Single_ended and Differential TDR Measurement with the aid of Ansoft's Full_Wave_SPICE

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Agenda

- Overview for getting the TDR Data
- Overview for Differential Mode and Common Mode Impedance
- Practical Example with Measurement Data Verified
- SMA Connector Modeling and its Application for Critical Net Simulation

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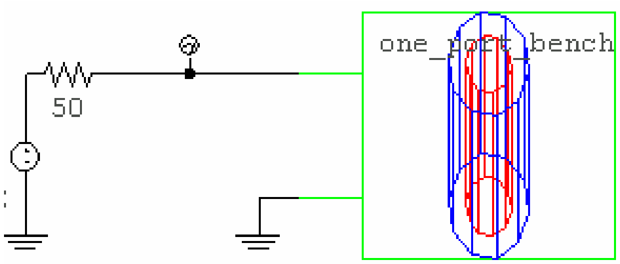
Overview for the TDR Data?

How to get the TDR data?

Pure Modeling: (Field Extractor + SPICE Solver)

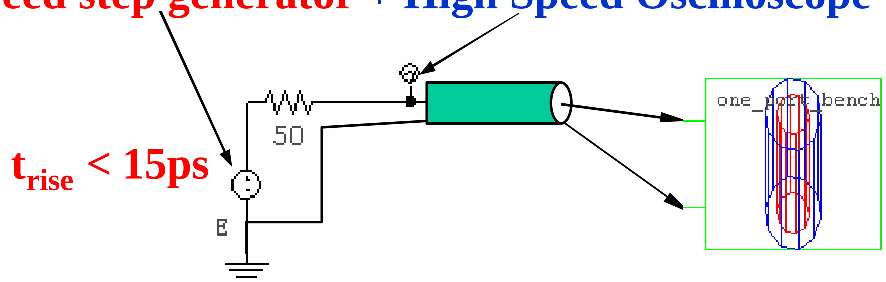


This box could be equivalent circuit from SPICELINK or S-Parameter from HFSS or Ensemble!!

The tools are fully available for Altra Broadband!!

Measurement:

1. High speed step generator + High Speed Oscilloscope



2. Wideband VNA + TDR option

Measurement + Math Calculation:

Wideband VNA to get 1 port S_parameter + Full_Wave_SPICE
(The purpose of this presentation material!!)

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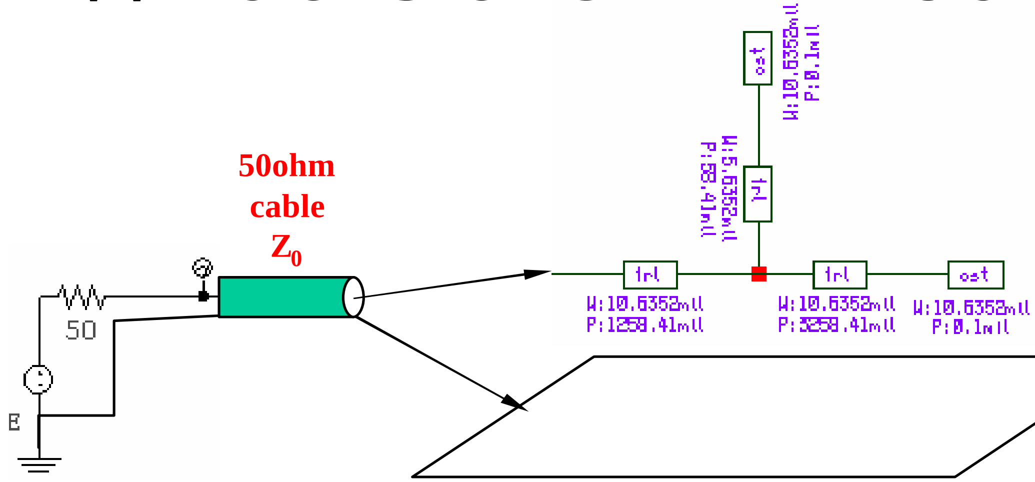
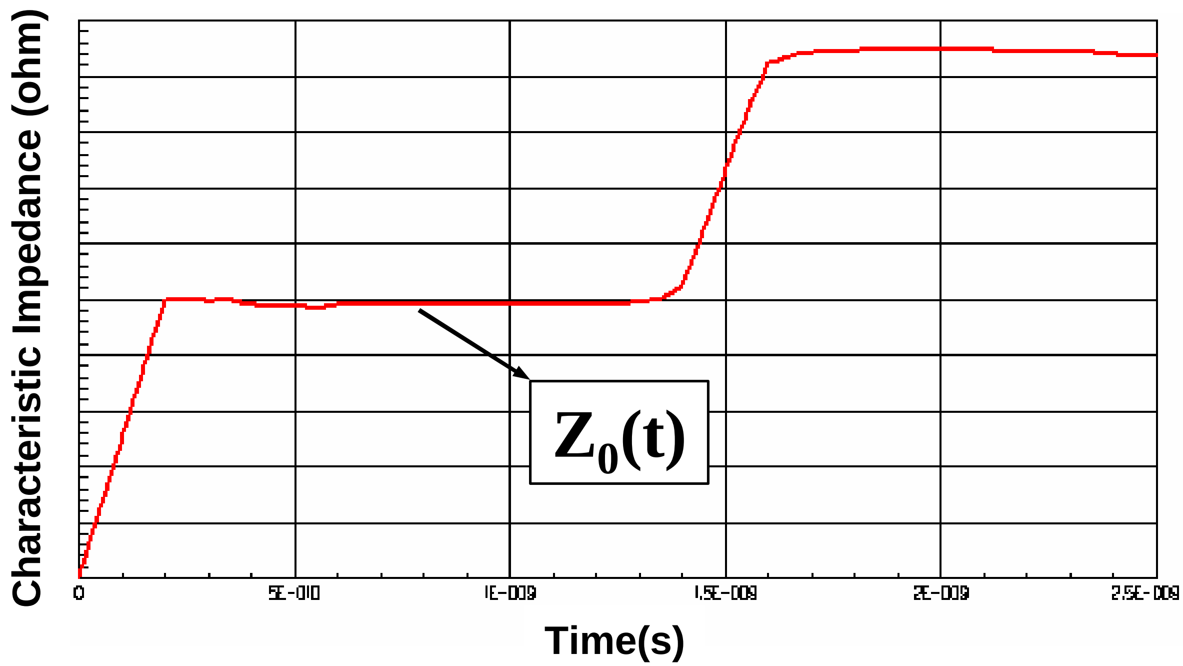
What is the TDR data?





TDR data should be characteristic impedance vs time!!

Why&How from VNA to TDR

Why?

Generally Speaking, in the lab, VNA is more popular than real TDR. Therefore, if we could find a efficient way to get the TDR data from VNA measurement result than we do no have to purchase another TDR setup.

How?

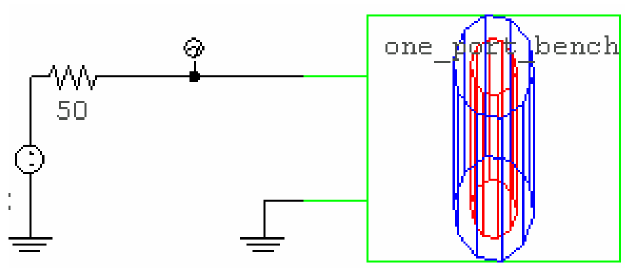
From VNA

# GHz	S MA	R 50.000000
0.010000	0.994813	-3.004953
0.020000	0.993534	-5.986811
0.030000	0.992128	-8.973242
…………		
9.980000	0.624802	141.488164
9.990000	0.623542	139.131339
10.000000	0.622256	136.766395

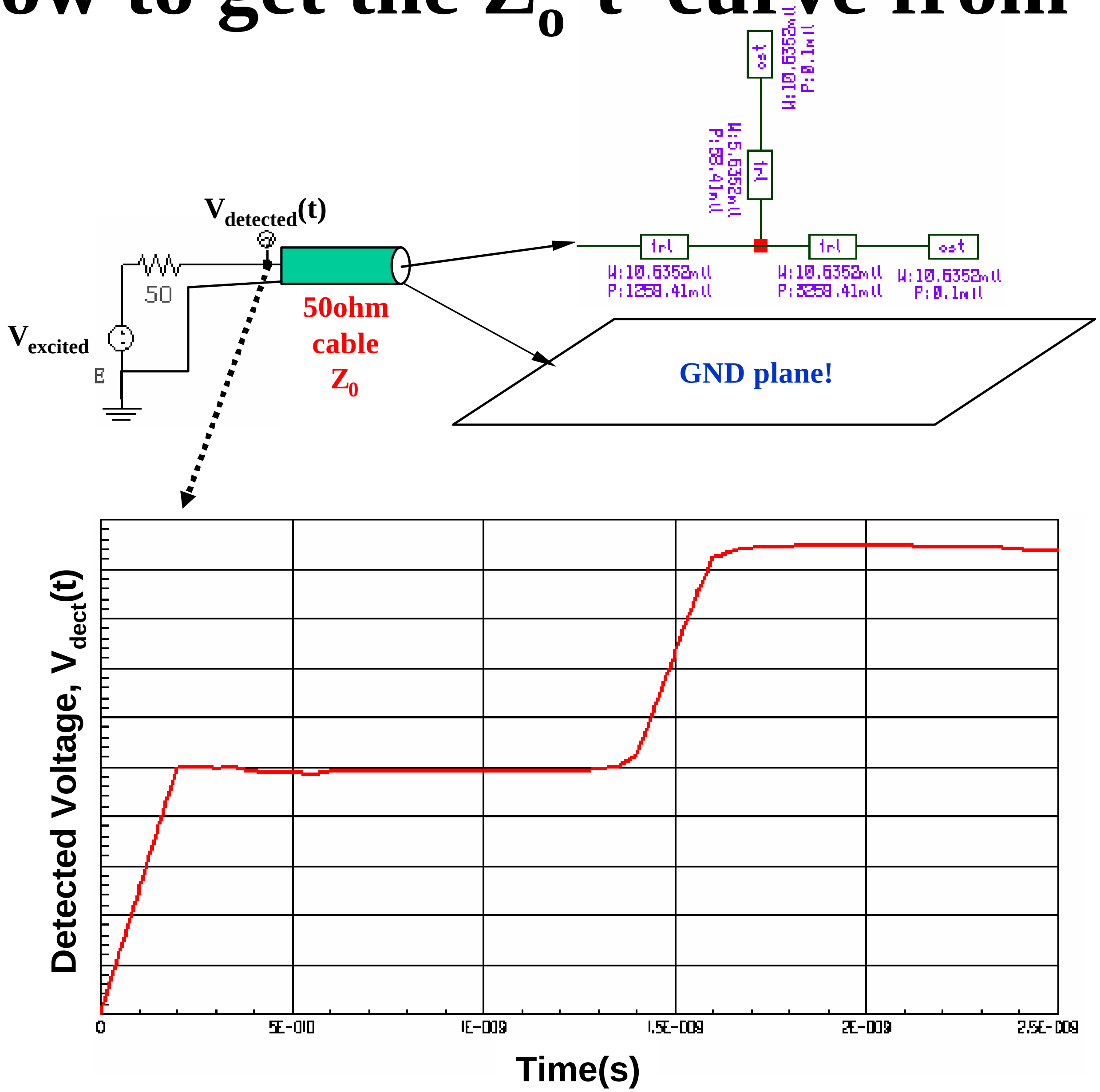
To Full_Wave SPICE format (*.fws)

```
#
#  S-parameter data for model one_port_bench
#
 Nports = 1
Freq_min = 0.0
Freq_max = 1e+010
 Npoints = 1001
   Zref = 50
#
      0          0.999958       -180
      0.01       0.99128        -5.067692
      0.02       0.98917        -10.100583
      0.03       0.98682        -15.140406
…………
     9.98        0.43084        -9.583413
     9.99        0.43611        -13.602669
     10.00       0.44109        -17.565645
# end of file
```

Simulate it in Full_Wave_SPICE



How to get the Z_o-t curve from V-t?



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How to get the Z_c-t curve from V-t? (cont'd)

$$V_{\text{detected}}(t) = V_{inc} + V_{reflect}(t)\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$where\, V_{inc} = \frac{Z_0}{50+Z_0} V_{excited}$$

$$\Theta\ \frac{V_{reflect}(t)}{V_{inc}} = \Gamma_{(tested)}(t) = \frac{Z_L(t)-Z_0}{Z_L(t)+Z_0} \xrightarrow{from(1)} \frac{V_{\text{detected}}(t)-V_{inc}}{V_{inc}} = \frac{Z_L(t)-Z_0}{Z_L(t)+Z_0}$$

$$\Rightarrow \frac{V_{\text{detected}}(t)}{V_{inc}} = \frac{2Z_L(t)}{Z_L(t)+Z_0} \ \Rightarrow\ Z_L(t) = \frac{V_{\text{detected}}(t)}{2V_{inc} - V_{\text{detected}}(t)} Z_0$$

$$if\ \ Z_0 = 50\Omega,\, then \qquad V_{inc} = \frac{V_{excited}}{2}$$

$$\therefore Z_L(t) = \frac{V_{\text{detected}}(t)}{V_{excited} - V_{\text{detected}}(t)} \cdot 50$$

$V_{excited}$ is user definable when doing the SPICE simulation

$V_{\text{detected}}(t)$ is node voltage at the input, which is calculated form the Full_Wave_SPICE.

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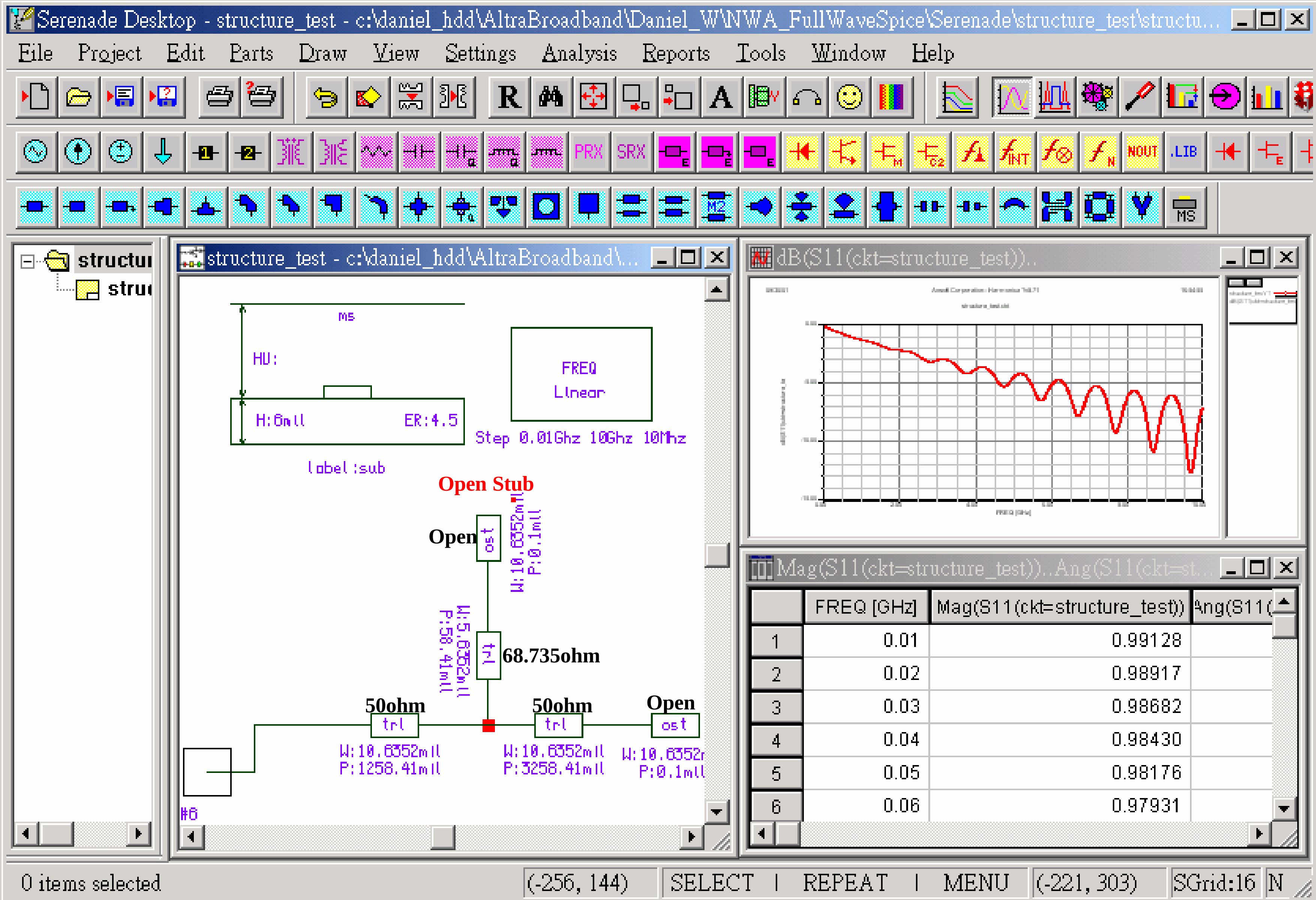
Example from VNA to TDR

1st, let's used the Harmonica to generate the virtual measurement data.



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Example from VNA to TDR (cont'd)

2nd, modify the file format of *.s1p into Full_Wave_SPICE format

GHz S MA R 50.000000

0.010000	0.994813	-3.004953
0.020000	0.993534	-5.986811
0.030000	0.992128	-8.973242
…………		
9.980000	0.624802	141.488164
9.990000	0.623542	139.131339
10.000000	0.622256	136.766395

Manually add file header, ending and DC information!

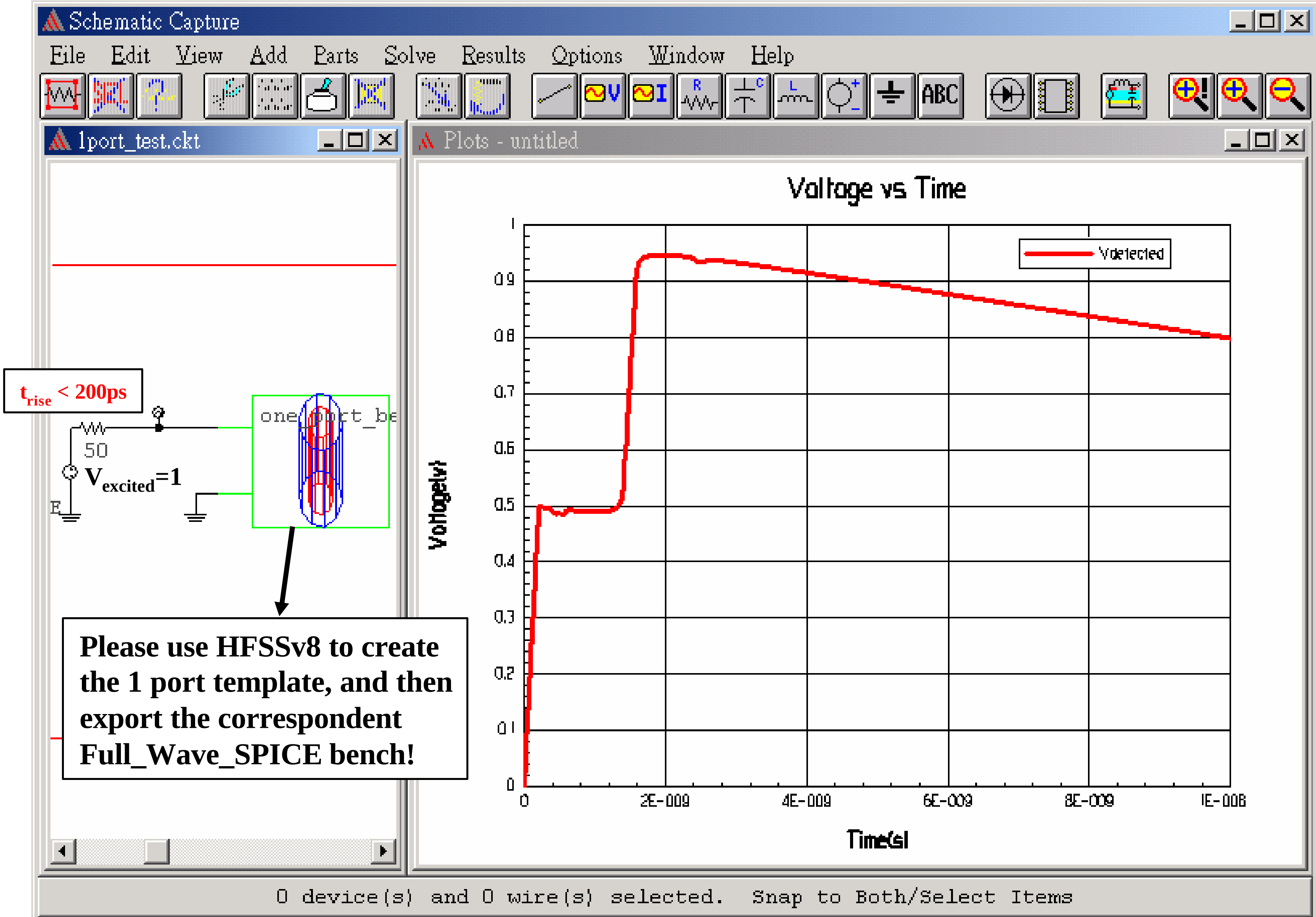
#
S-parameter data for model one_port_bench
#
Nports = 1
Freq_min = 0.0
Freq_max = 1e+010
Npoints = 1001
Zref = 50
#

0	0.999958	-180
0.01	0.99128	-5.067692
0.02	0.98917	-10.100583
0.03	0.98682	-15.140406
…………		
9.98	0.43084	-9.583413
9.99	0.43611	-13.602669
10.00	0.44109	-17.565645

end of file

Example from VNA to TDR (cont'd)

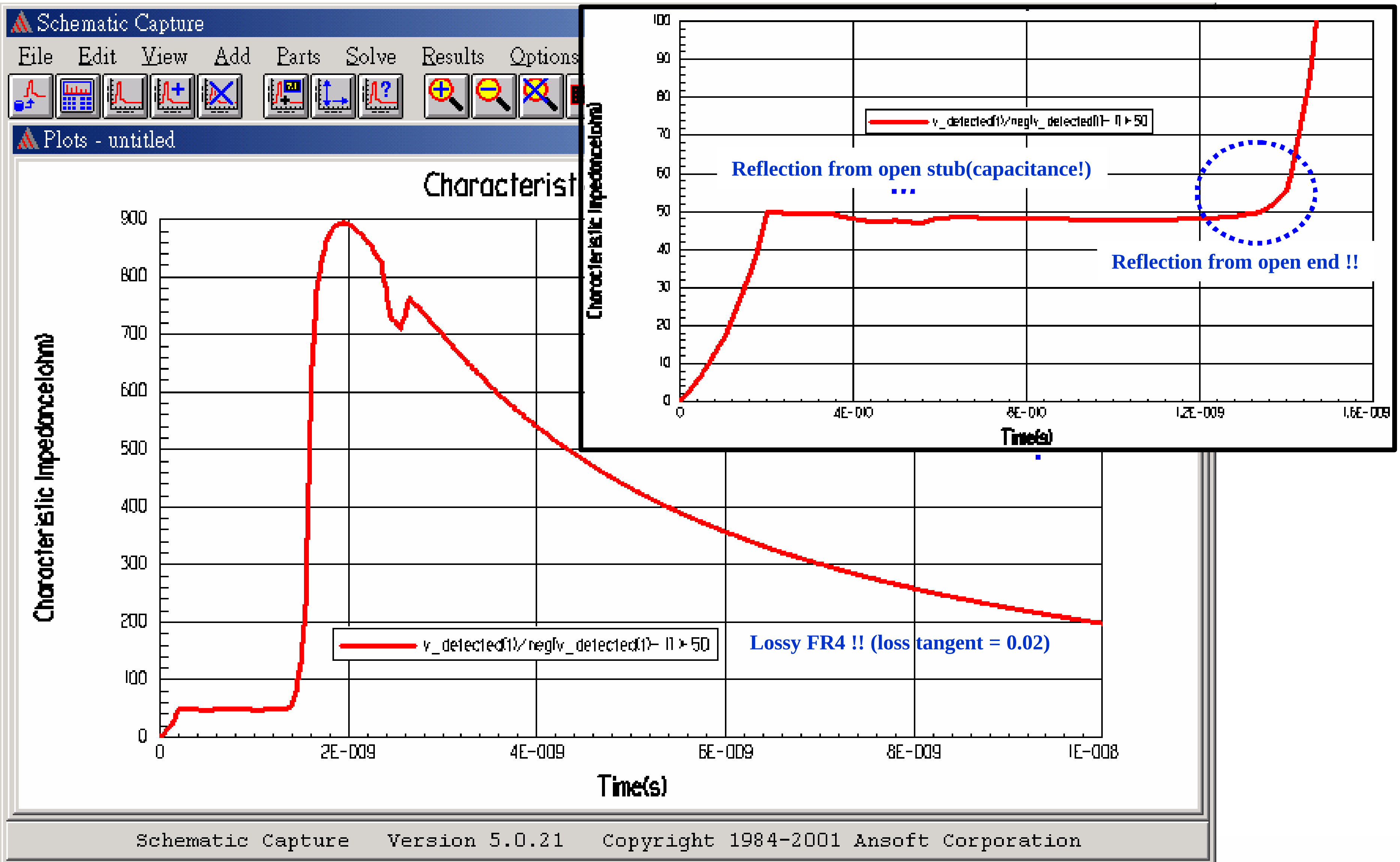
3rd, run the Full_Wave_SPICE to get the voltage waveform at input node.



Example from VNA to TDR (cont’d)

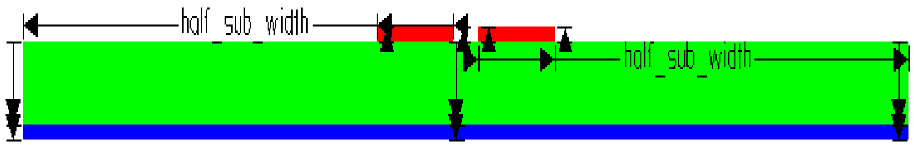
4th, use the waveform calculator to translate the V-t curve into Z_0-t curve.

In schematic capture, Result → Calculator → apply [$V_{detected}$(t)/(neg($V_{detected}$(t)-1))]*Z_0



Overview
for
Differential and Common Mode Impedance

Impedance for Differential Pair



The characteristic impedance should be a 2x2 matrix

$$Z_0 = \begin{bmatrix} Z_{011} & Z_{012} \\ Z_{012} & Z_{022} \end{bmatrix}$$

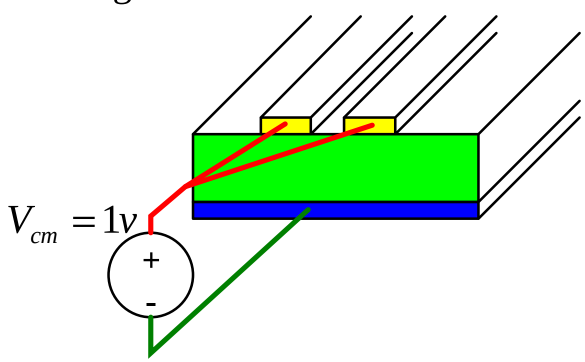
Recall that the characteristic impedance matrix relates the line voltage to the line current as follows:

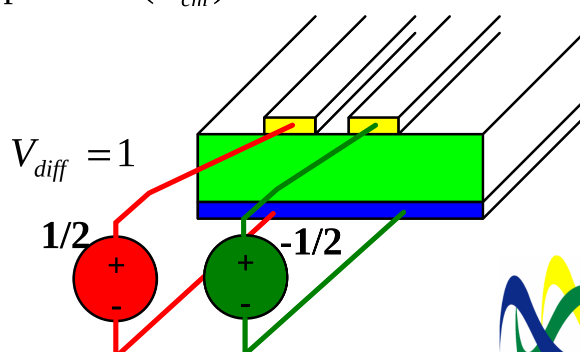
$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = Z_0 \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + reflection\ term$$

If we replace the $\begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$ & $\begin{bmatrix} i_1 \\ i_2 \end{bmatrix}$ (node v & i) with $\begin{bmatrix} v_{m1} = a_1 v_1 + a_2 v_2 \\ v_{m2} = a_3 v_1 + a_4 v_2 \end{bmatrix}$ & $\begin{bmatrix} i_{m1} = b_1 i_1 + b_2 i_2 \\ i_{m2} = b_1 i_1 + b_2 i_2 \end{bmatrix}$ (modal v & i)

then Z_0 will become $\begin{bmatrix} Z_{0even} & 0 \\ 0 & Z_{0odd} \end{bmatrix}$

If you *excite* the differential pair equally or differentially,
then the signals will suffer from common mode impedance (Z_{cm}) and differential mode impedance(Z_{diff}), respectively.





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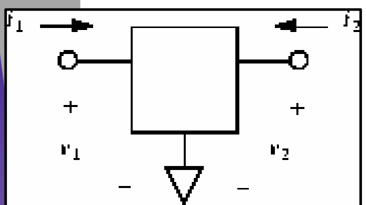
Impedance for Differential Pair(cont'd)

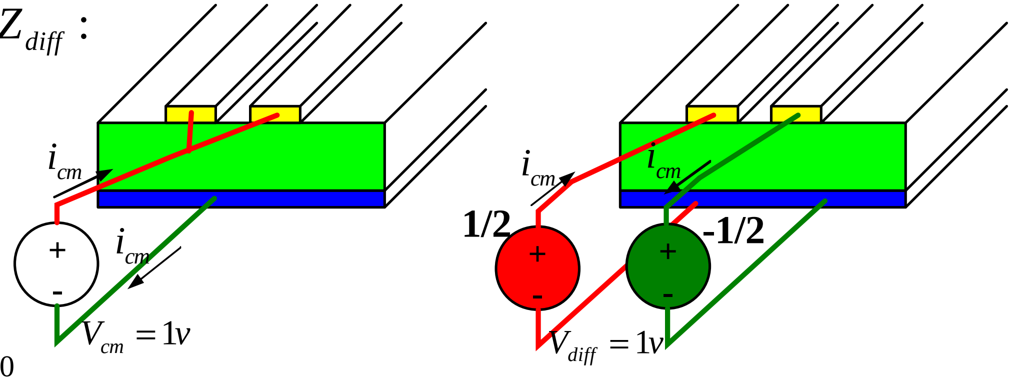
What's the relation between these impedances?

Relation between $Z_0 = \begin{bmatrix} Z_{011} & Z_{012} \\ Z_{012} & Z_{022} \end{bmatrix}$ and Z_{cm}, Z_{diff} :



$$v_d = v_1 - v_2,\quad v_{cm} = \frac{v_1 + v_2}{2}$$

$$Z_{diff} = \left.\frac{v_d}{i_d}\right|_{v_{cm}=0},\quad Z_{cm} = \left.\frac{v_d}{i_{cm}}\right|_{v_d=0}$$



Let's set the differential voltage signal to 1 Volt and zero the common-mode signal

This implies $v_1 = 1/2 \quad v_2 = -1/2$

$$\begin{bmatrix} 1/2 \\ -1/2 \end{bmatrix} = \begin{bmatrix} Z_{011} & Z_{012} \\ Z_{012} & Z_{011} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \Rightarrow \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \frac{1}{Z_{011}^2 - Z_{012}^2} \begin{bmatrix} Z_{011} & -Z_{012} \\ -Z_{012} & Z_{011} \end{bmatrix} \begin{bmatrix} 1/2 \\ -1/2 \end{bmatrix} = \frac{1/2}{Z_{011}^2 - Z_{012}^2} \begin{bmatrix} Z_{011} + Z_{012} \\ -(Z_{011} + Z_{012}) \end{bmatrix}$$

$$i_1 = \frac{1}{2(Z_{011} - Z_{012})} = -i_2 \Rightarrow i_{diff} = \frac{1}{2(Z_{011} - Z_{012})} \quad \therefore \quad \boxed{Z_{diff} = 2(Z_{011} - Z_{012})}$$

Let's zero the differential-mode voltage and set the common-mode voltage to 1 Volt

This implies $v_1 = 1 \qquad v_2 = 1$

$$\begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} Z_{011} & Z_{012} \\ Z_{012} & Z_{011} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \Rightarrow \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \frac{1}{Z_{011}^2 - Z_{012}^2} \begin{bmatrix} Z_{011} & -Z_{012} \\ -Z_{012} & Z_{011} \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \frac{1}{Z_{011}^2 - Z_{012}^2} \begin{bmatrix} Z_{011} - Z_{012} \\ Z_{011} - Z_{012} \end{bmatrix}$$

$$i_1 = i_2 = \frac{1}{Z_{011} + Z_{012}} \Rightarrow i_{cm} = \frac{2}{Z_{011} + Z_{012}} \quad \therefore \quad \boxed{Z_{cm} = \frac{Z_{011} + Z_{012}}{2}}$$

This slide refer the paper from Ansoft's AN, "Differential Pair Analysis" by J. Eric Bracken
and Tektronixs' presentation slide, "FibreChannel Interconnect Signal Integrity Measurement and Modeling Methodologies" by Dima Smolyansky, Dima@tdasystems.com
and CYPRESS Semiconductor Corporation's AN, "Termination and Biasing of HOTLinkII™ High-Speed Serial I/O"

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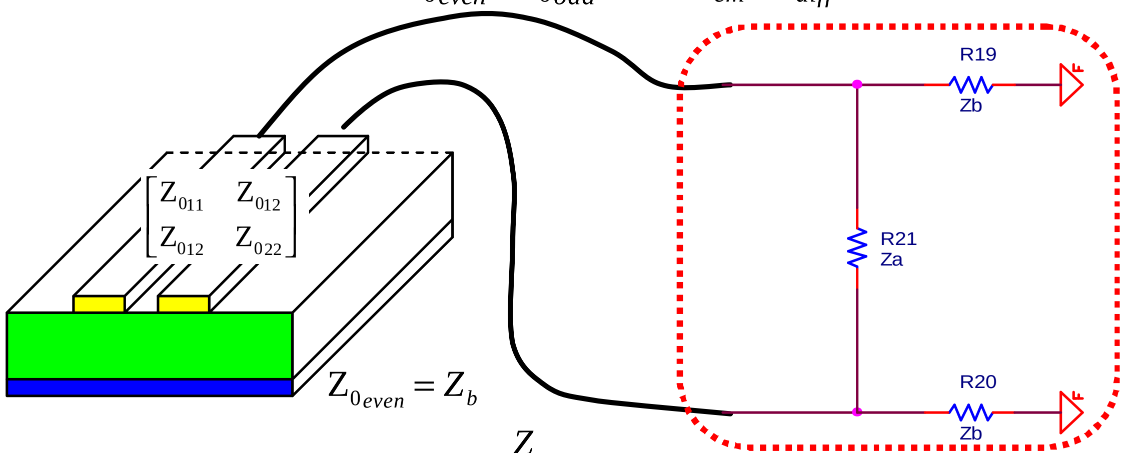
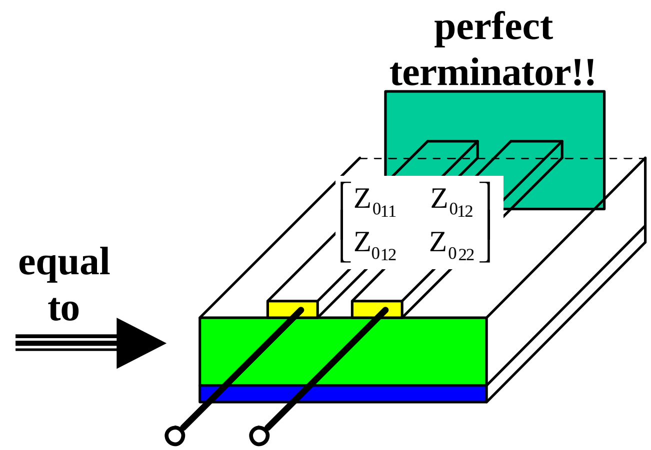
Impedance for Differential Pair(cont'd)

Relation between Z_{0even}, Z_{0odd} and Z_{cm}, Z_{diff} :





$$Z_{0even} = Z_b$$

$$Z_{0odd} = Z_b \,//\, \frac{Z_a}{2}$$

$$Z_{cm} = \frac{Z_b}{2} \xleftrightarrow{\text{from previous page}} 2(Z_{011} - Z_{012})$$ could be obtained from SPICELINK SI2D

$$Z_{diff} = 2Z_b \,//\, Z_a \xleftrightarrow{\text{from previous page}} \frac{Z_{011} + Z_{012}}{2}$$ could be obtained from SPICELINK SI2D

that is, Z_{cm}, R_b, Z_{diff} are not that difficult to be obtained!

$$\therefore Z_{0odd} = Z_b \,//\, \frac{Z_a}{2} \Leftrightarrow Z_{0odd} = \frac{Z_b \cdot \frac{Z_a}{2}}{Z_b + \frac{Z_a}{2}} \Leftrightarrow Z_a = \frac{2 \cdot Z_b \cdot Z_{0odd}}{Z_b - Z_{0odd}}$$

$$\boxed{Z_{cm} = \frac{Z_b}{2} = \frac{Z_{0even}}{2} = \frac{Z_{011} + Z_{012}}{2}}$$

$$\boxed{Z_{diff} = 2Z_b \,//\, Z_a} = \frac{2Z_b \cdot Z_a}{2Z_b + Z_a} = \frac{Z_b \cdot Z_a}{Z_b + \frac{Z_a}{2}} = 2 \cdot \frac{Z_b \cdot \frac{Z_a}{2}}{Z_b + \frac{Z_a}{2}} = 2 \cdot \left(Z_b \,//\, \frac{Z_a}{2} \right) \boxed{= 2 \cdot Z_{0odd} = 2(Z_{011} - Z_{012})}$$

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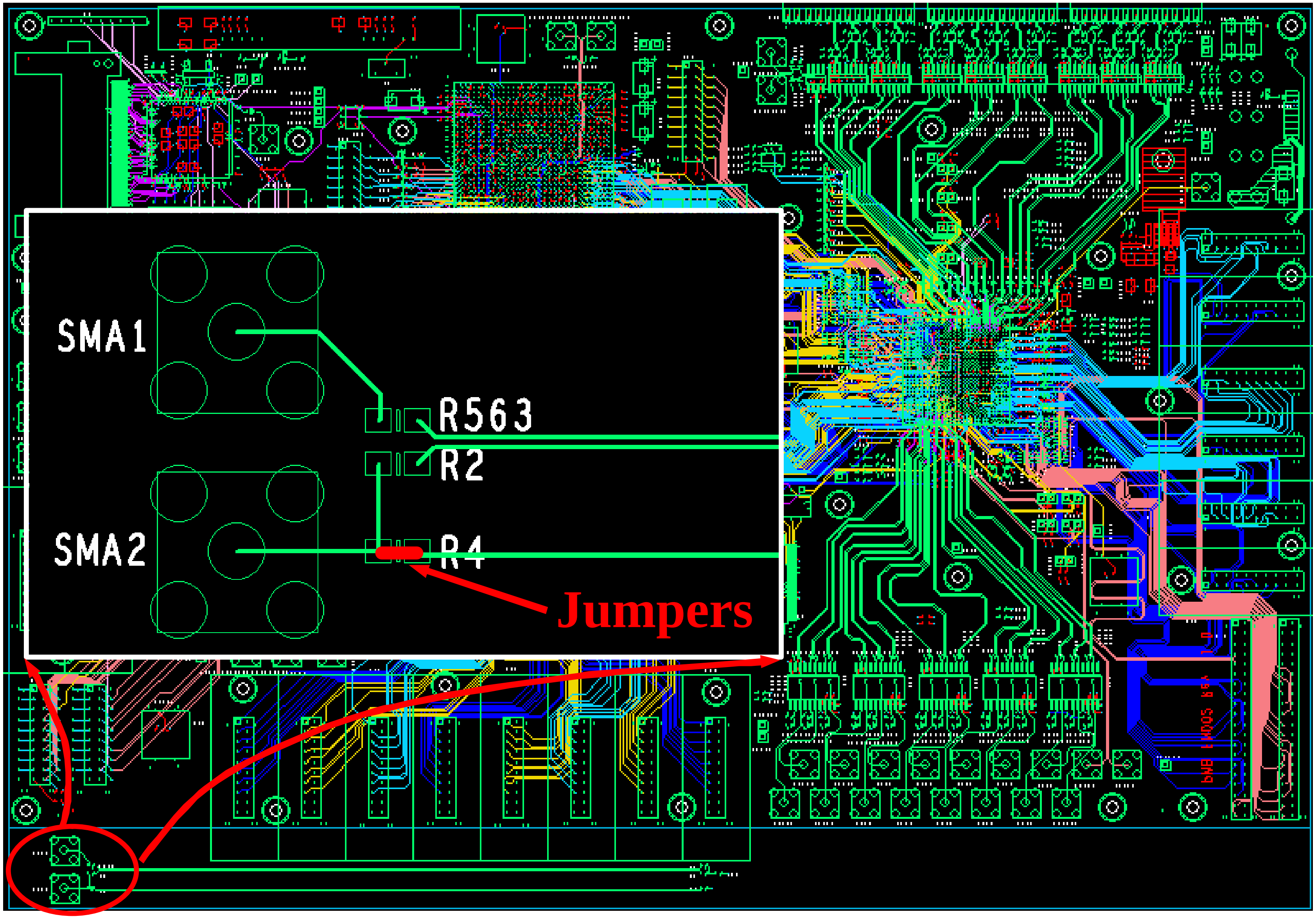
Practical Example
with
Measurement Data Verified

Single_ended Impedance



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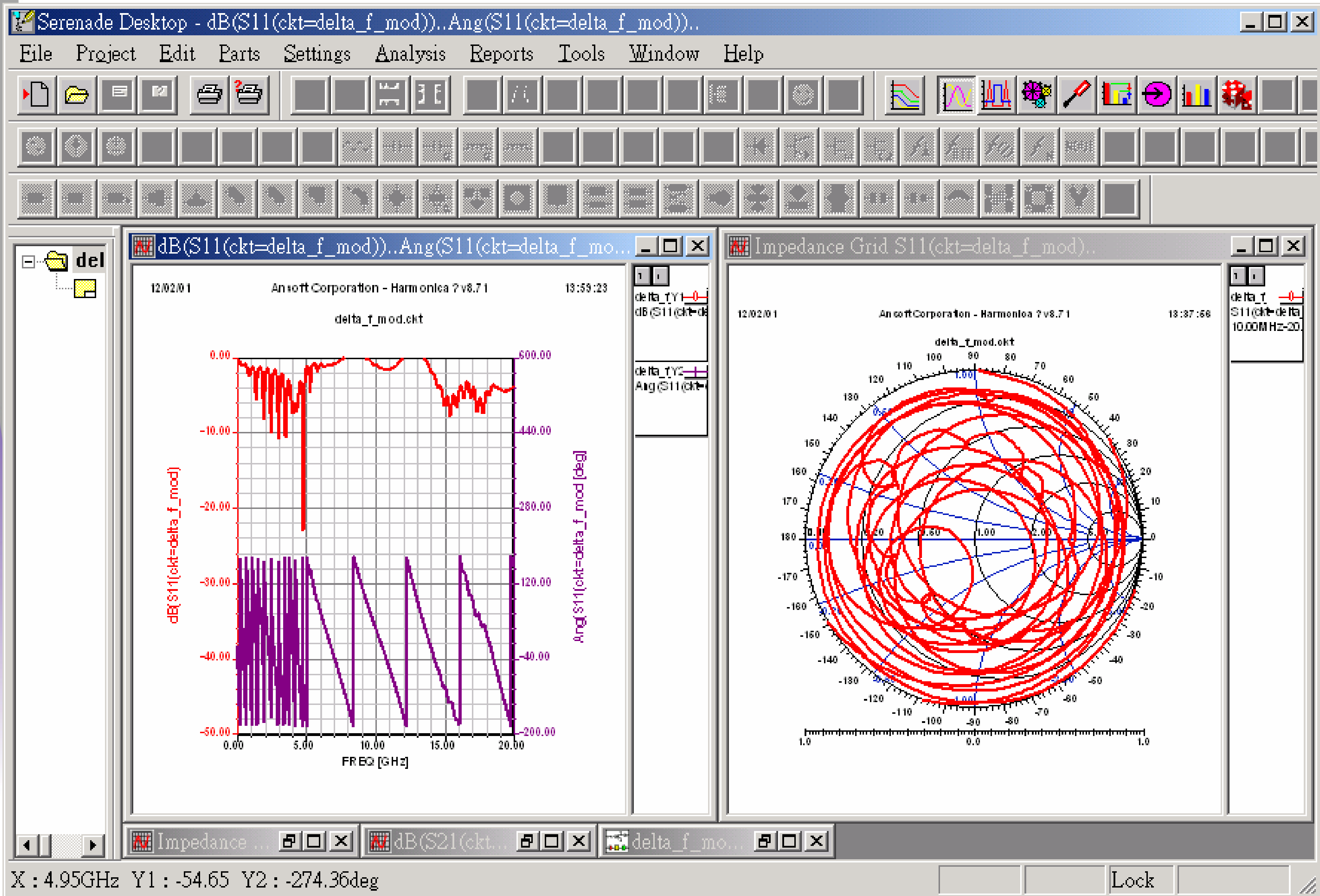
1-Port S-parameter for Single_ended TRL



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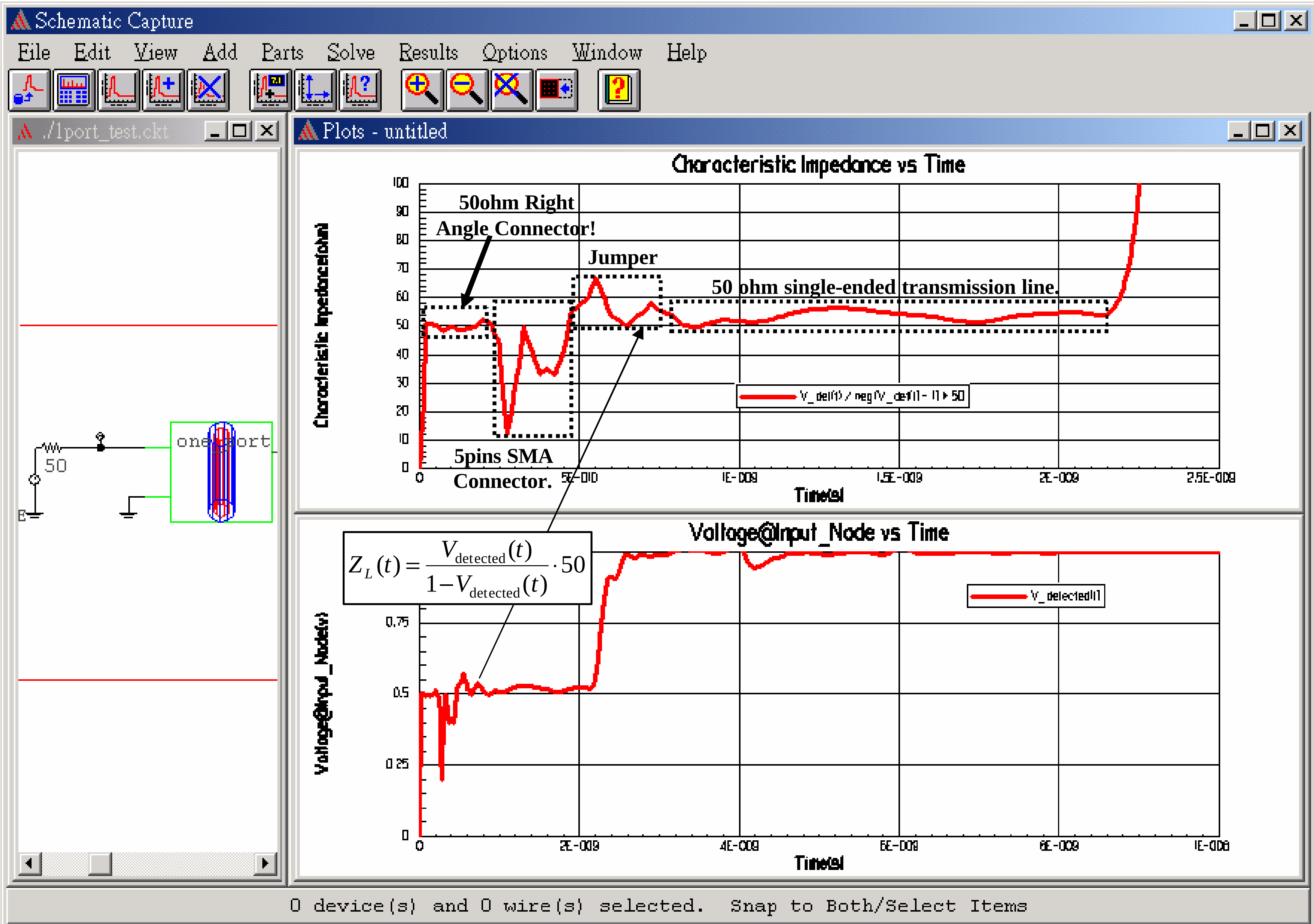
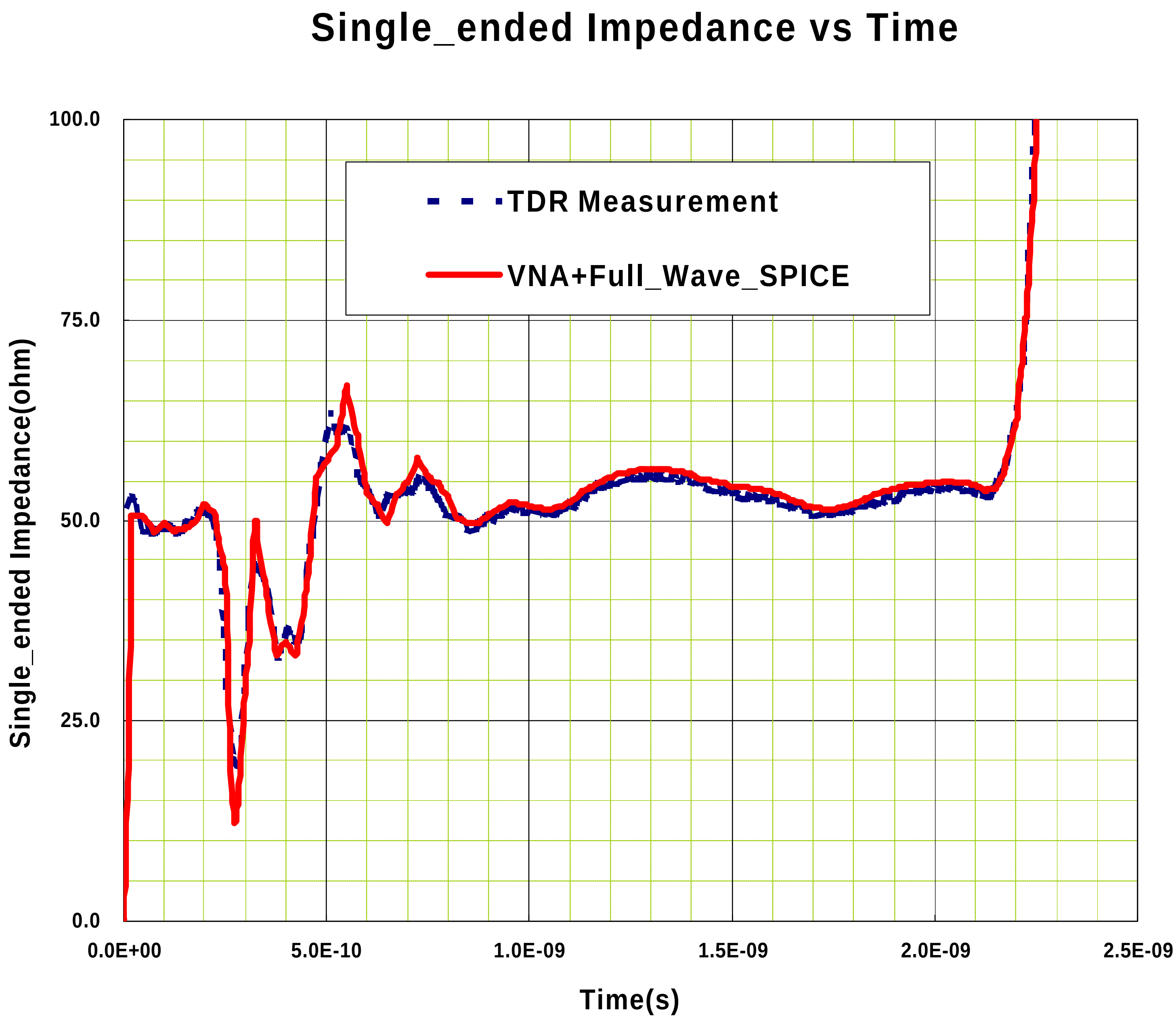
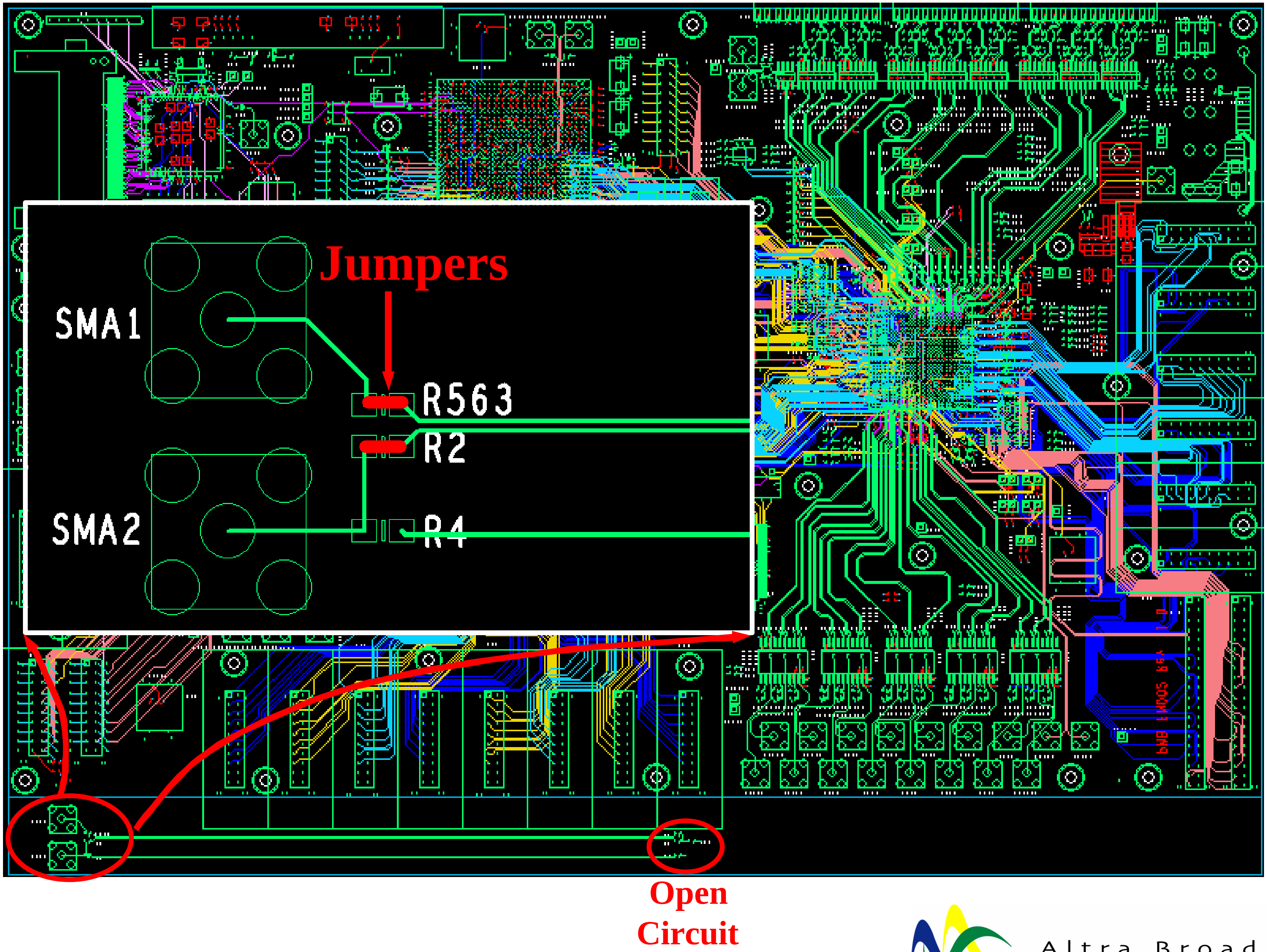
Voltage Waveform Sim and Single_ended Impedance Derivation In FWS



Single_ended Impedance Comparison with Real TDR



Differential Impedance



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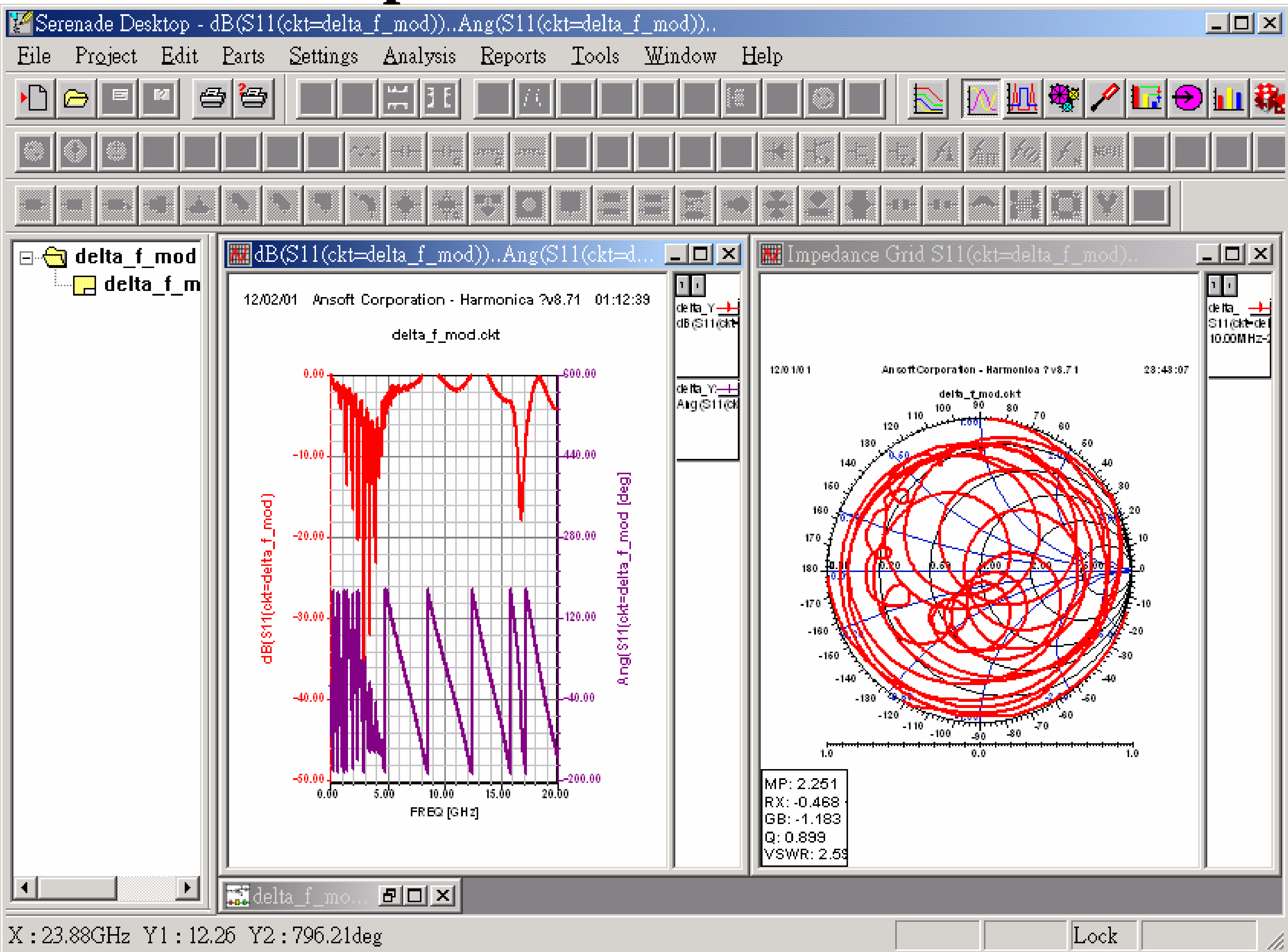
Full 2-Port S-parameter for Differential TRL



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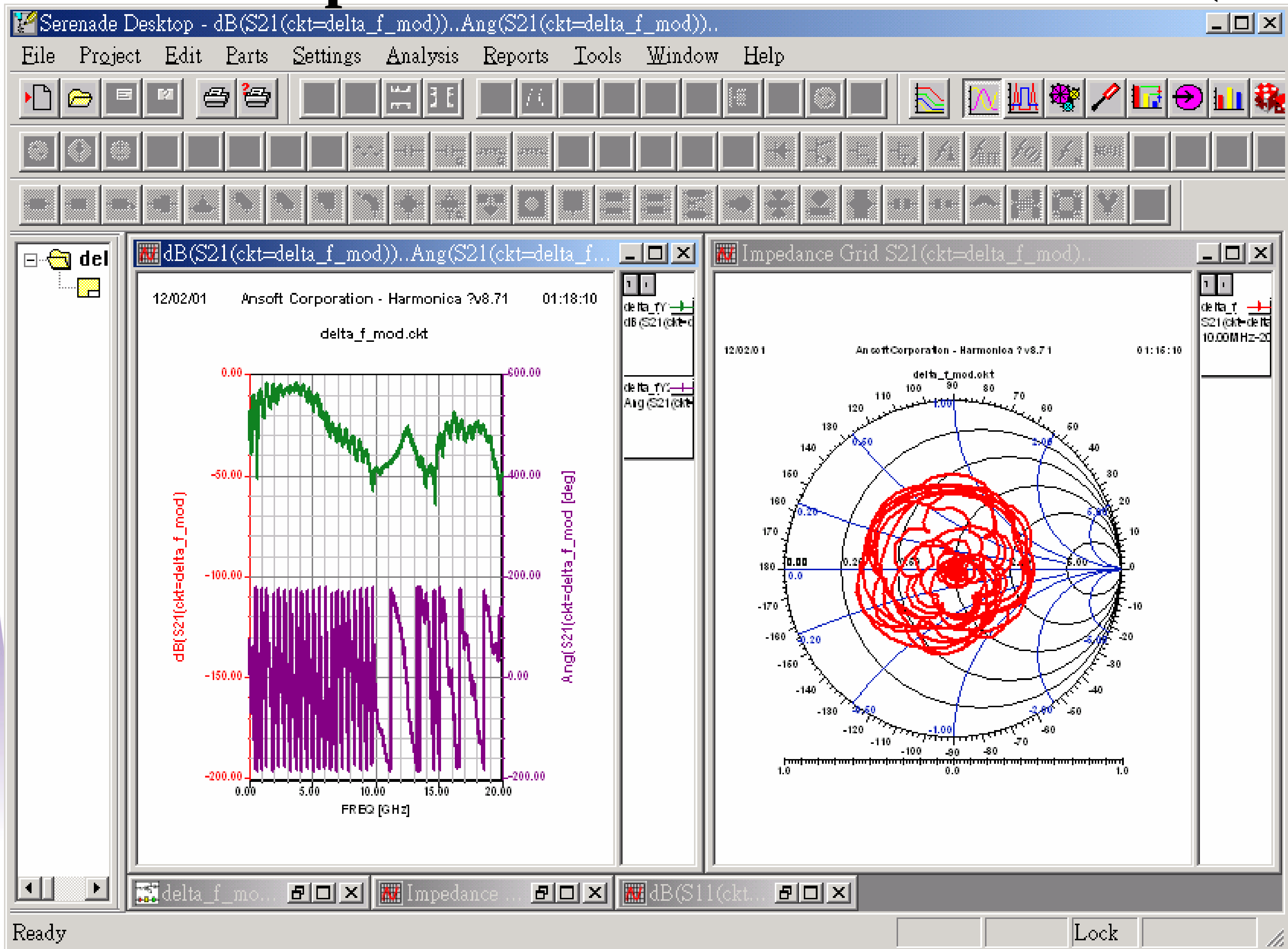
Full 2-Port S-parameter for Differential TRL(cont'd)



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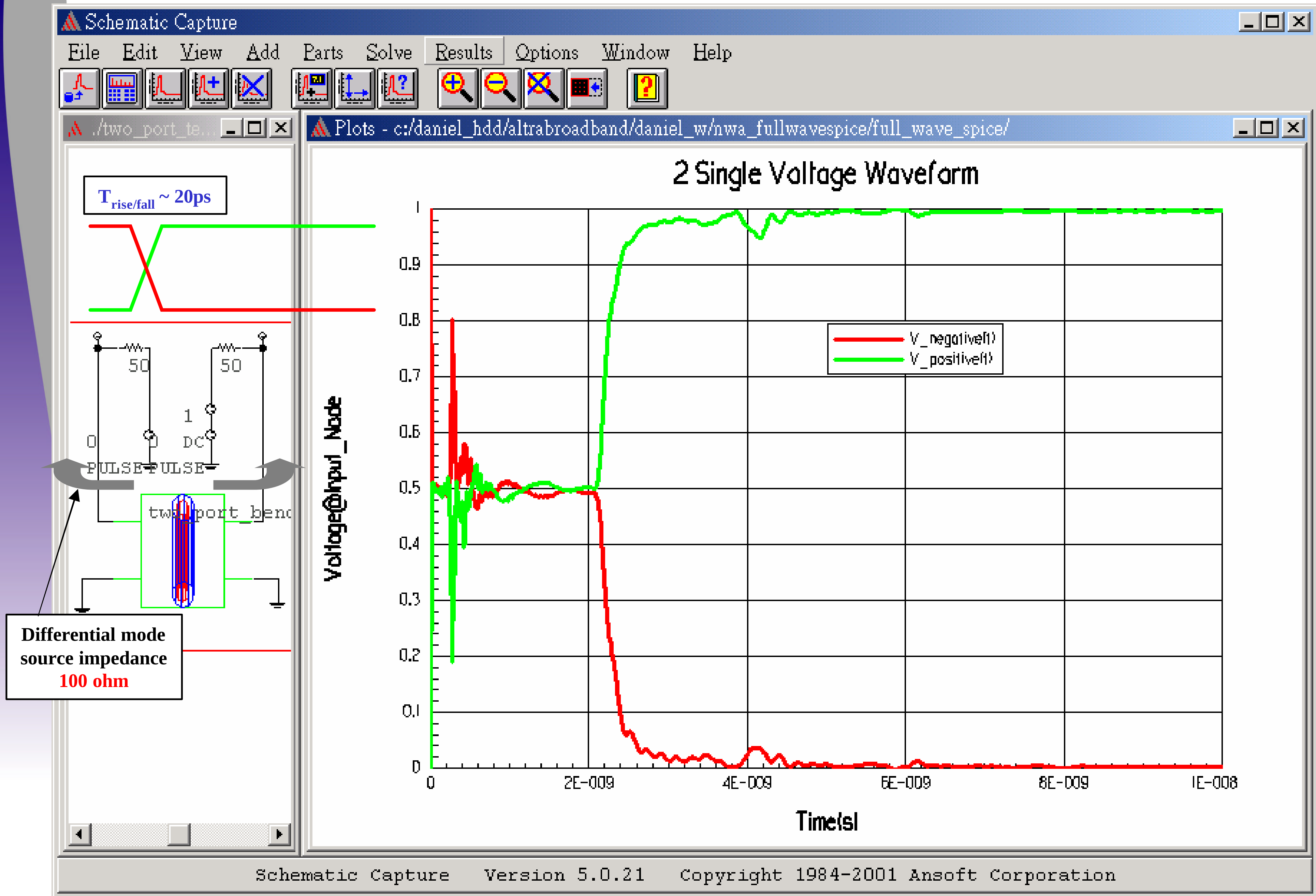
Full Wave SPICE Voltage Waveform Simulation



How to get the $Z_{c(diff)}$-t curve from $V_{(diff)}$-t?

$$V_{det\_diff}(t) = V_{initial\_diff} + V_{inc\_diff} + V_{refl\_diff}(t) \ldots\ldots\ldots\ldots (1)$$

$$where\ V_{inc\_diff} = V_{inc+} - V_{inc-} = \left(V_{excited+} \cdot \frac{Z_{0\_fixture}}{50 + Z_{0\_fixrure}}\right) - \left(V_{excited-} \cdot \frac{Z_{0\_fixture}}{50 + Z_{0\_fixrure}}\right)$$

$$\therefore \text{if we set } V_{excited+} = 1, V_{excited-} = \text{-}V_{excited+} \text{ and } Z_{0\_fixture} = 50, \text{ then } V_{inc\_diff} = 1 \text{ and } Z_{0\_diff} = 100\Omega$$

$$\Theta\ \frac{V_{refl\_diff}(t)}{V_{inc\_diff}} = \Gamma_{diff}(t) = \frac{Z_{L\_diff}(t) - Z_{0\_diff}}{Z_{L\_diff}(t) + Z_{0\_diff}} \xrightarrow{from\,(1)} \frac{V_{det\_diff}(t) - V_{inc\_diff} - V_{initial\_diff}}{V_{inc\_diff}} = \frac{Z_{L\_diff}(t) - Z_{0\_diff}}{Z_{L\_diff}(t) + Z_{0\_diff}}$$

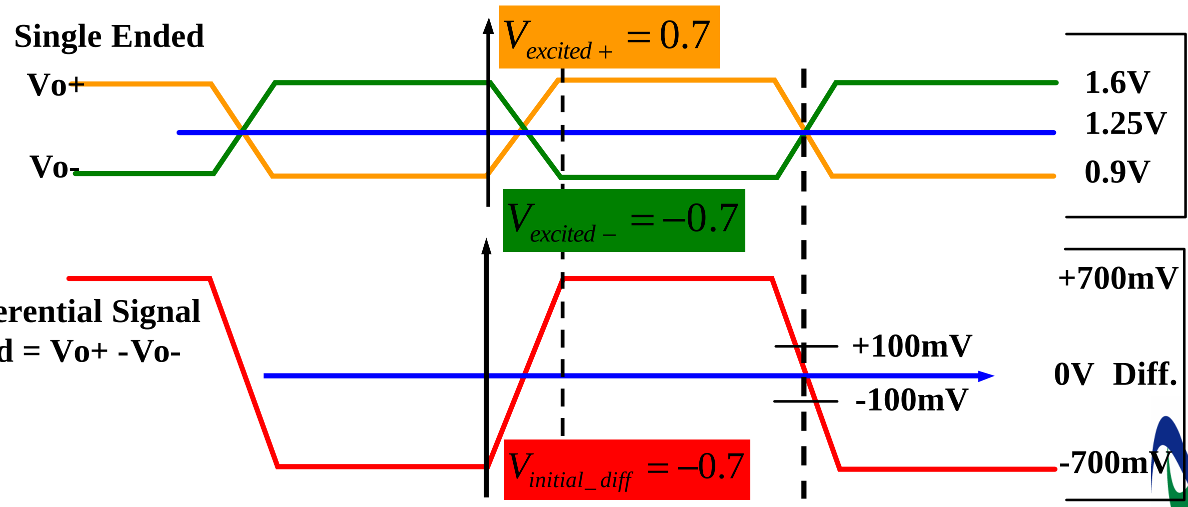
$$\Rightarrow \frac{V_{det\_diff}(t) - V_{initial\_diff}}{V_{inc\_diff}} = \frac{2Z_{L\_diff}(t)}{Z_{L\_diff}(t) + Z_{0\_diff}} \Rightarrow Z_{L\_diff}(t) = \frac{V_{det\_diff}(t) - V_{initial\_diff}}{2V_{inc\_diff} - V_{det\_diff}(t) + V_{initial\_diff}} \cdot Z_{0\_diff}$$

$$\Theta \text{ if } V_{excited+} = 1, \text{ then } V_{initial\_diff} = \text{-}1\ \therefore Z_{L\_diff}(t) = \frac{V_{det\_diff}(t) + 1}{2 - V_{det\_diff}(t) - 1} \cdot Z_{0\_diff} = \frac{1 + V_{det\_diff}(t)}{1 - V_{det\_diff}(t)} \cdot Z_{0\_diff}$$

$$\therefore Z_{L\_diff}(t) = \frac{1 + V_{det\_diff}(t)}{1 - V_{det\_diff}(t)} \cdot 100,$$ V_{inc_diff} & $V_{initial\_diff}$ are user definable when doing the SPICE simulation

$V_{det\_diff}(t)$ is node voltage at the differential input, which is calculated form the Full_Wave_SPICE.

Ex:



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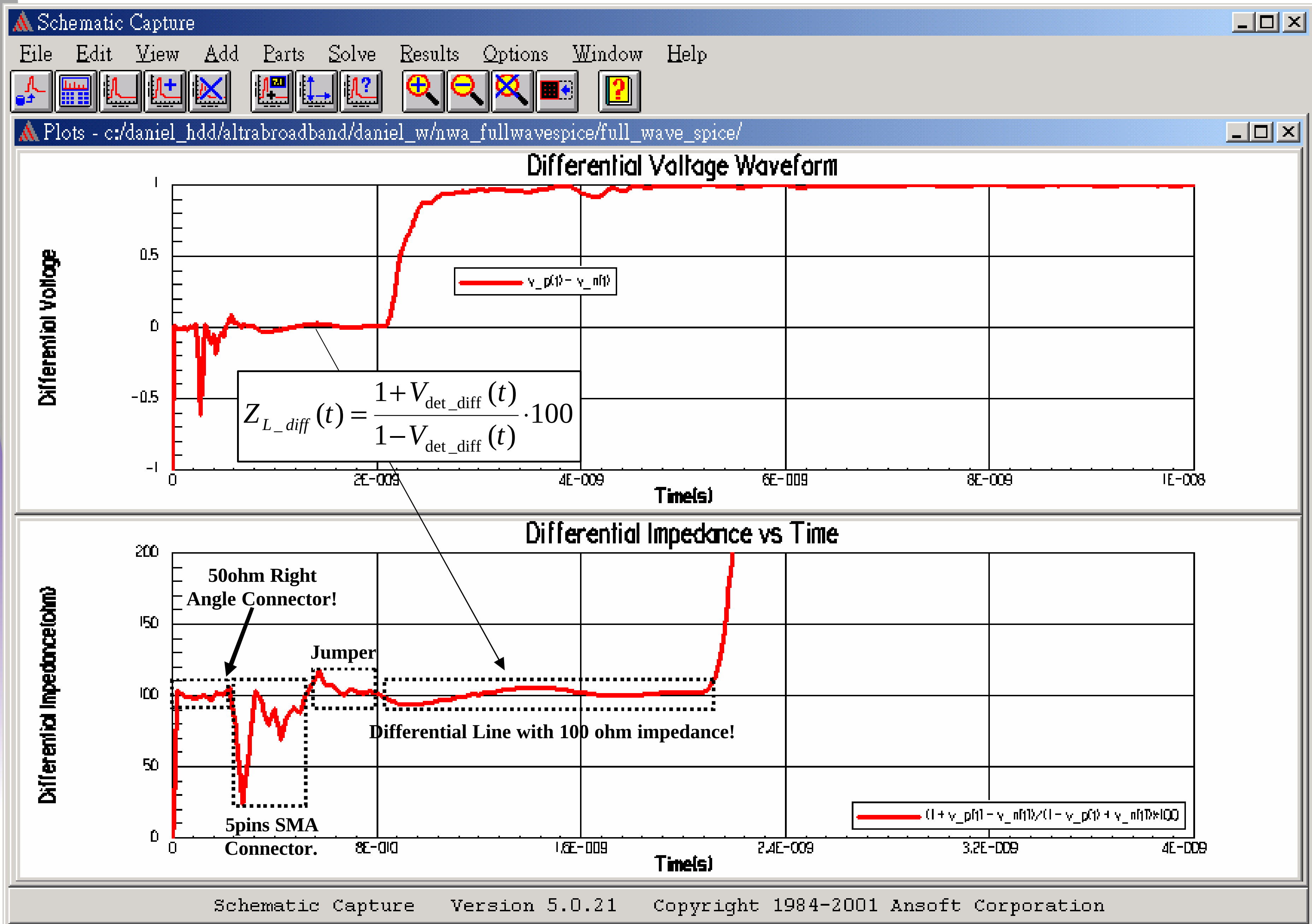
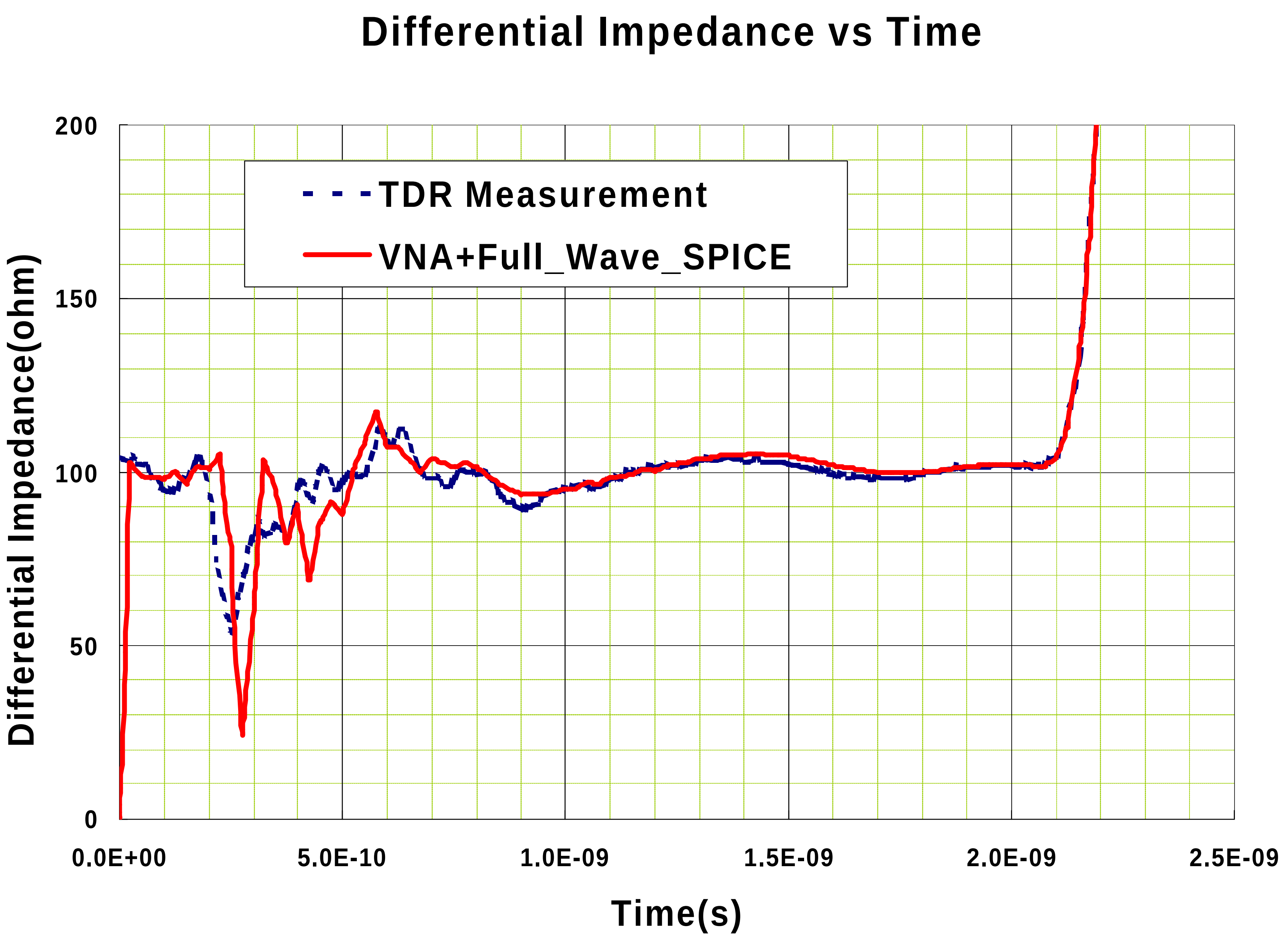
Differential Impedance Derivation in Full Wave SPICE



Differential Impedance Comparison with Real TDR



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SMA Connector Modeling
and
its Application
for
Critical Net Simulation

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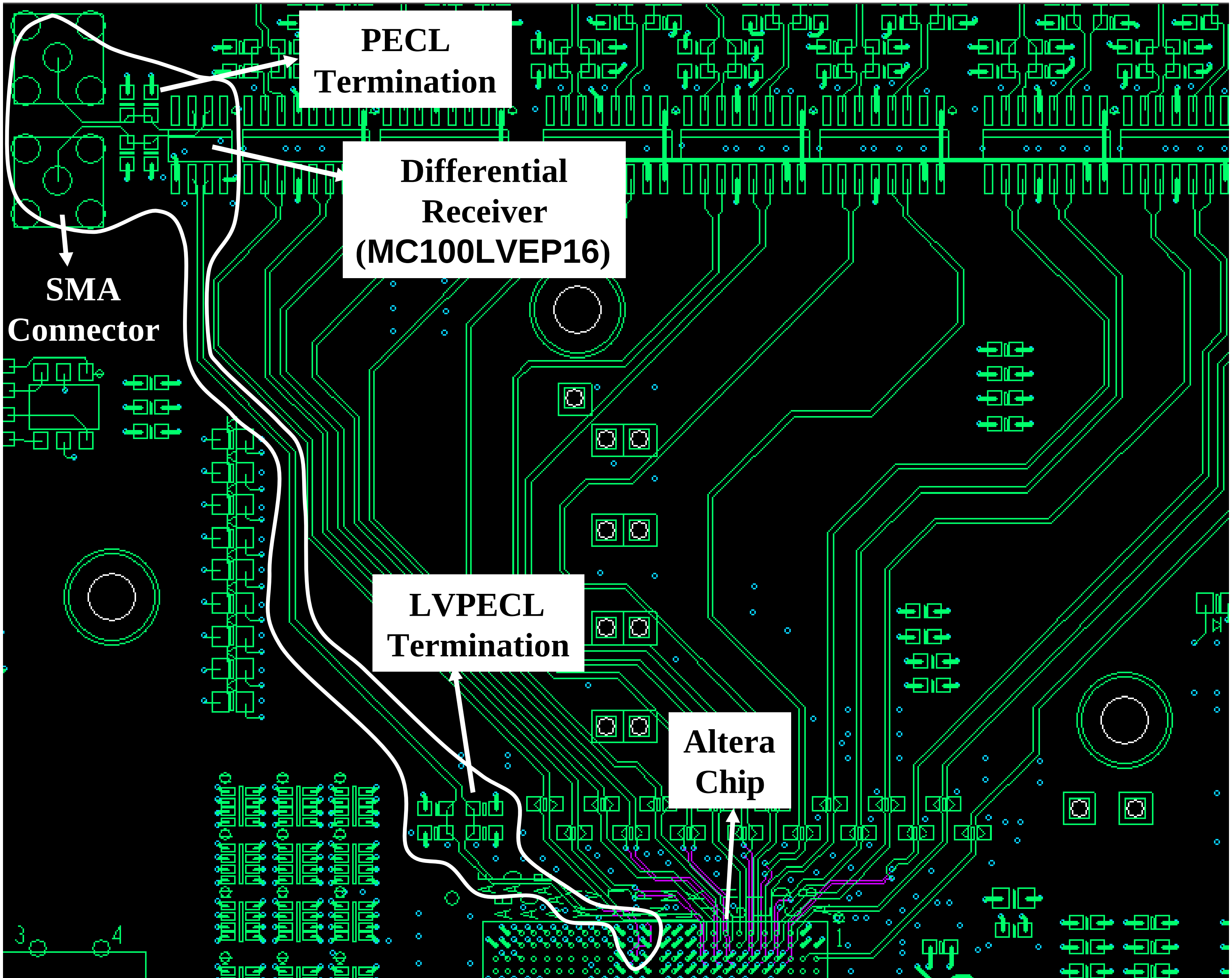
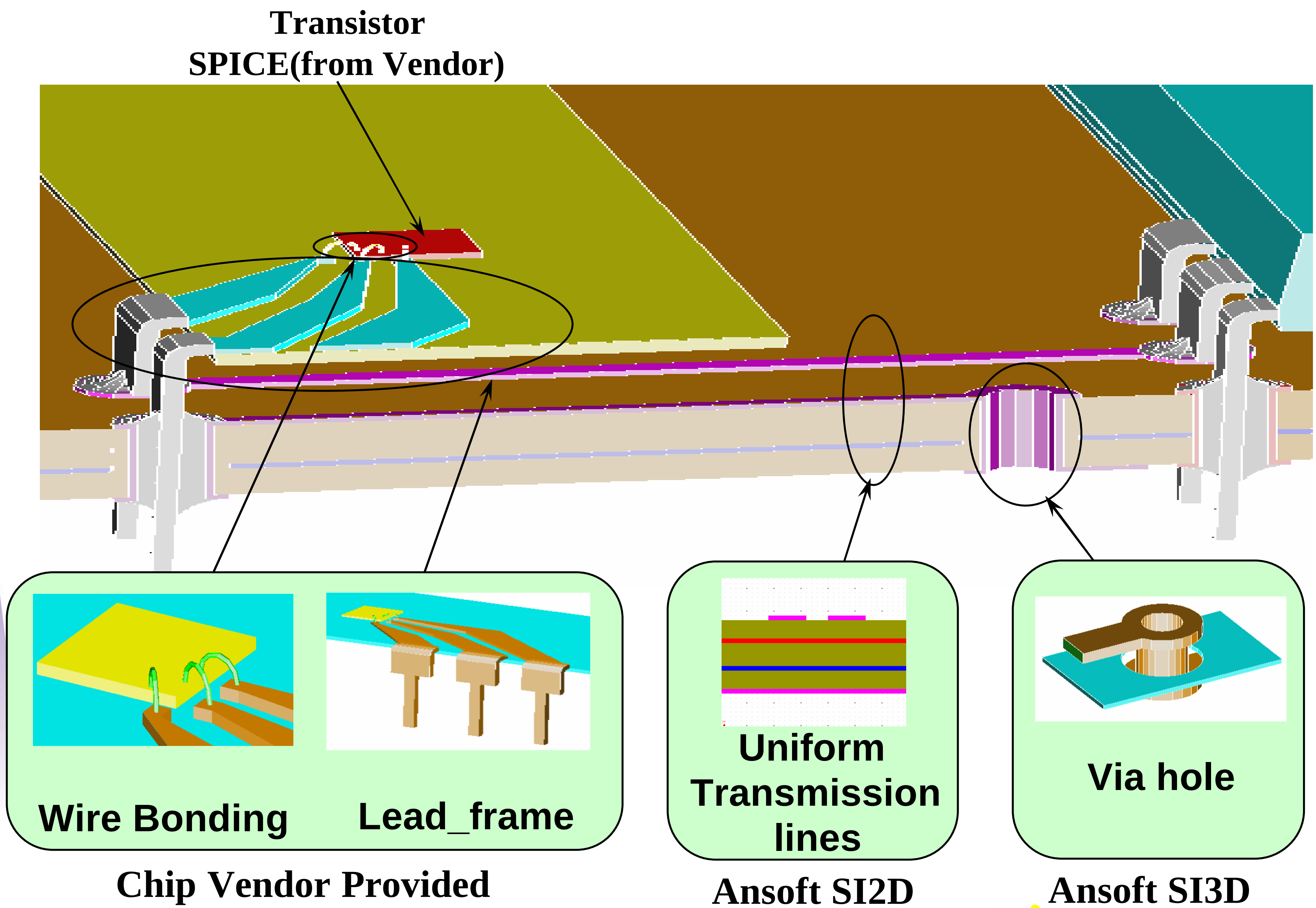
Critical Net Location



Analysis Strategy



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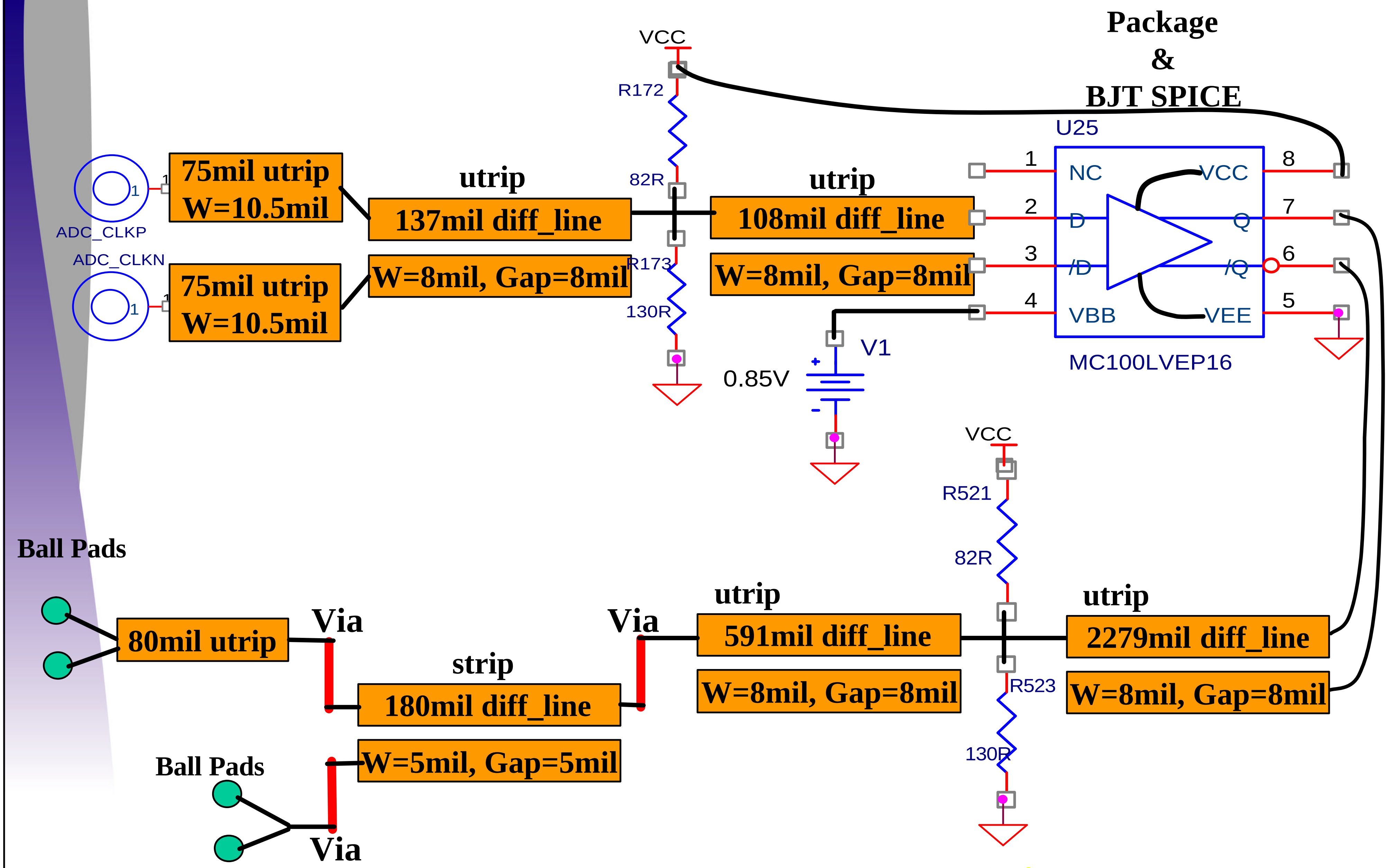
SPICE Deck for Simulation



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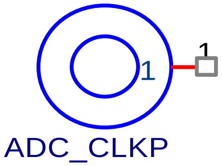
Where to get the SPICE Model?



Modeling from Tektronix TDR measurement

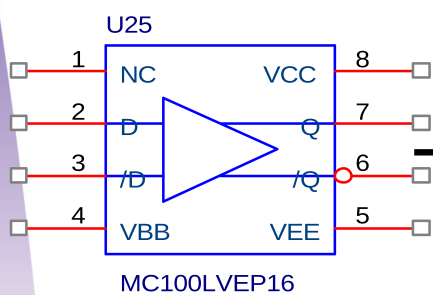
**mil utrip

Modeling from Ansoft SI2D

***mil diff_line

W=8mil, Gap=8mil

Modeling from Ansoft SI2D



Chip-vendor provided package and transistor level model (www.onsemi.com)

Modeling from Ansoft SI3D

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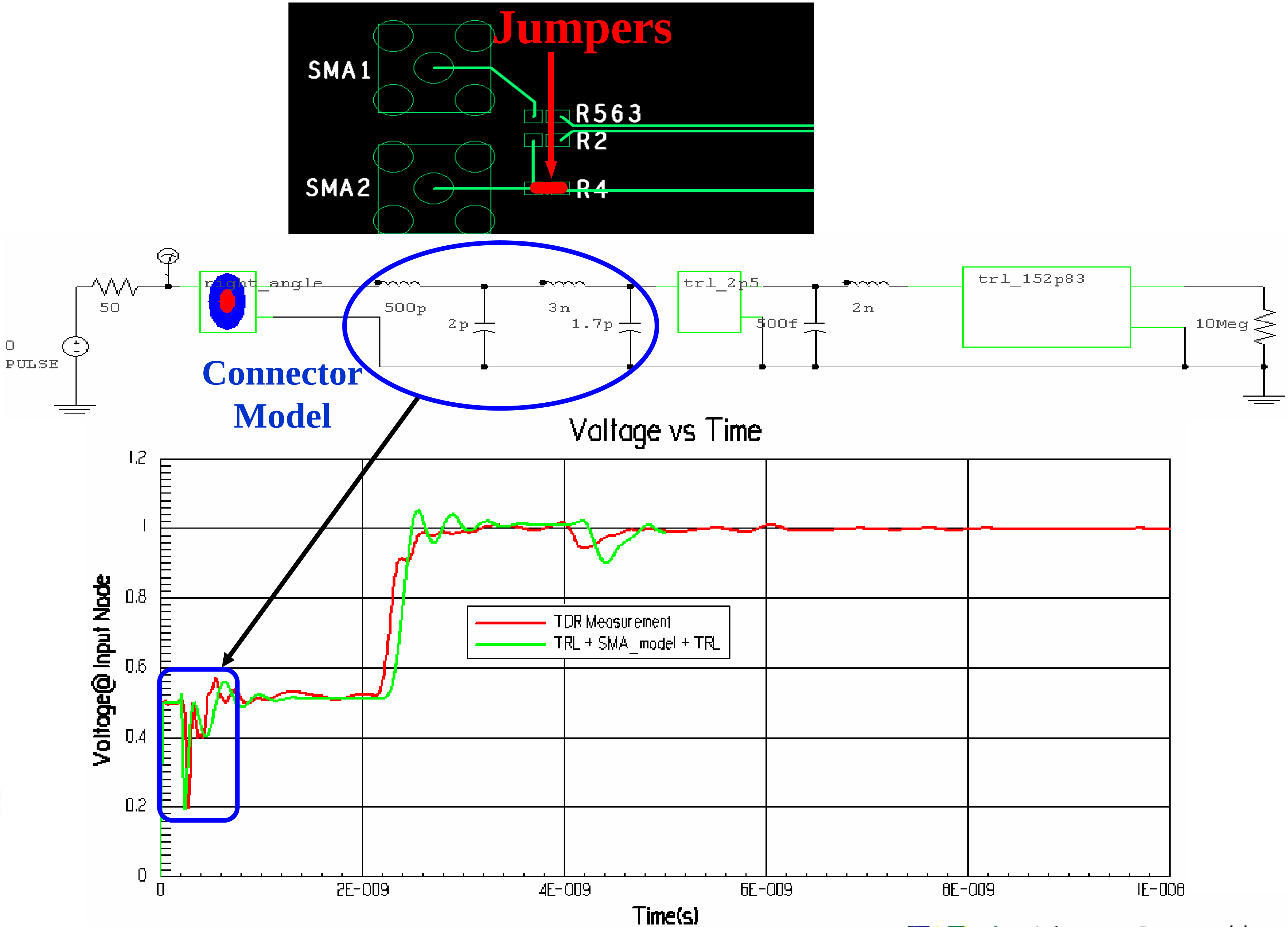
SMA Modeling from TDR Measurement



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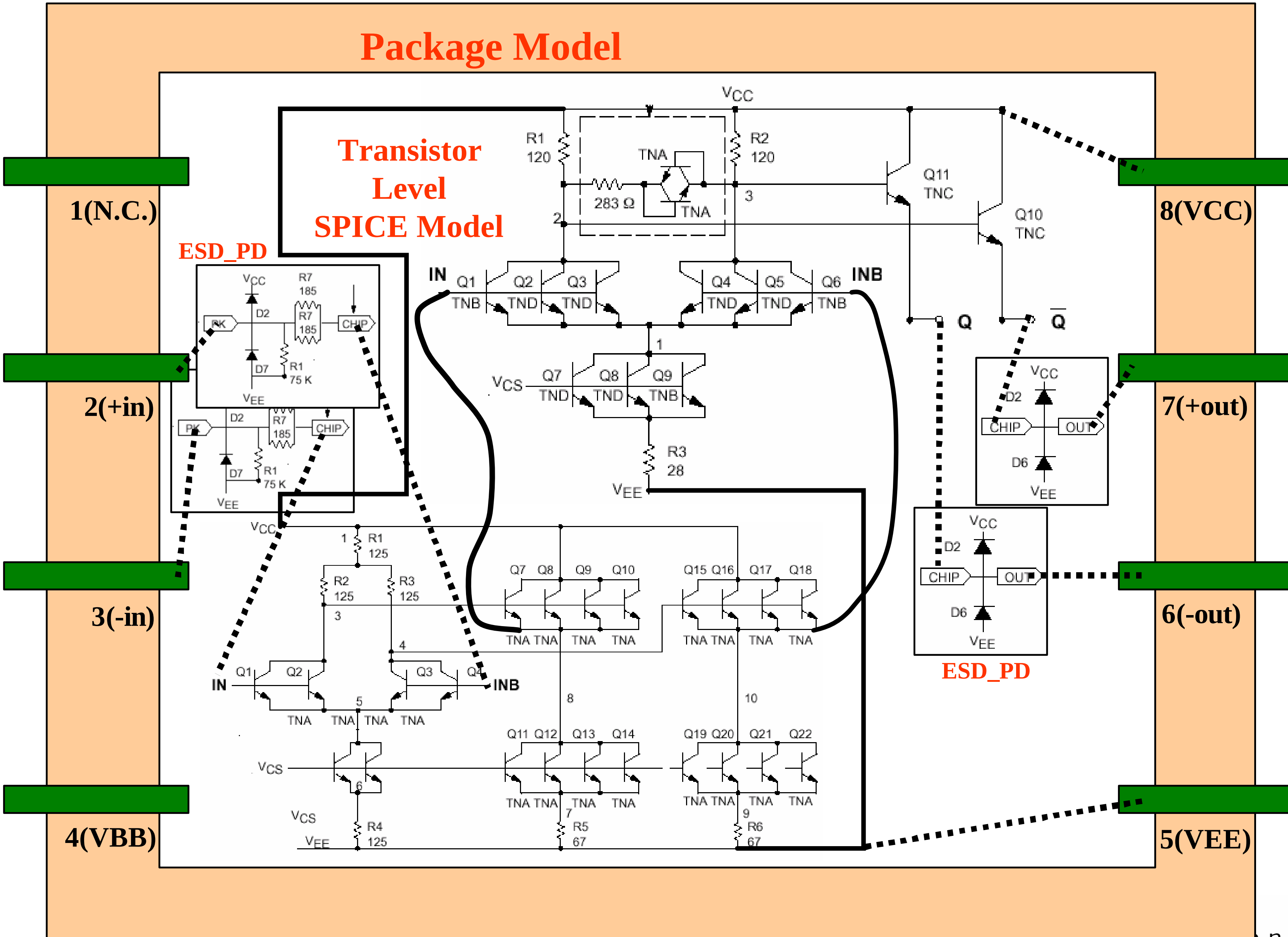
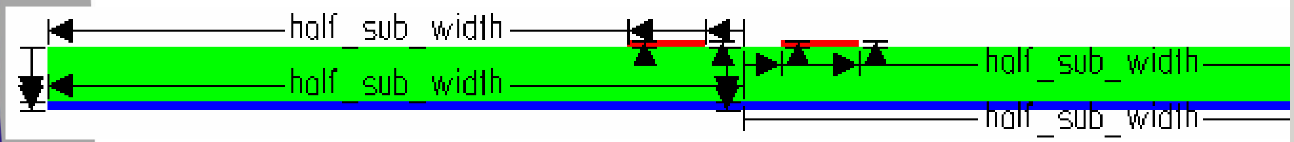
Vendor Provided SPICE Model

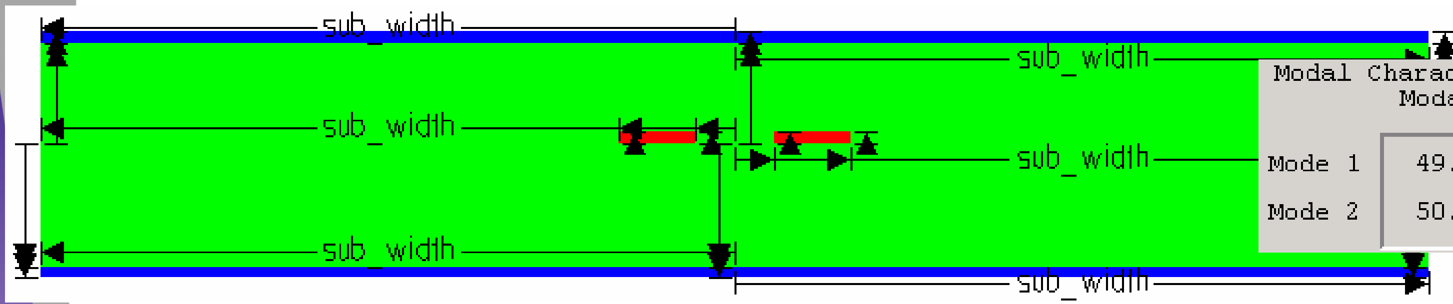


Model from Field Solver



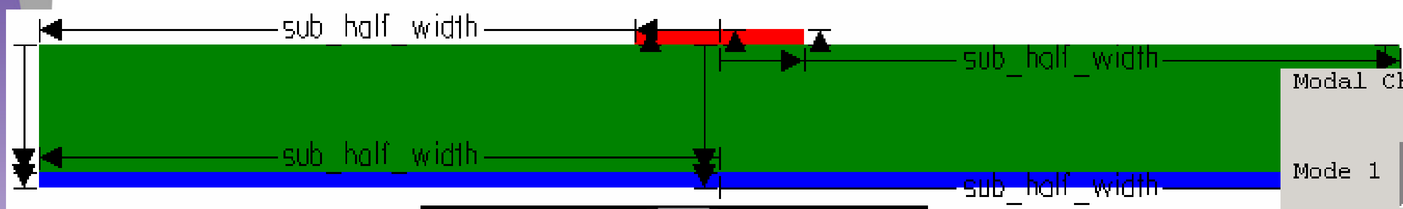
Modal Characteristic Impedance Values (Ohm)

Modal Characteristic Impedance	
Mode 1	62.924
Mode 2	50.306



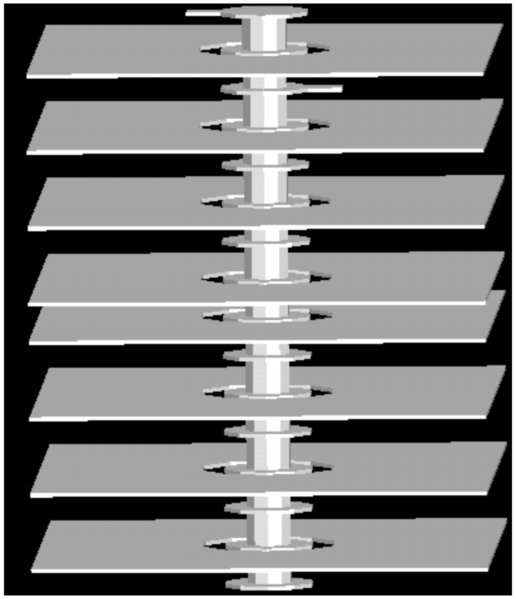
Modal Characteristic Impedance Values (Ohm)

Modal Characteristic Impedance	
Mode 1	49.298
Mode 2	50.566



Modal Characteristic Impedance Values (Ohm)

Modal Characteristic Impedance	
Mode 1	58.754



Capacitance

	box1
box1	2.26521e-014

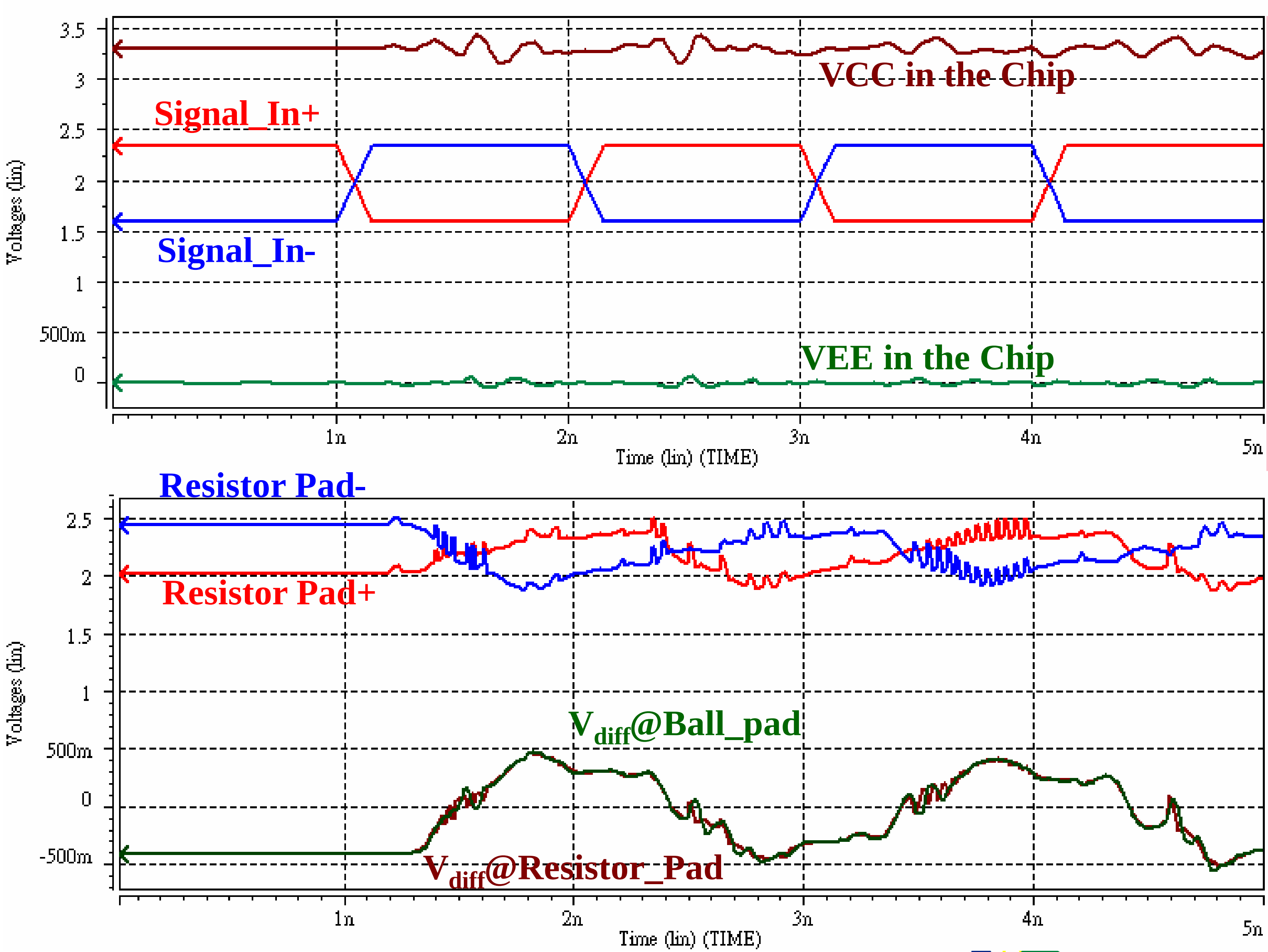
AC Inductance

	box1:src7
box1:src7	6.06751e-012

Altra Broadband

SPICE Simulation Result

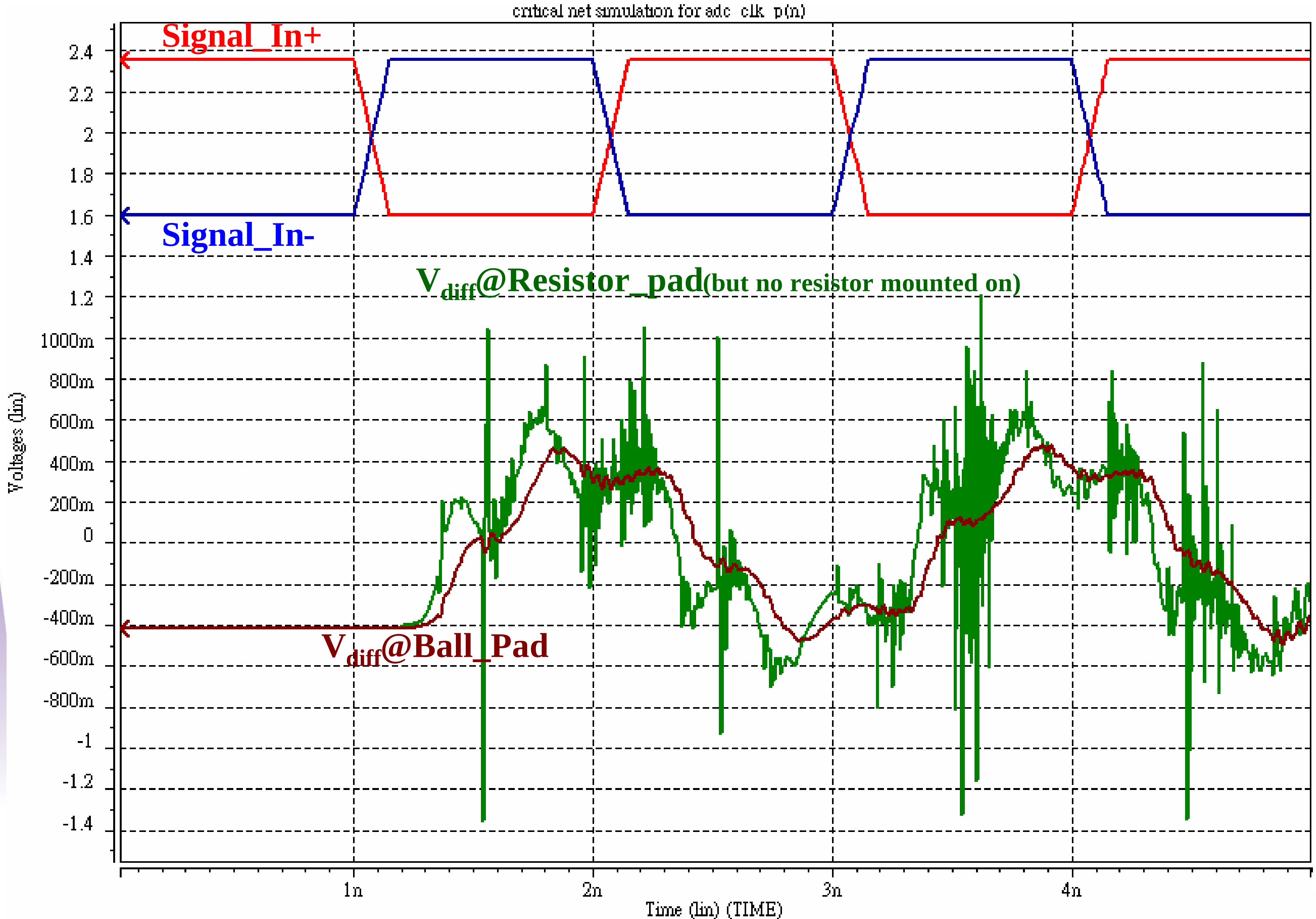
Clock = 500MHz, termination is added in the default position. (0603 Resistor Pads)



Altra Broadband

SPICE Simulation Result(cont'd)

Clock = 500MHz, termination is added in the Ball_Pads position.(Altera BGA)



Altra Broadband

Appendix I: Frequency Range Planning Before VNA Measurement

For Altra's 50Ω Transmission Line of mstrip : $e_{eff} \approx 3.82$

$$l = v \cdot t = \frac{c}{\sqrt{e_{eff}}} \cdot t = \frac{3\times10^{10} \cdot 394}{\sqrt{3.82}} \cdot t(mil) \cong 6047.6\times10^{9} \cdot t$$

$$1n\sec \xrightarrow{\approx} 6inches = 6000mils$$

Time Domain Resolution : t_s

Frequency Domain Resolution : Δf

Time Domain Span : T

Frequency Domain Span : $f_s = \frac{1}{t_s}$ ($for\ DSB$)

$$From\ FFT : \frac{f_s}{\Delta f} = N(\#\text{ of FFT points}) = \frac{T}{t_s}$$

In HFSS or measurement, if we sweep from 0 ~ 20GHz, which means SSB, then $f_s = 40GHz$

$$\therefore t_s = \frac{1}{f_s} = \frac{1}{40GHz} = 0.025ns = 250ps$$

$\Rightarrow$ Space Domain Resolution $\xrightarrow{\text{For Altra's } 50\Omega} 150mils$

Currently, the highest frequency the network analyzer could provide in Altra is 50GHz

$$\therefore t_s = \frac{1}{f_s} = \frac{1}{100GHz} = 0.01n \xrightarrow{\cong} 60mils \cong 1.5mm$$

$\equiv$ Achievable Space Domain Resolution in Altra

This should be accompanied with high quality flex cable for the VNA.

Altra Broadband

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4. “ECLinPS Plus™ SPICE Modeling Kit”, AND8009/D from On Semiconductor, prepared by Senad Lomigora, Paul Shockman
5. Data sheet for MC10LVEP16, MC100LVEP16, “2.5V / 3.3VECL Differential Receiver/Driver”, from On Semiconductor
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