LeCroy

A Technical Discussion of TDR Techniques, S-parameters, RF Sockets, and Probing Techniques for

High Speed Serial Data Designs

Presenter: Brian Shumaker
DVT Solutions, LLC,
650-793-7083
b.Shumaker@comcast.net

Agenda

Technical Discussion of TDR Techniques, S-parameters, Sockets, and Probing Techniques

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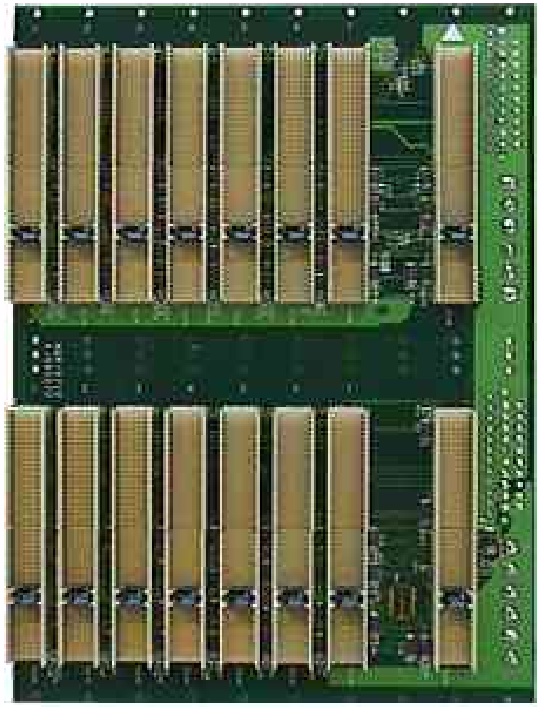
- *Why do we need TDR?*
- *What is TDR?*
  - *TDR Block Diagram*
- *What is TDT?*
- *Differential TDR/TDT*
- *Basic TDR measurements*
- Sources of L/C Discontinuities (sockets, connectors, etc.)
- Using TDR to Locate Discontinuities (open/short faults)
- *Enhancing TDR Measurement through Calibration (Normalization)*
- TDR Rise Time considerations
- *What are S-parameters?*
  - Impedance In the Time and Frequency Domains
  - *Comparison of TDR derived S-parameters vs. VNA*
- *TDR Probes*

Technology Developments in Data Transmission…

- Faster Clock and Data rates in computers, communications and network systems
- New standards are all in the Gbps range
  - *PCIE Gen(2) 5 Gb/s*
  - *SATA Gen(3)/SAS2*
  - *10 Gigabit Ethernet*

- *Faster rates imply sharper pulses with faster rise times*
- *Impedance - controlled transmission lines used to carry Serial transmission*



High speed backplane

High speed data link requirements…

- Factors originally ignored at slower data rates, now become critical design considerations – ***Crosstalk***, ***ISI***

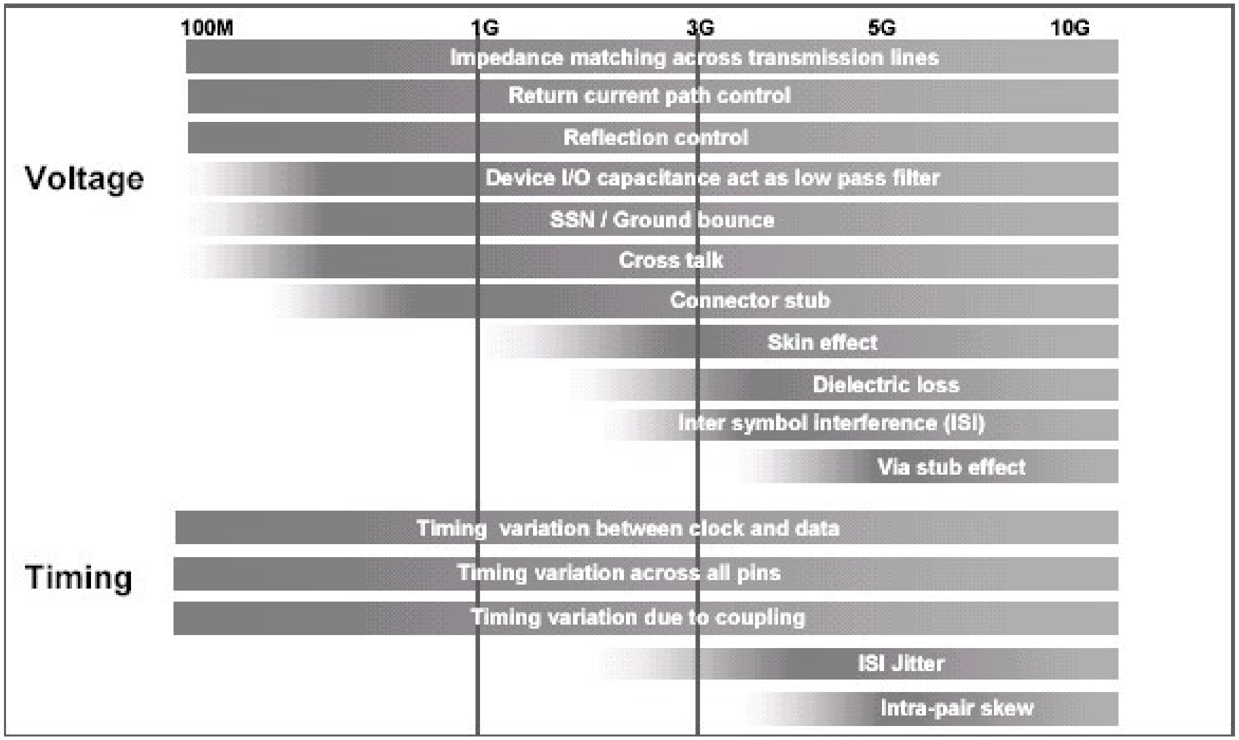


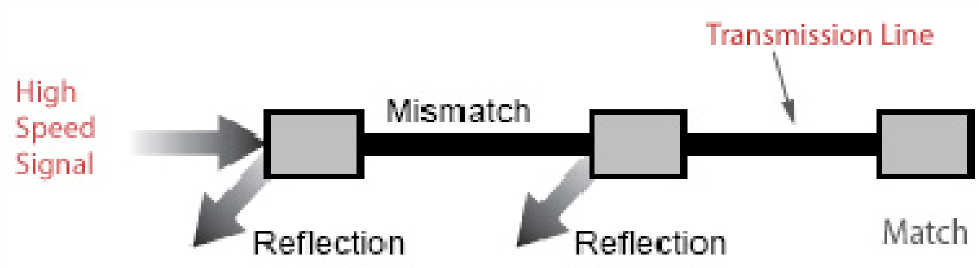
Figure shows the key timing and voltage related impairments that must be addressed as data rates increase

- Transmission line quality critical for data transfer at higher rates
- *TDR* analysis now part of signal integrity measurements of high speed circuits along with ***Jitter***

What is TDR & TDT

What is TDR?

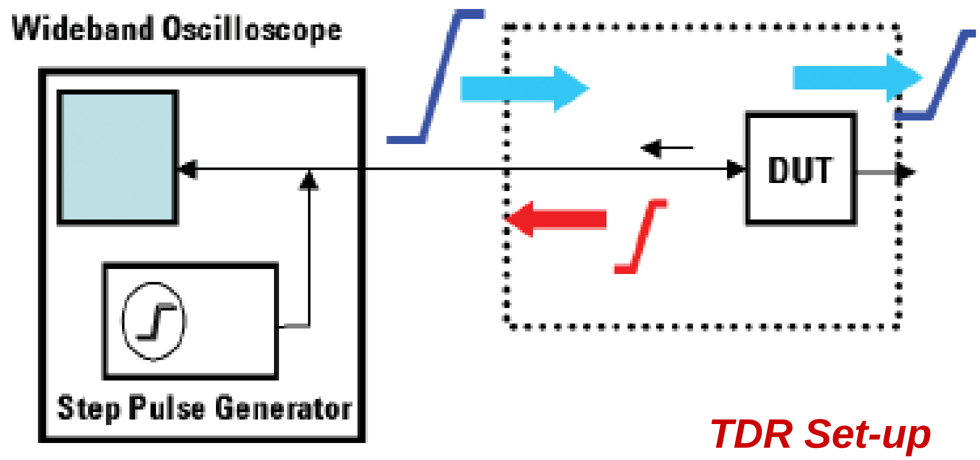
- **TDR** - Time Domain Reflectometry (TDR)



Voltage reflections as a result of discontinuities in a circuit

- Measure of Reflections on an *applied step pulse* to a Device Under Test (DUT) – *PCB traces, cables, etc.*
- Powerful tool for measuring *Impedance* through a circuit
  Also for measuring *Discontinuities* that cause reflections and the *Distance* of the discontinuities.
- Shows the effects of poor connections, mismatched traces, circuit discontinuities etc.

TDR Block Diagram



TDR Set-up

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

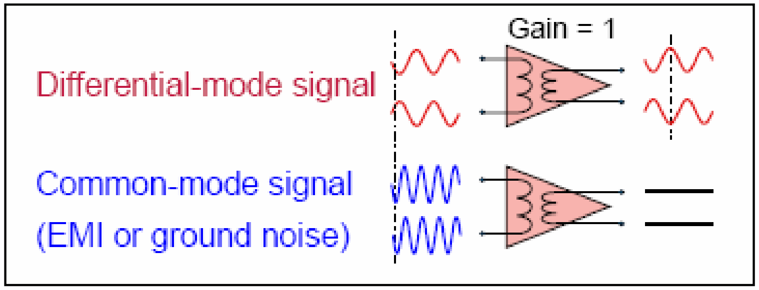
Differential TDR Measurements

- Requires *Two* incident step pulses to stimulate the DUT

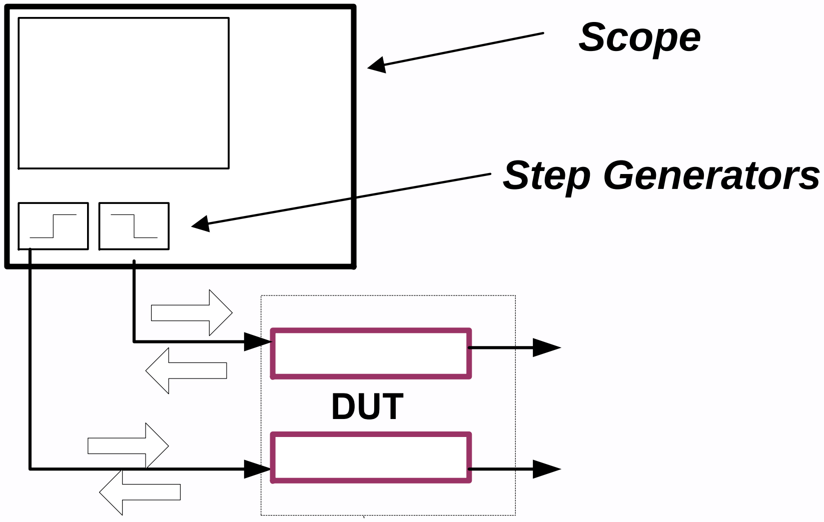
- TDR module has a unique capability to generate a *positive* and a *negative* step pulse

- The positive and negative pulses from the two TDR channels are *turned ON simultaneously for a TRUE differential measurement*

- *De-skew* between the two pulses is performed as part of the Normalization Procedure



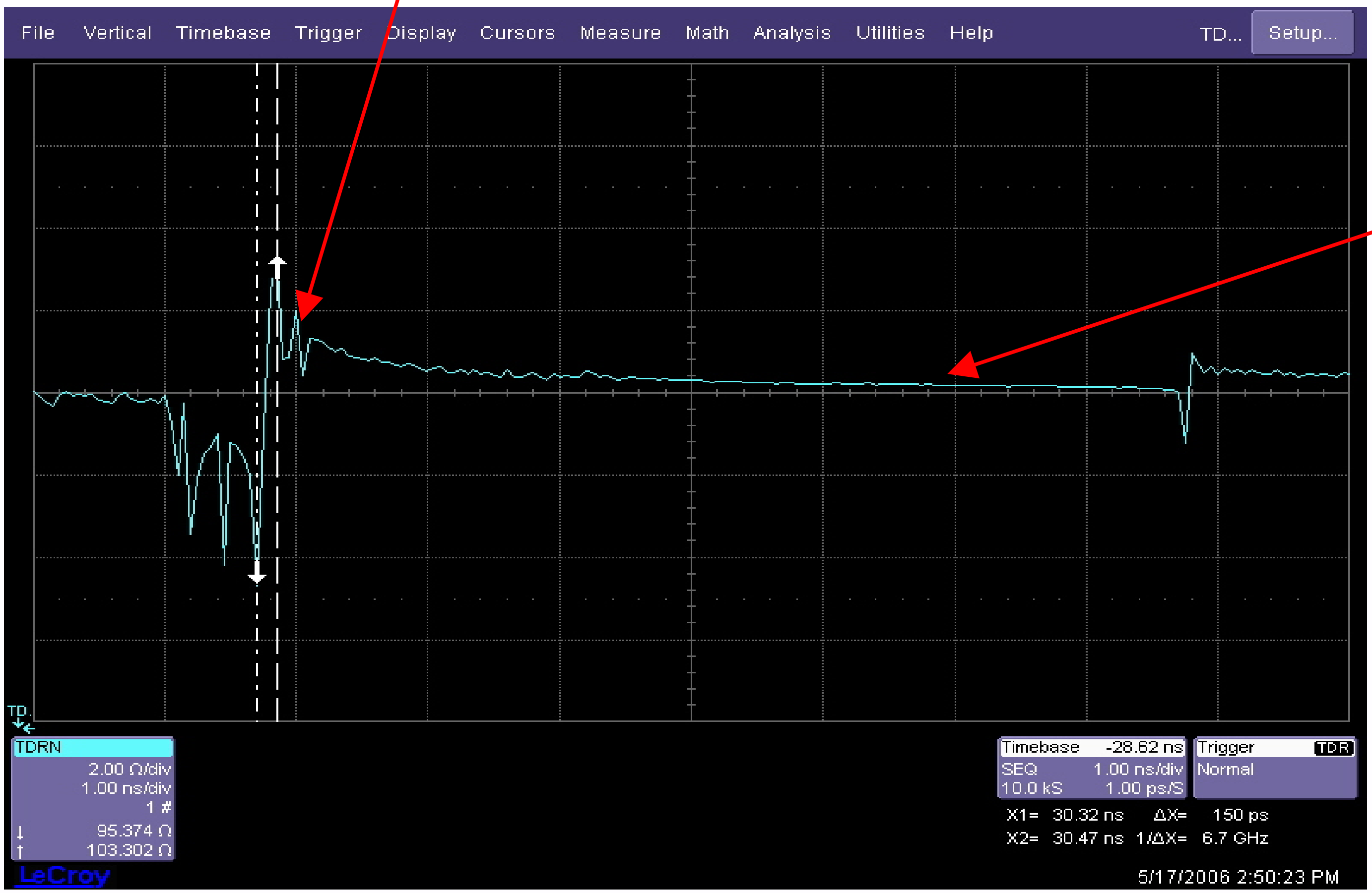
Differential devices – under differential and common-mode stimulus



Differential TDR meas. Set-up

Differential Measurement Example

Connector Response



100 Ω Reference

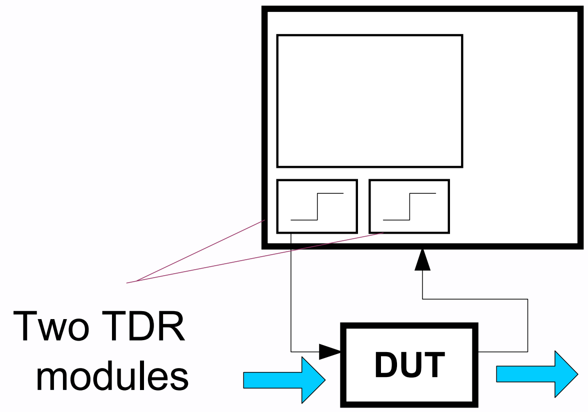
Differential TDR measurement

Differential Measurement Highlights

- *True Differential* input signal to the Device Under Test (DUT) by turning ON the two TDR channels simultaneously
- De-skew procedure removes
  - Sampling skew between modules
  - Skew between the Positive and Negative Step Pulses
  - Additional skew from external cables/connectors connected to the two channels
- Normalization procedure removes effect of external cables and adapters used in the set up for accurate differential measurements.

What is TDT?

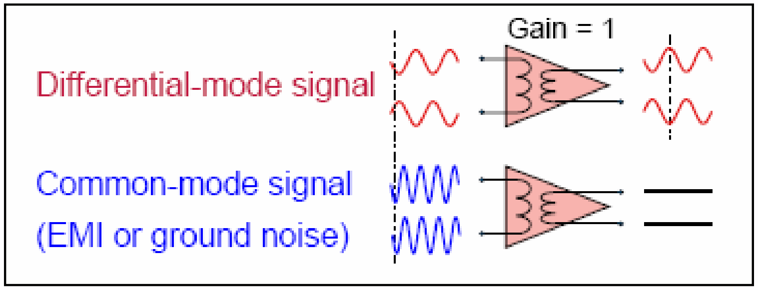
- (TDT) Time Domain Transmission
  Measure of the effects on a signal transmitted through a Device Under Test (DUT)
- Used to measure *Insertion (Transmission) Loss S21* through a system.
- TDT response converted to *frequency* response (also known as Transmission ***S-parameter)*** can help determine the effects on an eye diagram –
- Requires ***two*** TDR Channels – one to generate the step and other to sample



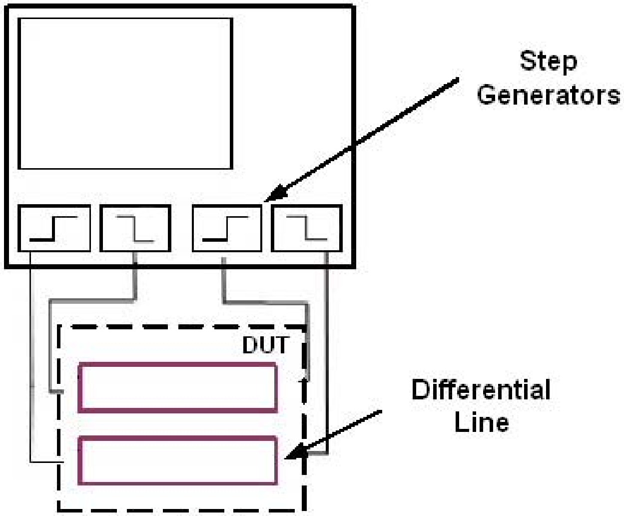
Simple TDT set-up

Differential TDT

- **Differential TDT** – Measure of the effects on a *differential signal* transmitted through a Device Under Test (DUT)
- Used to measure *Differential Insertion (Transmission) Loss* through a system.
- Requires ***four*** TDR Channels – two to generate the step and other two to sample



Differential devices – under differential and common-mode stimulus



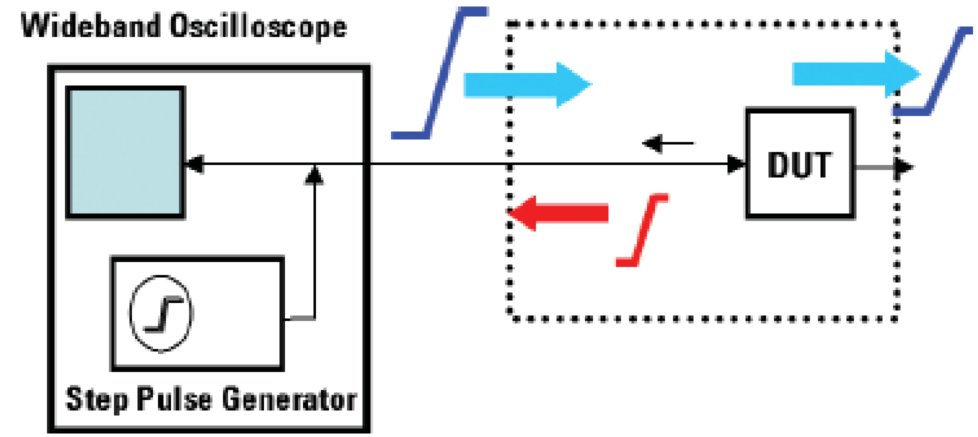
Differential TDT meas. Set-up

TDR Measurement
Basics

What Can You Extract from TDR/TDT Measurements?

- ***TDR Reflections*** help analyze the discontinuities in high speed circuits including the type *(short circuit, open circuit, capacitive etc.)*
- ***Location of discontinuity, Impedance, Crosstalk*** is calculated from the same measurement
  - Impedance tolerance specs. are now part of all digital transmission systems – USB 2.0, PCI-Express, FBDIMM etc.
- The acquisition of ***calibrated frequency dependent network parameters (S-parameters)***

TDR Impedance calculation



Sampling point

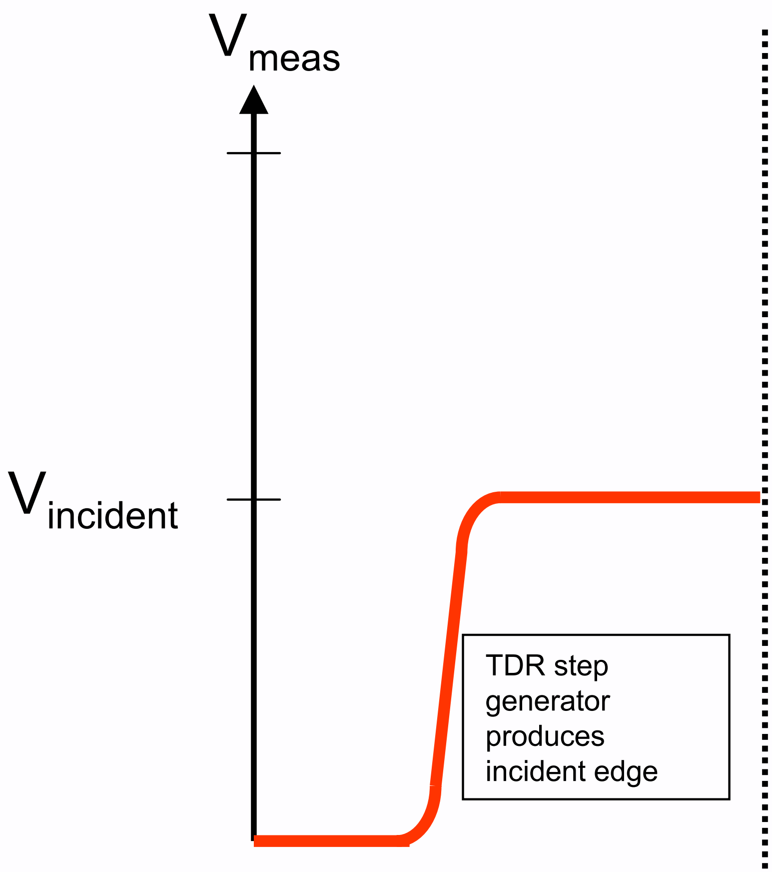
- The measured signal by the scope is
  $V_{measured} = V_{incident} + V_{reflected}$

$$\text{Reflection, } \rho = \frac{V_{reflected}}{V_{incident}} = \frac{Z_L - Z_O}{Z_L + Z_O}$$

$$V_{reflected} = V_{incident}\left(\frac{Z_L - Z_O}{Z_L + Z_O}\right)$$

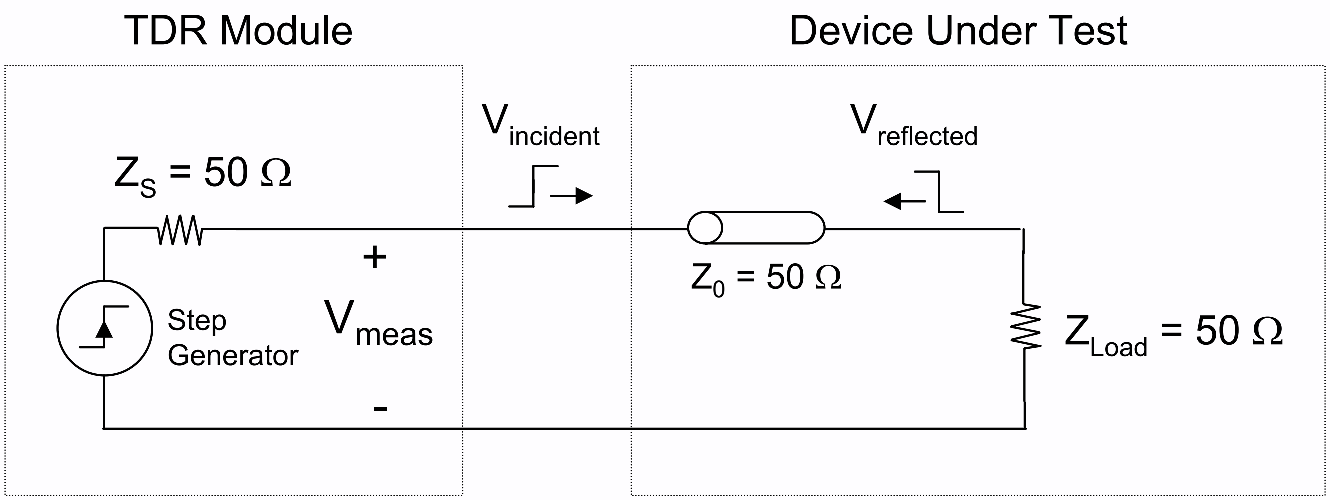
Basic TDR measurements

An incident step from the TDR (TDR module) is used as stimulus



Depiction of an incident pulse from the TDR

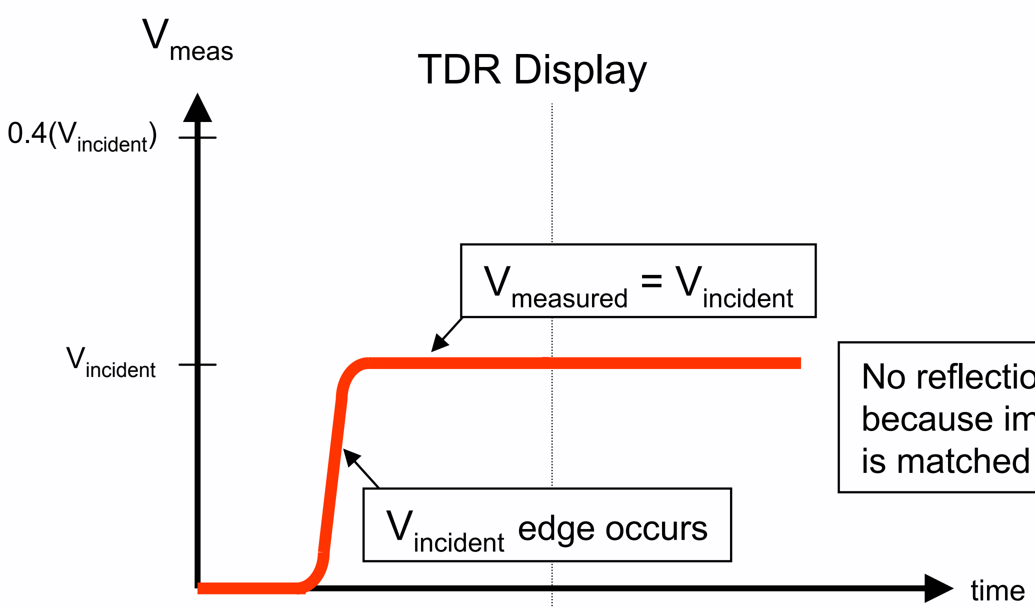
TDR Example: Matched Impedance (Z_L = 50 ohm load)



Solving for $V_{reflected}$:

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

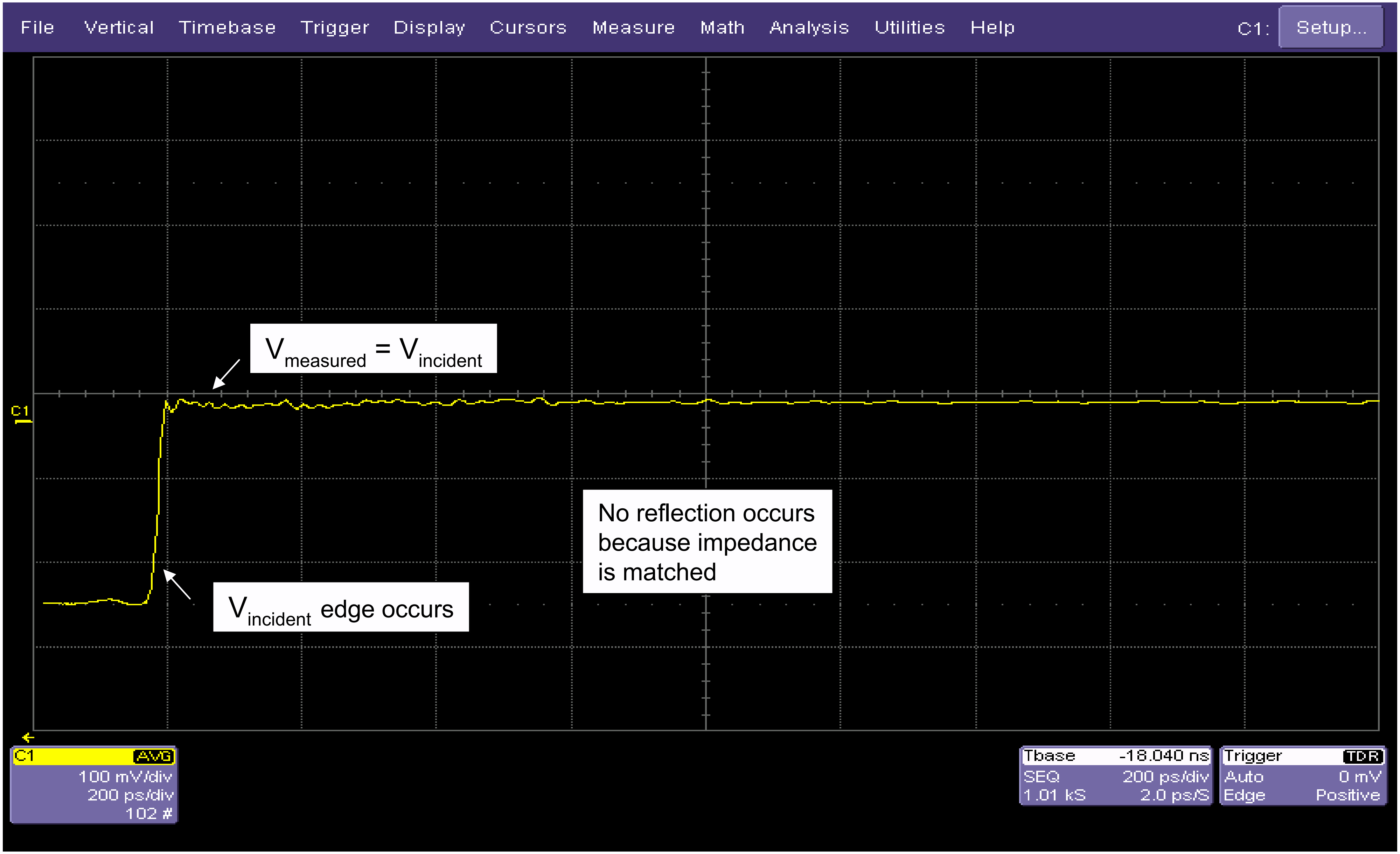
$$Z_{Load} = Z_0, \quad \Theta \; V_{reflected} = 0$$



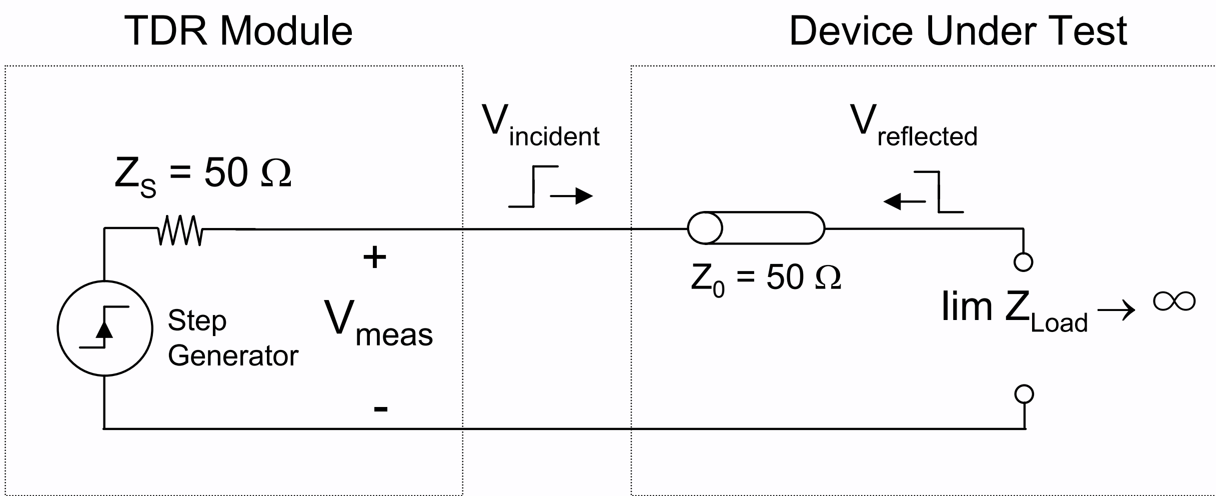
The most important design technique to control signal quality:

"Keep the impedance the signal sees constant all along the net"

TDR Example: Matched Impedance



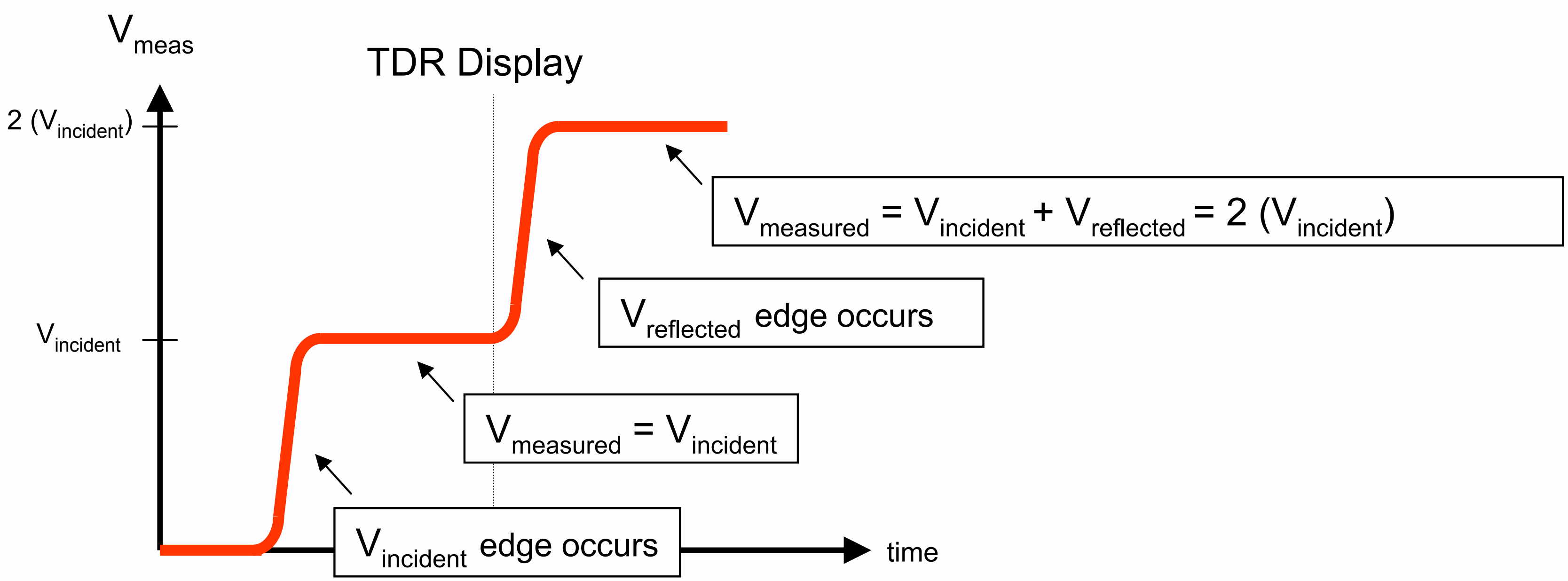
TDR Example: Open Circuit ($Z_{Load} \to \infty$,)



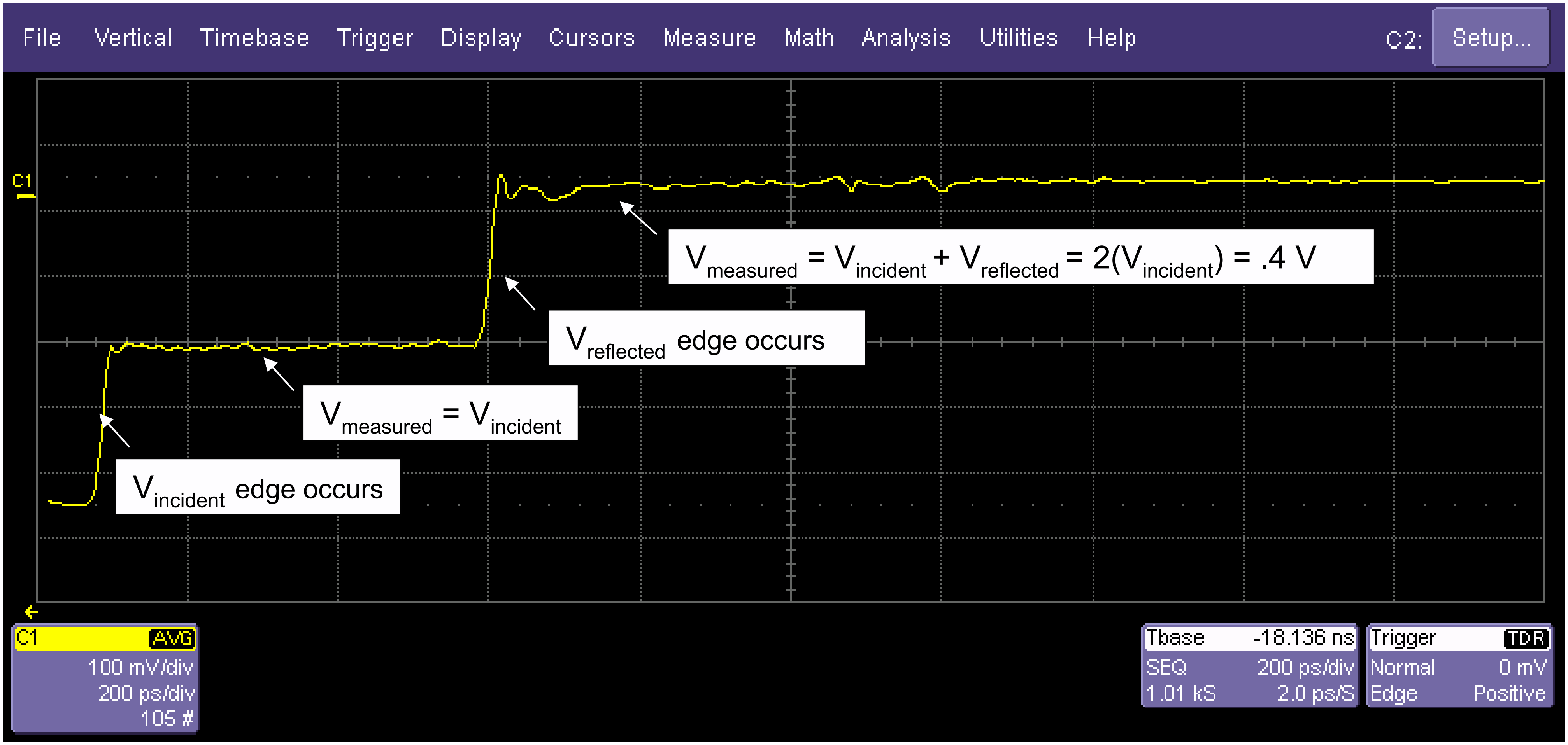
Solving for $V_{reflected}$:

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

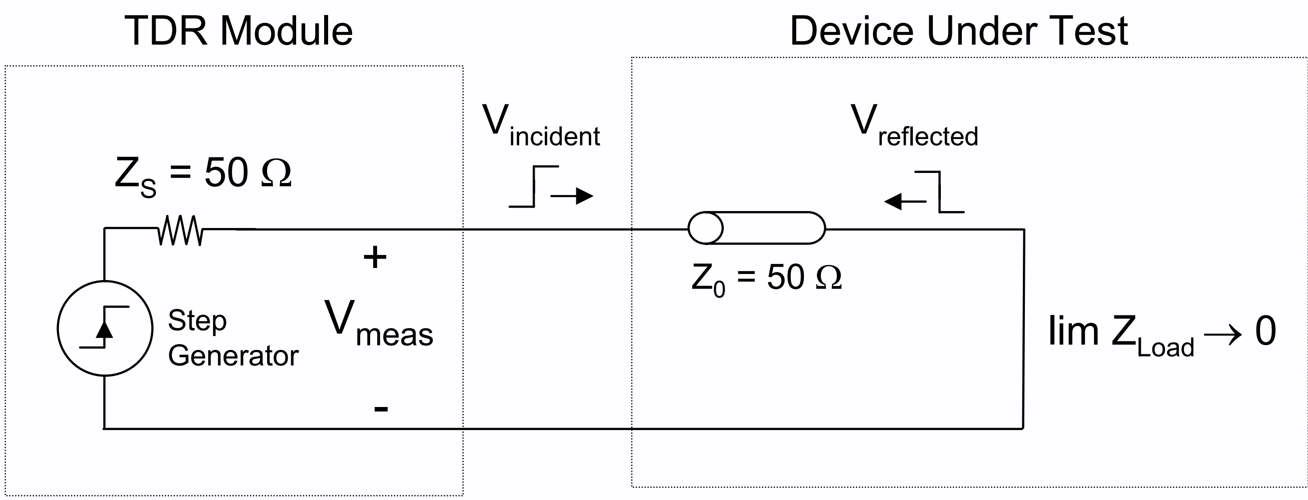
$\lim Z_{Load} \to \infty$, $V_{reflected} = V_{incident}$



TDR Example: Open in the air



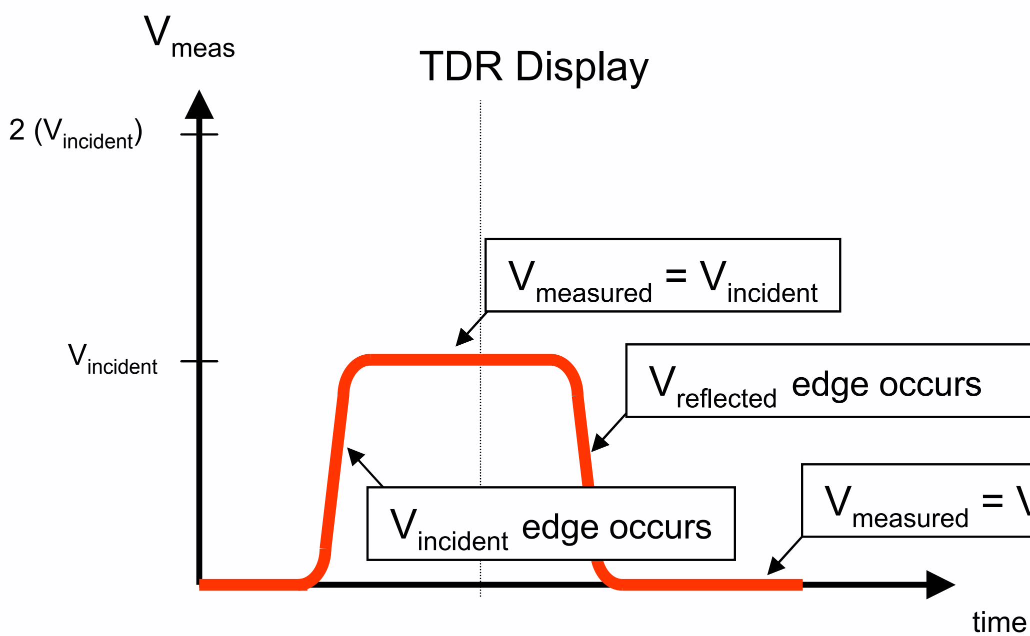
TDR Example: Short Circuit (Z_{Load} = 0,)



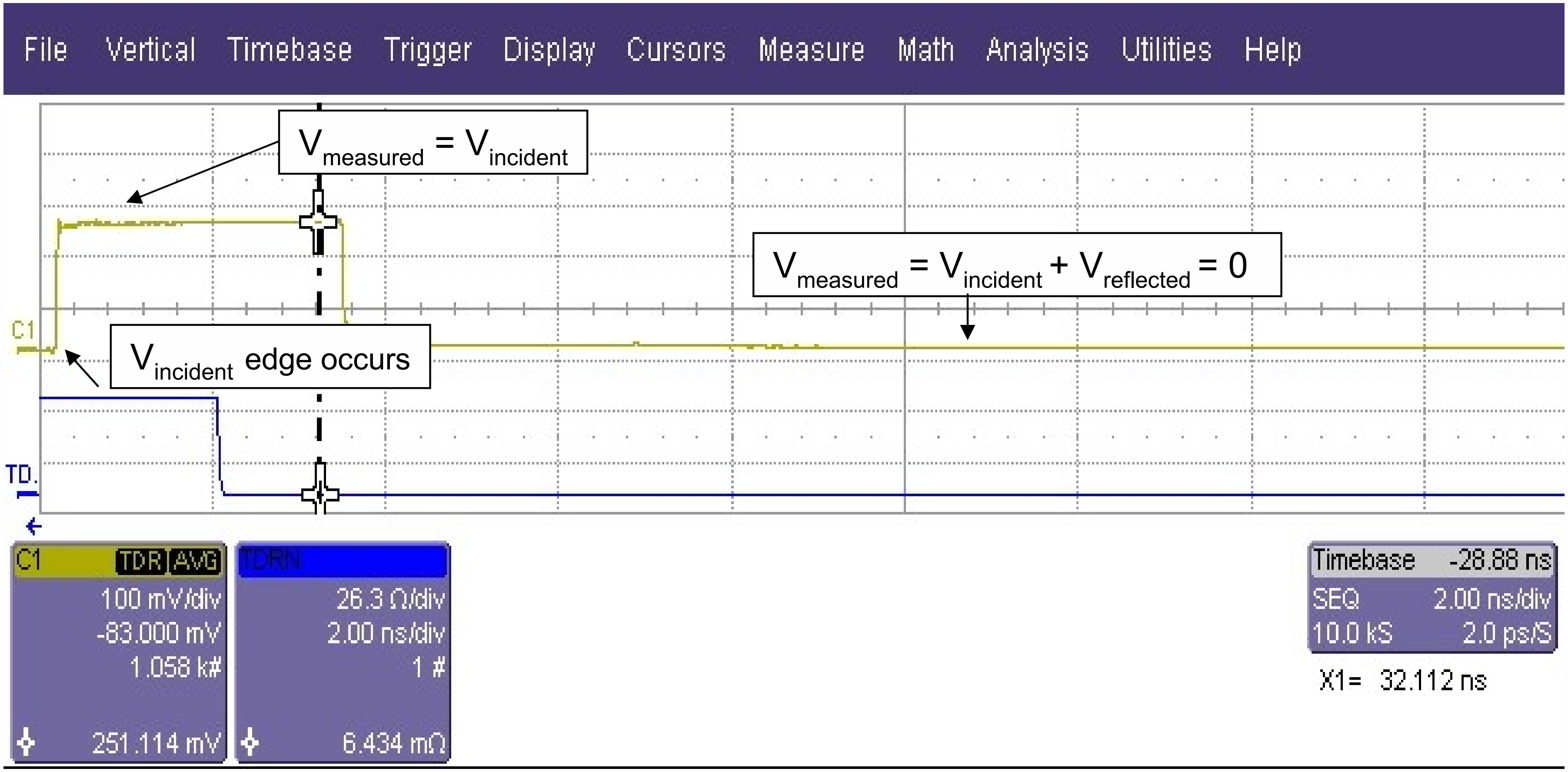
Solving for $V_{reflected}$:

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

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

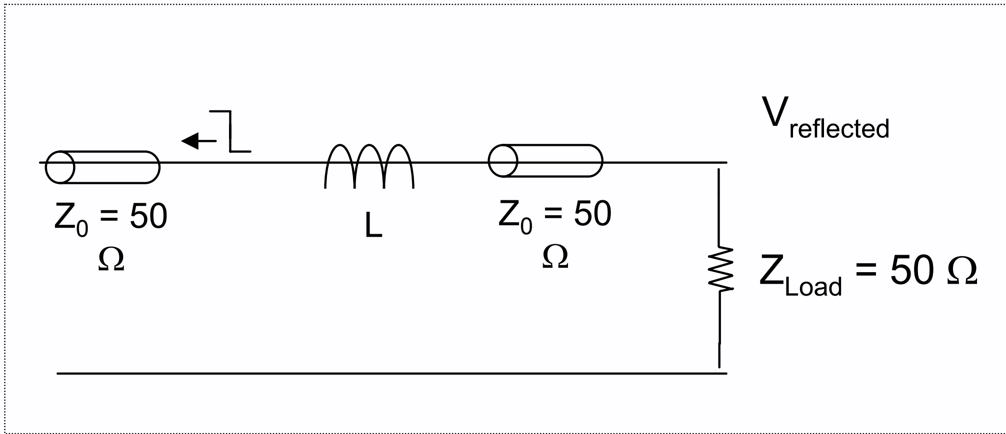


TDR Measurement: Short (Z_L = 0)

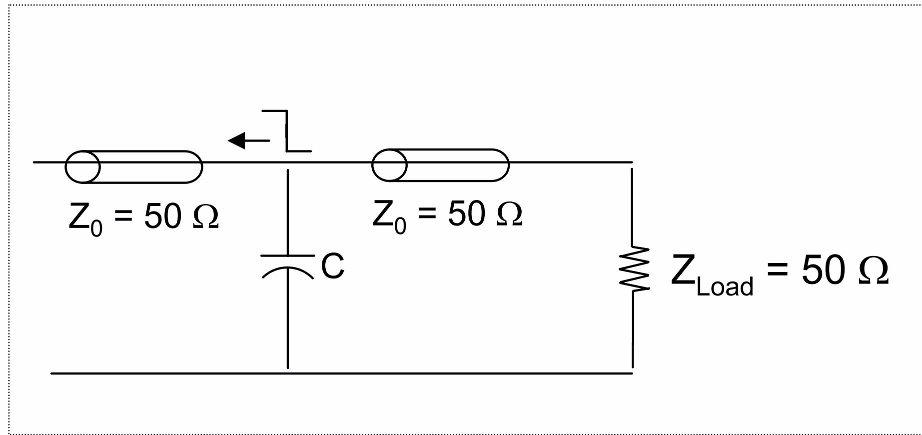


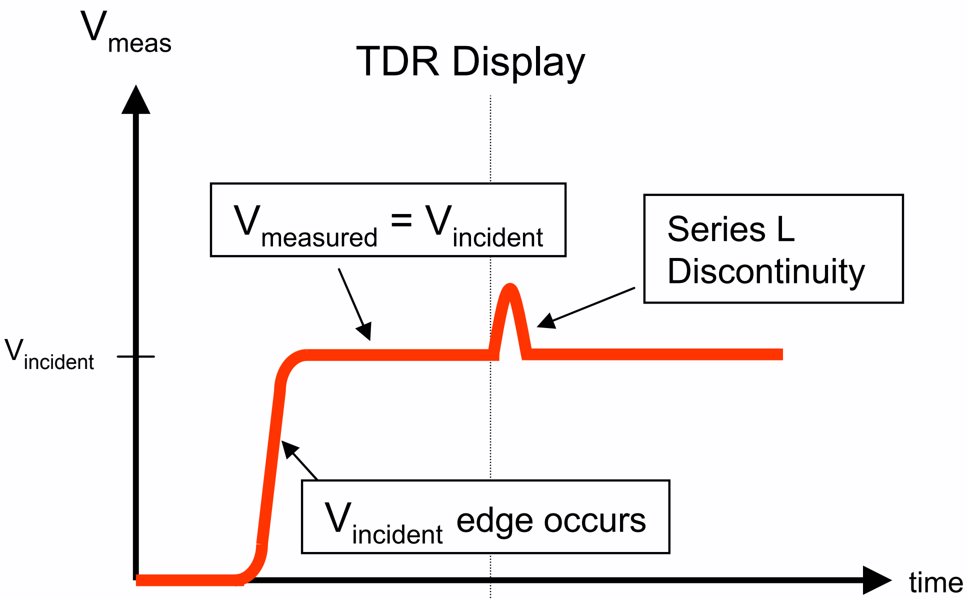
TDR Example: Reactive Elements - L and C Discontinuity

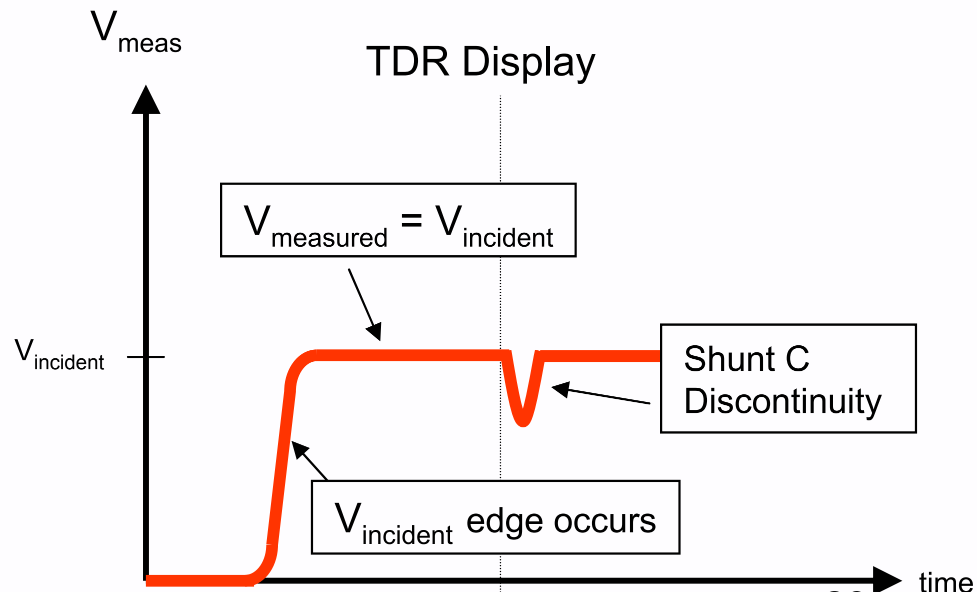
Device Under Test



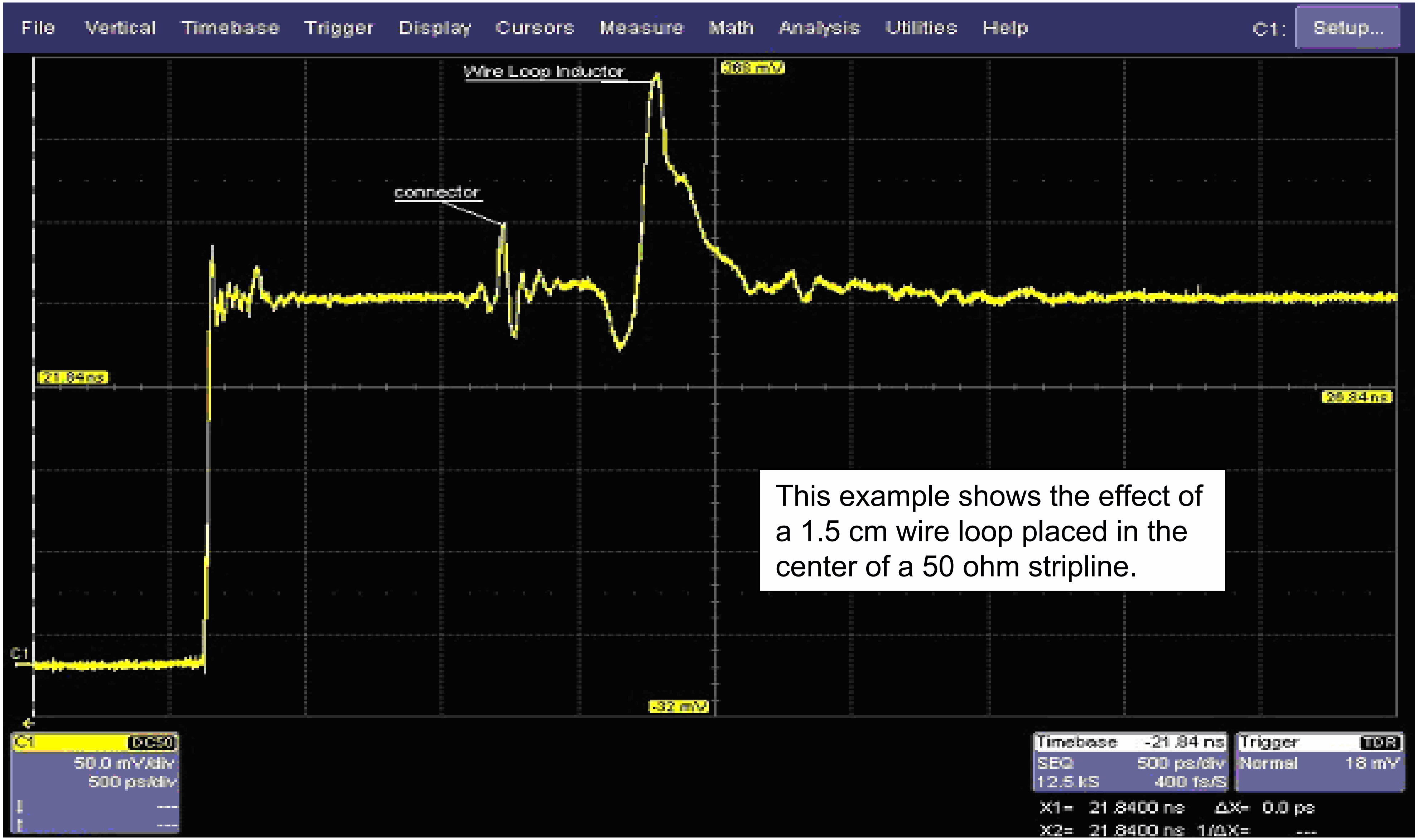
Device Under Test



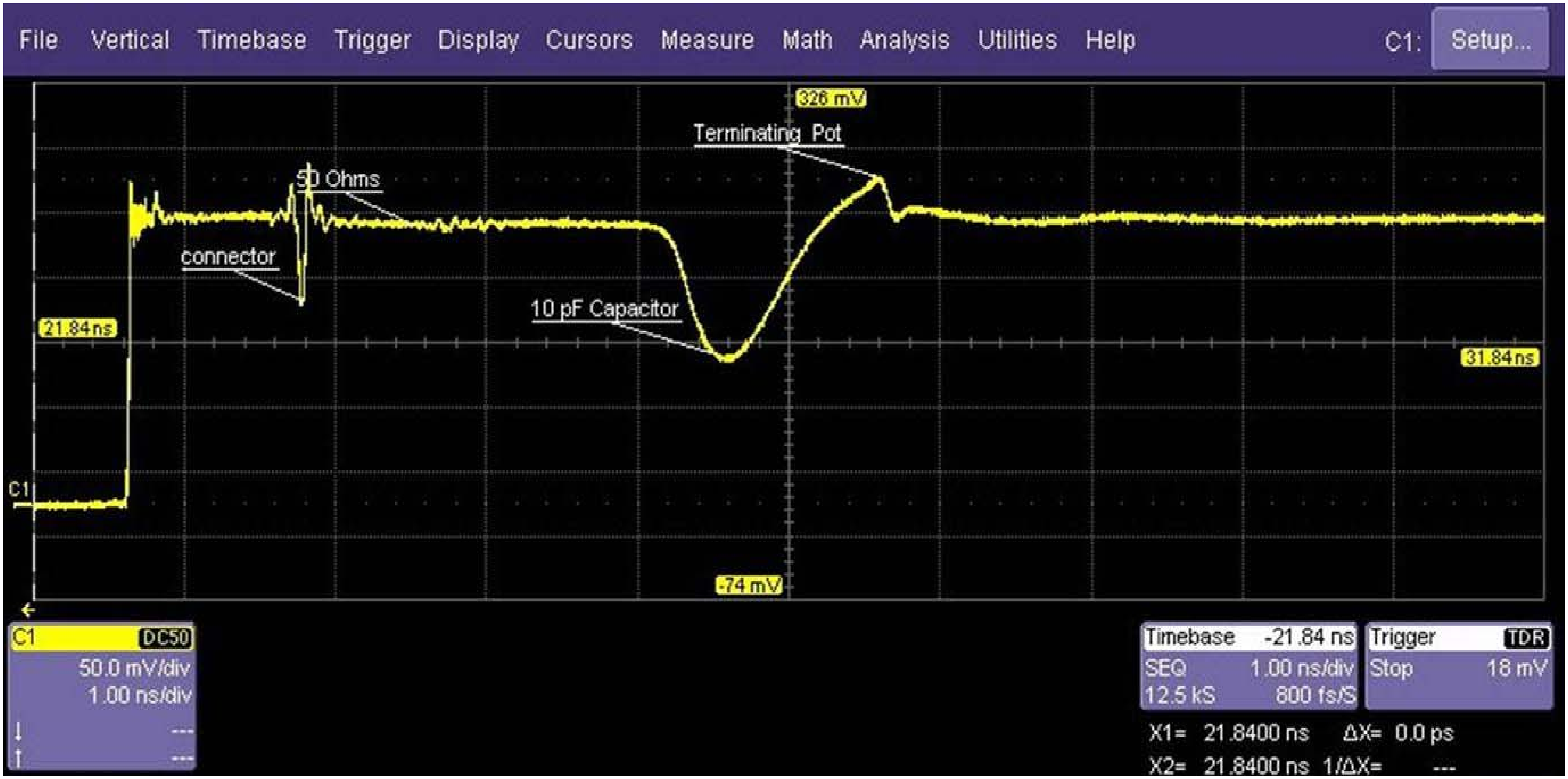




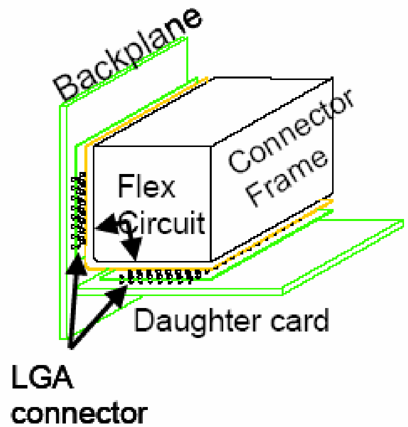
TDR Example: Series L Discontinuity

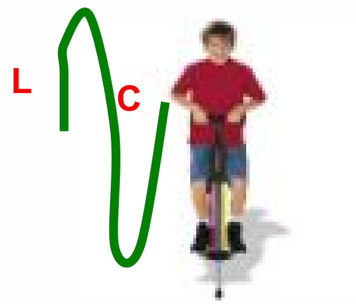


TDR Example: Shunt C Discontinuity



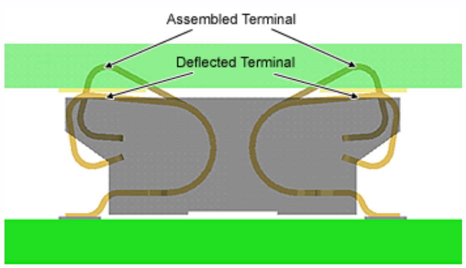
Source of L/C Discontinuities
Compression Connectors

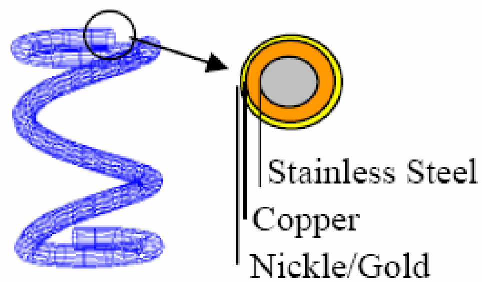


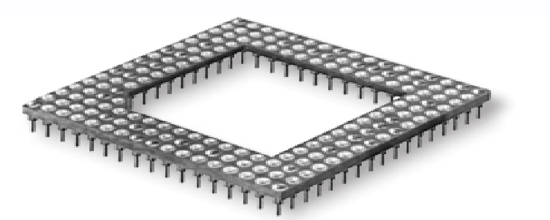


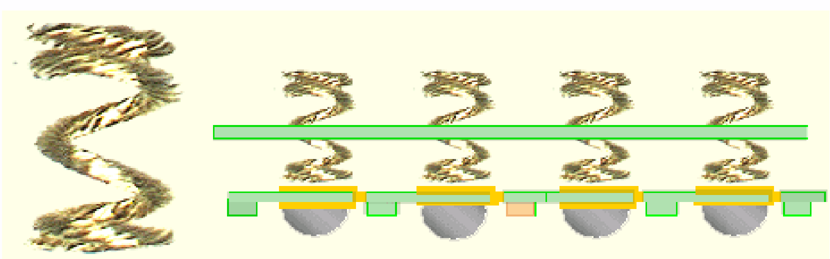
Socket interposers Pad to Pad compliance is achieved through Spring Compression Contacts

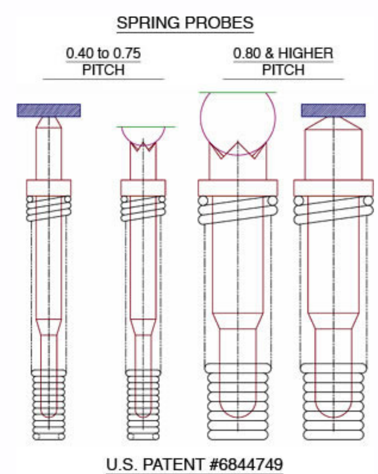
- **Induces L/C discontinuities**
- **Degrades interconnect system Return loss In Gbit data rates**







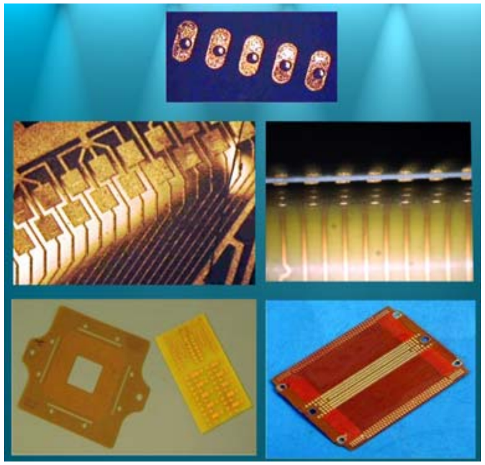




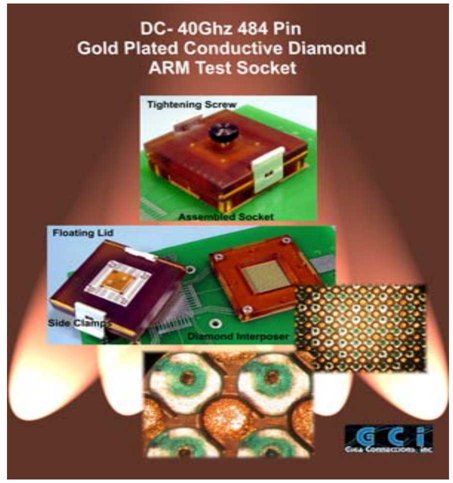
Compression Connectors are found in:

- **Board to board connectors**
- **Test sockets**
- **Package-to-Board Connectors**

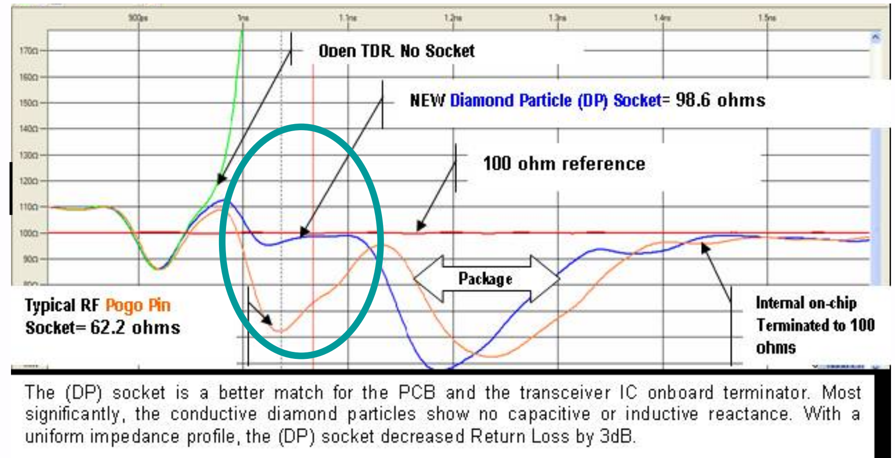
New 40Ghz ~~L/C~~ Interconnect Technology
Gold Plated Conductive Diamond Interposer



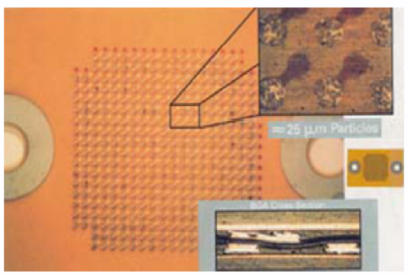
Board to Board Interconnects

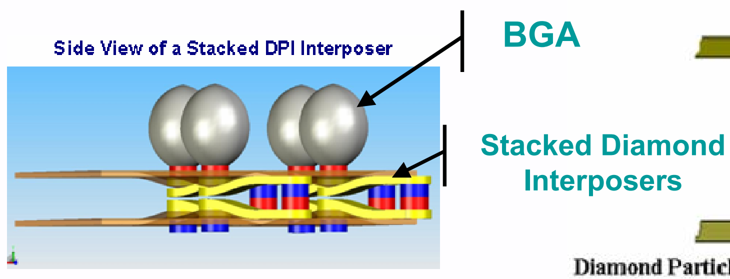


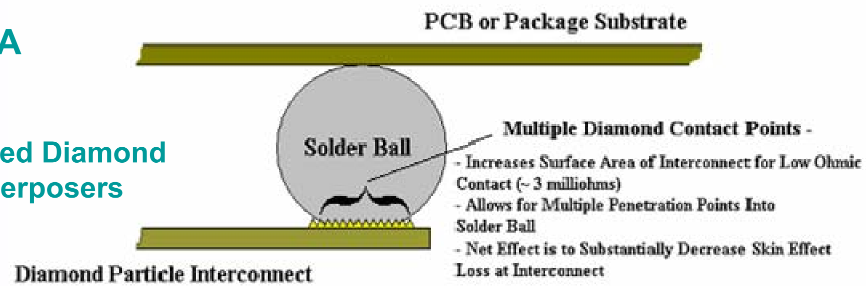
Pin-less RF Test Sockets



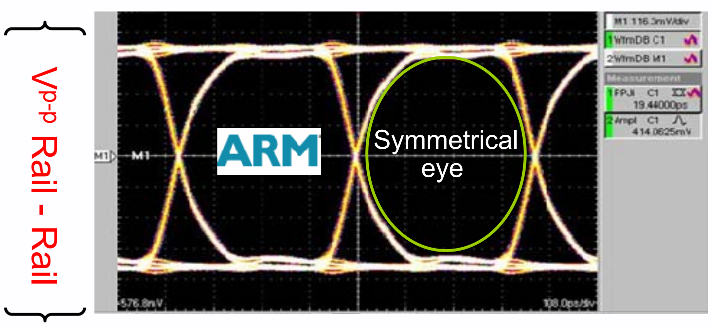
No Measurable L/C to 40Ghz



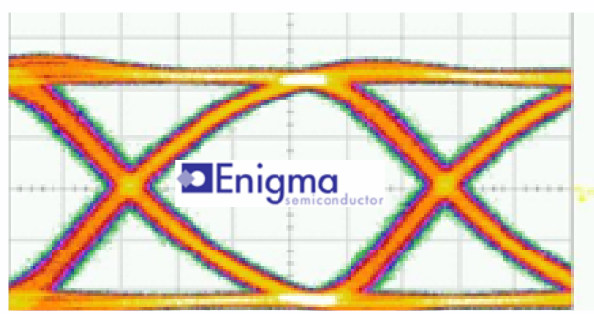




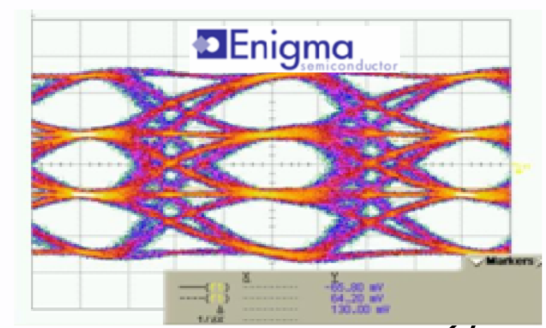
BGA Compliance using stacked off-set interposers



6Gbit PCI Express



6Gbit Custom IP Device



10 Gbit 4PAM

Gold Plated Conductive Diamond Interposer Specifications

Interposer Specifications

Signal Integrity
- > 40 GHZ bandwidth
- No measurable inductance, or capacitance
- ~1 % increase in impedance measured at 10gbits data rate

Interposer Interconnect Technology
- 10-20 um conductive diamonds
- 10 micro-inches gold plated
- Contact point size is 10um; 10-mil pitch can be achieved.
- RoHs compliance - lead free

Pin Count
- >2000

Maintenance
- Surface can be refurbished
- Clean with ultrasound bath

Reliability
- 100’s of thousands of insertions without measurable degradation in signal integrity

Force
- 10-15 Grams force per pad required to achieve electrical continuity

Current Handling
- ~15 amps per 10 mil diameter pad

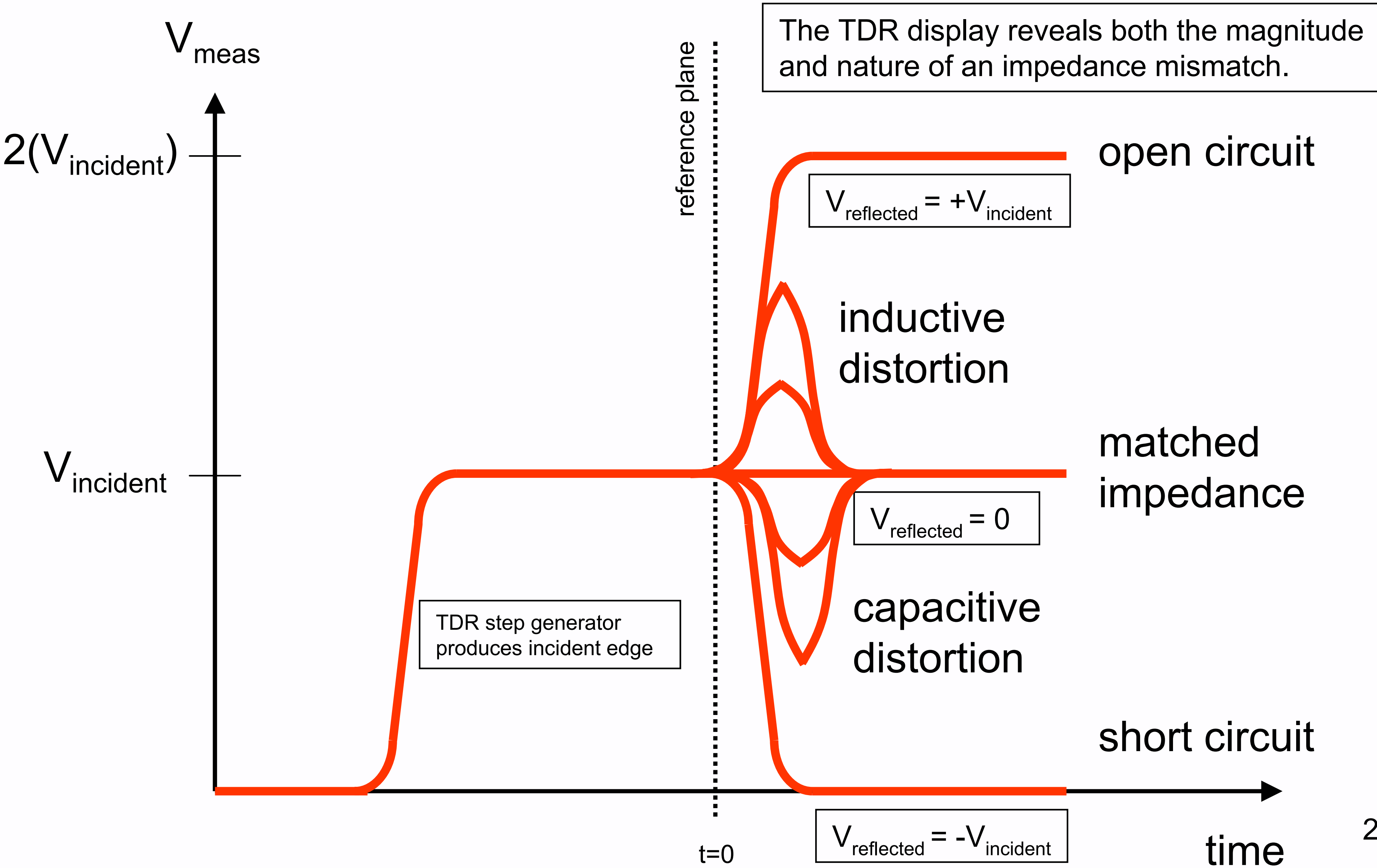
Temperature Range
- –60C to 200C for Kapton film Interposer

Available from

Giga Connection, inc.

www.gigaconnections.com

Summary: Interpreting the TDR Display



TDR measurements
Locating Discontinuity (open/short) Fault

Q. How do I know where the fault is in the system??

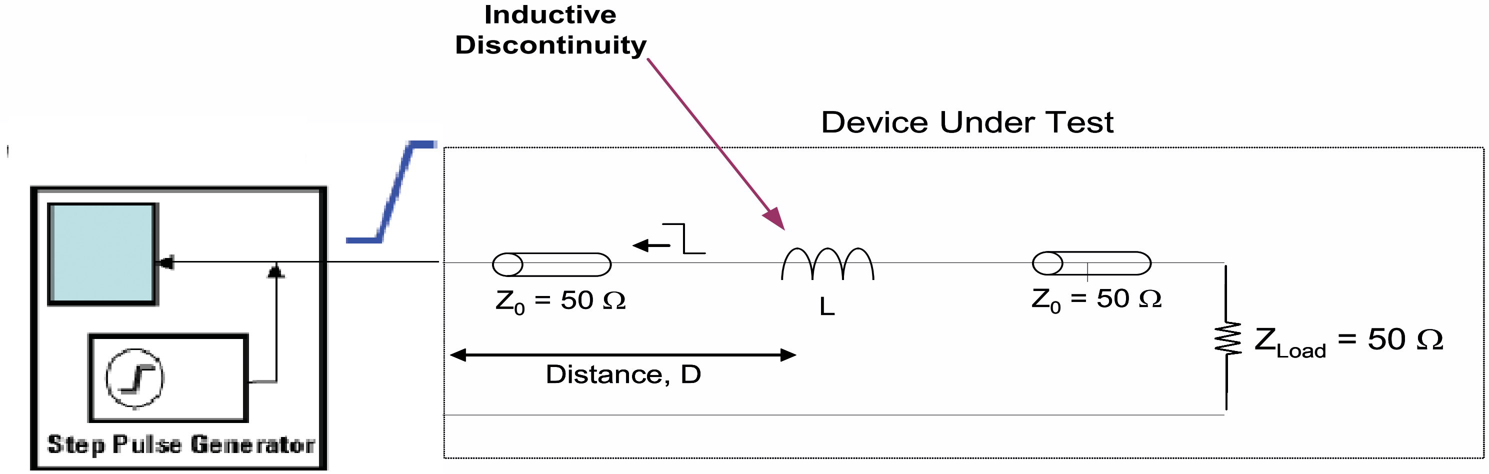
- *Scope measurement yields location of the faults in **time***
- *Time can be converted to **distance** by entering the propagation velocity (v_p) or dielectric constant (ε_R) of the medium*

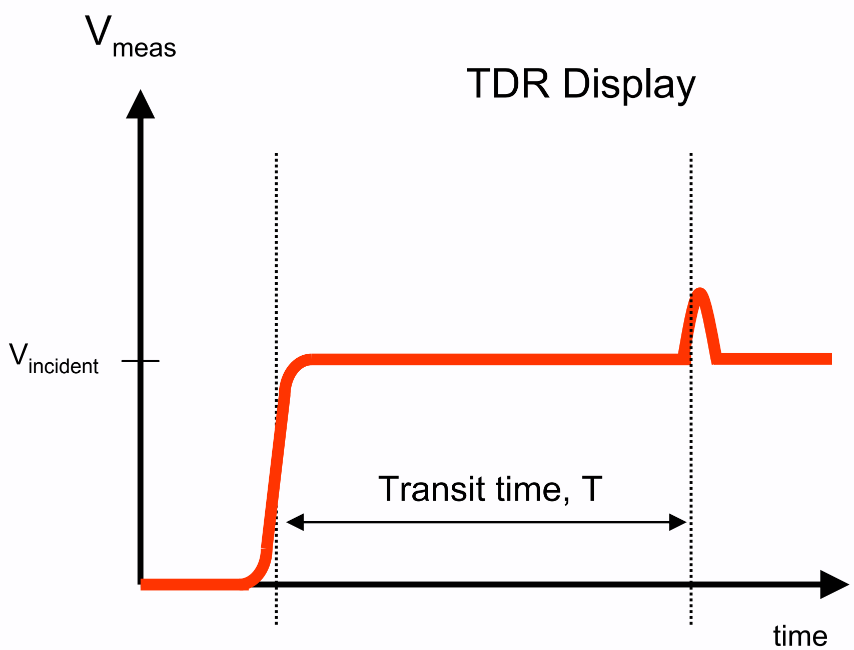
NOTE: *Dielectric constant of a medium may vary with distance, hence adding in a constant value for (ε_R) may not always yield the accurate distance*

Typical dielectric constant of FR4 = 4.2

The two main constituents of FR4 are glass with an Er of around 6 and resin with a dielectric constant of around 3.

TDR Example: Determining Fault Location





Physical distance to fault location can be determined by:

$$\boxed{D = 0.5*(T)*(v_p)}$$

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

Enhancing Accuracy of TDR measurements

- Use of low loss cables, adapters
- Use of extender cables to avoid losses due to using long cables
- Long memory length for better impedance resolution when measuring long interconnects like backplanes, Cables, etc.

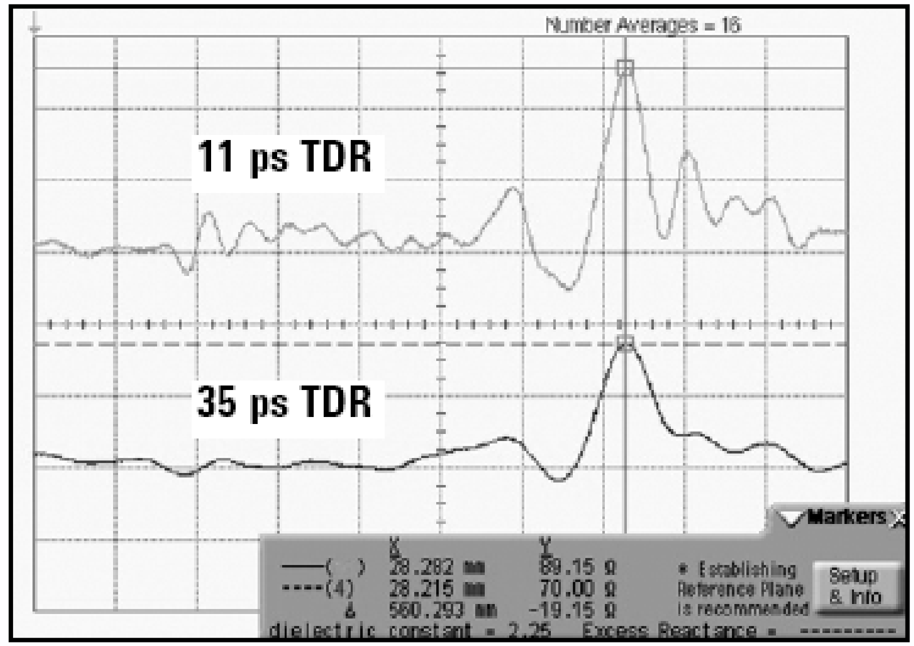
TDR Rise Time considerations

1) **FAST Rise time** results in better measurement resolution

- **18ps** (typical) Rise time for TDR
  Resolution ≈ ½ (Step rise time)

  WaveExpert = ½ (18 ps)
  ≈ 9 ps *(1.25 mm on PCB)*

Closely spaced discontinuities can be measured with higher accuracy



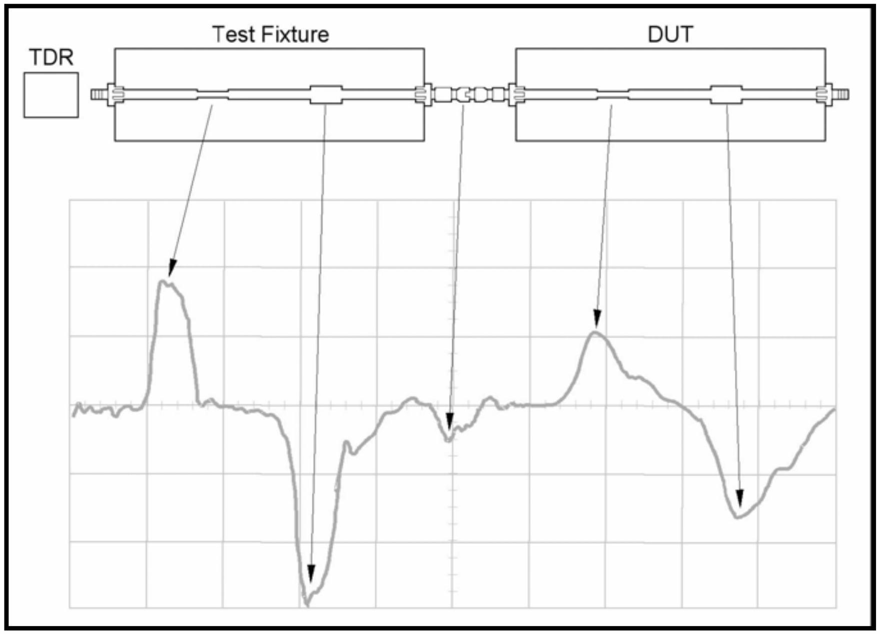
Measurement of a connector assembly using pulses with different rise times – Faster rise time pulse yields better measurement resolution

Calibration (Normalization)

TDR Calibration (Normalization)

Why is it required??

- We don't live in a PERFECT WORLD!



Typical ***TDR measurement set-up*** *consisting of cables and test fixture*

Errors in TDR measurement:

Typical TDR set-up will include:

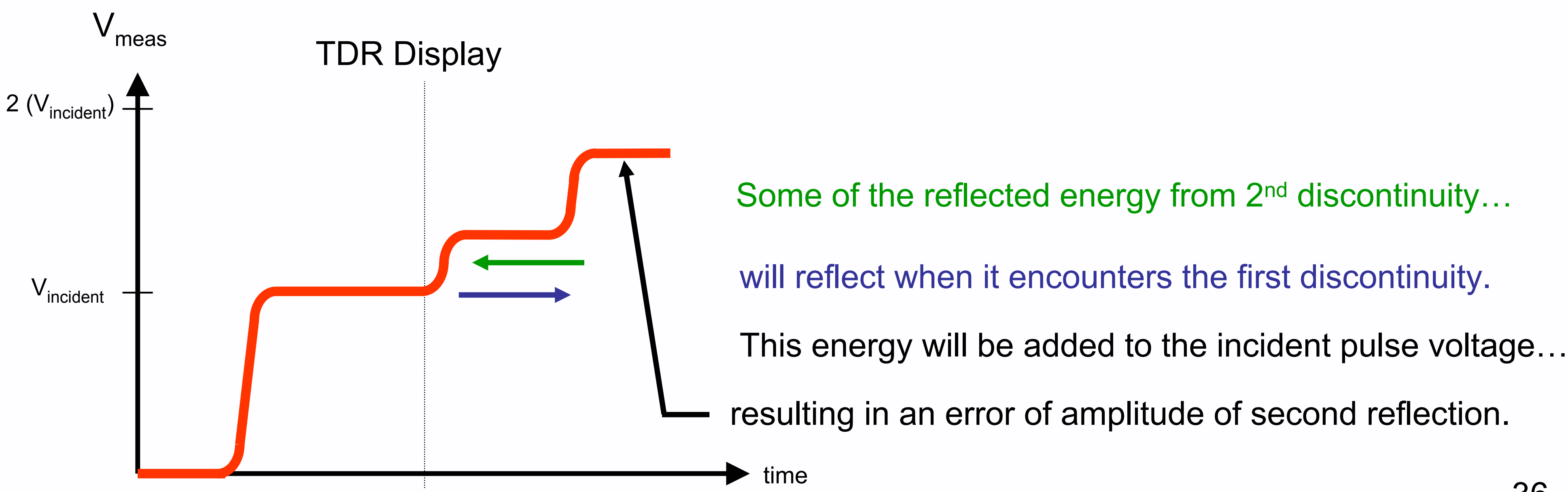
- *Cables, Adapters, etc*
- *Test fixture (if DUT is on a PCB)*

TDR measurement of the DUT will yield composite reflections from all the components present in the test path

$V_{refl} = V_{refl}\,(\text{Test fixture}) + V_{refl}\,(\text{conn.}) + V_{refl}\,(\text{adapters}) + V_{refl}\,(\text{DUT})$

Back Reflections

- TDR techniques have some limitations.
- Most users are aware of these:
  - Major discontinuities cause “back reflections”, resulting in reflected energy of the return reflection from additional discontinuities.
  - Thus, the accuracy of impedance measurements after the first major discontinuity is reduced.



TDR calibration (contd.)

- These errors can be *corrected* by performing a calibration with known standards.
- This adjusts the reference plane such that accurate time/distance measurements of the DUT are possible

Other sources of errors in TDR measurements:

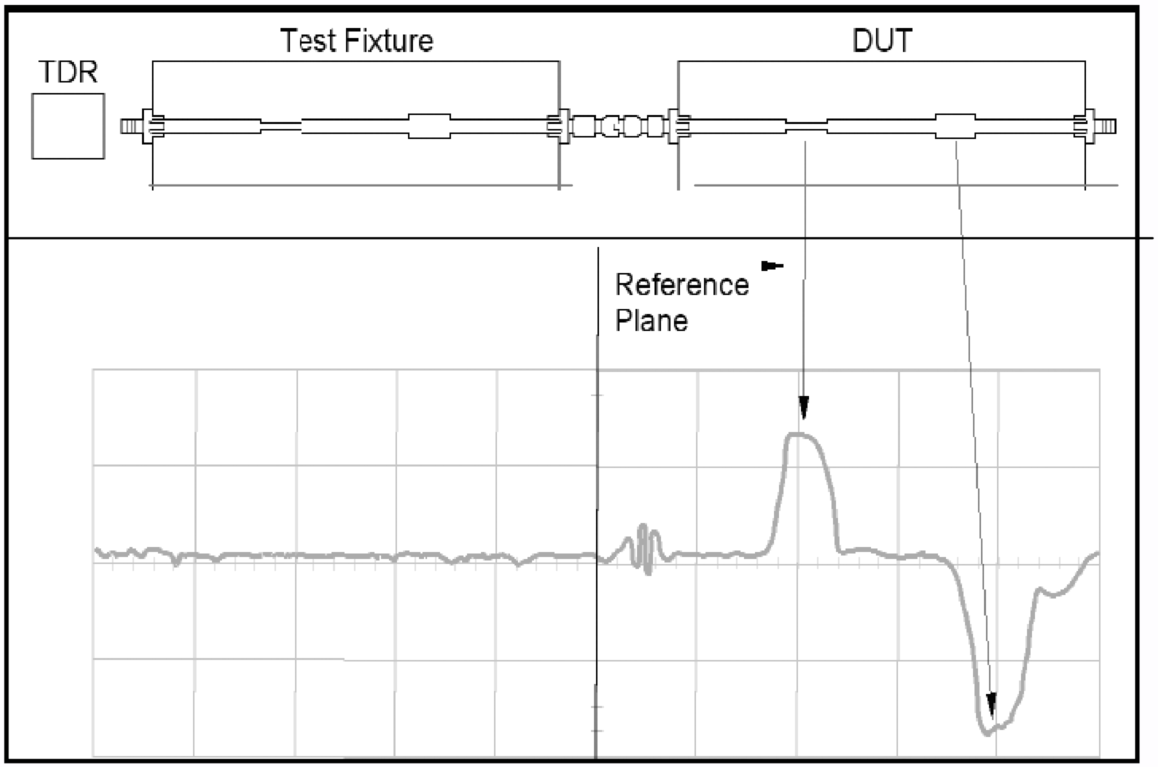
- Accuracy of the step from the TDR module
- Oscilloscope response

Errors that cannot be calibrated:

- Temperature drifts
- Connector repeatability

TDR Calibration (contd.)

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



<u>Reference Plane:</u>

The input reference point to the DUT for TDR meas.

Calibration/Normalization features

TDR Module Calibration

- Amplitude Variation correction

Reference Plane Calibration/Normalization

- Removal of Test Fixture/Cables/Adapters from measurement
- Pulse De-skew capability for differential measurements
- **Coaxial 3.5 mm** Calibration Kit

TDR Calibration Methods

Short Load (SL)

- Uses *Two* known standards to calibrate the oscilloscope for TDR measurements
  - Short standard (Impedance $Z_L = 0$ at input reference of DUT)
  - Load (or Match – an ideal 50 Ω impedance standard)
- Most commonly used calibration for TDR measurements

TDR Calibration Methods

Open Short Load (OSL)

- Uses *Three* known standards to calibrate the oscilloscope for TDR measurements
  - Open standard (Open circuit at input reference of DUT)
  - Short standard (Impedance $Z_L = 0$ at input reference of DUT)
  - Load (or Match – an ideal 50 Ω impedance standard)
- More accurate calibration technique than SL method; can characterize reflections better
- Coaxial Calibration kit from Maury Microwave

Differential TDR Calibrations

- Require simultaneous drive to the DUT (min. *two* **TDRs**)
  - *one* positive step and *one* negative step
- Any skew between the step pulses affects measurement accuracy
  - Cables connecting to DUT should be of similar lengths for de-skew procedure to work
- Reference Impedance is **100 ohms**
  - Still calibrated by using 50 ohm standards on each ports
- Normalized (Calibrated) trace displays a differential response

LeCroy

S-parameters

S-parameters (Scattering parameters) are ratios of power that represent the frequency performance of a device. Each S parameter is the ratio of the sine wave coming out to the sine wave going in the DUT.

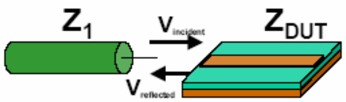
S21 for example, would be the ratio of the sine wave voltage coming out of port 2 to the sine wave voltage that goes into port 1.

Typical S-parameter terms include: Return Loss, Insertion Loss, and Crosstalk.

Measure Important Parameters

T_{DD11}	differential impedance profile
S_{DD21}	Signal quality of differential signal, time delay of differential signal
T_{CD11}	Conversion of differential signal to common signal in reflection (emissions)
S_{DC21}	Conversion of common signal to differential signal in transmission (susceptibility)
T_{CC11}	Common impedance profile
S_{CC21}	Signal quality of the common signal, time delay of common signal

Impedance
In the Time and Frequency Domains

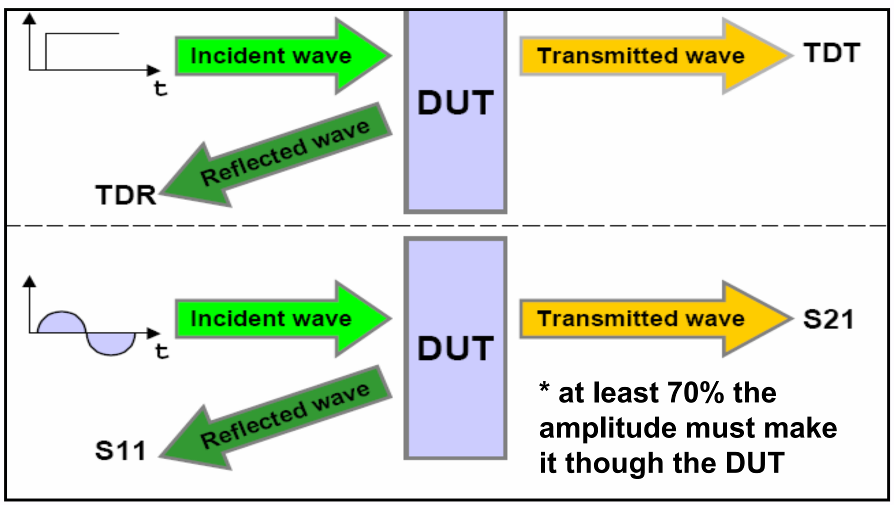


$$\frac{V_{reflected}}{V_{incident}} = \frac{Z_{DUT} - Z_1}{Z_{DUT} + Z_1}$$

Time domain $\rho = \dfrac{V_{reflected}}{V_{incident}}$ $Z_{DUT} = 50\Omega \dfrac{1+\rho}{1-\rho}$

(instantaneous impedance)

Frequency domain $S_{11} = \dfrac{V_{reflected}}{V_{incident}}$ $Z_{DUT} = 50\Omega \dfrac{1+S_{11}}{1-S_{11}}$



Time and Freq. Measurements

Time Domain

- TDR (S11) Impedance vs time discontinuities
- TDT (S21) Dielectric, Skin Effect loss
  - Noticed as rise time degradation in measured TDT pulse

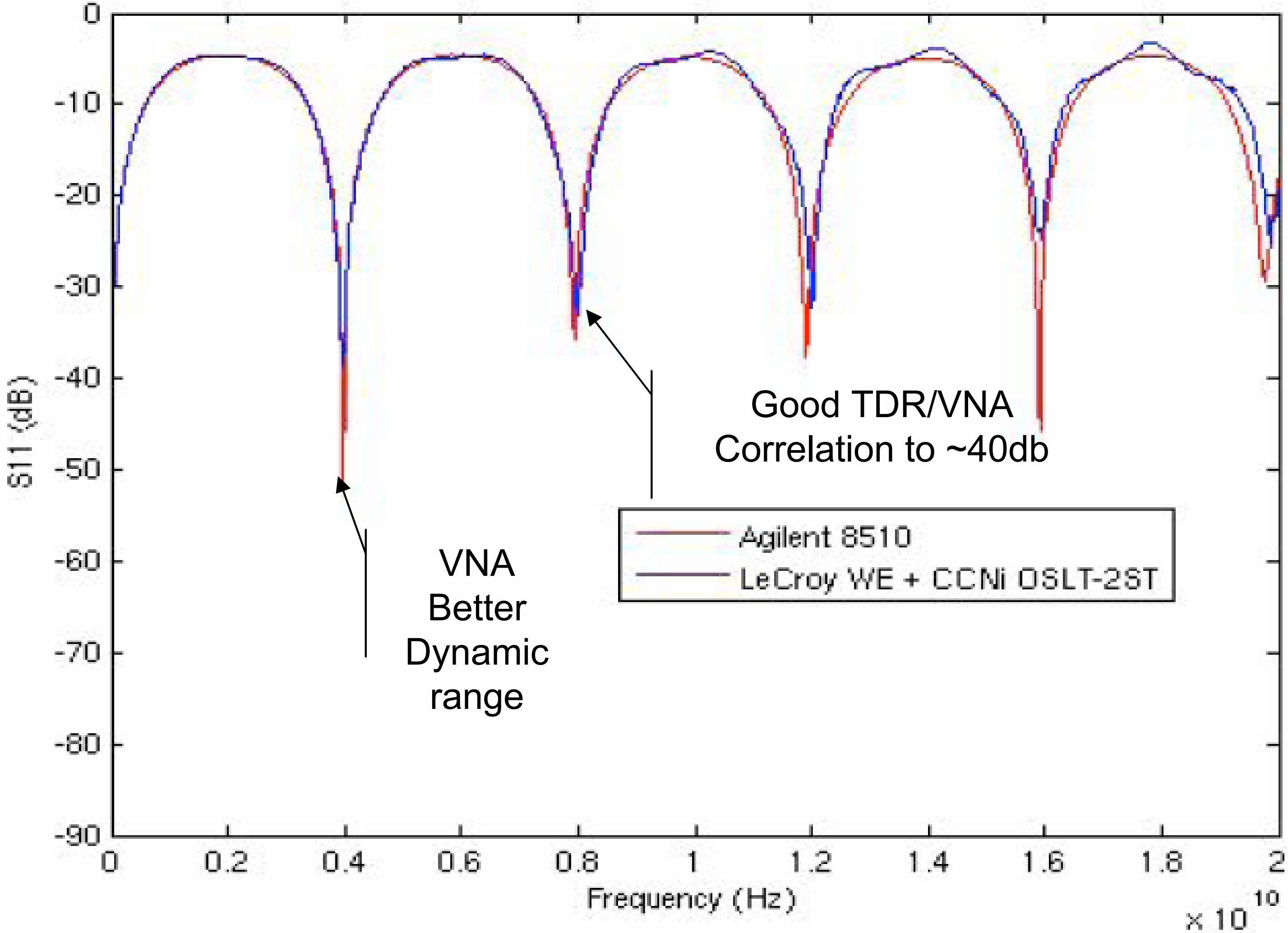
Frequency Domain

- (S11)Return Loss model Discontinuities
- Keep impedance ~ 10% of 50 Ohms,
- Reflected signal should be < 10% the incident signal, or the magnitude of S11 should be < 0.1. In dB, 10% is –20 dB.
- *–20 dB, a common spec for S11*

- (S21)Insertion model Dielectric, Skin Effect loss, etc.
- How much loss there is in the DUT
- If the DUT is ~ 50 Ohm impedance then > its losses, less signal will get through to the other end and the smaller S21
- – 3 dB a common spec for S21 and is a measure of the bandwidth

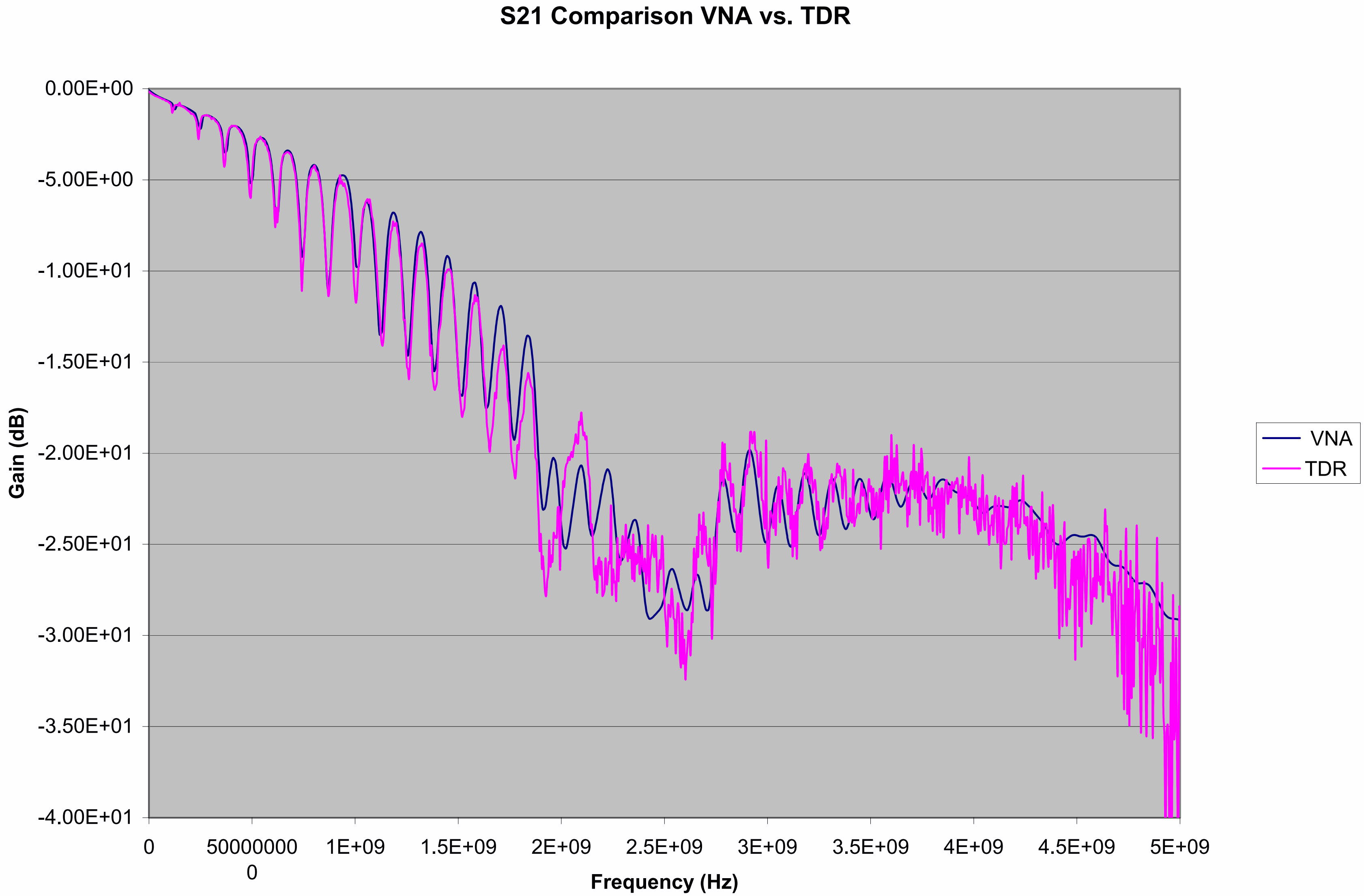
S-parameter Measurement Correlation
TDR/S-parameters vs. Vector Network Analyzer

S11 Return loss *Example*: Measurement of terminated Beatty Standard

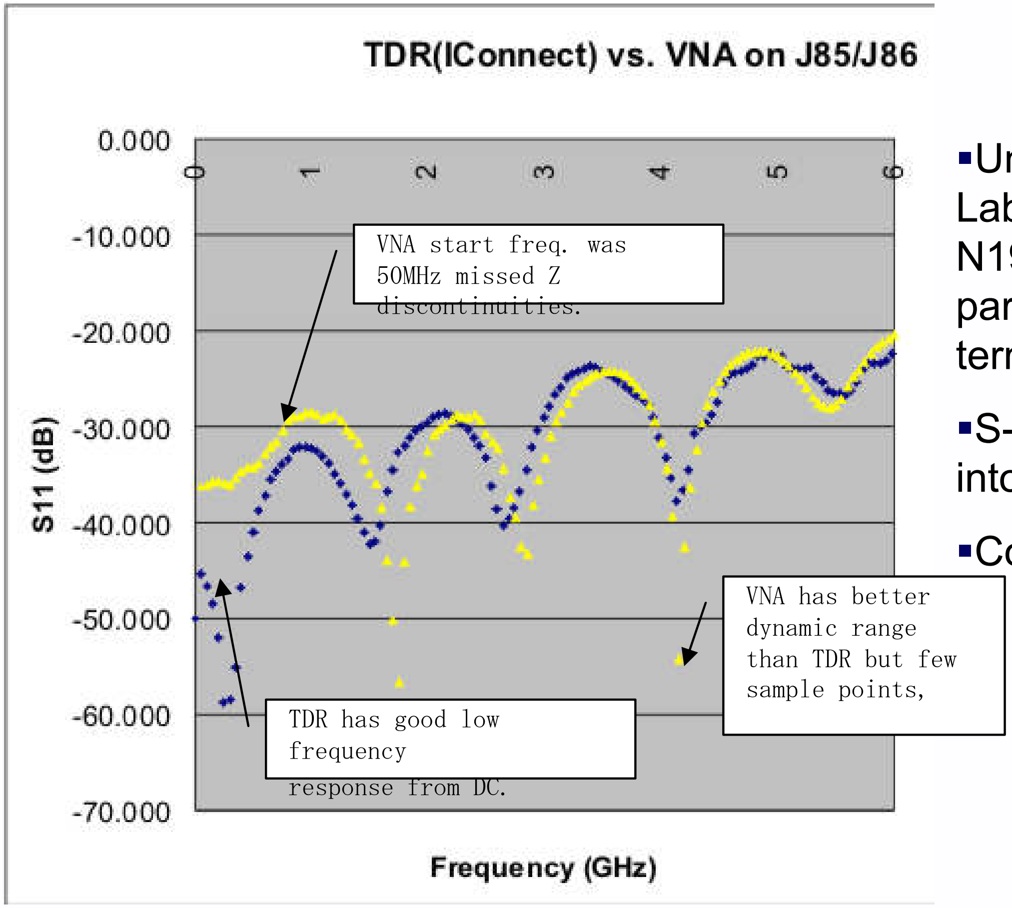


Agilent 8510 VNA compared to WaveExpert measurement using Matlab

S21 of a 24-inch backplane



TDR vs VNA
Showing DC correlation errors



Ref: DesignCon 2006 Single Port TDR Test For Calibrated S-Parameters by James Mayrand, & Brian Shumaker, Complete DVT Solutions

6 GHz TDR to VNA Calibration Test Example

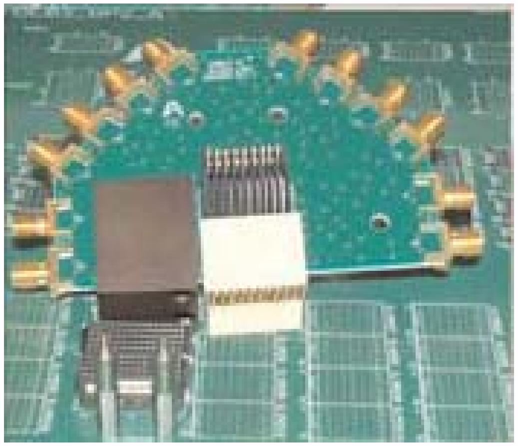
- University of New Hampshire Interoperability Laboratory (UNH) (http://www.iol.unh.edu/) used N1951A 20GHz PLTS VNA system to extract the s-parameters from 6 inches of etch on a SMA terminated IP test board
- S-parameters from VNA and TDR were imported into an Excel spreadsheet and plotted
- Correlation Issues:
  - TDR plotted from DC but VNA start frequency was 50MHz and did not model low frequency components
  - Another correlation issue is time domain record length. The TDR had 4000 sample points vs. Agilent of 1500 frequency points. TDR provide more delta f resolution.

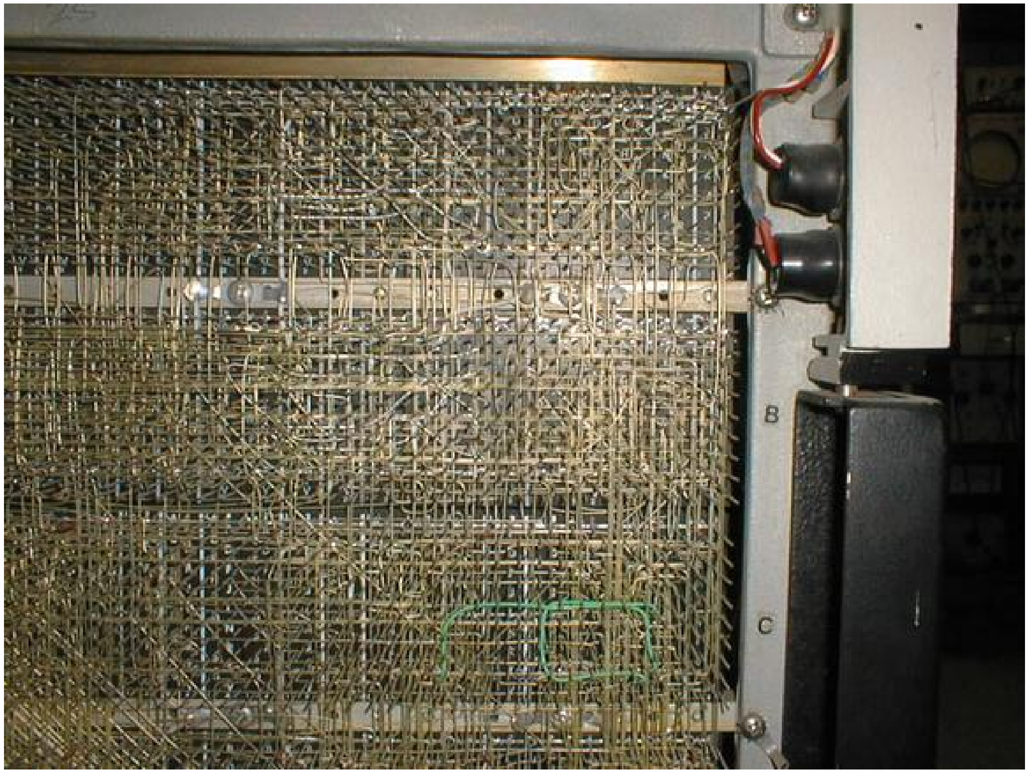
VNA vs. TDR/S-parameters
Advantages and Limitations

1. **TDR**
   1. Higher point density enables measurement of much longer devices, such as Back Planes – i.e. *better spatial resolution*
   2. Up to **100,000 pts** in any given time window Allows for ***Better frequency resolution*** for S-parameter measurement
   3. Ability to select a wider time window for calibration for measurement of longer devices in fixtures
   4. Able to move from time to frequency domain (TDR/T&S-Parameters)
   5. Easy to setup
   6. Fault locations (open/short) capability
   7. Less expensive

2. **VNA**
   1. Use VNA when you require more dynamic range than ~40-50dB
   2. Smaller horizontal sample points for limited time window
   3. Create complex s- parameter spice models
   4. More sensitive to calibration standards
   5. Limited TDR capability
   6. More expensive

TDR Probes
"When SMA's are not available"

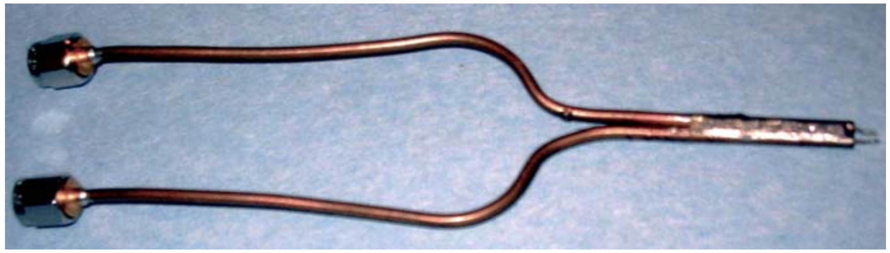




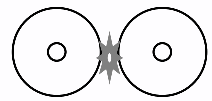
Probing Solution for TDR
50/100 ohm Hand Probe

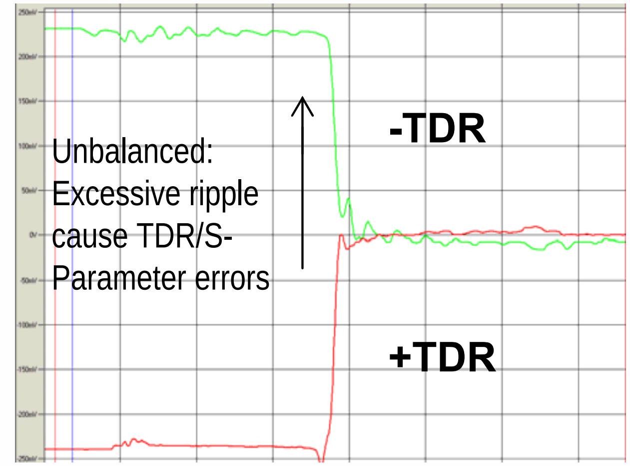
- Low Cost
- Un-Balanced Diff
- Bandwidth/RT/FT?
- Can cause TDR Impedance and S-parameters errors
- Probe tips oxidize

Homemade Soldered 50 ohm Ridge Coax



Soldered 50ohm Cables



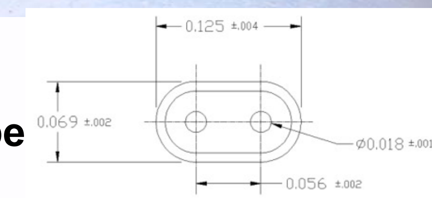


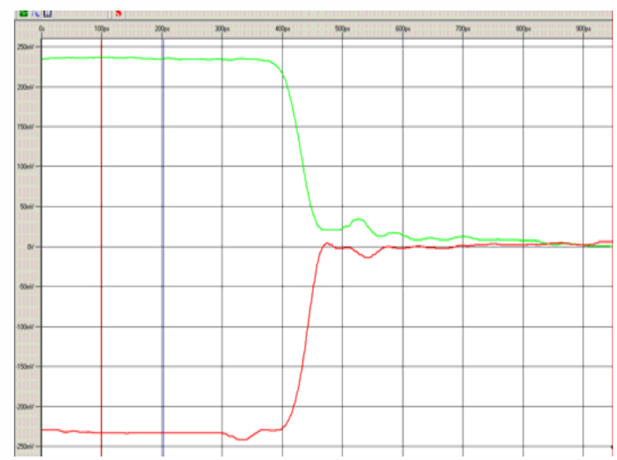
- Moderate Cost
- Balanced SMA Connector
- Balanced 100 ohm TwinAx
- Convert to 50ohm
- non oxidizing probe tips: Gold plated conductive diamond
- Known Rt/Ft
- More accurate Impedance and s-parameters

GigaProbes™

(www.gigaprobes.com)

Balanced 100 ohm SMA,s & TwinAx probe





Applications: Boards, Cables, Package (1mm bump side)

Probing Solution for TDR- Gigaprobes™

DVT Solutions, LLC

Gigaprobes™

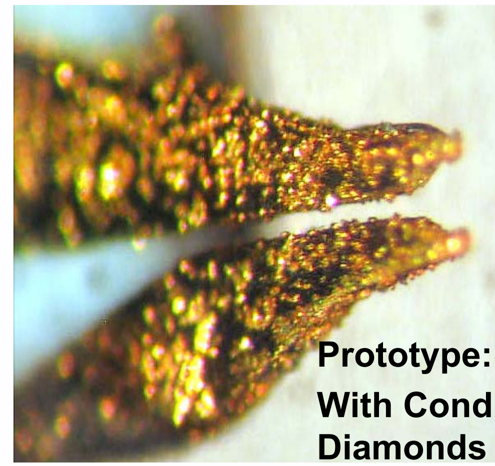
www.gigaprobes.com

Bandwidth	30 GHz
Launch Discontinuity	10mv
Pitch	.5-2mm
Probe Prop Delay	500ps
Use with Micro manipulator	Yes
Impedance	100 and 50 ohm
Accessories:	SMA wrench with ,5, 1 ,2mm for S-S pitch calibration
EZ-Grip Sleeves	Tie Wraps for Cable Management
Application CD	110 mm Tweezers
50 ohm Conversion kit	Manual & Datasheets
Four Right angle SMA's	Desk top Micro-Lens

Probing Solution for TDR
MicoProbes - For Micromanipulators

- Moderate cost but high support costs: requires probe station with microscope
- Probe tips easily damaged
- High bandwidth > 40Ghz
- SLOT Calibration substrates available to de-embed probe errors
- New conductive diamond tips may improve probe tip reliability
- 50 and 100 ohm (custom) available from GGB. Ind.

Cascade Microtech 50 ohm Probe



Prototype: Coated With Conductive Diamonds

GGB Ind. Pico Probes 100 ohm Probe

Applications: Die, board, package