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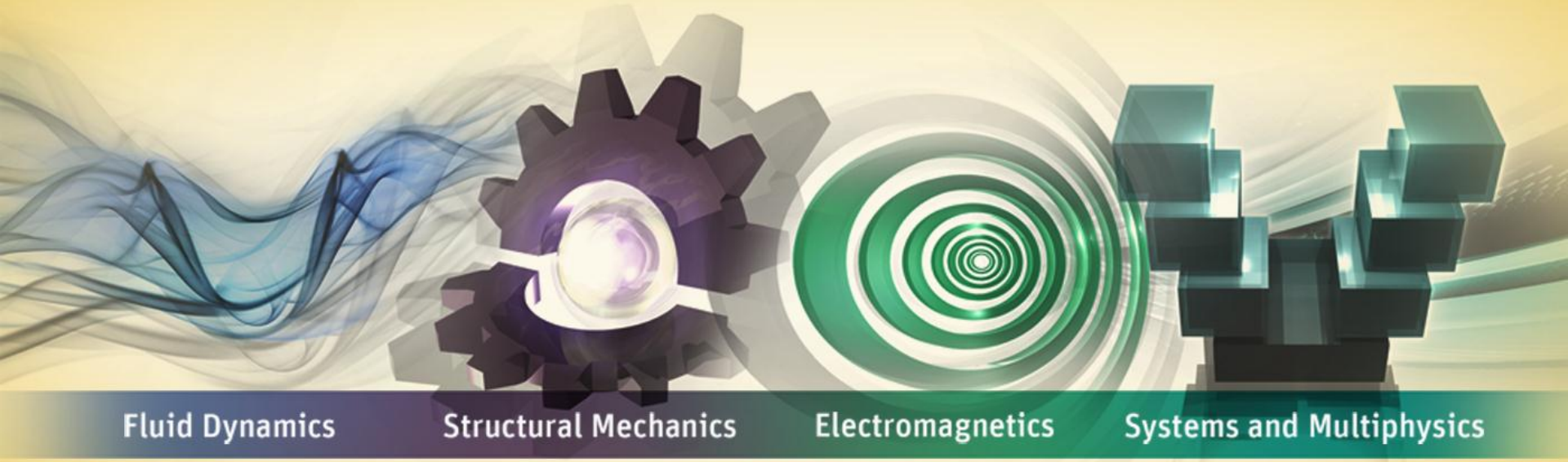
Best Practices for High-Speed Serial Link Simulation



Asian IBIS Summit

Taipei, Taiwan

November 17, 2014

侯明刚

minggang.hou@ansys.com

ANSYS China

Background

- High speed serial design becoming very common
- Increased reliance on s-parameter models in circuit simulation
- S-parameters can have subtle (and often not subtle) problems in simulation
- How can we best discover or avoid these issues before circuit simulation?

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Agenda

- Bandwidth
- Sampling Rate
- Model Concatenation
- Passivity
- Causality

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Data Bandwidth

"What is the appropriate bandwidth for a given model?"

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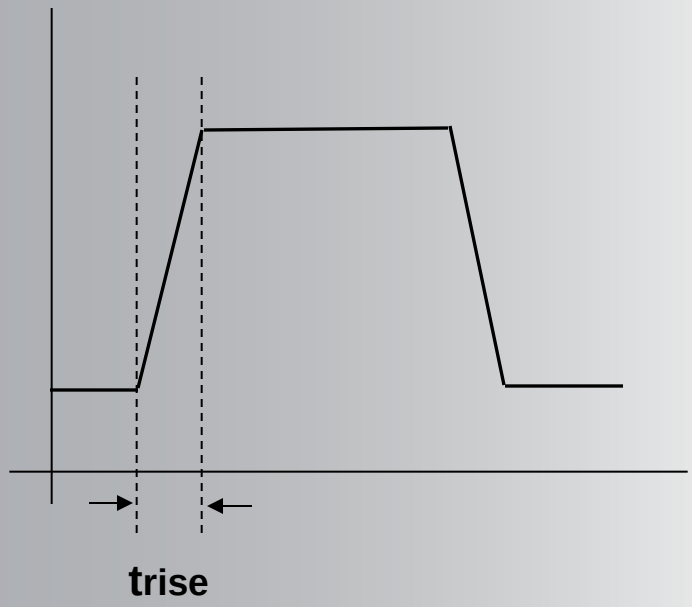
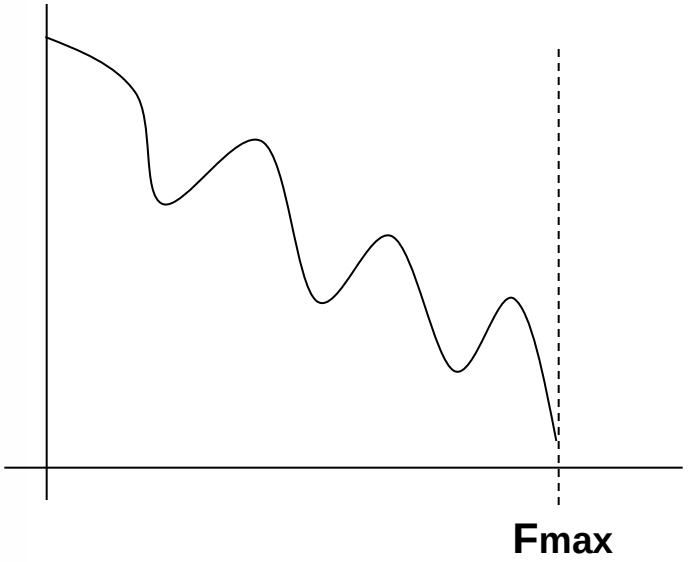
Data Bandwidth

- Always have a realistic DC point
- Maximum frequency dependent on application
- Rule of thumb
  - Fmax = .35/trise





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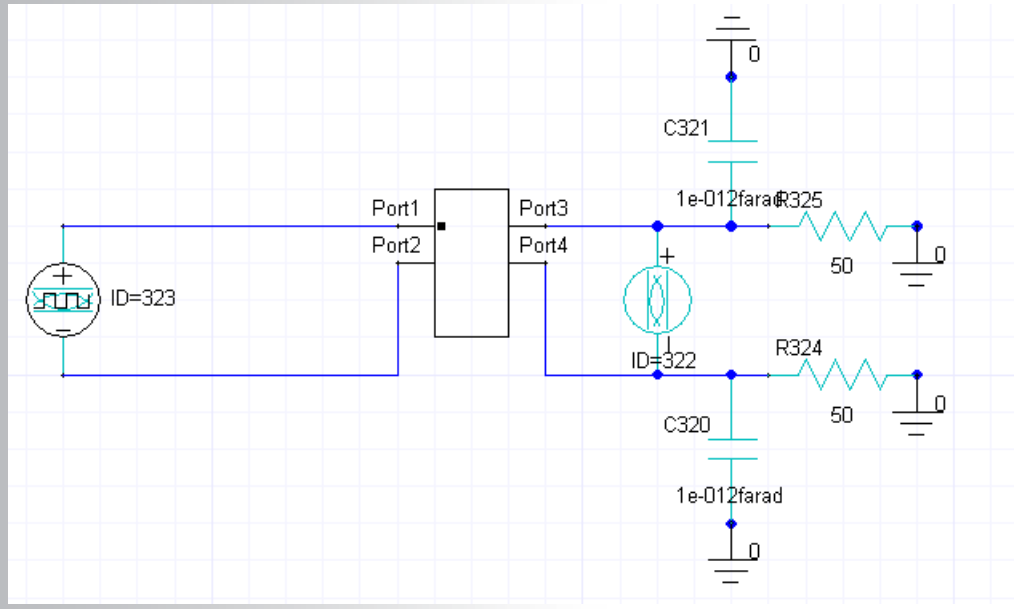
Max Frequency Study

- Set up test circuit
  - 10Gb/s data rate
  - 10ps rise/fall time
  - 750 mm stripline model
  - Sweep Fmax from 5 to 50GHz, 10MHz step



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Max Frequency Test

- QuickEye analysis
  - Convolution based fast transient
  - PRBS15 pattern
- VerifEye analysis
  - Statistical eye analysis
- Both take advantage of LTI assumption
  - Characterize linear channel with step response

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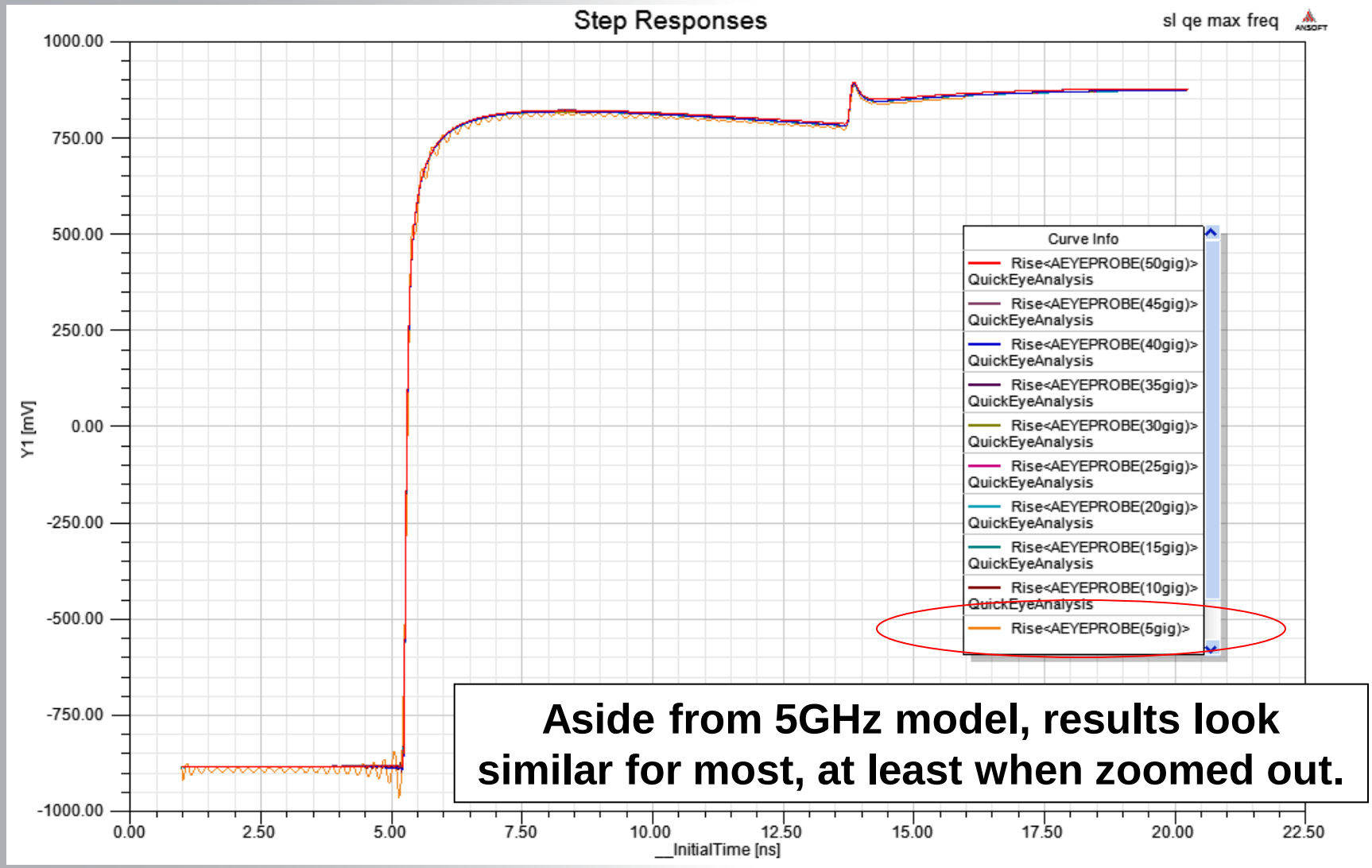
Max Frequency Sweep: Step Responses



Aside from 5GHz model, results look similar for most, at least when zoomed out.

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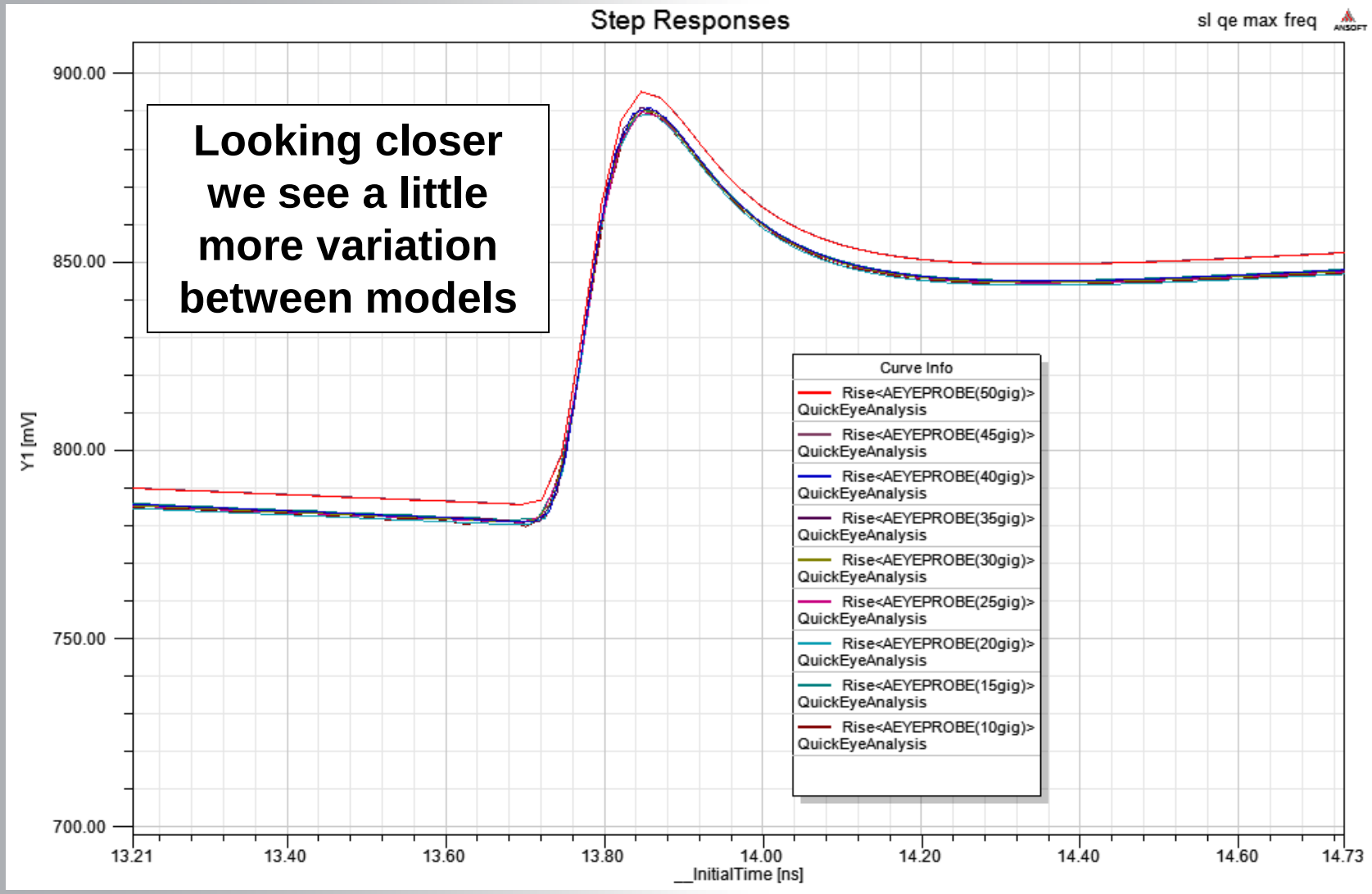
Max Frequency Sweep: Step Responses



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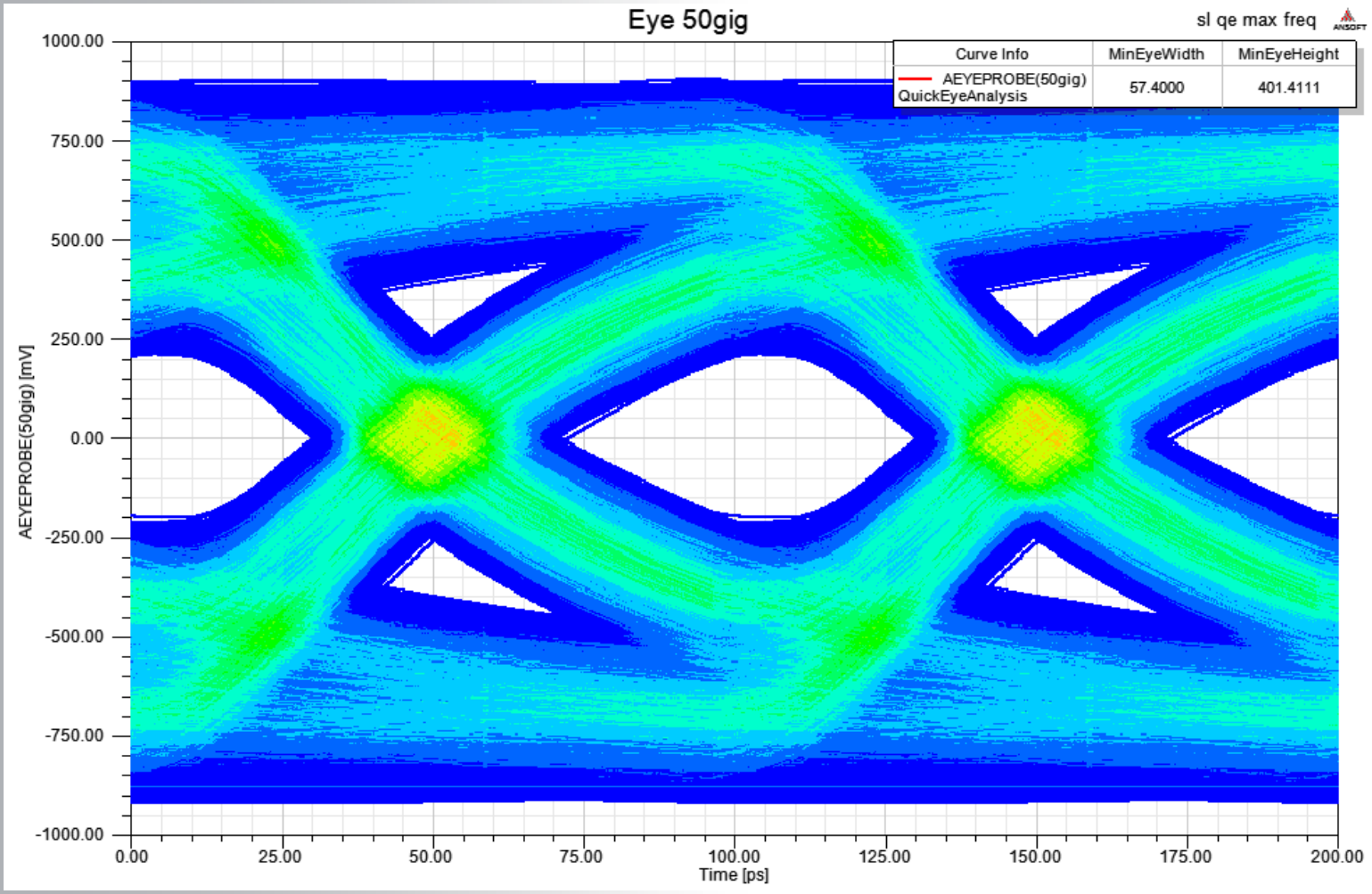
Max Frequency, QuickEye Results, 50GHz



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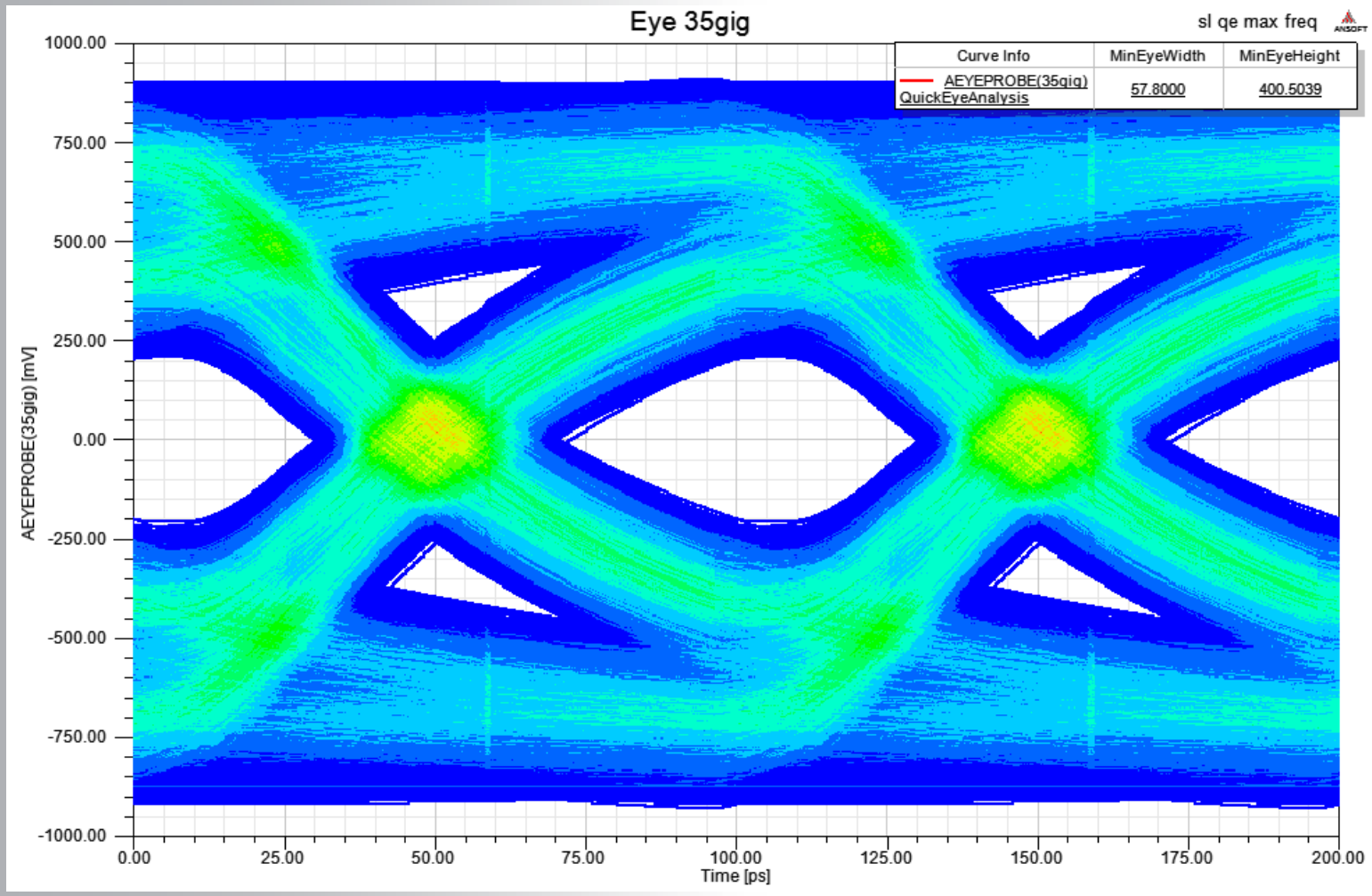
Max Frequency, QuickEye Results, 35GHz



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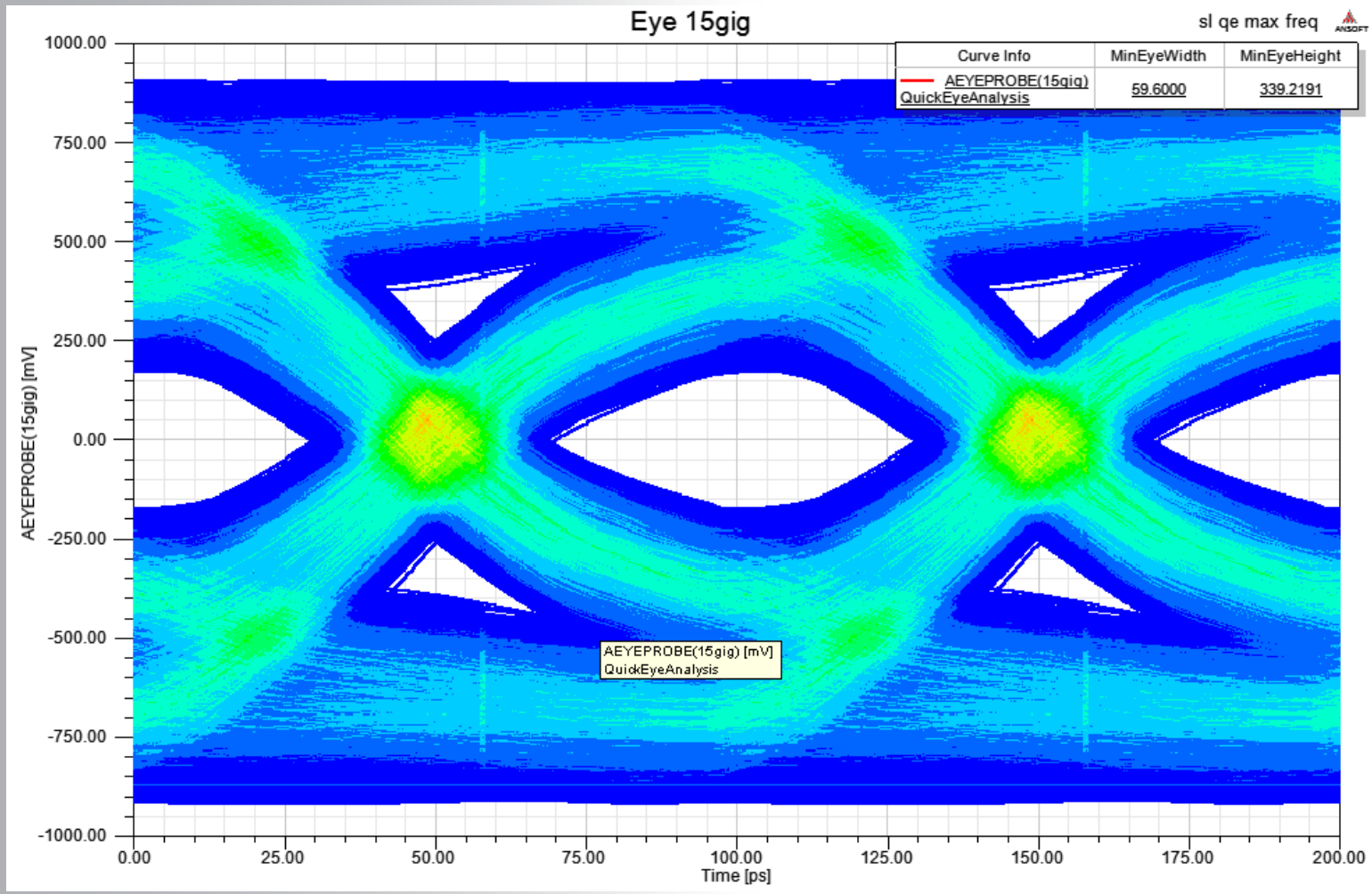
Max Frequency, QuickEye Results, 15GHz



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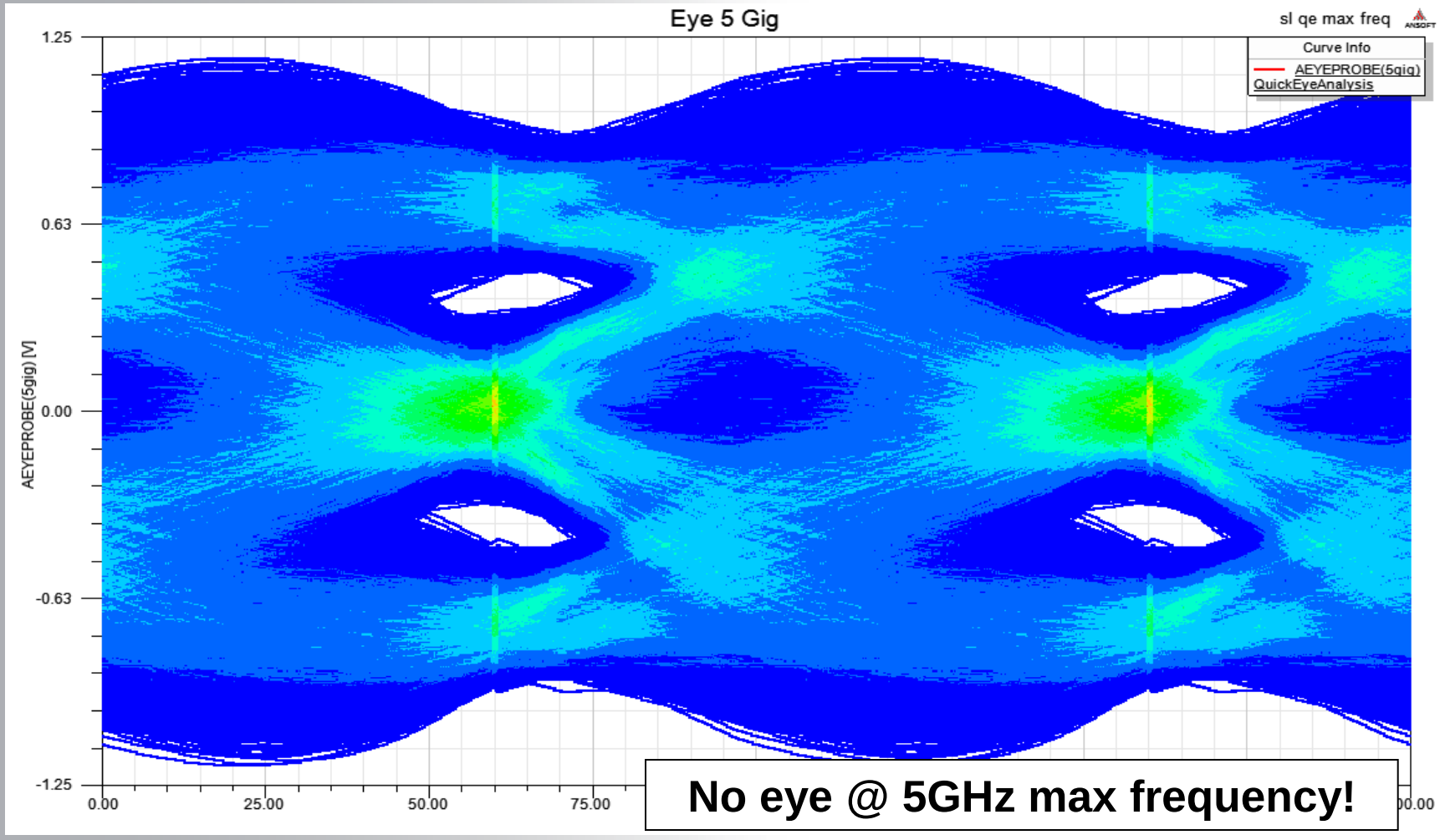
Max Frequency, QuickEye Results, 5GHz



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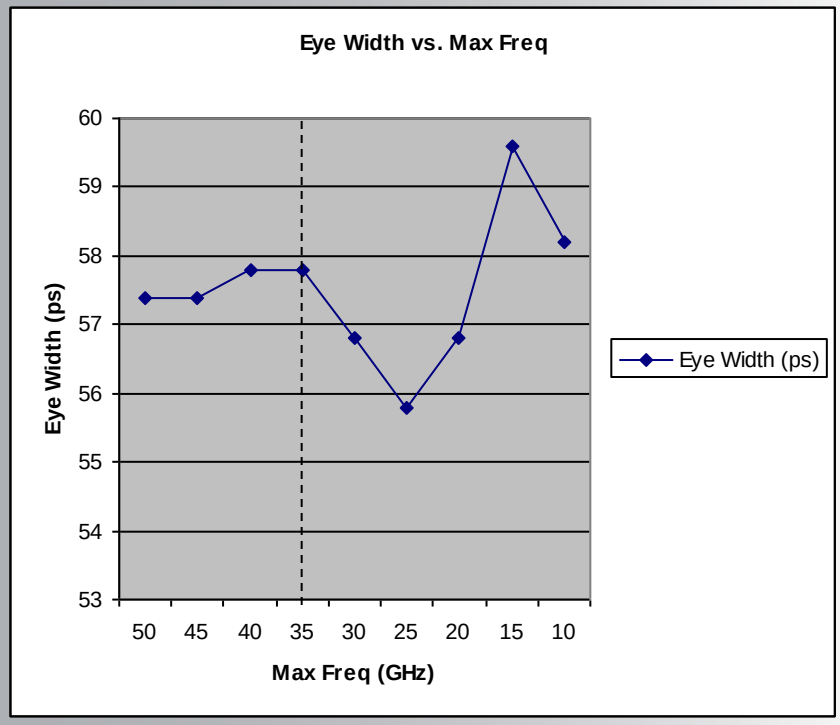
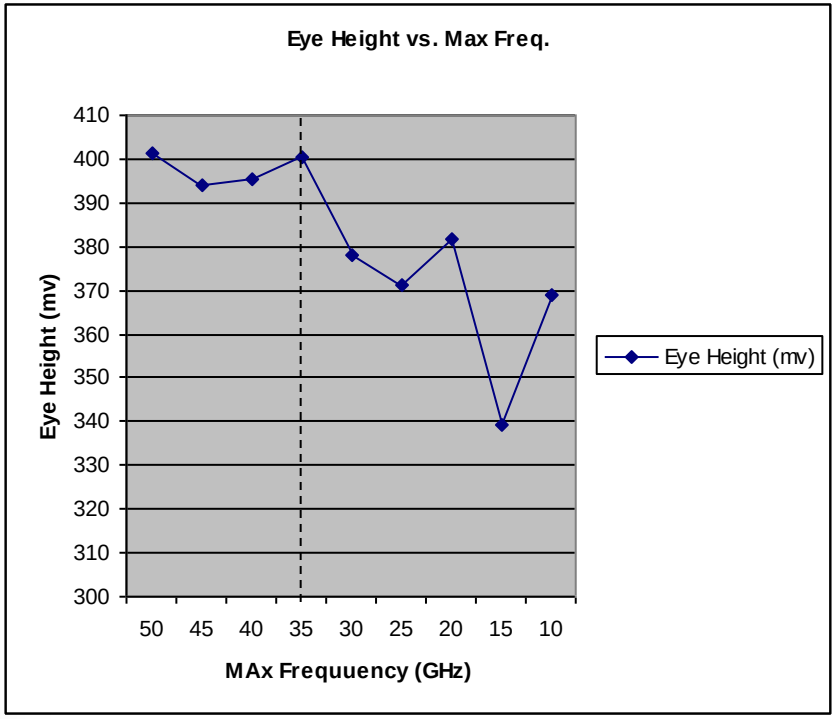
Max Frequency vs. Eye Opening

QuickEye Results





Fmax = .35/trise = .35/10ps = 35GHz

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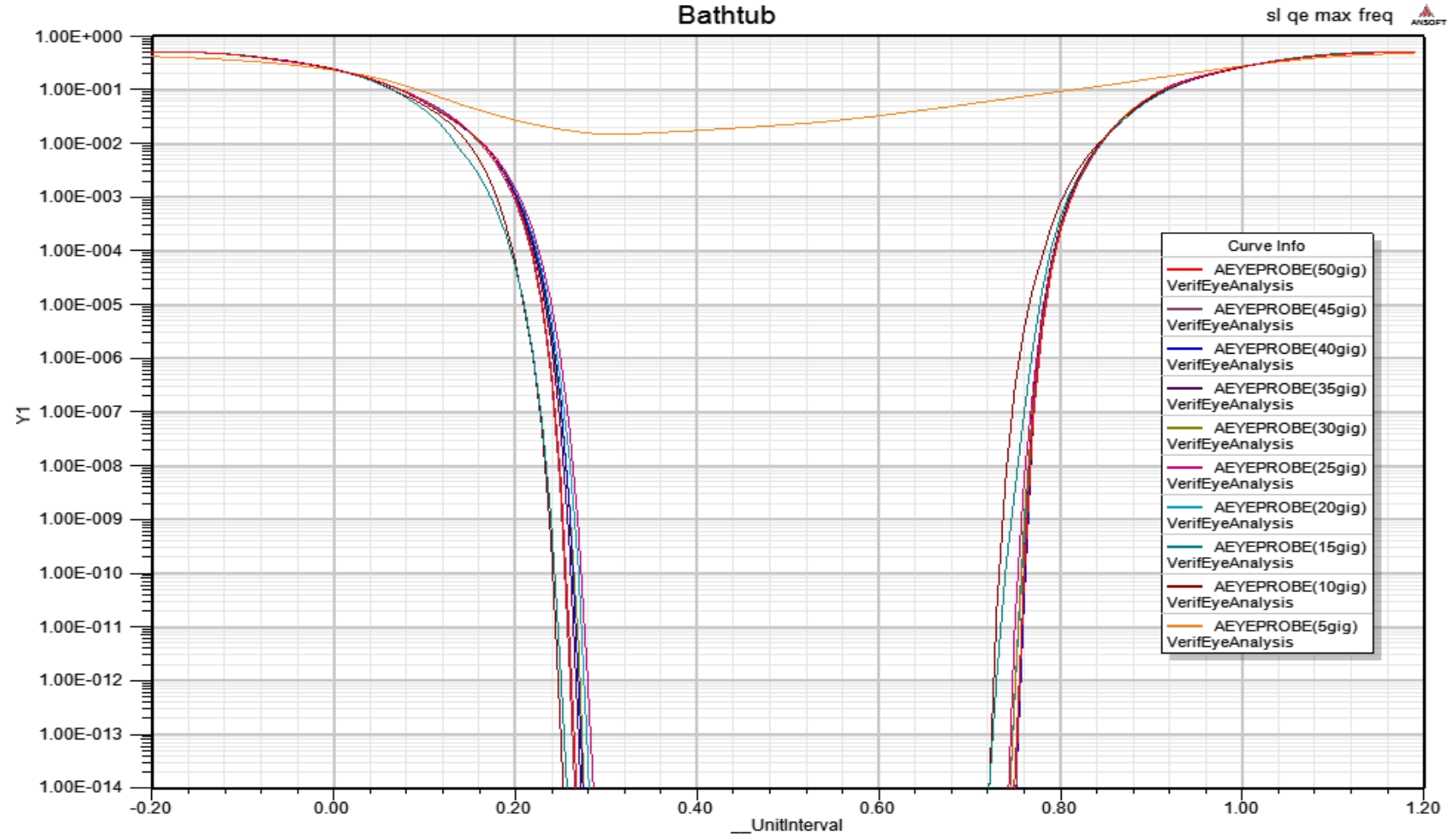
Max Frequency, VerifEye Results



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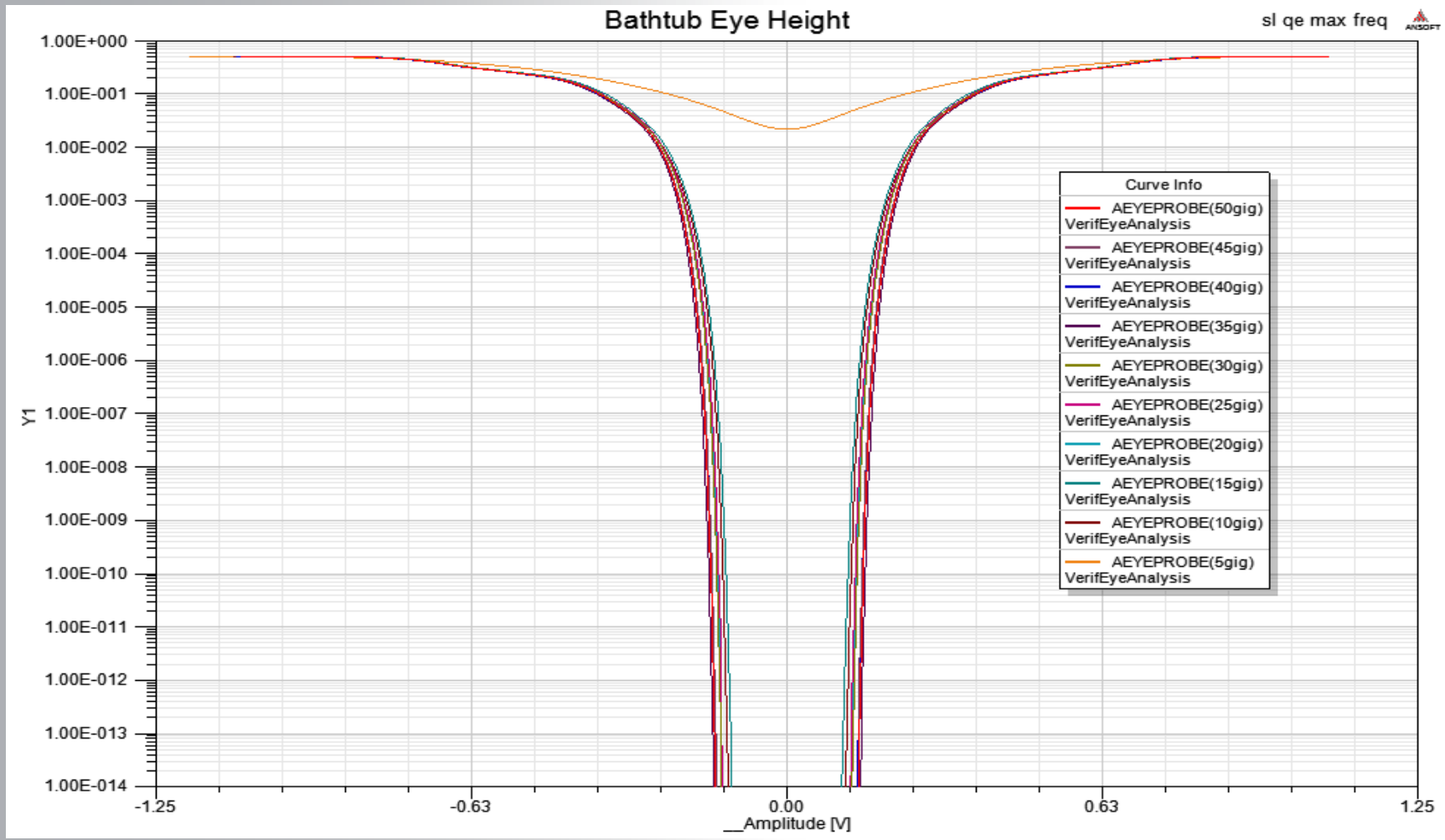
Max Frequency, VerifEye Results



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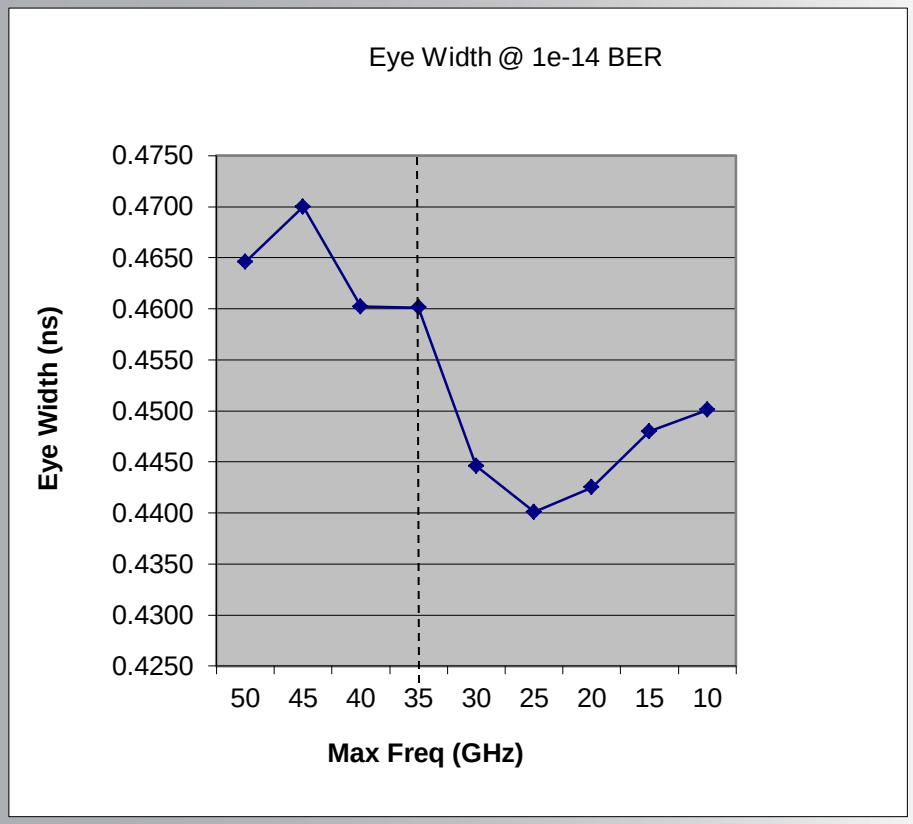
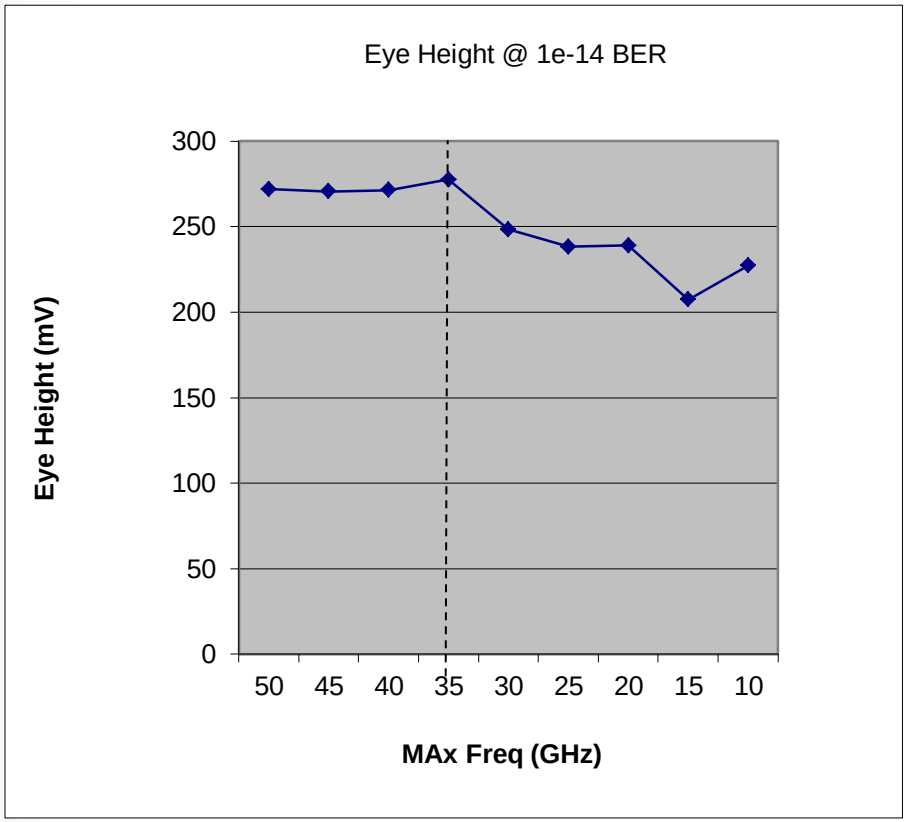
Max Frequency vs. Eye Opening

VerifEye Results





Fmax = .35/trise = .35/10ps = 35GHz

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Frequency Step

"Why do I care about low frequency data for a SERDES application? Doesn't encoding take care of that?"

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Frequency Step

- Tendency to focus on bandwidth and max frequency
- Remember to check if there is enough low frequency data in the model
  - Low frequency info required in order to reconstruct the propagation delay in the model
  - Remember Nyquist:
    - Ts = .5 / Fmax
    - Fs = .5 / Tmax

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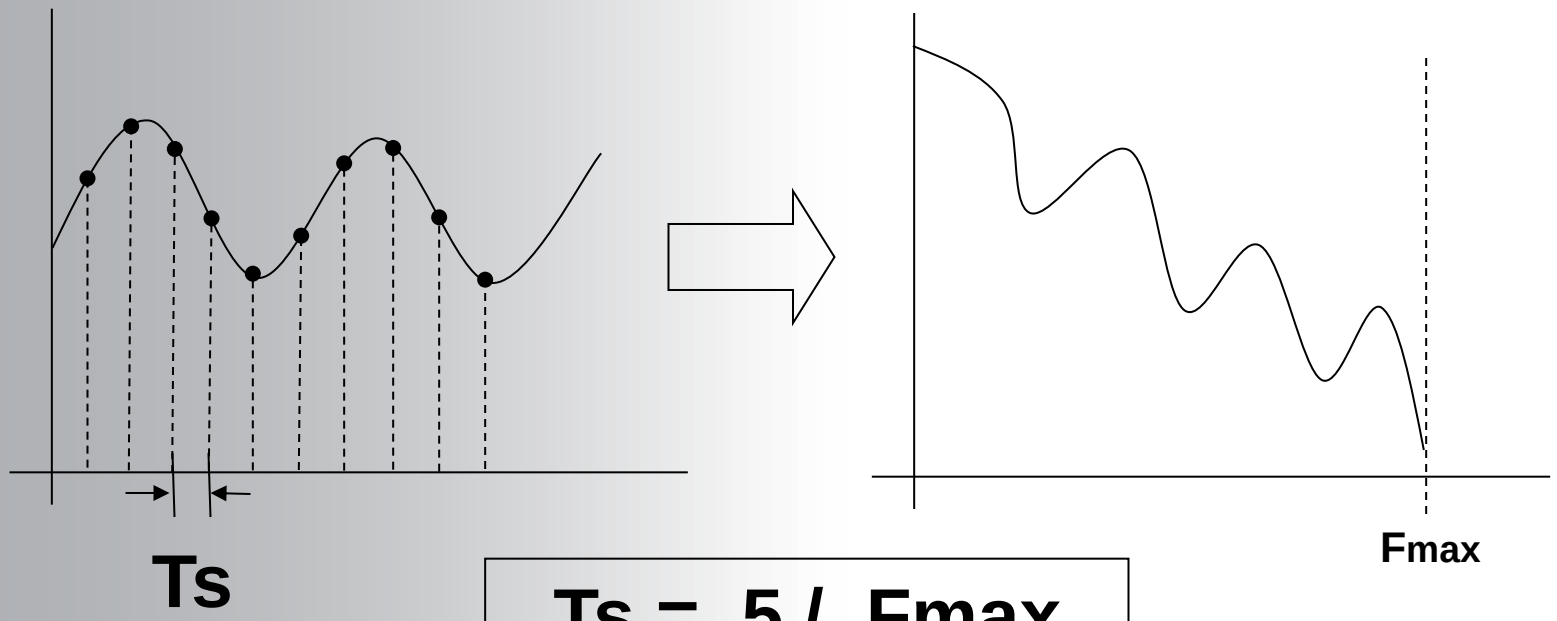
Nyquist and Sampling

- Traditionally taught as the time domain sample rate required to achieve a certain frequency domain bandwidth



Ts = .5 / Fmax

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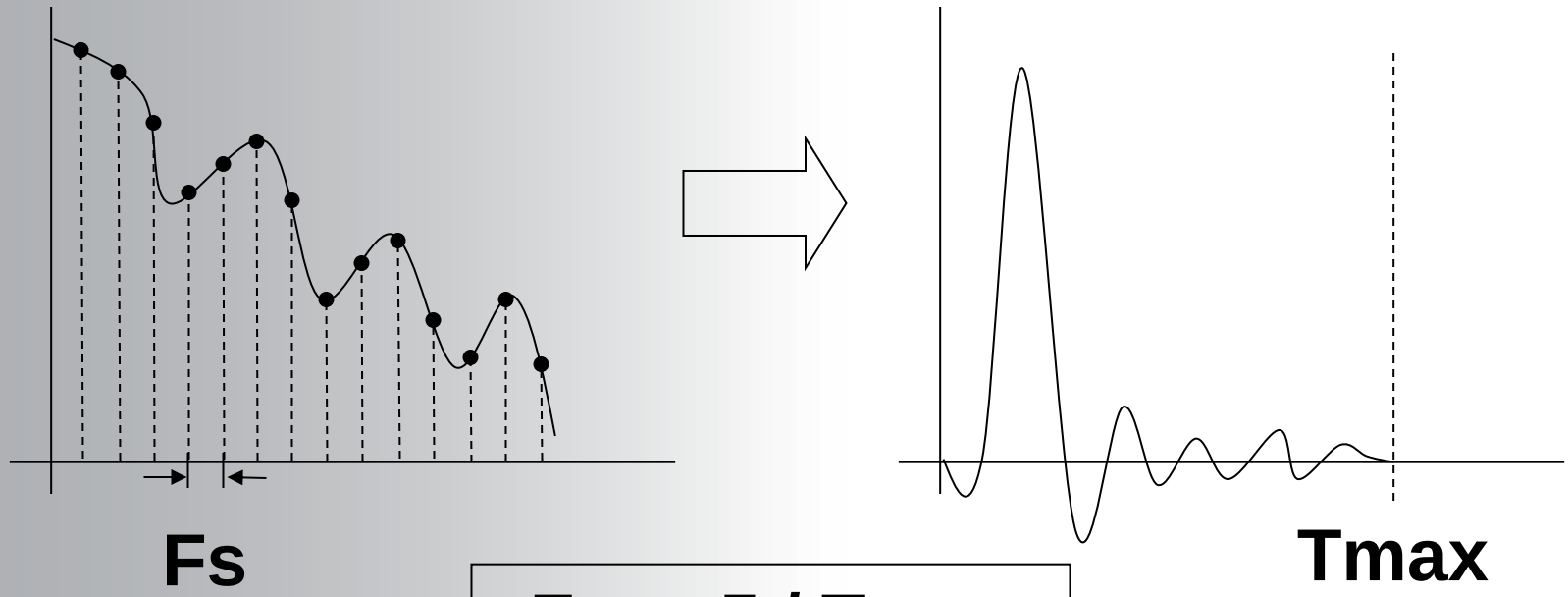
Nyquist and Sampling

- Given that frequency and time are duals of each other, there is a frequency domain sample rate requirement for reconstructing time delay



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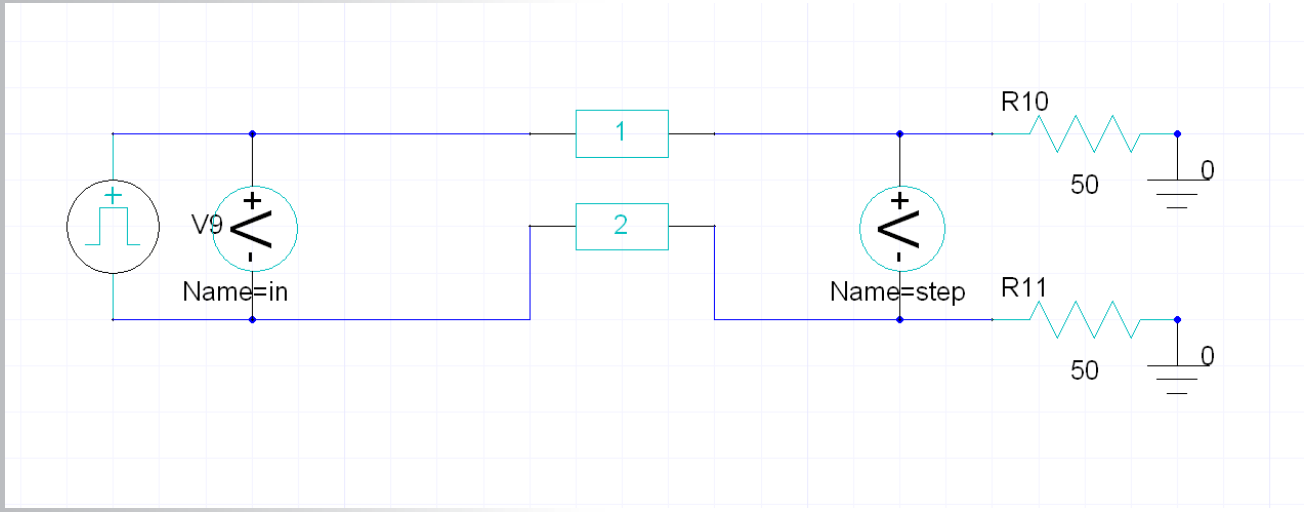
Test Channel for Sampling Experiment

- Step Source
- 750mm transmission line s-parameters
- Original data 0 to 50GHz, 10MHz step
- Resample at greater frequency step sizes



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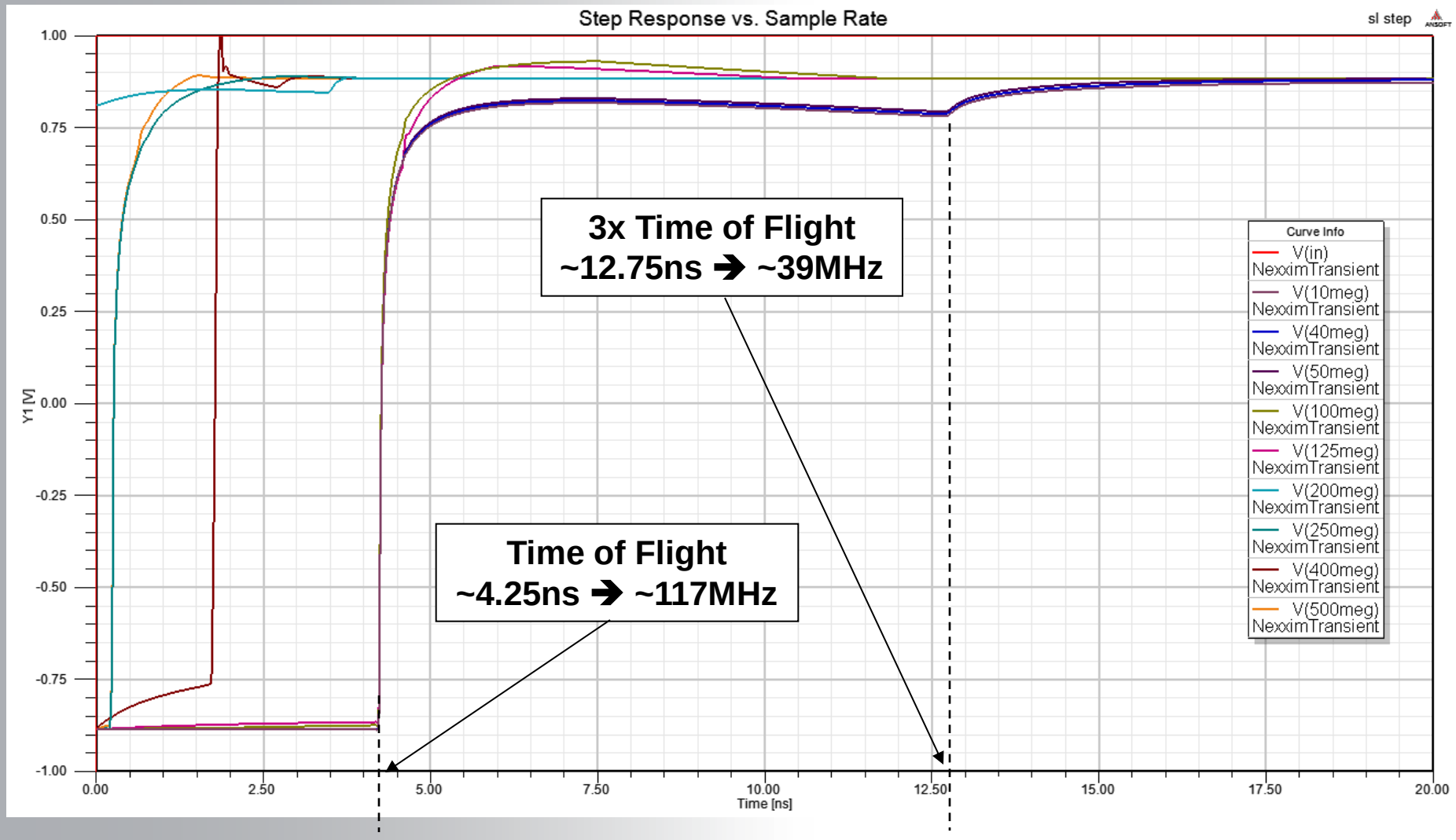
Step Responses



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Frequency Step Guidelines

- When considering your frequency step size, determine the actual delay time you need to capture
- Depending on terminations, you may need to account for multiple reflections
- Essentially the settling time for the step response of the model is the t_{max} that should dictate the sample rate

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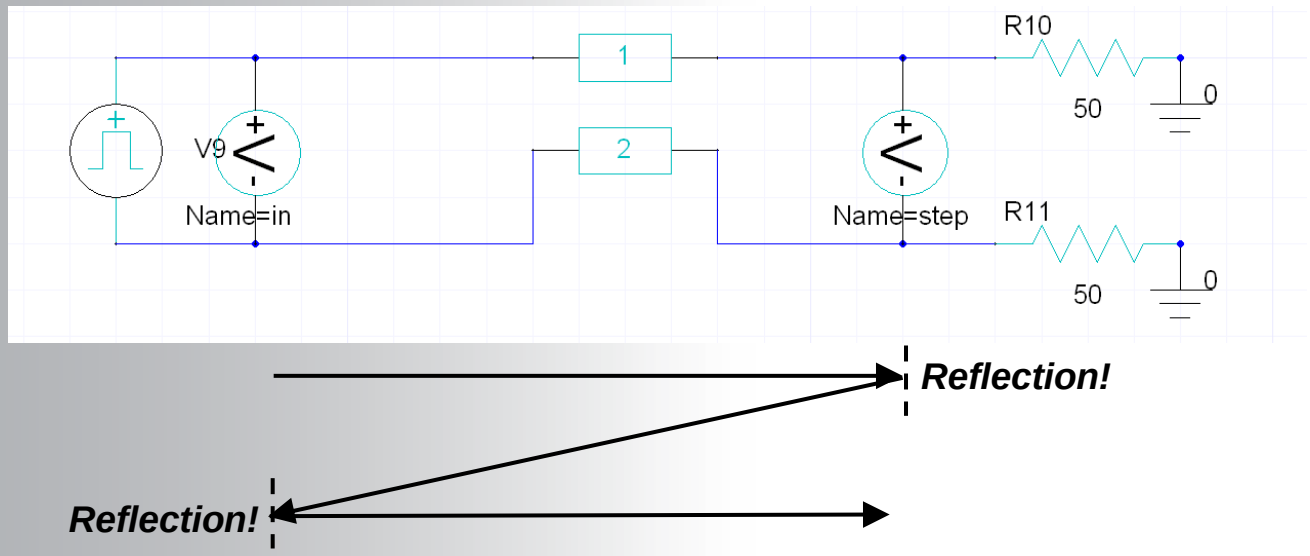
Frequency Step Guidelines

- Rule of thumb
  - 3x time of flight
  - This allows for a reflection at the far end to make an additional round trip to the near end and back



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Model Concatenation

"Do I have to do this for every single model if I need to make a single set of s-parameters for my whole channel?"

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Model Concatenation

- Sometimes there is the need to concatenate part or all of a channel into a single s-parameter model
- The step size in the new model is governed by the overall delay you need to capture
- This will require you to oversample each of the individual blocks in order to get the overall delay right

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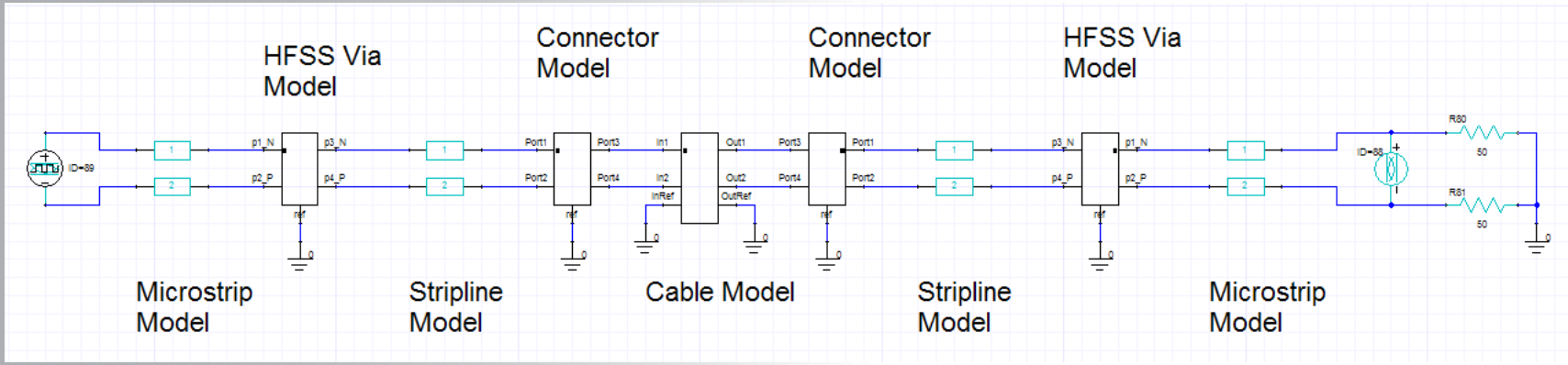
Model Concatenation



- Max frequency still dependant on rise time
- You can use the same 3x time of flight rule
- Better yet, look at the step response of the circuit for a more accurate view of the settling time

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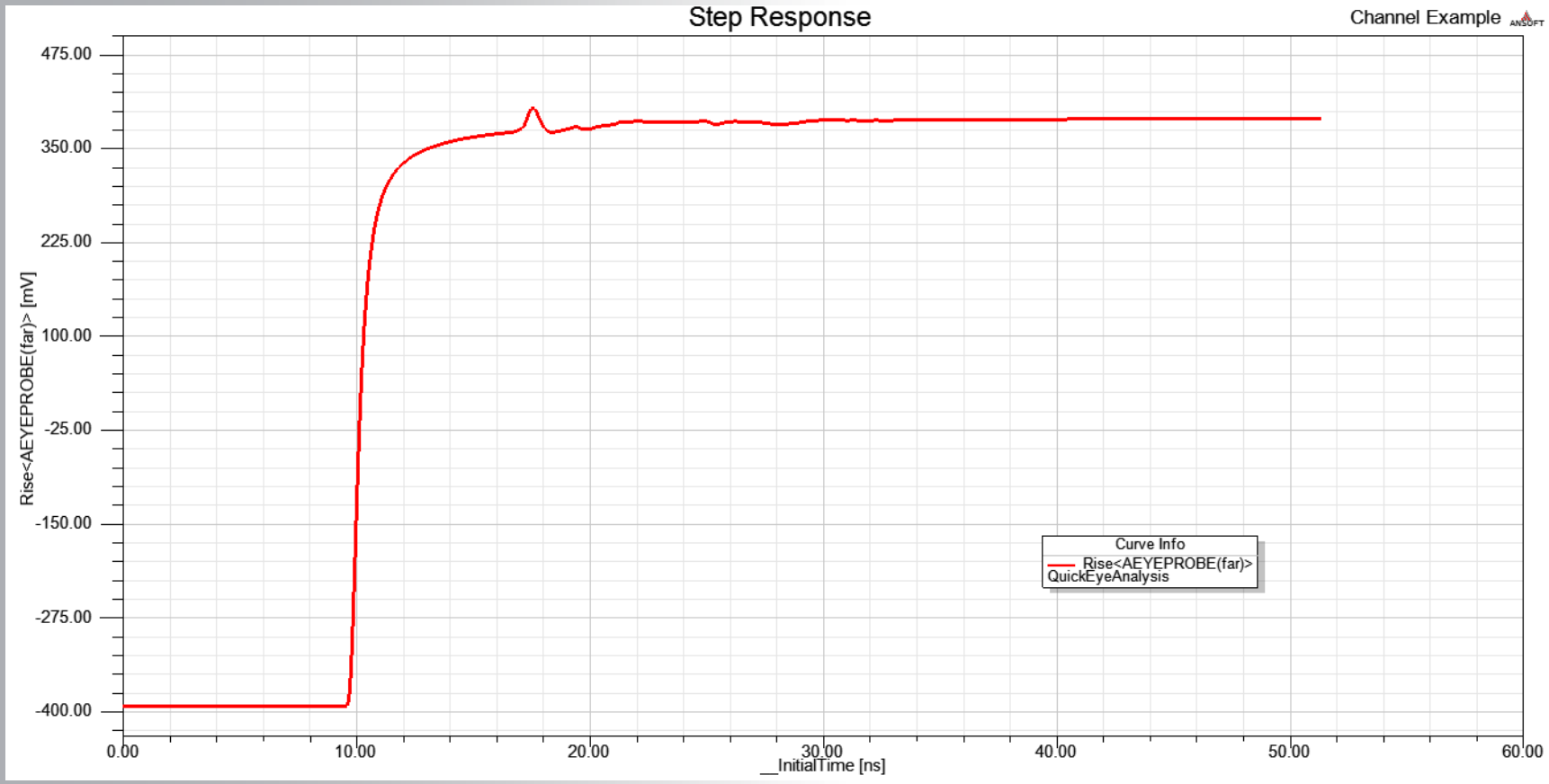
Model Concatenation



- **3x t.o.f would be 30ns, ~17MHz sample rate**
- **Real settling time closer to 50ns, 10MHz step needed for full accuracy**

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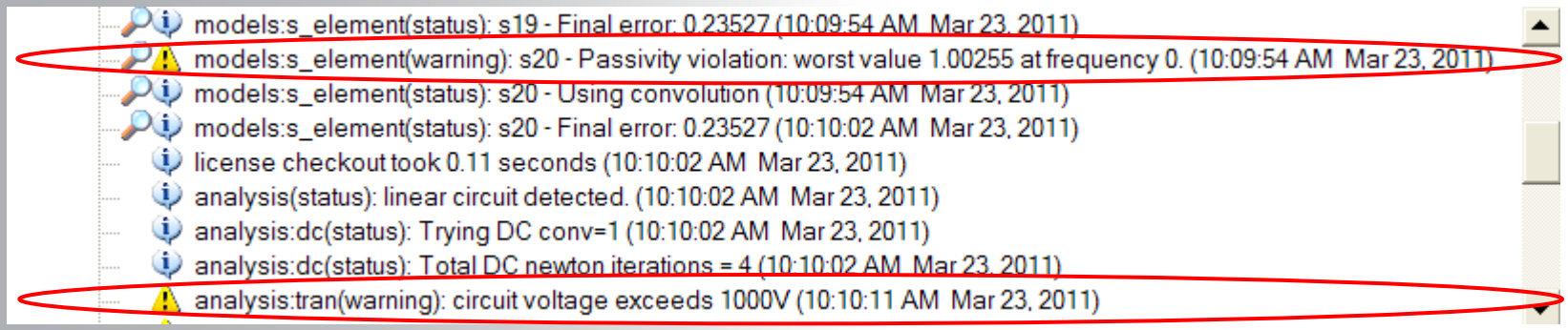
Passivity

"My simulation just failed! What do these warnings mean?"



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Passivity

- What is Passivity and why do I care?
  - Models must not create power/energy
  - Known source of inaccuracy in s-parameter models
  - Causes simulations to fail via non-convergence
  - Is a function of the entire matrix
  - Can check passivity using Singular Value Decomposition (SVD)
    - Max singular values of the s-matrix at each frequency point in the model must be <= 1

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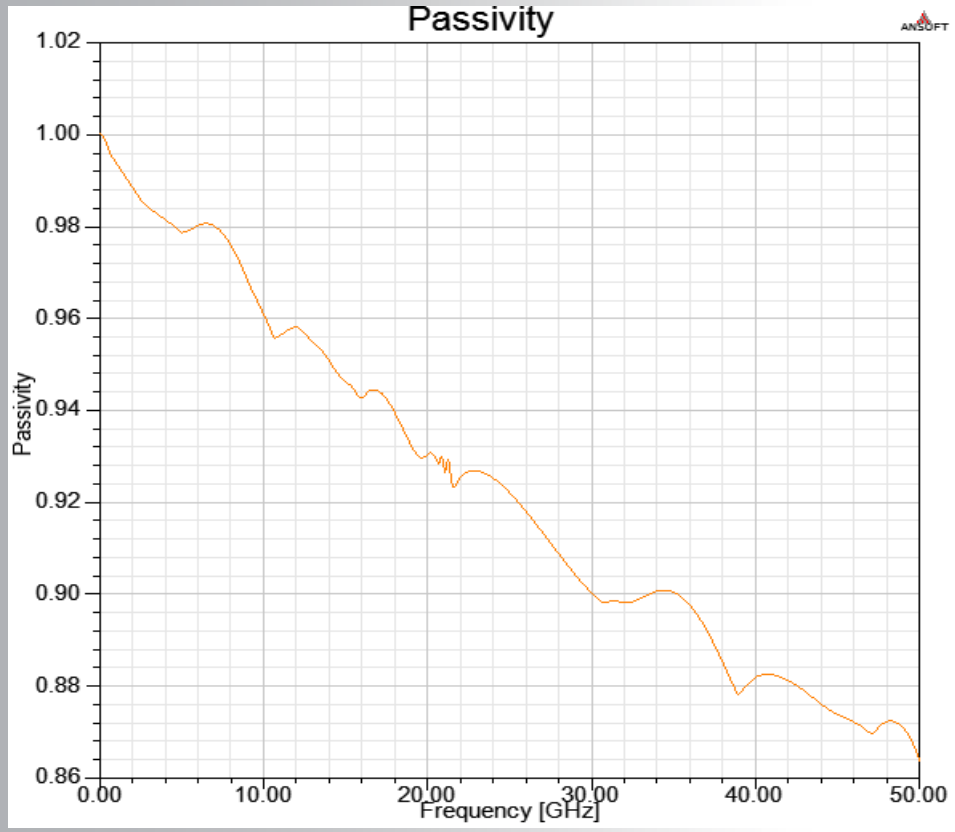
Look at Maximum Singular Value



Freq	Passivity
0.00000Hz	1.00007
0.00500GHz	1.00007
0.01000GHz	1.00007
0.01500GHz	1.00006
0.02000GHz	1.00006
0.02500GHz	1.00006
0.03000GHz	1.00006
0.03500GHz	1.00005
0.04000GHz	1.00005
0.04500GHz	1.00005
0.05000GHz	1.00004
0.05500GHz	1.00004
0.06000GHz	1.00003
0.06500GHz	1.00002
0.07000GHz	1.00002
0.07500GHz	1.00001
0.08000GHz	1.00000
0.08500GHz	0.99999
0.09000GHz	0.99998
0.09500GHz	0.99997
0.10000GHz	0.99996
0.10500GHz	0.99995
0.11000GHz	0.99994
0.11500GHz	0.99993
0.12000GHz	0.99992
0.12500GHz	0.99990
0.13000GHz	0.99989
0.13500GHz	0.99988
0.14000GHz	0.99986
0.14500GHz	0.99985
0.15000GHz	0.99983

Nexxim simulation will use local parameter scoping. To change this option, please go to Tools>Options>Nexxim Circuit Options. (1:14:41 PM Mar 19, 2011)
Analyzing...D:/edn/passivity.adsnresults/Circuit1/temp/DV17_S15_V18.cir (1:14:41 PM Mar 19, 2011)
(status): Nexxim version: 6.1.1 WIN32, build time: Jan 24 2011, 04:41:34 (1:14:41 PM Mar 19, 2011)
models:s_element(warning): s1 - Passivity violation: worst value 1.00007 at frequency 0. (1:14:45 PM Mar 19, 2011)
models:s_element(status): s1 - State-space system file 'D:/edn/passivity.adsnresults/Circuit1/temp/sss_f52fc1d075b3a7d225aed1d5a33baf80_4.sss' not found. (1:14:45 PM Mar 19, 2011)
models:s_element(status): s1 - Fitting state-space system using TWA. (1:14:45 PM Mar 19, 2011)

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Passivity

- *Is it OK if my model is "a little" non-passive?*
  - Short answer: No
  - Long answer: No, but you might be lucky
    - It can be hard to say if non-passive data will stay stable long enough to get good results in simulation
    - It might just be a matter of stop time
    - Termination can mask non-passivity by absorbing the extra energy produced by the matrix

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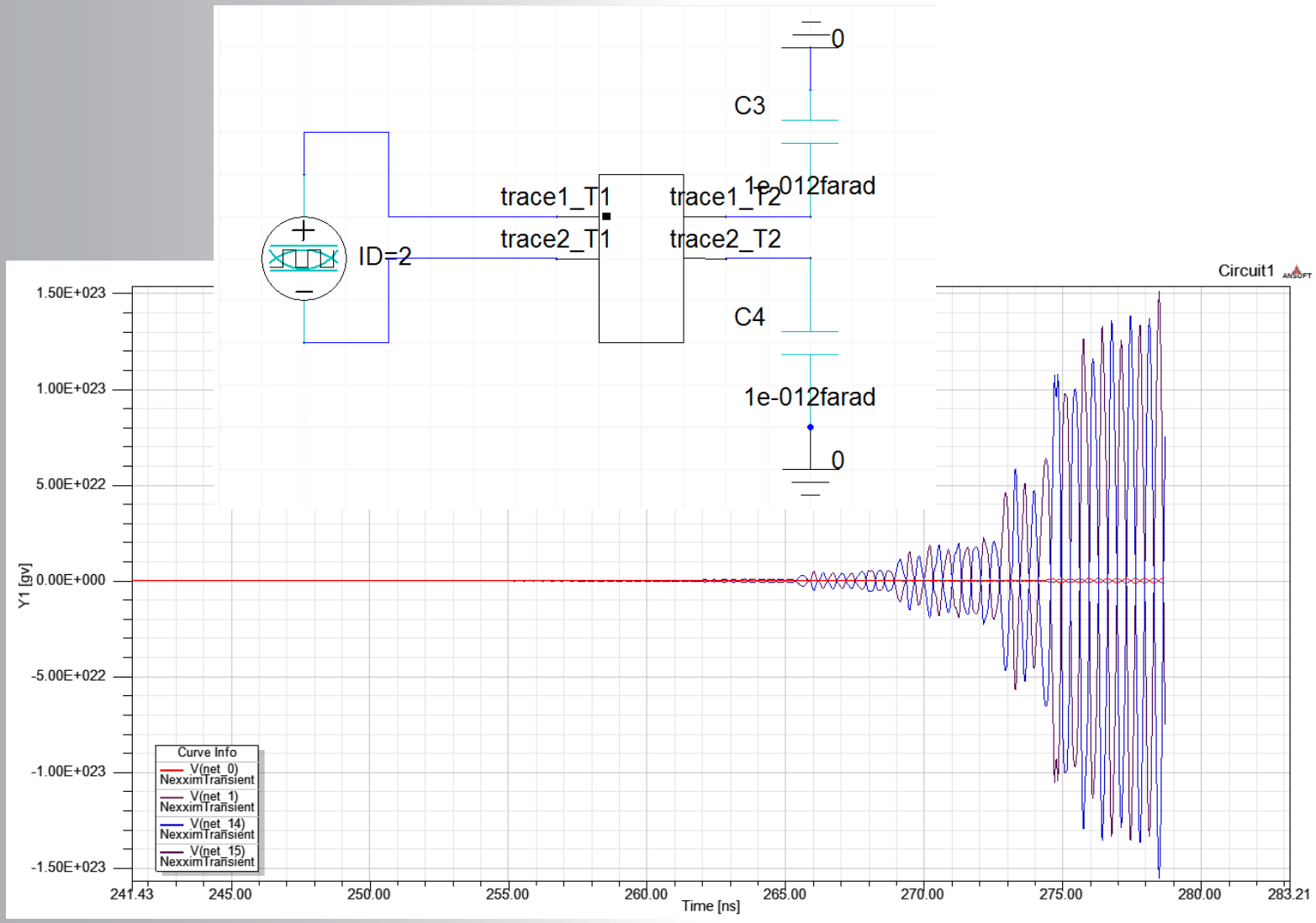
Non-Passive Data



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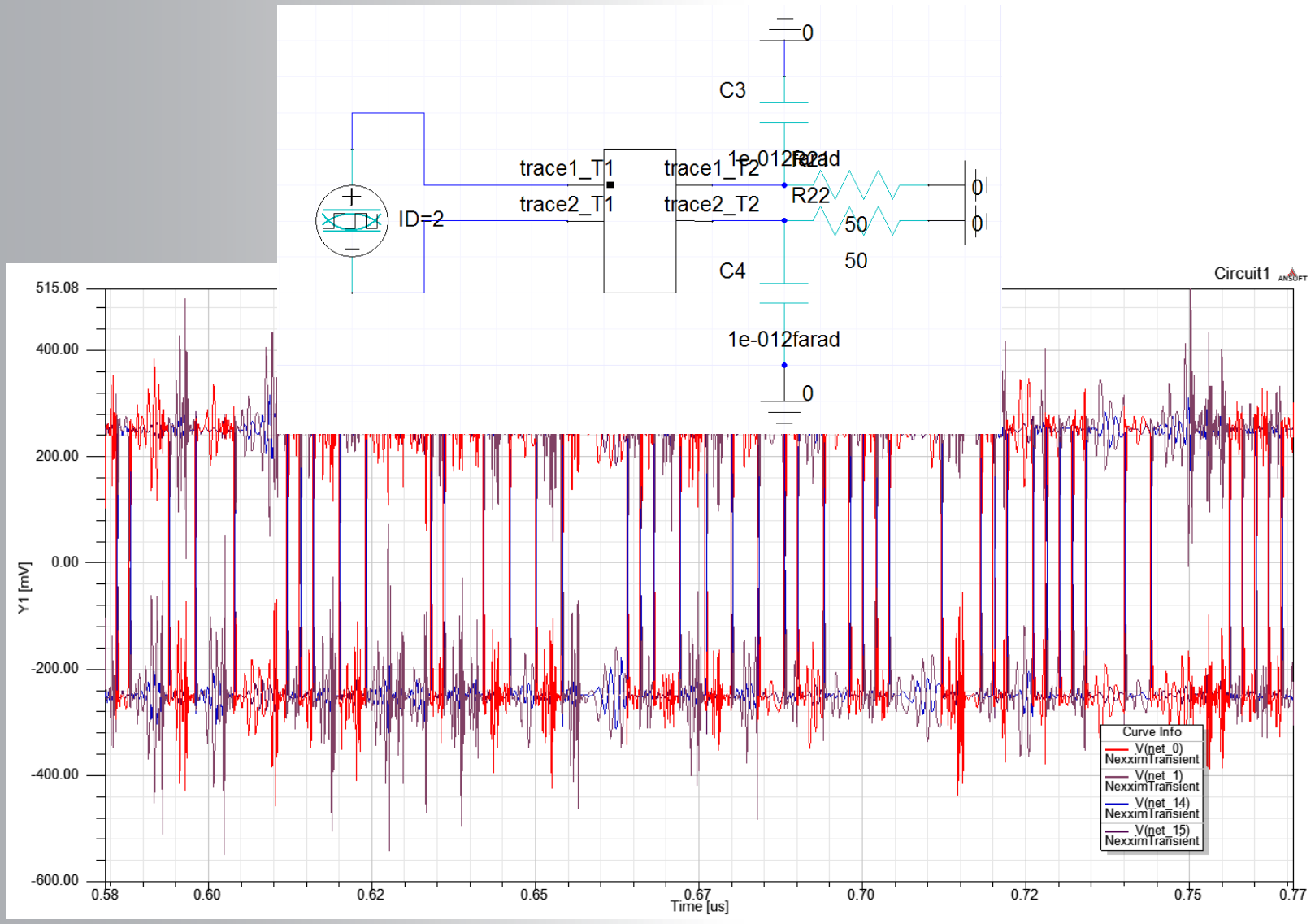
Termination Can Absorb Extra Energy



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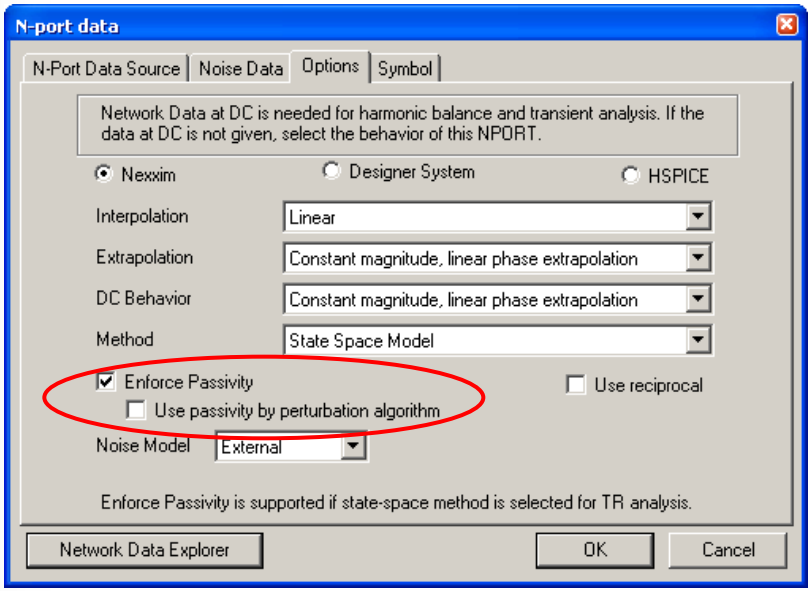
Passivity



- So what do I do?
  - Passivity Enforcement
    - Convex optimization
    - Perturbation
  - Drawbacks
    - Can result in worse fit to the data
    - Not always successful
  - For field solver models, consider tightening the error tolerance and re-simulating

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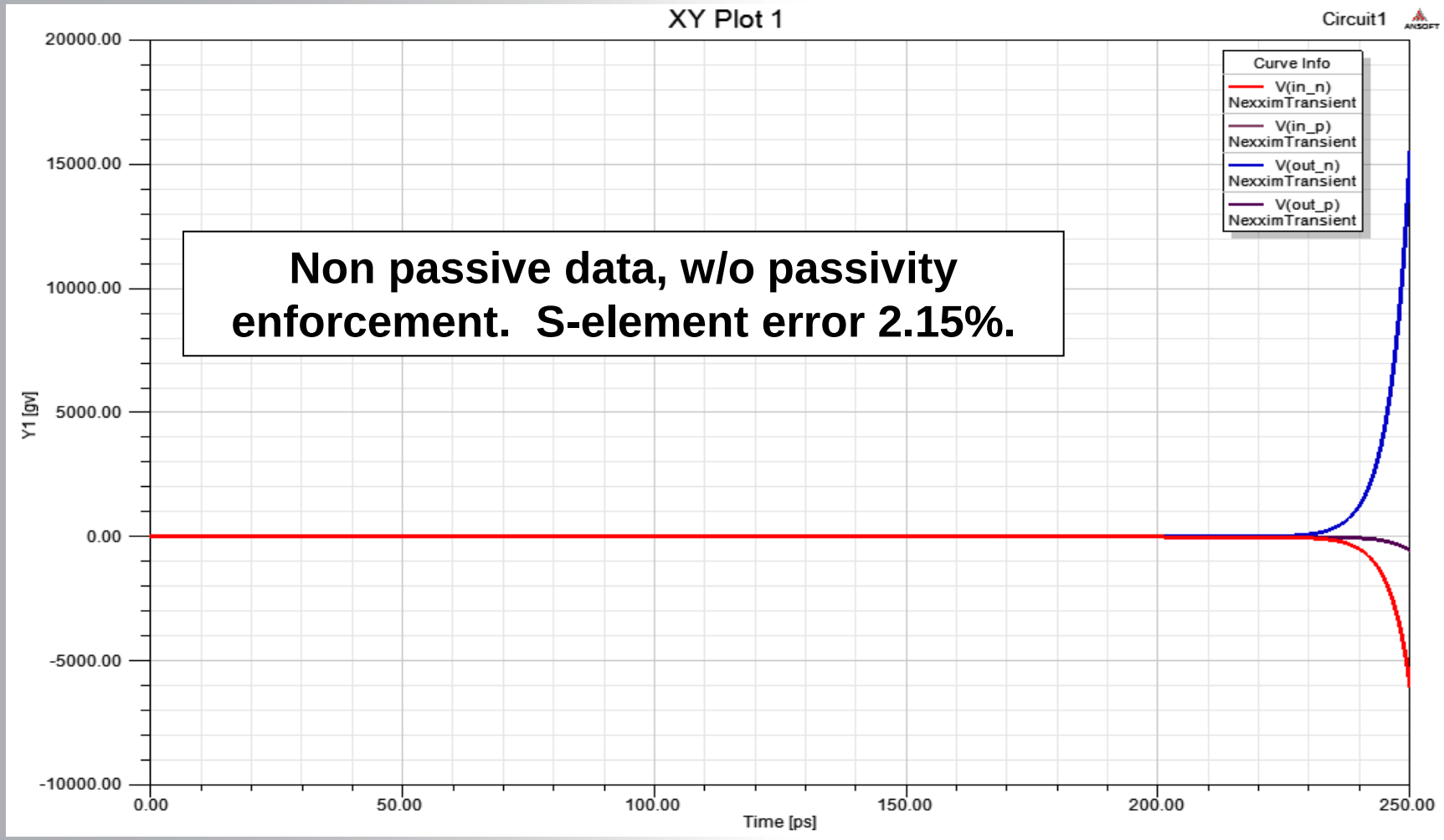
Passivity Enforcement



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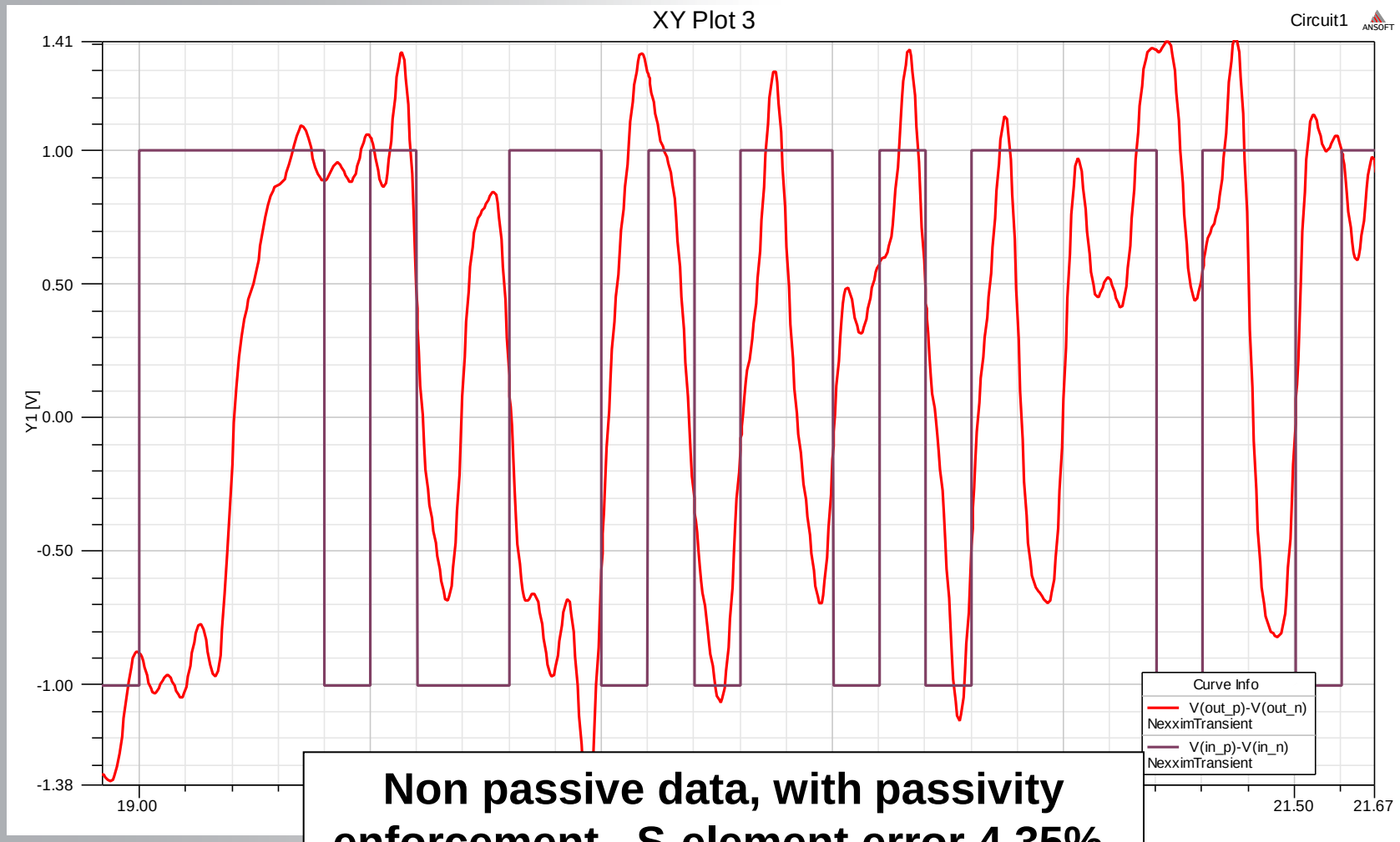
Passivity Enforcement



Non passive data, with passivity enforcement. S-element error 4.35%.

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Causality

"Why do I need to care about causality, and how do I know if I have a problem?"

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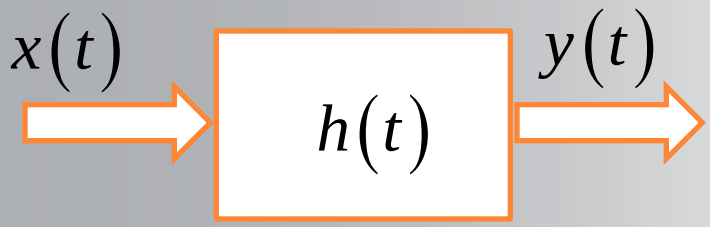
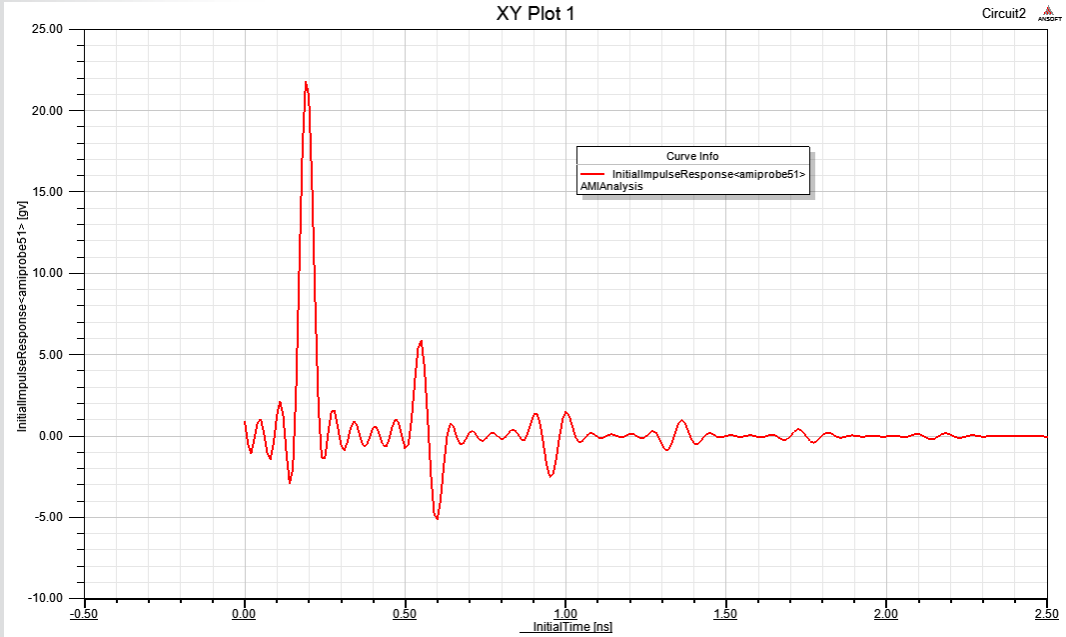
Causality

- Several definitions
  - Causes must precede effects
  - Impulse response is 0 before t=0
  - Signals cannot travel faster than the speed of light



$$h(t) = 0 \quad t < 0$$



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Causality

- What can cause non-causality in S-parameter models?
  - Bad dielectric models in fieldsolvers
  - Loose convergence criteria in fieldsolver
  - Under sampling leading to interpolation/extrapolation error
  - Measurement noise

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Causality

- Detection of non-causality is not as simple as non-passivity
  - Need to use Hilbert relationship
    - For LTI structures, the real and imaginary parts are even/odd complements in the frequency domain
    - The Hilbert transform allows the real or imaginary parts to be reconstructed from each other
    - In theory this should be straightforward, but sampled bandlimited data add significant numerical complexity

$$He(\omega) = SIGNUM(\omega) \otimes Ho(\omega)$$

$$SIGNUM(\omega) = \frac{2}{j\omega}$$

$$\mathrm{Re}[S_{ij}(f)] \otimes \frac{1}{\pi f} = \mathrm{Im}[S_{ij}(f)]$$

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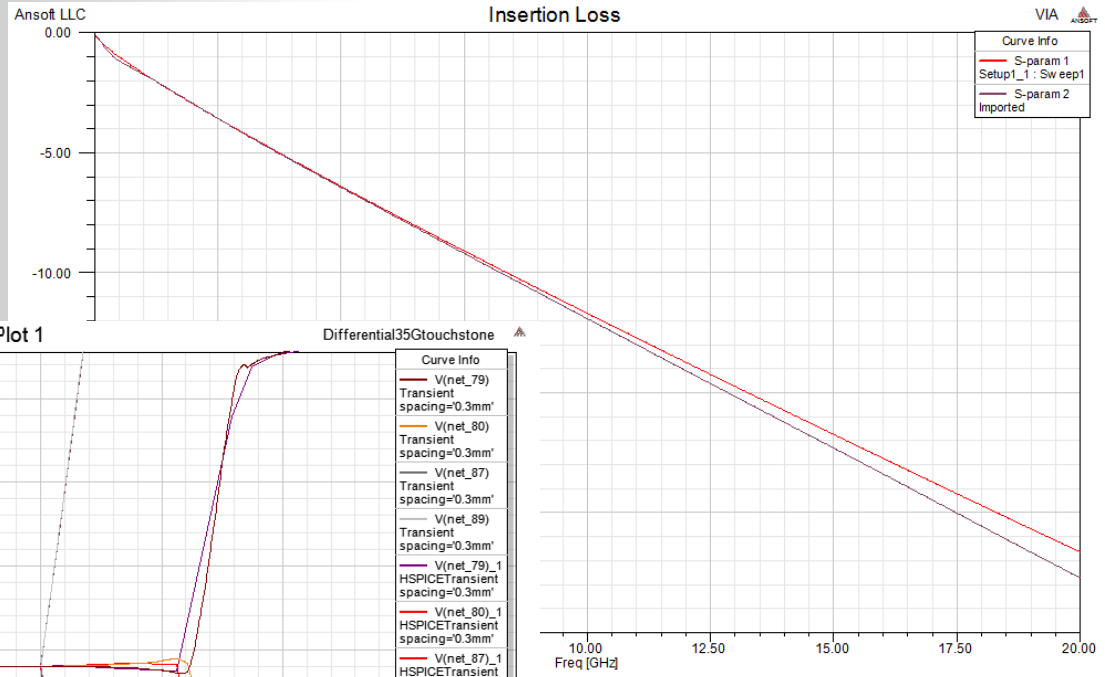
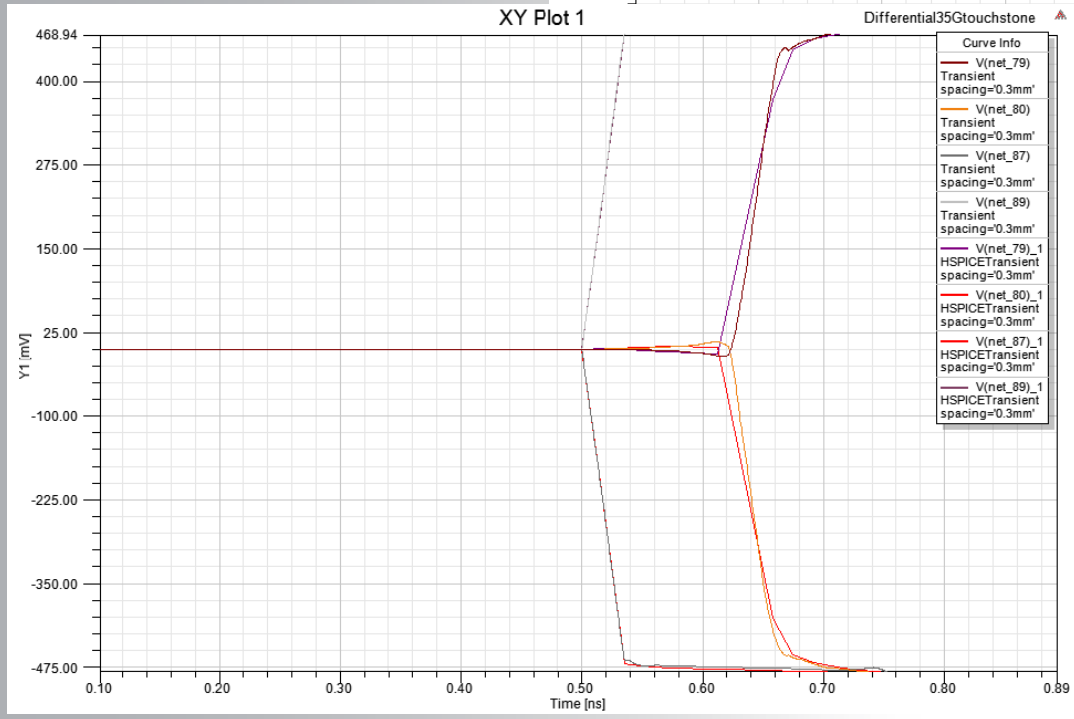
Which Model is Causal?





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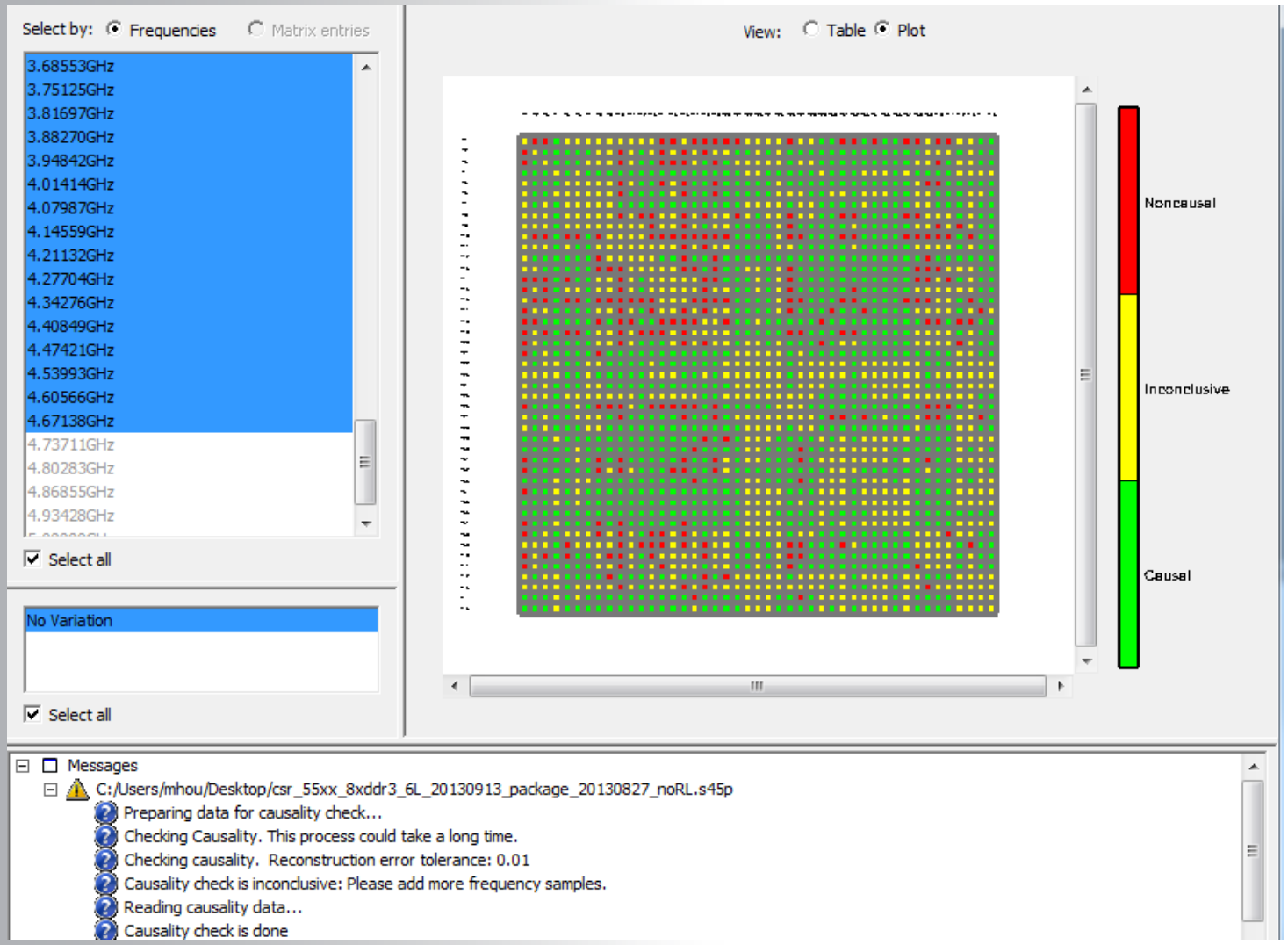
Causality Checking



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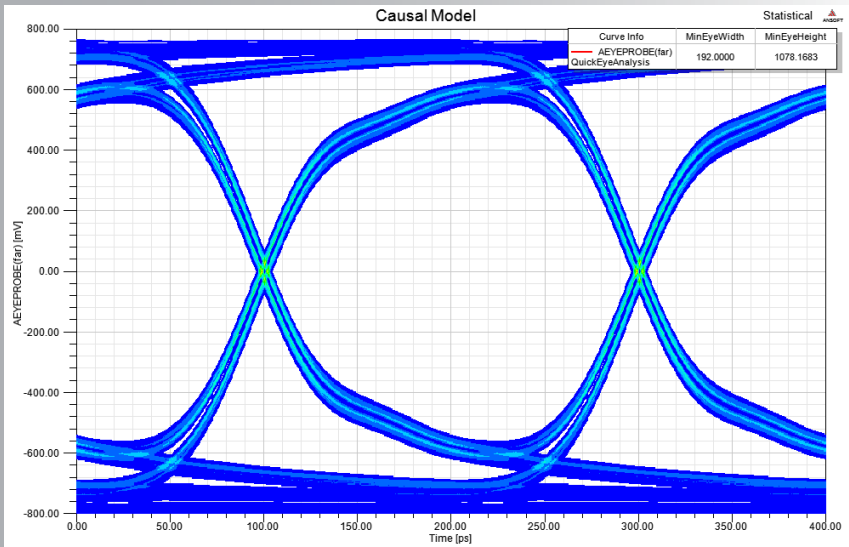
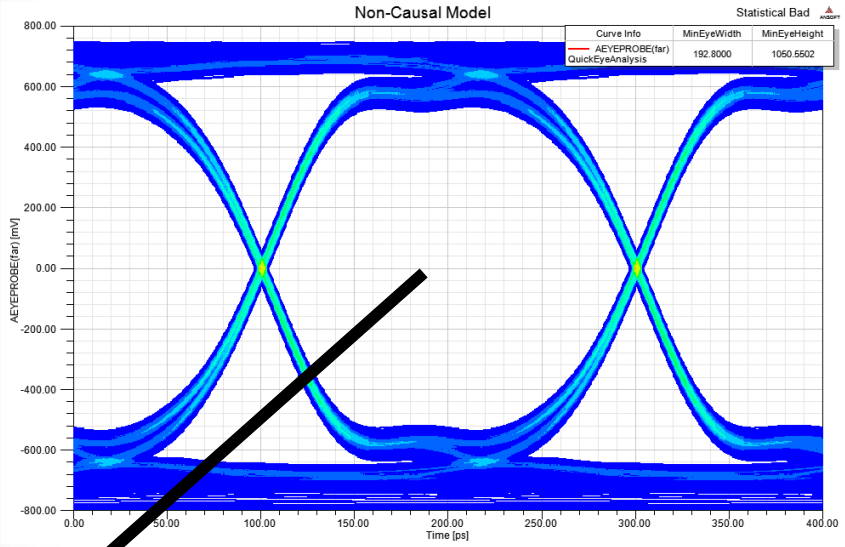
Causality Checking in State-Space





models:s_element(warning): s41 - Causality violation: Worst error relative to threshold for S(2,2) is 1.00483 percent. (12:01:09 PM Mar 23, 2011)
models:s_element(status): s41 - processing row 3 of 4 of the scattering data matrix... (12:01:09 PM Mar 23, 2011)
models:s_element(warning): s41 - Causality violation: Worst error relative to threshold for S(3,1) is 0.420155 percent. (12:08:20 PM Mar 23, 2011)
models:s_element(warning): s41 - Causality violation: Worst error relative to threshold for S(3,2) is 0.778083 percent. (12:15:31 PM Mar 23, 2011)
models:s_element(warning): s41 - Causality violation: Worst error relative to threshold for S(3,3) is 0.410643 percent. (12:22:14 PM Mar 23, 2011)
models:s_element(status): s41 - processing row 4 of 4 of the scattering data matrix... (12:22:14 PM Mar 23, 2011)
models:s_element(warning): s41 - Causality violation: Worst error relative to threshold for S(4,1) is 0.77204 percent. (12:28:37 PM Mar 23, 2011)
models:s_element(warning): s41 - Causality violation: Worst error relative to threshold for S(4,2) is 0.415145 percent. (12:35:11 PM Mar 23, 2011)
models:s_element(warning): s41 - Causality violation: Worst error relative to threshold for S(4,3) is 12.2196 percent. (12:41:52 PM Mar 23, 2011)

In general, violations greater then 0.25% are usually cause for concern.

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Causality Detection and Enforcement

- Enforcement
  - Use causal reconstruction instead of original data
- Issues with causality enforcement
  - If a model is non-causal it is not necessarily true to assume that either the real or imaginary part is “correct”
  - Essentially throwing away half of the s-parameter data
  - If the issue can be addressed in the fieldsolver tool, that will always be a more accurate option than enforcement

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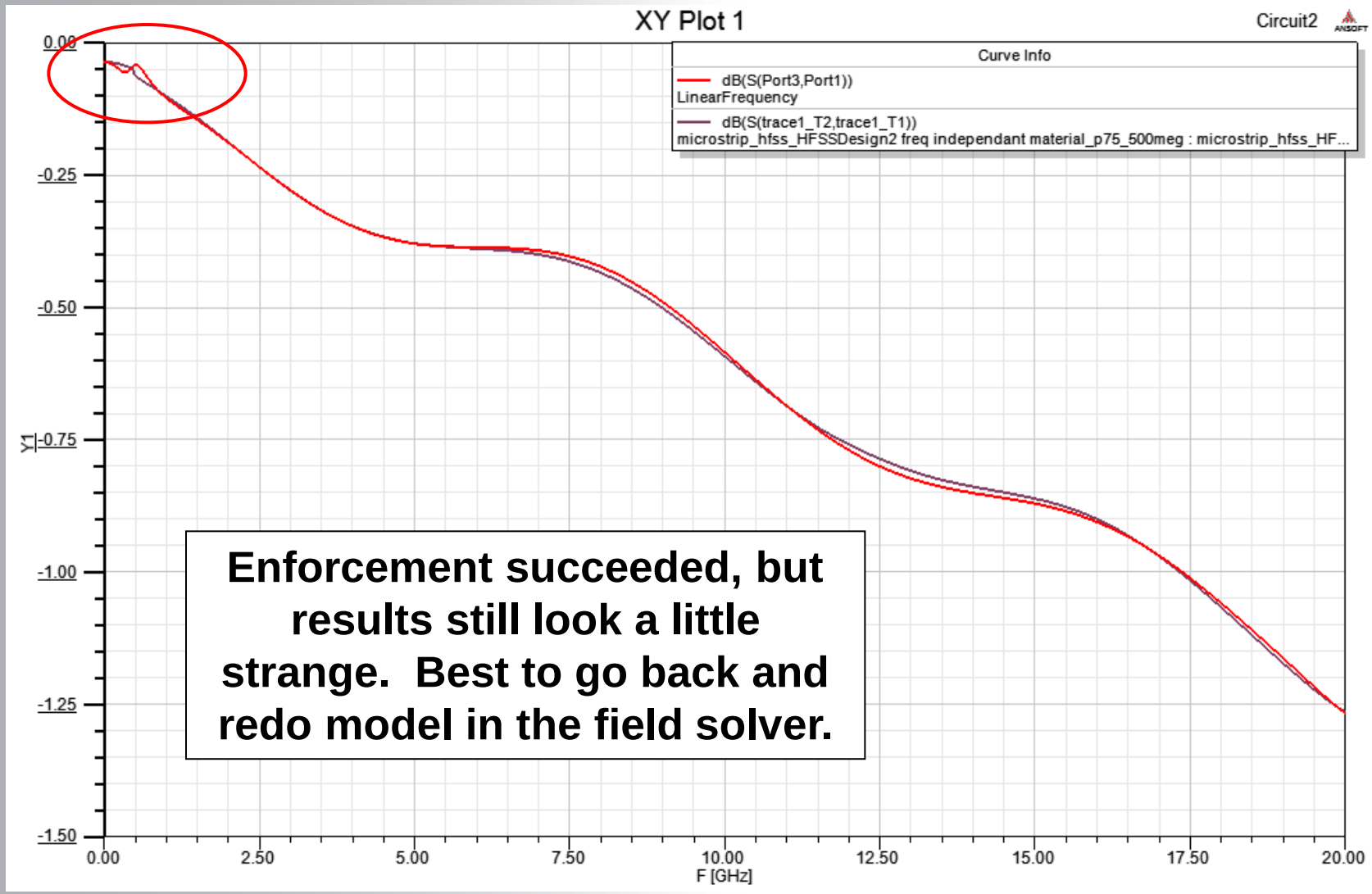
Non-causal Data (purple) vs. Causal Reconstruction (red)



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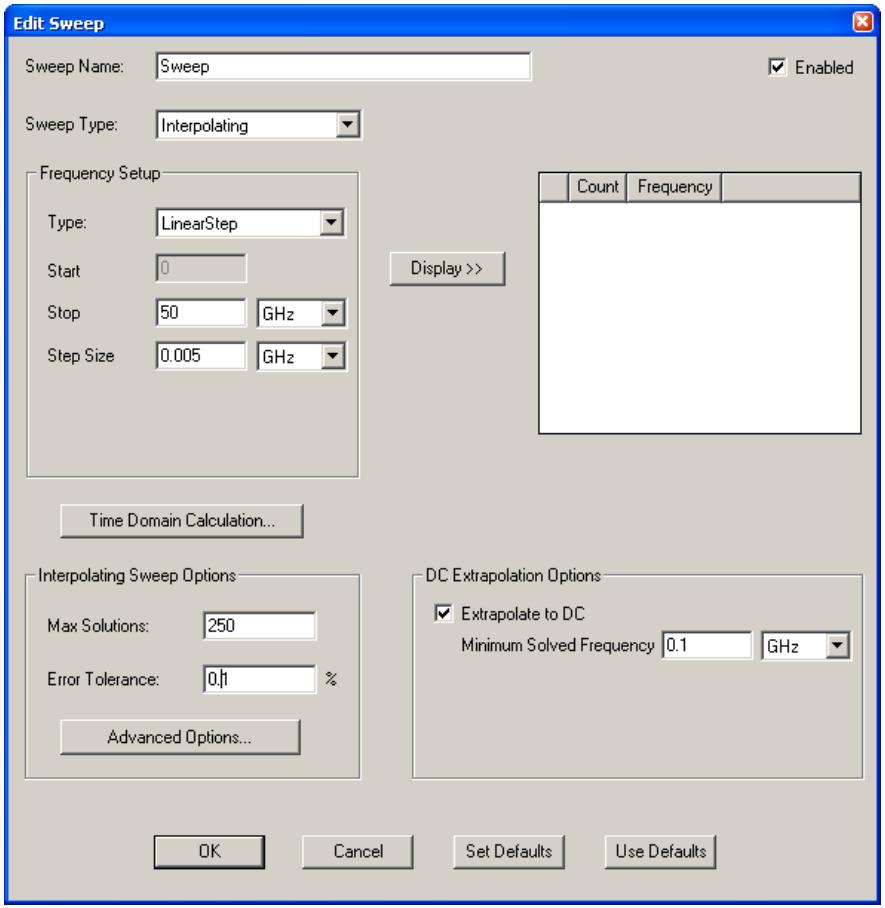
Going Back to the Fieldsolver

- A few things to try:
  - Causal dielectric models, e.g. Djordjevic-Sarkar
  - Tighten convergence criteria
  - Minimum solved frequency



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Causality and Passivity

- Non-causal data can lead to non-passive simulation results
  - Loss of accuracy with non-causal models
  - A bad fit to non-causal data can be the cause
  - Remember that both passivity and causality are requirements to ensure stability

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Conclusions

- Need to ensure that the model data is accurate and appropriate for simulation
  - Bandwidth
  - Frequency Sampling
  - Stability
    - Passivity
    - Causality
- Passivity and causality can be enforced, but this can affect accuracy
- S-parameter data integrity is key for good signal integrity simulations

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