Time Domain Reflectometry (TDR) and S-parameters

"Advanced Measurements …not only Signal Integrity" *- July2009*

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Agenda

- ❑ **Time Domain Reflectometry**
  - ❑TDR and TDT measurements
  - ❑True Differential measurements
  - ❑Deskew
  - ❑Reference Plane Calibration (SL vs. OSL)
- ❑ **S-parameters**
  - ❑ Concept and Definition
- ❑ **Return Loss and Insertion Loss**
- ❑ **Cross-talk interference**
  - ❑NEXT and FEXT concepts
- ❑ **Introduction to mixed-mode S-parameters**
- ❑ **TDR vs. VNA – S-parameter correlation**

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- Time Domain Reflectometry
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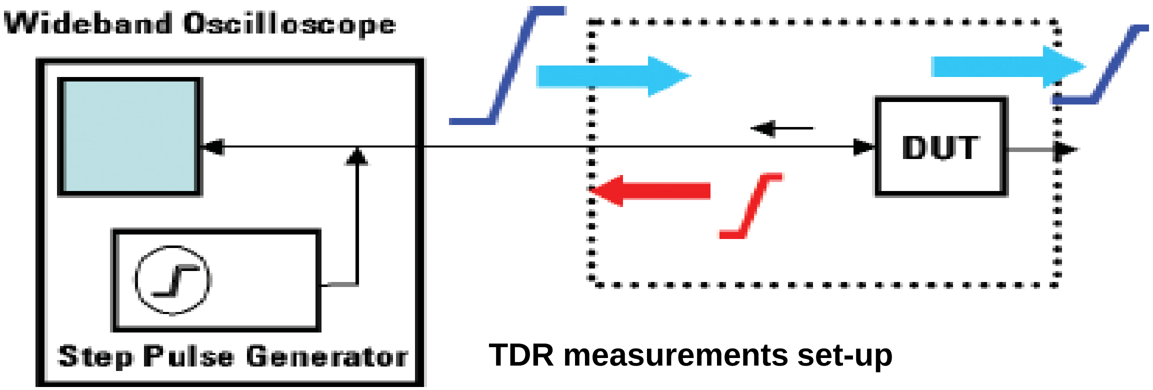
- Cross-talk interference
  - NEXT and FEXT concepts
- Introduction to mixed-mode S-parameters
- TDR vs. VNA – S-parameter correlation

What is TDR ?

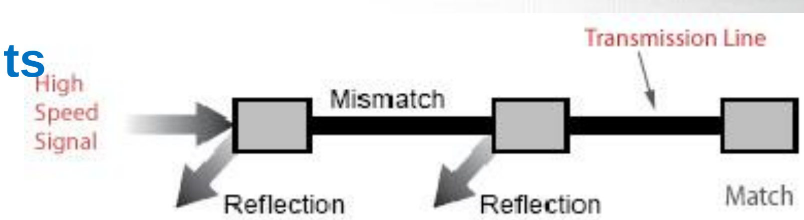
TDR - Time Domain Reflectometry (TDR)



TDR measurements set-up

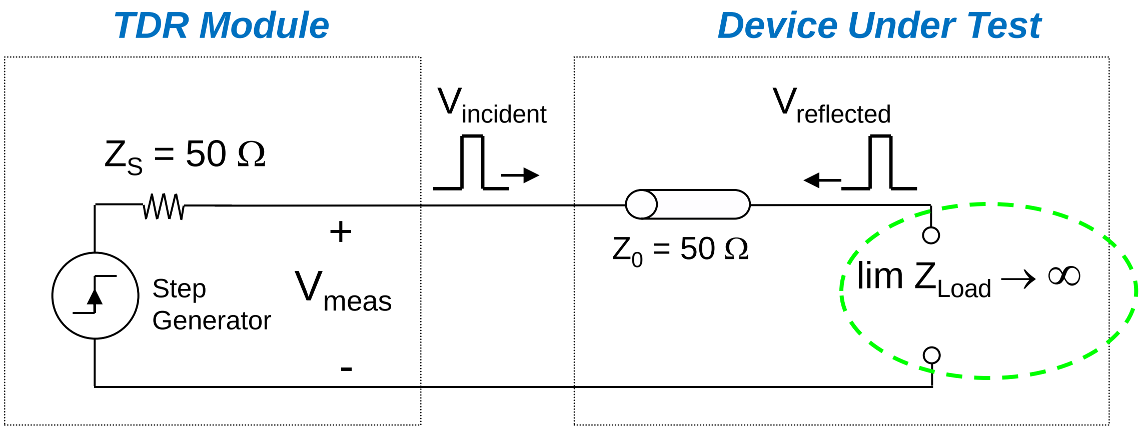
❖*I t is the measurements of the reflection in the time domain*

- ✓ ***A pulse generator is used to provide an incident step pulse (stimulus)***
- ✓ **Voltage Reflection from the Device Under Test (DUT) is measured by the scope≈ TDR mismatch**
- ✓ **Shape of the measured Reflection helps determine the type of discontinuity and its location**



❖***TDR measures Discontinuities* that cause reflections and their *Distance***

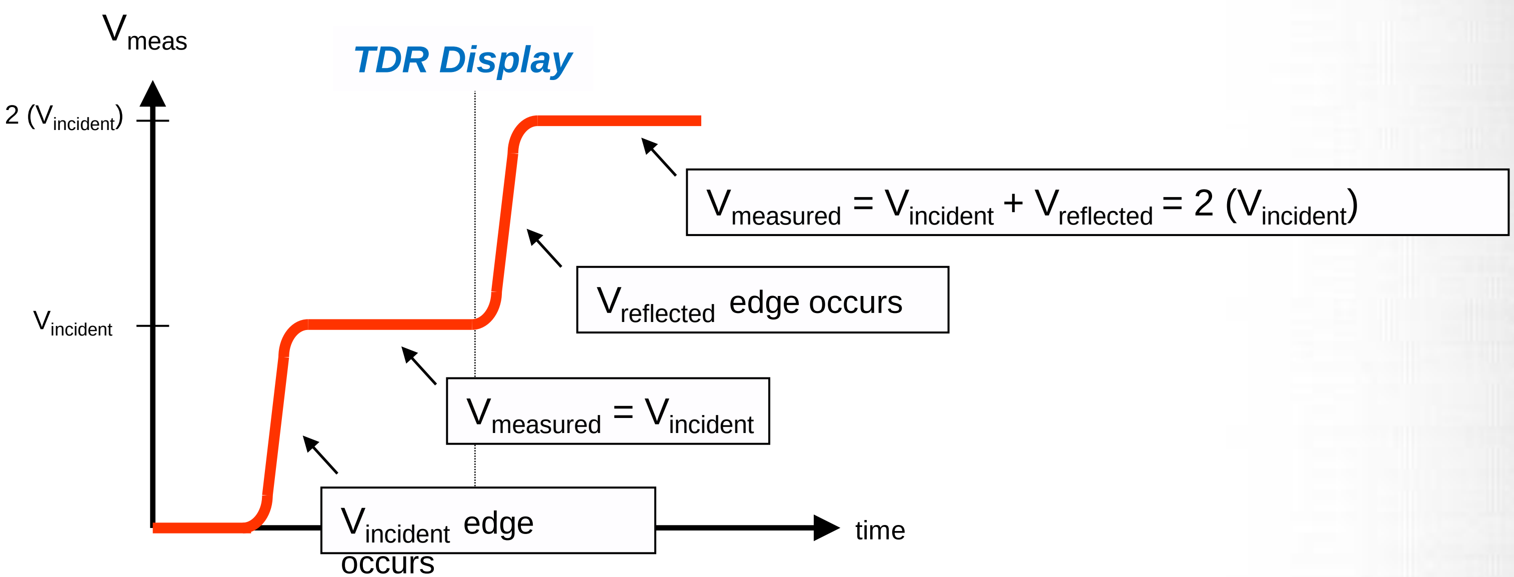
Open Circuit ($Z_{load} \to \infty$)
TDR example



Solving for $V_{reflected}$:

$$V_{reflected} = V_{incident} \left(\frac{Z_{Load} - Z_0}{Z_{Load} + Z_0} \right)$$

$$\lim Z_{Load} \to \infty, \quad \therefore V_{reflected} = V_{incident}$$



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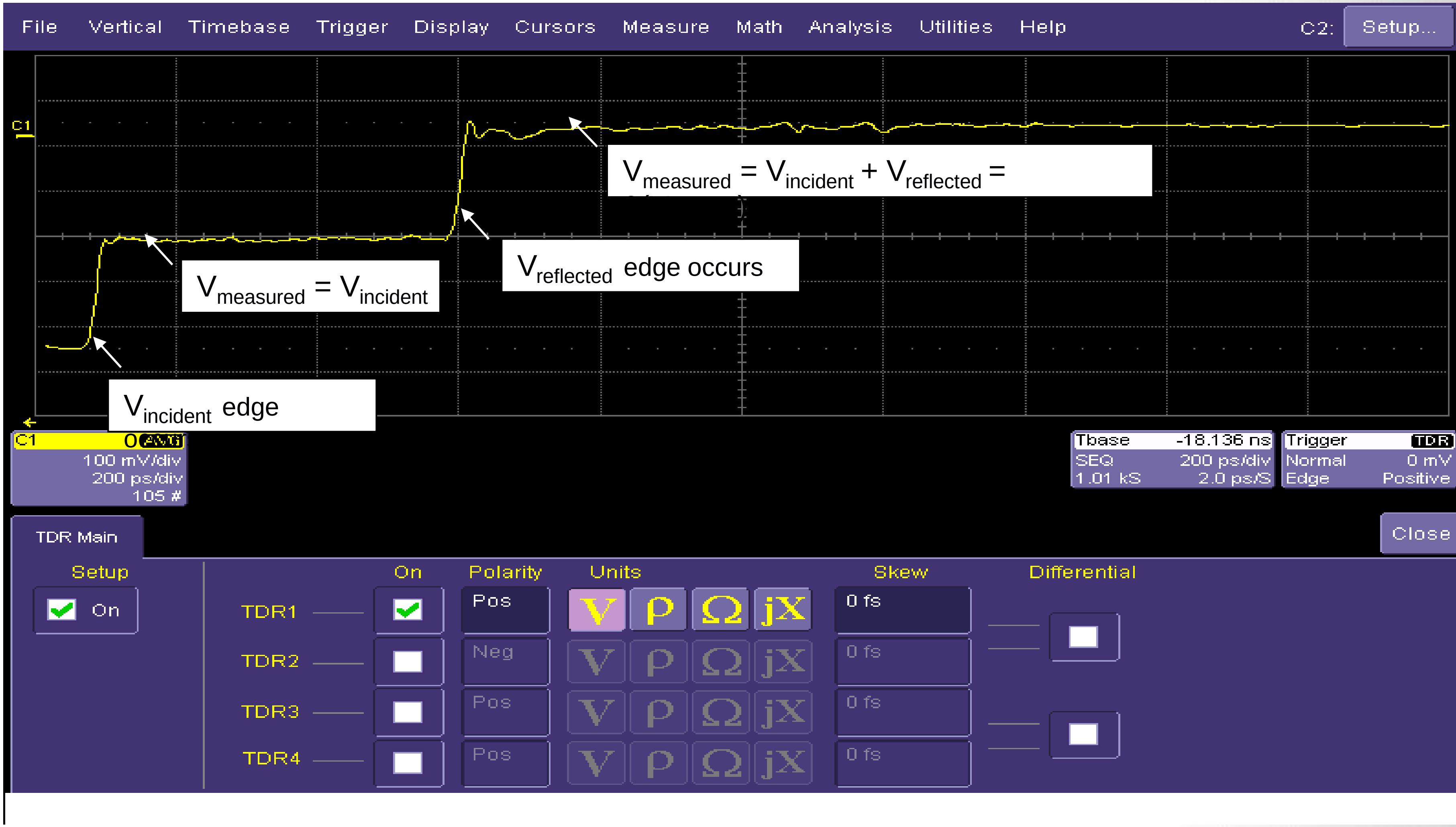
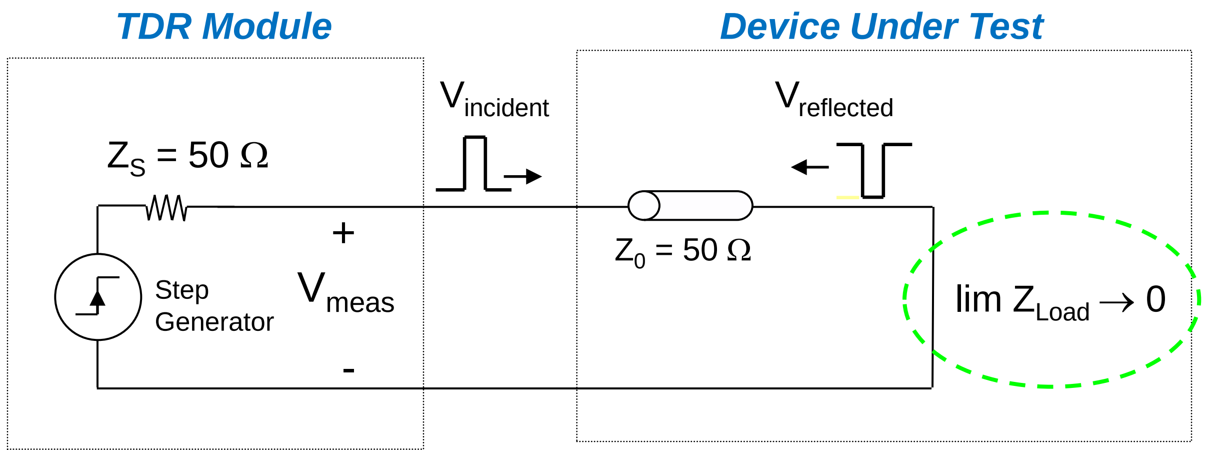
Open in the air
TDR example



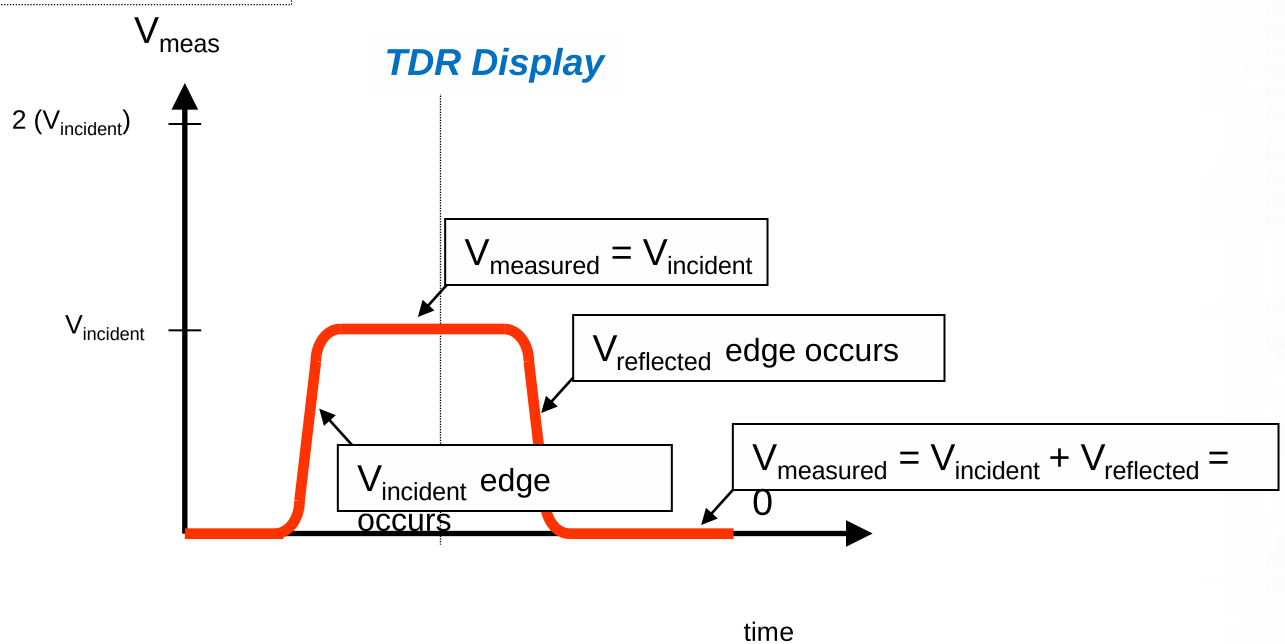
Short Circuit (Z_{load} =0)
TDR example



Solving for $V_{reflected}$:

$$V_{reflected} = V_{incident} \left(\frac{Z_{Load} - Z_0}{Z_{Load} + Z_0} \right)$$

$$\lim Z_{Load} \rightarrow 0, \quad \therefore V_{reflected} = -V_{incident}$$



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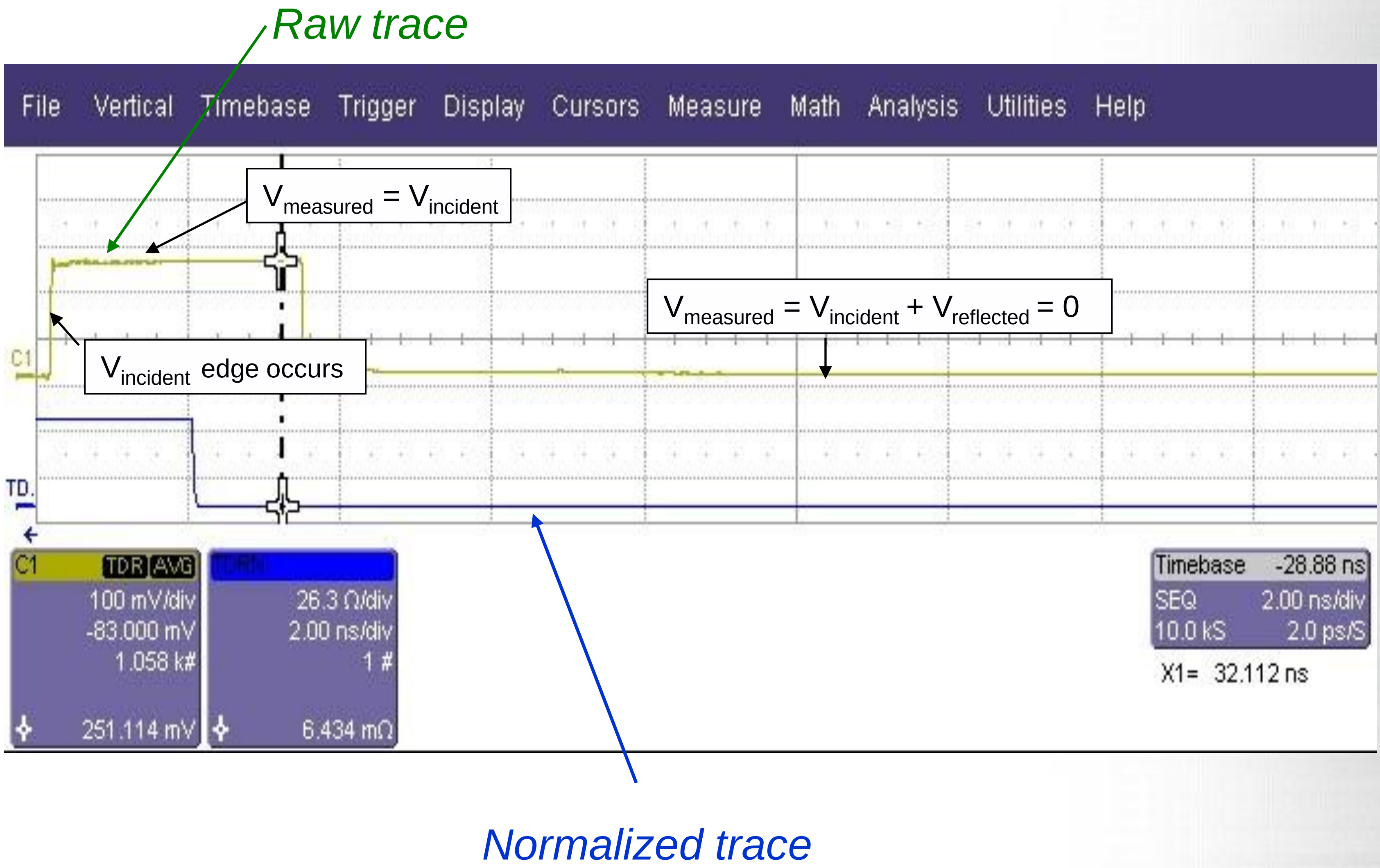
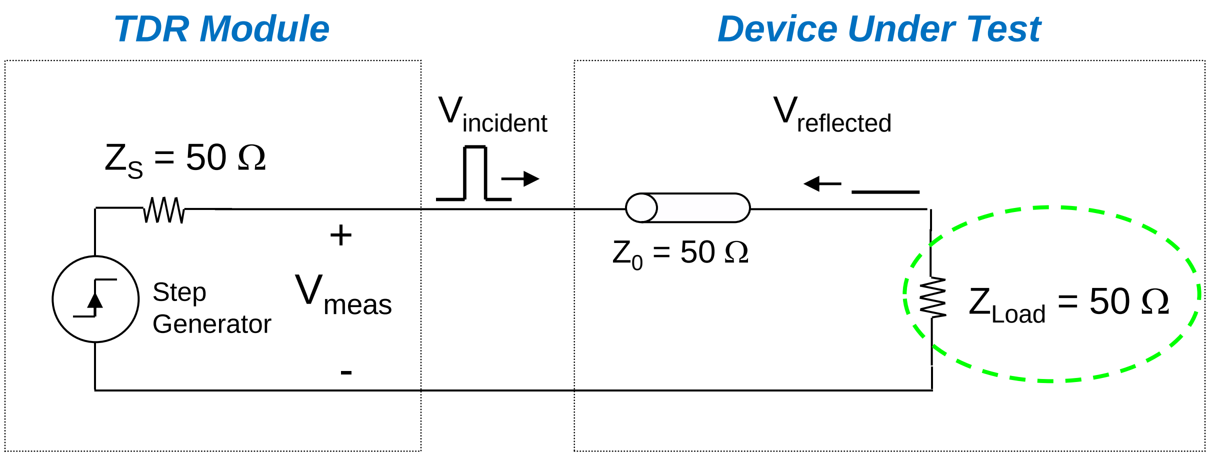
Short terminated (Z_{load} = 0)
TDR example



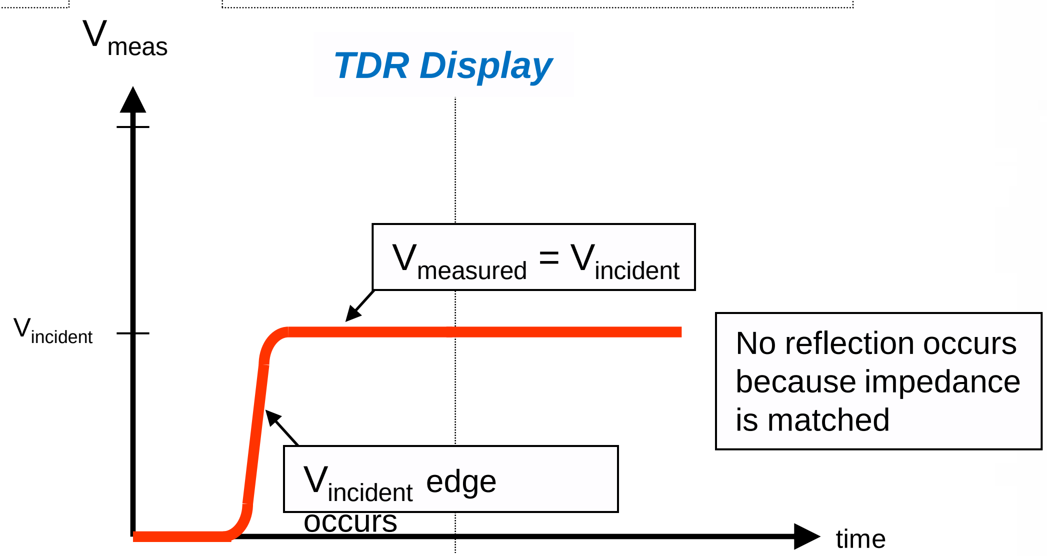
Matched Impedance (Z_{load} =50 Ohm)
TDR example



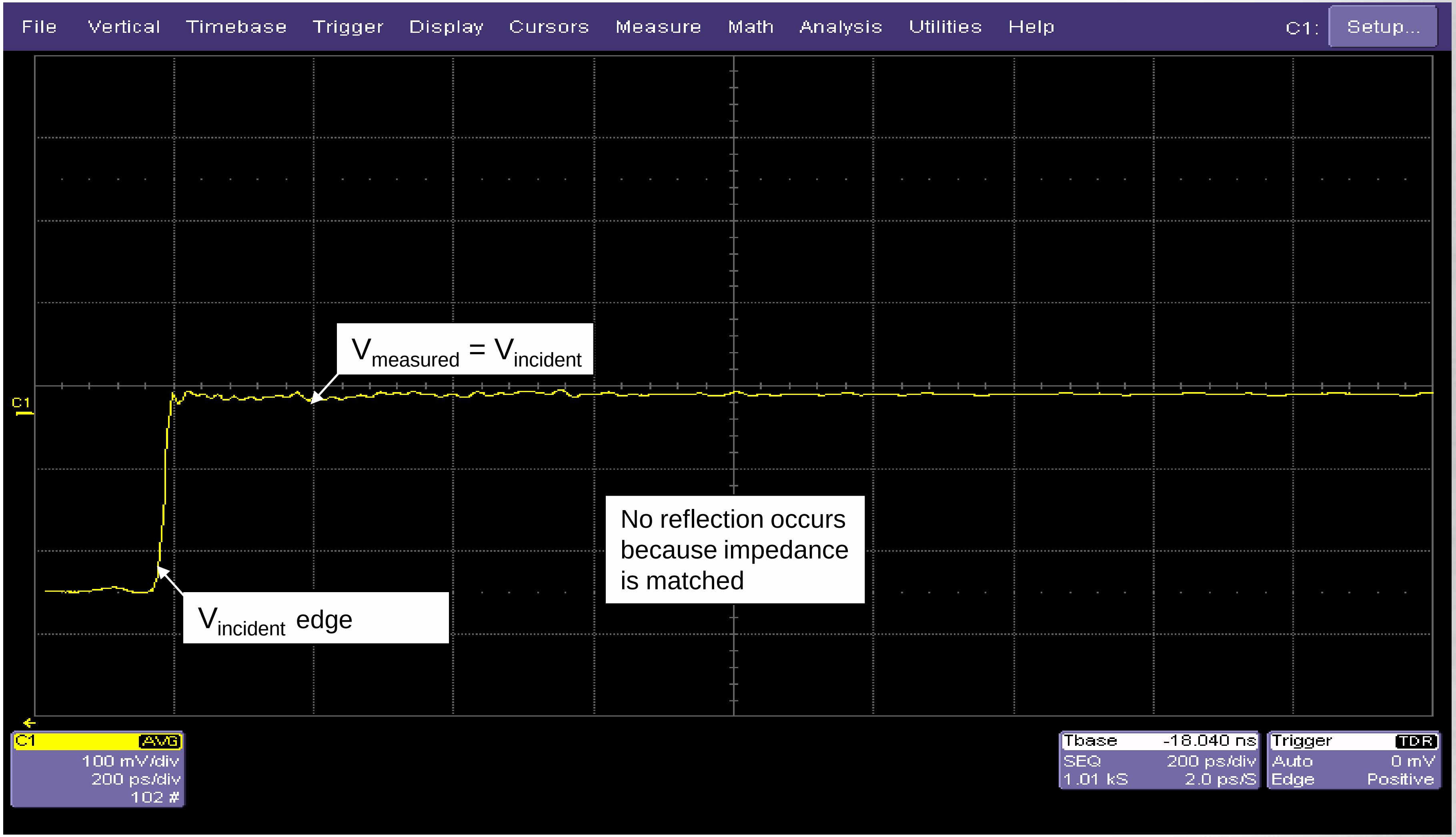
Solving for $V_{reflected}$:

$$V_{reflected} = V_{incident}\left(\frac{Z_{Load} - Z_0}{Z_{Load} + Z_0}\right)$$

$$Z_{Load} = Z_0, \quad \therefore\ V_{reflected} = 0$$

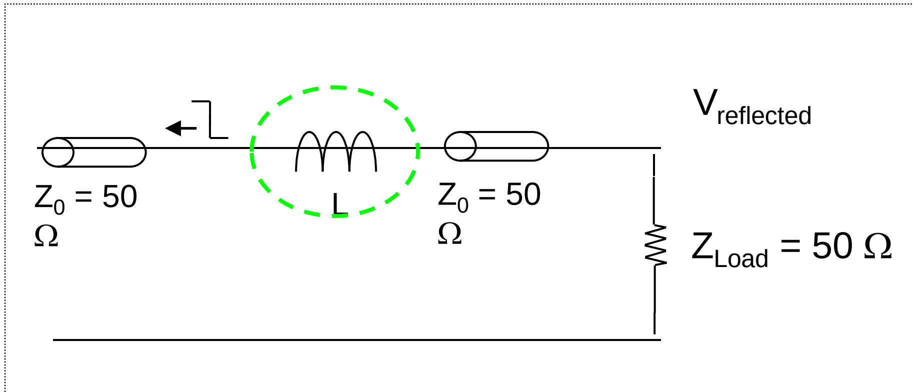


Matched Impedance
TDR example

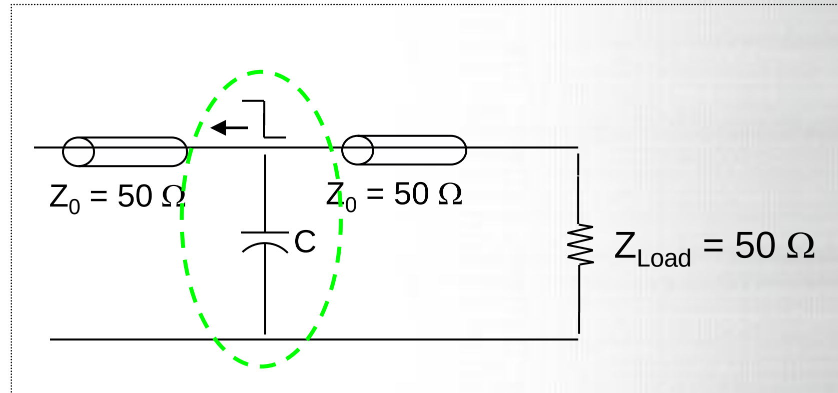


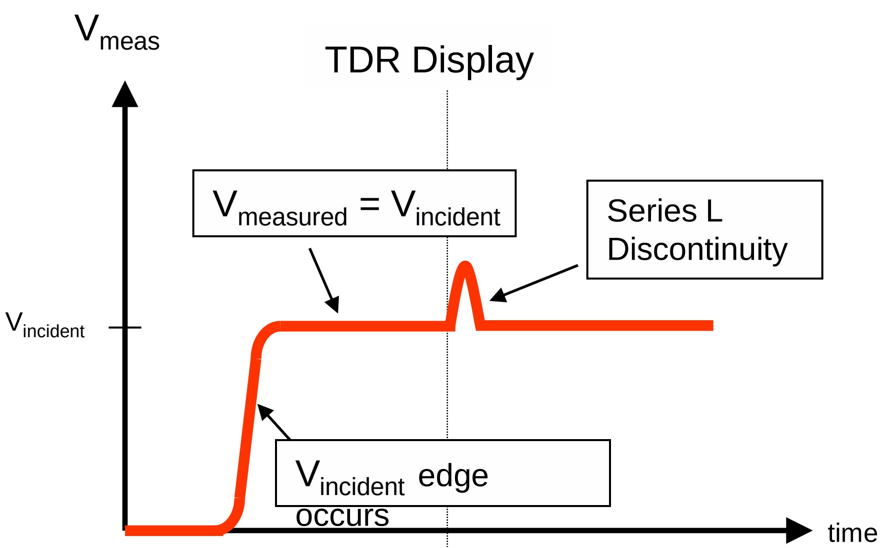
Inductance (L) and Capacitance (C)
TDR example

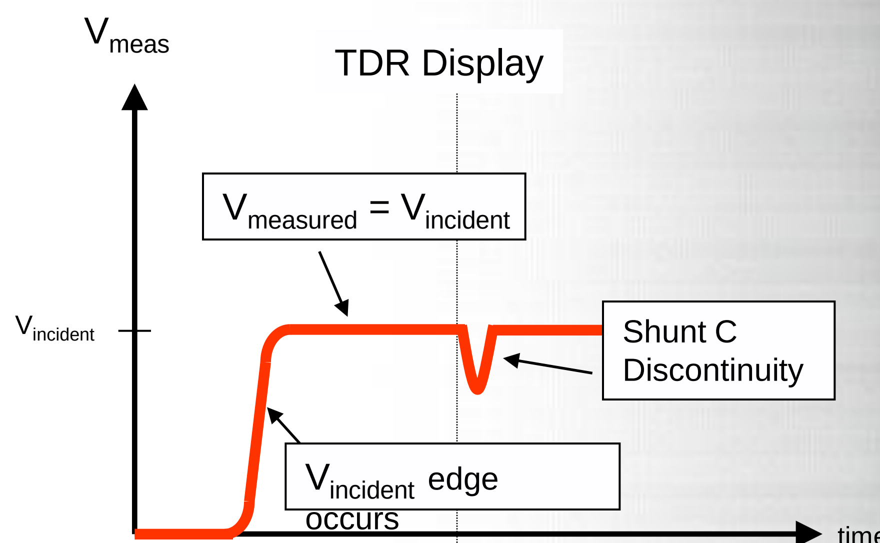
Device Under Test



Device Under Test







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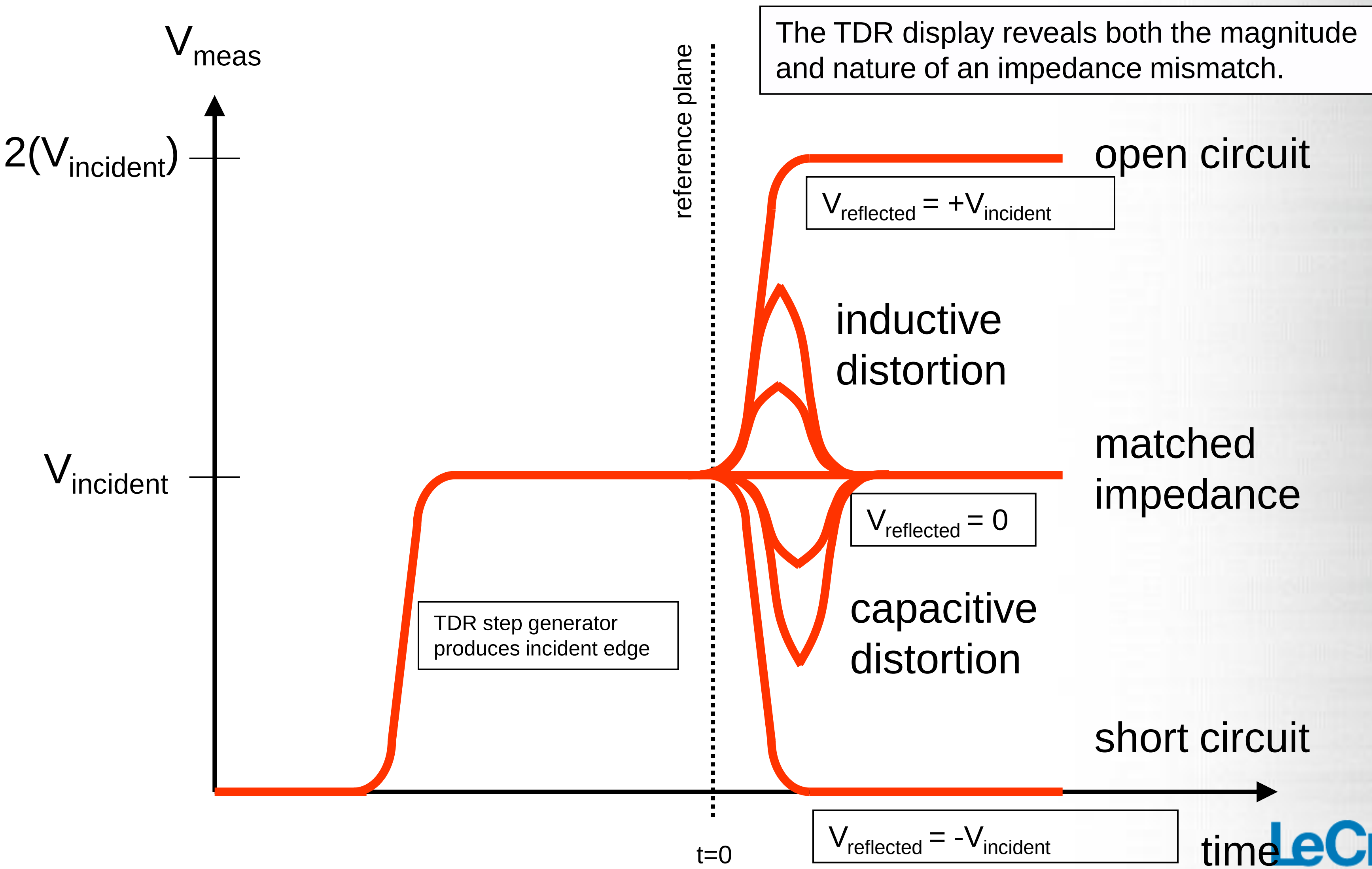
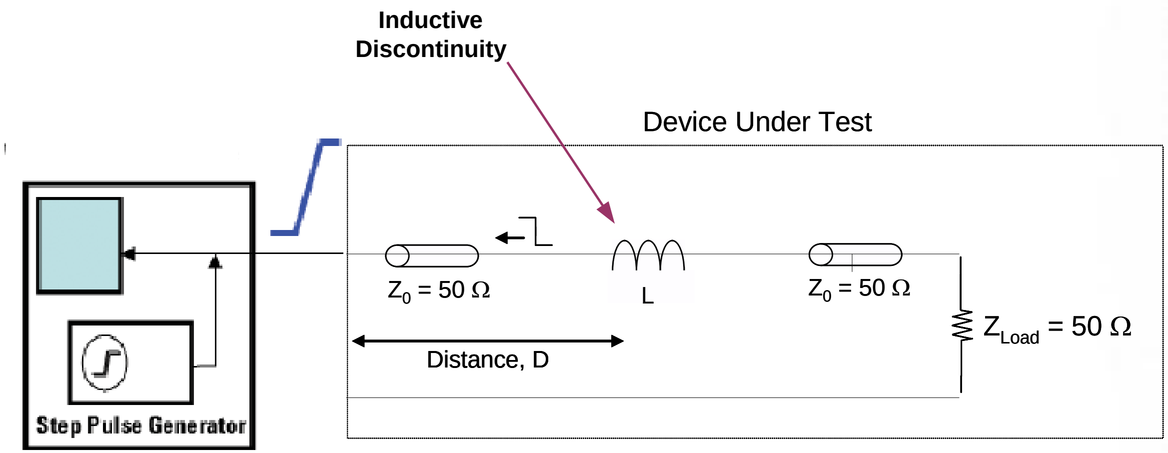
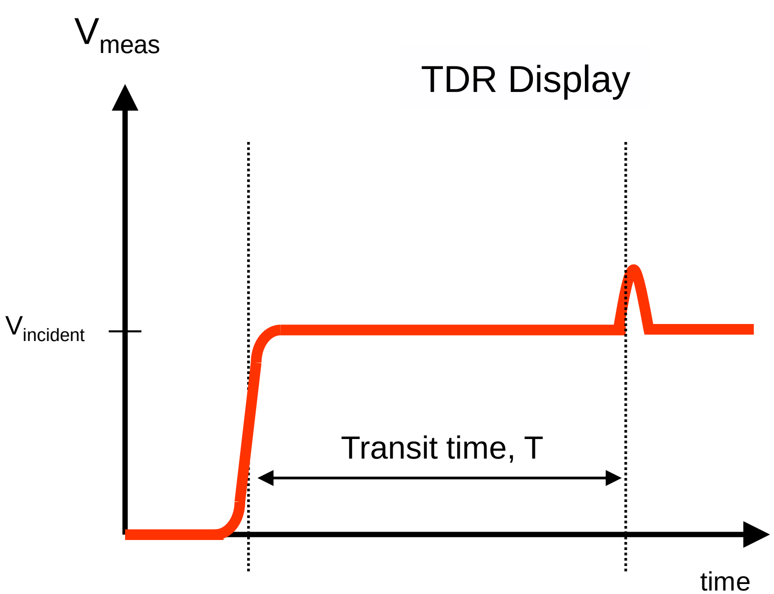
Understanding TDR display



Determining Fault Location
TDR example





Physical distance to fault location can be determined by:

$$D = 0.5*(T)*(v_p)$$

D = physical distance to fault location
T = transit time from monitoring point to mismatch and back (round trip delay)
$\mathbf{v_p}$ = velocity of propagation (material property)

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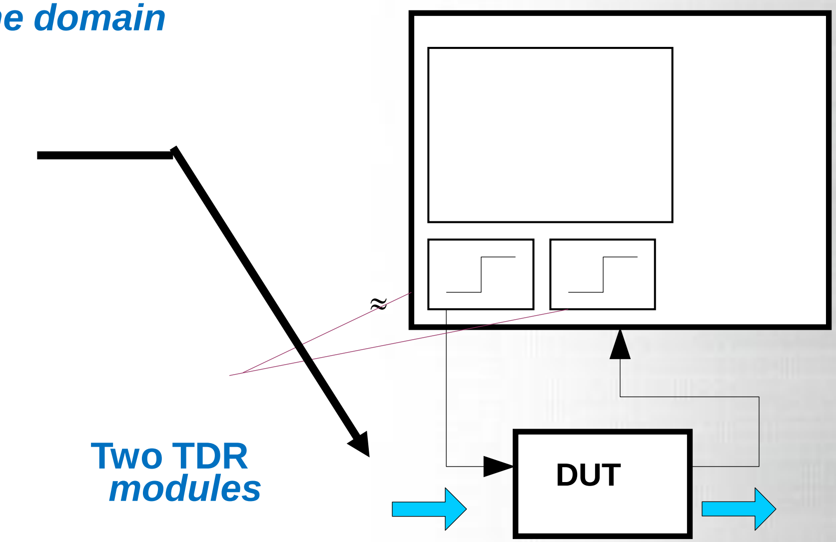
Multi Stage Impedance
TDR example

What is TDT?

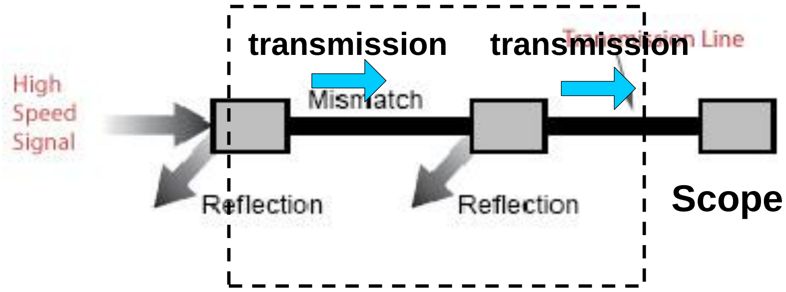
TDT - Time Domain Transmission (TDT)

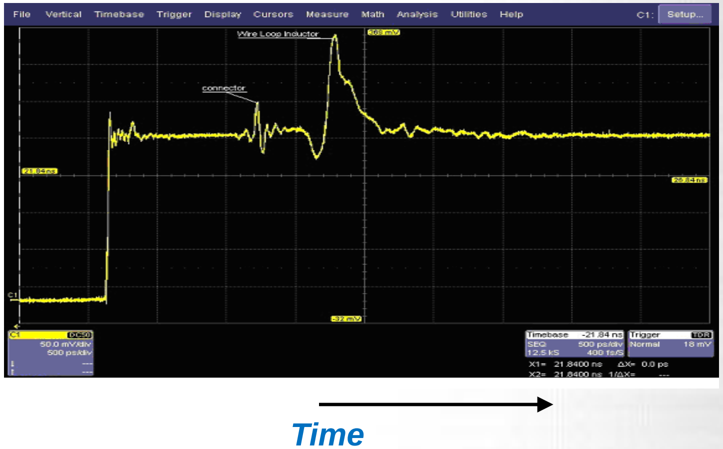
❖*It is the measurements of the transmission in the time domain*

- ✓ ***A pulse generator is used to provide an incident step pulse (stimulus)***
- ✓ ***Voltage Transmission from the Device Under Test (DUT) is measured by the scope***
- ✓ ***TDT ≈ Insertion (Transmission) Loss***
- ✓ ***Requires two TDR modules – one to generate the step and other to sample***



TDT measurements set-up





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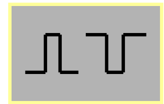
<u>True</u> Differential TDR / TDT

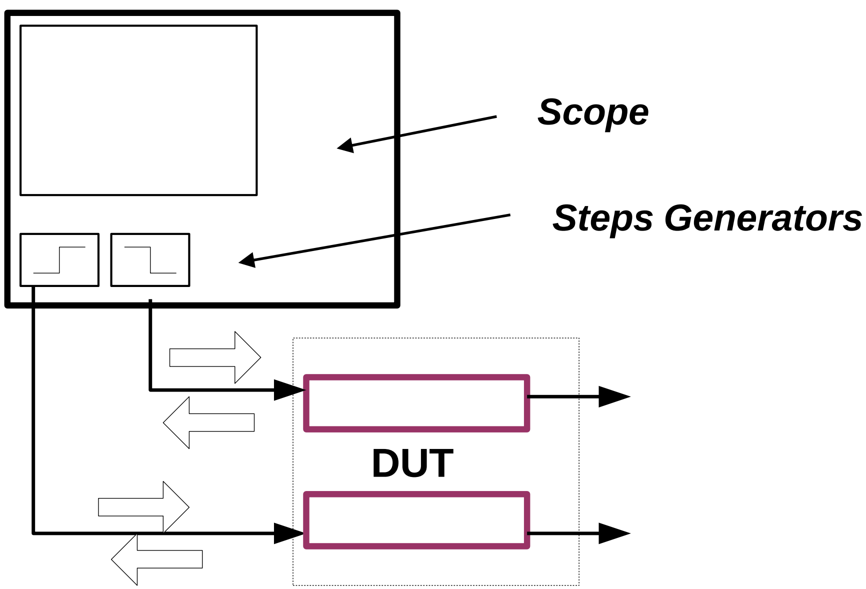
- ✓ *High Speed digital systems are mainly differential*



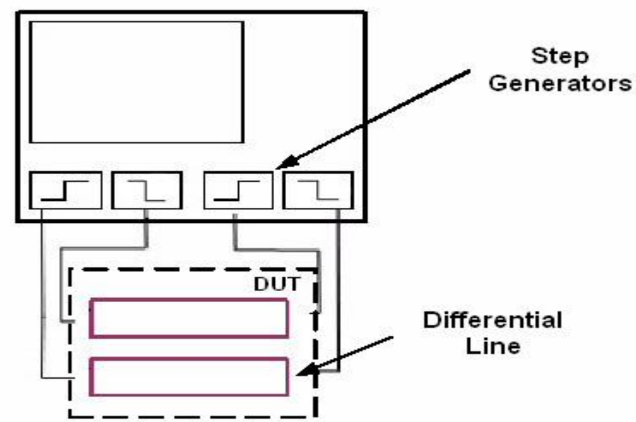
- ✓ *TDR requires <u>two</u> ST-20 modules to provide the differential signal (stimulus), step pulses, positive and negative (automatically changes polarity when selecting differential)*

- ✓ *De-skew control aligns the two pulses from each of the two ST-20 modules.*
  - ✓ *HW deskew ($\pm$50 ps)*

- ✓ *Requires <u>four</u> TDR modules – two to generate the differential signal and other two to receive the differential signal*



Differential TDR measurements set-up



Differential TDT measurements set-up

Reference Plane Calibration

❖*Before calibration – effects of test fixture and connectors are included in the response*

Calibration Methods :

❖***S**hort **L**oad (SL)*

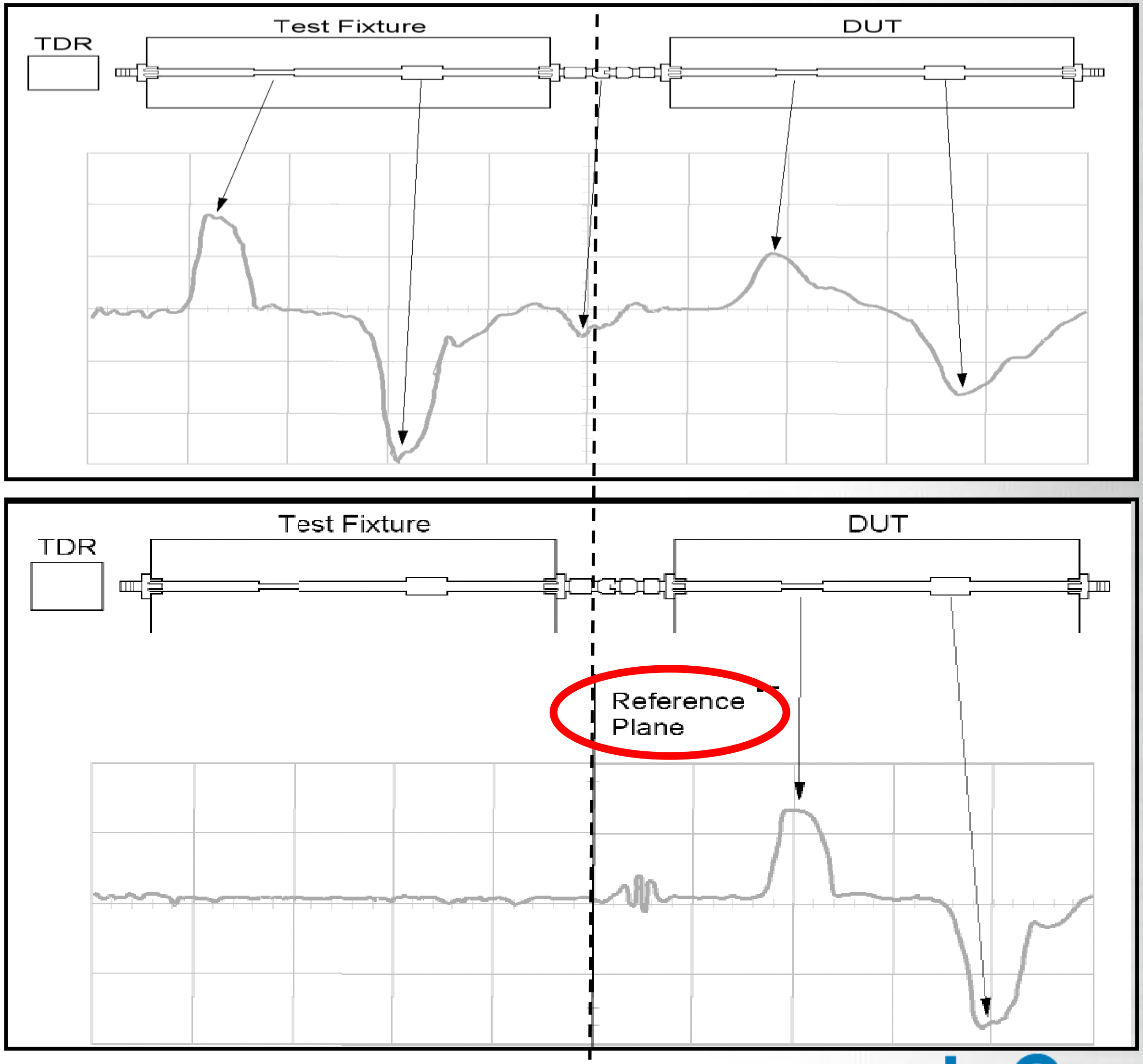
*Uses **Two** known standards (Short & Load)*

❖***O**pen **S**hort **L**oad (OSL)*

*Uses **Three** known standards*

(Open , Short & Load)

❖*After calibration – effects of test fixture and connectors are removed from response*



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  - TDR and TDT measurements
  - True Differential measurements
  - Deskew
  - Reference Plane Calibration (SL vs. OSL)
- **S-parameters**
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- Cross-talk interference
  - NEXT and FEXT concepts
- Introduction to mixed-mode S-parameters
- TDR vs. VNA – S-parameter correlation

Introduction to S-Parameters

✓ *S-parameters (Scattering matrix) are the way we electrically accurately describe how RF energy propagates through a multi-port DUT.*

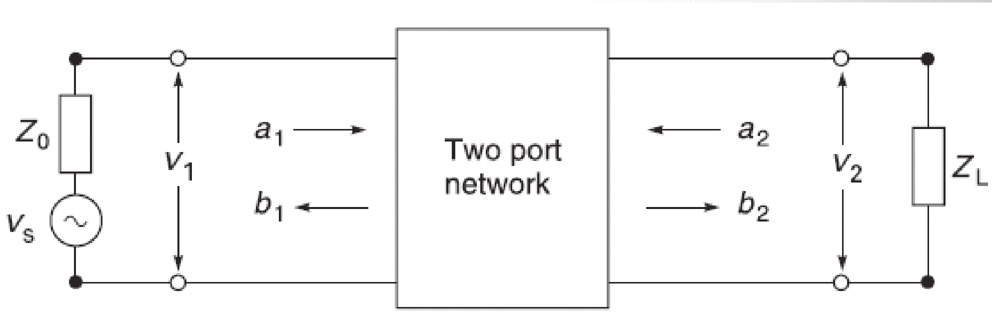
✓ *DUT even if incredibly complicated is considered as simple “black box”*

✓*The S-parameter matrix for an N-port DUT contains N^2 S-parameters*

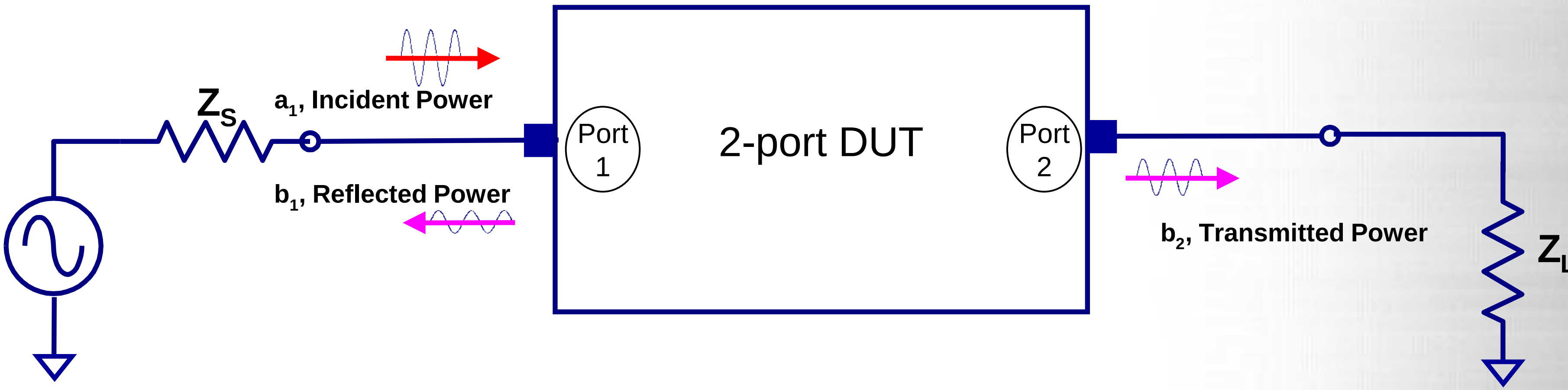
✓ *S-parameters are complex numbers (magnitude and phase)*

S11 – Magnitude Reflection

Frequency

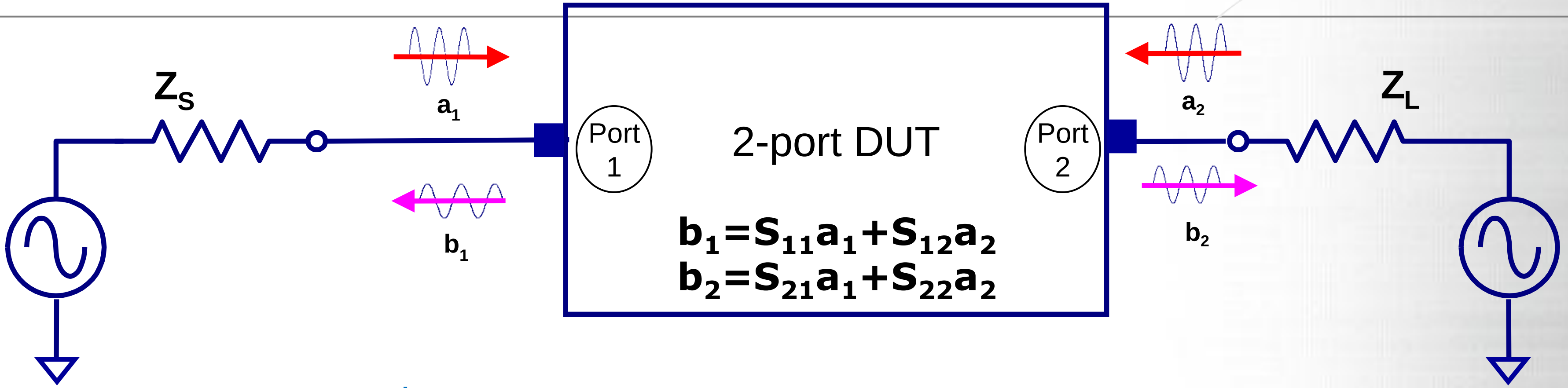


What are S-Parameters ?



- ***S-parameters are a measure of reflection and transmission properties of power in a DUT***
- ***'S' stands for "Scattering"***
- ***DUT could be for example: a coax cable, passive antenna, active amplifier, microwave filter, etc.***
- ***S-parameters have magnitude (dB) and phase (degrees)***
- ***Naming Scheme : S<output port><input port>***
  - ***Example S21 = transmission from port 1 to port 2***
- ***Vector Network Analyzer (VNA) and TDR (Time Domain Reflectometer) are typically used to measure S-parameters.***

2-Port S-Parameter Definitions



- $S_{11} = b_1/a_1 \,|\, a_2 = 0$ ***Input reflection** coefficient with the output port terminated by a matched load*
- $S_{21} = b_2/a_1 \,|\, a_2 = 0$ ***Forward transmission** gain with the output port terminated by a matched load*
- $S_{22} = b_2/a_2 \,|\, a_1 = 0$ ***Output reflection** coefficient with the input port terminated by a matched load*
- $S_{12} = b_1/a_2 \,|\, a_1 = 0$ ***Reverse transmission** gain with the output port terminated by a matched load*

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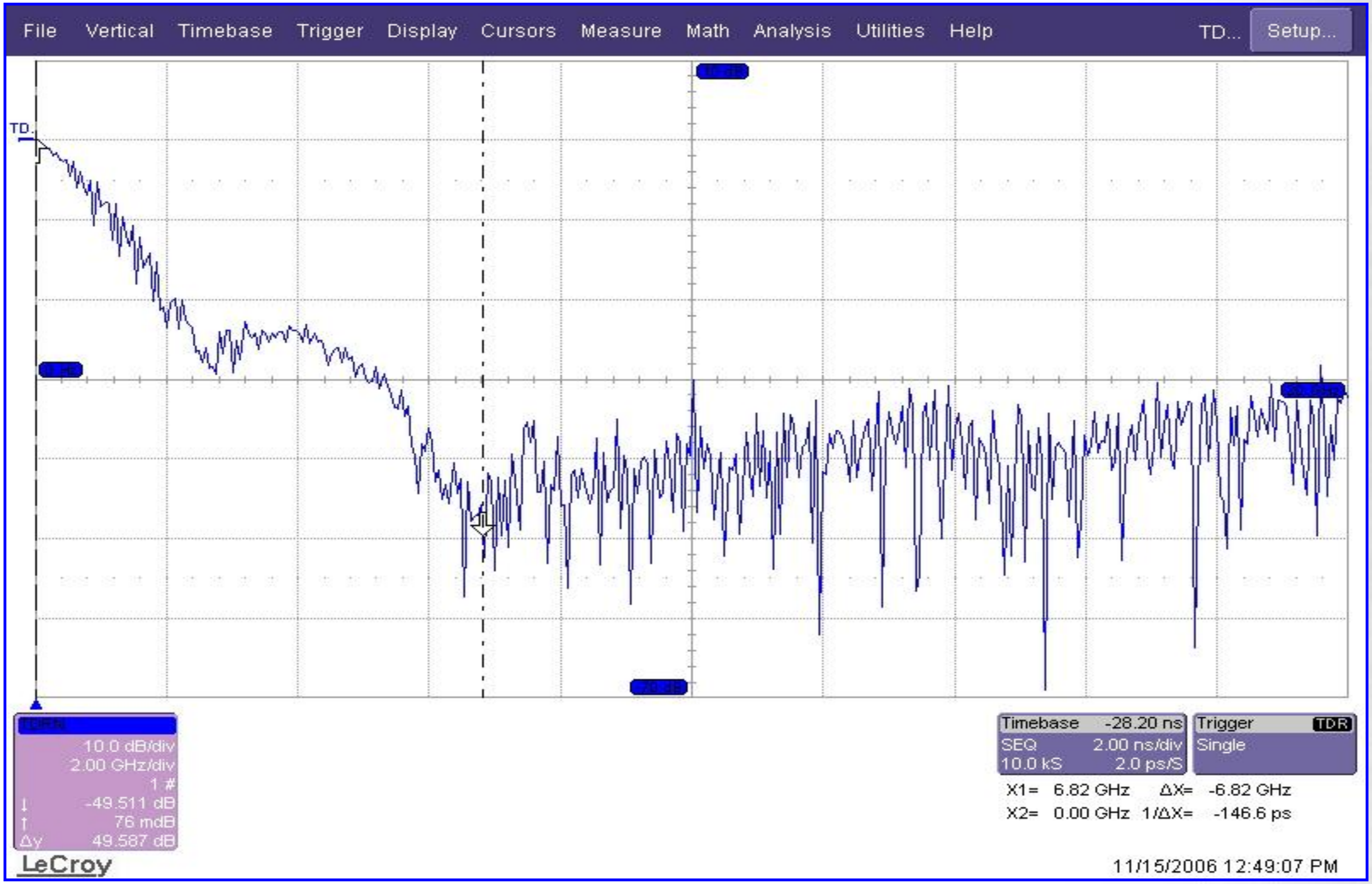
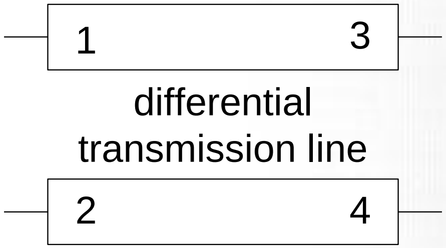
S_{21} calculation for a 24" backplane

Example of S-parameter plot



Port Numbering Problem Answer

$$\begin{bmatrix} -9 & -32 & -1 & -33 \\ -32 & -9 & -35 & -1.6 \\ -1.4 & -34 & -9.5 & -32 \\ -34 & -1.4 & -32 & -8.5 \end{bmatrix}$$



= Trace Impedance Match/Mismatch

= Strong Port-Port Coupling

Ports 1 and 3 are strongly coupled

Ports 2 and 4 are strongly coupled

```
# Hz S dB R 50
10000000 -9.325388e+000 1.696448e+001 -3.212368e+001 3.957784e+001 -1.384781e+000 -4.905982e+001 -3.381277e+001 1.285916e+002
 -3.230127e+001 4.017078e+001 -9.149292e+000 1.045316e+001 -3.461039e+001 1.259645e+002 -1.607169e+000 -4.862178e+001
 -1.398305e+000 -4.915537e+001 -3.441459e+001 1.250791e+002 -9.583646e+000 1.170182e+001 -3.219268e+001 4.153238e+001
 -3.382233e+001 1.293954e+002 -1.482399e+000 -4.926255e+001 -3.227425e+001 4.223647e+001 -8.501068e+000 1.329251e+001
20000000 -8.415854e+000 -7.429701e+001 -2.185791e+001 -6.994311e+000 1.589352e-001 -1.004102e+002 -2.742099e+001 1.961331e+001
 -2.194702e+001 -4.438735e+000 -7.701551e+000 -8.483125e+001 -2.915839e+001 1.245748e+001 4.715231e-001 -1.000467e+002
 1.677796e-001 -9.970387e+001 -2.906990e+001 1.002416e+001 -9.329252e+000 -8.454984e+001 -2.182191e+001 -6.116842e+000
 -2.748248e+001 2.258983e+001 5.479714e-001 -1.001441e+002 -2.189178e+001 -3.320241e+000 -6.462896e+000 -7.856100e+001
30000000 -1.08640[illegible] -1.781489e+002 -2.063685e+001 -7.824953e+001 -4.649954e-001 -1.581036e+002 -2.615018e+001 -1.204220e+00[illegible]
[illegible]
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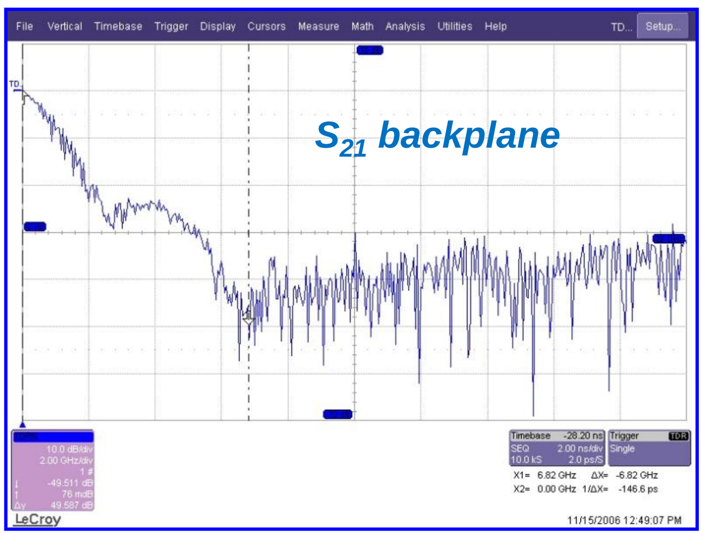
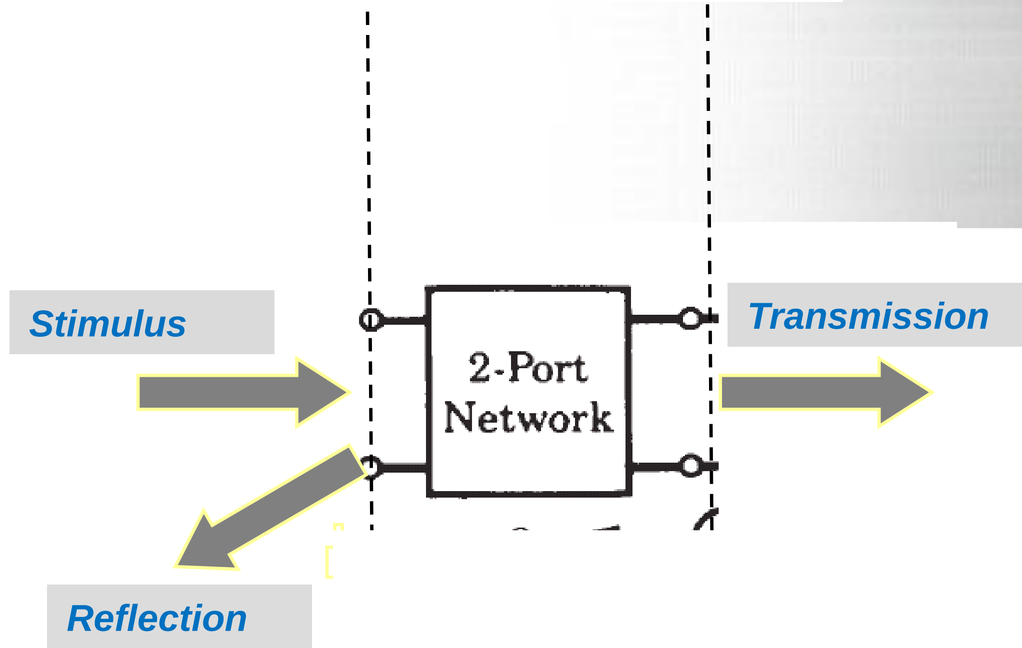
Reflection / Transmission
(Frequency Domain)

- ✓ ***Reflection:*** Return Loss (dB)
  - *ratio in dB of the reflected signal power relative to the incident signal power*
- ✓ ***Transmission :*** Insertion Loss (dB)
  - *ratio in dB of the transmitted signal power relative to the incident signal power*



Frequency



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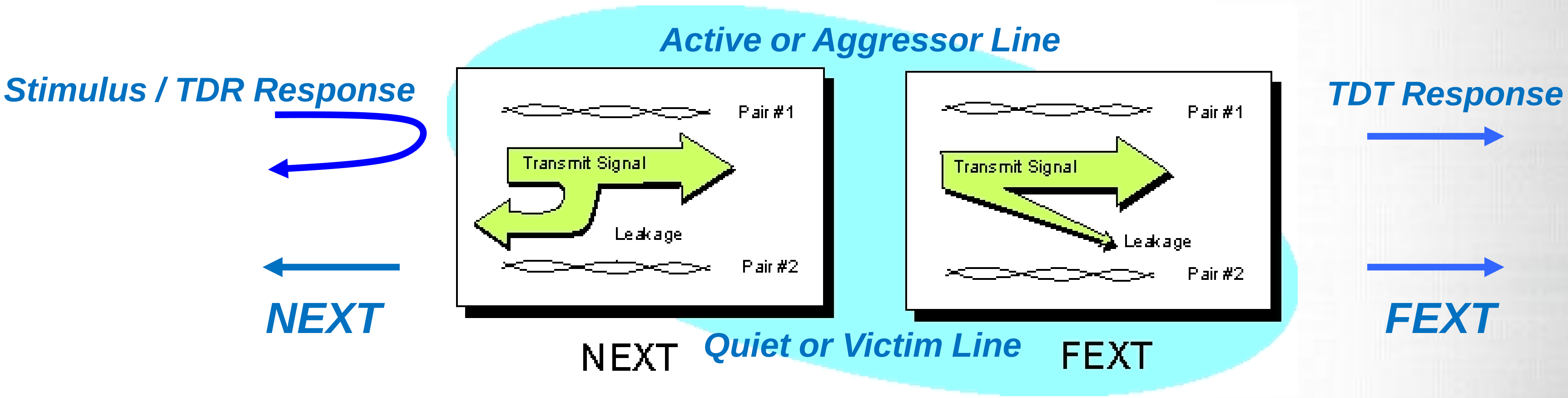
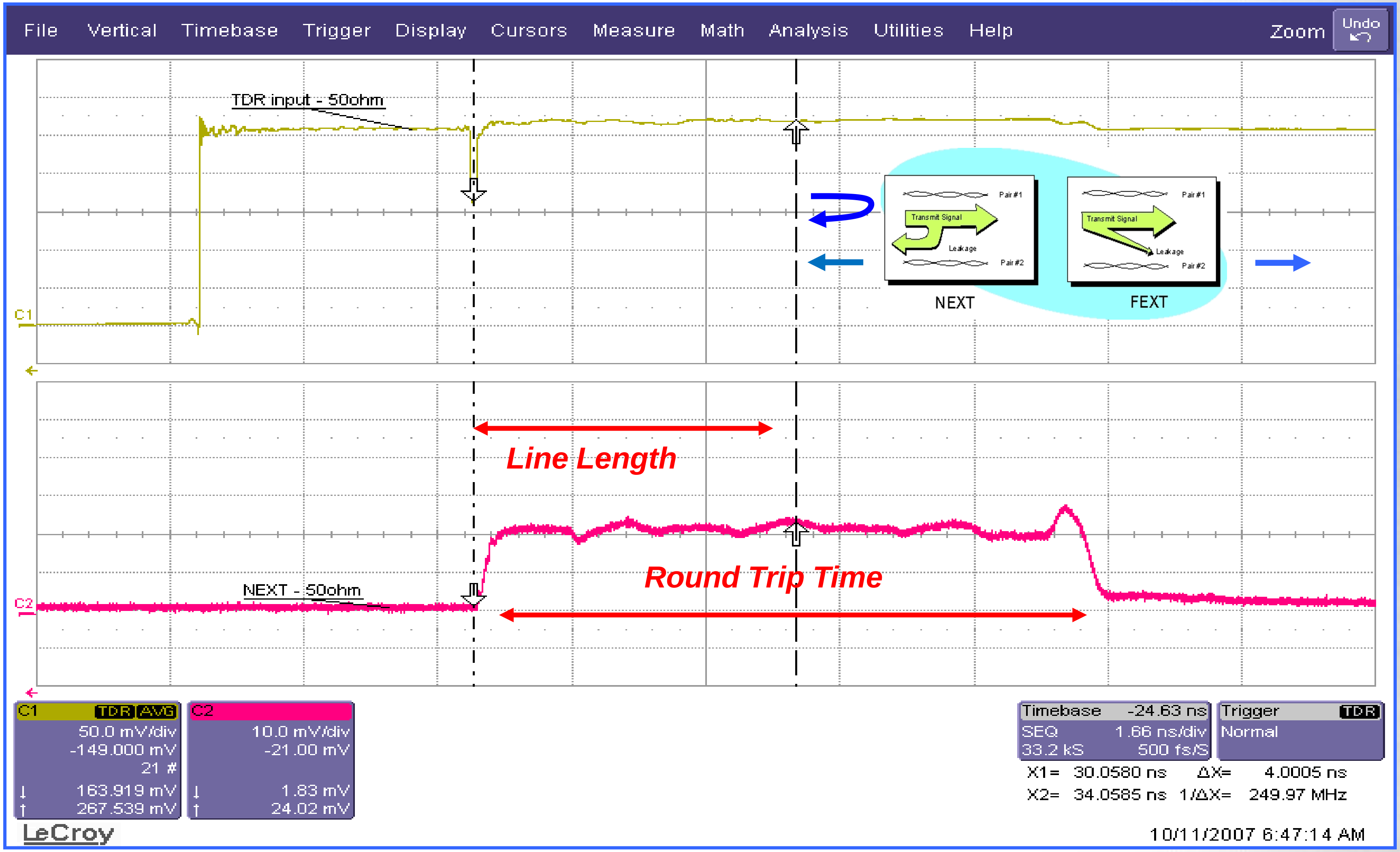
NEXT/FEXT on adjiacent trasmission lines



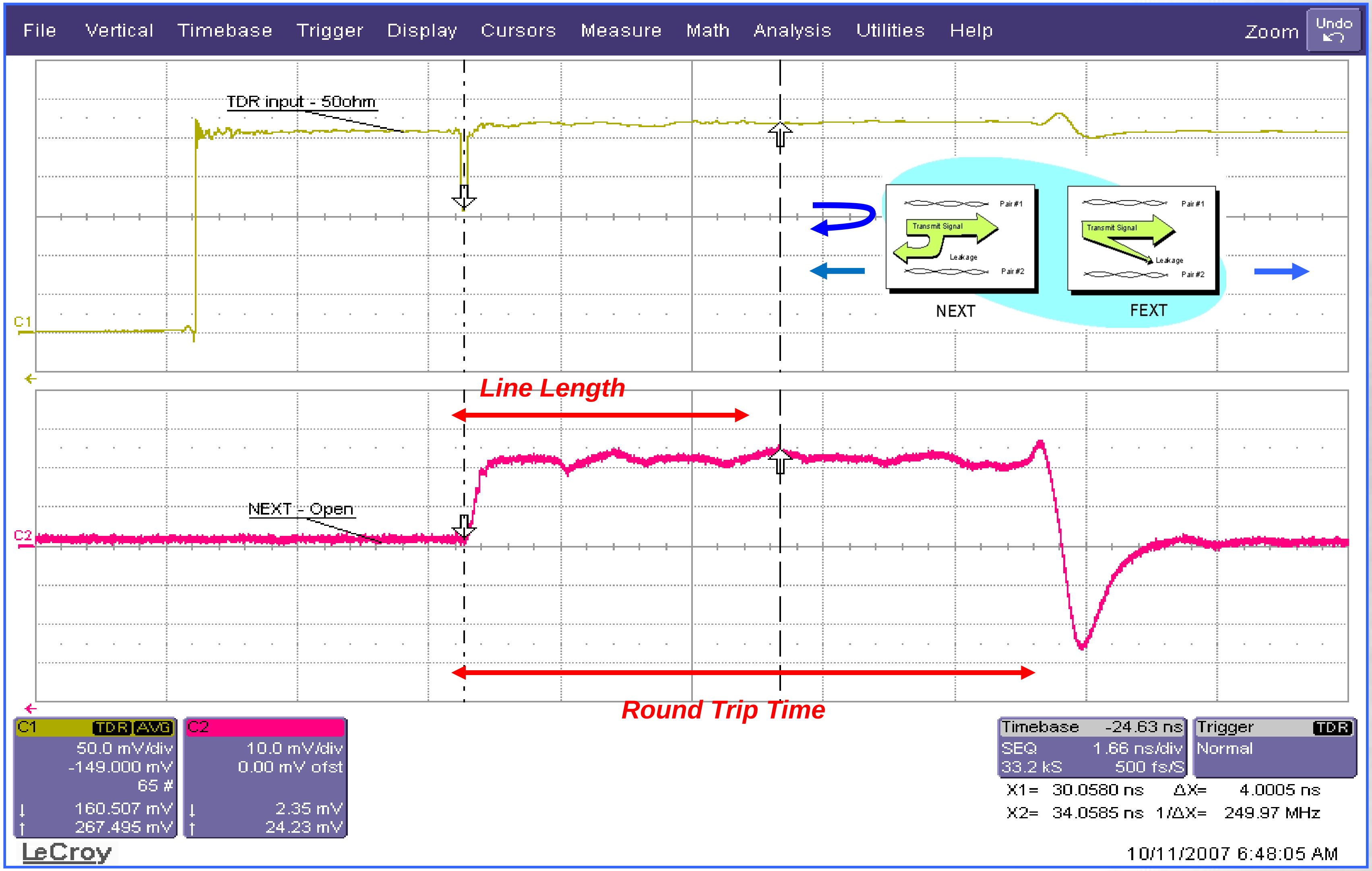
- ❑ ***Near-End Cross Talk (NEXT) is the ratio between the voltage measured on the near end on the quiet line and the stimulus.***
- ❑ ***Far-End Cross Talk (FEXT) is the ratio between the voltage measured on the far end on the quiet line and the stimulus.***

✓ ***NEXT-FEXT Cross-talk measured the coupling between two adjacent transmission lines***

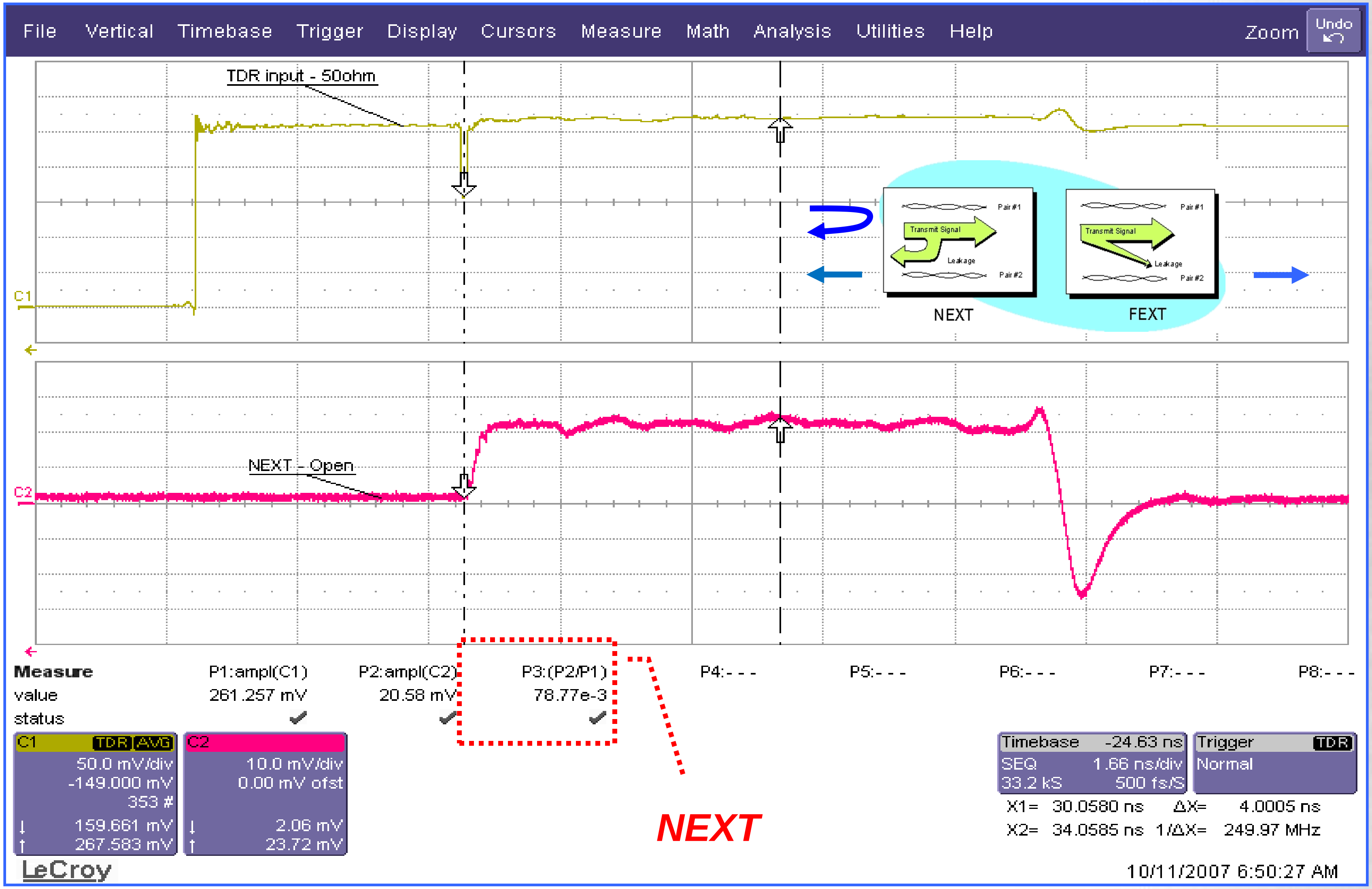
NEXT – Quiet Line @ 50Ω



NEXT – Quiet Line Open Terminated



NEXT – Quiet Line Open Terminated readout



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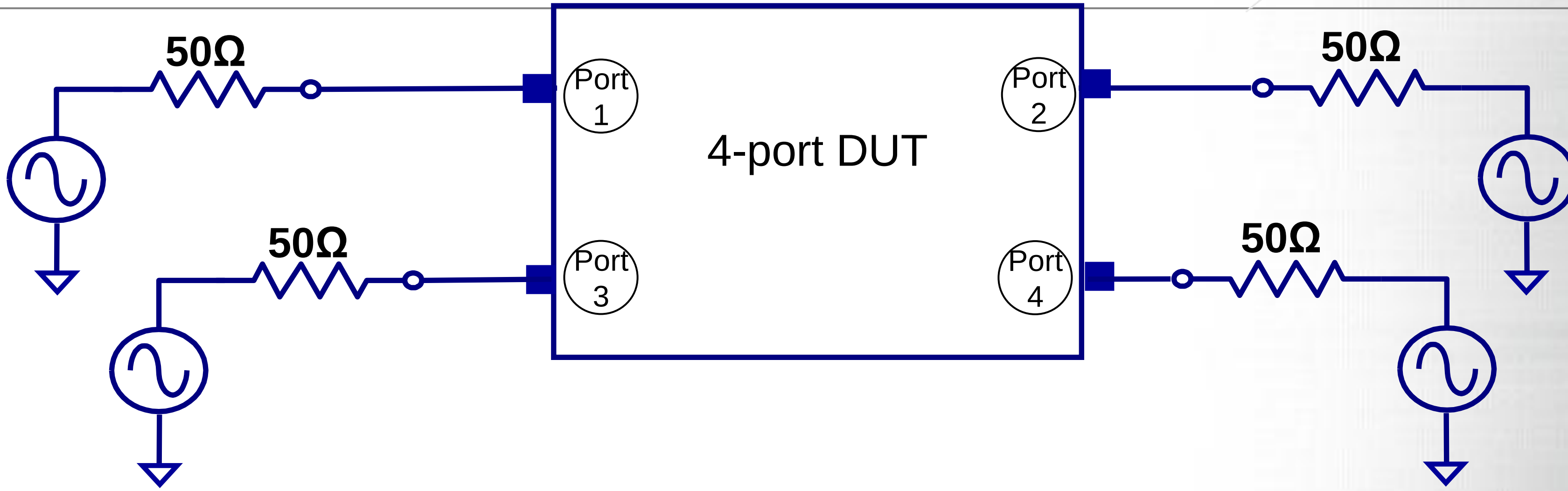
General 4 port Measurement Setup



- *4-port DUT can be modeled as single-ended or differential*
  - *Single ended S-parameter measurements for a 4-port network are straightforward—just like 2-port case, only more S-parameters*

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{21} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{24} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix}$$

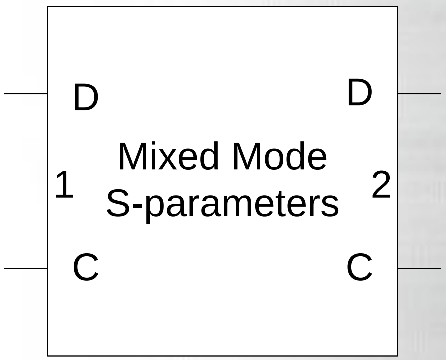
  - *A 4-port DUT can also be modeled as 2-port differential DUT and in this case represented using “Mixed-Mode” S-Parameters*

Mixed Mode S-Parameters

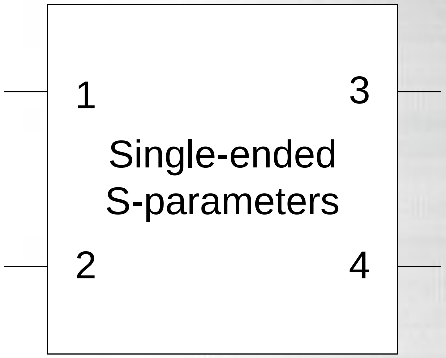
Differential Mode Terms

$$\begin{bmatrix} Sdd_{11} & Sdd_{12} & Sdc_{11} & Sdc_{12} \\ Sdd_{21} & Sdd_{22} & Sdc_{21} & Sdc_{22} \\ Scd_{11} & Scd_{12} & Scc_{11} & Scc_{12} \\ Scd_{21} & Scd_{22} & Scc_{21} & Scc_{22} \end{bmatrix} \begin{bmatrix} da_1 \\ da_2 \\ ca_1 \\ ca_2 \end{bmatrix} = \begin{bmatrix} db_1 \\ db_2 \\ cb_1 \\ cb_2 \end{bmatrix}$$

Common Mode Terms



$$\begin{pmatrix} s_{11} & s_{12} & s_{13} & s_{14} \\ s_{21} & s_{22} & s_{23} & s_{24} \\ s_{31} & s_{32} & s_{33} & s_{34} \\ s_{41} & s_{42} & s_{43} & s_{44} \end{pmatrix} \cdot \begin{pmatrix} a1 \\ a2 \\ a3 \\ a4 \end{pmatrix} = \begin{pmatrix} b1 \\ b2 \\ b3 \\ b4 \end{pmatrix}$$



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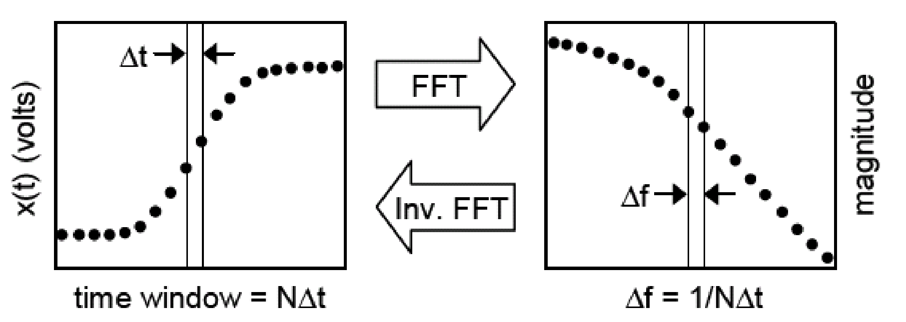
TDR/TDT and VNA – S-parameter

✓ TDR/TDT and S-parameter are describing reflection / transmission respectively in the time domain and in the frequency domain .

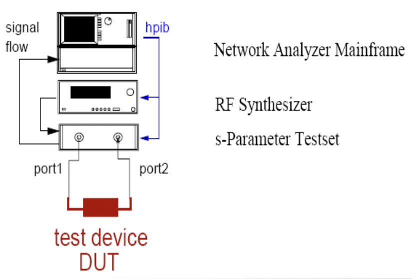
✓TDR/ TDT measurements may be converted into the frequency domain for S-parameter analysis.

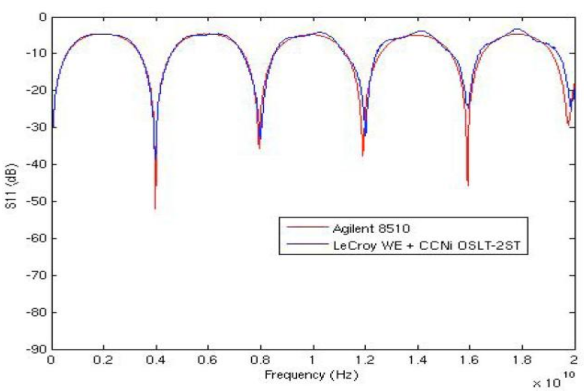
✓ S-parameter measurements may be converted into the time domain for TDR/TDT measurements



TDR/TDT

S-Parameter





Reflection – Correlation on S_{11}

VNA S-parameter measurement compared to WaveExpert extracted S-parameter from TDR measurement