TDR and VNA: The Right Tools for the Right Measurements

August 20, 2002

presented by:

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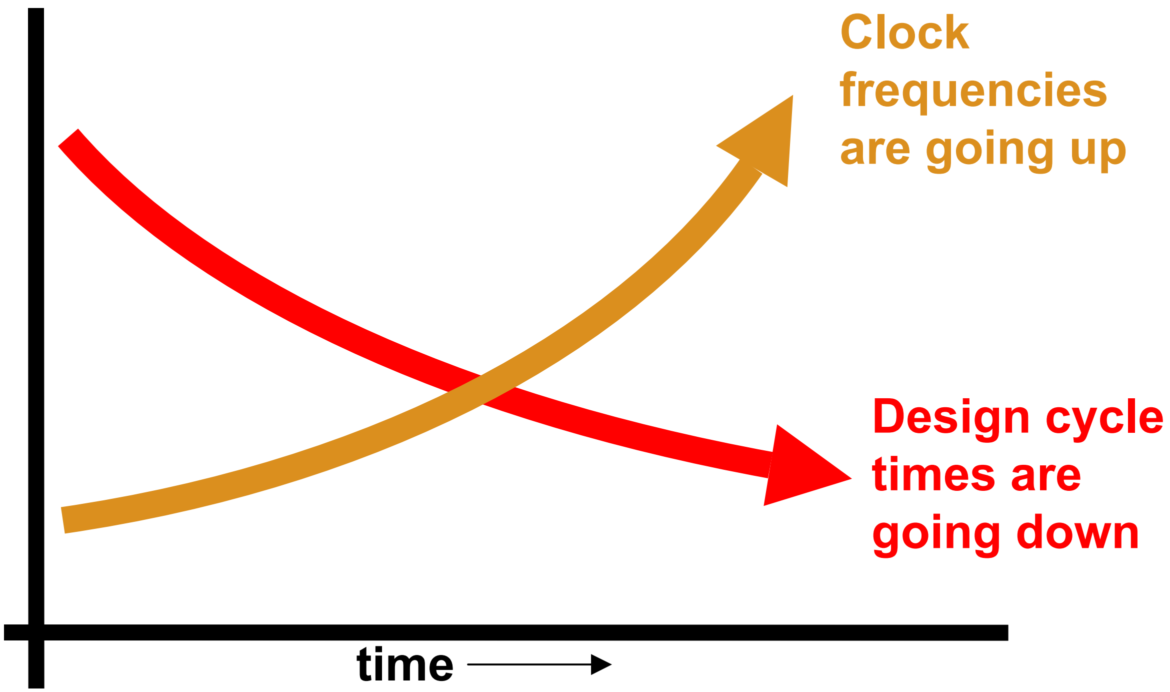
Overview

- Why characterization will be in your future
- TDR (Time Domain Reflectometer) and VNA (Vector Network Analyzer) systems: similarities and differences
- TDR techniques
- VNA techniques
- The right tool for your applications

High Speed Product Design will only get Harder



- Key ingredient to the new high speed design methodology: *predictability*
- Measurements are essential to reduce *risk*

The Critically Important Role of Measurements

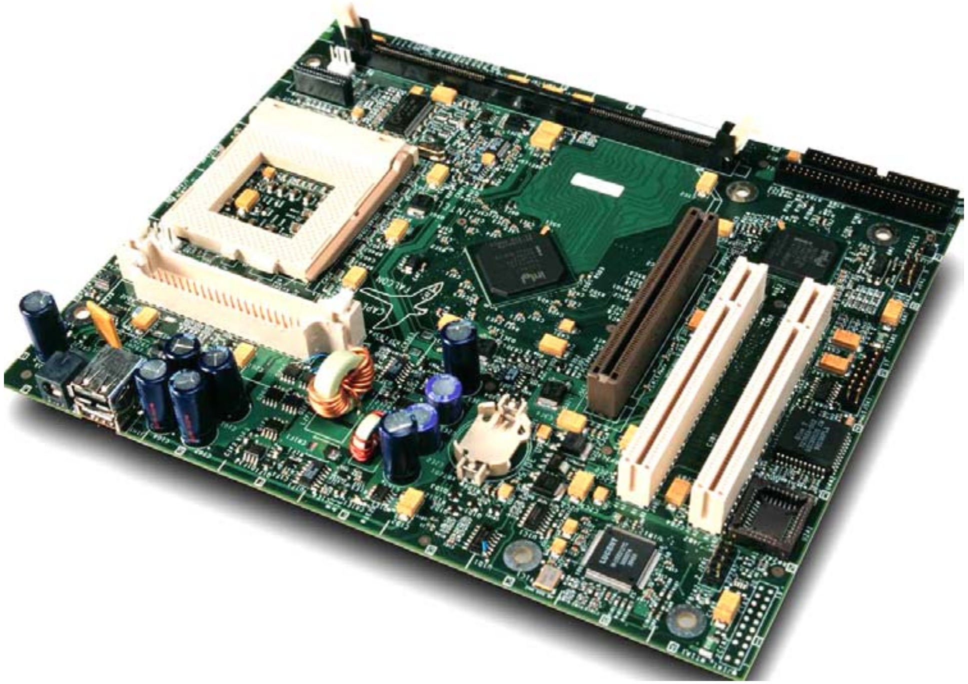
Create a model from a real structure

Validate a model and simulation from a calculation (anchor to reality)

Emulate the system level performance

VNA and TDR Based Measurements

- When an external precision signal is required
- Applies to any passive interconnect or component
  - Discretes
  - Packages
  - Connectors
  - PCB structures
  - Material properties



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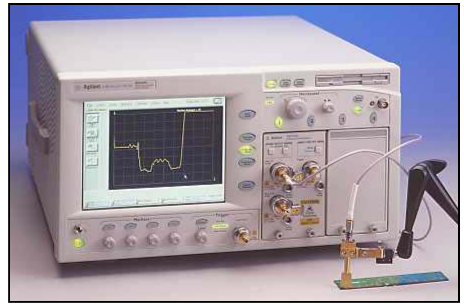
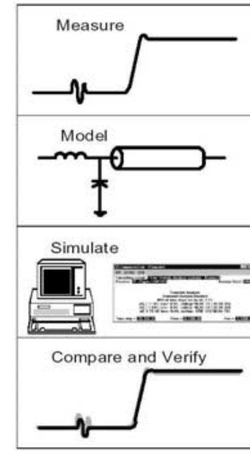
Complete Characterization System Solutions

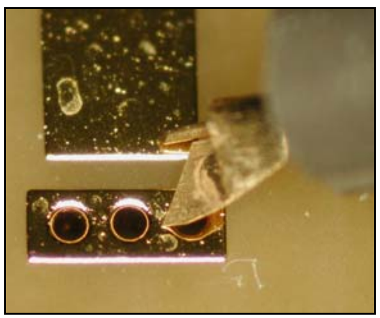


TDR

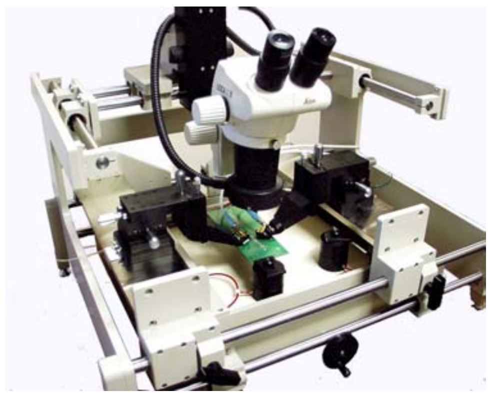
+

TDA Systems IConnect

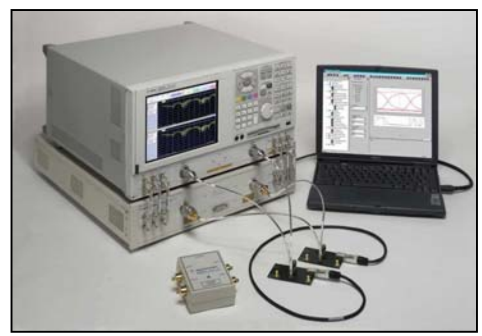




DUT + microprobes



GigaTest Probe Station



Physical Layer Test System (PLTS): VNA + software

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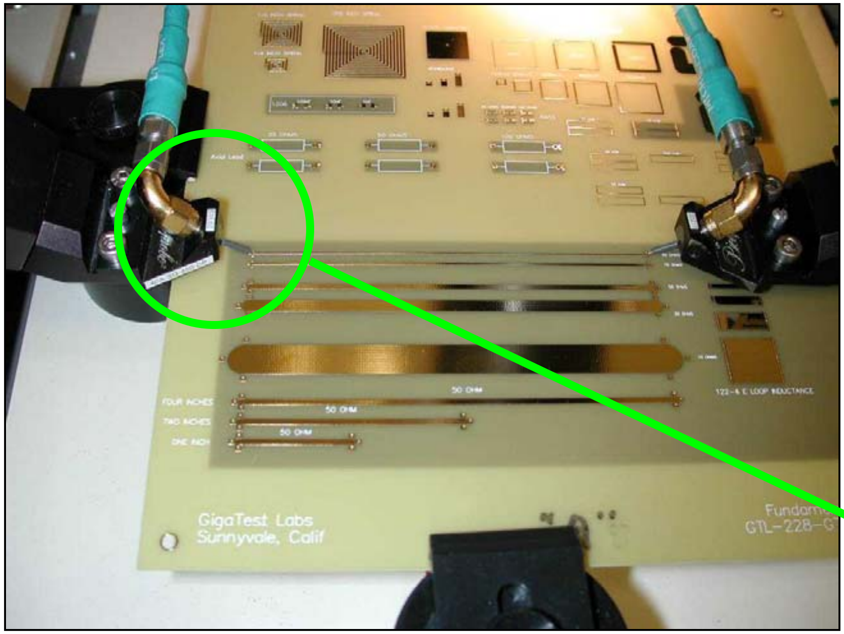
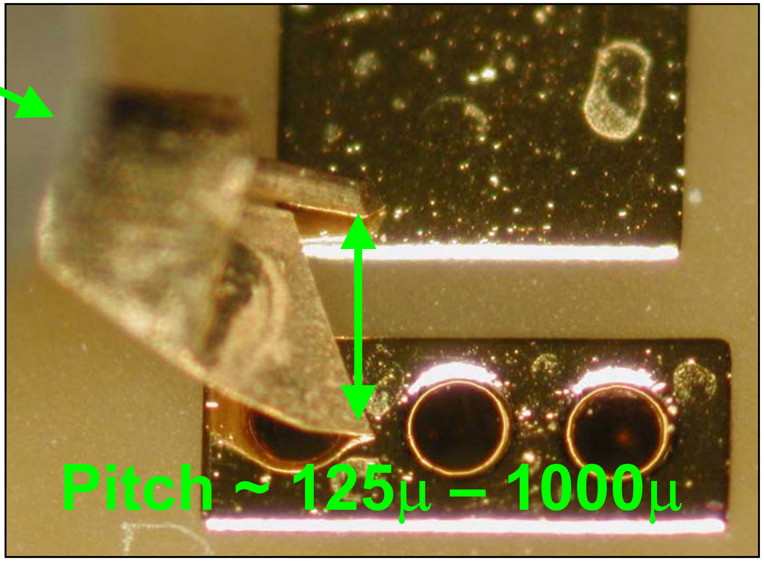
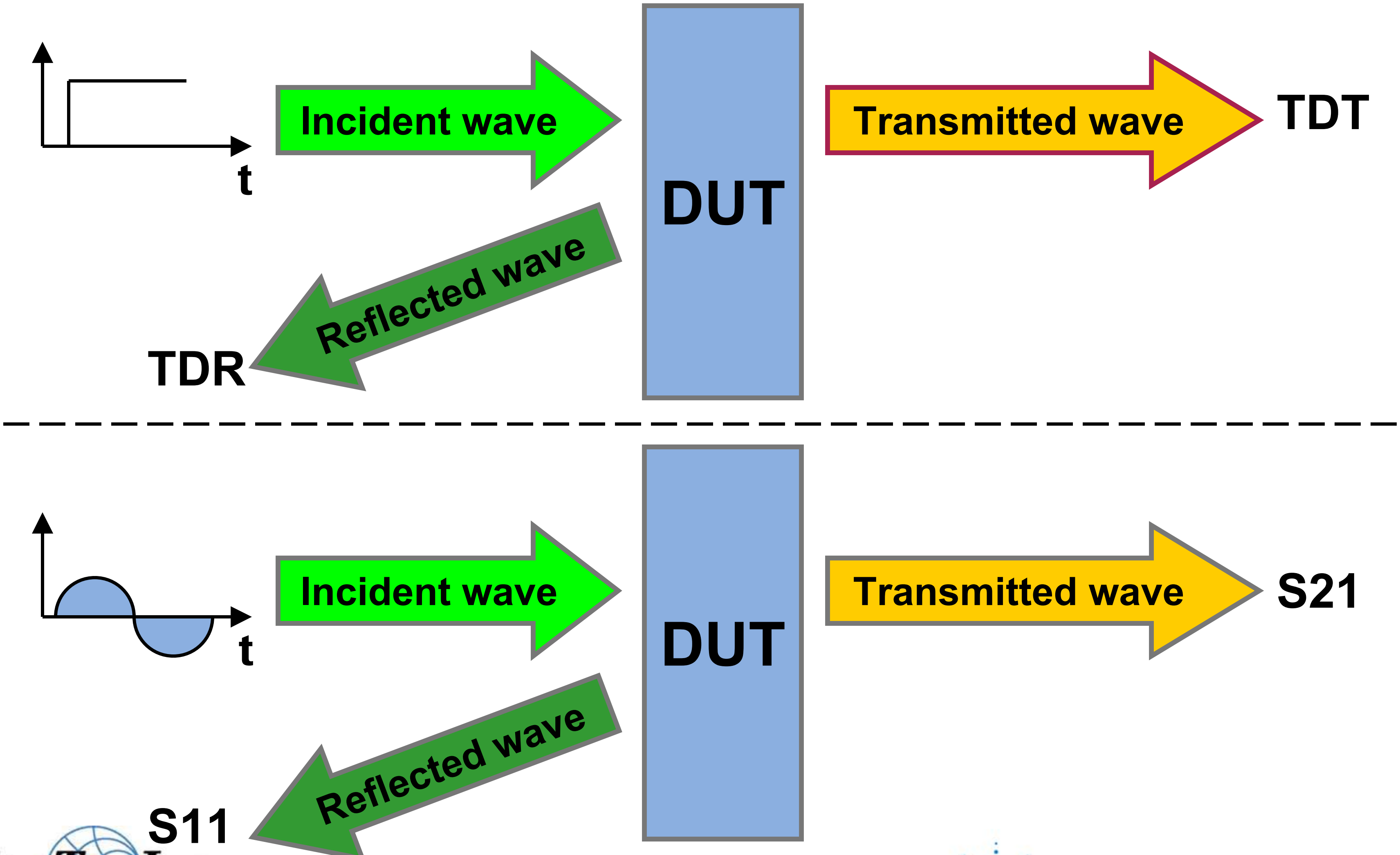
Microprobes Allow Precision Probing of Structures with Minimal Artifacts



Close up



TDR and VNA Techniques



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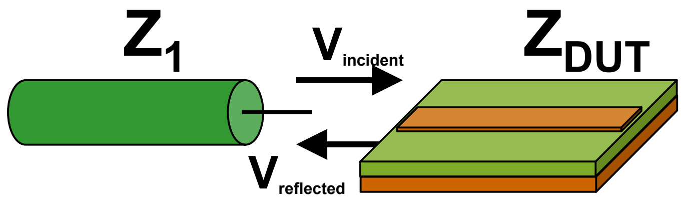
Impedance in the Time or Frequency Domains



$$\frac{V_{reflected}}{V_{incident}} = \frac{Z_{DUT} - Z_1}{Z_{DUT} + Z_1}$$

Time domain

$$\rho = \frac{V_{reflected}}{V_{incident}} \qquad Z_{DUT} = 50\Omega \frac{1+\rho}{1-\rho}$$

Frequency domain

$$S_{11} = \frac{V_{reflected}}{V_{incident}} \qquad Z_{DUT} = 50\Omega \frac{1+S_{11}}{1-S_{11}}$$

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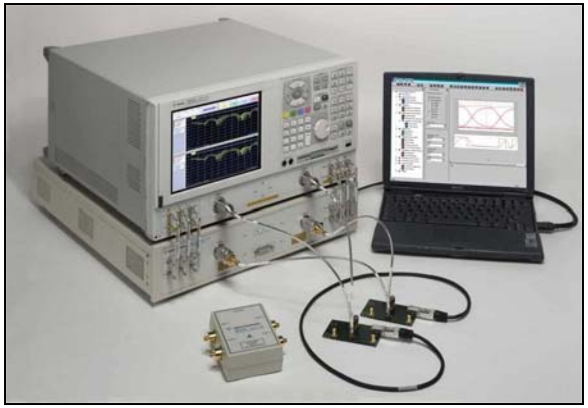
There is no fundamental difference in the information content between the time domain and the frequency domain

There is a difference in the capabilities of the two systems:

TDR + TDA Systems IConnect



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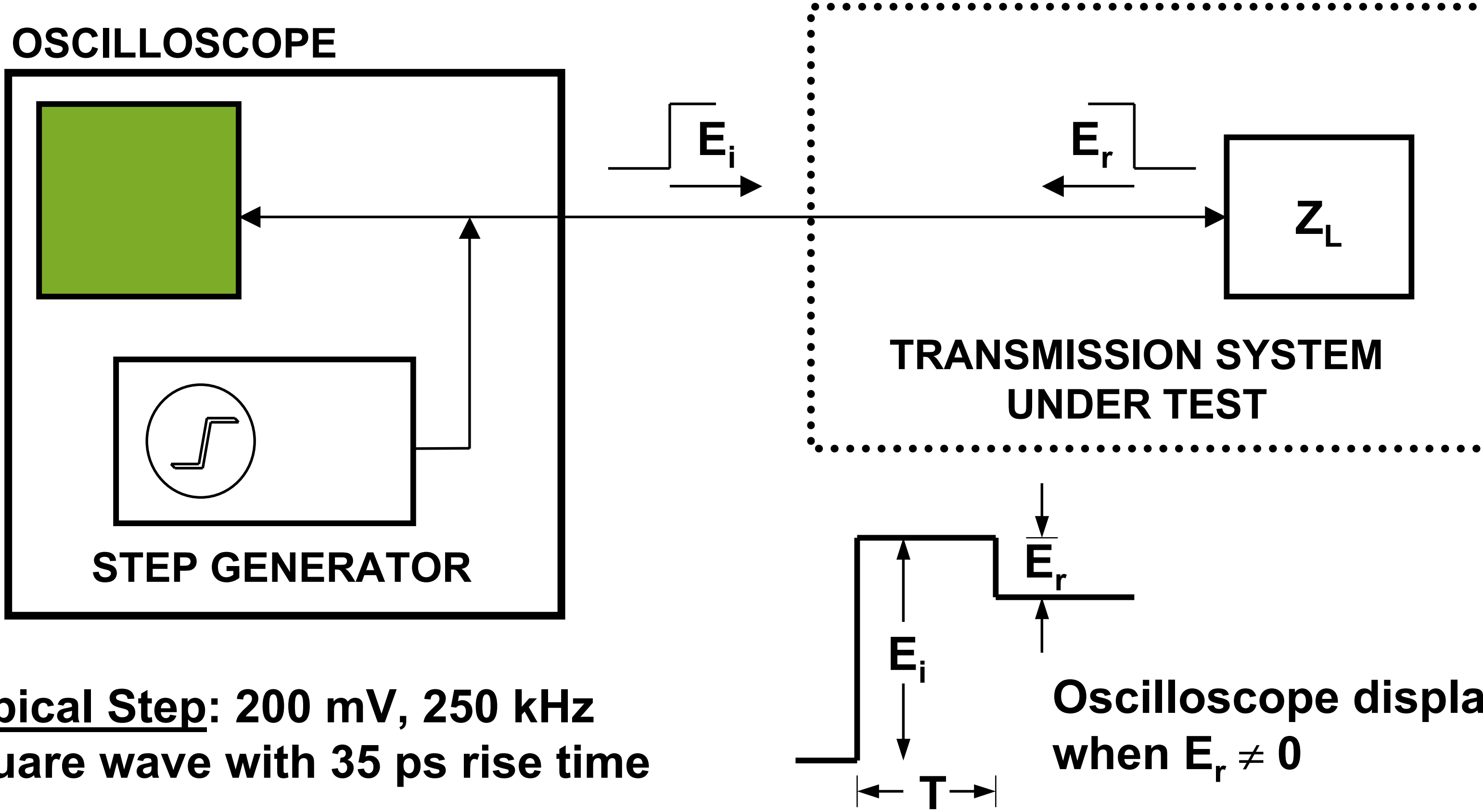
TDR and VNA Systems: What's the Difference?

- Great deal of overlap in features, capabilities: T lines, discontinuities, cross talk, differential impedance, …
- A TDR is simple to use and can be quickly set up for general applications: transmission lines and discontinuities
- SNR is better for VNA than TDR
  - important for low insertion loss components
  - Important for low levels of mode conversion
- The PLTS simplifies the analysis of 4 port differential interconnects

TDR Agenda

- TDR Overview - What is it?
- Impedance Problems - Where are they?
- Microstrip Examples
- Excess Reactance
- TDR vs. TDT
- TDR Normalization
- Real World TDR Set up

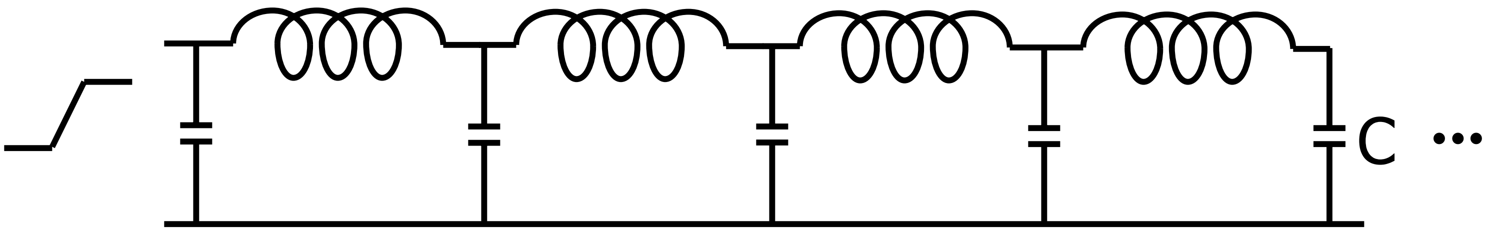
What is TDR?
(Time Domain Reflectometry)



Oscilloscope display when $E_r \neq 0$

<u>Typical Step</u>: 200 mV, 250 kHz square wave with 35 ps rise time

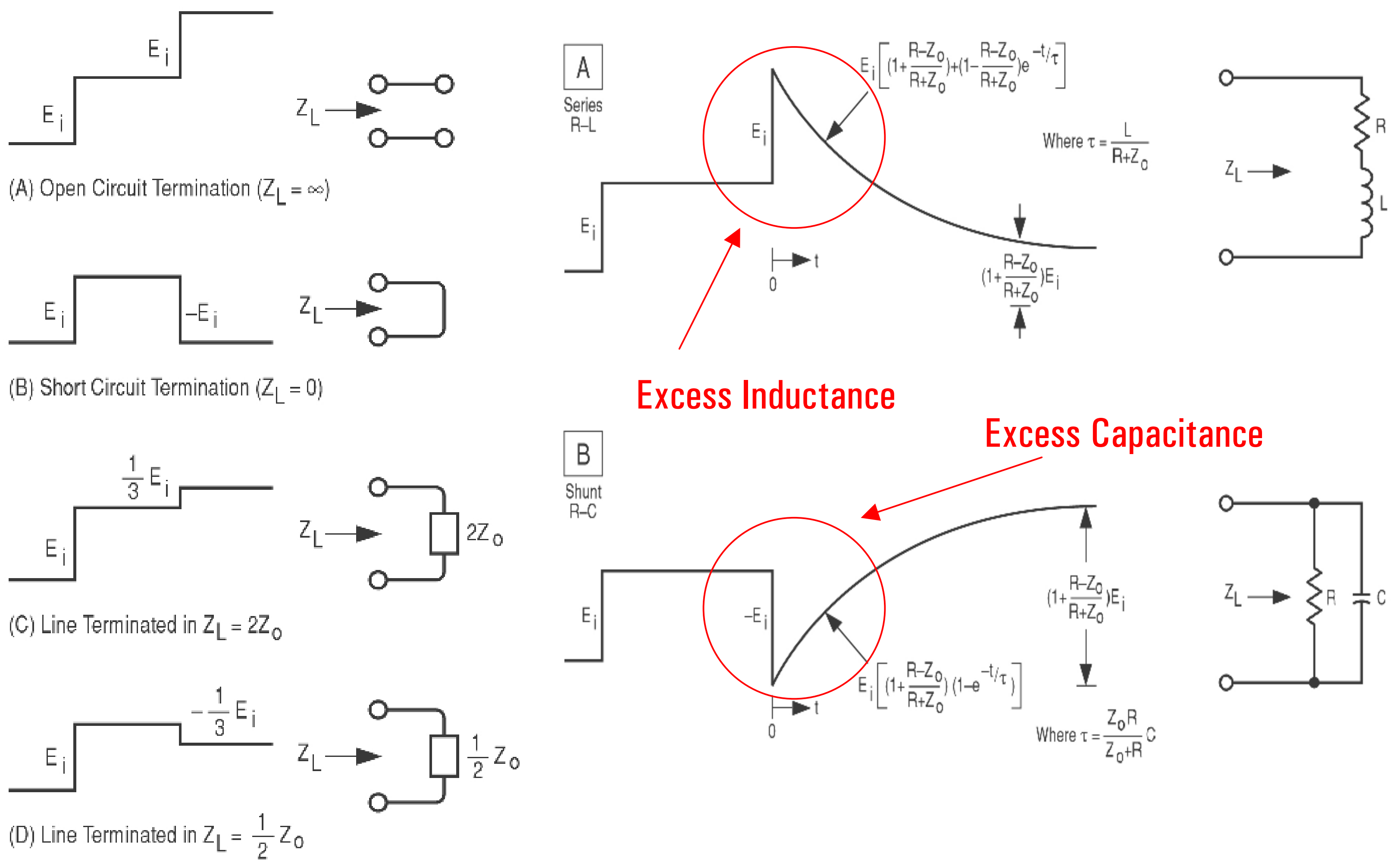
Transmission Line Model



$$Z_0 = \sqrt{L/C}$$

Discontinuities occur when the impedance changes. This will happen when the L or C changes or an R is introduced.

Basic TDR Waveform Analysis



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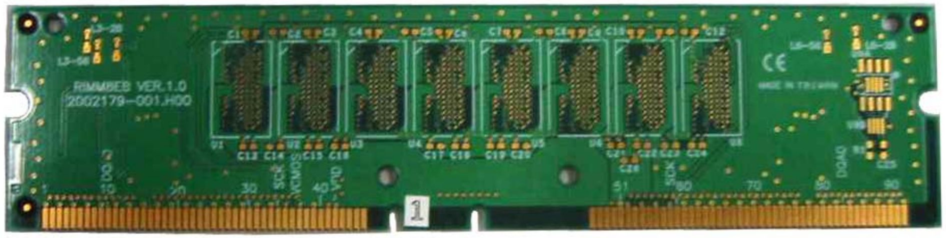
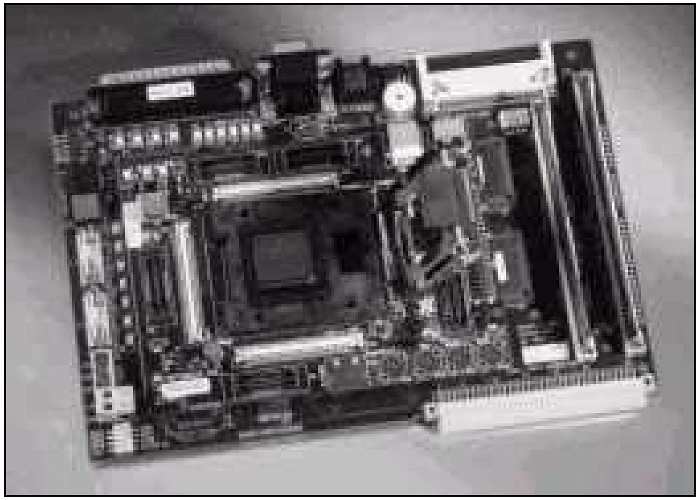
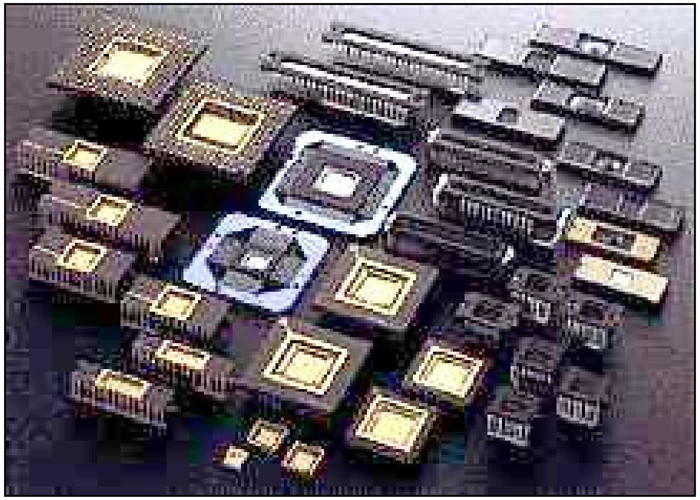
Impedance Problems are Everywhere



PC BOARDS BACKPLANES





TDR is useful for characterizing passive, linear devices

IC PACKAGES SOCKETS

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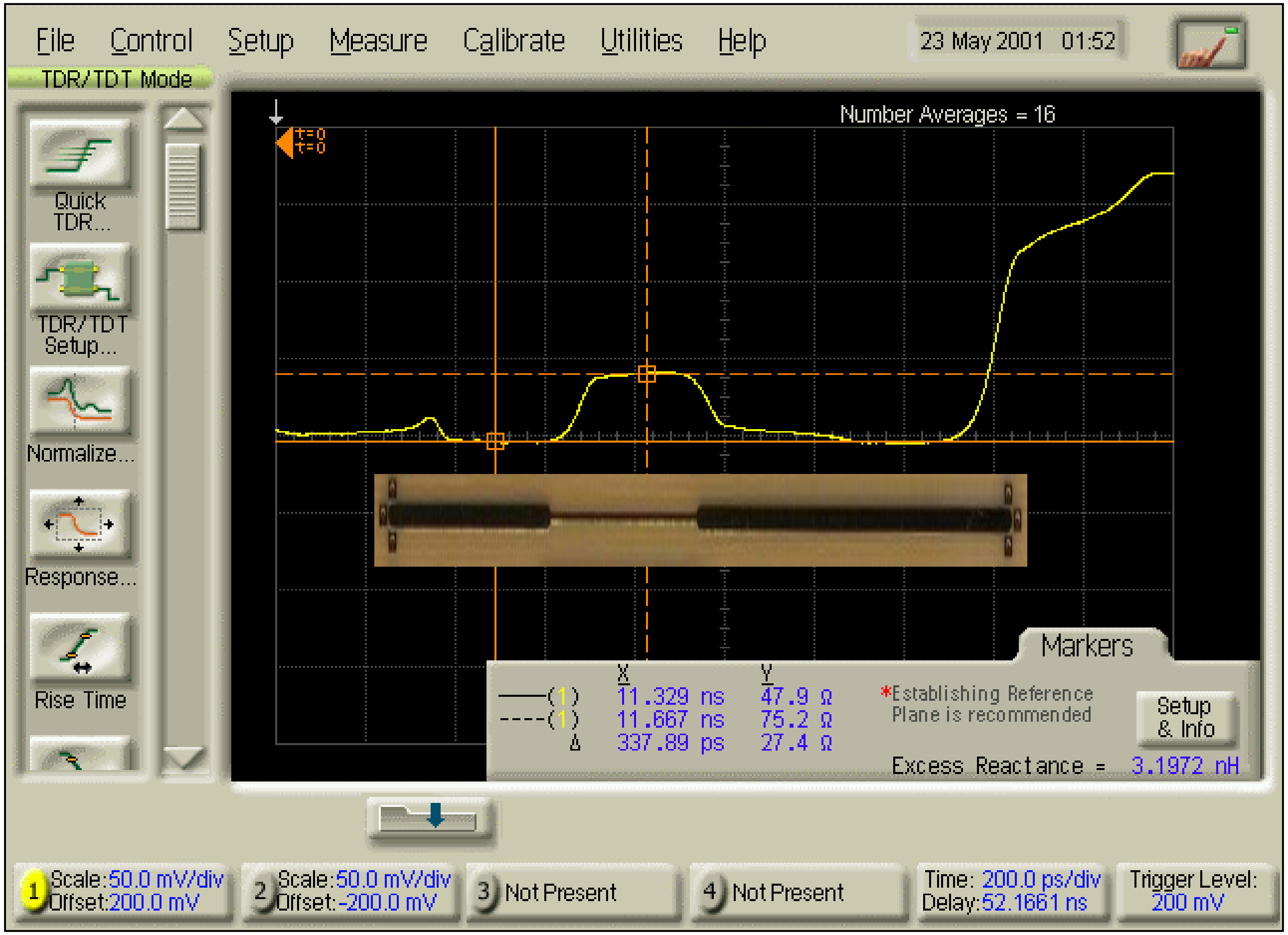
Display in the Time Domain: TDR is "Instantaneous Impedance"



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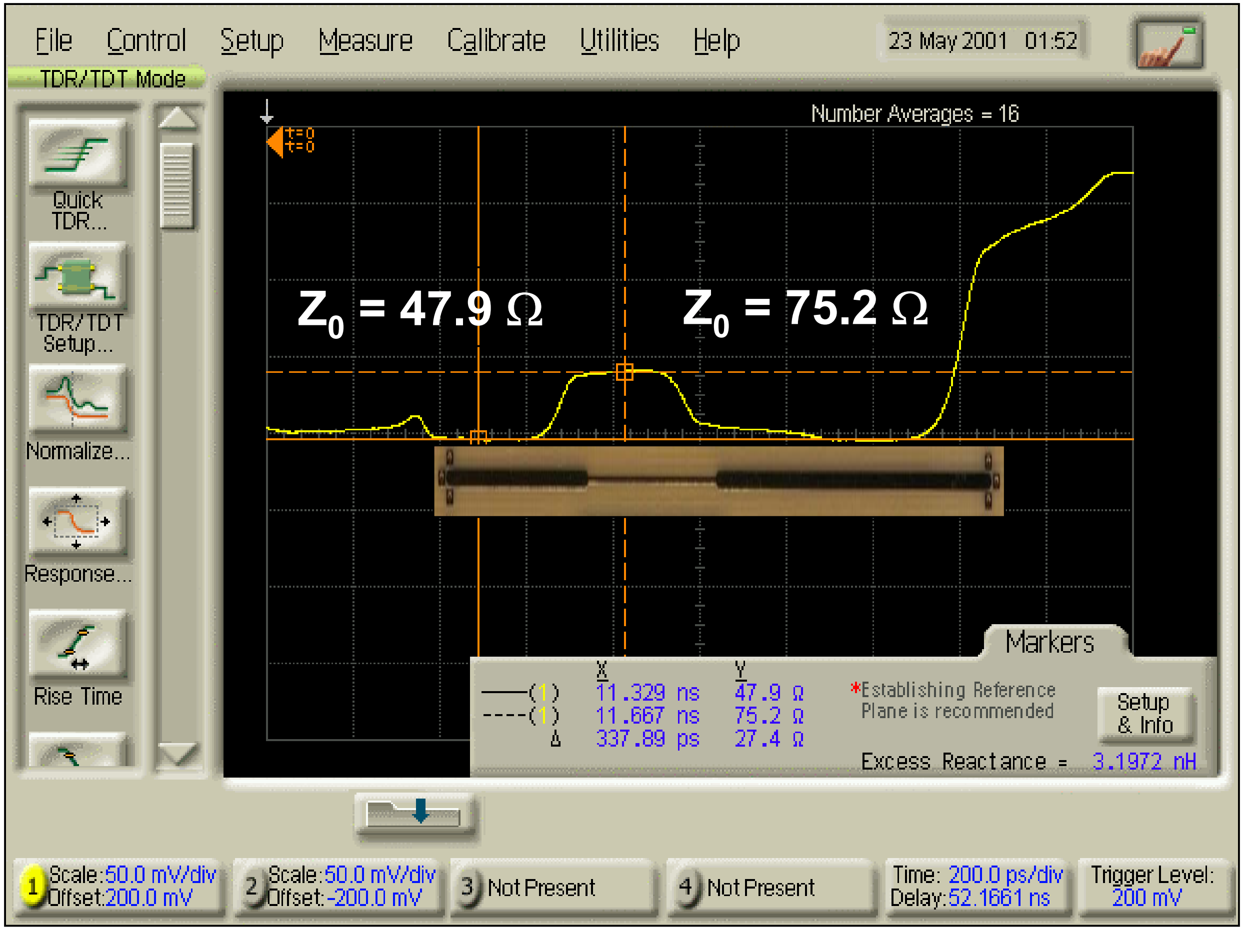
Quick Z_0 with TDR



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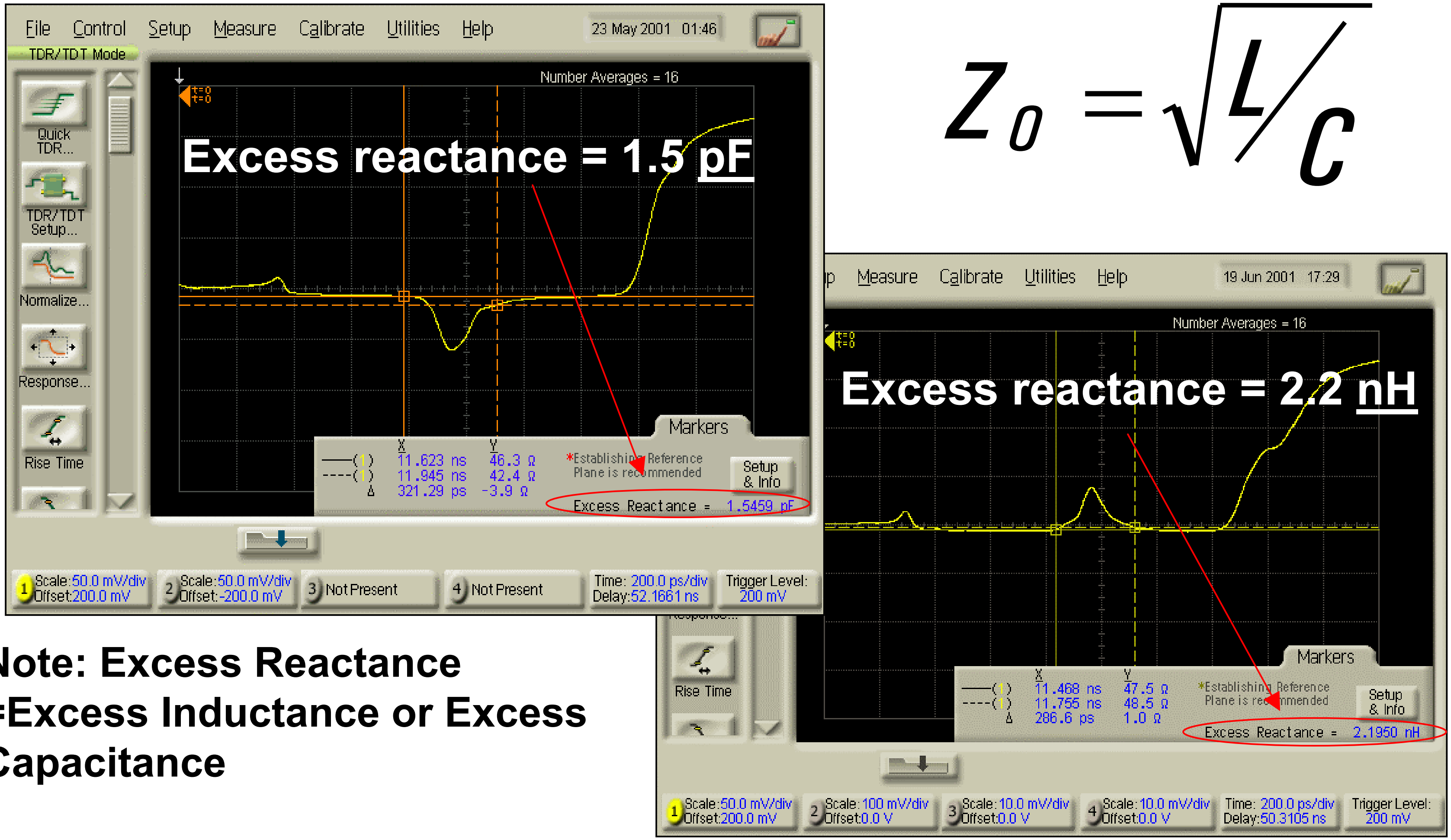
Quick C, L Extraction with TDR



$$Z_0 = \sqrt{L/C}$$

Note: Excess Reactance =Excess Inductance or Excess Capacitance

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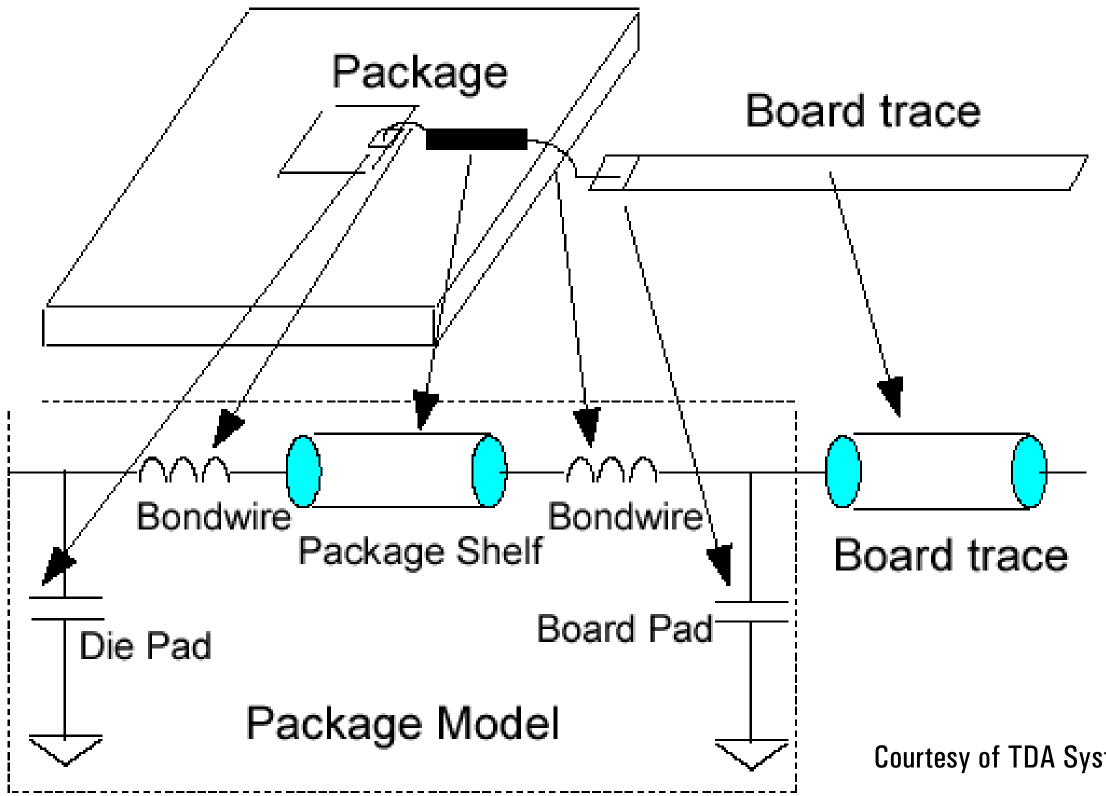
IConnect™ Modeling Software

TDR interconnect modeling



Courtesy of TDA Systems, Inc.

Physical model: correlates to the DUT geometry

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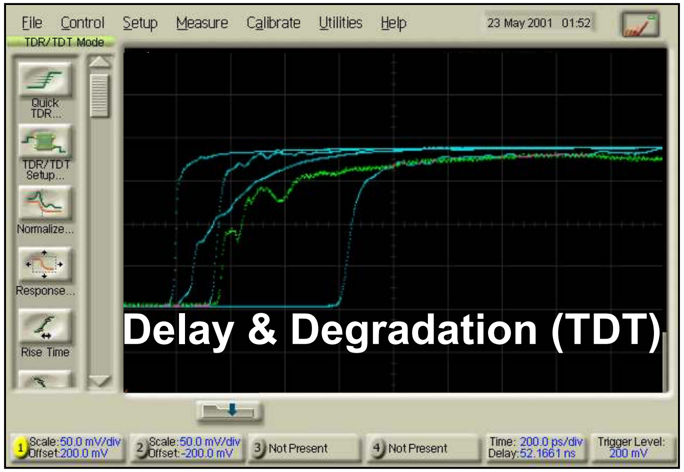
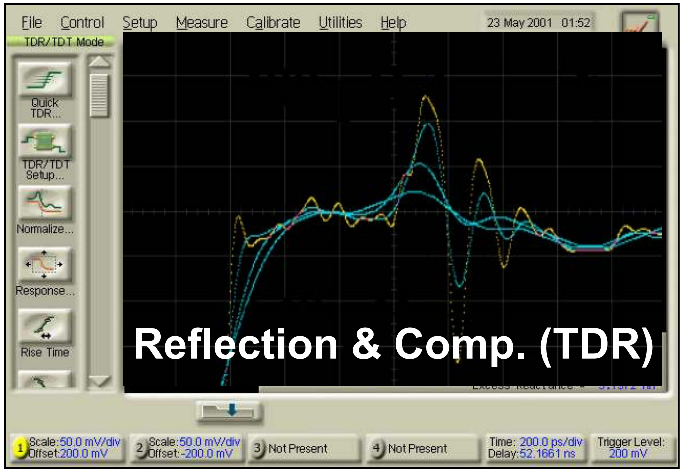
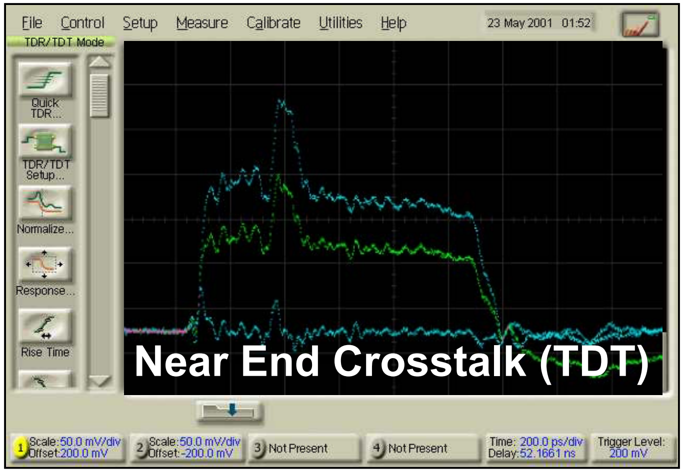
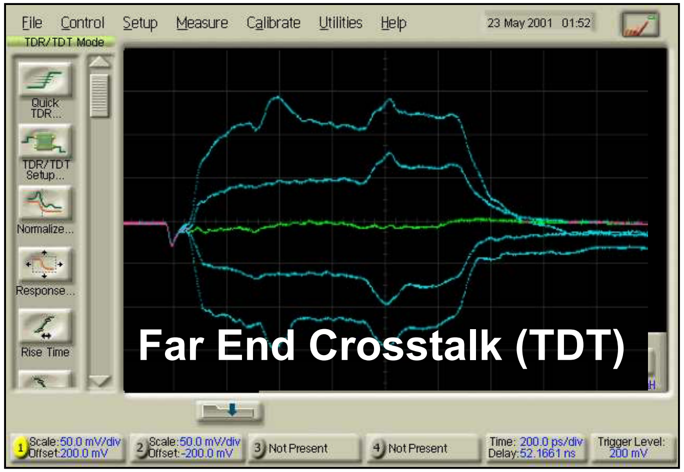
Time Domain Analysis:TDR/TDT



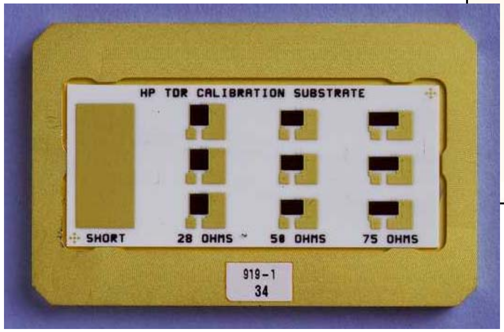






How Do I Probe My Passive Device?

- Motherboards
- RIMMs
- Connectors
- Coaxial cables
- Microstrip

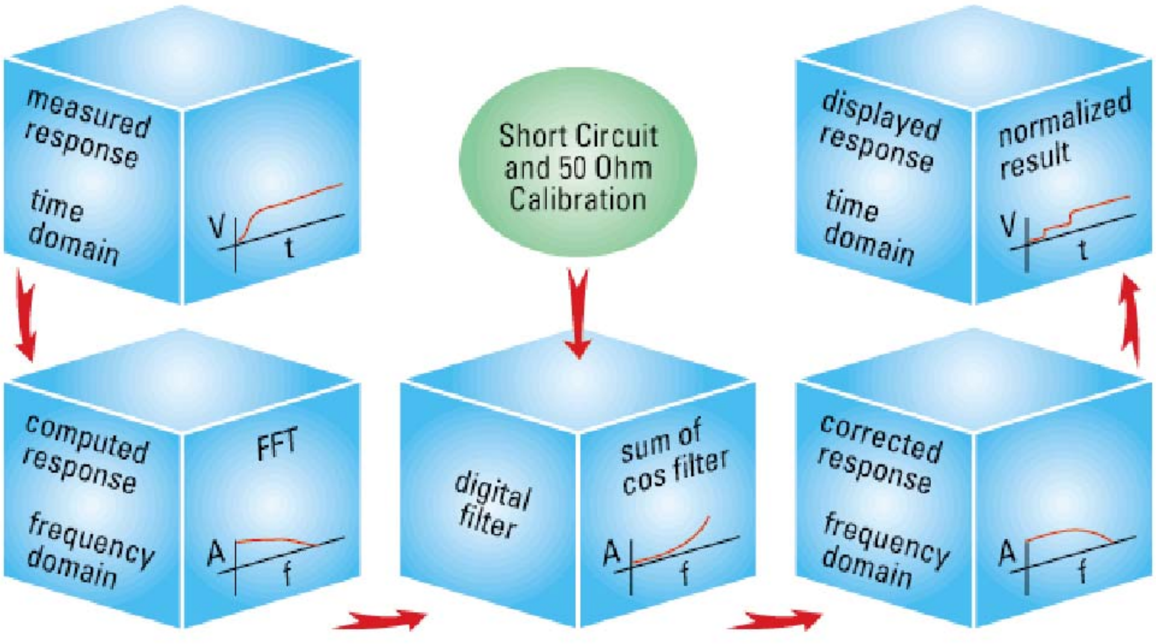


Calibration Substrate

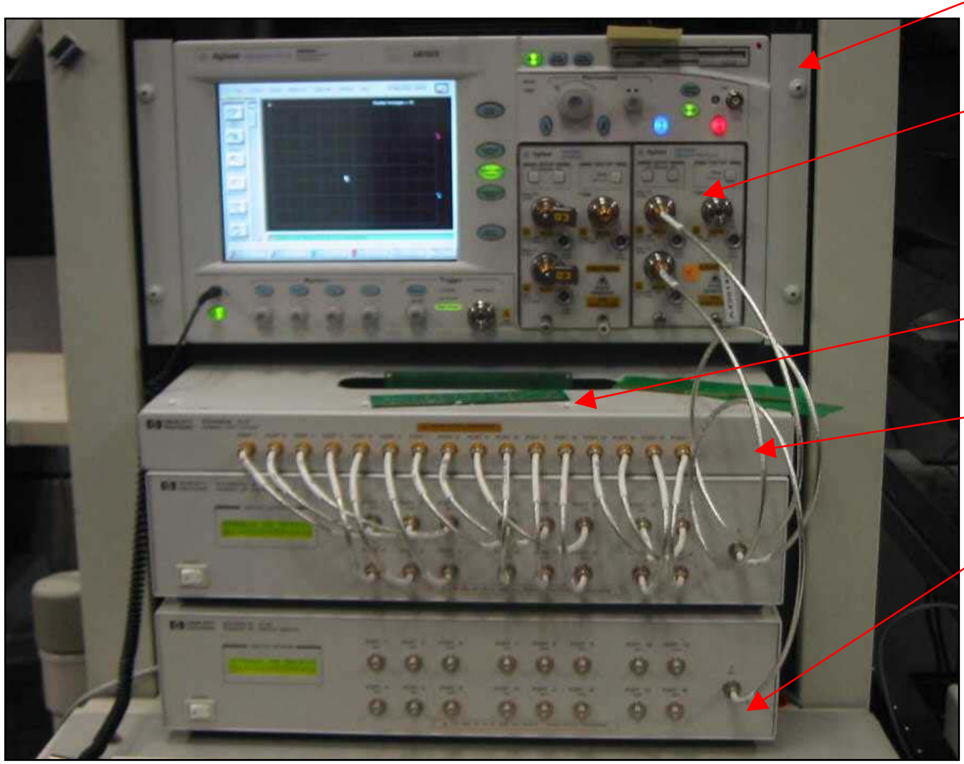
Single -ended probe
w/articulating arm (N1020A)

What is TDR Normalization?

- Digital Filter
- Constructed In Frequency Domain
- Removes Test Fixture Error
- Improves Impedance Accuracy



Differential TDR Test Set Up



86100A DCA

54754A Differential TDR Module

Device Under Test: Rambus™ RIMM

Test Fixture: Switch Matrix

Differential Impedance with and w/o TDR Normalization

Blue Trace - Normalized

Green Trace - Standard

Error = 2.3 ohms

Test Fixture **Device Under Test**

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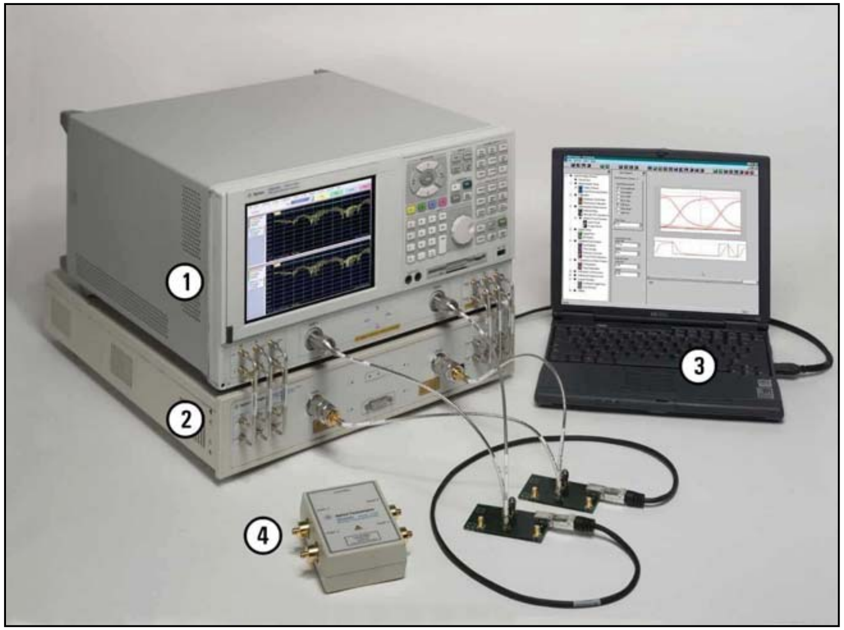
Summary

- TDR is an easy to use, intuitive test tool
- Digital design speeds are increasing
- Normalization is critical
- Remove test fixture error
- TDR is an integral part of the signal integrity lab

Agenda

- Network Analyzer-Based System Configuration
- Differential Device Characterization
- Major Advantages of the VNA-Based System

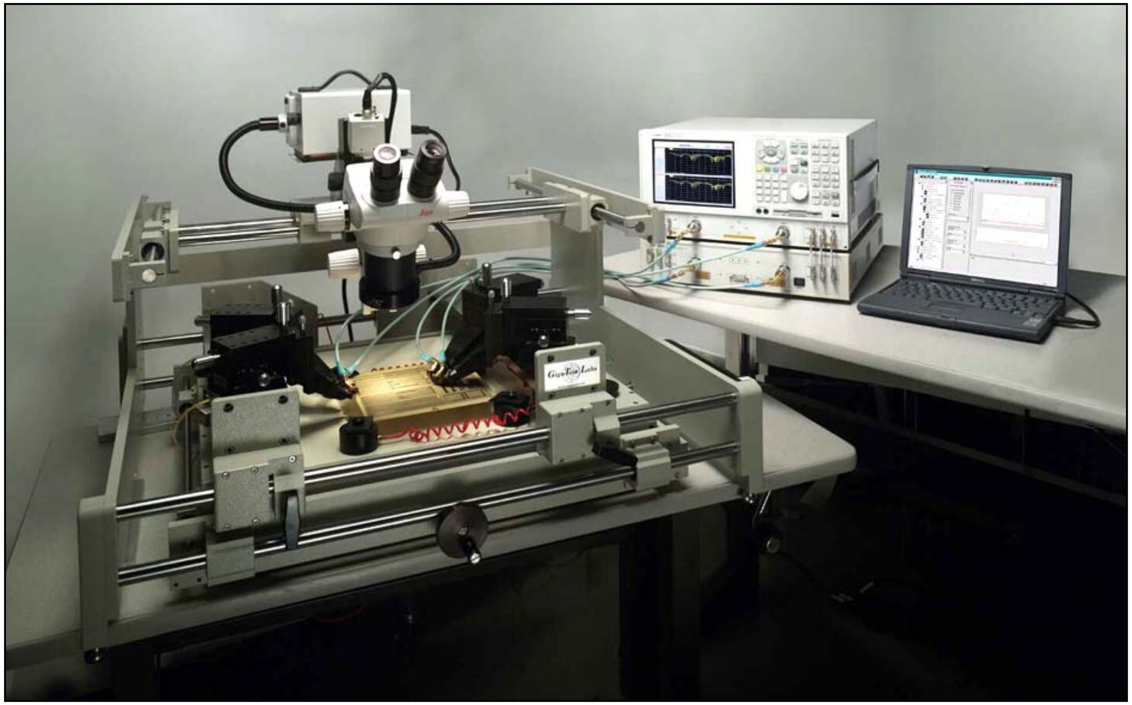
VNA-Based System Configuration



1. Network Analyzer
2. External Test Set
3. PC with Physical Layer Test System (PLTS) SW
4. Four-port Electronic Calibration Module or Mechanical Calibration Kit

Currently Available Systems				
RF BW (f_{max})	Rise Time (10%-90%)	Approx. Effective Data Rate (inclusion to 1st Harmonic)	Approx. Effective Data Rate (inclusion to 3rd Harmonic)	Approx. Effective Data Rate (inclusion to 5th Harmonic)
6 GHz	120 pS	6 GB/sec	3 GB/sec	2 GB/sec
9 GHz	80 pS	9 GB/sec	4.5 GB/sec	3 GB/sec
20 GHz	36 pS	20 GB/sec	10 GB/sec	6.7 GB/sec
50 GHz	15 pS	50 GB/sec	25 GB/sec	16.5 GB/sec

System Configuration with GigaTest Probe Station



Probing solutions are recommended, particularly when:

- DUT cannot be connectorized due to physical constraints
- When fixturing (signal launchers, etc…) dominates measurement performance

Decision to use probing is performance dependent, not frequency dependent!

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Frequency Domain Characterization

S-Parameters Answer the Question …

If a single port of a device is stimulated,

what are the corresponding responses
on all ports of the device?

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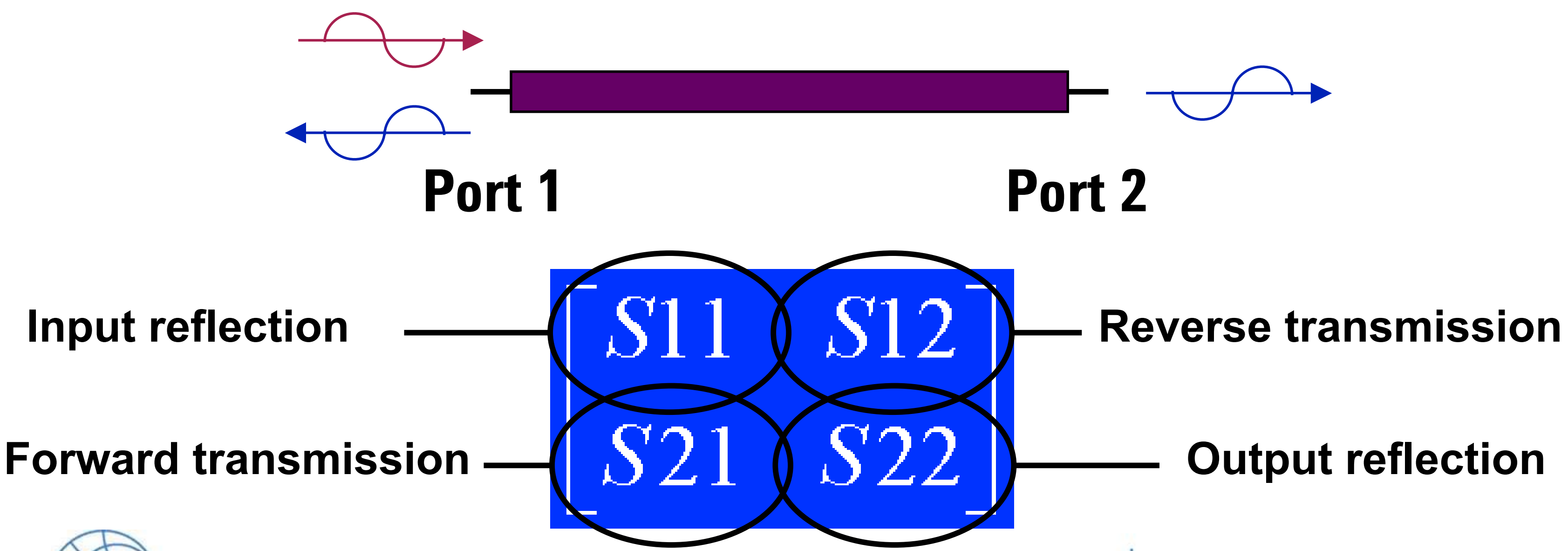
Frequency Domain Characterization

- An s-parameter is similar to a TDR or TDT response, but it only considers one frequency component at a time.
- Commonly represented in matrix form to fully characterize a device.
- A single-ended device with 2 ports has four s-parameters.



Unbalanced and Balanced Devices

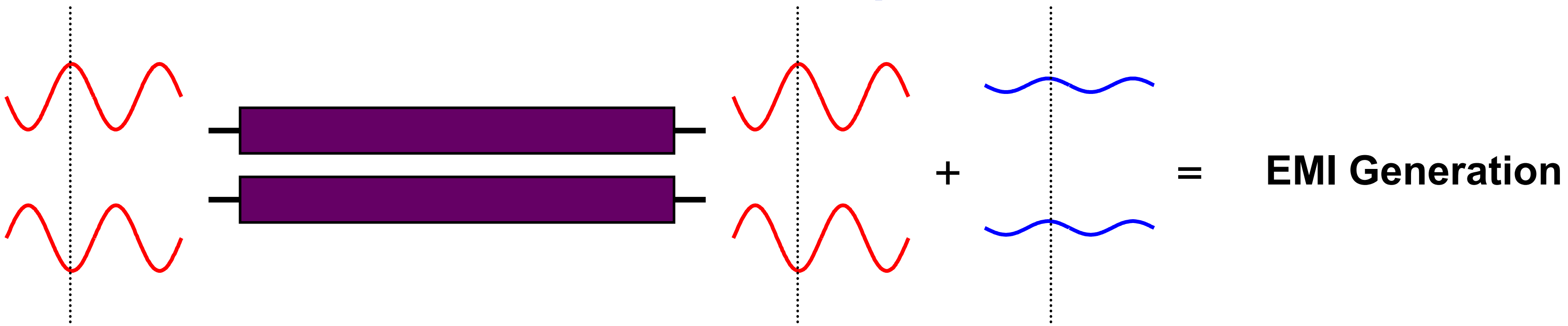
- **Unbalanced (Single-ended) devices are referenced to gnd (S-parameters)**

- **Balanced (Differential) devices are pairs (Mixed-Mode S-parameters)**

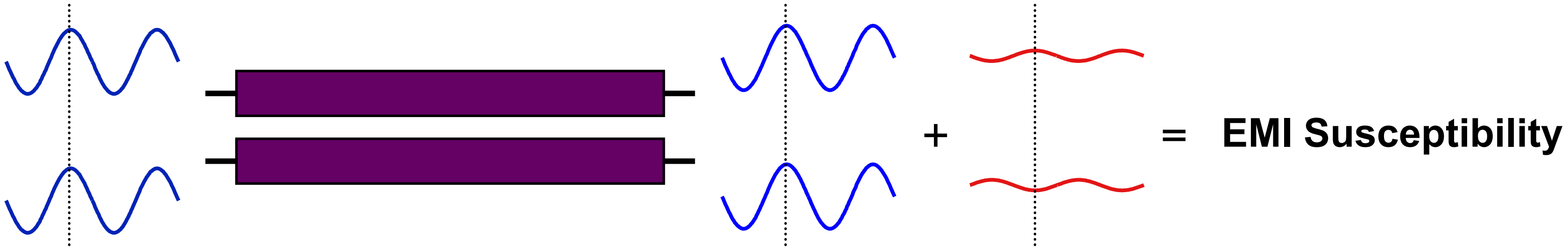
What About Non-Ideal Devices?

Mode conversions occur...

- Differential-stimulus to common-response conversion



- Common-stimulus to differential-response conversion



Balanced Device Characterization

Differential Stimulus/Response
- Intended Operating Mode
- Forward and Reverse Transmission and Reflection

Mode Conversion from C-to-D
- Typically Overlooked
- Results from Device Asymmetry
- Related to Susceptibility to EMI

$$\begin{bmatrix} S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\ S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\ S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\ S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22} \end{bmatrix}$$

Mode Conversion from D-to-C
- Typically Overlooked
- Results from Device Asymmetry
- Related to Generation of EMI

Common Stimulus/Response
- Mode of Noise
- Forward and Reverse Transmission and Reflection

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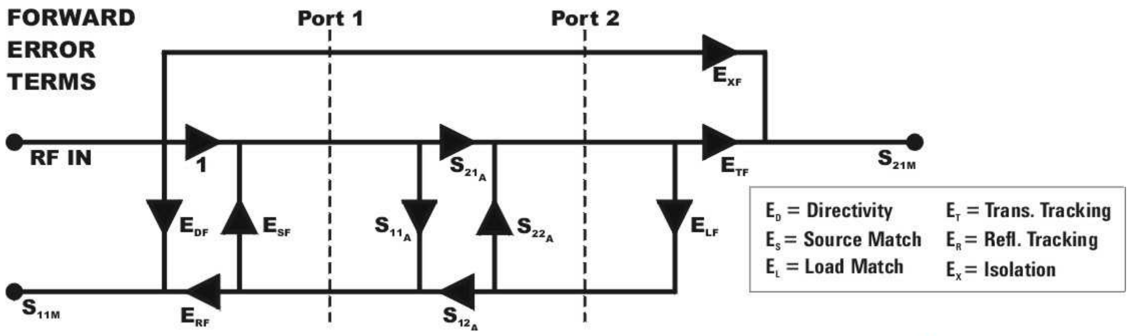
Advantages of the VNA-Based System

- Superior **accuracy**
- Significantly better **dynamic range**
  - Up to approx. -110 dB
- Greater ability to **remove unwanted effects** of fixtures from the measurement with greater accuracy
  - Gating, Port Extensions, De-Embedding, Direct Measurement
- **Comprehensive characterization and analysis**

Superior Accuracy

- Inherent Source and Receiver Accuracy
  - Low Noise Source, Less Random Error
  - Tuned, Super-Heterodyne, Phase-Locked Receiver
- Precision, Phase-Stable Test Cables and Connectors. Metrology Grade Calibration Kits
- Systematic Error-Correction with Four-Port Error Model
  - Well-Defined Calibration and DUT Reference Planes



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Superior Accuracy

- TDR uses integrated waveform
  - Receiver must discriminate small signal of interest from broadband content
  - Best results require TDR and DUT edge rates to match
- VNA uses standing waves
  - Results are accurate for any edge rate
  - Receiver is tuned to the source, like a tracking filter

Why is Dynamic Range Important?

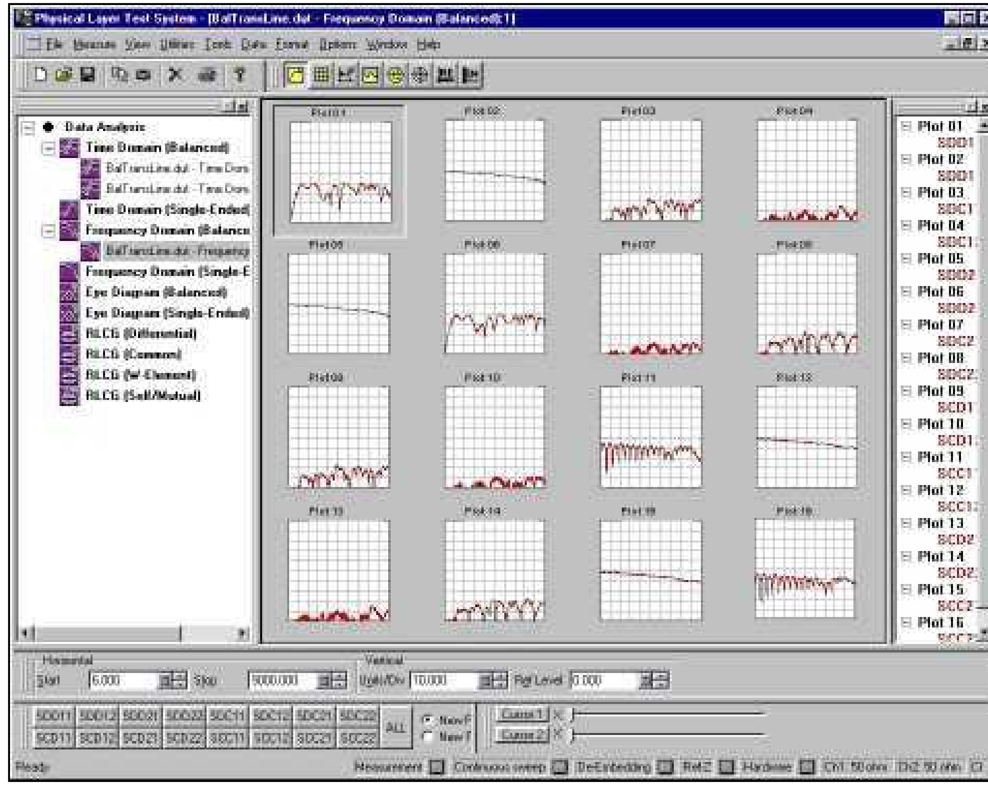
- Crosstalk
- Mixed-Signal applications
- Helps defeat masking effects
  - Greater ability to resolve deep/hidden structures
- Important for Mode Conversion, yet often overlooked
  - Related to susceptibility and generation of EMI

Removing Unwanted Effects from the Measurement

- **Time-Domain Gating**
  - Easiest method. Less accurate.
- **Port Extension**
  - Also easy. Requires “ideal” fixturing.
- **De-embedding**
  - More difficult. Extremely accurate!
- **Calibration at the DUT Reference Plane**
  - Requires probing solutions or calibration standards on board.

Comprehensive Characterization and Analysis

- Frequency Domain
  - Forward and reverse transmission and reflection
  - Single-ended-, differential-, and mixed-modes
  - 32 frequency domain plots per measurement
  - Log mag, linear mag, phase, group delay, Smith, Polar, real, imaginary



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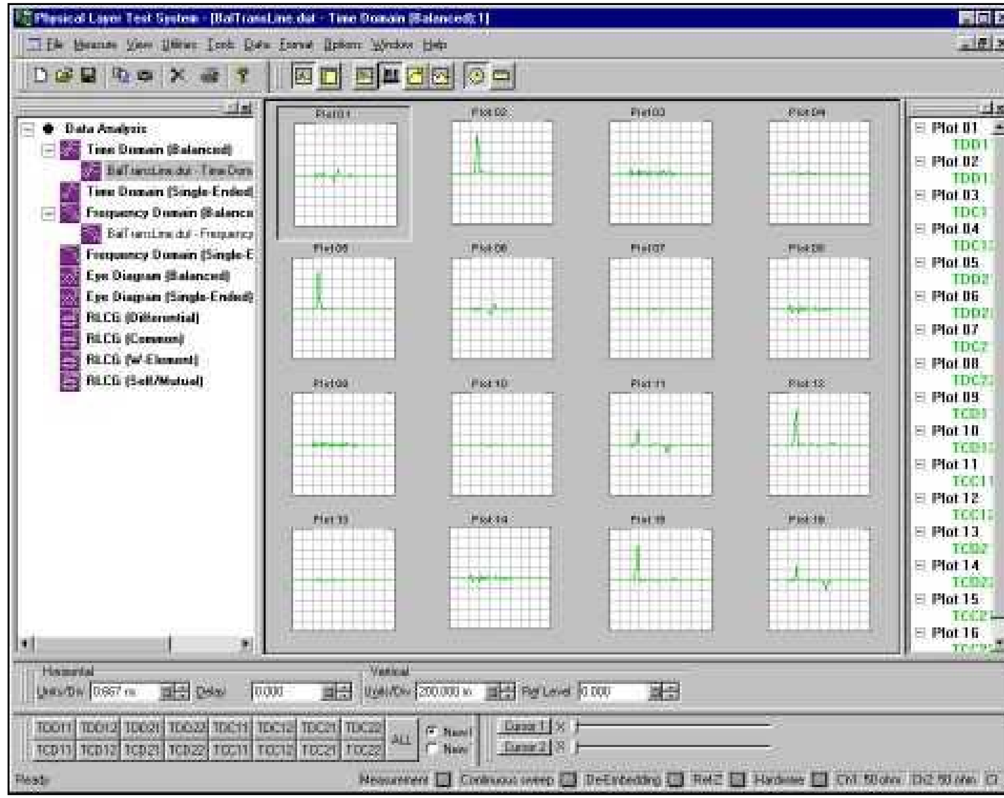
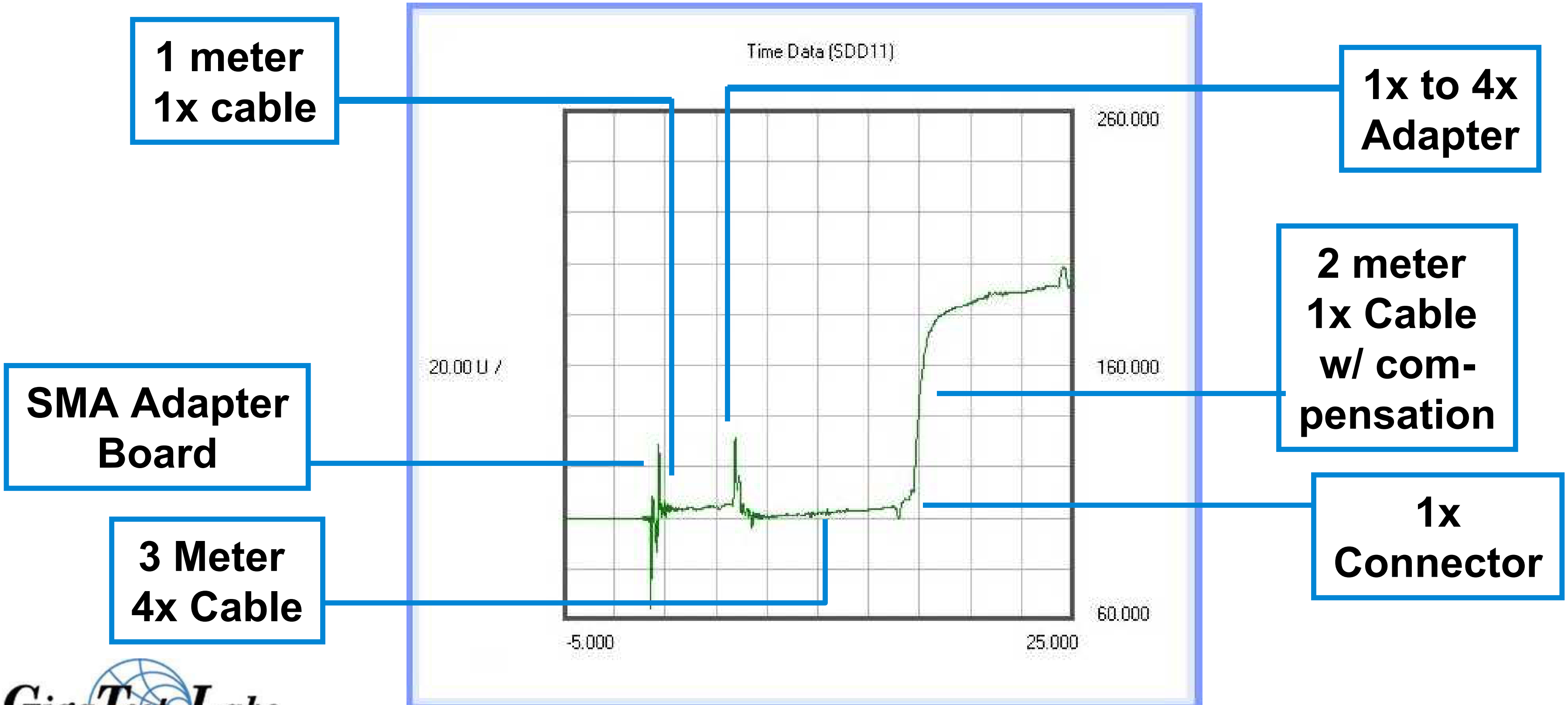
Comprehensive Characterization and Analysis

- Time Domain
  - Input and output TDR and TDT
  - Single-ended-, differential-, and mixed-modes
  - 32 time domain plots per measurement
  - Impulse or step
  - Volts, real, log mag, or impdance
  - nS or cm



Comprehensive Characterization and Analysis

Differential Impedance Profile of Complex Structure



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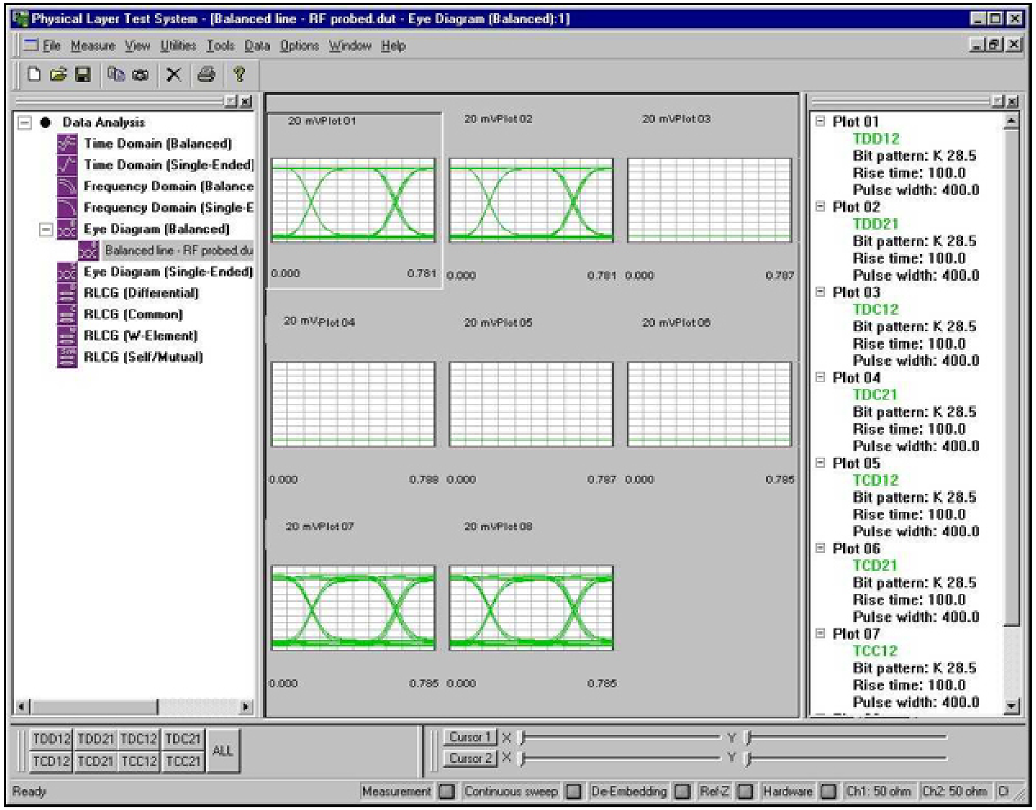
Comprehensive Characterization and Analysis

- Measurement-based Eye Diagrams
  - Forward and Reverse Transmission and Reflection
  - Single-ended-, Differential-, Common-, and Mixed-Modes
  - Virtual Pulse Generator
    - Arbitrary Bit Patterns



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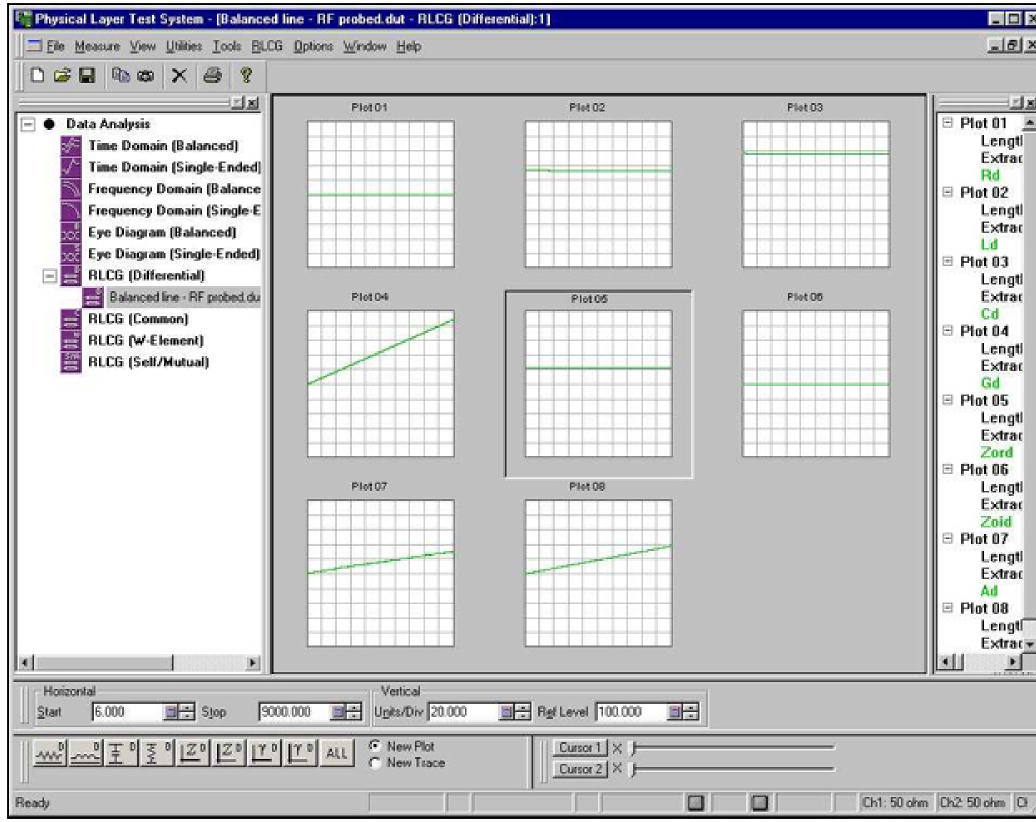
Comprehensive Characterization and Analysis

- **RLCG Model Extraction**
  - **Differential, Common, W-Element, Self and Mutual Terms**
  - **Linkage to modeling and simulation tools**
    - **ADS**
    - **Hspice**



Ideal Instrument

The VNA-Based System Takes the Best from Each World:

- **From RF World ...**
  - Frequency Domain Data
  - Accuracy
  - Dynamic Range
  - Well-Defined Reference Plane
  - Removal of Fixture Effects
  - Complete Characterization
- **From Digital World ...**
  - TDR & TDT Responses
  - Impedance Profiling
  - Eye Diagrams
  - RLCG Model Extraction

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- SNR is better for VNA than TDR
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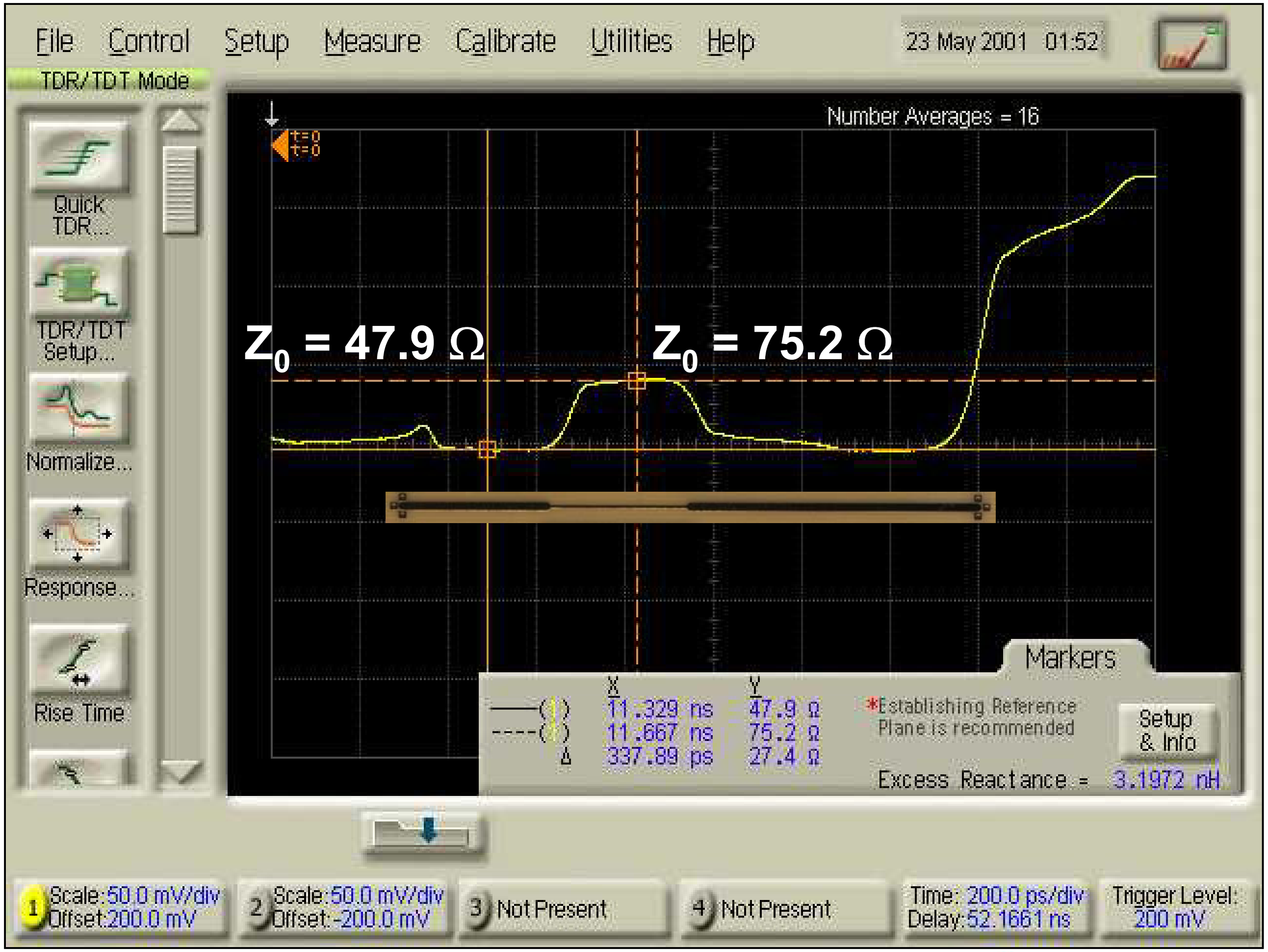
  - Important for low levels of mode conversion
- The PLTS simplifies the analysis of 4 port differential interconnects

Quick Z_0 with TDR



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Quick C, L Extraction with TDR

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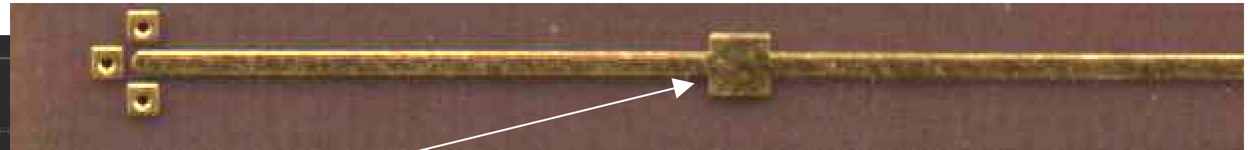
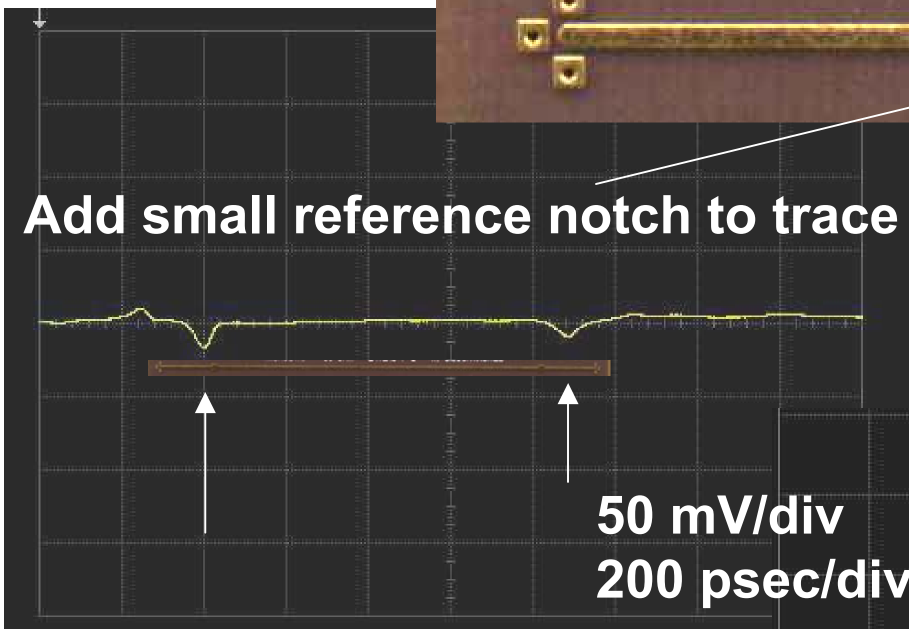
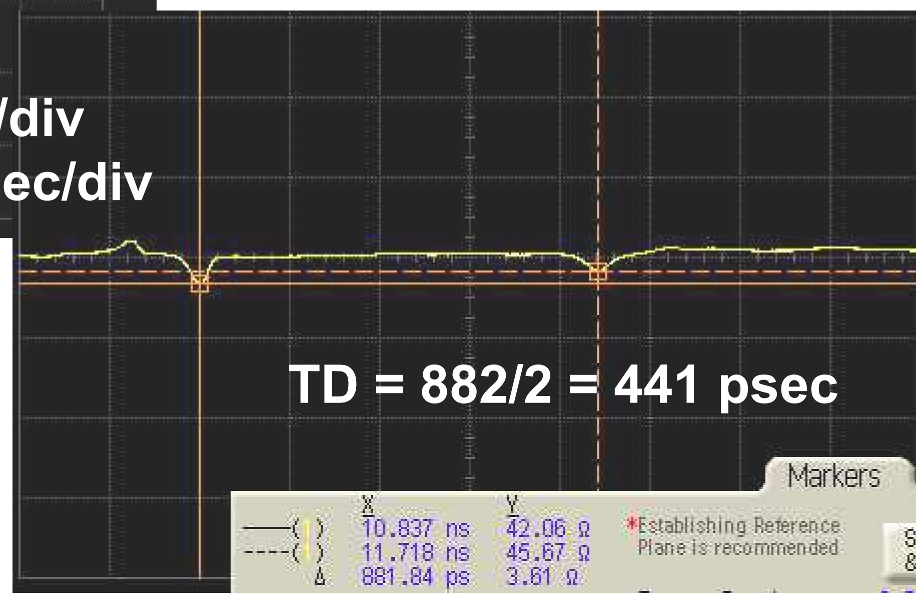
Quick, Accurate Propagation Speed From TDR







Len = 3 inches
Vel = 3 inches/0.44 nsec
= 6.82 inches/nsec

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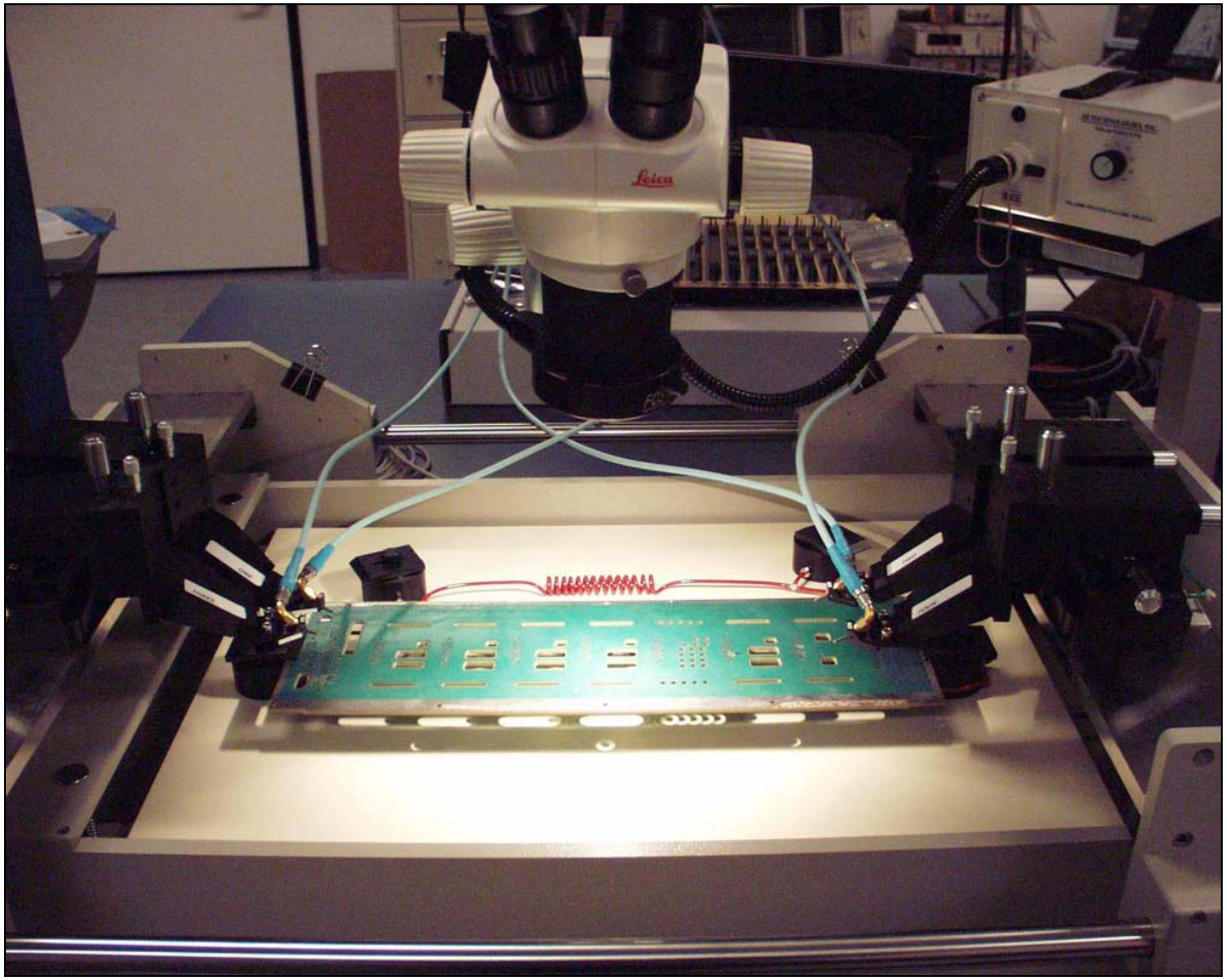
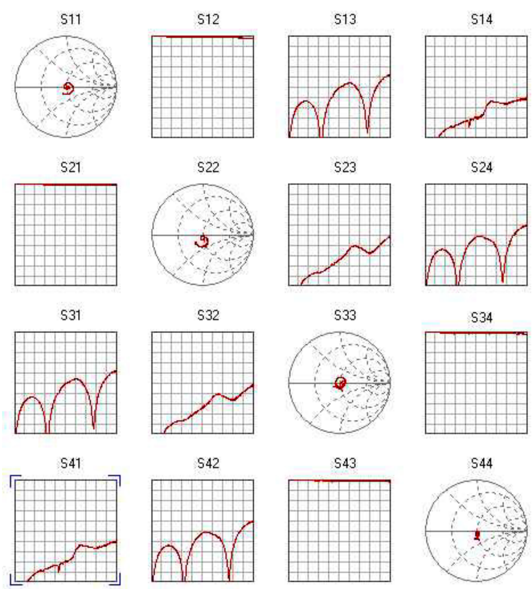
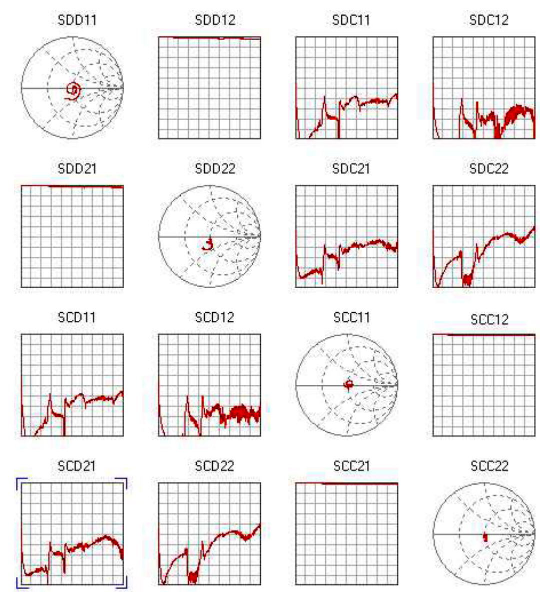
Fast, Complete Differential Pair Characterization with 4 port VNA Based System

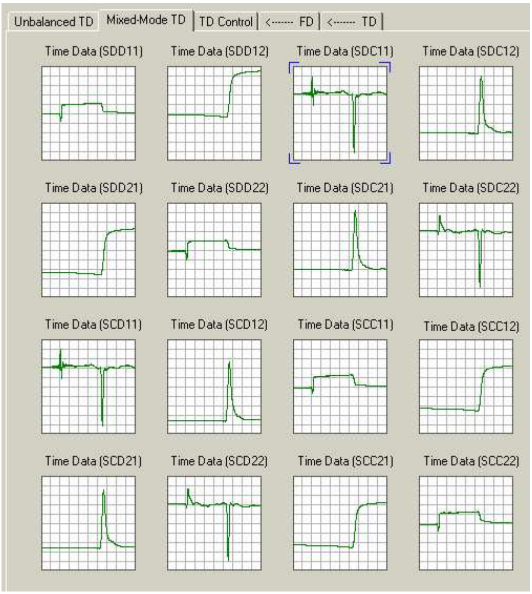


Data Management:
16 Element S Parameter Matrix

Single ended S Parameters → **Mixed Mode S Parameters** → **Mixed Mode S Parameters Displayed in the Time Domain**







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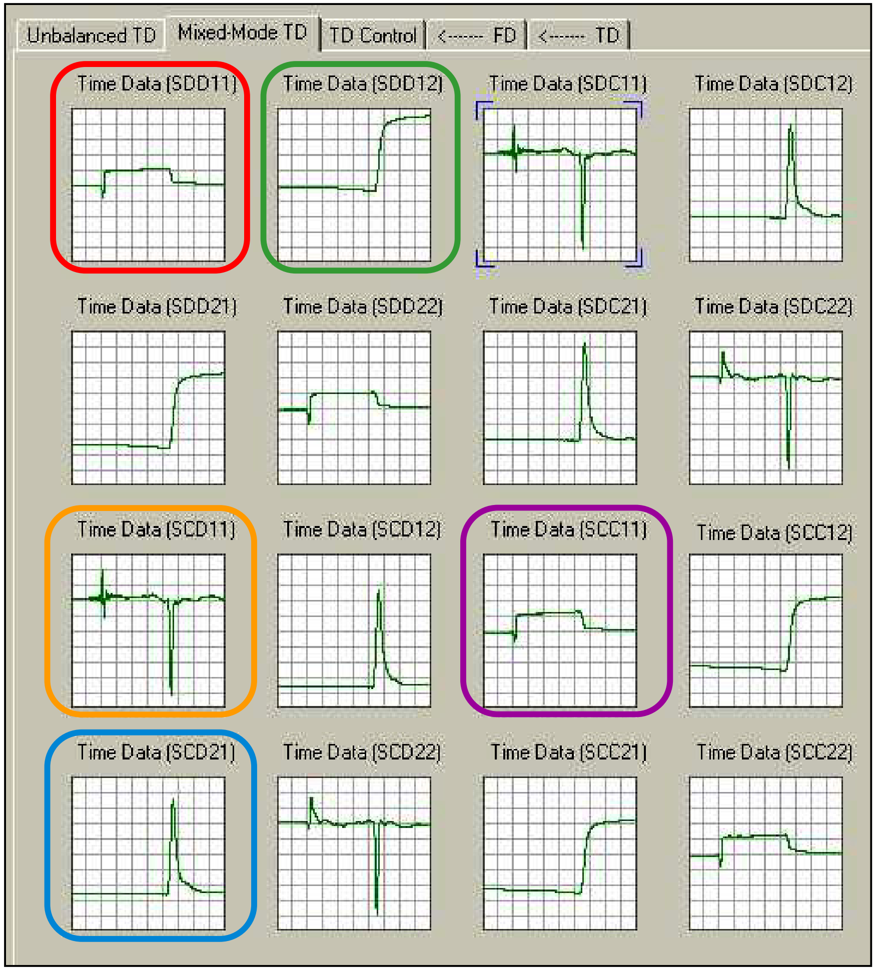
Balanced Time Domain Response



Five important terms:

SDD11: Differential Impedance

SCC11: Common impedance

SDD21: transmitted diff signal

SCD21: mode conversion: diff signal in, common signal out

SCD11: mode conversion: diff signal in, common signal reflected back

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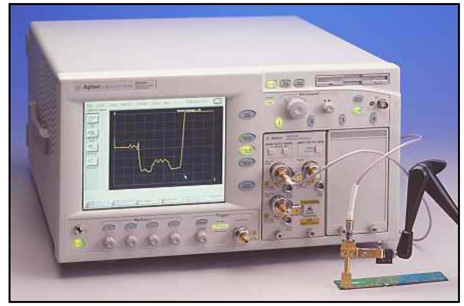
Which System is Right for You?

- TDR based system is for you if you….
  - Don't want to know about S parameters
  - Want to quickly generate first order models of transmission lines and small discontinuities
  - Want to be able to build general models of passive structures
- VNA based system is for you if you…
  - Have low loss or low insertion loss components
  - Want to fully characterize differential pairs quickly
- Use both systems if you….
  - Want the most versatility for quick and easy first order characterization of interconnects
  - Want full, complete characterization of diff pairs and small coupling effects at high bandwidth

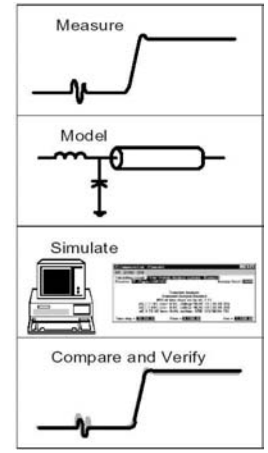
GigaTest Labs Signal Integrity Engineering Turn Key Systems

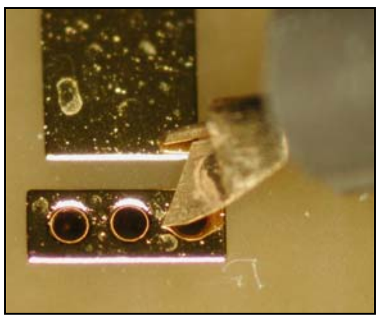


TDR

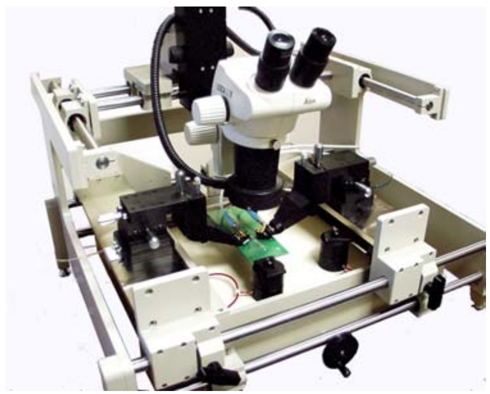
+

TDA Systems IConnect

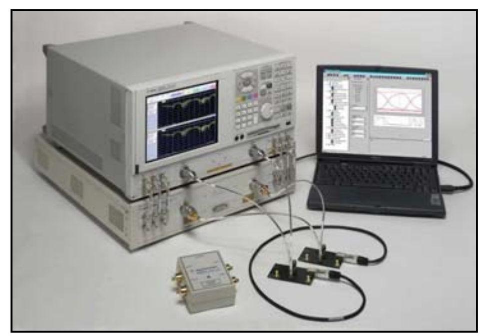




DUT + microprobes



GigaTest Probe Station



Physical Layer Test System (PLTS): VNA + software

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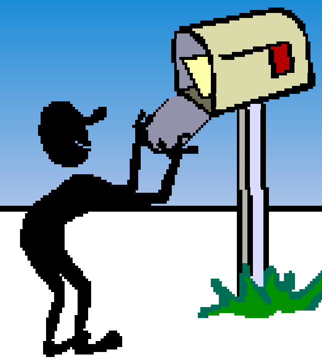

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