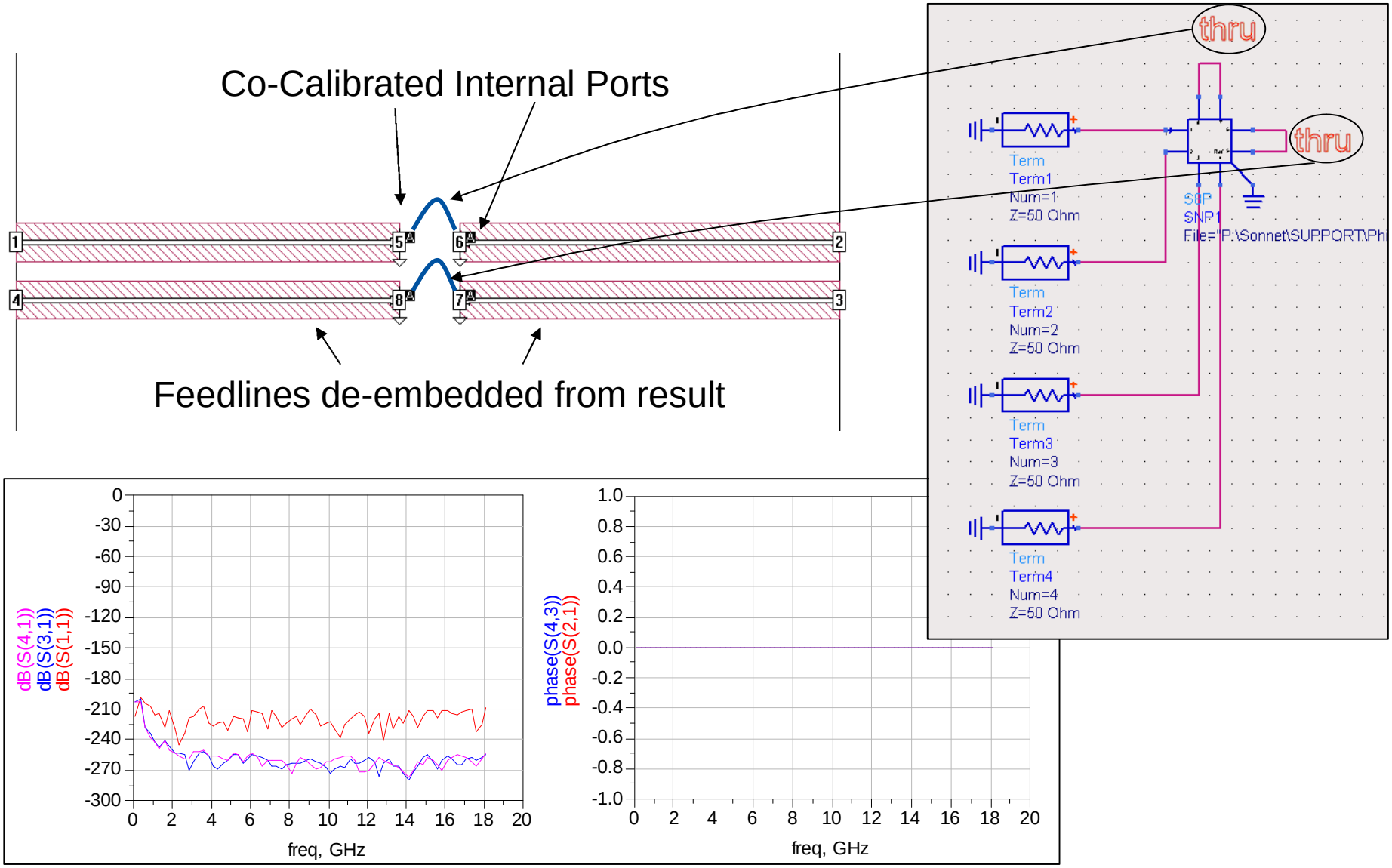
Co-Calibrated Internal Ports



De-embedding error in |S11| and cross-terms for each line lower than < -200 dB

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Output from EM

S-Params and extracted models

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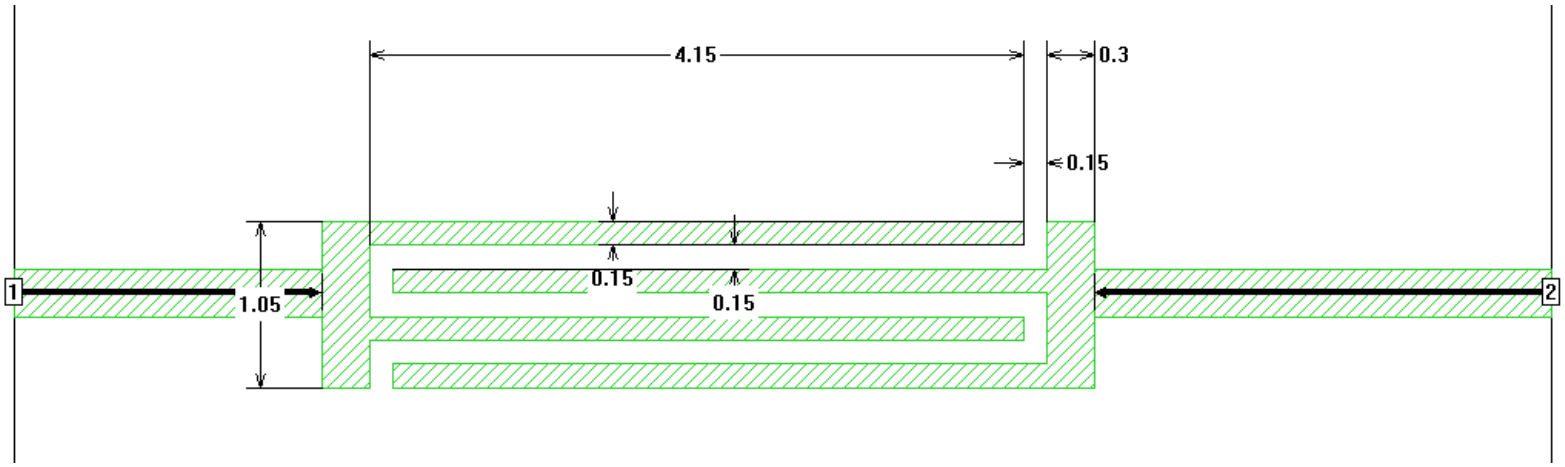
Example:Interdigital Capacitor



This is a "capacitor" used in the lowpass example shown before.

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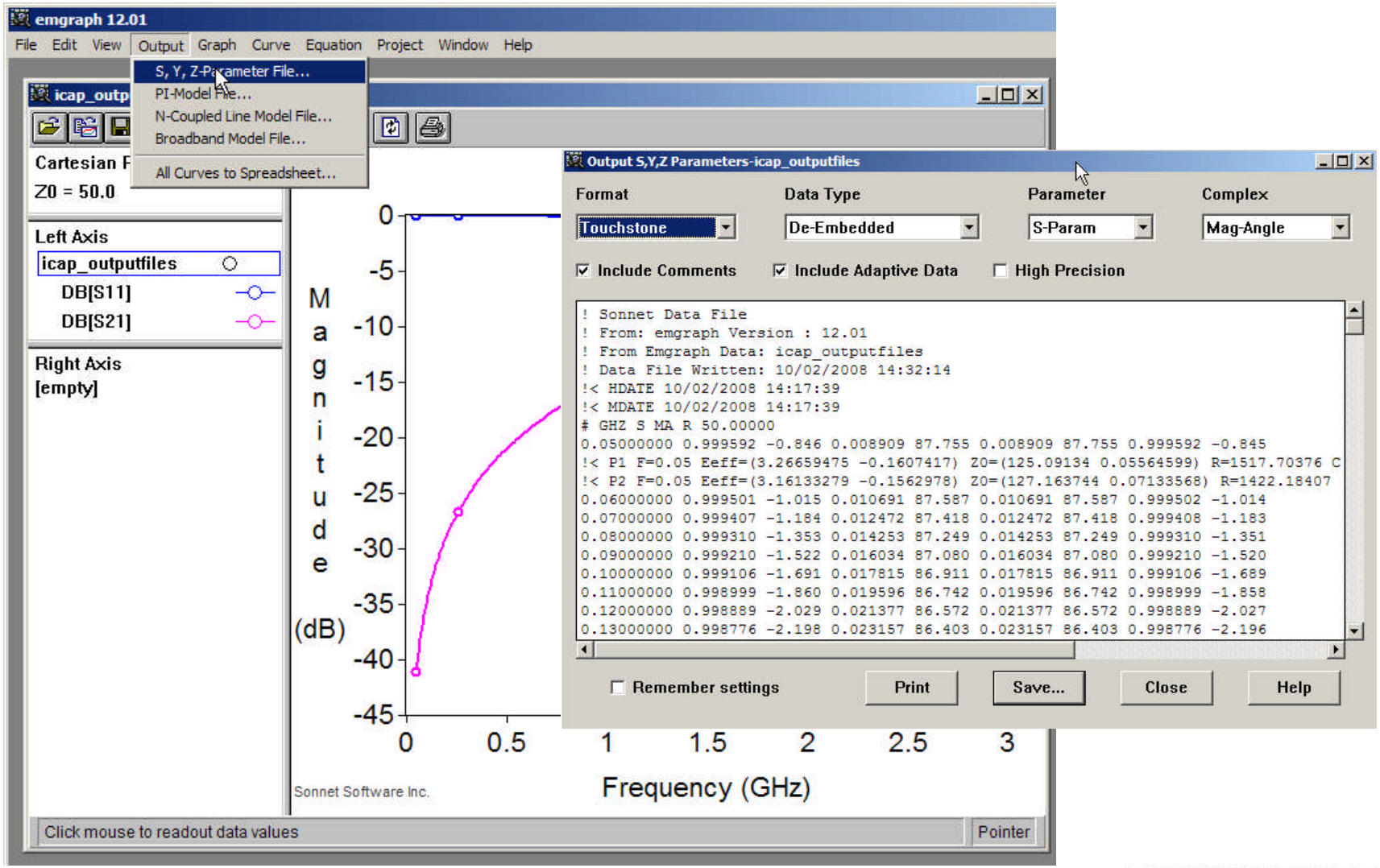
S-Parameter Export



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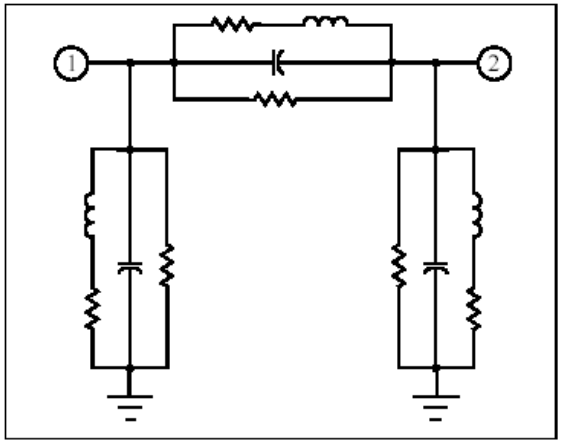
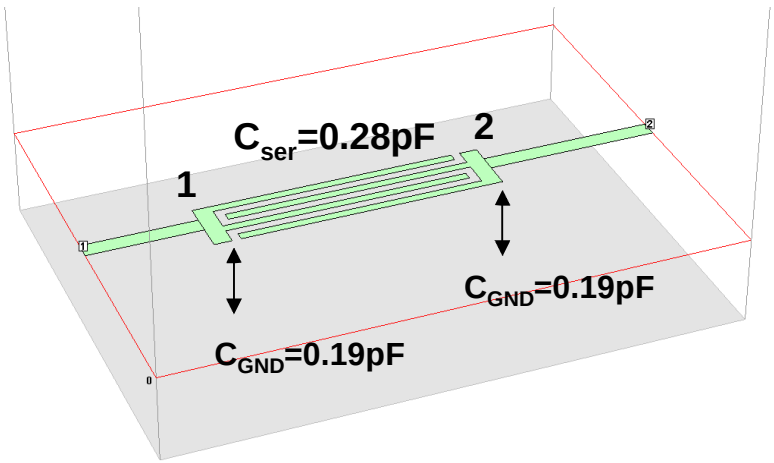
Pi Model Export



Equivalent circuit of a two-port structure using the PI Model. Mutual inductances also exist between all inductors, but are not shown. Any component whose value is outside of the open circuit limits are not printed in the SPICE output file.




```
*  Spice Data
* Limits: C>0.01pF L<100.0nH R<1000.0Ohms
K>0.01
    *  Analysis frequencies: 50.0, 60.0 MHz
.subckt SON4_0 1 2 GND
C_C1 1 GND 0.186163pf
C_C2 1 2 0.283703pf
C_C3 2 GND 0.18565pf
.ends SON4_0

    *  Analysis frequencies: 60.0, 70.0 MHz
.subckt SON4_1 1 2 GND
C_C1 1 GND 0.186164pf
C_C2 1 2 0.283734pf
C_C3 2 GND 0.185652pf
.ends SON4_1

    *  Analysis frequencies: 70.0, 80.0 MHz
.subckt SON4_2 1 2 GND
C_C1 1 GND 0.18617pf
C_C2 1 2 0.28377pf
C_C3 2 GND 0.18566pf
.ends SON4_2

…
```

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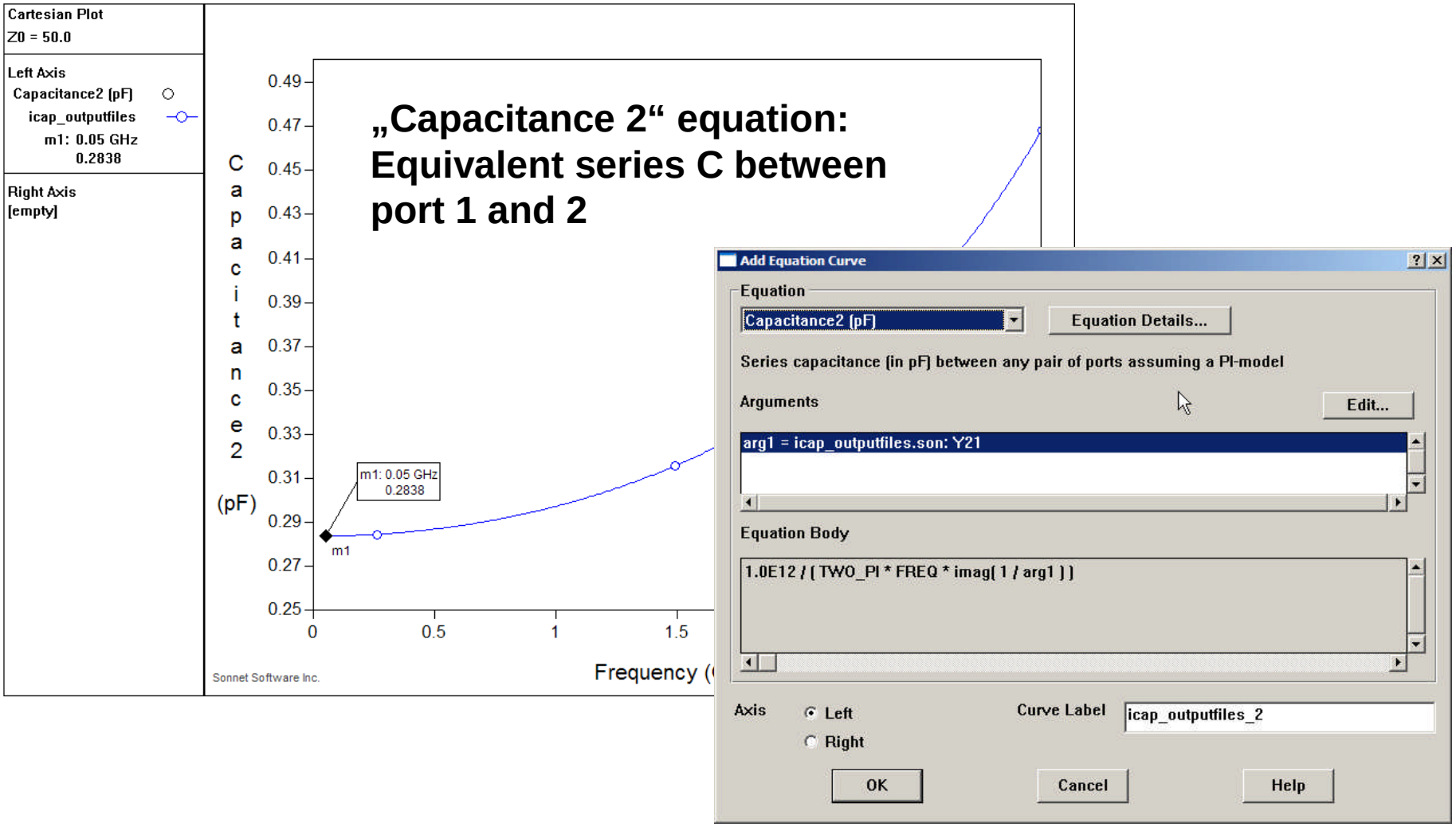
Equations in Data Display



N-Coupled Lines RLGC Model

```
FORMAT Freq:    L1:1      L2:1      L2:2
                R1:1      R2:1      R2:2
                C1:1      C2:1      C2:2
                G1:1      G2:1      G2:2
;
;  Matrix values extracted from structure of length 1.25e-4 meters.
;
;  Z0 Matrix Eigenvectors:
;  0.70709973181 1.01204653e-7  0.70710975084 0.00000000000
;  0.70711383049 0.00000000000 -0.7071038115 -4.2771946e-8
;
;
;  Z0 Matrix Eigenvalues:
;  72.7927707171 -0.1079821489  16.5623742613 -0.1588181627
;
;  Gamma Matrix Eigenvectors:
;  0.70709735571 2.43871317e-7  0.70712912656 0.00000000000
;  0.70711620654 0.00000000000 -0.7070844351 -5.7766439e-7
;
;
;  Gamma Matrix Eigenvalues:
;  0.28101510488 189.350366291  0.97887215574 102.080263771
;
2000000000.0 :  6.15674302e-7  4.81156085e-7  6.15695041e-7
                36.6622803867  4.23884026037  36.6646940705
                3.4873268e-10 -1.417338e-10  3.4873269e-10
                1.33833238e-6 -4.3751531e-7  1.33785617e-6
```

Modal Excitation Vector From Z_0 Matrix (Odd Mode)

Modal Excitation Vector From Z_0 Matrix (Even Mode)

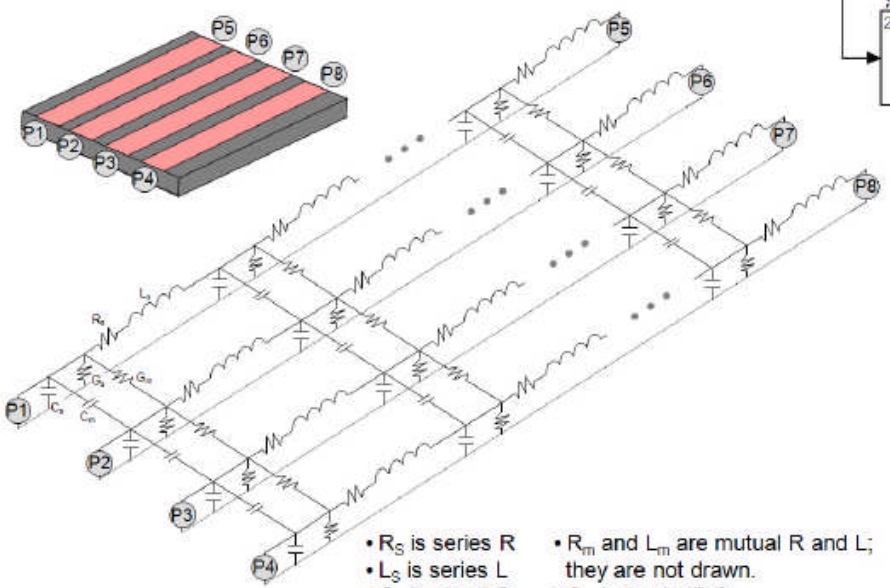
Z_{0e} (Even Mode) Z_{0o} (Odd Mode)

Modal Excitation Vector From γ Matrix (Odd Mode)

Modal Excitation Vector From γ Matrix (Even Mode)

γ_e (Even Mode) γ_o (Odd Mode)

RLGC Data



- R_S is series R
- L_S is series L
- C_S is shunt C
- G_S is shunt G
- R_m and L_m are mutual R and L; they are not drawn.
- C_m is "mutual" C
- G_m is "mutual" G

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Broad Band SPICE Extraction

- Useful for very wideband model extraction of arbitrary structures
- Creates „black box“ model for SPICE
- Arbitrary topology, not limited in complexity
- License required for this feature

```
.SUBCKT icap_outputfiles 1 2 3

ER1N i1 1 1 c1 1.0000000000000000000000
GR1P i1 c1 i1 c1 0.0100000000000000000000

ER2N i2 2 2 c2 1.0000000000000000000000
GR2P i2 c2 i2 c2 0.0100000000000000000000

*  Coefficient set (1, 1 ) 3 Coefficients
G_c1P npc101 3 i1 3 1.0000000000000000000000
G_c1N nnc101 3 i1 3 1.0000000000000000000000
E_c1P ac100 c1 npc101 3
1.0000000000000000000000
E_c1N ac100 b102 nnc101 3
1.0000000000000000000000
*  Coefficient: 1 SINGLE
R_1_c1 npc101 npc102 0.0065844947841434166000
C_1_c1 npc101 npc102 2.7396391981312136000e-8

*  Coefficient: 2 PAIR
C1_2_c1 nnc101 nnc102 2.2930571209259956000e-11
R1_2_c1 nnc101 nnc102 0.9732049276718901500000
L1_2_c1 nnc101 nnc102 3.9362648317687720000e-11
…
```

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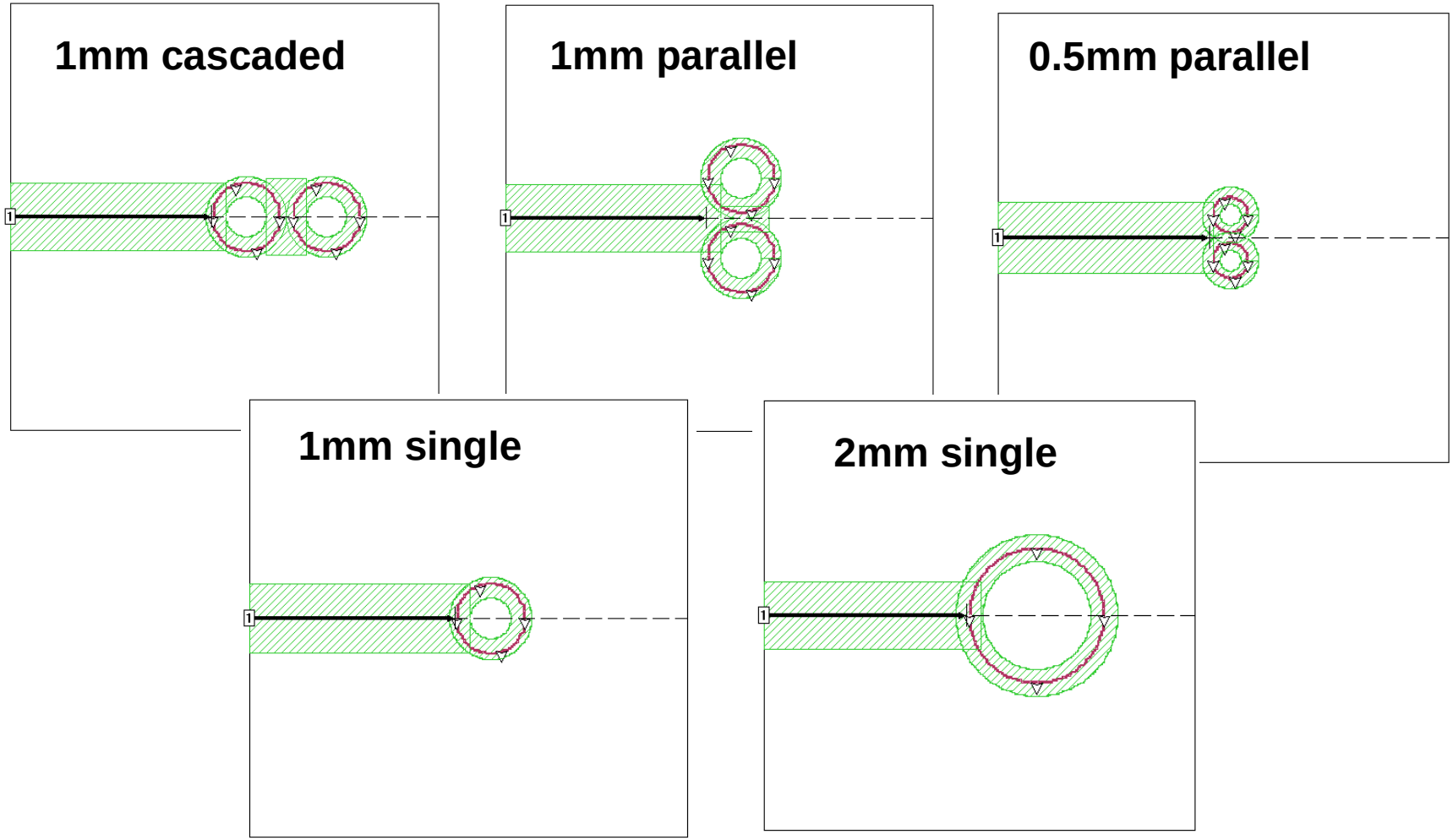
Via Inductance

Comparison of via geometries

Which via geometry is best?



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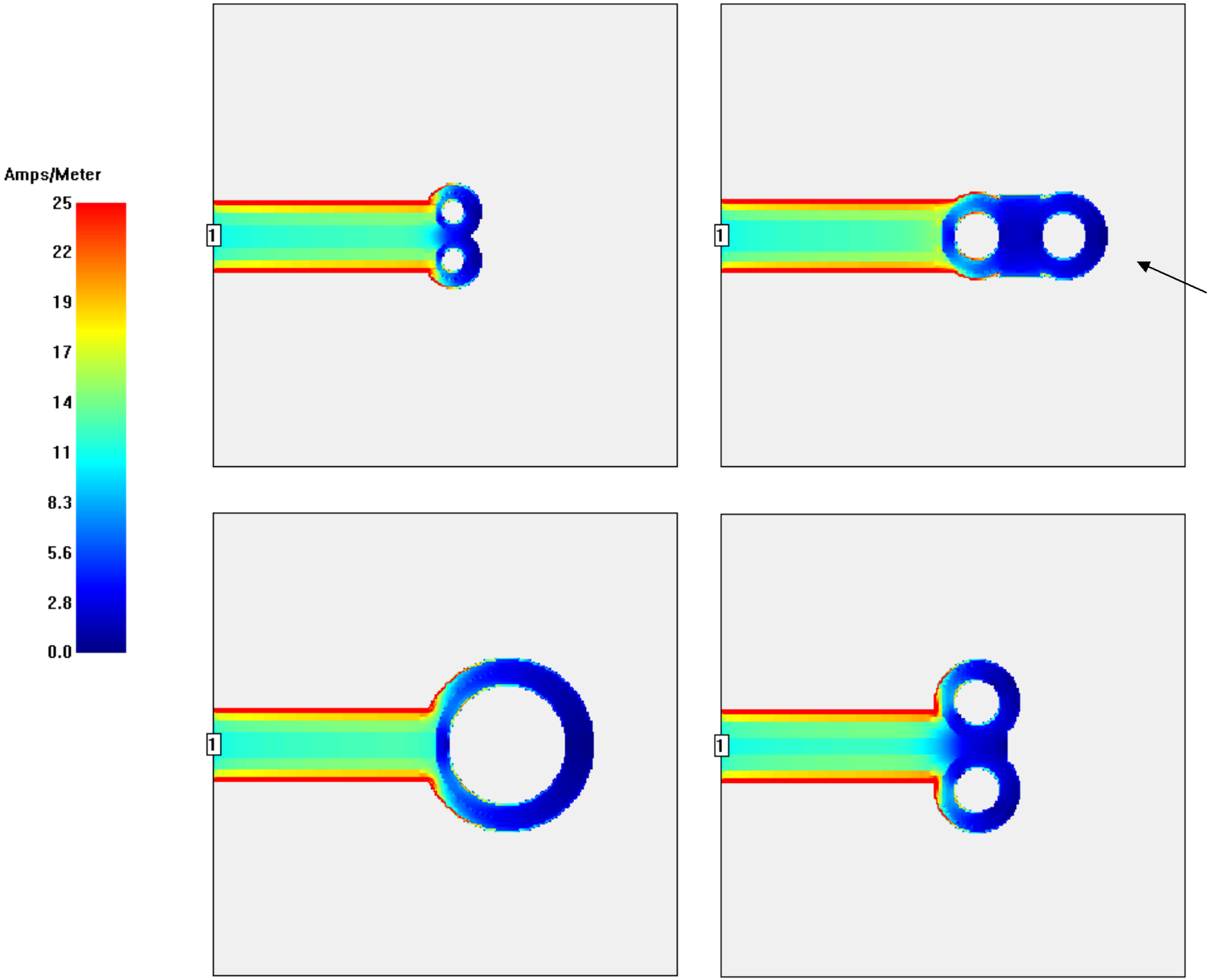

second via has almost no current, useless for RF

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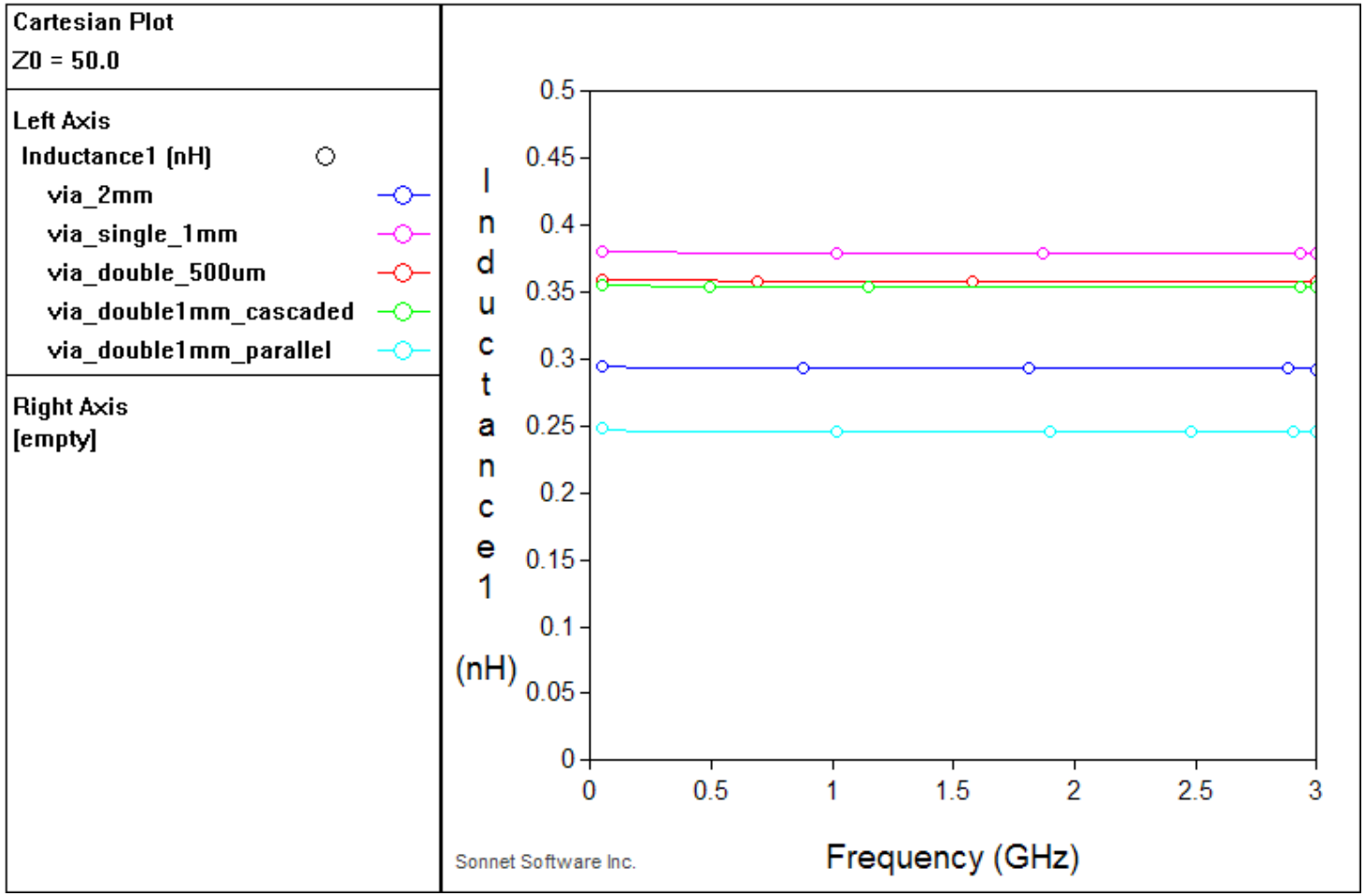
Inductance Comparison



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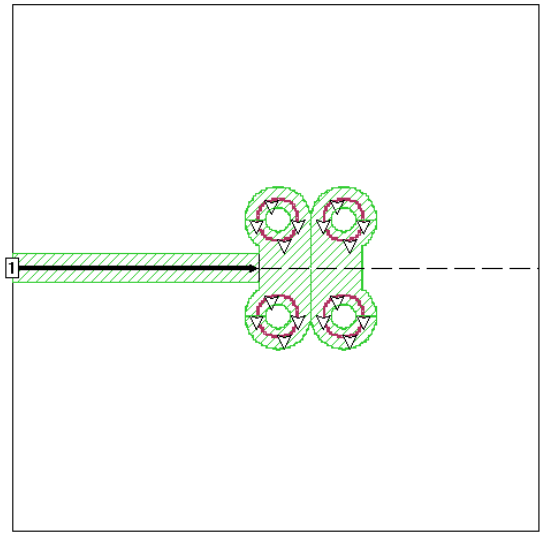
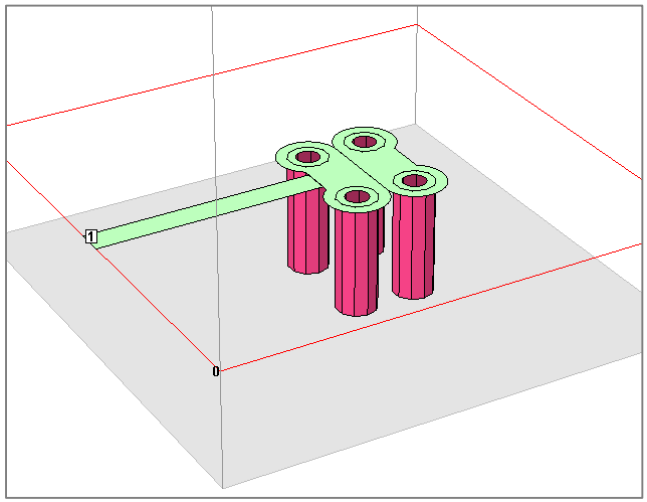
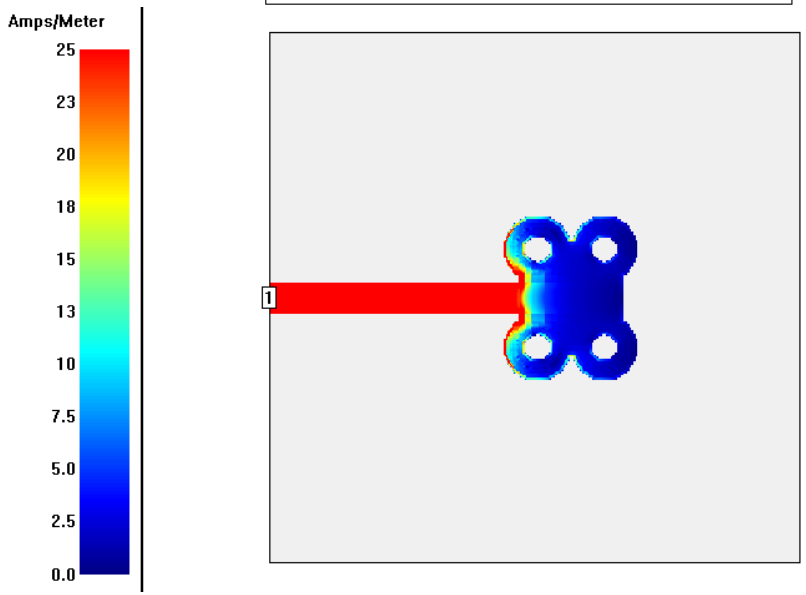
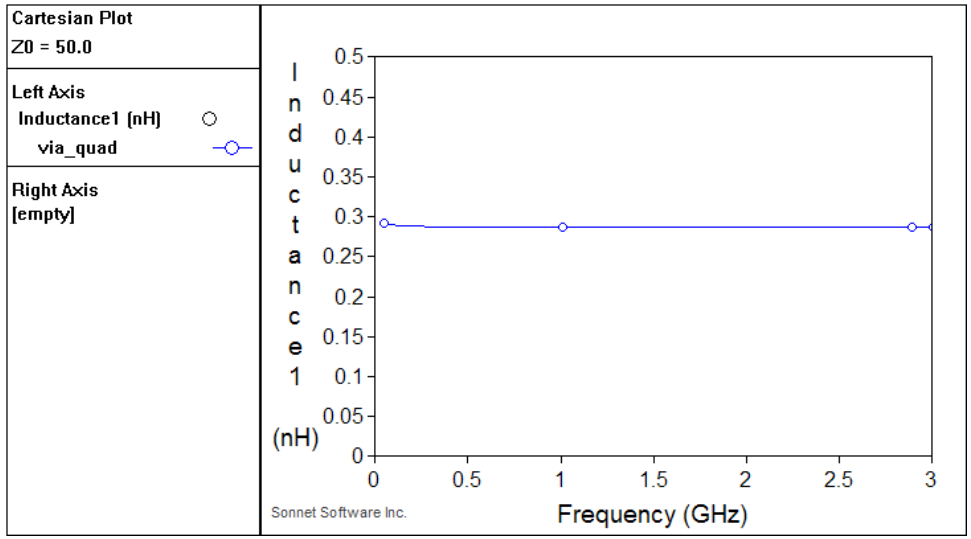
Quad Via









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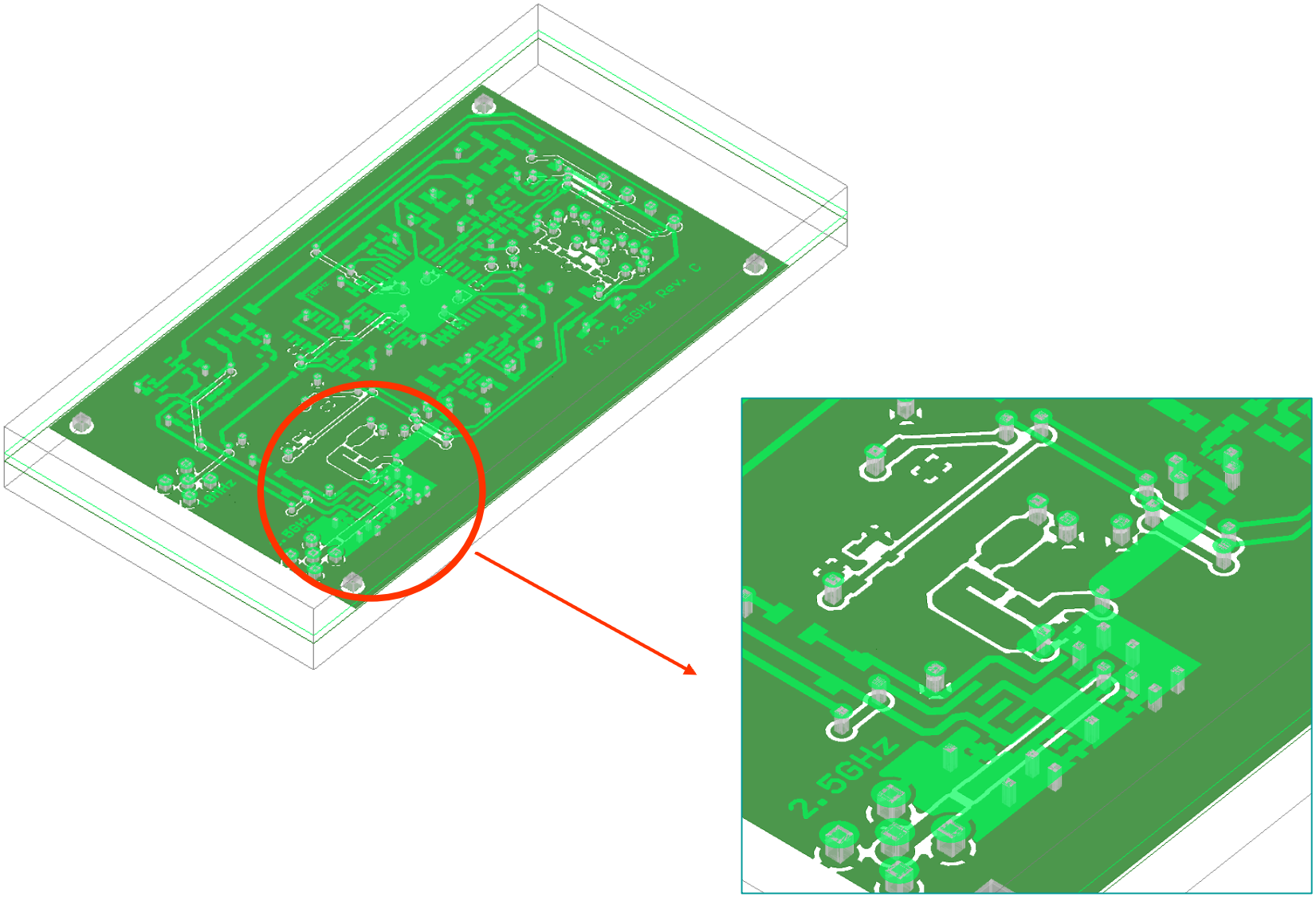
PCB Example

Finding a resonance problem

Data Import from Gerber RS274X File



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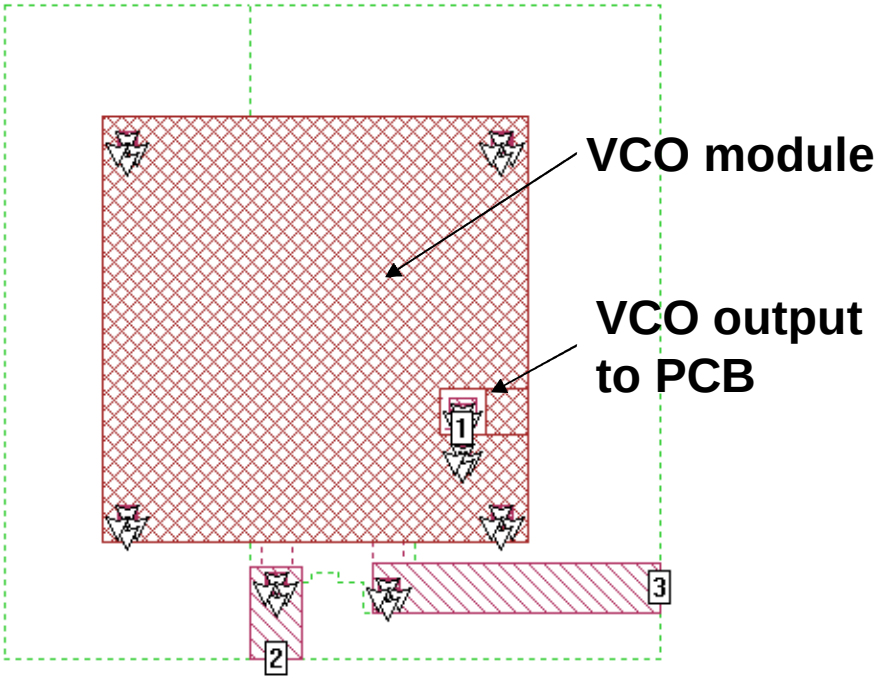
2.5GHz VCO on PCB

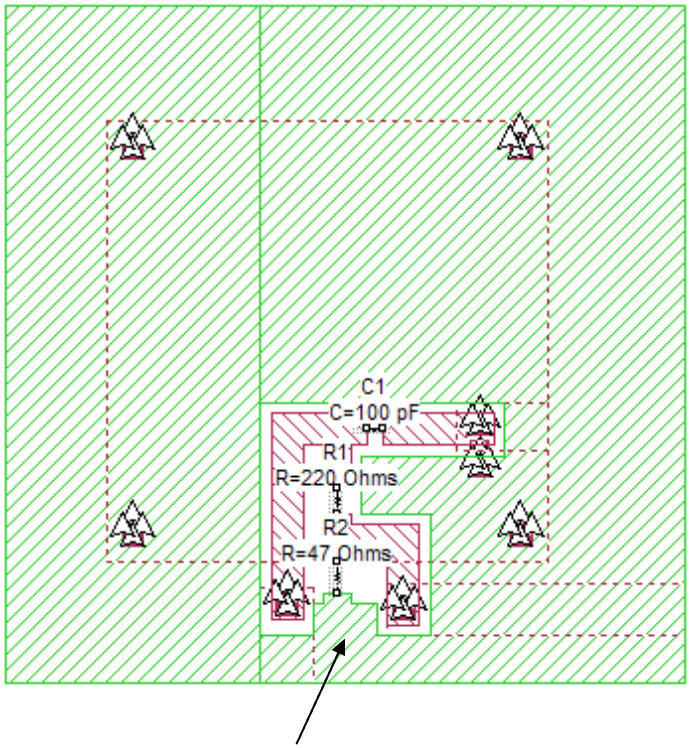
Top (Level 0)



main output
-1 dB

ref output
-21dB

Bottom (Level 1)



voltage divider 220 Ω / 47 Ω

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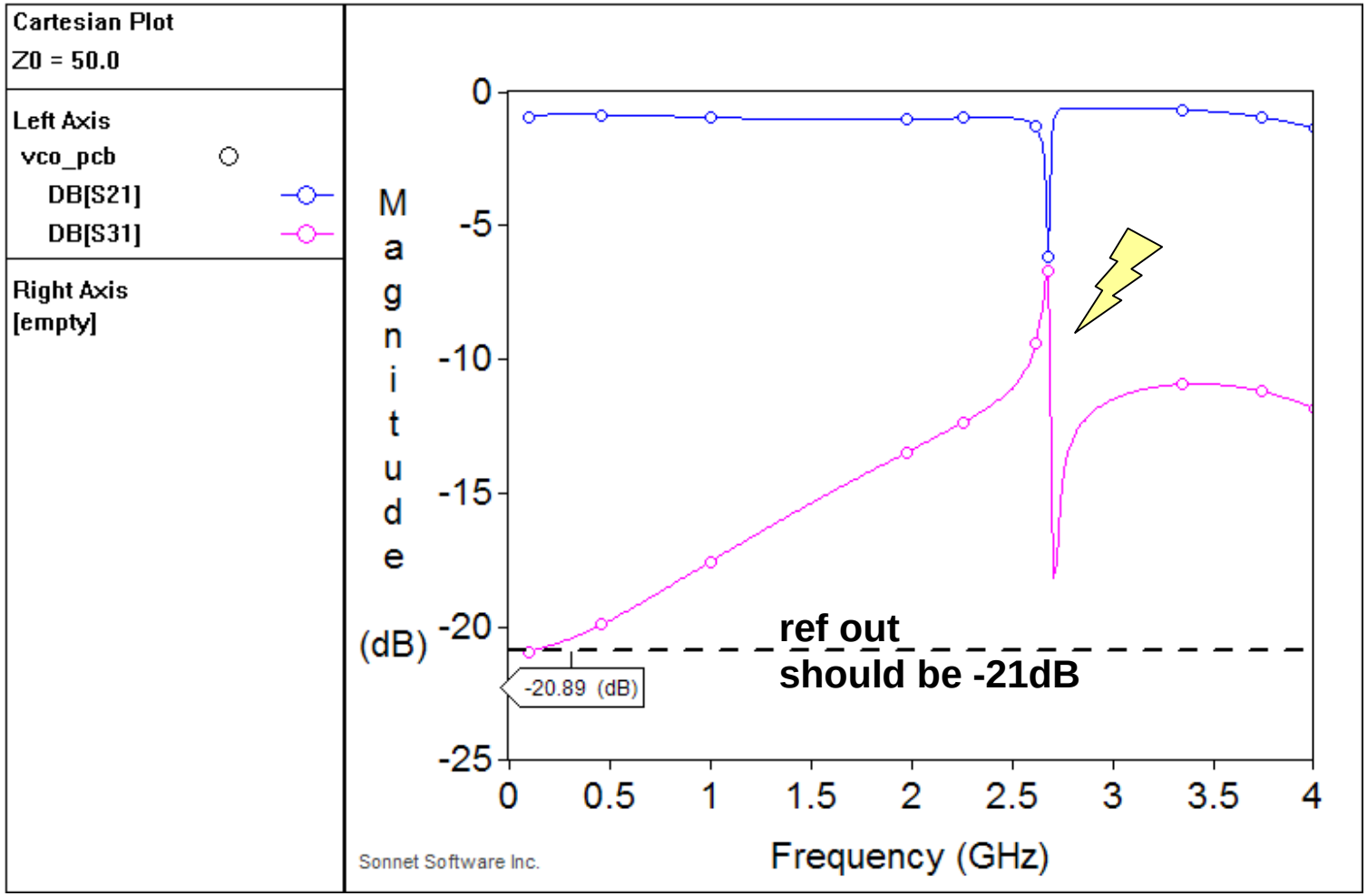
Simulation Result



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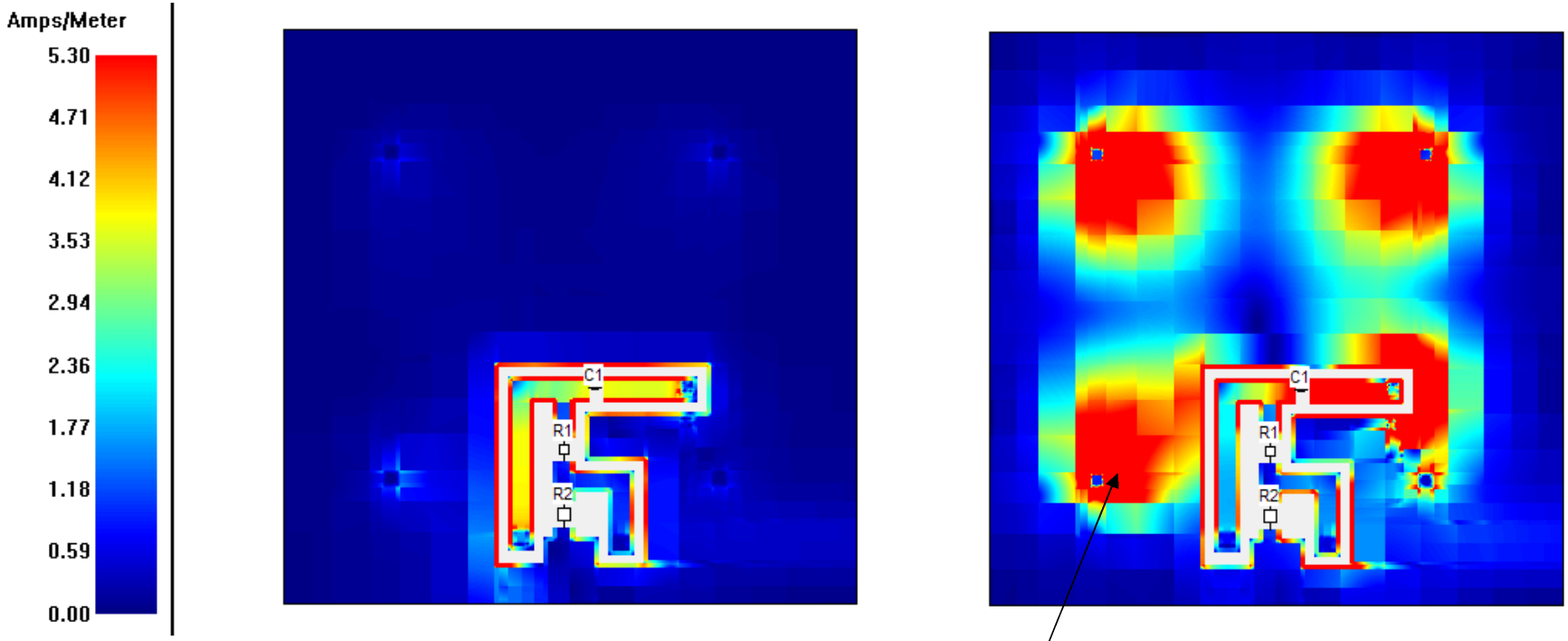
Current Density



2GHz

2.68 GHz

High current on top side going down through vias !?

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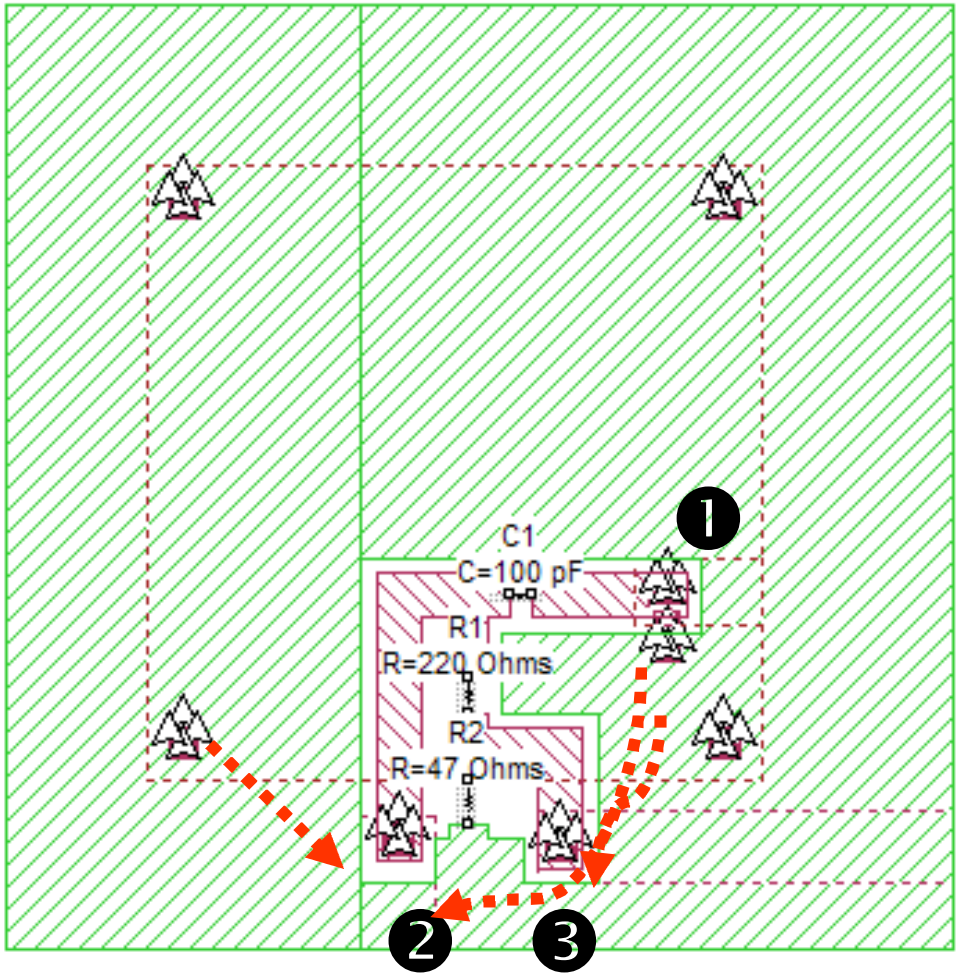
Ground Problem



Same long ground path for both outputs causes inductive coupling between both signals

Solution:
Provide better ground, so that each signal has its own proper ground path

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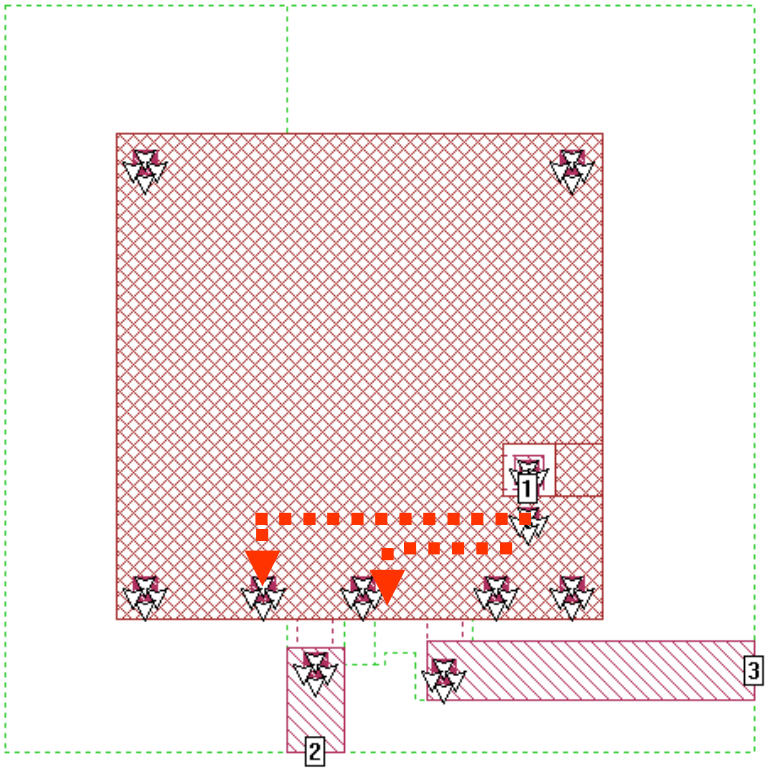
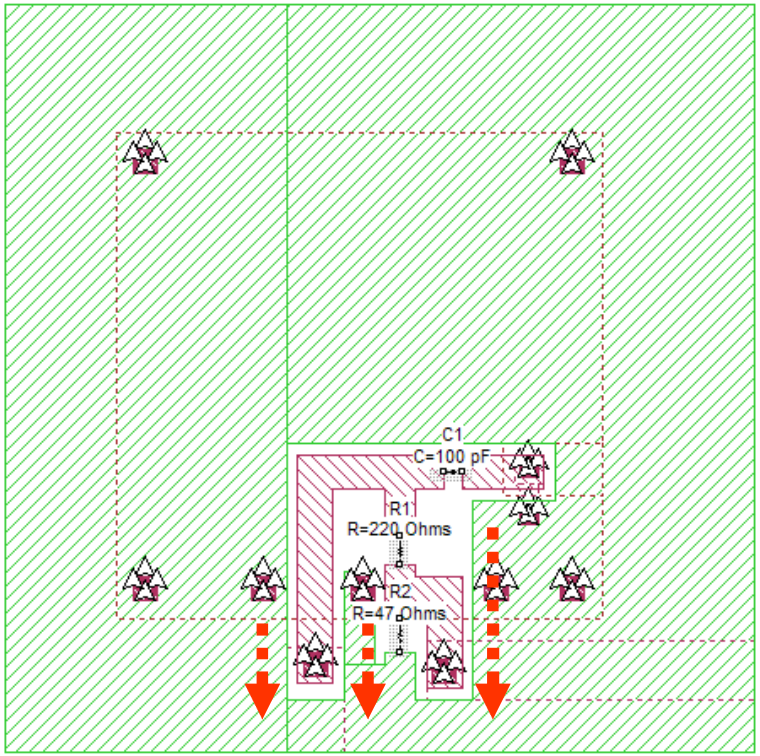
Better Ground





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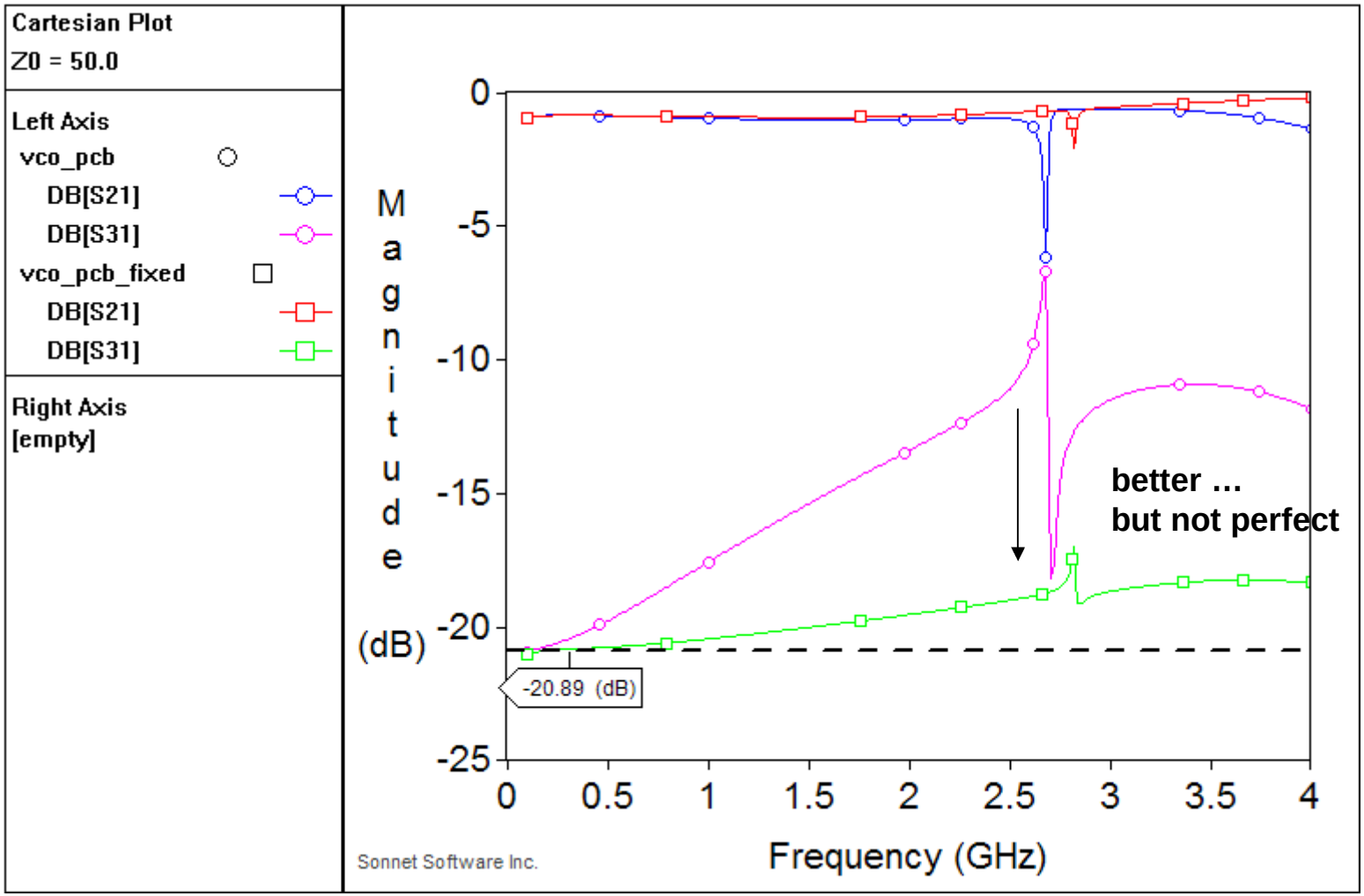
Better Ground



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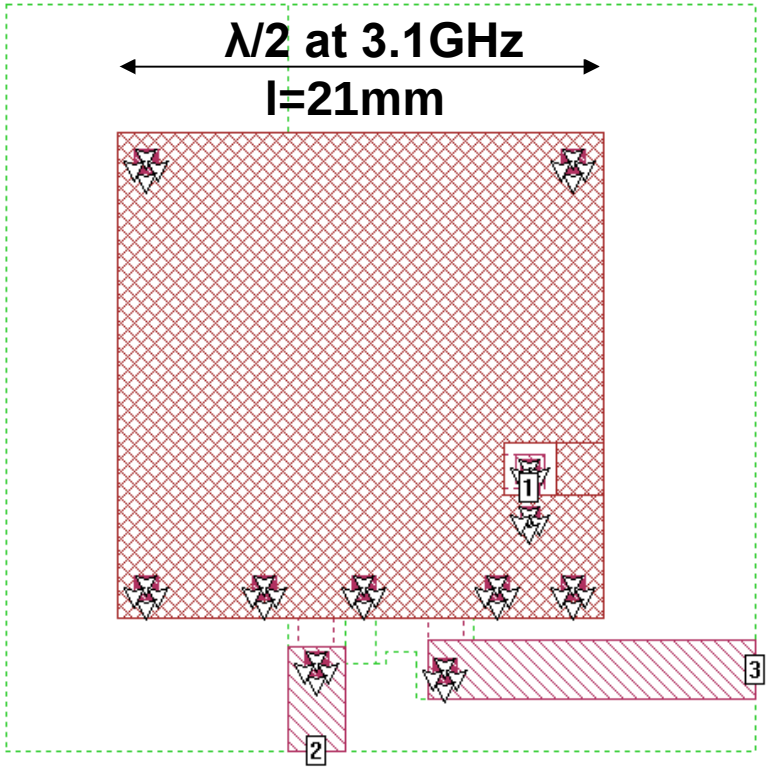
Resonance ?



f=3.1GHz
λ=96mm in air
λ=43mm in ε_r=4.9

Not exactly our frequency, but close. The vias are part of the parasitic resonator and might shift the resonance down.

Place additional vias at maximum E field to short resonance condition

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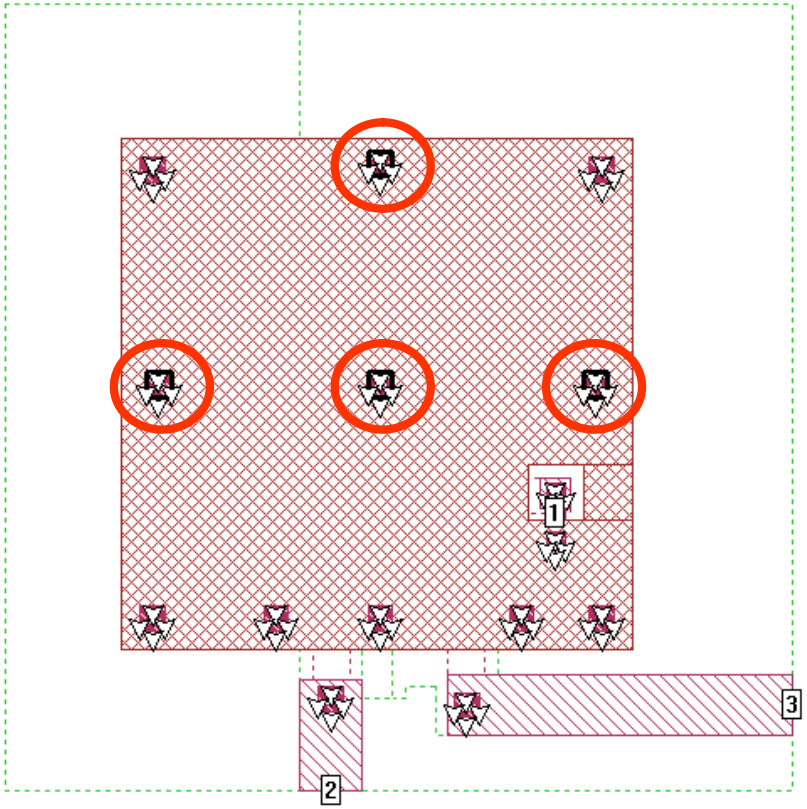
Additional Vias



Place additional vias at maximum E field to short resonance condition

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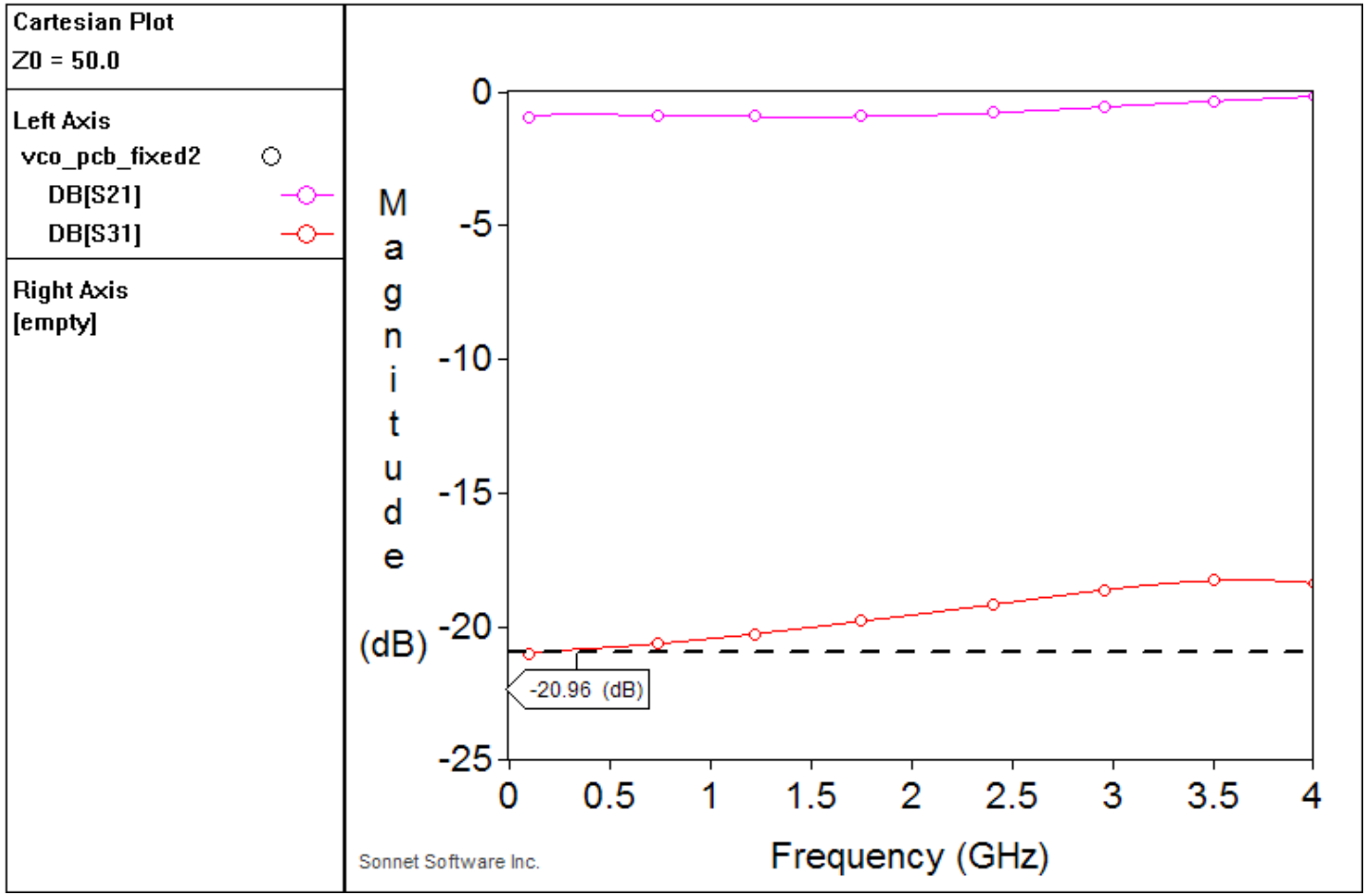
Success!



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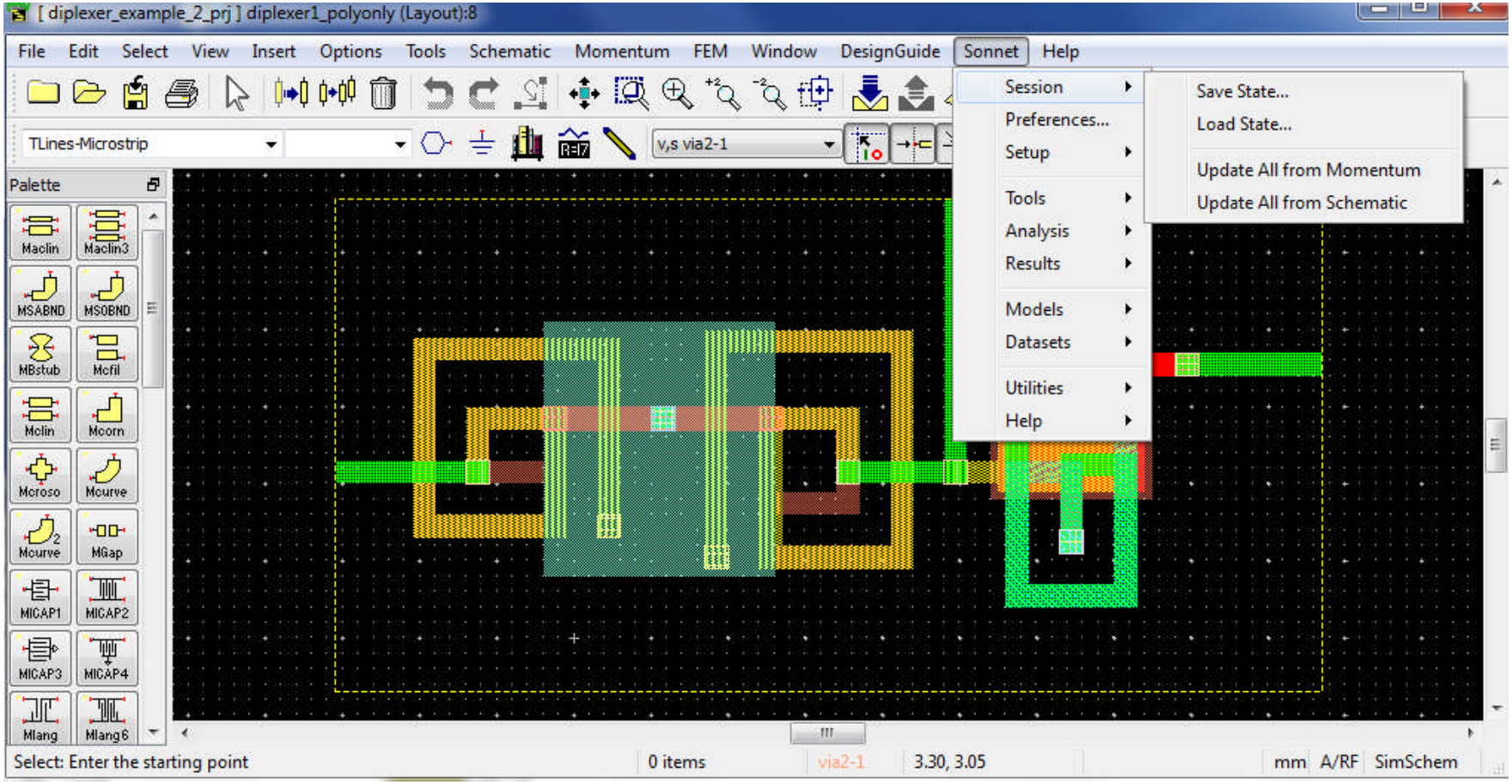
Sonnet Framework Integration



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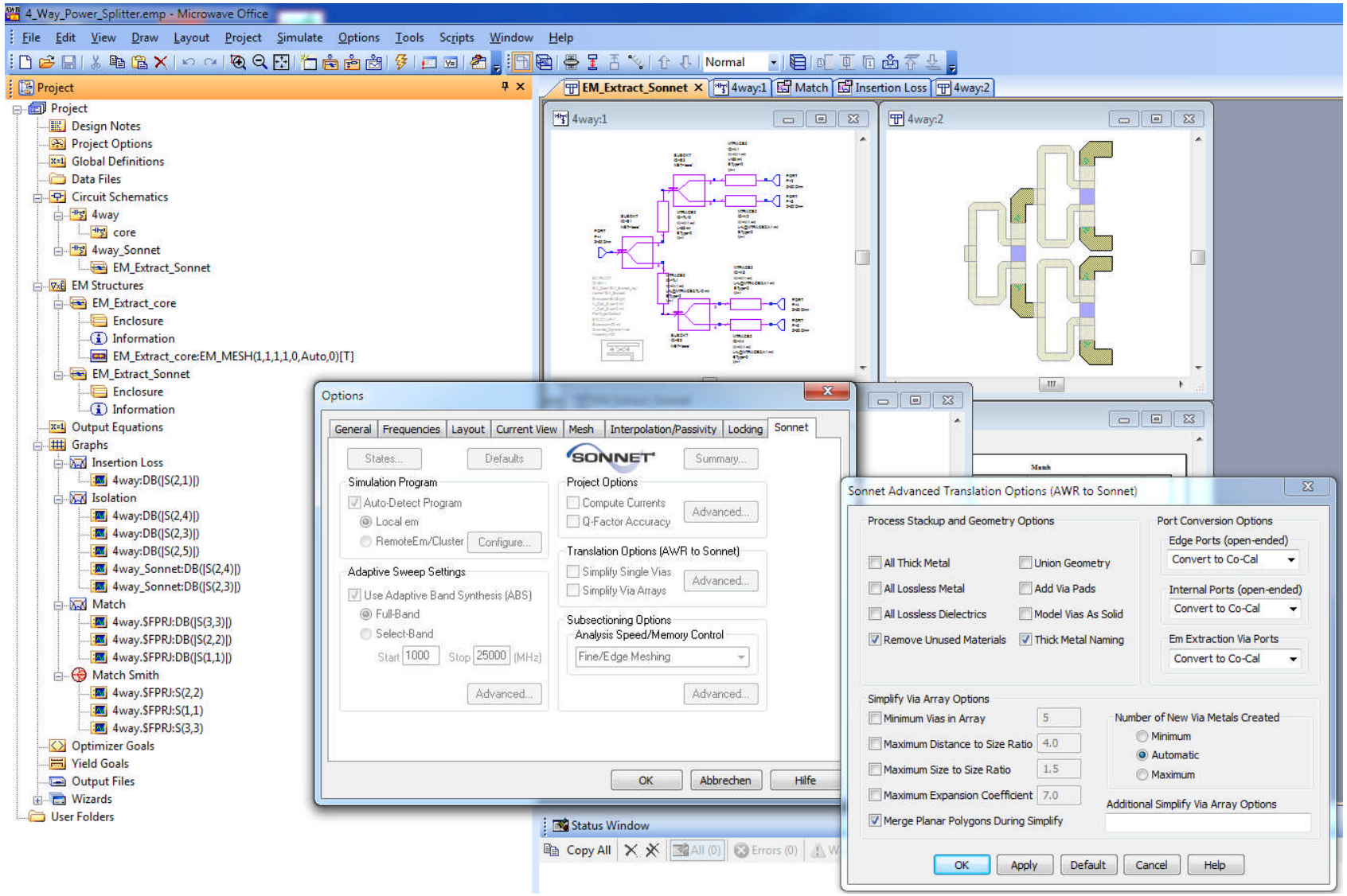
Sonnet Framework Integration



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Summary

- The devil is in the detail. EM can help to design the little details properly, before they cause trouble.
- EM can help to identify parasitic coupling, ground path issues, resonances and radiation.
- Highly accurate FFT based method and flexible meshing in Sonnet can provide very accurate, consistent, reliable results.
- Accurate port calibration in Sonnet allows to extract small details with very high precision.
- Accurate port calibration in Sonnet allows to insert components into the EM model with very high precision.
- Sonnet can be used stand alone, or integrated into popular RF design frameworks.

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Thank You!

For questions:

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