3D Simulations for Signal Integrity

Jim DeLap

Goal

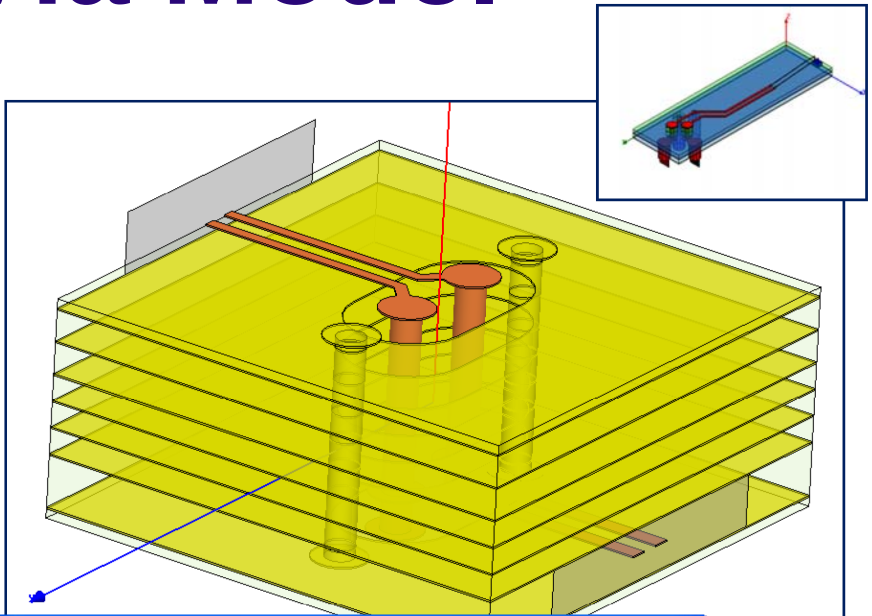
- Use frequency domain tool, HFSS, to analyze and optimize passive high-speed channels
- Take information from 3D electromagnetic simulations and use in time domain circuit analysis

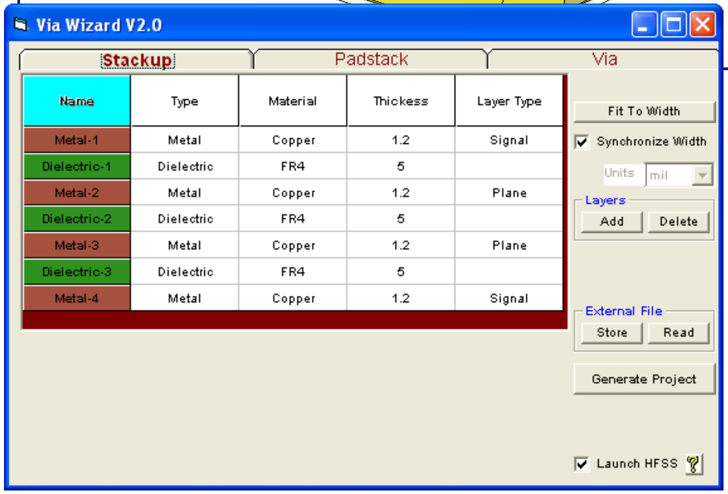
Prerequisites

- Need some guidelines for setting up simulation to have high degree of confidence that time domain simulations will be accurate
- Need to be able to modify basic model to enable optimization

Simple 3D Via Model

- 3D Models for SI applications can be created several different ways
  - Manual drawing of board layers and traces
  - Export from eCAD packages (Allegro, Boardstation, etc.) though Ansoft Links
  - Export from Ansoft Designer PlanarEM
  - Import through DXF, GDS, etc.
  - Via Wizard





Name	Type	Material	Thickess	Layer Type
Metal-1	Metal	Copper	1.2	Signal
Dielectric-1	Dielectric	FR4	5	
Metal-2	Metal	Copper	1.2	Plane
Dielectric-2	Dielectric	FR4	5	
Metal-3	Metal	Copper	1.2	Plane
Dielectric-3	Dielectric	FR4	5	
Metal-4	Metal	Copper	1.2	Signal

☑ Synchronize Width

Units mil

Layers

☑ Launch HFSS

Simulation Parameters

- Solution Setup
    - Adaptive Frequency
    - Setup options
    - Frequency Sweep
- Model parameterization and optimization
    - Geometry manipulation

SOLUTION SETUP

Adaptive Solution Setup

- The frequency at which the adaptive solution is performed in HFSS will determine not only the **accuracy** of the results, but also the simulation **resources** required.
  - Frequency ↑
  - Edge length of tetrahedra ↓
  - Number of tetrahedra ↑
  - Memory required ↑
- We'll utilize the concept of "knee frequency" to help us optimize the adaptive solution setup

Knee Frequency

- Howard Johnson, in his book *High Speed Signal Propagation,* references a calculation for the “Knee frequency” which is a guide that helps determine the relevant spectral content of a digital signal
- It is defined as:

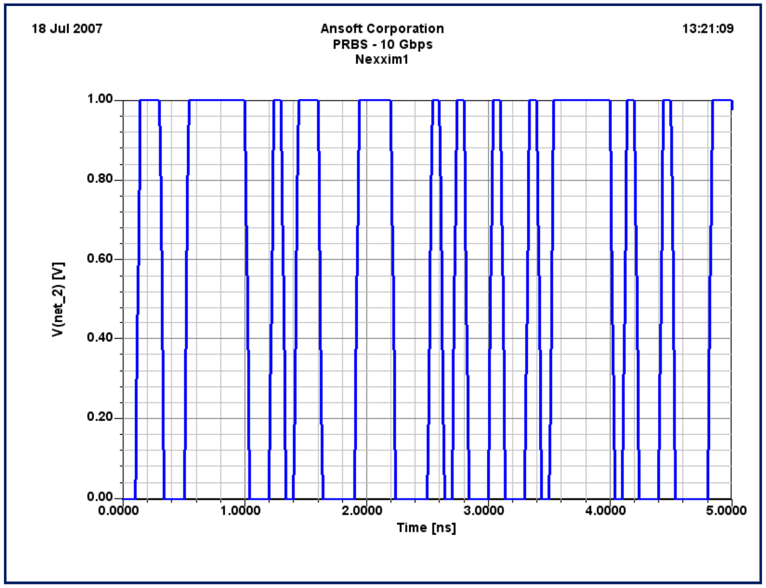
$$f_{knee} \cong \frac{0.5}{t_r}$$

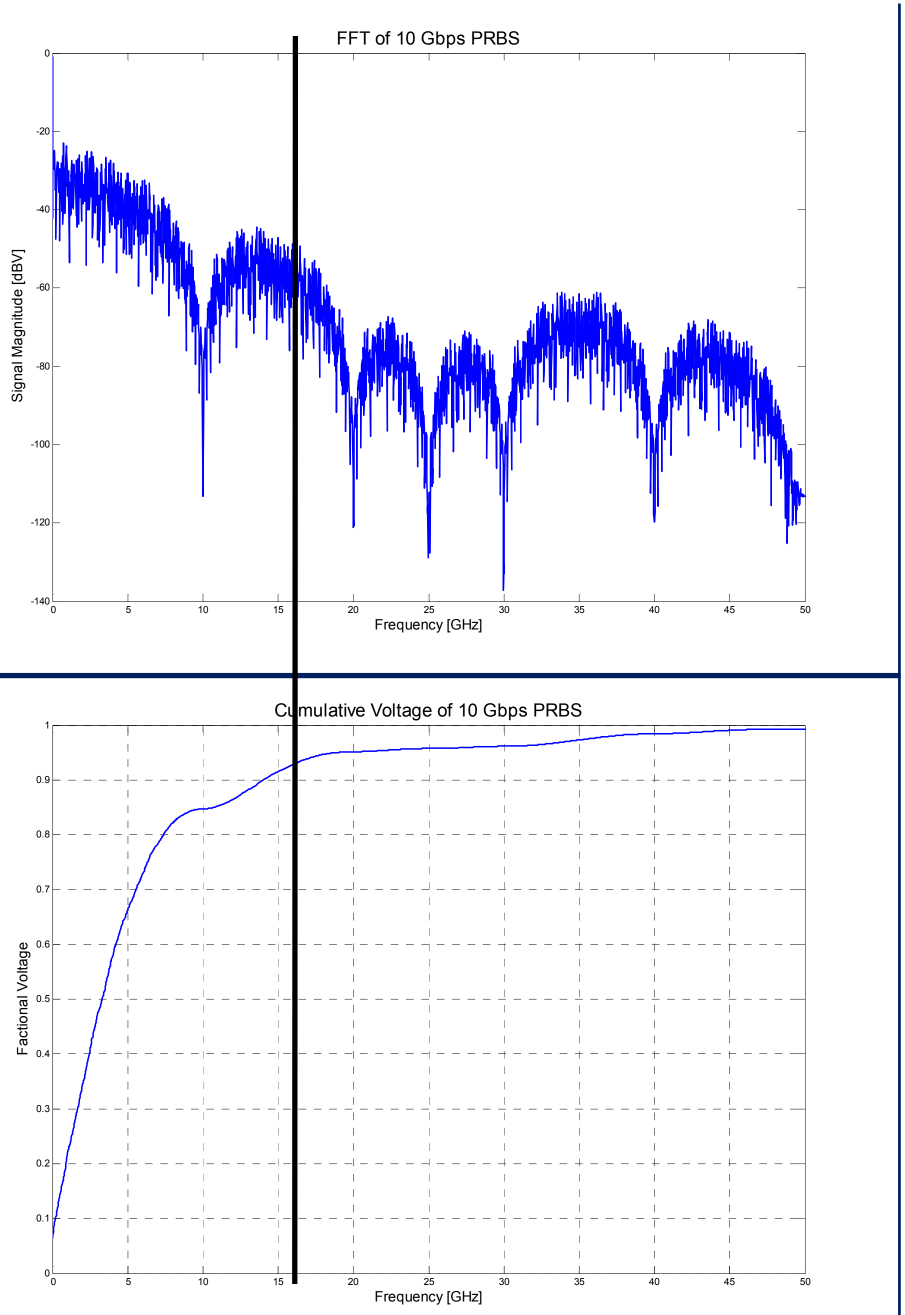
- Where t_r is the 10%-90% rise time of the signal
- This frequency represents the frequency below which, the majority of the spectral content is contained

Knee Frequency - Example

- Simulate a PRBS signal
  - Bitrate = 10 Gbps
  - t_r = 40 ps (0-100%) → 32 ps (10-90%)

  - f_{knee} = 15.625 GHz



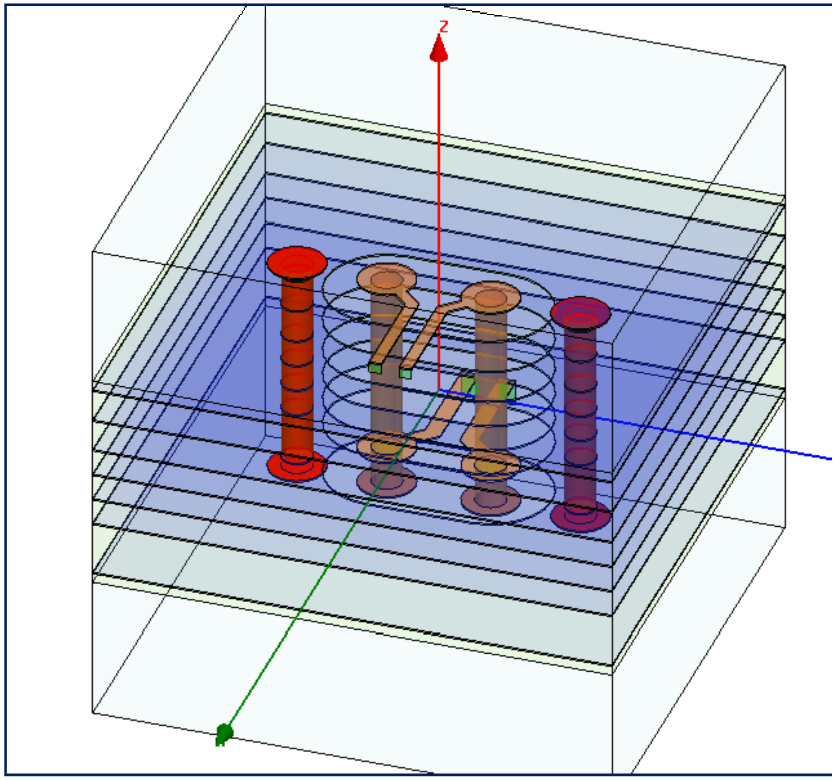


PRBS Spectral Content

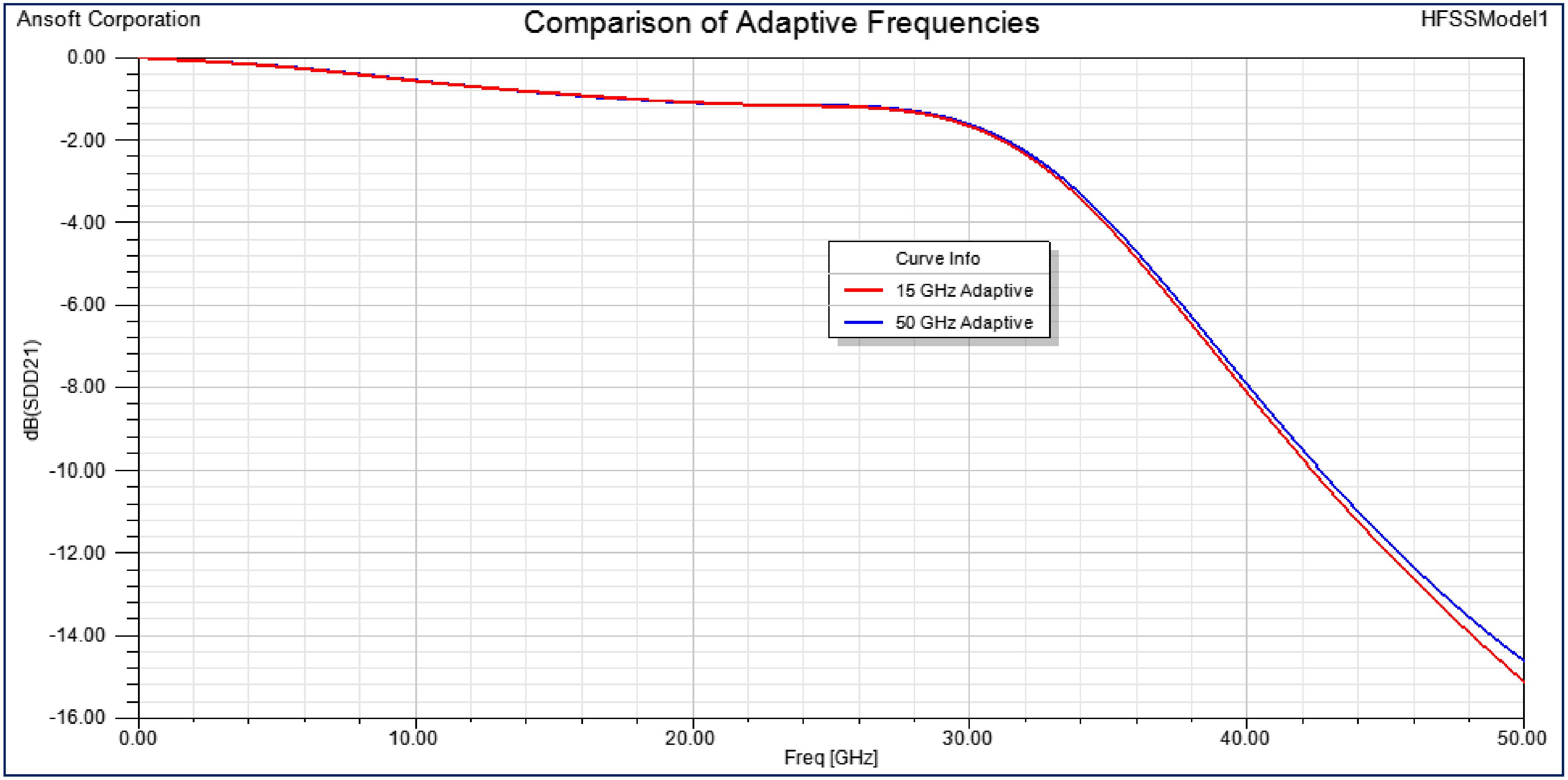
- Extract the FFT of the signal to obtain the spectral content
- Bottom plot shows cumulative energy of signal
- Marker at ~ 15.6 GHz shows that 92% of spectral energy is captured below the knee frequency

Implications of F_{knee}

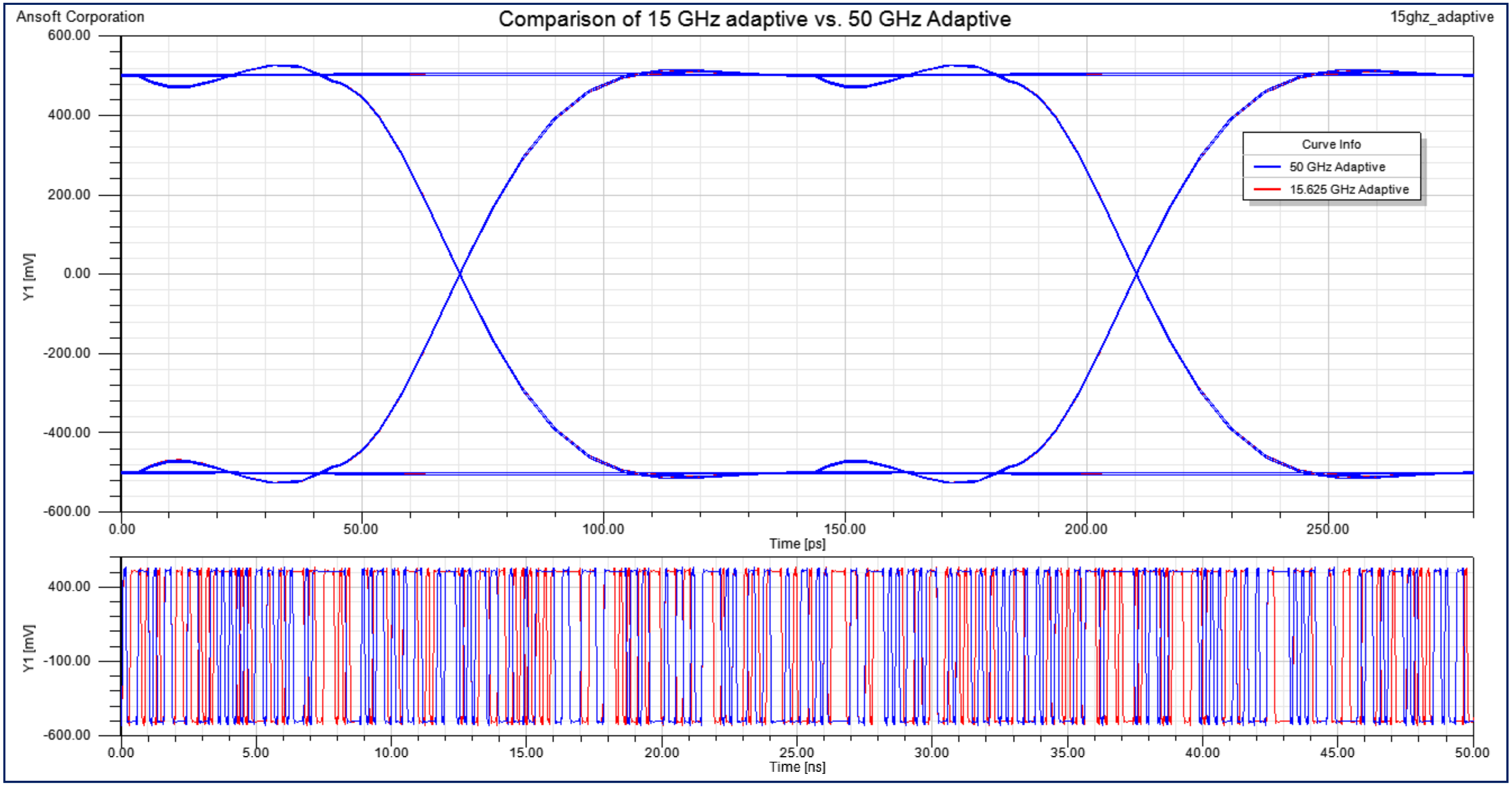
- How can we use this information to our advantage?
- Example – Differential via
  - Simulate with the adaptive frequency set to:
    - F_{knee} (15.625 GHz for t_r=40 ps)
    - 50 GHz
  - Run interpolating sweep out to 50 GHz in both cases



Implications of F_{knee}



Implications of F_{knee}



Implications of F_{knee}

F_{knee} Adaptive

- 8 passes
- $\Delta S = 0.008805$
- 1.2 GB RAM
- 121 Minutes CPU Time

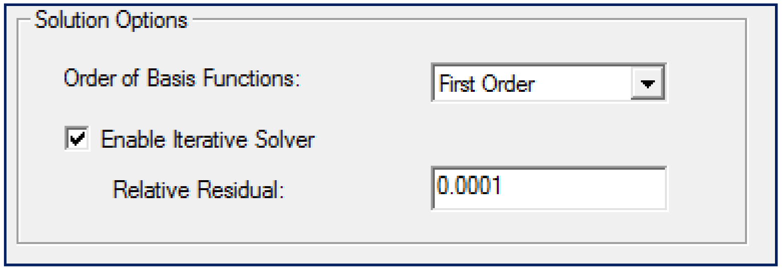
50 GHz Adaptive

- 10 passes
- $\Delta S = 0.0082597$
- 2.19 GB RAM
- 251 Minutes CPU Time

- Lower the Adaptive solution frequency reduces the memory required by **45%** and reduces the simulation time by **52%** with no loss in accuracy

Iterative Solver Option

- Solver – Iterative
- How does it work?
    - The Iterative Matrix Solver works by “guessing” a solution to the matrix of unknowns, and then recursively updating the “guess” until an error tolerance has been reached
- What is the advantage?
    - Reduced RAM
- Where do you control the Iterative Solver?
    - Options Tab from Solution Setup dialog
    - No reason to change value for Relative Residual

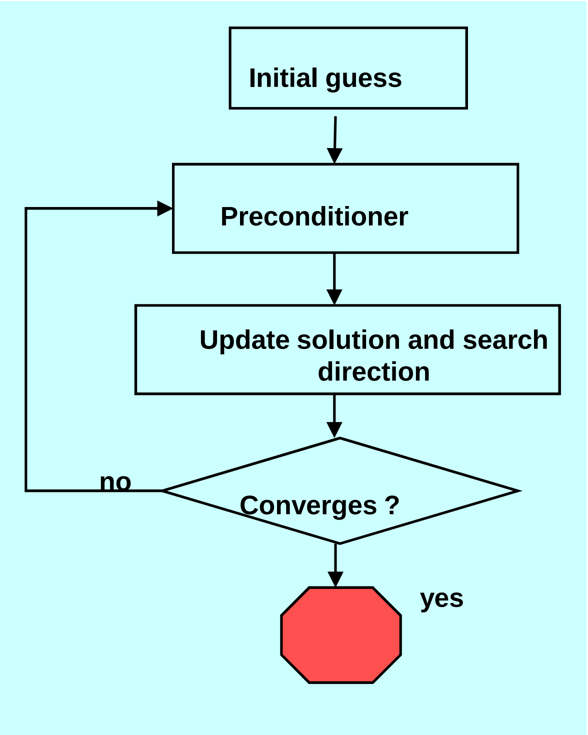


Solution Options

Order of Basis Functions: First Order

☑ Enable Iterative Solver

Relative Residual: 0.0001



Initial guess

Preconditioner

Update solution and search direction

Converges ?

no

yes

Iterative Solver Implications

- For the via example used here, the model is solved with and without the Iterative solver
- Direct solver
  - 492 MB / 16.5 minutes
- Iterative solver
  - 210 MB / 25 minutes
- With the Iterative solver, this problem required **57%** less memory !!

- Cannot use the iterative solver on problems requiring zero order basis functions

Frequency Sweep Options for Time Domain Simulations

- Frequency sweep issues are related to the Fourier transform which converts the frequency domain information to the time domain
- Without enough information in the frequency domain, you will get incorrect results in the time domain

Joseph Fourier

Basics to consider

- Through Nyquist sampling, we know that to capture a time step of Ts, we need to obtain frequency domain information up to:

$$F_{\max} = \frac{1}{2 \times t_s}$$

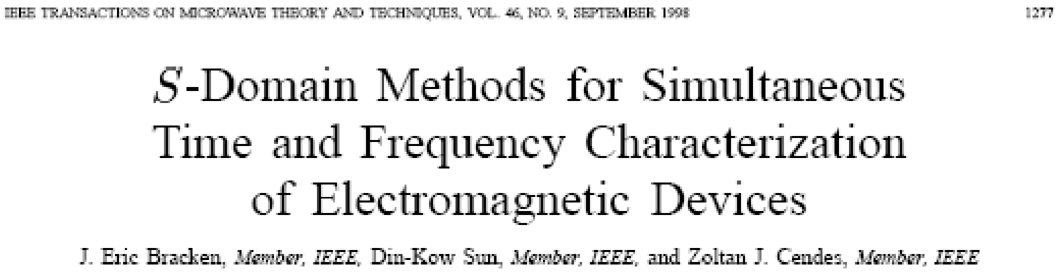
- For a time domain waveform with a risetime of 40 ps, in order to capture the ringing in the time domain, we would want to capture at least 4 samples during this risetime
- This implies a sampling time of 10 ps
- According to the above equation, we need data from HFSS up to 50 GHz

Interpolating Sweep

- This method fits s-parameter data to a rational polynomial transfer function using a minimum number of discrete finite element method (FEM) solutions.
- The interpolating sweep yields the poles and zeros of the transfer function.

$$S = \frac{\beta_q (s - z_q)(s - z_{q-1}) \ldots (s - z_1)}{\alpha_q (s - p_q)(s - p_{q-1}) \ldots (s - p_1)}$$

See: IEEE Trans. Microwave Theory Tech., Vol. 46, No. 9, Sept. 1998



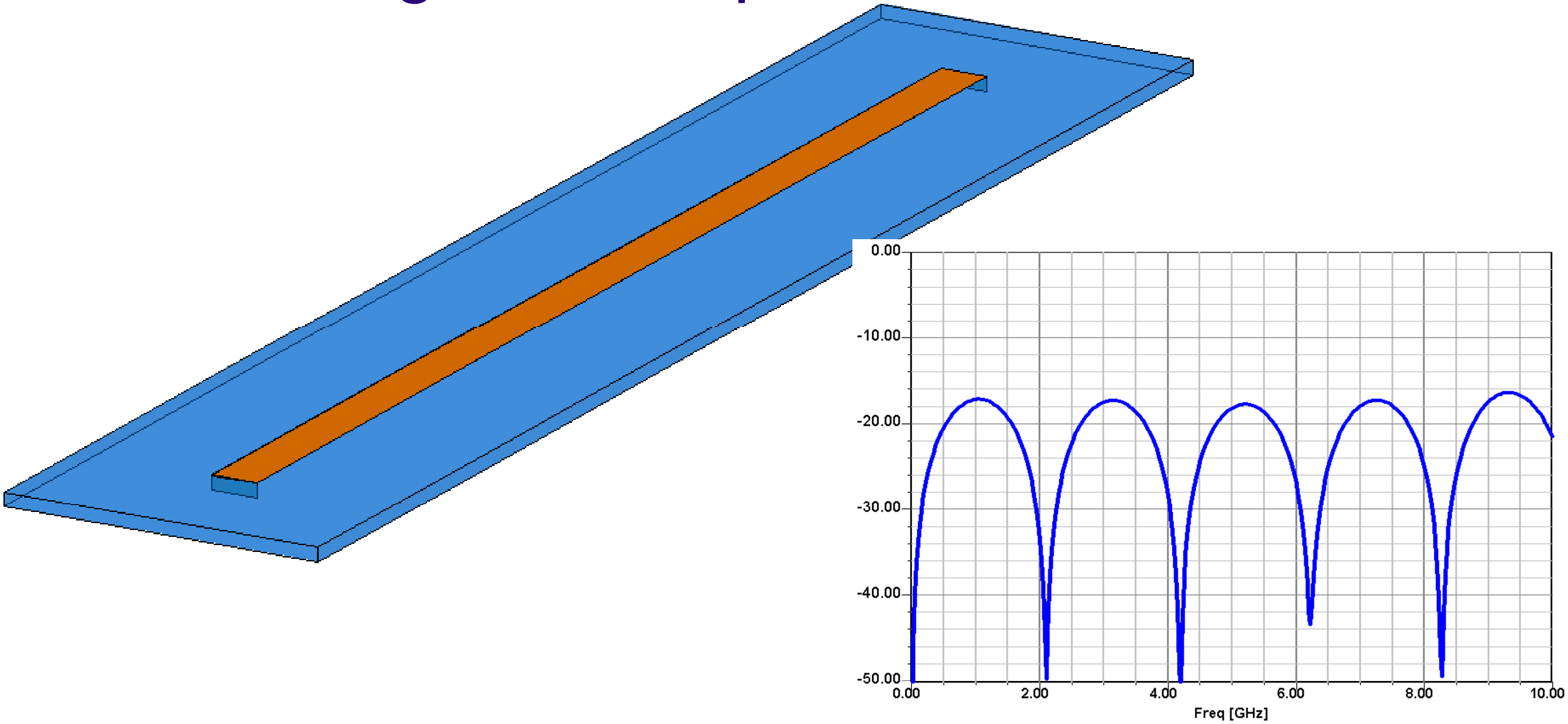
IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 46, NO. 9, SEPTEMBER 1998 1277

S-Domain Methods for Simultaneous
Time and Frequency Characterization
of Electromagnetic Devices

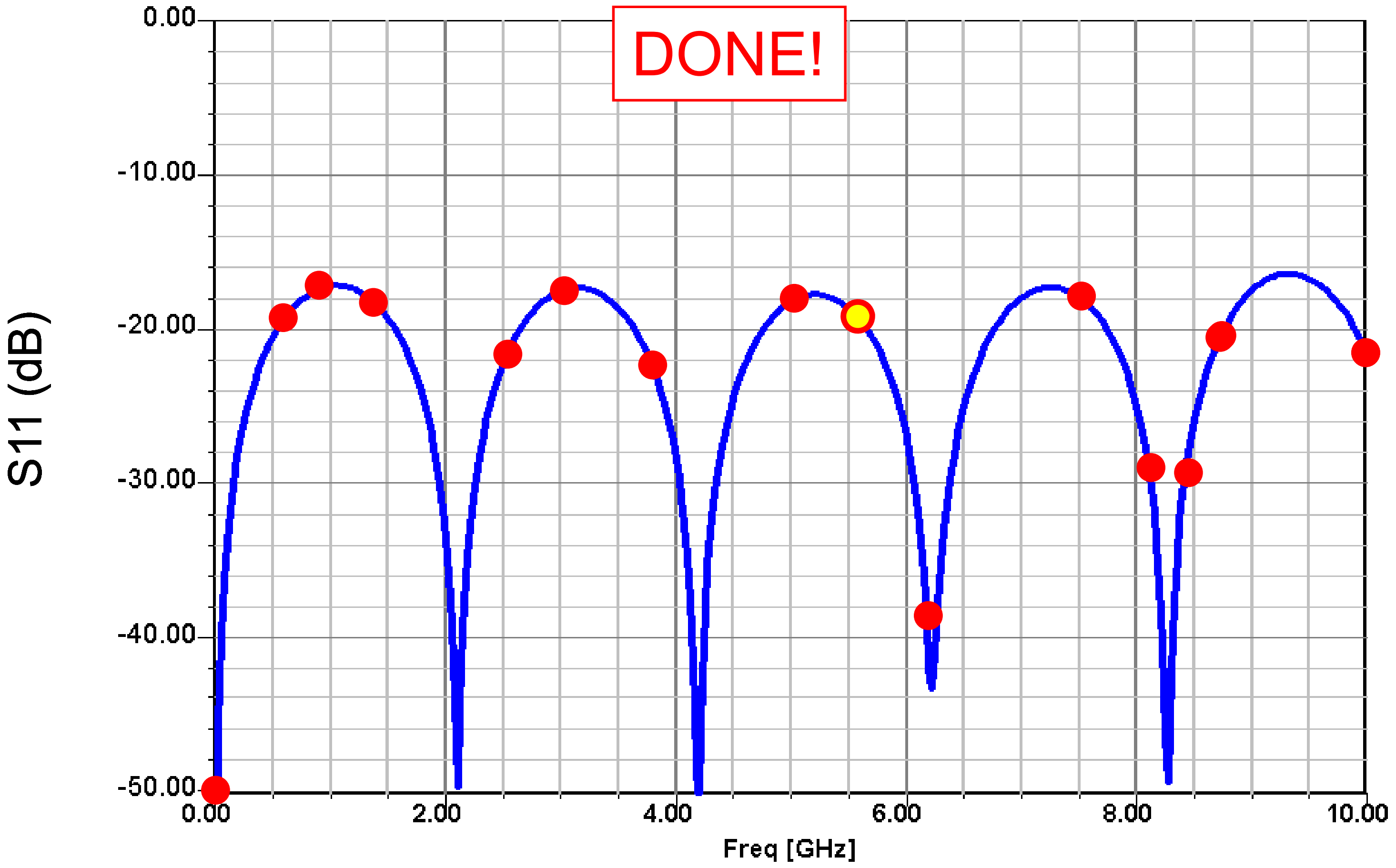
J. Eric Bracken, *Member, IEEE*, Din-Kow Sun, *Member, IEEE*, and Zoltan J. Cendes, *Member, IEEE*

Interpolating Sweep

- 5 cm long microstrip transmission line

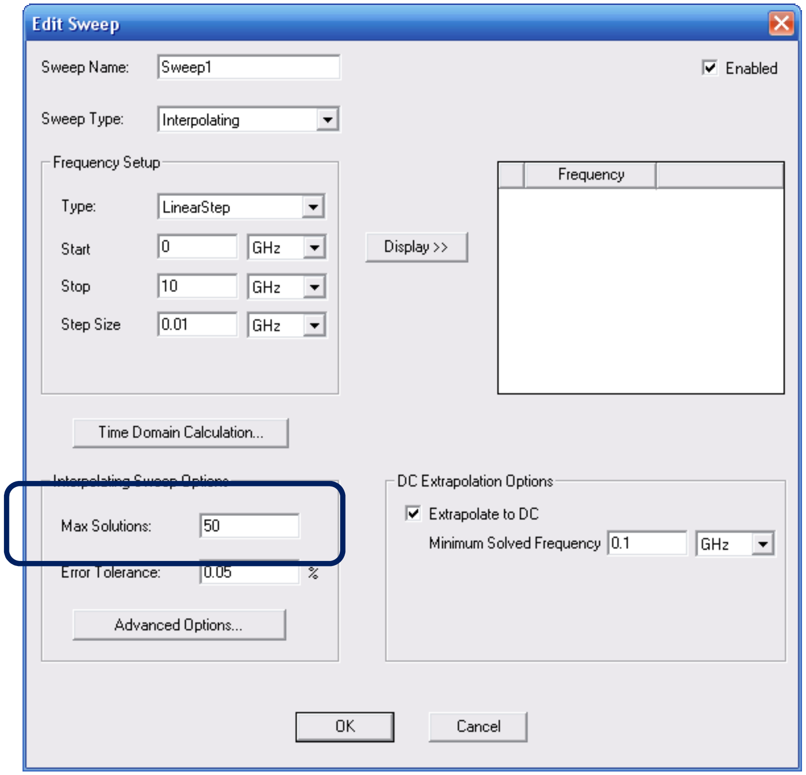


Interpolating Frequency Sweep



"Active" S-parameters

- Insufficient number of solutions in polynomial function can lead to |S| > 1
- Solution → Increase Max. Solutions



Sweep Name: Sweep1

☑ Enabled

Sweep Type: Interpolating

Frequency Setup

Type: LinearStep

Start 0 GHz

Stop 10 GHz

Step Size 0.01 GHz

Interpolating Sweep Options

Max Solutions: 50

Error Tolerance: 0.05 %

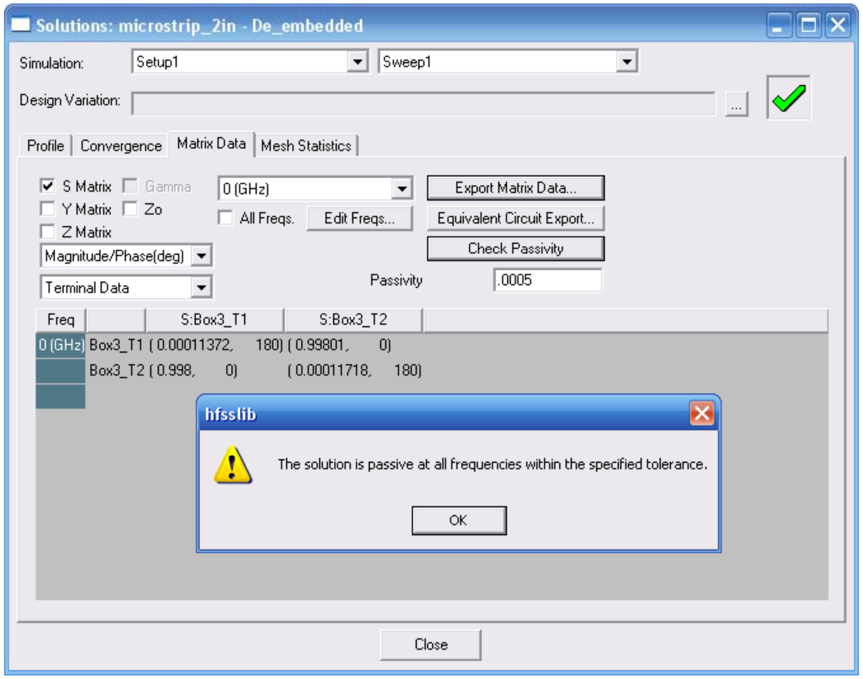
DC Extrapolation Options

☑ Extrapolate to DC

Minimum Solved Frequency 0.1 GHz

“Active” S-parameters

- You can also test for “Active” or passive S-parameters in the Matrix Data Display



Simulation: Setup1 | Sweep1

Design Variation:

☑ S Matrix

0 (GHz)

Magnitude/Phase(deg)

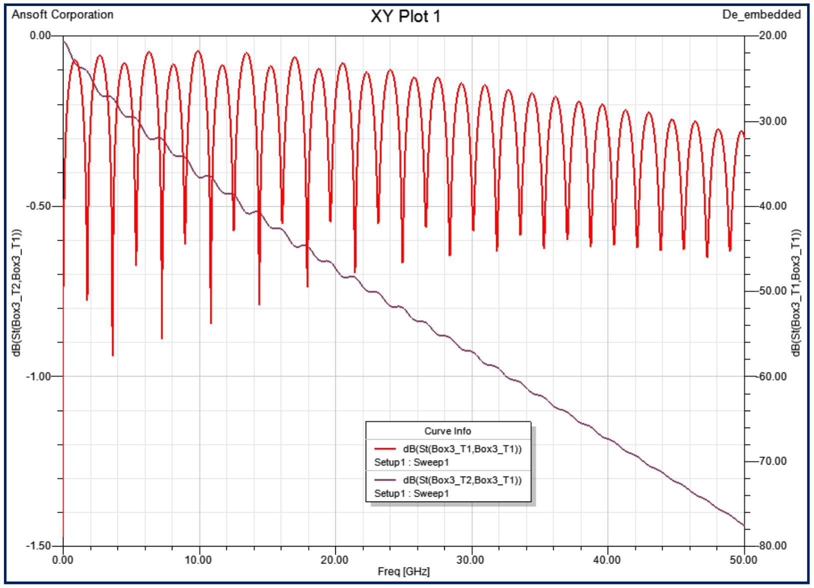
Terminal Data

Passivity .0005

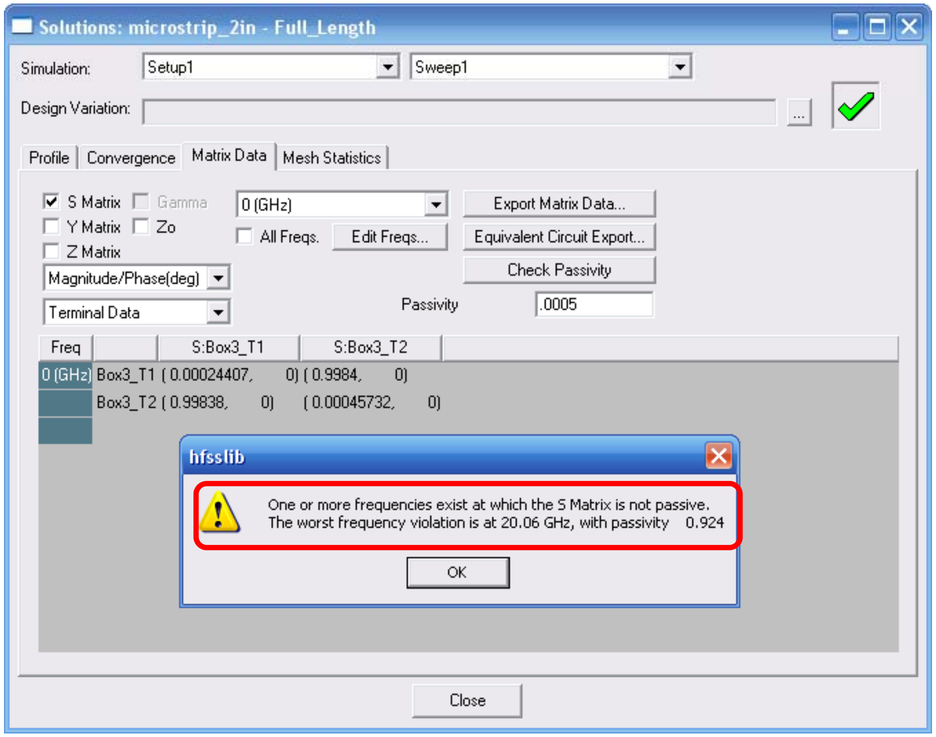
Freq		S:Box3_T1	S:Box3_T2
0 (GHz)	Box3_T1	(0.00011372, 180)	(0.99801, 0)
	Box3_T2	(0.998, 0)	(0.00011718, 180)

hfsslib

The solution is passive at all frequencies within the specified tolerance.



“Active” S-parameters



Simulation: Setup1 Sweep1

Design Variation:

☑ S Matrix ☐ Gamma

☐ Y Matrix ☐ Zo

☐ Z Matrix

Magnitude/Phase(deg)

Terminal Data

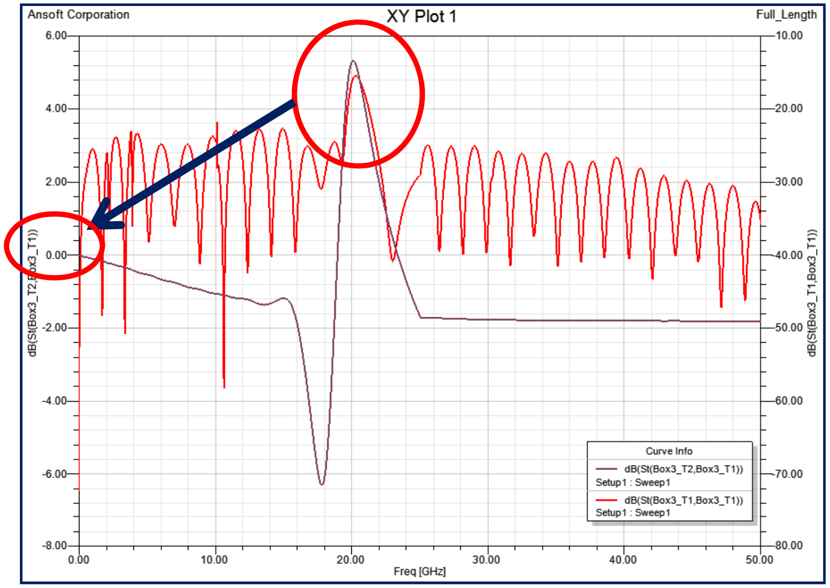
0 (GHz)

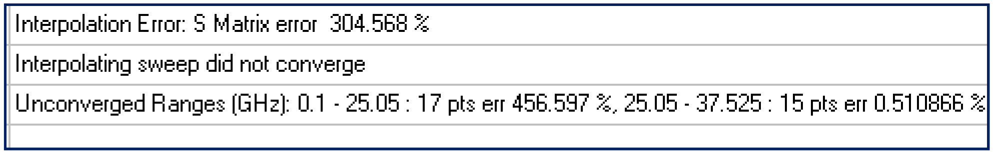
☐ All Freqs.

Passivity .0005

Freq		S:Box3_T1	S:Box3_T2
0 (GHz)	Box3_T1	(0.00024407, 0)	(0.9984, 0)
	Box3_T2	(0.99838, 0)	(0.00045732, 0)

One or more frequencies exist at which the S Matrix is not passive.
The worst frequency violation is at 20.06 GHz, with passivity 0.924





```
Interpolation Error: S Matrix error  304.568 %
Interpolating sweep did not converge
Unconverged Ranges (GHz): 0.1 - 25.05 : 17 pts err 456.597 %, 25.05 - 37.525 : 15 pts err 0.510866 %
```

Causality

- Another issue when dealing with transferring frequency domain data to the time domain is causality
- According to Wikipedia "a causal system is a system with output and internal states that depends only on the current and previous input values."
- Basically cause precedes effect

Causality

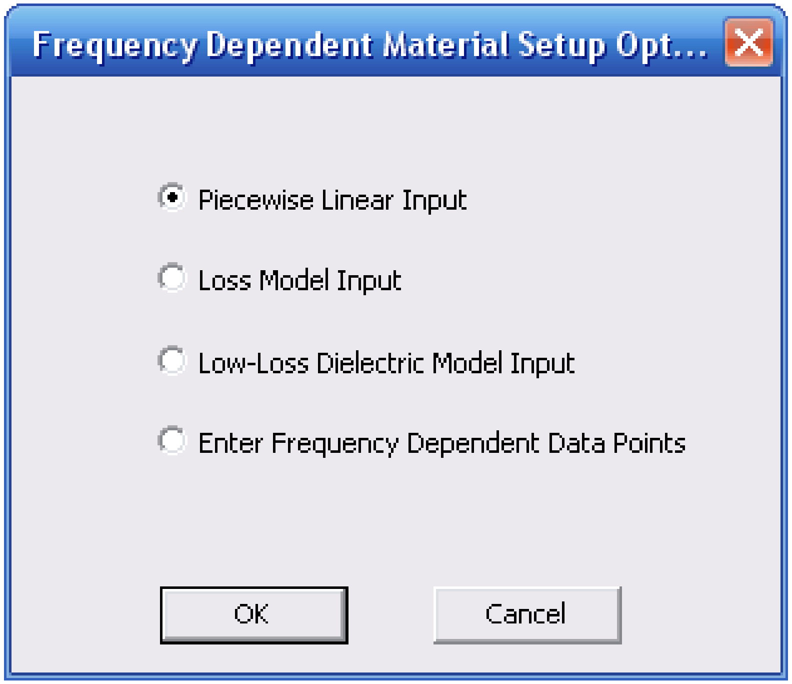
- Non-causal results from HFSS are manifested in the time domain as signal detected at the output of a transmission **before** the delay of the line
- If you have a transmission line with a time delay of 10 ns, but the time domain simulation shows output voltage (even small values) at a time prior to 10 ns, then the frequency domain results are non-causal

Causes of Non-causality

- Principle reason for non-causal data is the violation of the Kramers-Kronig relationship
- Basically describes the relationship between the real and imaginary parts of the permittivity of the model
- At least the real, imaginary, or both components of the material properties must be frequency dependent in order to satisfy the Kramers-Kronig relationship

Solution to Guarantee Causality

- Fortunately, HFSS provide an easy way to guarantee causality for a material
- Enter material properties as frequency dependent



Frequency Dependent Material Setup Opt...

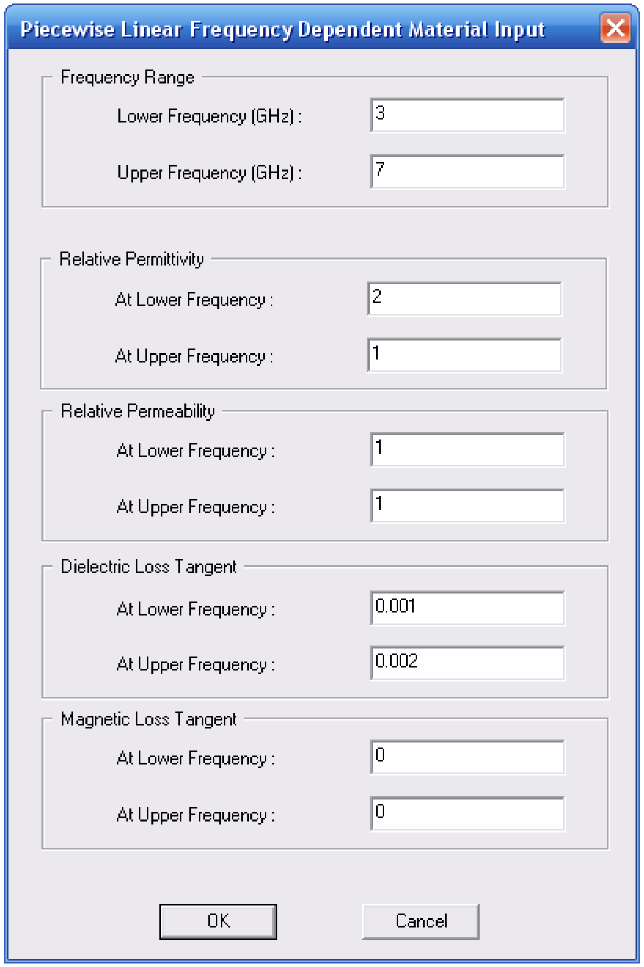
● Piecewise Linear Input

○ Loss Model Input

○ Low-Loss Dielectric Model Input

○ Enter Frequency Dependent Data Points

Frequency Dependent Materials
Piecewise Linear Input



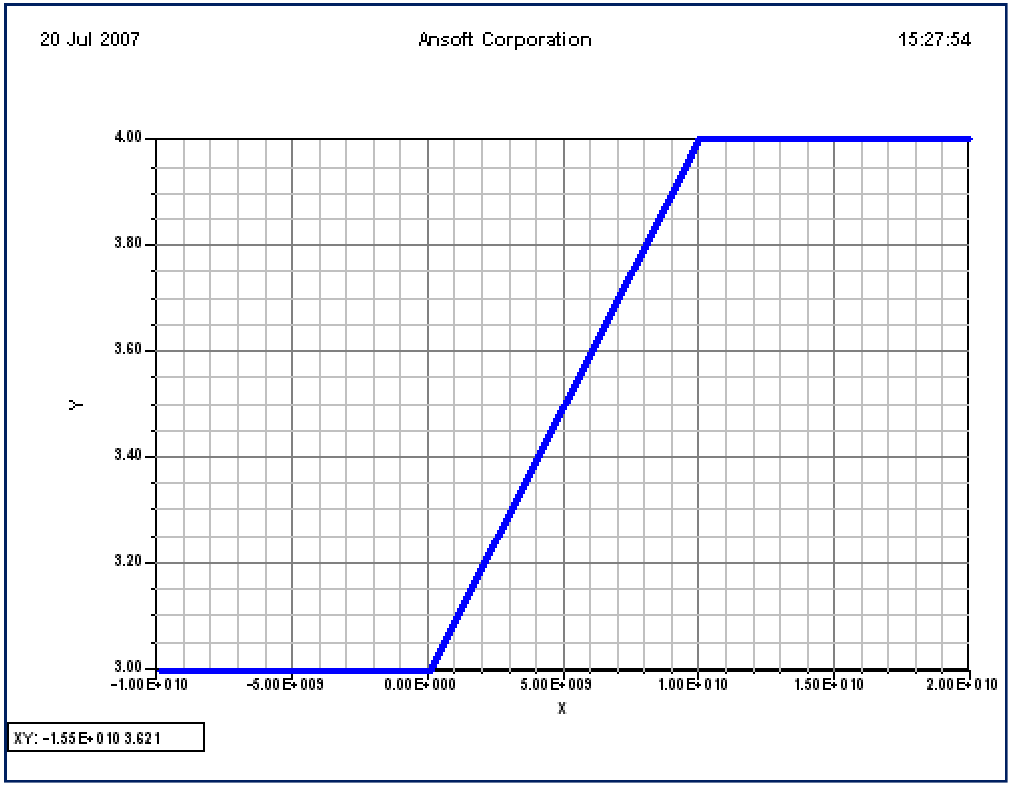
Frequency Range
Lower Frequency (GHz) : 3
Upper Frequency (GHz) : 7

Relative Permittivity
At Lower Frequency : 2
At Upper Frequency : 1

Relative Permeability
At Lower Frequency : 1
At Upper Frequency : 1

Dielectric Loss Tangent
At Lower Frequency : 0.001
At Upper Frequency : 0.002

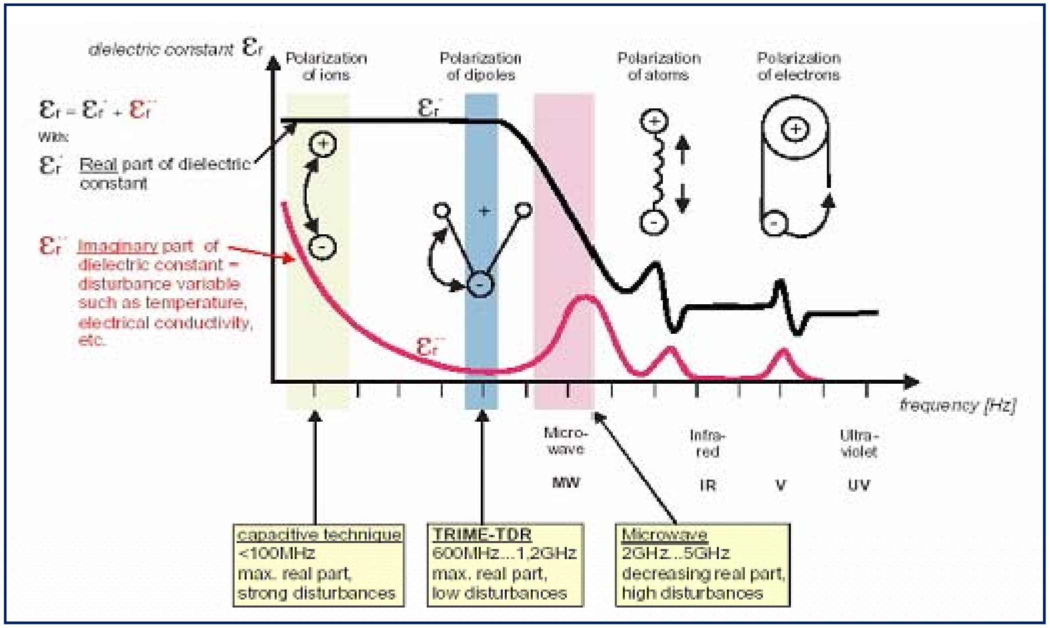
Magnetic Loss Tangent
At Lower Frequency : 0
At Upper Frequency : 0

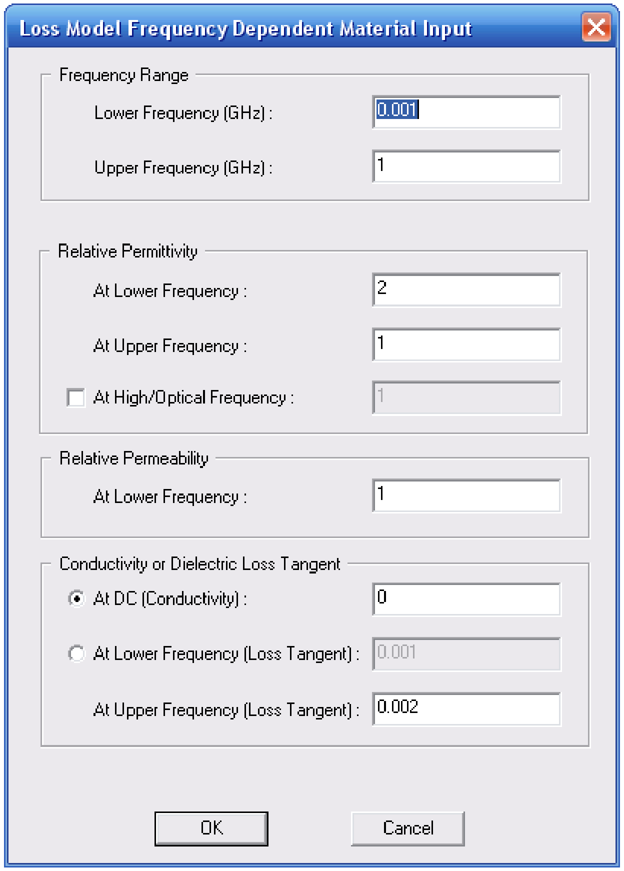


Frequency Dependent Loss Model Input

- Adheres to Debye model of materials

$$\varepsilon_{rcomplex} = \varepsilon_{roptical} + \frac{(\varepsilon_{rstatic} - \varepsilon_{roptical})}{1 + j\omega\tau}$$





Loss Model Frequency Dependent Material Input

Frequency Range

Lower Frequency (GHz) : 0.001

Upper Frequency (GHz) : 1

Relative Permittivity

At Lower Frequency : 2

At Upper Frequency : 1

☐ At High/Optical Frequency : 1

Relative Permeability

At Lower Frequency : 1

Conductivity or Dielectric Loss Tangent

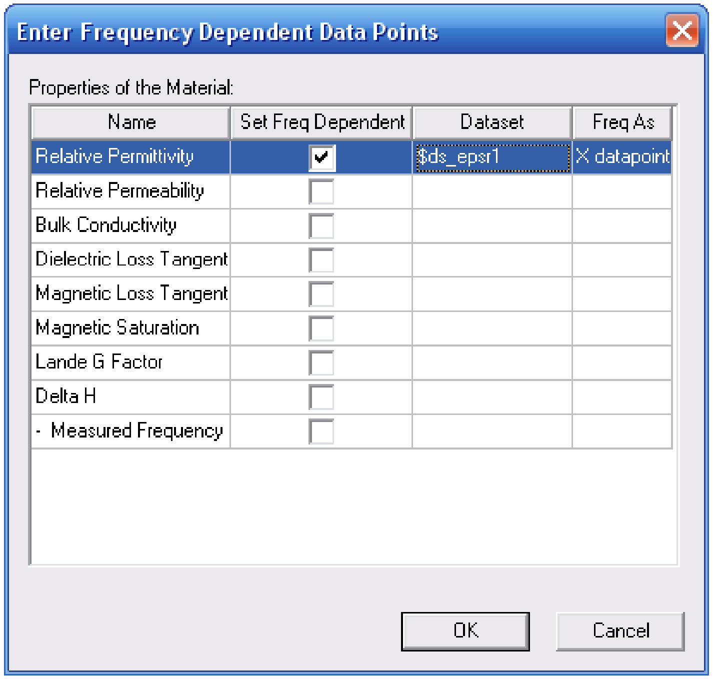
● At DC (Conductivity) : 0

○ At Lower Frequency (Loss Tangent) : 0.001

At Upper Frequency (Loss Tangent) : 0.002

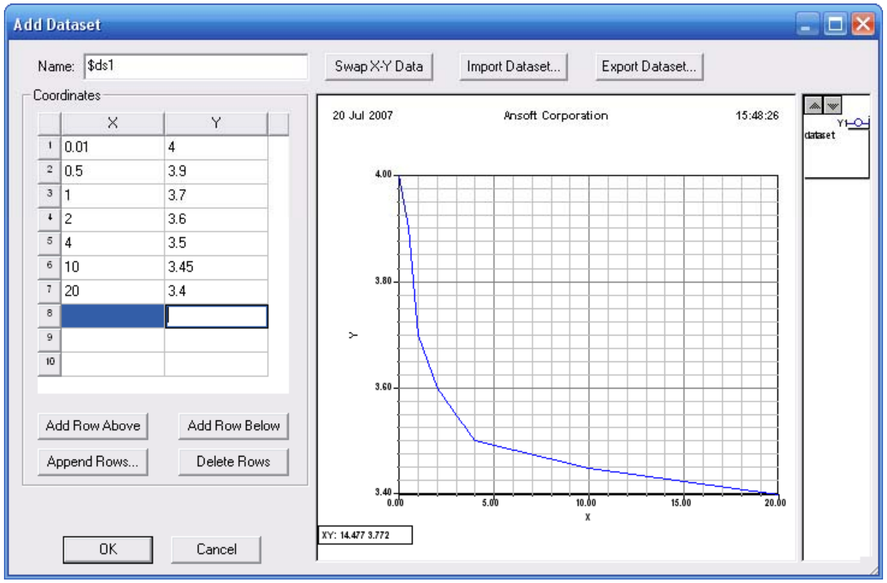
Frequency Dependent Data Points

- Data entered or imported as custom data points



Properties of the Material:

Name	Set Freq Dependent	Dataset	Freq As
Relative Permittivity	☑	$ds_epsr1	X datapoint
Relative Permeability	☐		
Bulk Conductivity	☐		
Dielectric Loss Tangent	☐		
Magnetic Loss Tangent	☐		
Magnetic Saturation	☐		
Lande G Factor	☐		
Delta H	☐		
- Measured Frequency	☐		



Name: $ds1

Coordinates

	X	Y
1	0.01	4
2	0.5	3.9
3	1	3.7
4	2	3.6
5	4	3.5
6	10	3.45
7	20	3.4
8		
9		
10		

XY: 14.477 3.772

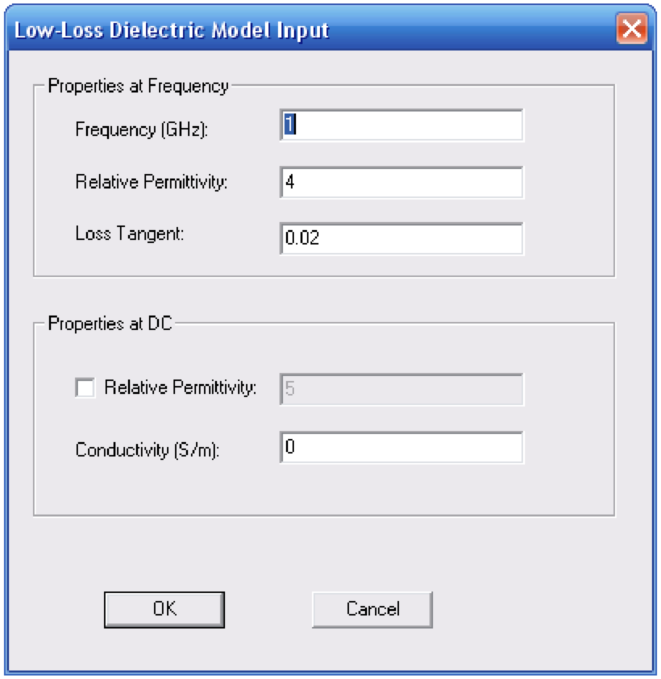
Frequency Dependent Low Loss Model Input

- Model follows Djordjevic-Sarkar equations

Wideband Frequency-Domain Characterization of FR-4 and Time-Domain Causality

Antonije R. Djordjević, Radivoje M. Biljić,
Vladana D. Likar-Smiljanić, and Tapan K. Sarkar

$$\varepsilon_r(\omega) = \varepsilon'_\infty + \frac{\Delta\varepsilon'}{m_2 - m_1}\,\frac{\ln\dfrac{\omega_2 + j\omega}{\omega_1 + j\omega}}{\ln 10} - j\frac{\sigma}{\omega\varepsilon_0}.$$



Properties at Frequency

Frequency (GHz): 1

Relative Permittivity: 4

Loss Tangent: 0.02

Properties at DC

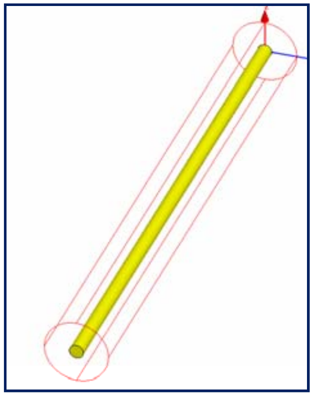
☐ Relative Permittivity: 5

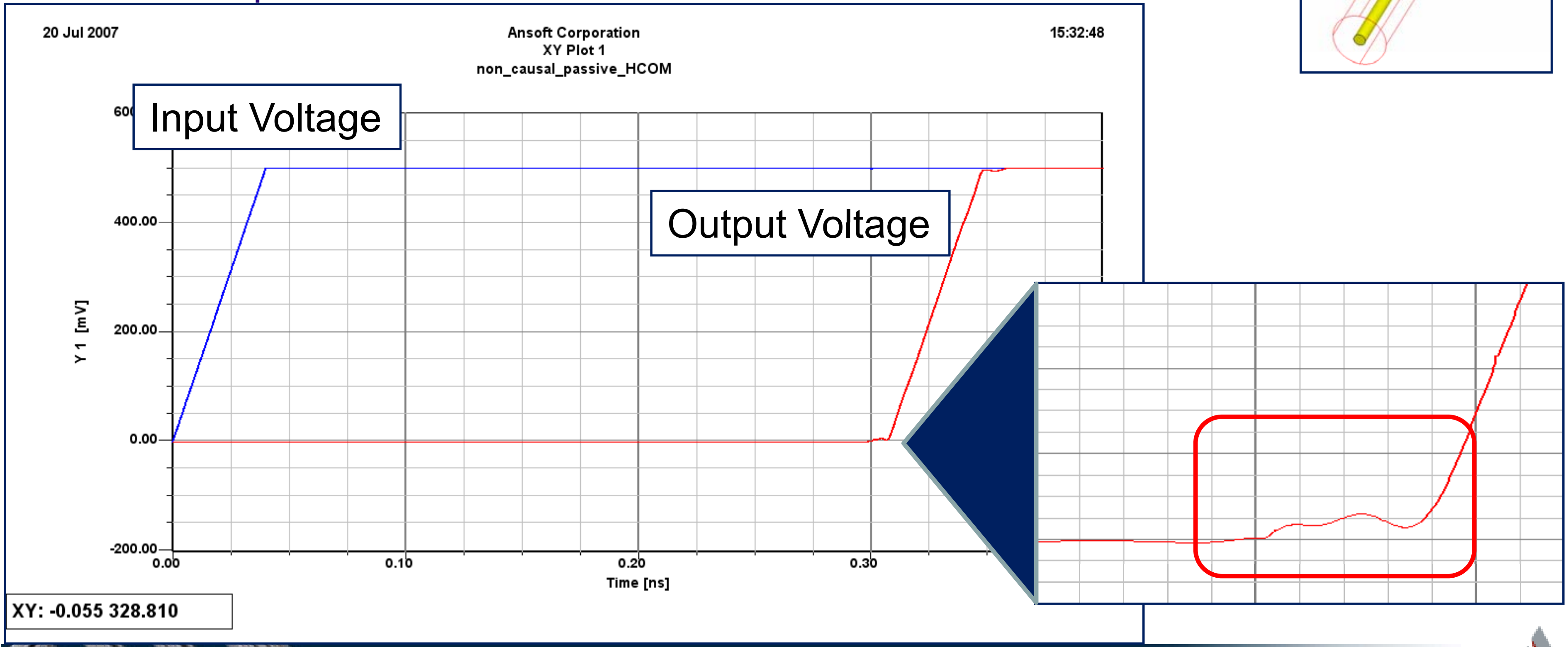
Conductivity (S/m): 0

IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY, VOL. 43, NO. 4, NOVEMBER 2001

Causality - Example

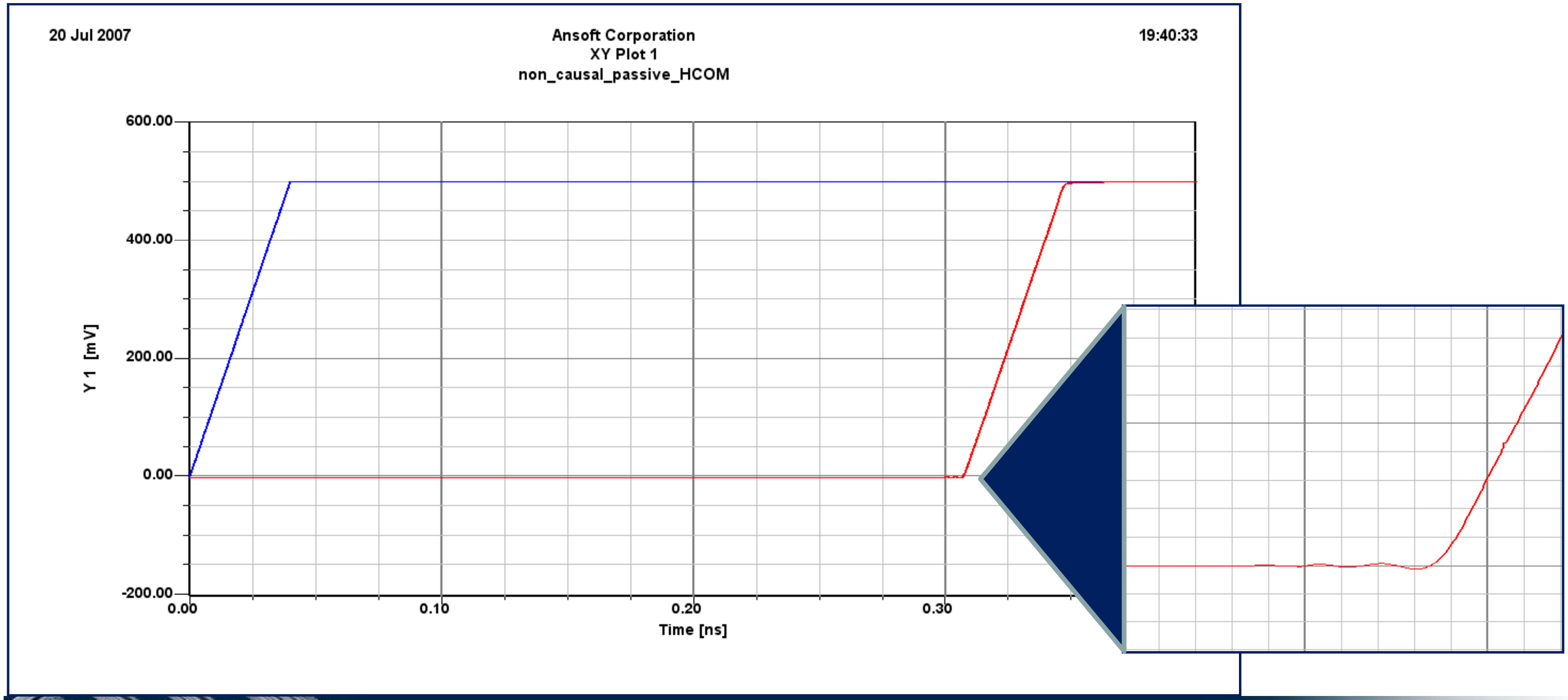
- 2” Coaxial transmission line
    - $\varepsilon_r = 3.3$





Causality - Example

- 2” Coaxial Transmission line using D-S model for frequency dependent materials

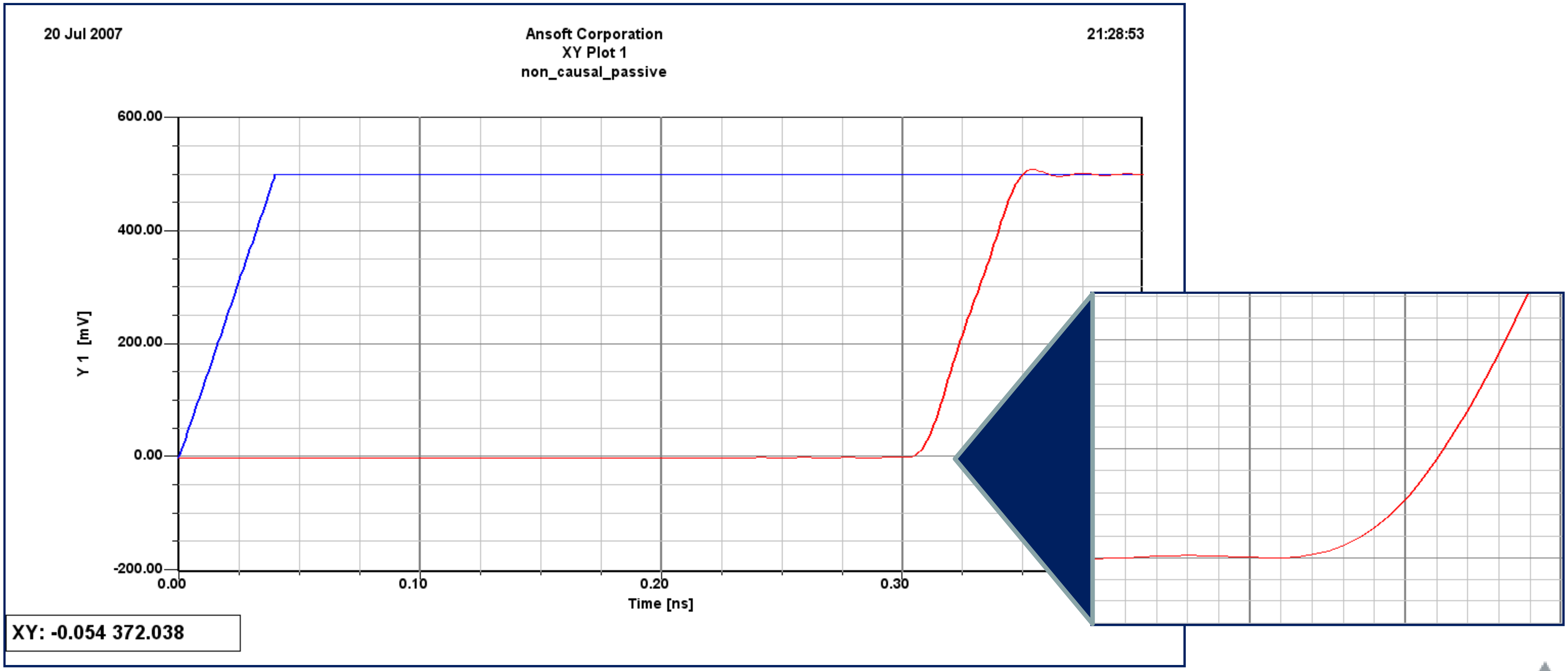


Causality - Example

- Another way to fix causality is to use a time domain simulator which corrects for causality errors
- Nexxim does exactly this
- Nexxim uses a state-space method of creating a polynomial fit to the S-parameters
- This state-space fit is **inherently** causal

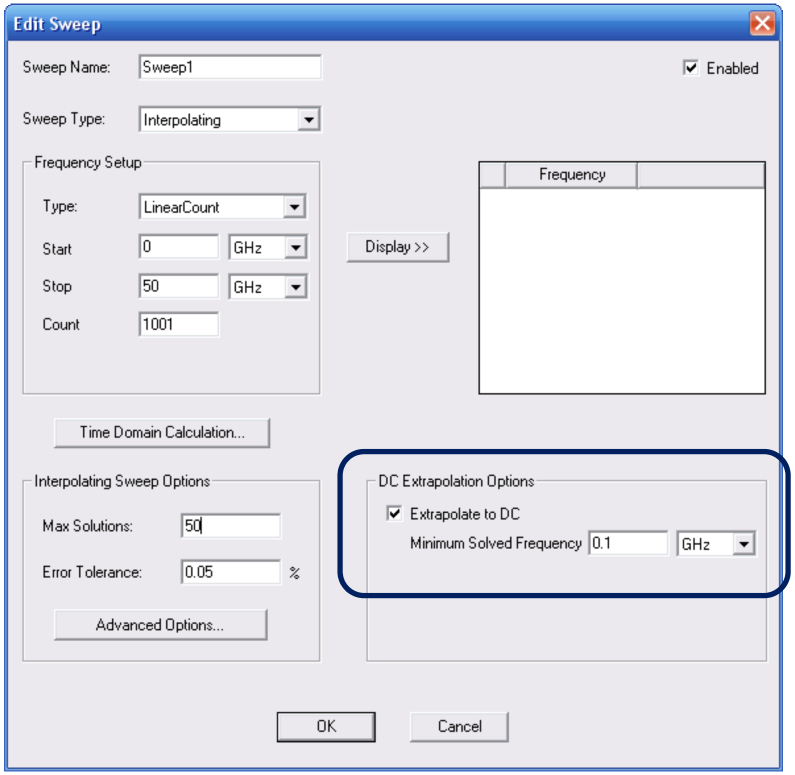
Causality in Nexxim

- 2” Coaxial transmission line with frequency **independent** material properties simulated in Nexxim without any modifications



DC Extrapolation

- All non-linear simulations, transient and harmonic balance, need a DC solution
- HFSS provides the DC extrapolation as the means to extract the DC point
- Do not set the Minimum Solved Frequency too low
  - 100 MHz is low enough
- For an accurate DC extrapolation, set the Error Tolerance to 0.05%



Edit Sweep

Sweep Name: Sweep1

☑ Enabled

Sweep Type: Interpolating

Frequency Setup

Type: LinearCount

Start: 0 GHz

Stop: 50 GHz

Count: 1001

Interpolating Sweep Options

Max Solutions: 50

Error Tolerance: 0.05 %

DC Extrapolation Options

☑ Extrapolate to DC

Minimum Solved Frequency: 0.1 GHz

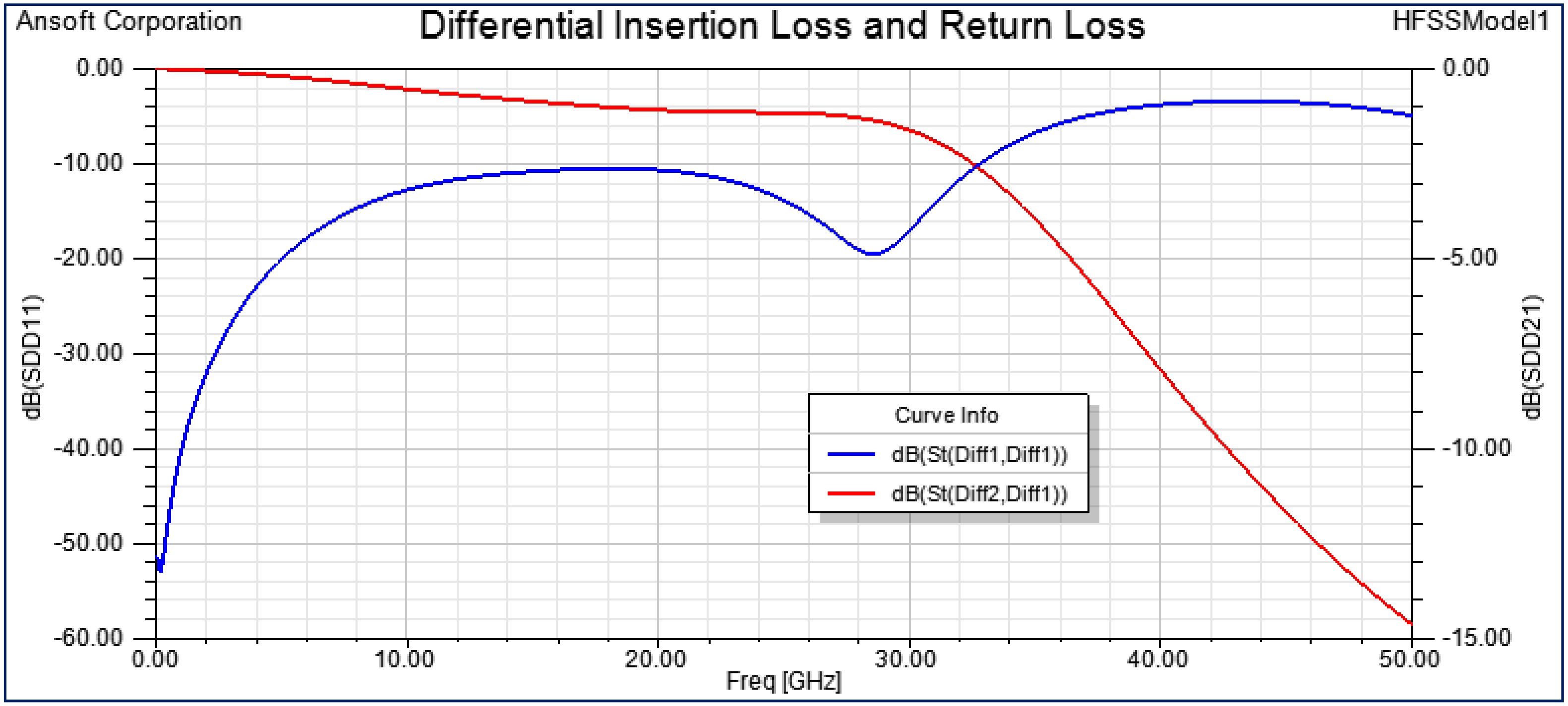
Summary for Time Domain

- F_{max} related to minimum sampling time and NOT clock frequency
- F_{max} and Adaptive frequency don’t have to be the same
  - Use the knee frequency for the Adaptive solution
- Add extra points to interpolating sweep to maintain passivity
  - To completely avoid passivity errors, use a discrete sweep instead.
- To mitigate causality problems, use a frequency dependent material model and/or Nexxim to perform the time domain simulations

INTERPRETING SIMULATION RESULTS

Frequency Domain Results

- For the simple differential via, the S-parameters are shown below

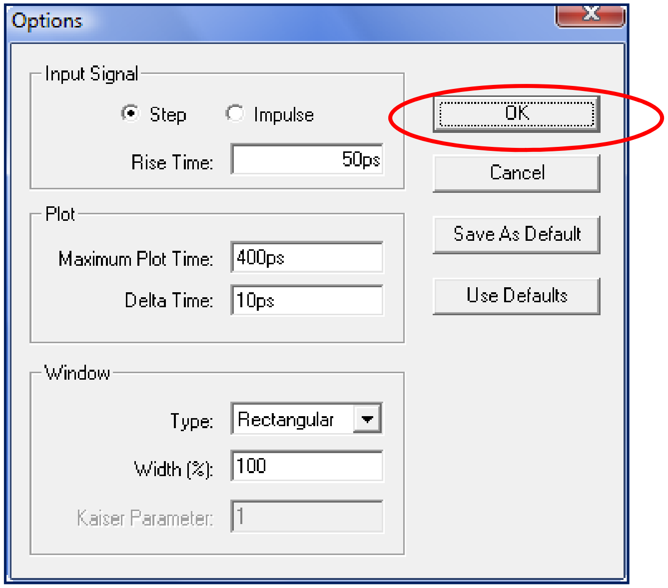


Time Domain Reflectometry

- TDR testing consists of injecting a pulsed voltage on one port, with all others terminated, and observing the reflected voltage.
- TDR is basically the time domain representation of the reflection coefficient, or S_{11}
- For the differential via model, we show the TDR plot on the next page

Time Domain Reflectometry

- To create a TDR plot in HFSS
  - HFSS > Results > Create Terminal Solution Data Report > Rectangular Plot



Options

Input Signal

● Step ○ Impulse

Rise Time: 50ps

Plot

Maximum Plot Time: 400ps

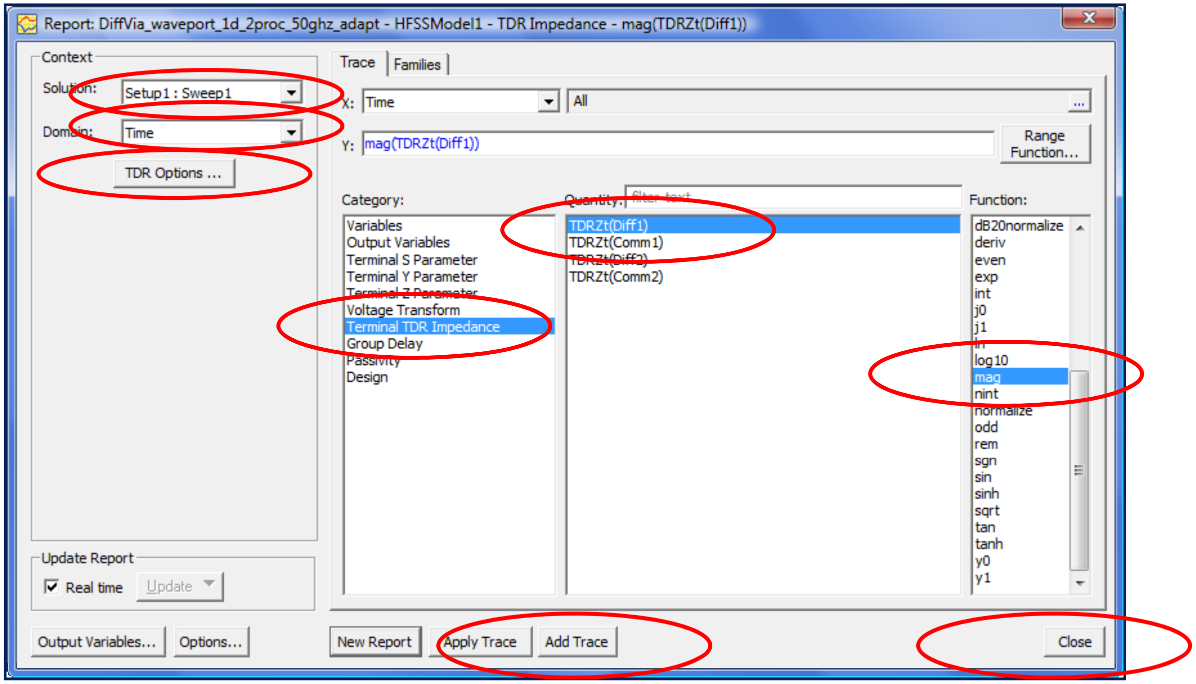
Delta Time: 10ps

Window

Type: Rectangular

Width (%): 100

Kaiser Parameter: 1



Report: DiffVia_waveport_1d_2proc_50ghz_adapt - HFSSModel1 - TDR Impedance - mag(TDRZt(Diff1))

Context

Solution: Setup1 : Sweep1

Domain: Time

X: Time All

Y: mag(TDRZt(Diff1))

Category: Terminal TDR Impedance

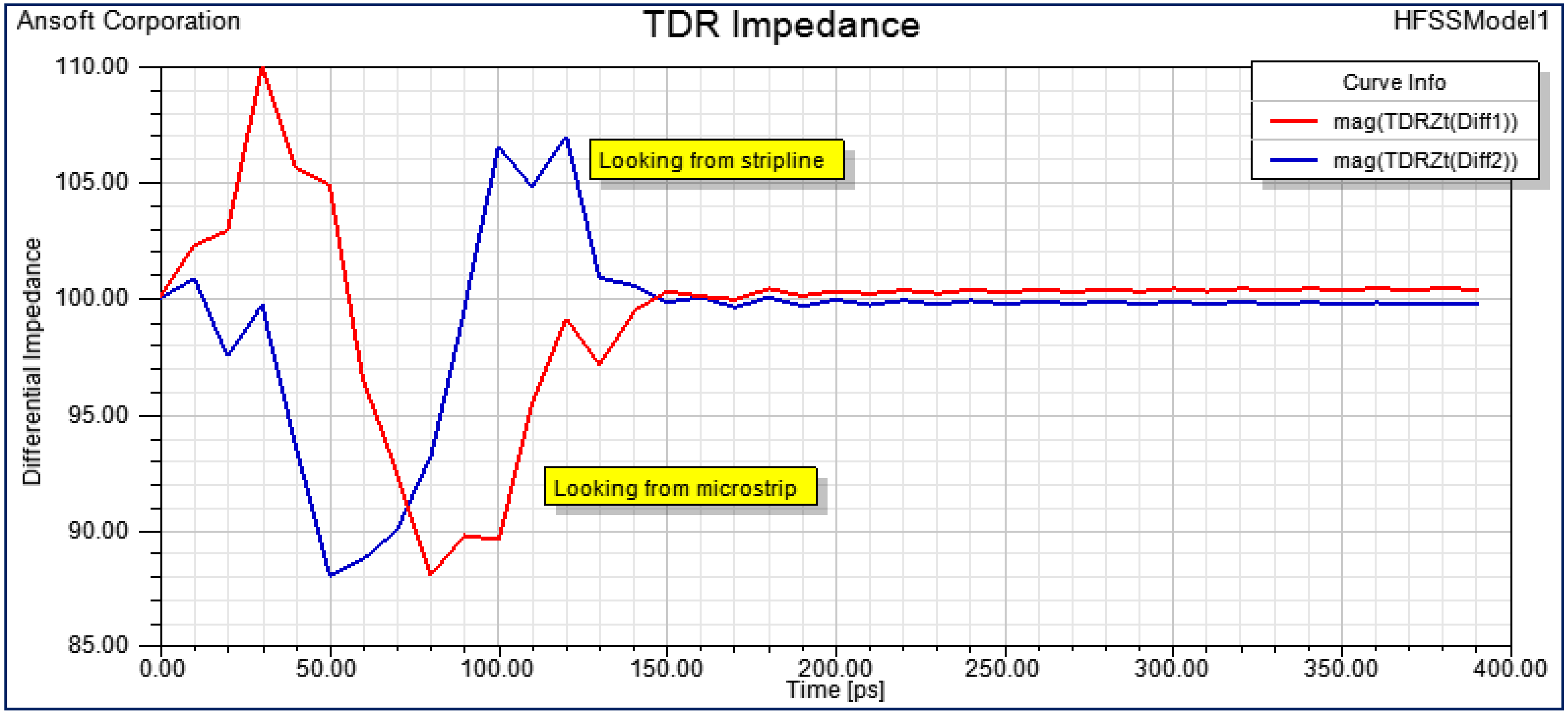
Quantity: TDRZt(Diff1)

Function: mag

Update Report

☑ Real time

Time Domain Reflectometry

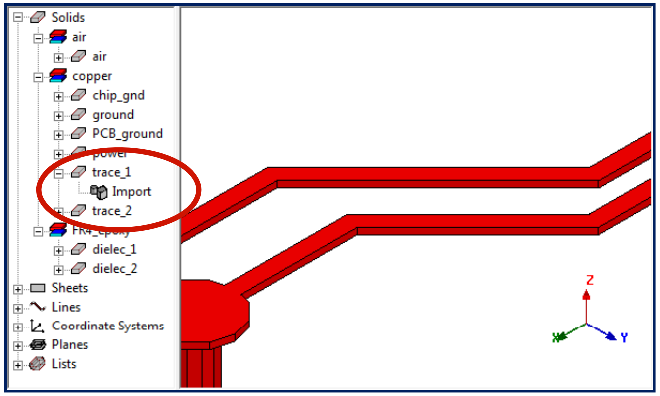


- Positive-going spikes indicate inductive changes to the impedance
- Negative-going spikes indicate capacitive changes to the impedance
- For the trace looking from the microstrip, we first see the inductance of the trace, then the capacitance of the via transition
- For better time (spatial) resolution, we would need a smaller sampling time, and thus a higher stop frequency for our sweep

MODEL OPTIMIZATION

Geometry Manipulation

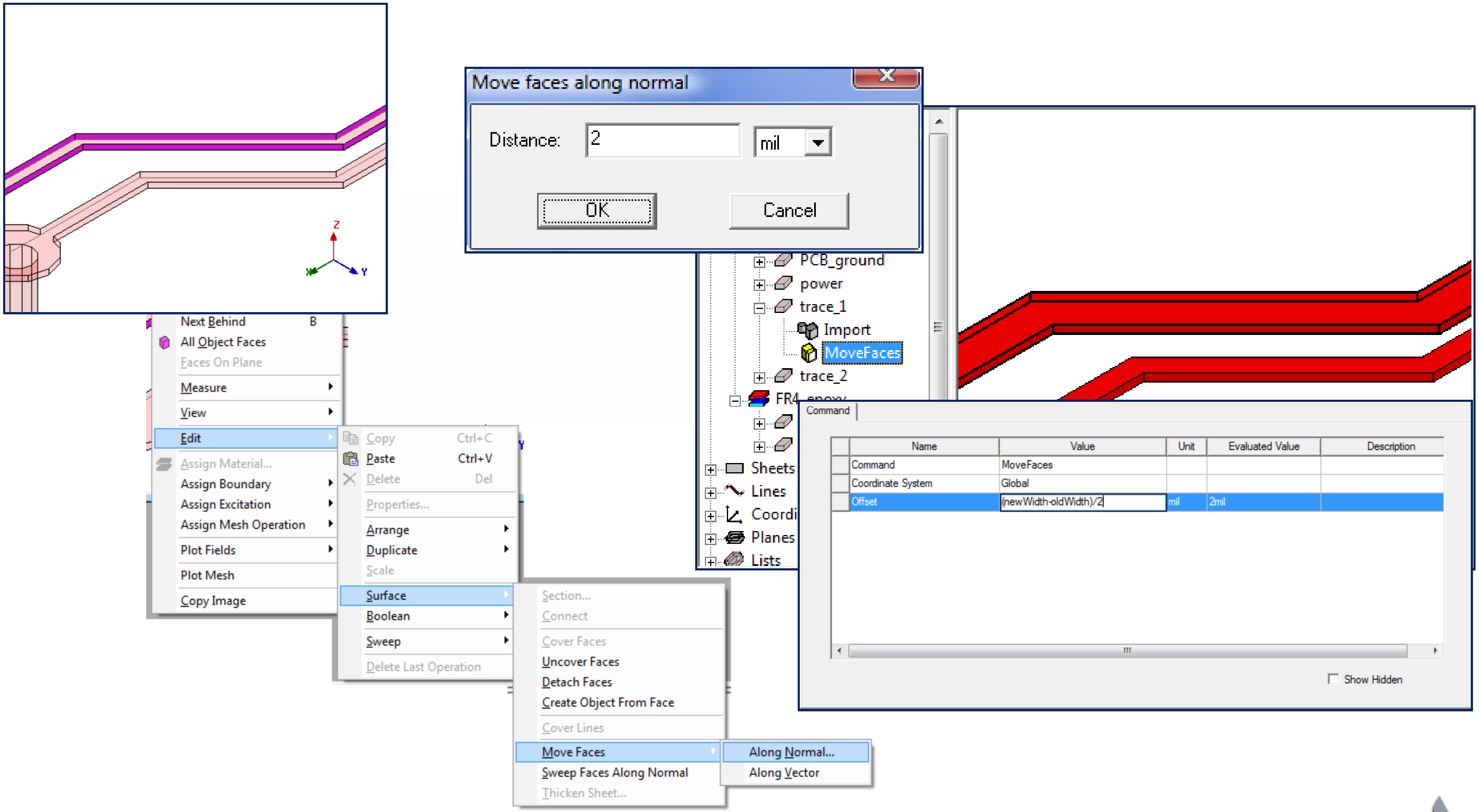
- Geometry imported with “Script” option or drawn in HFSS, is relatively easy to parameterize
- Imported geometry with no history presents a challenge to parameterize, BUT it can be done



Geometry Manipulation

- Use:
  - Modeler / Surface / Move Faces / Along Normal
    - Grow/shrink widths/openings
  - Edit / Arrange / Move (objects)
    - Translation of objects
  - Modeler / Surface / Move Faces / Along Vector
    - Translation of faces

Geometry Manipulation



Move faces along normal

Distance: 2 mil

Name	Value	Unit	Evaluated Value	Description
Command	MoveFaces			
Coordinate System	Global			
Offset	(newWidth-oldWidth)/2	mil	2mil	

Optimization Overview

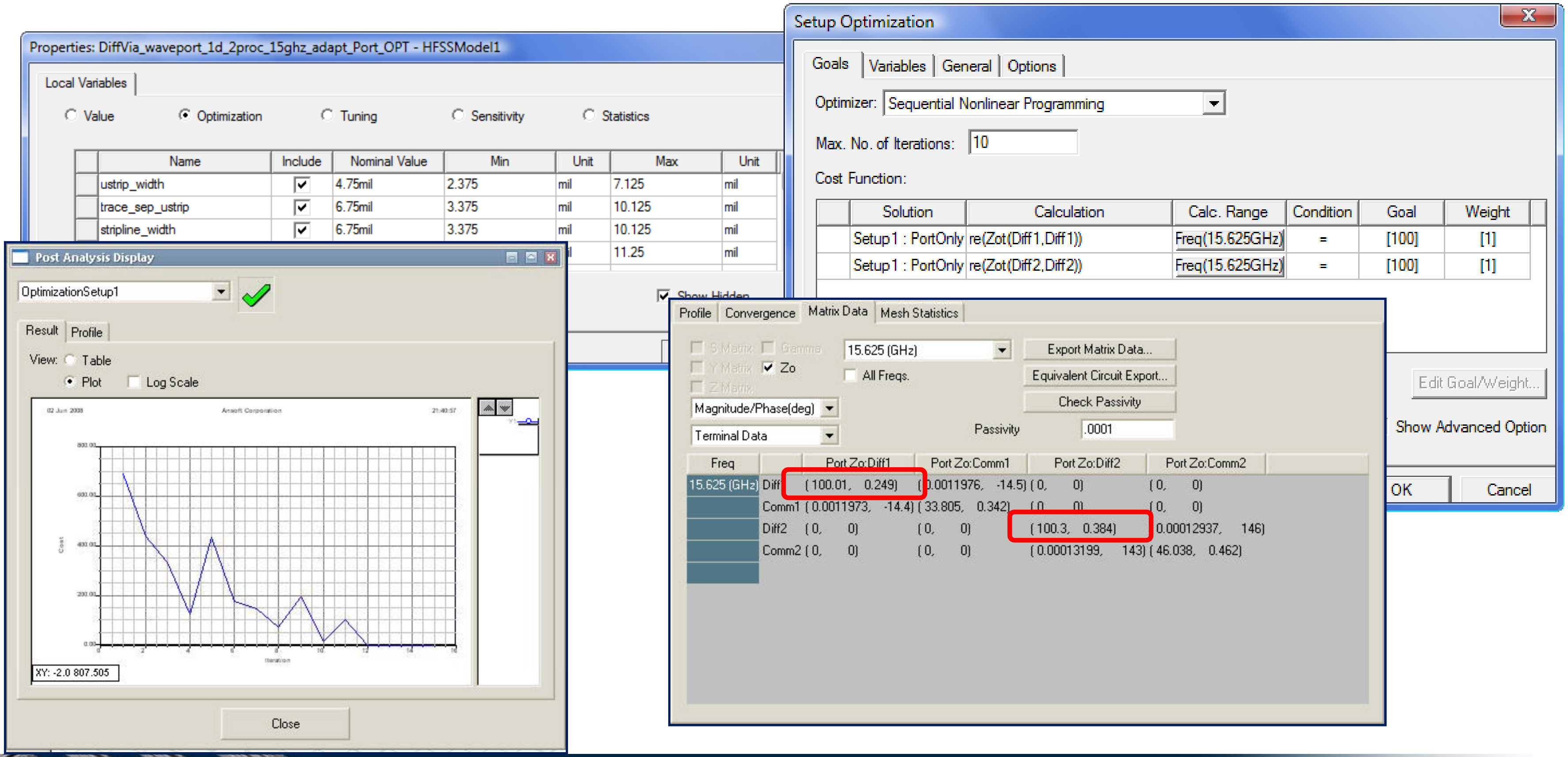
- Ansoft Optimetrics has 5 optimization algorithms
  - Quasi-Newton – Useful if close to optimum
  - Pattern Search – Produces better results than Q-N if not close to optimum
  - Sequential Non-Linear Programming – Works faster than Q-N, and produces better results if farther away from optimum
  - Sequential Non-Linear Mixed Integer Programming – Similar to SNLP, but allows integer values
  - Genetic Algorithm – Can explore vast parameter space by mimicking natural selection, but requires many iterations

Optimization of SI Problems

- Unless using the Genetic Algorithm for design-space exploration, the SNLP algorithm is most efficient
- Generally, you can only optimize 3-5 variables at a time.
- What optimization problems are most amenable to 3D electromagnetic simulations?
    - Use HFSS as a transmission line calculator to optimize port impedance
    - Optimize via transition for match and minimum through loss

Optimization of Port Impedance

- Set HFSS to run a Ports Only solution, and then optimize trace widths and separation to obtain 100 Ohm port impedance



Properties: DiffVia_waveport_1d_2proc_15ghz_adapt_Port_OPT - HFSSModel1

Local Variables

○ Value ● Optimization ○ Tuning ○ Sensitivity ○ Statistics

Name	Include	Nominal Value	Min	Unit	Max	Unit
ustrip_width	☑	4.75mil	2.375	mil	7.125	mil
trace_sep_ustrip	☑	6.75mil	3.375	mil	10.125	mil
stripline_width	☑	6.75mil	3.375	mil	10.125	mil
					11.25	mil

☑ Show Hidden

Setup Optimization

Goals | Variables | General | Options

Optimizer: Sequential Nonlinear Programming

Max. No. of Iterations: 10

Cost Function:

Solution	Calculation	Calc. Range	Condition	Goal	Weight
Setup1 : PortOnly	re(Zot(Diff1,Diff1))	Freq(15.625GHz)	=	[100]	[1]
Setup1 : PortOnly	re(Zot(Diff2,Diff2))	Freq(15.625GHz)	=	[100]	[1]

Post Analysis Display

OptimizationSetup1

Result | Profile

View: ○ Table
● Plot ☐ Log Scale

Profile | Convergence | Matrix Data | Mesh Statistics

☐ S Matrix ☐ Gamma
☐ Y Matrix ☑ Zo
☐ Z Matrix

15.625 (GHz)

☐ All Freqs.

Magnitude/Phase(deg)

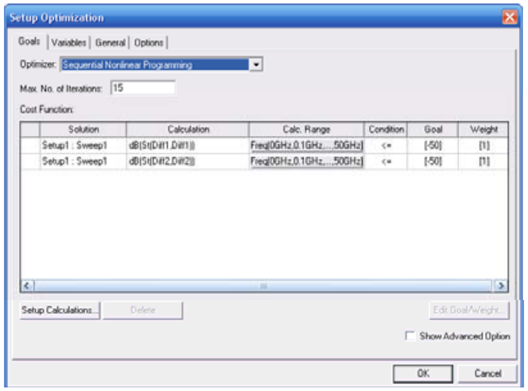
Terminal Data

Passivity .0001

Freq		Port Zo:Diff1	Port Zo:Comm1	Port Zo:Diff2	Port Zo:Comm2
15.625 (GHz)	Diff1	(100.01, 0.249)	(0.0011976, -14.5)	(0, 0)	(0, 0)
	Comm1	(0.0011973, -14.4)	(33.805, 0.342)	(0, 0)	(0, 0)
	Diff2	(0, 0)	(0, 0)	(100.3, 0.384)	0.00012937, 146)
	Comm2	(0, 0)	(0, 0)	(0.00013199, 143)	(46.038, 0.462)

Optimization of Via

- Set trace widths and separations as found in the previous optimization, and now use variable such as via separation and anti-pad opening to minimize insertion loss of via transition



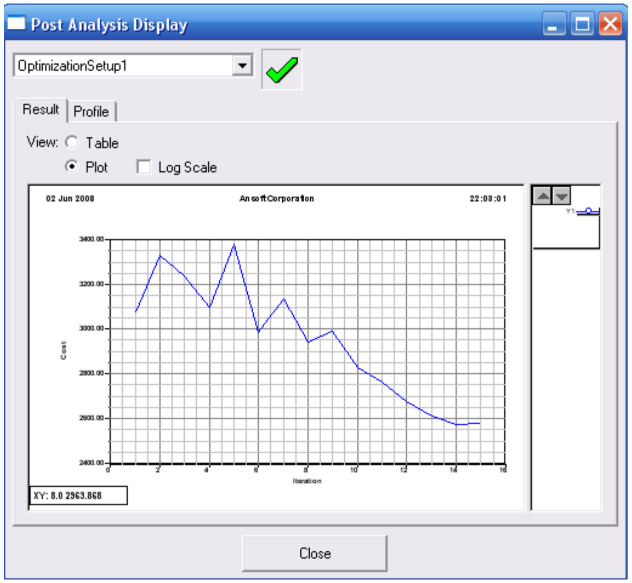
Optimizer: Sequential Nonlinear Programming

Max. No. of Iterations: 15

Cost Function:

Solution	Calculation	Calc. Range	Condition	Goal	Weight
Setup1 : Sweep1	dB(St(Diff1,Diff1))	Freq[0GHz,0.1GHz,...,50GHz]	<=	[-50]	[1]
Setup1 : Sweep1	dB(St(Diff2,Diff2))	Freq[0GHz,0.1GHz,...,50GHz]	<=	[-50]	[1]

☐ Show Advanced Option



OptimizationSetup1

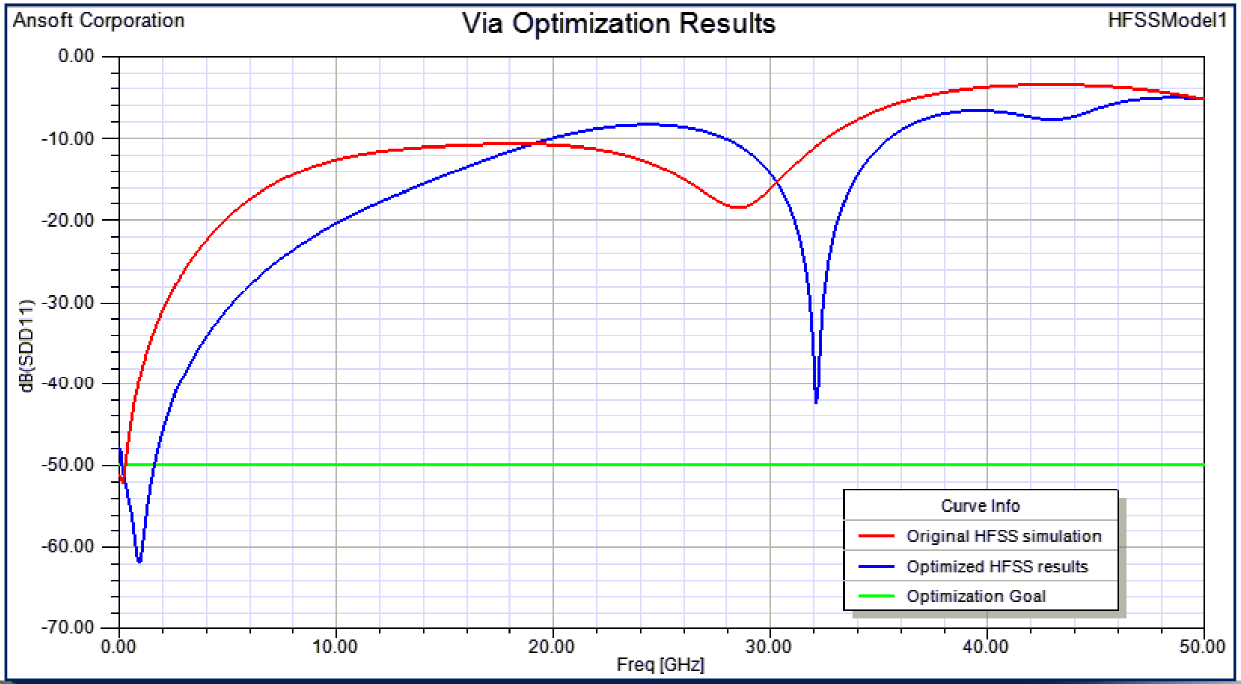
View: ○ Table

● Plot ☐ Log Scale

XY: 8.0 2963.868

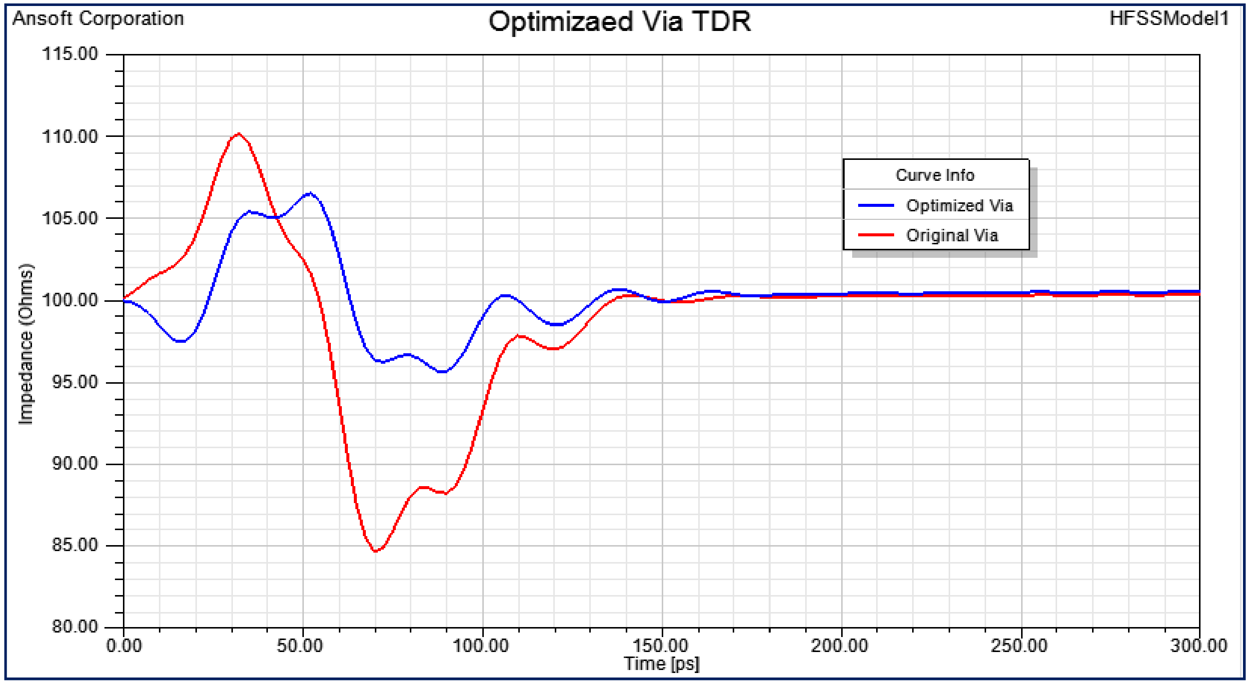
Optimization Results

- The optimized results do look better in certain bands, but worse in others.
- How does this affect the time domain results ?



Optimized Via - TDR

- We can see that the optimization did indeed flatten out our impedance profile



Conclusions

- With the proper settings in HFSS, we can be confident that the outputs will give reliable data for time domain simulations
- We can effectively use the parametric model to optimize many aspect of the 3D model