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The Application of Vector Network Analyzers in Balanced Transmission Line Signal Integrity Measurements

Agenda

- 1. Introduction
  - 1.1 The Application and Advantages of Balanced Transmission Lines
  - 1.2 Important Parameters and Characteristics for Balanced Transmission Lines
  - 1.3 Characteristic Impedance, Structural Return Loss (SRL), Attenuation, Delay, Skew, Near End Crosstalk (NEXT), Far End Crosstalk (FEXT)
  - 1.4 Single Ended, Common Mode, Differential Mode, Mixed Mode Scattering Parameters (S Parameters), Mode Conversion
- 2. Techniques Used to Connect Vector Network Analyzers (VNA) to Balanced Transmission Lines
  - 2.1 Use of Baluns to Transform a 50 Ohm Un-balanced VNA Test Port to 100 Ohm Balanced Transmission Line
  - 2.2 Use of a Multiport VNA Test Set to Transform 50 Ohm Un-balanced VNA Test Ports to 100 Ohm Balanced Transmission Lines
  - 2.3 Advantages and Limitations of Each Approach
- 3. Frequency Domain Measurements for Balanced Transmission Lines
  - 3.1 Frequency Domain Measurement with a VNA
  - 3.2 Frequency Domain Measurement with a TDR / TDT (FFT)
  - 3.3 Advantages and Limitations of Each Approach

Agenda

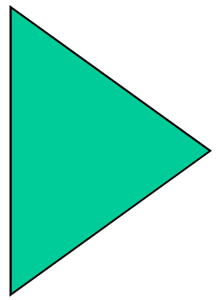
- 4. Time Domain Characteristics and Parameters for Balanced Transmission Lines
  - 4.1 Characteristic Impedance, Fault Type and Location, Attenuation, Delay, Skew, Near End Crosstalk (NEXT), Far End Crosstalk (FEXT)
  - 4.2 Single Ended, Differential Mode, Common Mode, Mixed Mode, Mode Conversion
  - 4.3 Time Domain Measurement with a VNA (IFT)
  - 4.4 Time Domain Measurement with a TDR / TDT
  - 4.5 Advantages and Limitations of Each Approach
- 5. Techniques Used with MultiPort Vector Network Analyzers (VNA) for Balanced Transmission Line Measurements
  - 5.1 Use of Mathmatical Superposition with a Single Source MultiPort VNA for Balanced Transmission Line Measurements
  - 5.2 Use of Dual Differential Sources MultiPort VNA for Balanced Transmission Line Measurements
  - 5.3 Advantages and Limitations of Each Approach
- 6. Fixture and Launch Considerations in Connecting to Balanced Structures

Introduction
What is Signal Integrity (SI)?

- An Engineering Practice
  - That ensures all signals transmitted are received correctly
  - That ensures signals don’t interfere with one another in a way to degrade reception.
  - That ensures signals don’t damage any devices
  - That ensures signals don’t pollute the electromagnetic spectrum

Introduction
Components of High Speed Design

✓ Transmitter

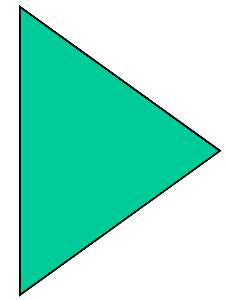


- Transistors
- Sources
- Algorithms
- Passives
- Memory

✓ Interconnect

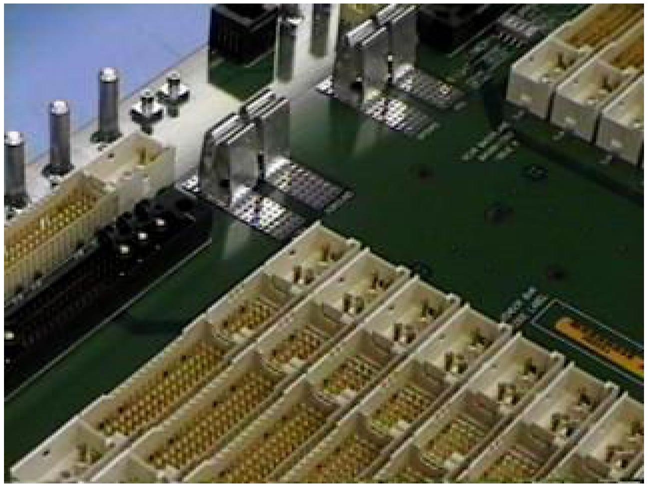
- Circuit elements
- Transmission lines
- S – parameter blocks

✓ Receiver

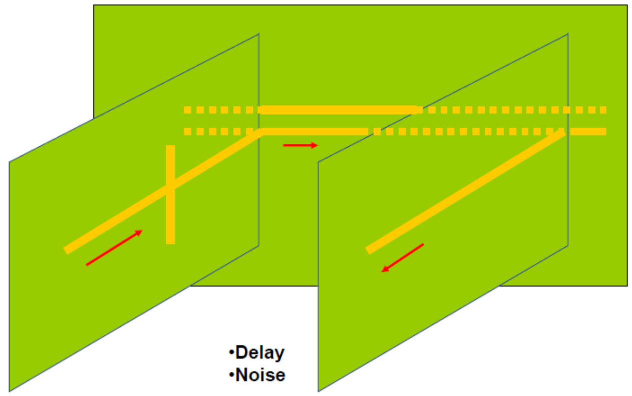


- Transistors
- Passives
- Algorithms
- Memory

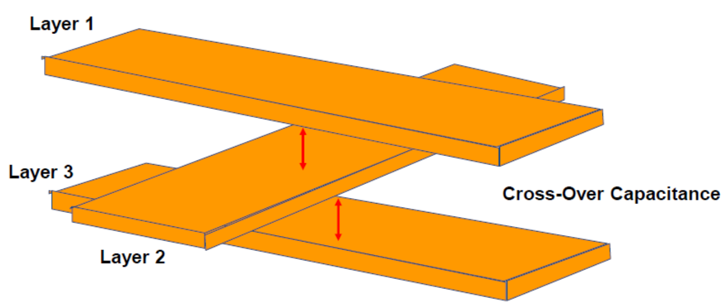
Introduction
Components of High Speed Design



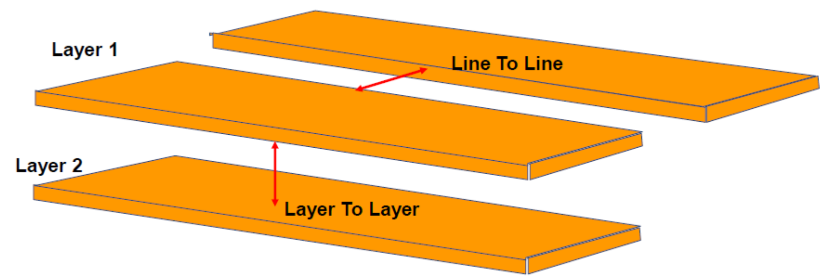
SIGNAL INTEGRITY



SIGNAL INTEGRITY
IMPEDANCE CHANGE
Cross-Over Capacitance



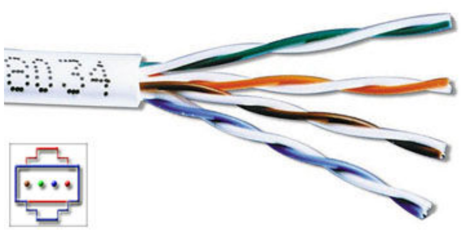
SIGNAL INTEGRITY
CROSSTALK



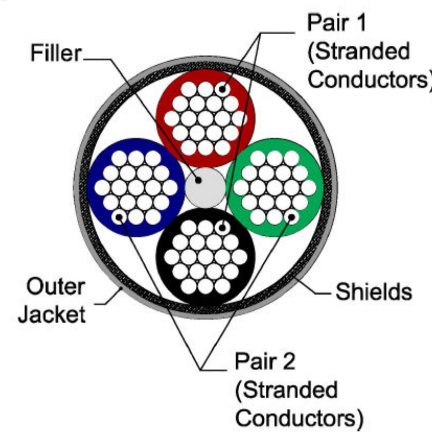
The Application and Advantages of Balanced Transmission Lines

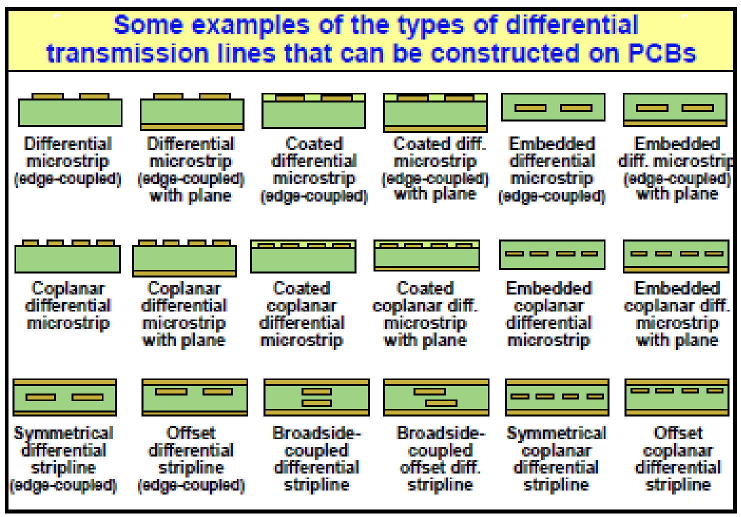
Shielded twisted pair (STP)

Unshielded twisted pair (UTP)

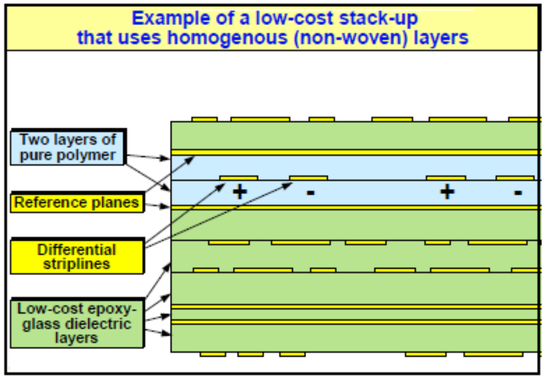


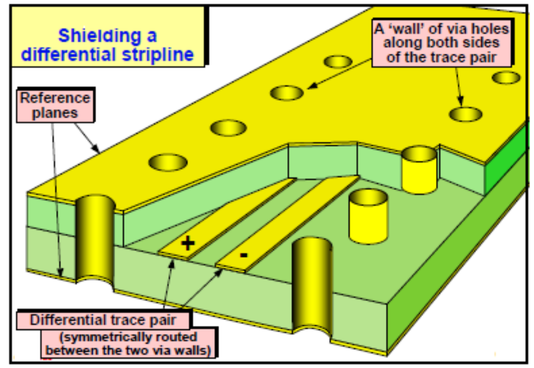
Shielded Quad Data Cable (Fiber-Channel)

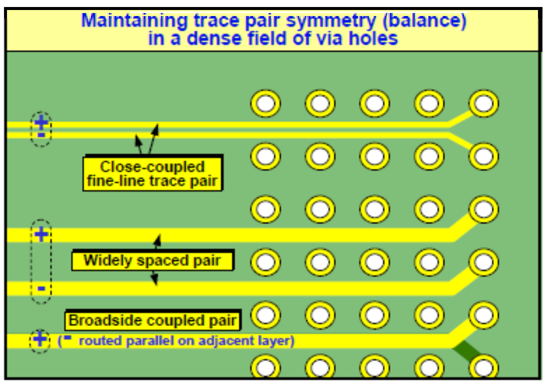


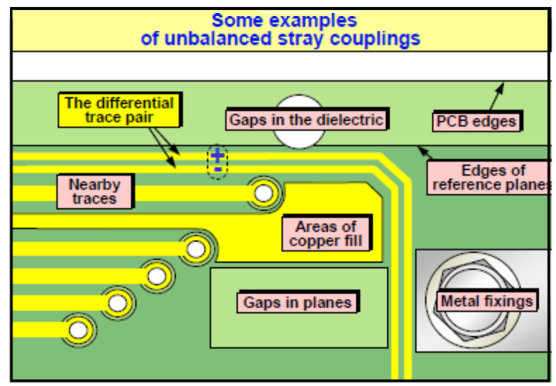


The Application and Advantages of Balanced Transmission Lines

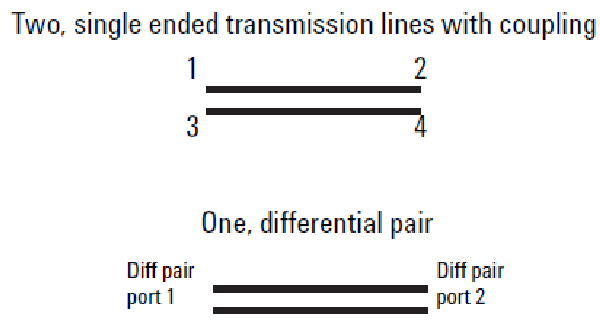








Important Parameters and Characteristics for Balanced Transmission Lines

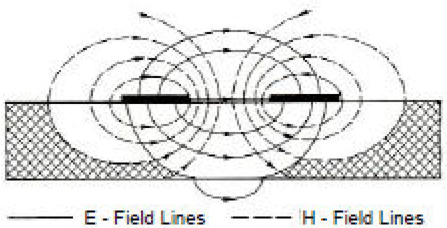


Two equivalent views.

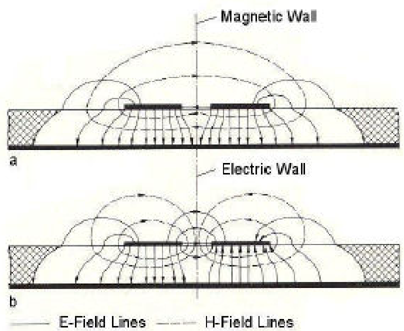
			Stimulus			
			Differential signal		Common signal	
			port 1	port 2	port 1	port 2
Response	Differential signal	port 1	SDD11	SDD12	SDC11	SDC12
		port 2	SDD21	SDD22	SDC21	SDC22
	Common signal	port 1	SCD11	SCD12	SCC11	SCC12
		port 2	SCD21	SCD22	SCC21	SCC22

Differential S parameters

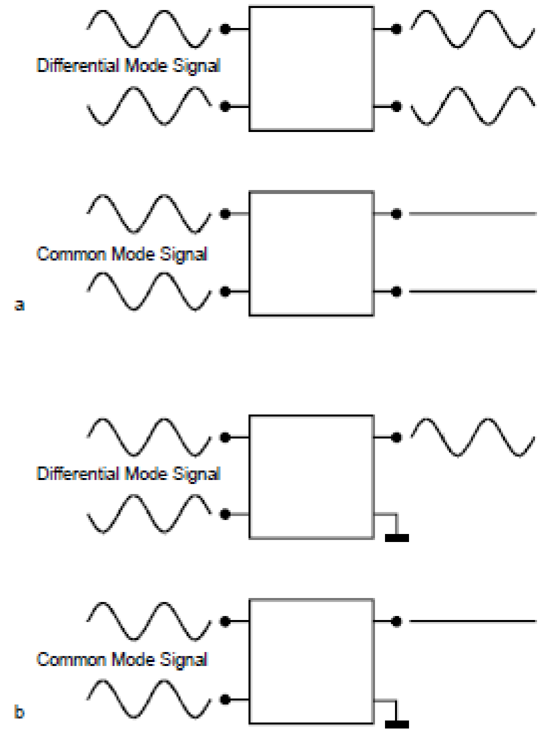
Important Parameters and Characteristics for Balanced Transmission Lines



Cross section of a planar balanced transmission line



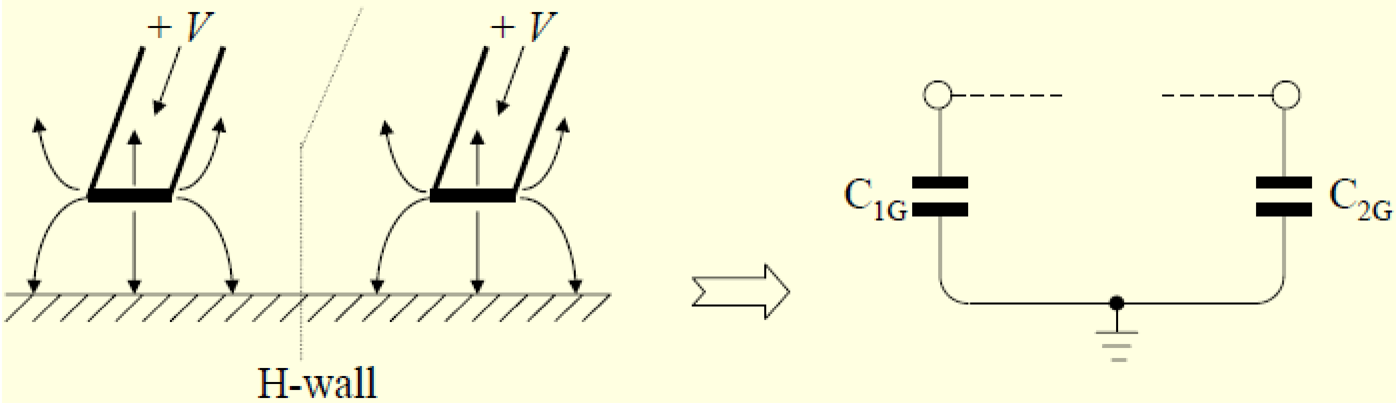
Cross section of a planar balanced transmission line, with electric and magnetic field lines
a: Even or common mode
b: Odd or differential mode



Ideal balanced devices:
a: Fully balanced
b: Balanced-to-single-ended

Important Parameters and Characteristics for Balanced Transmission Lines

Even Mode (Field)

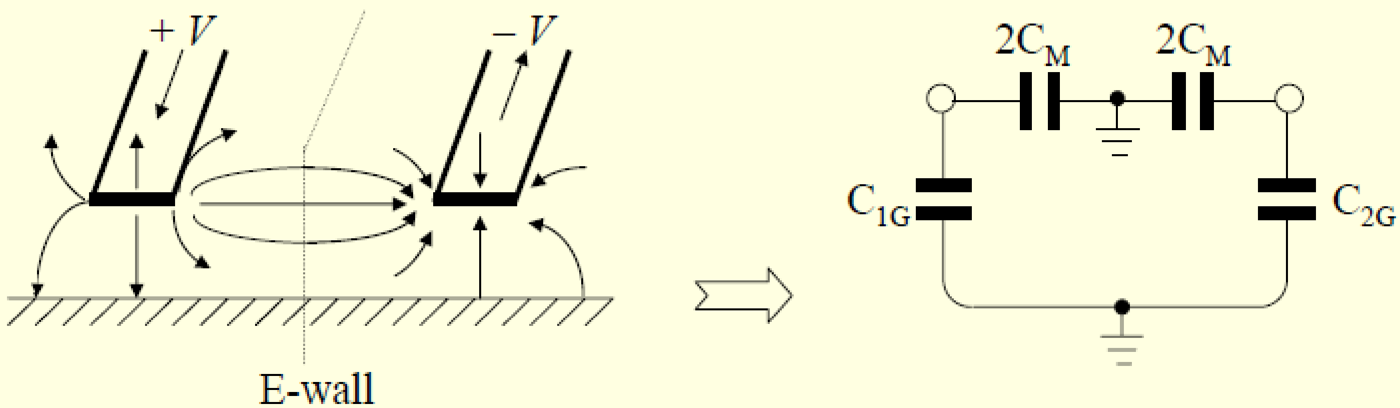


$$Z_{0e} = \sqrt{\frac{L_e}{C_e}} = \sqrt{\frac{L + L_M}{C_{1G}}} = \sqrt{\frac{L + L_M}{C_{2G}}}$$

$$v_{p,e} = \sqrt{\frac{1}{L_e C_e}} \quad \left\{ = \frac{c}{\sqrt{\varepsilon_r}} \right\} \text{ for homogeneous medium}$$

Important Parameters and Characteristics for Balanced Transmission Lines

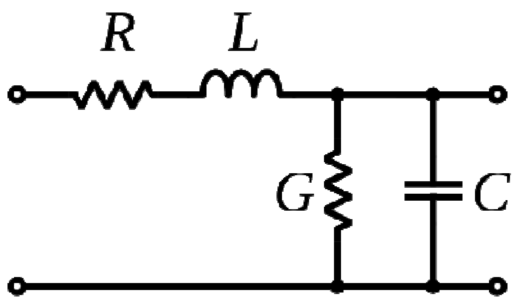
Odd Mode (Field)



$$Z_{0o} = \sqrt{\frac{L_o}{C_o}} = \sqrt{\frac{L - L_M}{C_{1G} + 2C_M}} = \sqrt{\frac{L - L_M}{C_{2G} + 2C_M}}$$

$$v_{p,o} = \sqrt{\frac{1}{L_o C_o}} \quad \left\{ = \frac{c}{\sqrt{\varepsilon_r}} \right\} \text{ for homogeneous medium}$$

Important Parameters and Characteristics for Balanced Transmission Lines



Propagation equation

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta$$

α is the attenuation (loss) factor

β is the phase (velocity) factor

Characteristic Impedance equation

$$Z0 = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}}$$

- ***Propagation delay per unit length (T_0) {time/distance} [ps/in]***
  - ***Or Velocity (v_0) {distance/ time} [in/ps]***
- ***Characteristic Impedance (Z_0)***
- ***Per-unit-length Capacitance (C_0) [pf/in]***
- ***Per-unit-length Inductance (L_0) [nf/in]***
- ***Per-unit-length (Series) Resistance (R_0) [W/in]***
- ***Per-unit-length (Parallel) Conductance (G_0) [S/in]***

Important Parameters and Characteristics for Balanced Transmission Lines

- Knowing any two out of Z_0, T_d, C_0, and L_0, the other two can be calculated.
- C_0 and L_0 are reciprocal functions of the line cross-sectional dimensions and are related by constant $\mu\varepsilon$.
- ε is electric permittivity
  - ε_0= 8.85 X 10^{-12} *F/m* (free space)
  - ε_r i s relative dielectric constant
- μ is magnetic permeability
  - μ_0= 4p X 10^{-7} *H/m* (free space)
  - μ_r is relative permeability

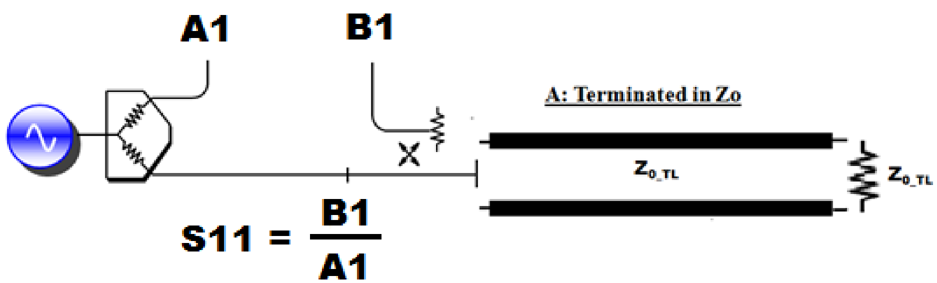
$$Z_0 = \sqrt{\frac{L_0}{C_0}} \qquad T_d = \sqrt{L_0 C_0}$$

$$C_0 = \frac{T_0}{Z_0} \qquad L_0 = Z_0 T_0$$

$$v_0 = \frac{1}{\sqrt{\mu\varepsilon}} \qquad C_0 L_0 = \mu\varepsilon$$

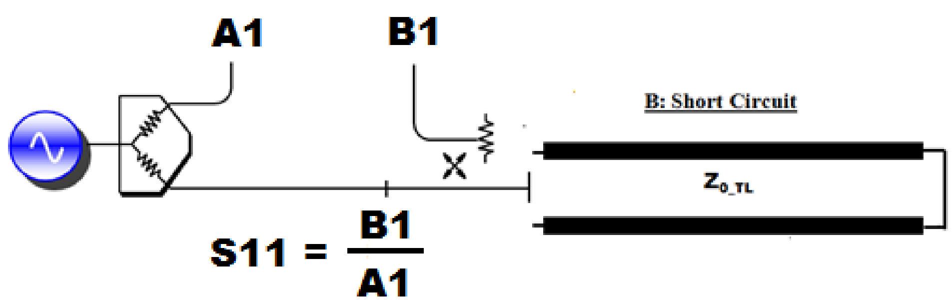
$$\mu = \mu_r \mu_0 \qquad \varepsilon = \varepsilon_r \varepsilon_0$$

Important Parameters and Characteristics for Balanced Transmission Lines
Measurement of Characteristic Impedance Z_0



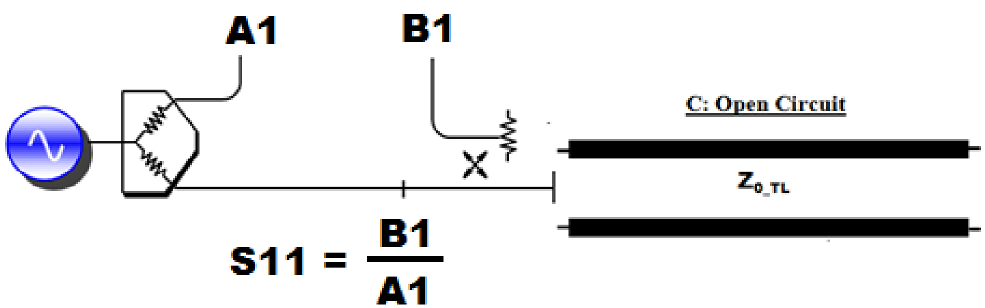
Measure S11 with Far End Terminated in Z_0

$$Z_{0\_TL} = \frac{1 + S11}{1 - S11} * Zo$$



Measure S11 with Far End Terminated in Short Circuit

$$Z_{oc} = \frac{1 + S11}{1 - S11} * Zo$$



Measure S11 with Far End Terminated in Open Circuit

$$Z_{sc} = \frac{1 + S11}{1 - S11} * Zo$$

$$Z_{0\_TL} = \sqrt{Z_{oc} * Z_{sc}}$$

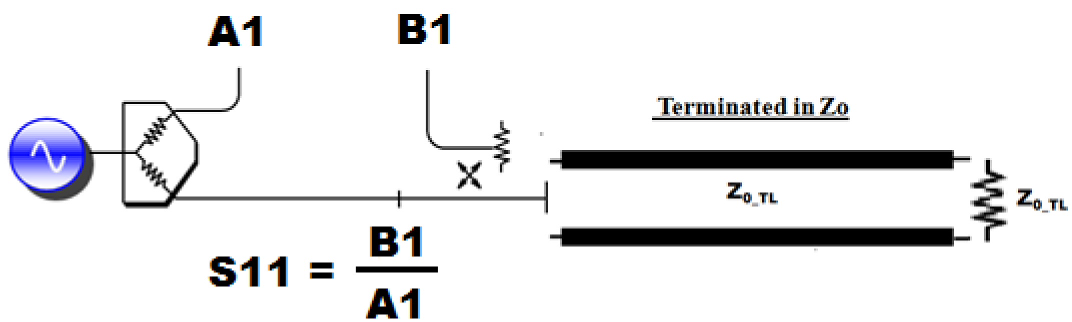
Important Parameters and Characteristics for Balanced Transmission Lines
Measurement of Reflection Characteristics

Reflection Coefficient = ρ = S_D1_D1 = b_1 / a_1 = reflected / incident

Voltage Standing Wave Ratio = VSWR = $$\frac{1 + |S_D1_D1|}{1 - |S_D1_D1|}$$

Return Loss (dB) = - 20 $\log_{10}$ (| S_D1_D1 |)

[Structural Return Loss (dB)]



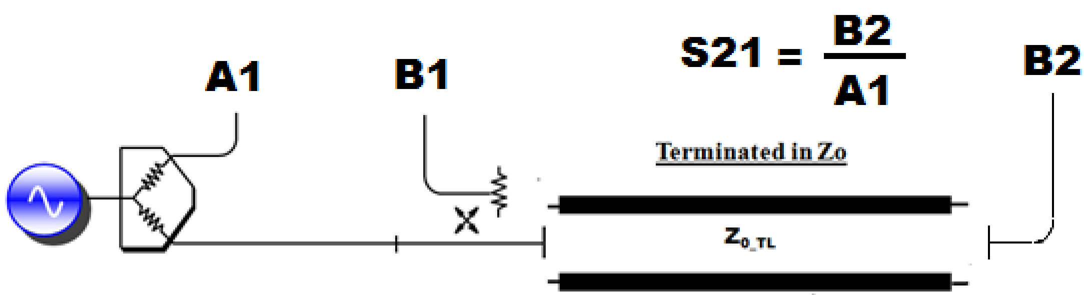
Important Parameters and Characteristics for Balanced Transmission Lines
Measurement of Transmission Characteristics

Single Pair Measurements

Insertion Loss (dB) = $20 \log_{10} (| S_D 2_D 1 |)$ [Log Magnitude]

Attenuation (dB/in) = $20 \log_{10} (| S_D 2_D 1 |)$ / (Length of Transmission Line)

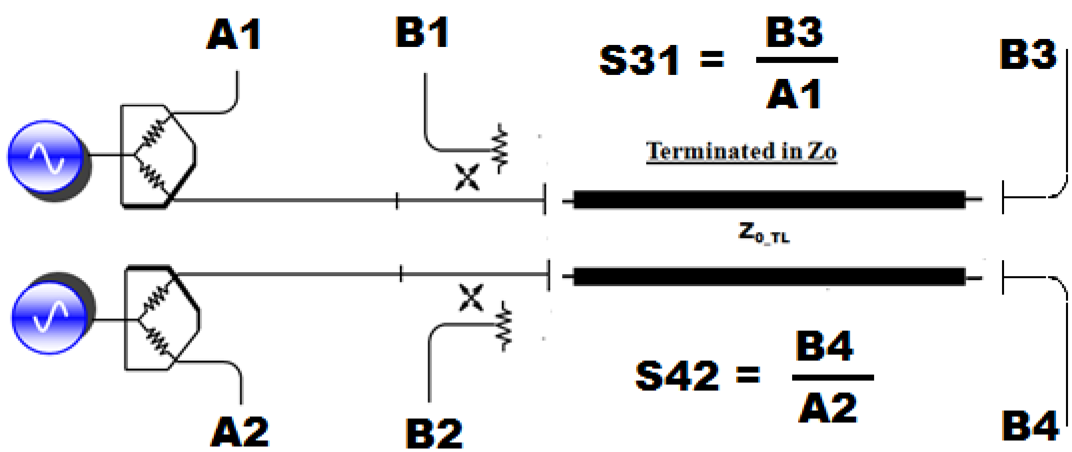
Delay (ns) = $(S_D 2_D 1)$ [Group Delay]



Important Parameters and Characteristics for Balanced Transmission Lines
Measurement of Transmission Characteristics

Single Pair Measurements

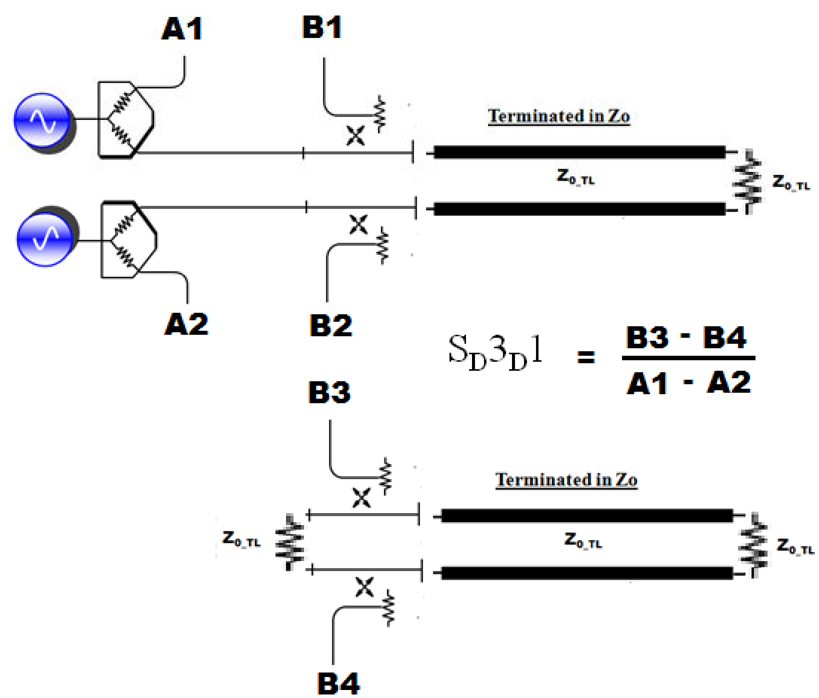
Delay Skew (ns) = (S31) [Group Delay] - (S42) [Group Delay]



Important Parameters and Characteristics for Balanced Transmission Lines
Measurement of Transmission Characteristics

<u>Two Pair Measurements</u>

Near End Crosstalk (NEXT) (dB) = (S_D3_D1)   [Log Magnitude]

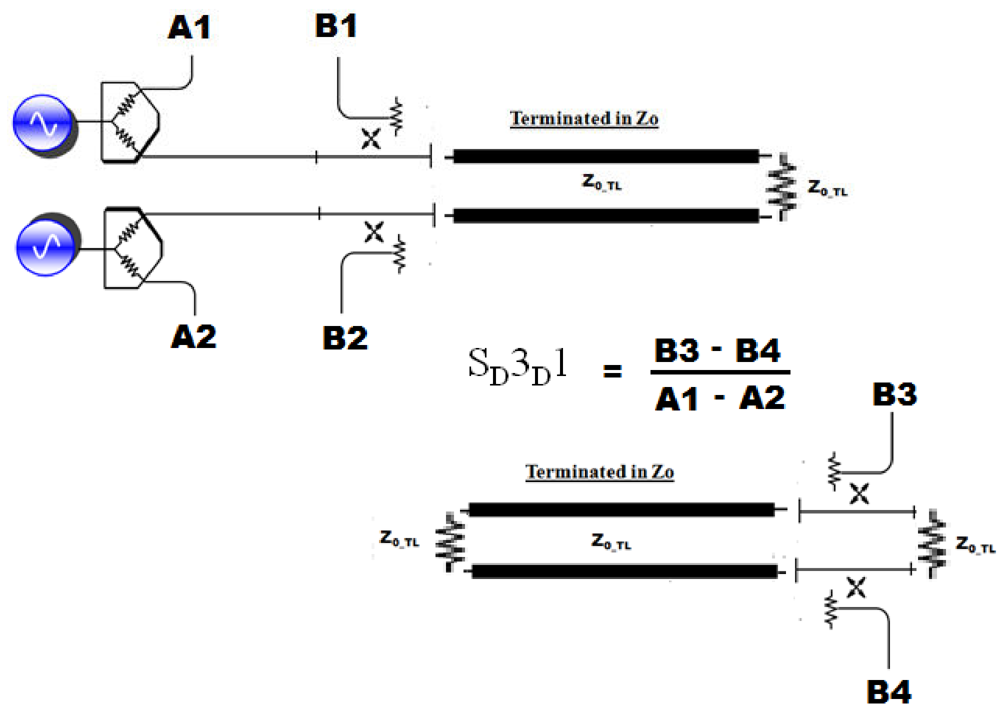


$$S_D3_D1 = \frac{B3 - B4}{A1 - A2}$$

Important Parameters and Characteristics for Balanced Transmission Lines
Measurement of Transmission Characteristics

Two Pair Measurements

Far End Crosstalk (FEXT) (dB) = (S_D3_D1) [Log Magnitude]

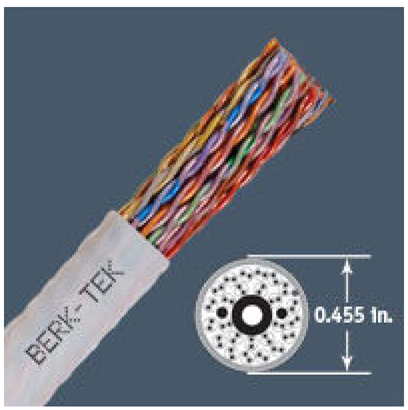


Important Parameters and Characteristics for Balanced Transmission Lines
Measurement of Transmission Characteristics

Multiple Pair Measurements

Power Sum - NEXT (dB) = Σ NEXT Reference Pair to All Other Pairs

Power Sum - ELFEXT (dB) = Σ FEXT Reference Pair to All Other Pairs



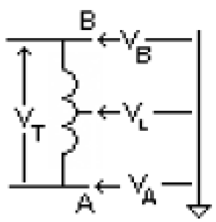
TECHNICAL DATA ELECTRICAL

FREQUENCY (MHz)	Insertion Loss (dB/100 m max.)	RL (dB min.)	SRL (dB min.)	PS-NEXT (dB min.)	NEXT (dB min.)	ELFEXT (dB min.)	PS-ELFEXT (dB min.)
1	2	20	25	62.3	65.3	63.8	60.8
4	4.1	23	25	53.2	56.3	51.7	48.7
10	6.5	25	25	47.3	50.3	43.8	40.8
16	8.2	25	25	44.2	47.3	39.7	36.7
20	9.3	25	25	42.7	45.8	37.7	34.7
31.25	11.7	23.6	23.6	39.8	42.9	33.9	30.9
62.5	17	21.5	21.5	35.3	38.4	27.8	24.8
100	22	20.1	20.1	32.3	35.3	23.8	20.8
150	27.5	18.9	18.9	29.7	32.7	20.2	17.2
200	32.4	18.0	18.0	27.8	30.8	17.7	14.7
250	36.9	17.3	17.3	26.3	29.3	15.8	12.8

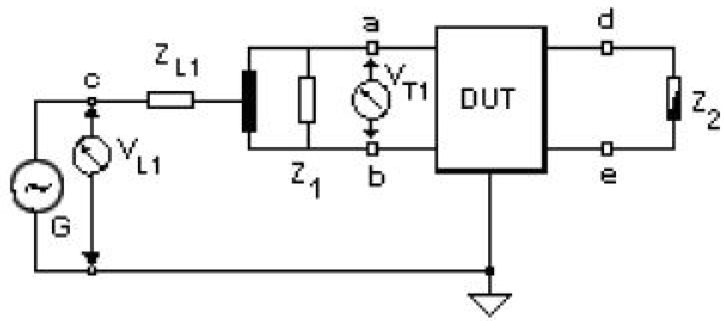
IMPORTANT: Berk-Tek performance guarantees are based on swept-frequency testing and apply to all frequencies for the entire specified frequency range and are not limited to the tables of data shown which are presented to demonstrate our guarantees at "representative" frequencies. Values above 100 MHz are for engineering information. Other jacket colors available.

Important Parameters and Characteristics for Balanced Transmission Lines

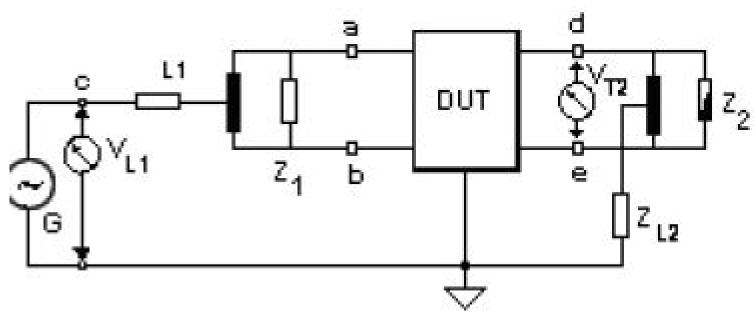
Measurement of Longitudinal Balance



Balanced Circuit

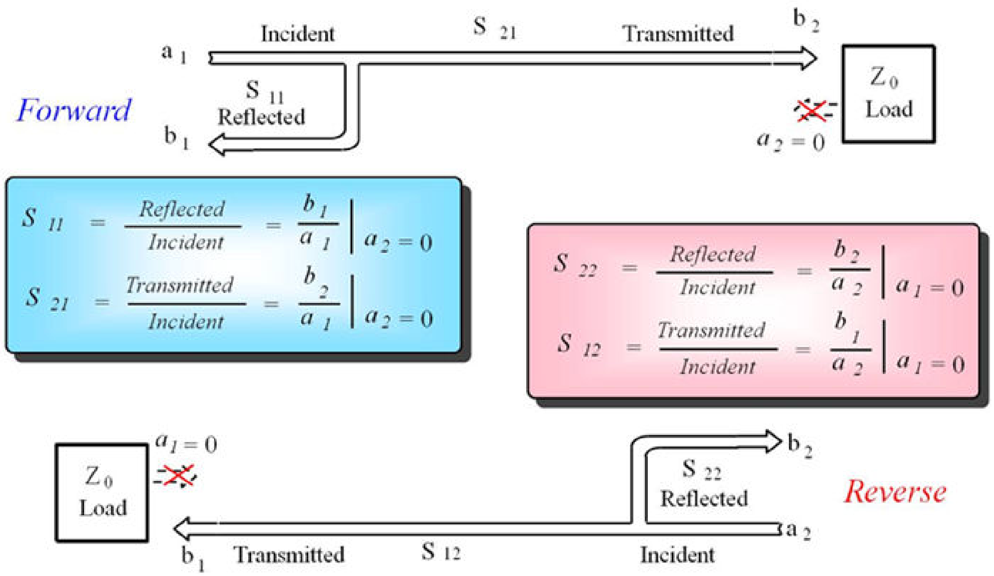


One-port Balance Test



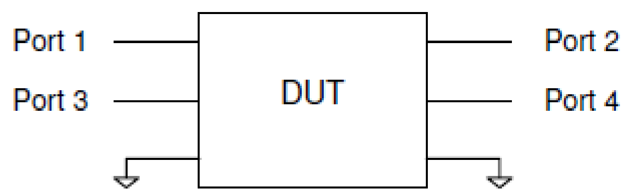
Two-port Balance Test

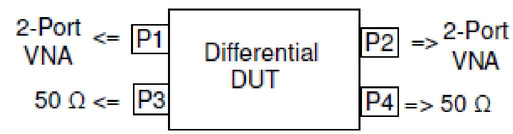
Important Parameters and Characteristics for Balanced Transmission Lines
Single Ended S-Parameters



- Traditional S-Parameters
- All Measurements Use Ground as the Return (Common Mode)
- Balanced Lines and Devices Measured One Side at a Time
- Delay Skew is Based on Single Ended Measurements

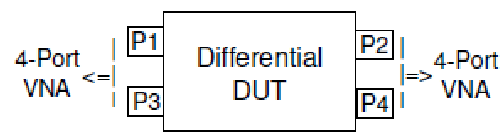
Important Parameters and Characteristics for Balanced Transmission Lines
Common Mode S-Parameters





For single-ended 2-port VNA.

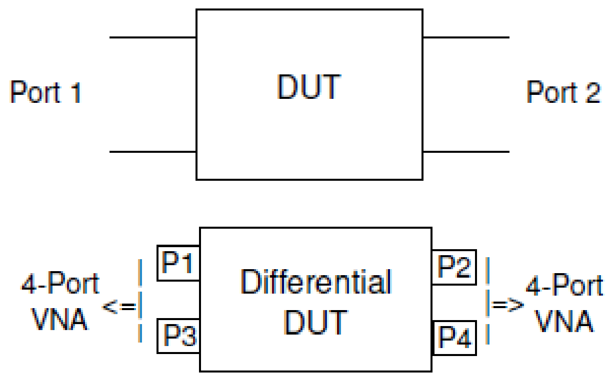
$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}$$



For differential-ended 4-port VNA.

- Balanced Transmission Lines / Devices Treated as a 4 Port
- Ground is Common Return For All Ports (May be Virtual)
- Each DUT “Port” is Connected to a VNA Port Center Conductor
- Delay Skew Can Be Derived From Common Mode Measurements

Important Parameters and Characteristics for Balanced Transmission Lines
Differential Mode S-Parameters

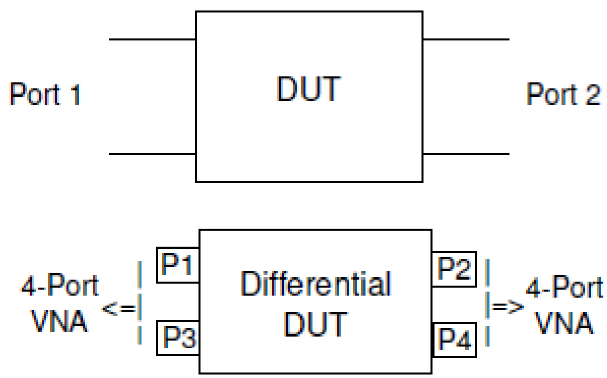


For differential-ended 4-port VNA.

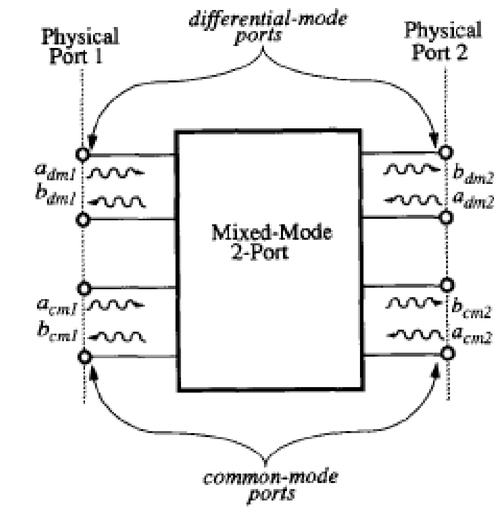
$$\begin{bmatrix} S_{DD}11 & S_{DD}12 \\ S_{DD}21 & S_{DD}22 \end{bmatrix}$$

- Balanced Transmission Lines / Devices Treated as a 4 Port
- Ground is Common Return For All Ports (May be Virtual)
- Each DUT “Port” is Connected to a VNA Port Center Conductor
- Delay Skew Can Be Derived From Common Mode Measurements

Important Parameters and Characteristics for Balanced Transmission Lines
Mixed Mode S-Parameters



For differential-ended 4-port VNA.



Conceptual diagram of mixed-mode two-port.

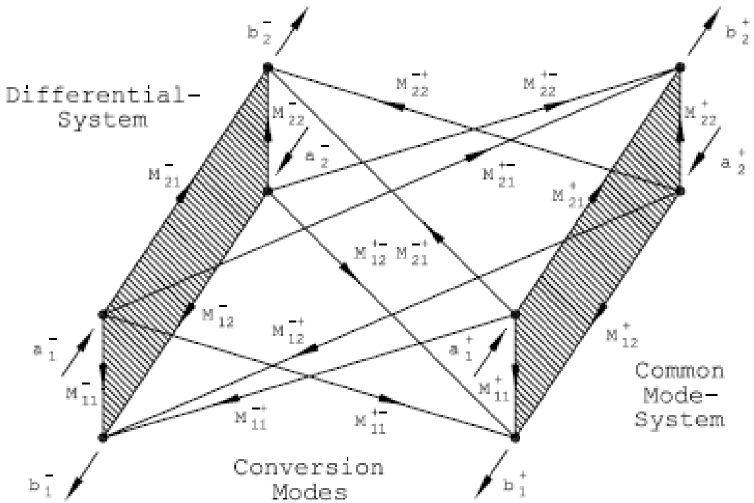
$$\begin{bmatrix} a_{d1} \\ a_{d2} \\ a_{c1} \\ a_{c2} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix}$$

$$\begin{bmatrix} b_{d1} \\ b_{d2} \\ b_{c1} \\ b_{c2} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix}$$

$$\begin{bmatrix} b_{d1} \\ b_{d2} \\ b_{c1} \\ b_{c2} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} S_{dd11} & S_{dd12} \\ S_{dd21} & S_{dd22} \end{bmatrix} & \begin{bmatrix} S_{dc11} & S_{dc12} \\ S_{dc21} & S_{dc22} \end{bmatrix} \\ \begin{bmatrix} S_{cd11} & S_{cd12} \\ S_{cd21} & S_{cd22} \end{bmatrix} & \begin{bmatrix} S_{cc11} & S_{cc12} \\ S_{cc21} & S_{cc22} \end{bmatrix} \end{bmatrix} \begin{bmatrix} a_{d1} \\ a_{d2} \\ a_{c1} \\ a_{c2} \end{bmatrix}$$

- Balanced Transmission Lines / Devices Treated as a 4 Port
- Ground is Common Return For All Ports (May be Virtual)
- Each DUT “Port” is Connected to a VNA Port Center Conductor
- Mixed Mode Parameters Include Important Mode Conversion Parameters , Differential Mode ⇔ Common Mode

Important Parameters and Characteristics for Balanced Transmission Lines
Mode Conversion



Signal flow diagram of the multi-mode parameters

M-parameters for the differential mode:

$$M_{11}^{-} = \frac{1}{2}(S_{11} + S_{22} - S_{12} - S_{21})$$
$$M_{12}^{-} = \frac{1}{2}(S_{13} + S_{24} - S_{14} - S_{23})$$
$$M_{21}^{-} = \frac{1}{2}(S_{31} + S_{42} - S_{41} - S_{32})$$
$$M_{22}^{-} = \frac{1}{2}(S_{33} + S_{44} - S_{34} - S_{43})$$

M-parameters for the common mode:

$$M_{11}^{+} = \frac{1}{2}(S_{11} + S_{22} + S_{12} + S_{21})$$
$$M_{12}^{+} = \frac{1}{2}(S_{13} + S_{24} + S_{14} + S_{23})$$
$$M_{21}^{+} = \frac{1}{2}(S_{31} + S_{42} + S_{41} + S_{32})$$
$$M_{22}^{+} = \frac{1}{2}(S_{33} + S_{44} + S_{34} + S_{43})$$

Conversion parameters for the differential into the common mode:

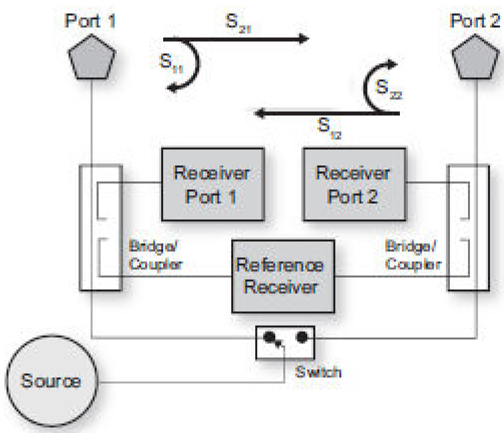
$$M_{11}^{+-} = \frac{1}{2}(S_{11} - S_{22} - S_{12} + S_{21})$$
$$M_{12}^{+-} = \frac{1}{2}(S_{13} - S_{24} - S_{14} + S_{23})$$
$$M_{21}^{+-} = \frac{1}{2}(S_{31} - S_{42} + S_{41} - S_{32})$$
$$M_{22}^{+-} = \frac{1}{2}(S_{33} - S_{44} - S_{34} + S_{43})$$

Conversion parameters for common into the differential mode:

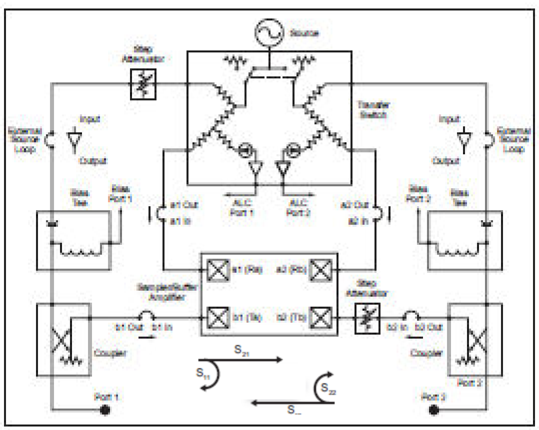
$$M_{11}^{-+} = \frac{1}{2}(S_{11} - S_{22} + S_{12} - S_{21})$$
$$M_{12}^{-+} = \frac{1}{2}(S_{13} - S_{24} + S_{14} - S_{23})$$
$$M_{21}^{-+} = \frac{1}{2}(S_{31} - S_{42} - S_{41} + S_{32})$$
$$M_{22}^{-+} = \frac{1}{2}(S_{33} - S_{44} + S_{34} - S_{43})$$

- Balanced Transmission Lines / Devices Treated as a 4 Port
- Ground is Common Return For All Ports (May be Virtual)
- Each DUT “Port” is Connected to a VNA Port Center Conductor
- Mixed Mode Parameters Include Important Mode Conversion Parameters , Differential Mode ⇔ Common Mode

Techniques Used to Connect Vector Network Analyzers (VNA) to Balanced Transmission Lines



Typical 2 Port VNA (3 Receiver)



Typical 2 Port VNA (4 Receiver)

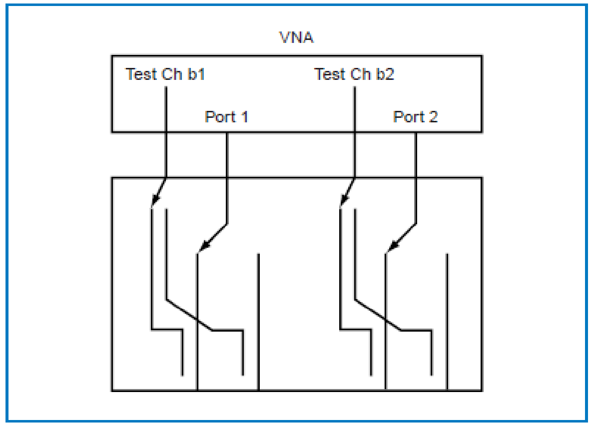


Figure 1. A coupler test set architecture is shown here: the test couplers are on the DUT-side of the multiplexing switches. As N becomes large, this test set becomes quite complex.

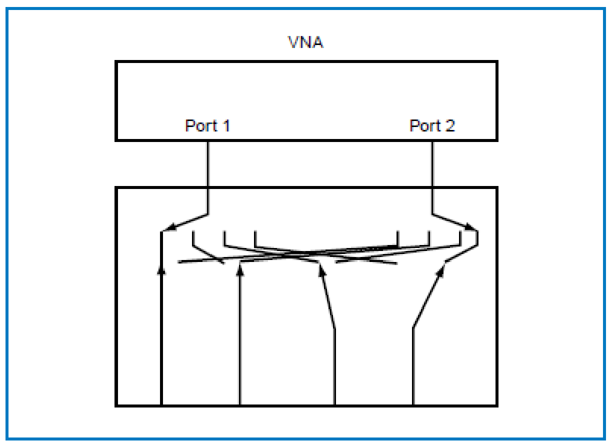
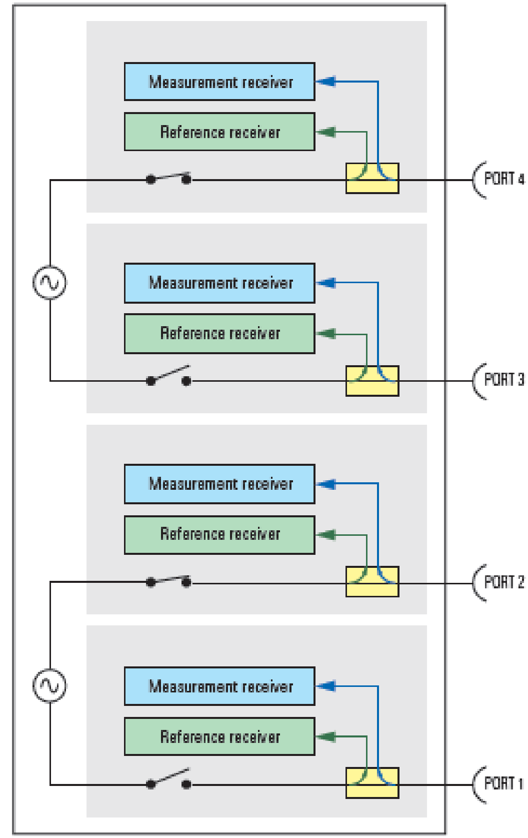
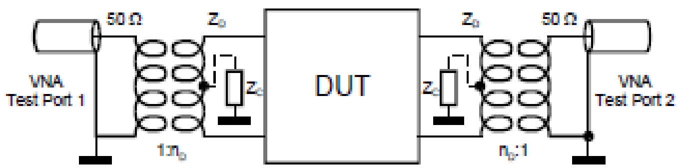


Figure 2. A no-coupler architecture for the 4x2 problem is shown here. In this case, any VNA port can be connected to any test port although this is not needed for most measurements. This test set can be simpler for large N but does have limitations.

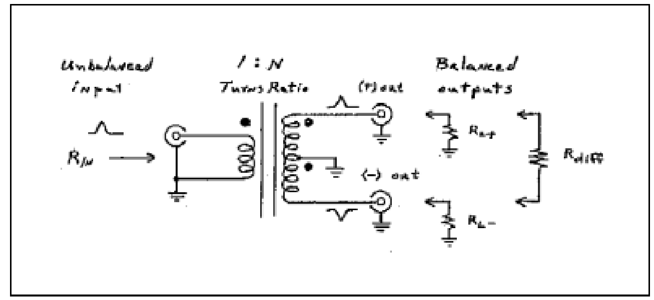


Typical 4 Port VNA (2 Source)

Use of Baluns to Transform a 50 Ohm Un-balanced VNA Test Port to 100 Ohm Balanced Transmission Line

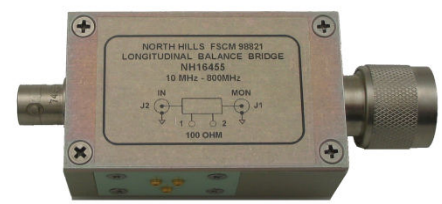


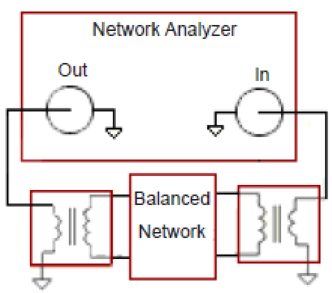
Measuring the differential mode characteristics of a two-port DUT using baluns

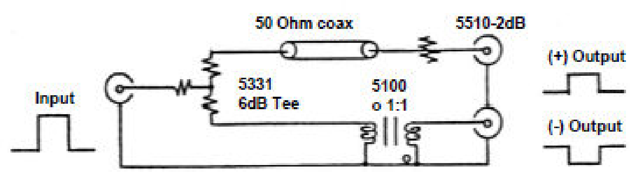


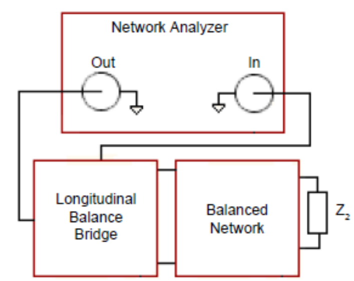
BALUN Transformer with Center-Tapped Output

Picosecond Pulse Labs Model 5315A BALUN
17 GHz typical BW







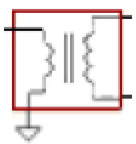


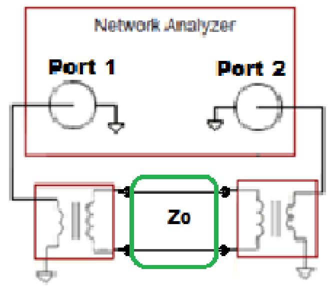
Port 1 Longitudinal Balance Test

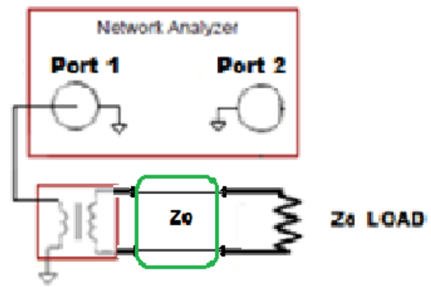
Use of Baluns to Transform a 50 Ohm Un-balanced VNA Test Port to 100 Ohm Balanced Transmission Line
VNA Configurations for Balun Based Measurements

<u>Reflection Measurements</u>

Balun Based

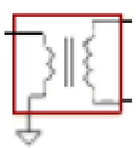
50Ω  100Ω

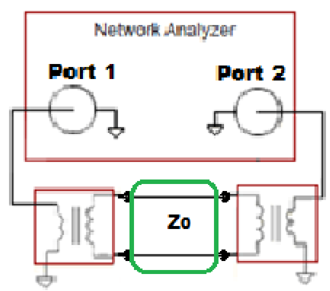




<u>Transmission Measurements</u>

Balun Based

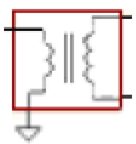
50Ω  100Ω

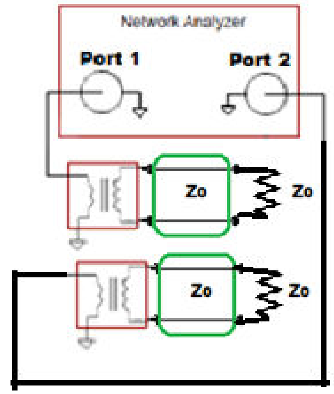


Use of Baluns to Transform a 50 Ohm Un-balanced VNA Test Port to 100 Ohm Balanced Transmission Line
VNA Configurations for Balun Based Measurements

<u>NEXT Measurements</u>

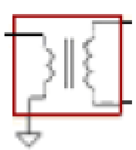
Balun Based

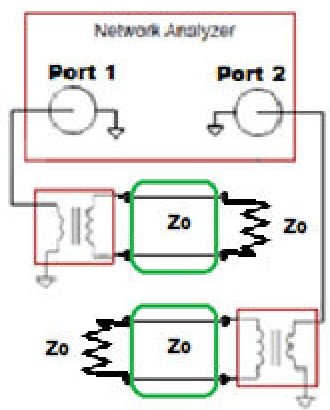
50Ω  100Ω



<u>FEXT Measurements</u>

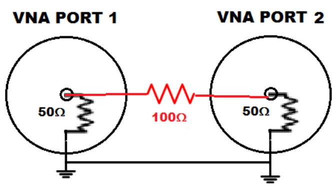
Balun Based

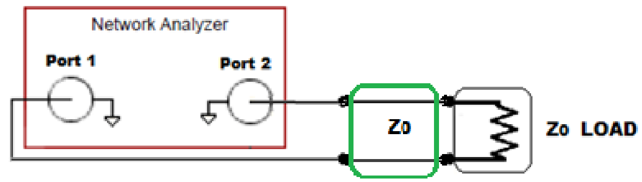
50Ω  100Ω



Use of a 2 Port VNA Test Set to Transform 50 Ohm Un-balanced VNA Test Ports to 100 Ohm Balanced Transmission Lines VNA Configurations for Reflection Measurements

Multiport (2 Port) Based

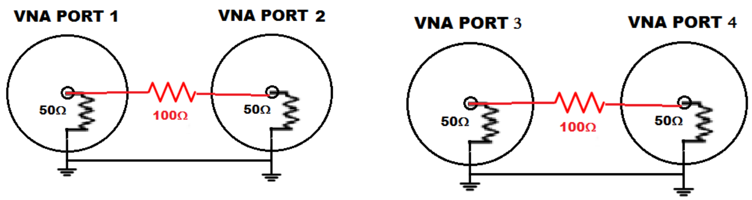


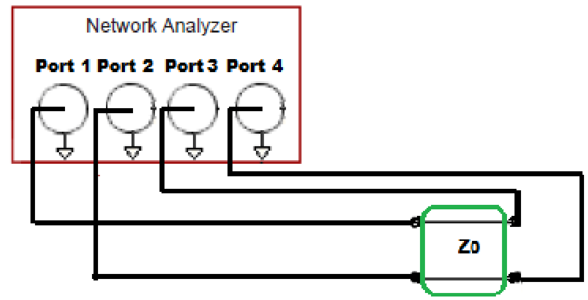


Use of a Multiport VNA Test Set to Transform 50 Ohm Un-balanced VNA Test Ports to 100 Ohm Balanced Transmission Lines

VNA Configurations for Reflection Measurements

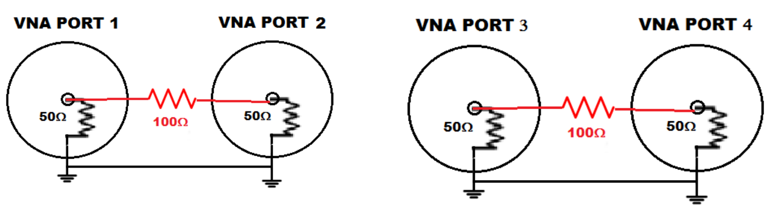
Multiport (4 Port) Based

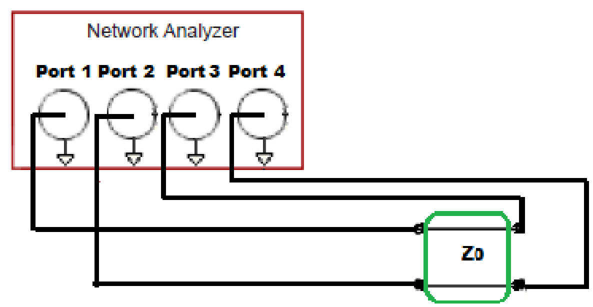




VNA Configurations for Transmission Measurements

Multiport (4 Port) Based

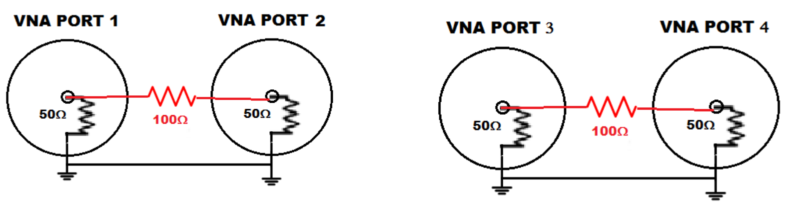


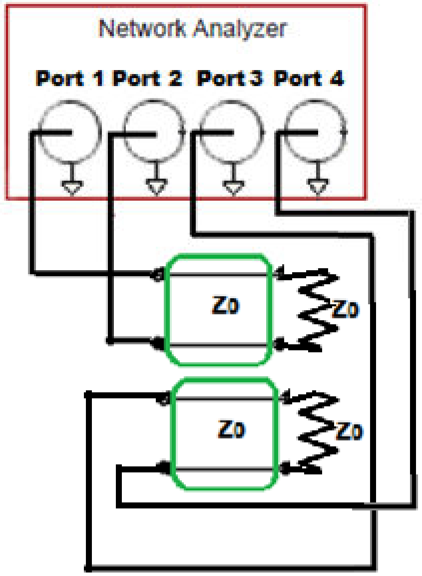


Use of a Multiport VNA Test Set to Transform 50 Ohm Un-balanced VNA Test Ports to 100 Ohm Balanced Transmission Lines

VNA Configurations for NEXT Measurements

Multiport (4 Port) Based

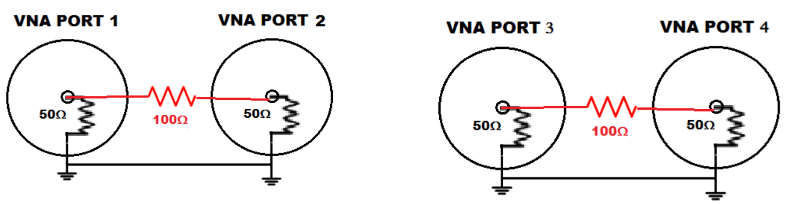


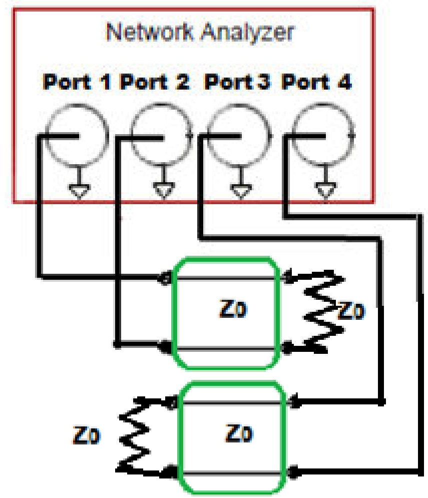


Use of a Multiport VNA Test Set to Transform 50 Ohm Un-balanced VNA Test Ports to 100 Ohm Balanced Transmission Lines

VNA Configurations for FEXT Measurements

Multiport (4 Port) Based





Advantages and Limitations of Each Approach
Balun Based Balanced VNA

Advantages

1. Lowest Cost Balanced VNA Approach
2. True Differential Stimulus
3. Simple Balanced VNA Calibration (SOLT , TRL) With Fewer Connections
4. Traditional Balanced VNA Approach

Limitations

1. Limited Measurement Bandwidth With Transformer Baluns
2. Difficult to Separate Residual Common Mode Component (Longitudinal Balance)
3. Difficult to Measure Mixed Mode and Common Mode S Parameters
4. No Single VNA Vendor Support – "Science Fair Project"
5. VNA Based Reflection and Transmission Time Domain (TDR / TDT) Limited to Band Pass, Impulse Response

Advantages and Limitations of Each Approach
2 Port Based Balanced VNA

Advantages

1. Lowest Cost VNA Configuration
2. Simple Balanced VNA Reflection Calibration (SOLT)
3. Full VNA Reflection Time Domain (TDR) Available

Limitations

1. Reflection Only Balanced VNA Measurements
2. Not True Differential Stimulus (Superposition) With Standard, Lowest Cost 2 Port VNA's

Advantages and Limitations of Each Approach
Multiport 4 Port Based Balanced VNA

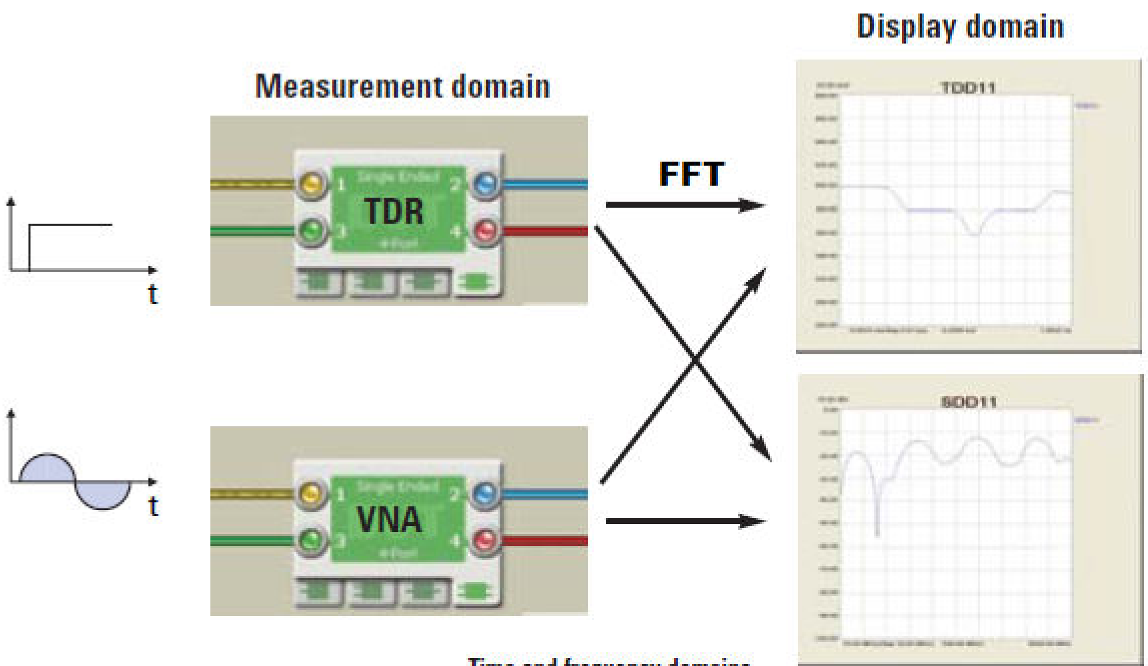
Advantages

1. True Differential Stimulus With Two Coherent Source 4 Port VNA
2. Simple to Measure Differential Mode, Mixed Mode and Common Mode S Parameters
3. Full VNA Reflection and Transmission Time Domain (TDR / TDT) Available

Limitations

1. Not True Differential Stimulus (Superposition) With Standard, Single Source 4 Port VNA's
2. Cumbersome Balanced VNA Calibration (SOLT) With Many Connections
3. Most Expensive Balanced VNA Approach
4. External Test Set Multiport 4 Port Based Balanced VNA Usually Requires External Software for Test Set Control

Frequency Domain Measurement for Balanced Transmission Lines

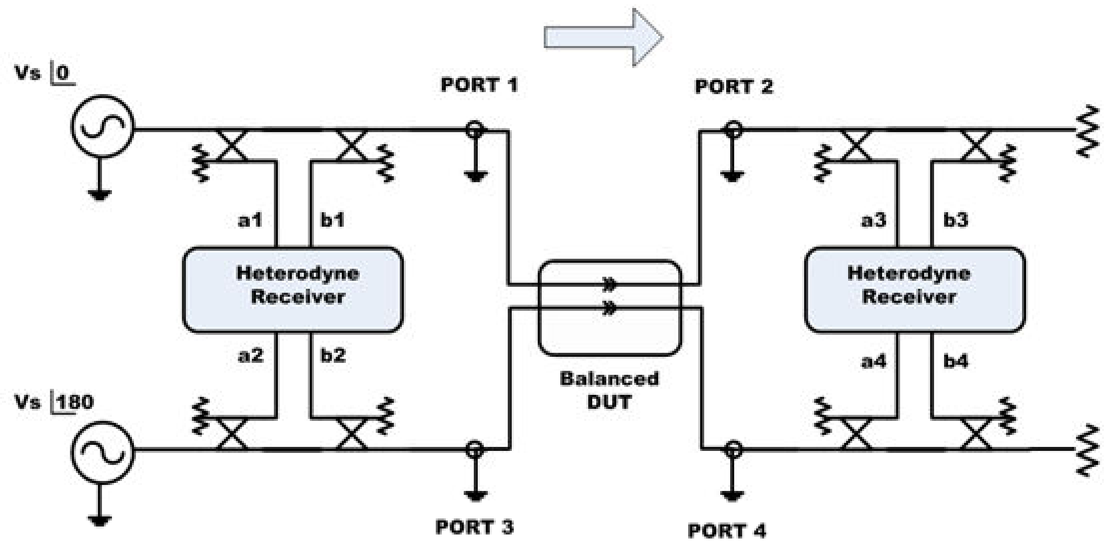


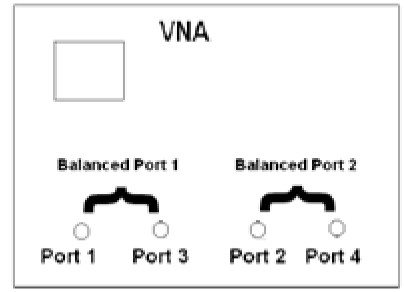
Time and frequency domains.

- S Parameters are Complex Numbers (Real and Imaginary) or (Magnitude and Phase)
- Frequency Domain Measurements are Parameter Versus Frequency
- Frequency Domain Measurements Represent a Weighted Average Over Time
- Time Domain Measurements are Parameter Versus Time
- Time Domain Measurements Represent a Weighted Average Over Frequency

Frequency Domain Measurement with a VNA

Forward Measurements VNA Configuration

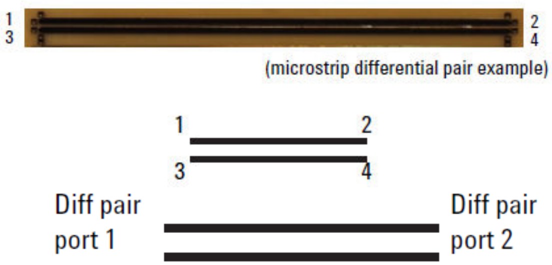




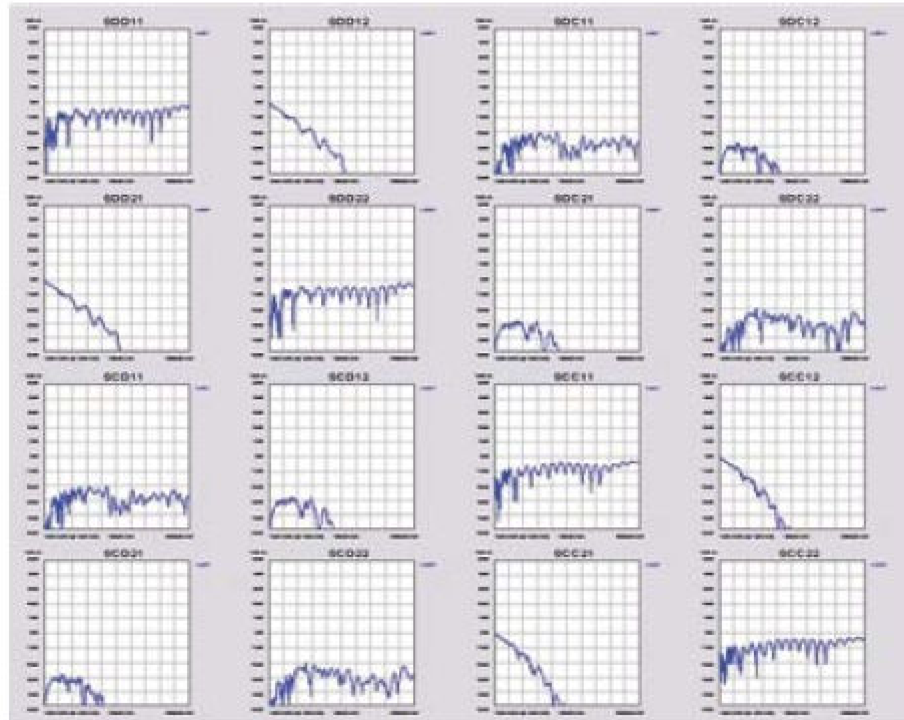
PARAM.	Meas.	Stim. Port*	Meas. Port*
SD1D1	Return loss	P! Diff	P! Diff
SD1D2	Rev Transmission	P2 Diff	P! Diff
SD1C1	Return loss	P1 Com	P! Diff
SD1C2	Rev Transmission	P2 com	P! Diff
SD2D1	Fwd Transmission	P1 Diff	P2 Diff
SD2D2	Return loss	P2 Diff	P2 Diff
SD2C1	Fwd Transmission	P1 Com	P2 Diff
SD2C2	Return loss	P2 Com	P2 Diff
SC1D1	Return loss	P1 Diff	P1 Com
SC1D2	Rev Transmission	P2 Diff	P1 Com
SC1C1	Return loss	P1 Com	P1 Com
SC1C2	Rev Transmission	P2 Com	P1 Com
SC2D1	Fwd Transmission	P1 Diff	P2 Com
SC2D2	Return loss	P2 Diff	P2 Com
SC2C1	Fwd Transmission	P1 Com	P2 Com
SC2C2	Return loss	P2 Com	P2 Com

- Stimulus Sources are Sine Wave Oscillators that are Stepped in Frequency
- All Receiver Channels are Narrowband Tuned Receivers Synchronized to the Stimulus Sources
- S Parameters are Complex Numbers (Real and Imaginary) or (Magnitude and Phase)
- Frequency Domain Measurements are Parameter Versus Frequency
- Frequency Domain Measurements Represent a Weighted Average Over Time

Frequency Domain Measurement with a VNA



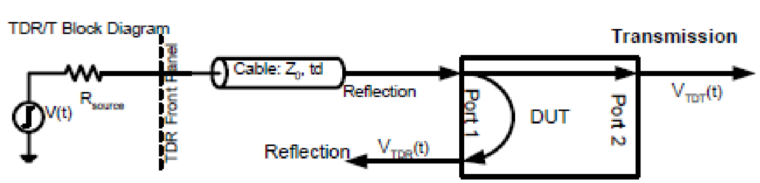
			Stimulus			
			Differential signal		Common signal	
			port 1	port 2	port 1	port 2
Response	Differential signal	port 1	SDD11	SDD12	SDC11	SDC12
		port 2	SDD21	SDD22	SDC21	SDC22
	Common signal	port 1	SCD11	SCD12	SCC11	SCC12
		port 2	SCD21	SCD22	SCC21	SCC22



Mixed Mode S Parameters

- SDD are Differential (Balanced) In and Out
- SCC are Common (Single-Ended) In and Out
- SDC are Differential (Balanced) In and Common (Single-Ended) Out
- SCD are Common (Single-Ended) In and Differential (Balanced) Out

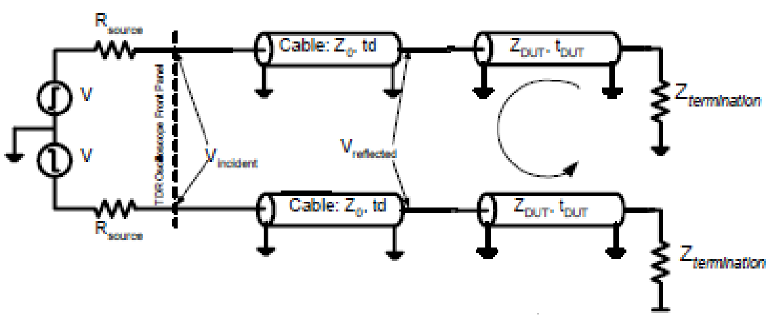
Frequency Domain Measurement with a TDR / TDT (FFT)



Time Domain Reflection and Transmission (TDR and TDT) block diagram. A similar diagram can be drawn for reverse measurements (from port 2 to port 1).

$$TDR: \quad \rho = \frac{V_{reflected}}{V_{incident}} = \frac{Z_{load} - Z_0}{Z_{load} + Z_0} \qquad Z_{DUT} = Z_0 \cdot \frac{1+\rho}{1-\rho}$$

$$VNA: \quad S_{11} = \frac{V_{reflected1}}{V_{incident1}} = \frac{Z_{input(DUT)} - Z_0}{Z_{input(DUT)} + Z_0} \qquad Z_{input(DUT)} = Z_0 \cdot \frac{1+S_{11}}{1-S_{11}}$$



A differential, common mode or mixed mode measurement would require a 4-port measurement setup

Differential stimulus, differential response (differential quadrant)

Common mode stimulus, differential response (mixed mode)

$$\begin{bmatrix} S_{11dd} \leftrightarrow TDR_{11dd} & S_{12dd} \leftrightarrow TDT_{12dd} & S_{11dc} \leftrightarrow TDR_{11dc} & S_{12dc} \leftrightarrow TDT_{12dc} \\ S_{21dd} \leftrightarrow TDT_{21dd} & S_{22dd} \leftrightarrow TDR_{22dd} & S_{21dc} \leftrightarrow TDR_{21dc} & S_{22dc} \leftrightarrow TDR_{22dc} \\ S_{11cd} \leftrightarrow TDR_{11cd} & S_{12cd} \leftrightarrow TDT_{12cd} & S_{11cc} \leftrightarrow TDR_{11cc} & S_{12cc} \leftrightarrow TDT_{12cc} \\ S_{21cd} \leftrightarrow TDT_{21cd} & S_{22cd} \leftrightarrow TDT_{22cd} & S_{21cc} \leftrightarrow TDT_{21cc} & S_{22cc} \leftrightarrow TDR_{dd} \end{bmatrix}$$

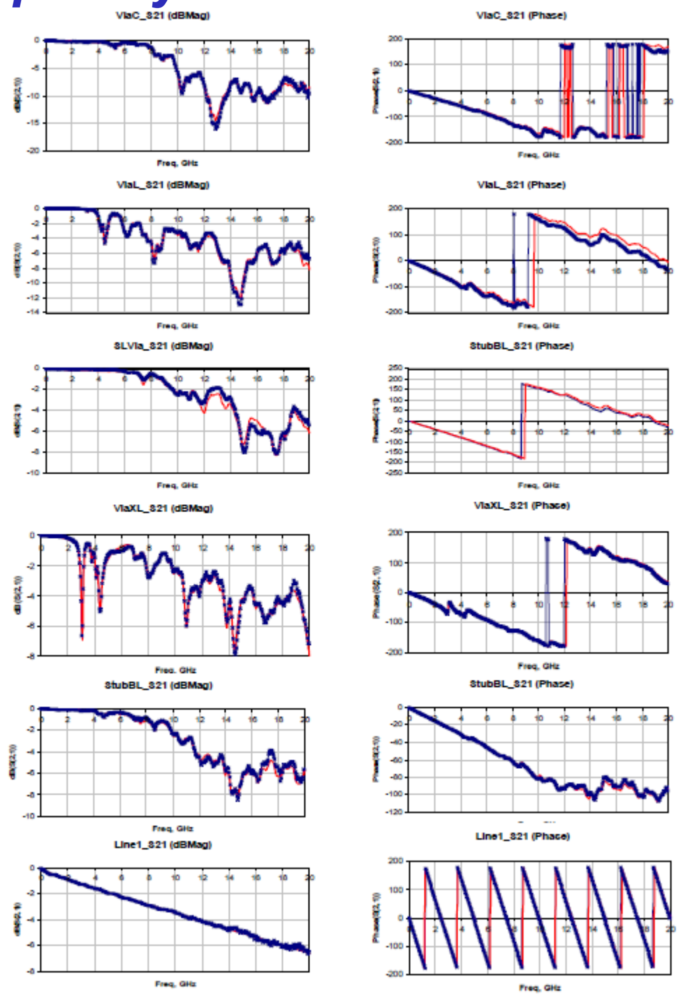
Differential stimulus, common mode response (mixed mode)

Common mode stimulus, common mode response (common mode quadrant)

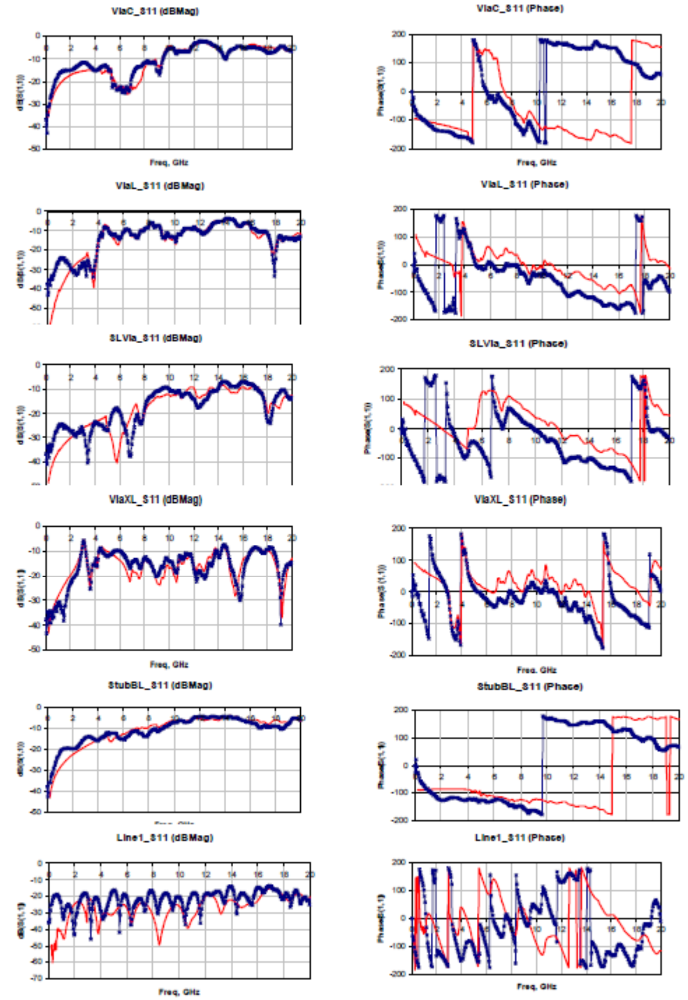
Correspondence between time and frequency domain waveforms

- Measurements Made With Fast Rise Time Voltage Step Generator
- Both Reflection (TDR) and Transmission (TDT) Made in Time Domain
- Step Response Differentiated to Calculate Impulse Response
- Chirp Z Fast Fourier Transform (FFT) Applied to Impulse Response to Calculate Frequency Domain S Parameters

Frequency Domain Measurement Comparison VNA vs TDR / TDT



S21 magnitude and phase comparison for test structures. Red: VNA, Blue: TDR/TDT

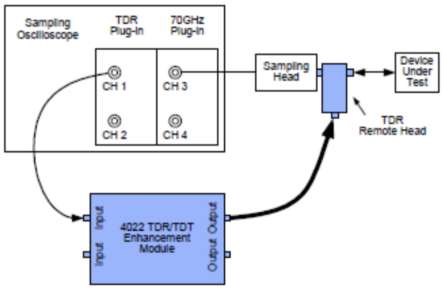


S11 magnitude and phase comparison for test structures. Red: VNA, Blue: TDR/TDT

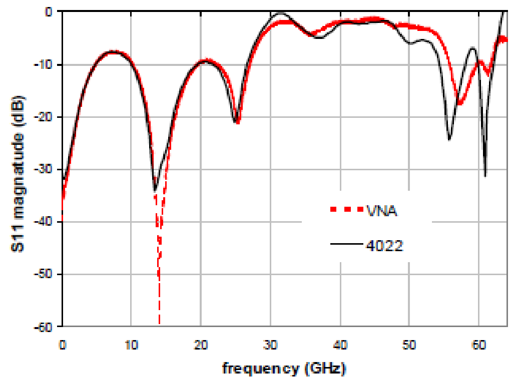
Correlation between VNA and TDR/TDT Extracted S-Parameters up to 20 GHz

Cherry Wakayama, Jeff Loyer
Intel Corporation/ The University of Washington, wakayama@ee.washington.edu
Intel Corporation, jeff.loyer@intel.com

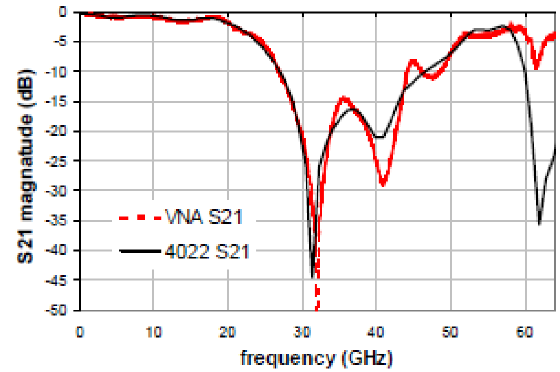
Frequency Domain Measurement Comparison VNA vs TDR / TDT



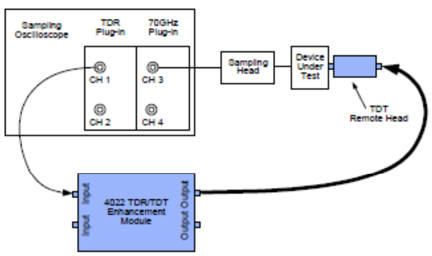
PSPL Model 4022 TDR Test
Configuration Used to Measure S11 Data



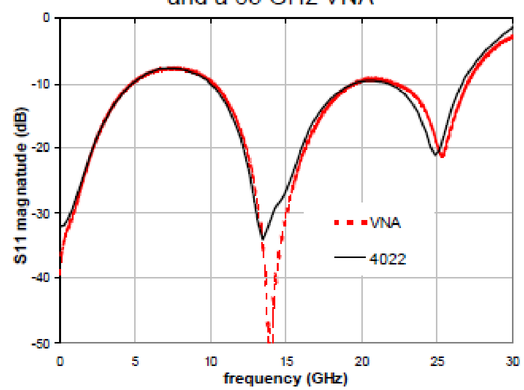
0-64 GHz S11 Plot Measured
with the PSPL Model 4022 TDR System
and a 65 GHz VNA



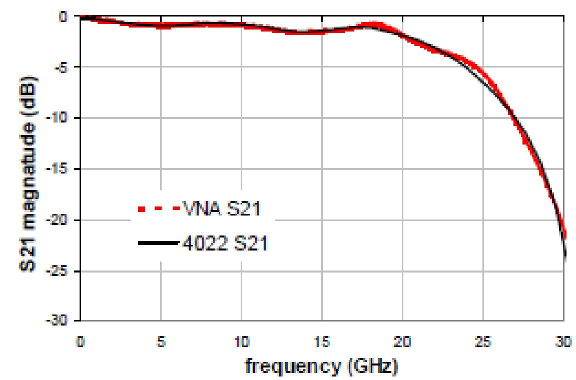
0-64 GHz S21 Plot PSPL TDR
System and 65 GHz VNA Measurements



Model 4022 TDT Test Configuration
Used to Measure S21 Data



0-30 GHz S11 Plot Measured
with the PSPL Model 4022 TDR System
and a 65 GHz VNA



0-30 GHz S21 Plot PSPL TDR
System and 65 GHz VNA Measurements

System	S-parameter bandwidth; dyn. range	TDR/T risetime
65 GHz VNA	65 GHz; >60 dB	14 ps
Model 4022 10 ps TDR	30 GHz; >25 dB	10 ps

Comparison of TDR/T and VNA
Measurement System Capabilities

S-parameter Measurements with the PSPL
Model 4022 High-Speed TDR and TDT System

Kipp Schoen, Picosecond Pulse Labs (PSPL), Boulder, Colorado, USA

Advantages and Limitations of Each Approach
Frequency Domain Measurement with a VNA

Advantages

1. Higher Source Power and Tuned Receiver → High Dynamic Range (> 100 dB)
2. Applies to Both Active and Passive Linear Devices
3. Direct Frequency Domain Measurements → No Post Processing Required
4. Traditional Measurement Approach For Frequency Domain Performance
5. Better Signal to Noise → Measurements More Repeatable, Less Deviation

Limitations

1. All Measurements are Causal → No Insight Into DUT Topology
2. Higher Cost Than Comparable TDR/TDT Oscilloscope
3. Slower Measurement Speed Than Comparable TDR/TDT Oscilloscope
4. More Complex, Less Bandwidth Signal Separation Test Set

Advantages and Limitations of Each Approach
Frequency Domain Measurement with a TDR/TDT

Advantages

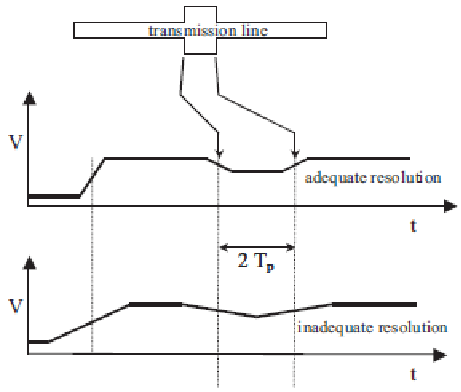
1. Wide Measurement Bandwidth → DC to Max Frequency
2. Lower Cost Stimulus (Step Generator(s))
3. Lower Cost Per Measurement Channel
4. Broadband Receiver → Measurements Made Faster, Single Shot Capture

Limitations

1. Applies to Only Passive Devices
2. Limited Dynamic Range → 40 dB to 50 dB
3. Limited Power in Harmonics of Voltage Step Generator → Less Signal to Noise
4. Direct Time Domain Measurements → FFT Post Processing Required
5. Additional Software Required For Frequency Domain Performance

Time Domain Characteristics and Parameters for Balanced Transmission Lines

TDR Spatial Resolution Requirements



Rise time, ps	Resolution in air, mm	Resolution in FR4, buried run (v_p=0.446*C_{light}), mm
10	1.50	0.67
15	2.25	1.00
20	3.00	1.34
28	4.20	1.87
40	6.00	2.68
150	22.50	10.04

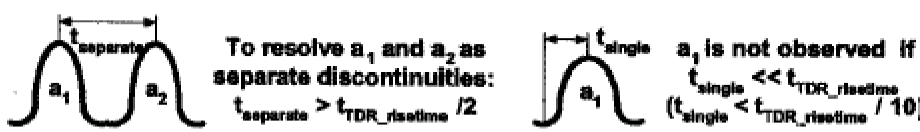
Rise Time Requirements for Serial Standards

Standards	Datarates, Gb/s*	$t_{standard\ rise}$ as a ratio of bit width
1st generation standards	1.125 - 3.125	15%
2nd generation standards	4.25 - 6.5	20%
3rd generation standards	8 - 12	25%

Rise time as percentage of the bit width for three generation of standards.

Faster pulse risetime = better resolution

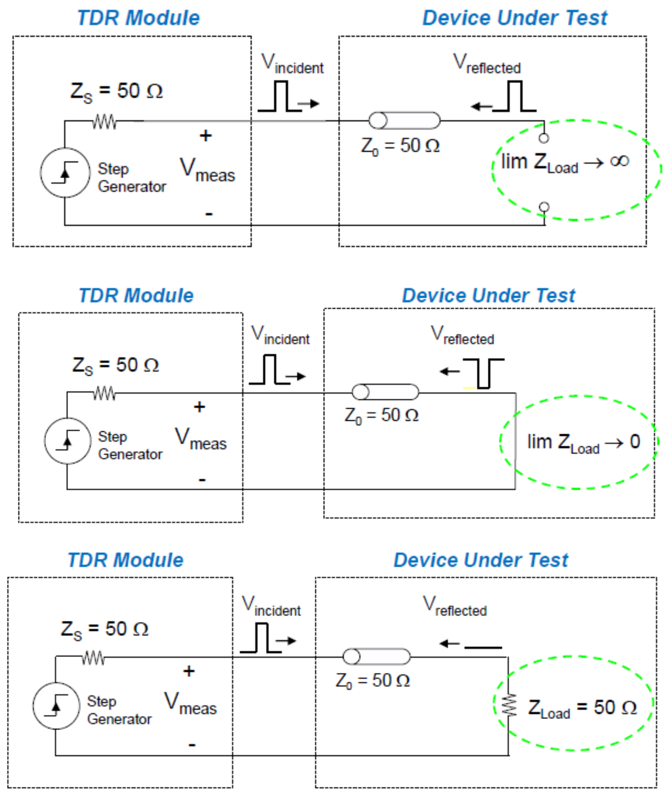
TDR resolution rules of thumb.



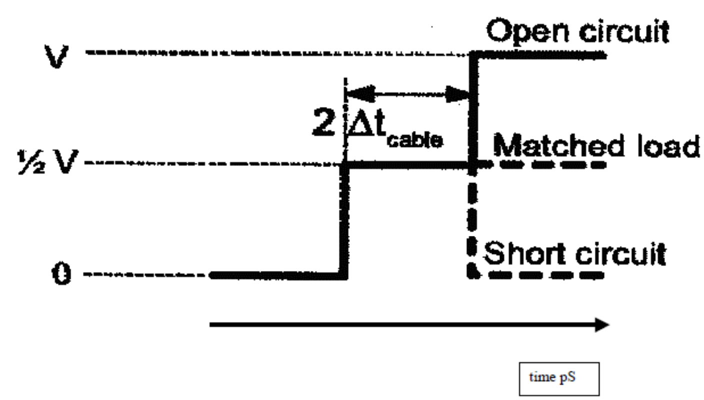
With standard TDR:

($t_{separation}$ > ½ TDR risetime = 17.5pS) (1/10 TDR risetime = 3.5pS)

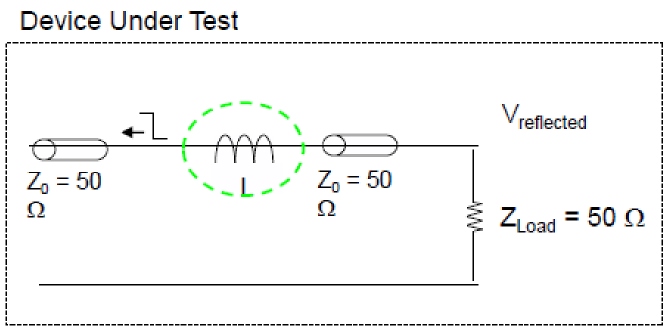
Time Domain Characteristics and Parameters for Balanced Transmission Lines
Impedance

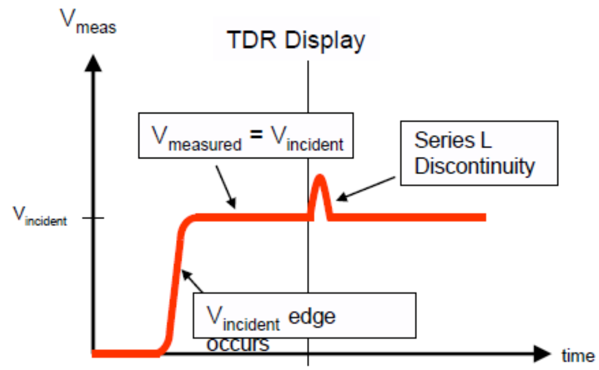


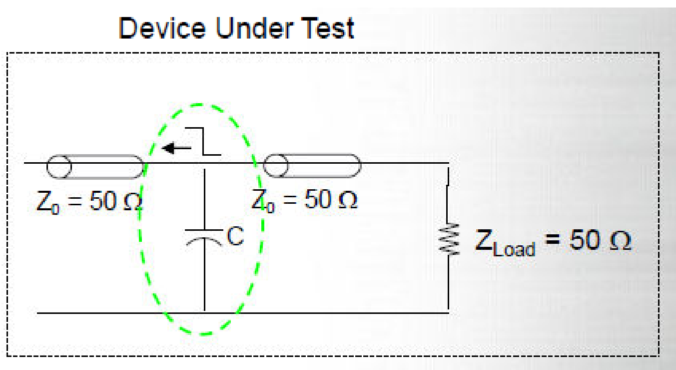
Measurement of impedance from Reflection Coefficient.

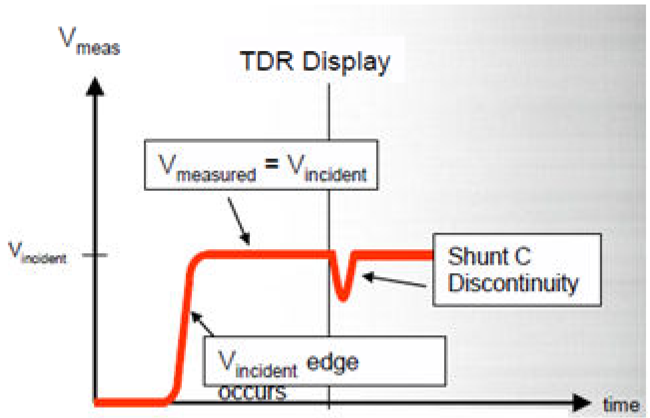


Time Domain Characteristics and Parameters for Balanced Transmission Lines
Fault Type and Location

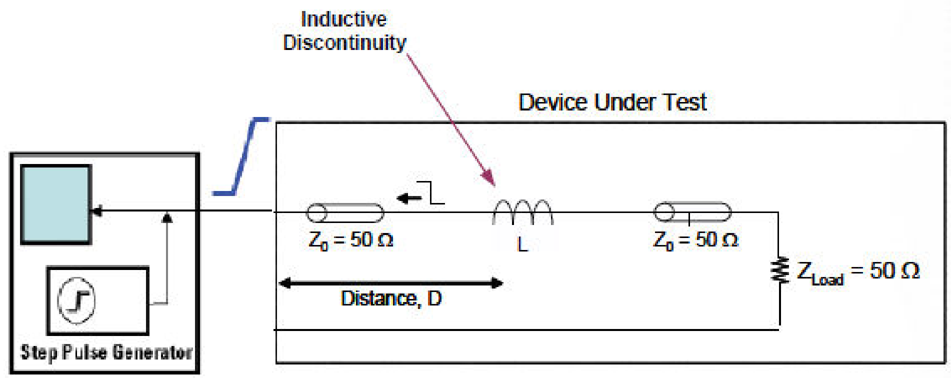


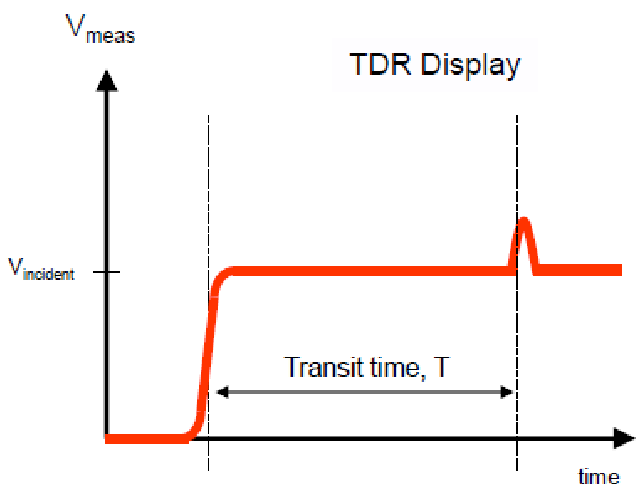






Time Domain Characteristics and Parameters for Balanced Transmission Lines
Determining Fault Location





Physical distance to fault location can be determined by:

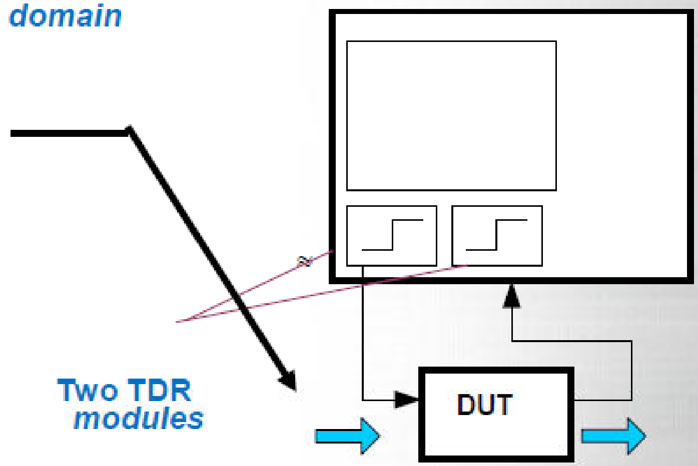
$$D = 0.5*(T)*(v_p)$$

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

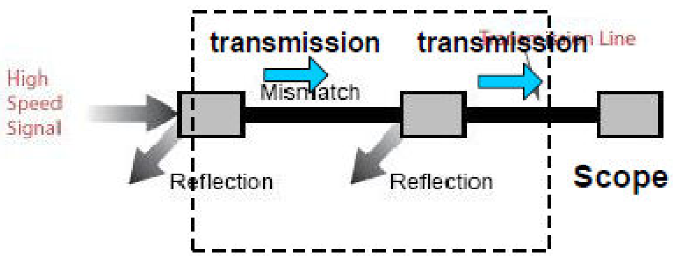
Time Domain Characteristics and Parameters for Balanced Transmission Lines
TDT - Time Domain Transmission, Insertion Loss, Delay, Skew

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

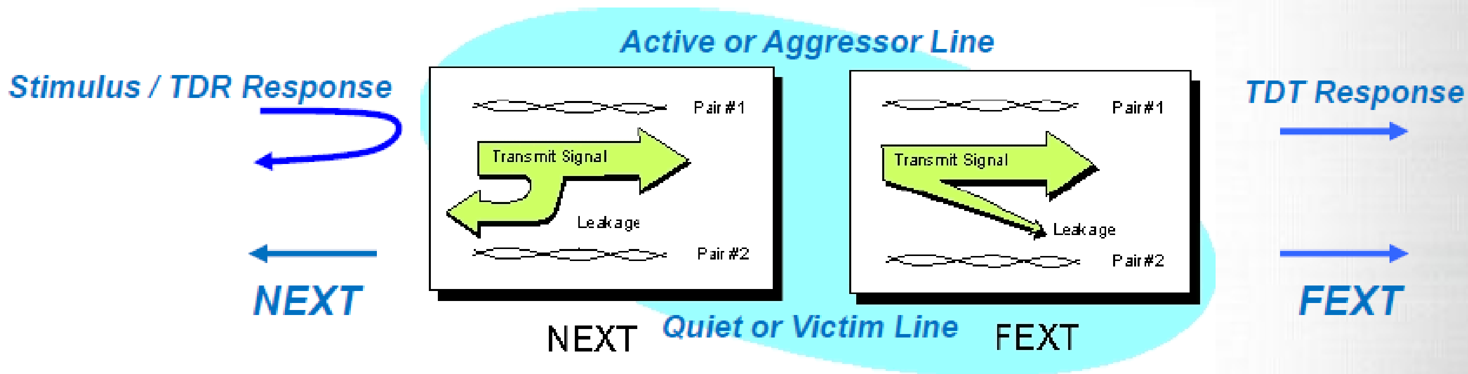
- ✓ *A pulse generator is used to provide an <u>incident step pulse</u> (stimulus)*
- ✓ *<u>Voltage Transmission</u> from the Device Under Test (DUT) is measured by the scope*
- ✓ *TDT $\approx$ Insertion (Transmission) Loss*
- ✓ *Requires <u>two</u> TDR modules – one to generate the step and other to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



TDT measurements set-up



Time Domain Characteristics and Parameters for Balanced Transmission Lines
Near End Crosstalk (NEXT), Far End Crosstalk (FEXT)

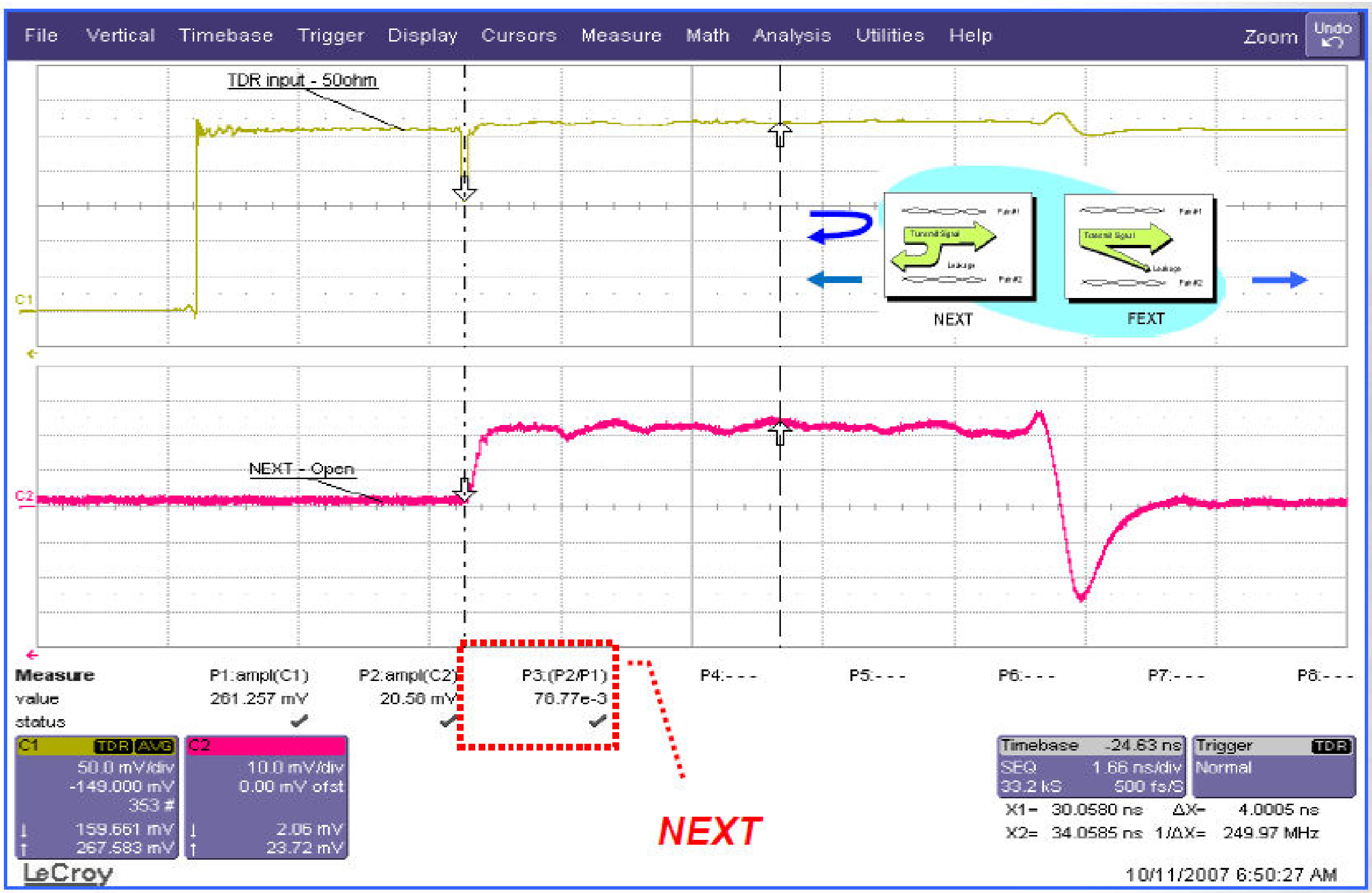


- ❑ *Near-End Cross Talk (NEXT) is the ratio between the voltage measured on the near end on the quiet line and the stimulus.*
- ❑ *Far-End Cross Talk (FEXT) is the ratio between the voltage measured on the far end on the quiet line and the stimulus.*

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

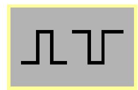
Time Domain Characteristics and Parameters for Balanced Transmission Lines

Near End Crosstalk (NEXT), Quiet Line Open Terminated

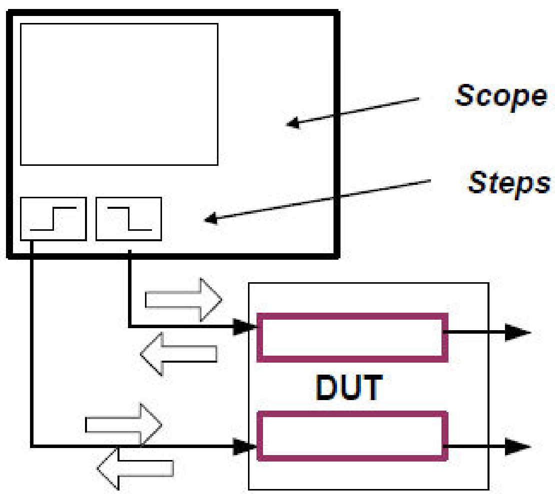


Time Domain Characteristics and Parameters for Balanced Transmission Lines
True Differential TDR / TDT

- ✓ High Speed digital systems are mainly differential



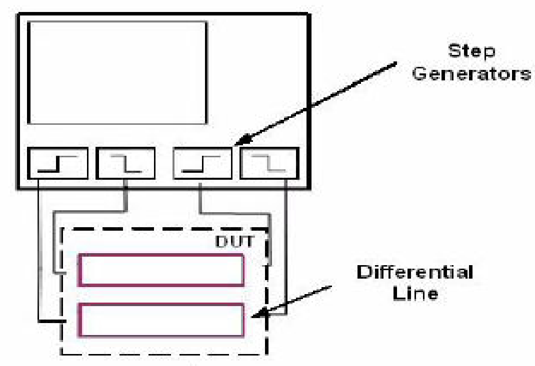
- ✓ TDR requires <u>two</u> TDR modules to provide the differential signal (stimulus), step pulses, positive and negative (automatically changes polarity when selecting differential)



Differential TDR measurements set-up

- ✓ De-skew control aligns the two pulses from each of the two TDR modules.
  - ✓ HW deskew (±50 ps)

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



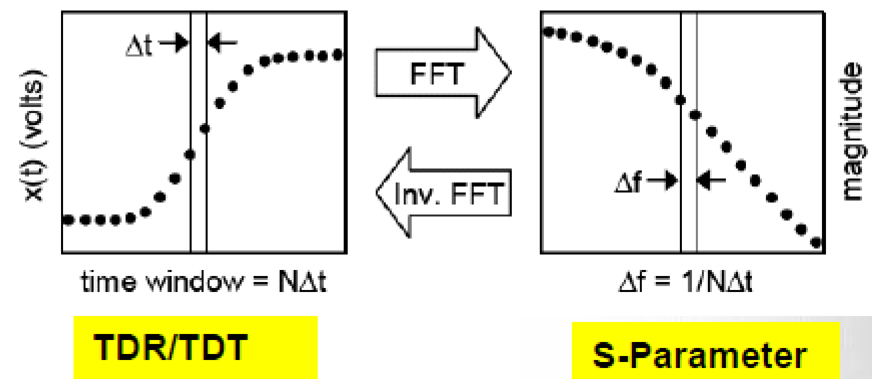
Differential TDT measurements set-up

Time Domain Characteristics and Parameters for Balanced Transmission Lines
TDR/TDT and VNA

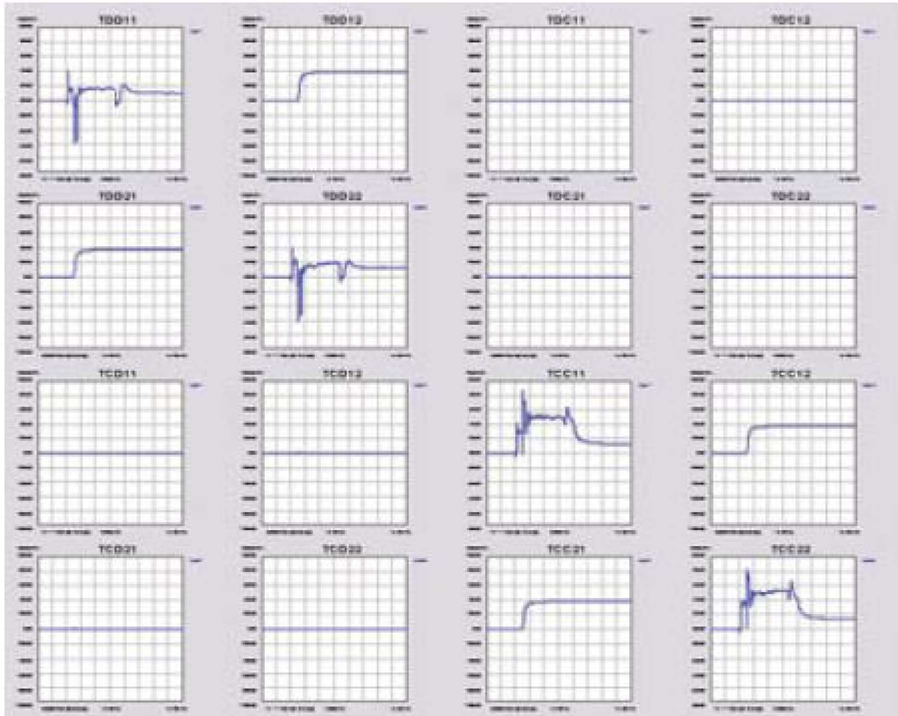
✓ TDR/TDT and S-parameter are describing reflection / transmission respectively in the time domain and in the frequency domain .

✓**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**

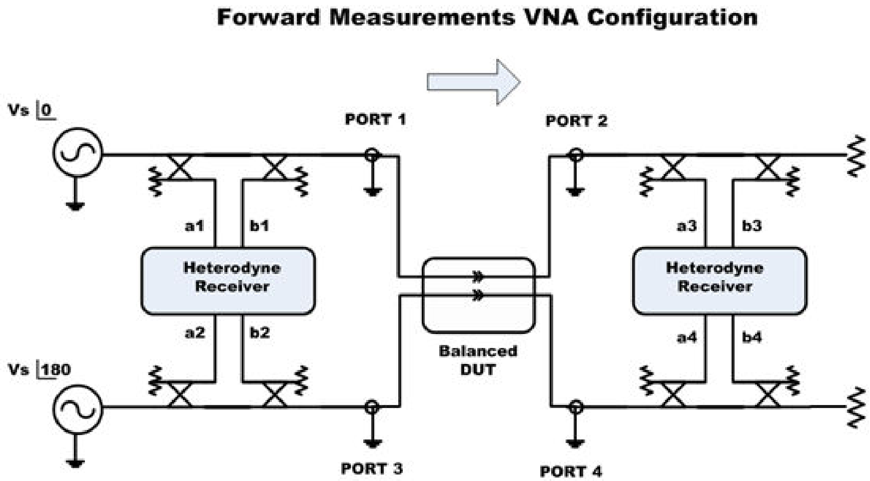


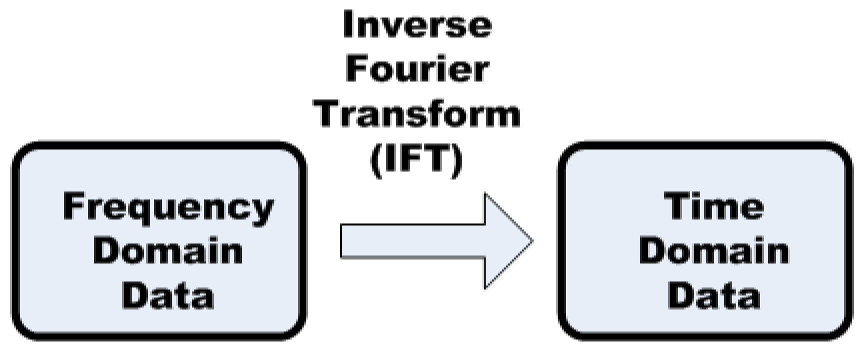
Single Ended, Differential Mode, Common Mode, Mixed Mode, Mode Conversion



- ***Time Domain Measurements are Parameter Versus Time / Distance***
- ***Time Domain Measurements Represent a Weighted Average Over Frequency***

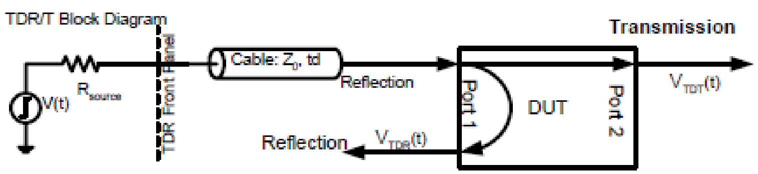
Time Domain Measurement with a VNA (IFT)



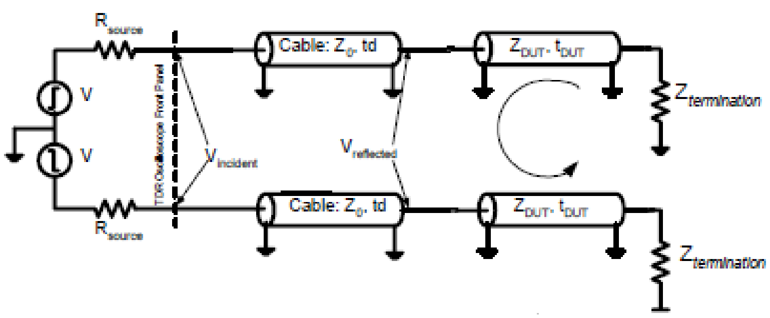


- Measurements Made in Frequency Domain and Converted to Time Domain by Inverse Fourier Transform (IFT)
- Step Response, Impulse Response, and Band Pass Impulse Response
- Step Response and Impulse Response Require Harmonic Related Frequencies
- Time Resolution Related to (1/ Frequency Span)
- Time Range Related to (1/ΔF)
- Windowing Used to Deal With Frequency Truncation Error (Finite Frequency Range)

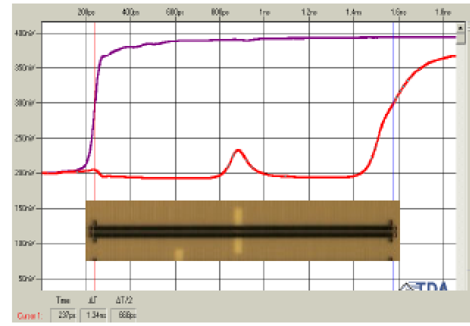
Time Domain Measurement with a TDR / TDT



Time Domain Reflection and Transmission (TDR and TDT) block diagram. A similar diagram can be drawn for reverse measurements (from port 2 to port 1).



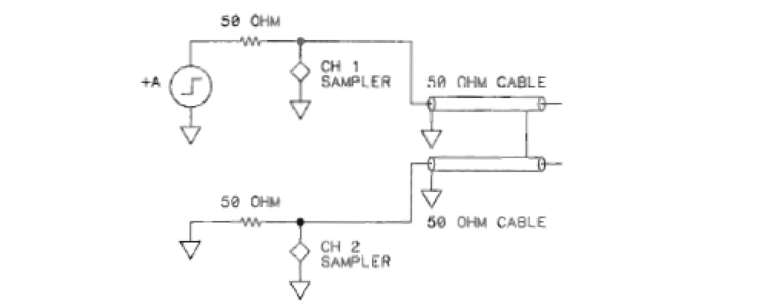
A differential, common mode or mixed mode measurement would require a 4-port measurement setup



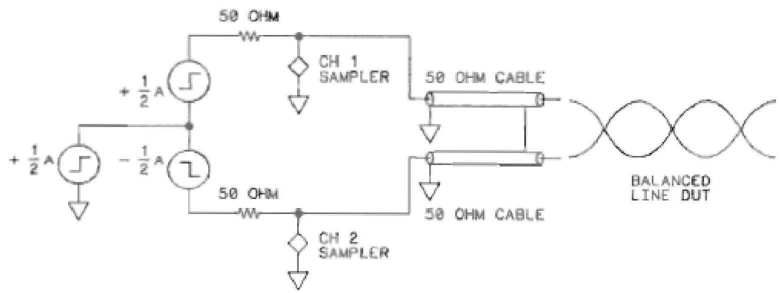
Measured TDR profile of a transmission line with initial via and small gap in the return path.

- Measurements Made With Fast Rise Time Voltage Step Generator
- Both Reflection (TDR) and Transmission (TDT) Made in Time Domain
- Step Response Standard For Time Domain Measurements
- TDT Direct Measurement of Insertion Loss, Crosstalk, and Delay
- TDR Direct Measurement of Reflection Coefficient and Impedance with Location

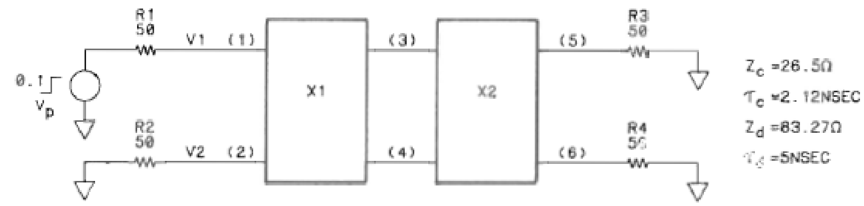
Time Domain Measurement with a TDR / TDT
Differential TDR Using a Single Step Generator



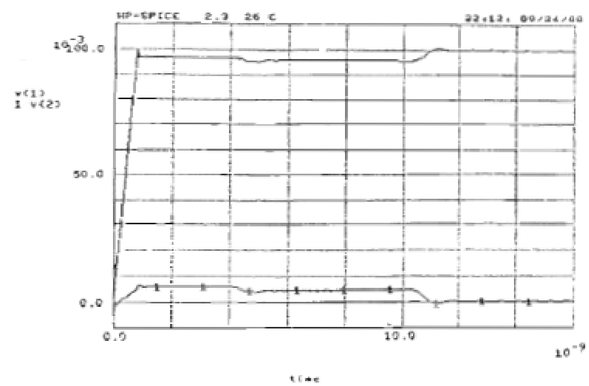
Single ended pulse generator built into Ch 1, and Ch 2 input with no step



Equivalent circuit of TDR step and scope inputs represented by common mode and differential mode step sources.



Configuration for single ended drive, balanced termination



V(1) and V(2) responses, single edged drive, balanced termination

- Requires Launch Into Balanced Transmission Line
- Complement Step Generated in Transmission Line by Reciprocity
- Stimulus From Transmission Line is True Differential

Advantages and Limitations of Each Approach Time Domain Measurement with a VNA (IFT)

Advantages

1. Higher Source Power and Tuned Receiver → Faster Effective Rise Time, Better Time Resolution
2. Both Step and Impulse Response Available
3. Impulse Response of High Pass or Band Pass Devices
4. Time Domain Gating Available
5. DC Response of DUT Not Required (DC Blocks Not a Problem)

Limitations

1. Time Domain Requires Software Post Processing (IFT)
2. Higher Cost Than Comparable TDR/TDT Oscilloscope
3. Slower Measurement Speed Than Comparable TDR/TDT Oscilloscope
4. Windowing Required to Deal With Frequency Truncation Error (Finite Frequency Range)

Advantages and Limitations of Each Approach
Time Domain Measurement with a TDR/TDT

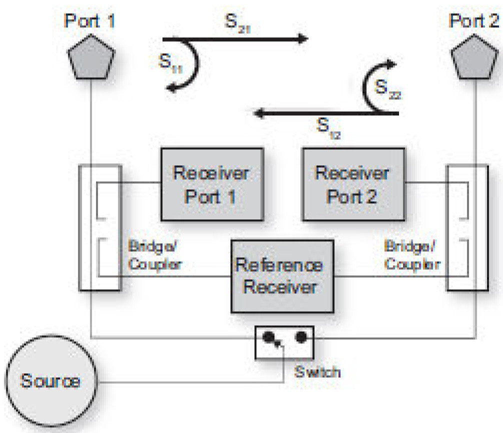
Advantages

1. Direct Time Domain Measurements
2. Direct Time Base Based Delay Measurements
3. Frequency Response of Step Generator Not Band Limited, Windowing Not Required
4. Lower Cost Than Comparable VNA
5. Differential Step Generators With Adjustable Skew

Limitations

1. Step Response Only
2. DC Response of DUT Required (DC Blocks a Problem)
3. Limited Dynamic Range → 40 dB to 50 dB
4. Limited Power in Harmonics of Voltage Step Generator → Slower Rise Time, Less Time Resolution

Techniques Used with MultiPort Vector Network Analyzers (VNA) for Balanced Transmission Line Measurements



Typical 2 Port VNA (3 Receiver)

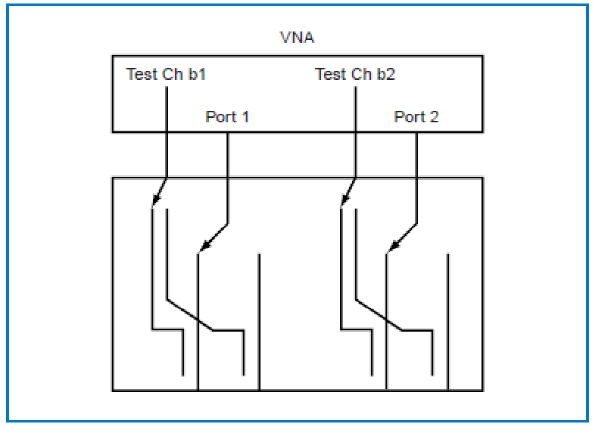
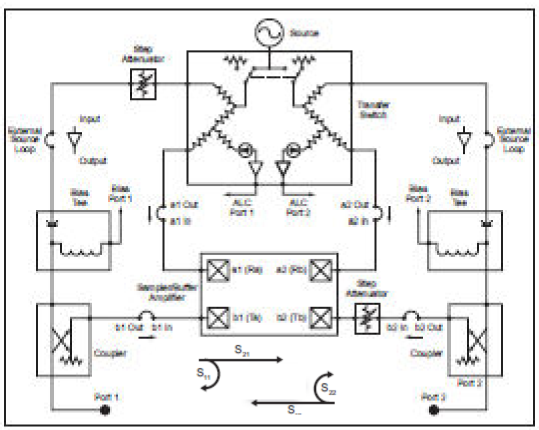


Figure 1. A coupler test set architecture is shown here: the test couplers are on the DUT-side of the multiplexing switches. As N becomes large, this test set becomes quite complex.



Typical 2 Port VNA (4 Receiver)

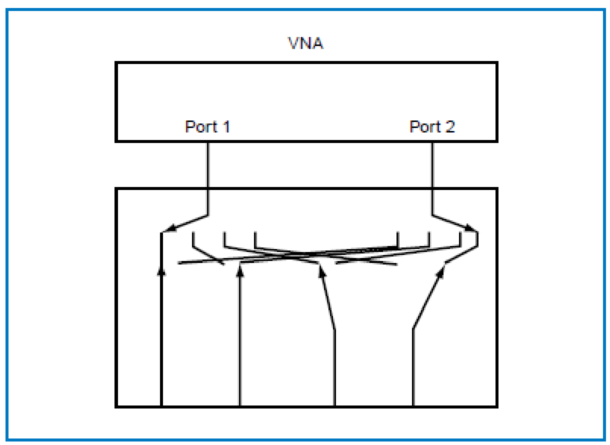
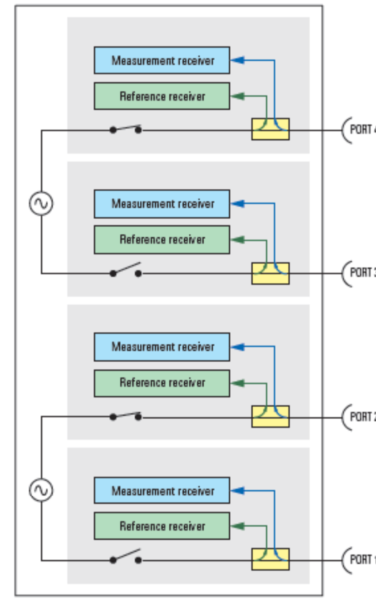
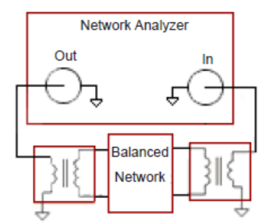


Figure 2. A no-coupler architecture for the 4x2 problem is shown here. In this case, any VNA port can be connected to any test port although this is not needed for most measurements. This test set can be simpler for large N but does have limitations.

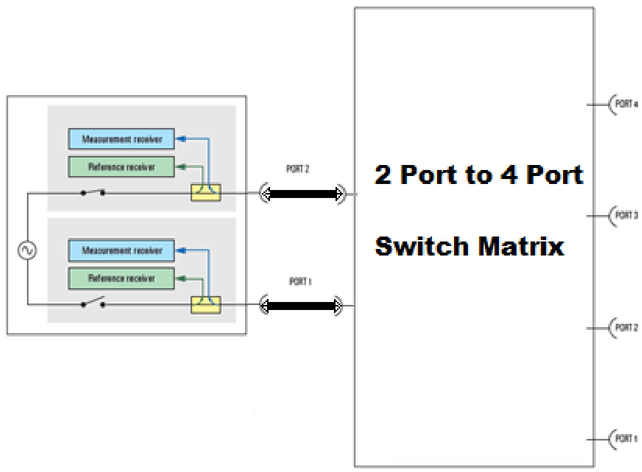


Typical 4 Port VNA (2 Source)



Typical Balun Based VNA

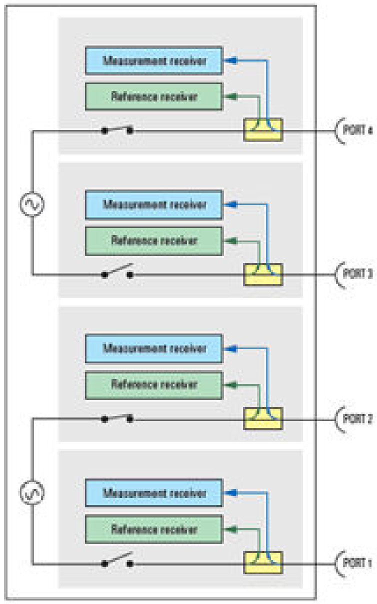
Use of Mathematical Superposition with a Single Source MultiPort VNA for Balanced Transmission Line Measurements



- Passive Balanced / Differential DUT
    - Transmission Lines
    - PCB
    - Lumped Components
    - Passive Filters
    - UTP, STP, Quad Cables
    - Connectors / Interfaces
- Linear Active Balanced / Differential DUT
    - Linear Amplifiers, Differential Amplifiers
    - Linear Active Filters
    - Input / Output Match ADC / DAC

- Standard Single Source VNA Used With Switch Matrix
- Single Ended S Parameters Measured for All Path Combinations
- Differential and Mixed Mode Parameters Calculated by Superposition
- Basic Assumption That DUT Is Linear
- If Interconnect From 4 Port Test Set to DUT Uses Balanced Transmission Lines, True Differential Stimulus Generated By Reciprocity

Use of Dual Differential Sources MultiPort VNA for Balanced Transmission Line Measurements



- Passive Balanced / Differential DUT
  - Transmission Lines
  - PCB
  - Lumped Components
  - Passive Filters
  - UTP, STP, Quad Cables
  - Connectors / Interfaces
- Linear Active Balanced / Differential DUT
  - Linear Amplifiers, Differential Amplifiers
  - Linear Active Filters
  - Input / Output Match ADC / DAC
- Non Linear Active Balanced / Differential DUT
  - Devices in Compression / Saturation
  - Log Amplifiers

- Dual Source VNA Used
- Sources Are Synchronous and 180 Degree Phase Difference
- Common, Differential and Mixed Mode Parameters Measured Directly
- DUT Can Be Linear or Nonlinear
- True Differential Stimulus
- Balun Based VNA True Differential for Differential Mode Parameters

Advantages and Limitations of Each Approach
Mathematical Superposition with a Single Source MultiPort VNA

Advantages

1. Lower VNA System Cost
2. If Interconnect From 4 Port Test Set to DUT Uses Balanced Transmission Lines, True Differential Stimulus Generated By Reciprocity
3. Single Ended 2 Port VNA Can Be Upgraded to 4 Port Balanced VNA By Adding Test Set
4. Valid Balanced / Differential Measurements For All Linear DUT's

Limitations

1. Requires Software For Mathematical Superposition Calculation
2. Stimulus Not True Differential * → May Not Be Valid For Non Linear DUT's
3. Switch Matrix Repeatability Can Degrade Systematic Error Correction Resulting in Higher Residual Errors (Ripple) in Corrected Measurements

Advantages and Limitations of Each Approach
Dual Differential Sources MultiPort VNA

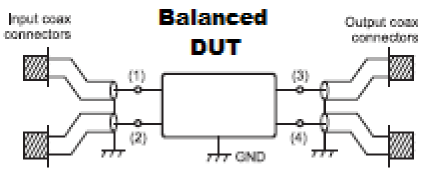
Advantages

1. True Differential Stimulus
2. Valid Balanced / Differential Measurements For All Linear and Non Linear DUT's
3. Better Test Set Repeatability → Lower Residual Errors (Ripple) in Corrected Measurements

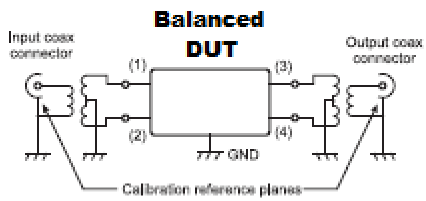
Limitations

1. Higher VNA System Cost
2. 180 Degree Phase Relationship Difficult to Maintain From VNA to DUT → Skew Error → Problematic For Non Linear DUT's

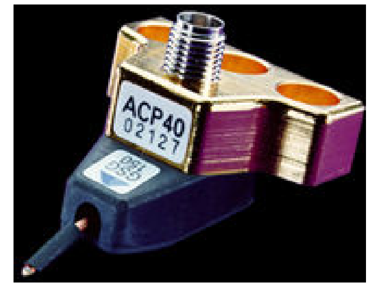
Fixture and Launch Considerations in Connecting to Balanced Structures

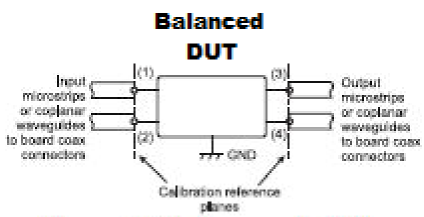


Four-port test jig using short, equal length fixtures.

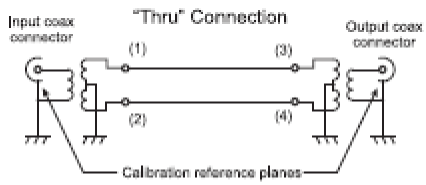


Measurement set-up using input/output baluns

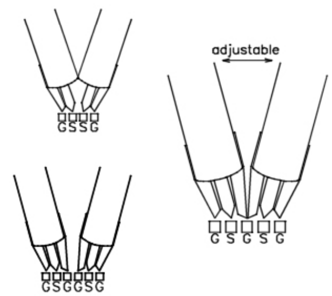


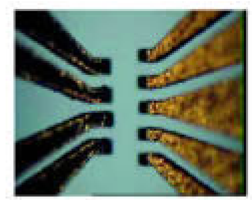


Four-port high-frequency test fixture.

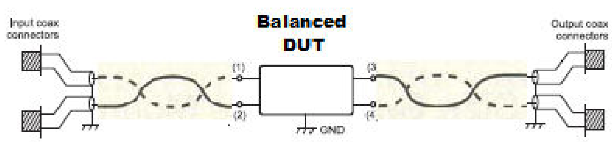


Baluns response calibration





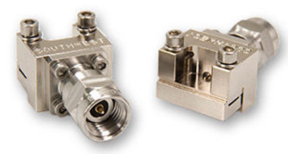
ACP-GSSG (left) vs. ACP-GSGSG (right)

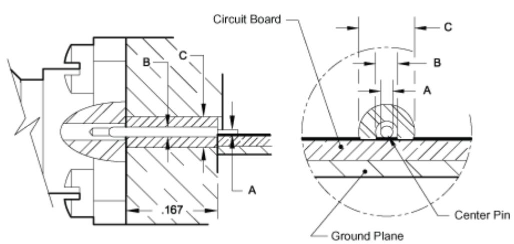


Coax to UTP Transition

Fixture and Launch Considerations in Connecting to Balanced Structures

End Launch Connectors





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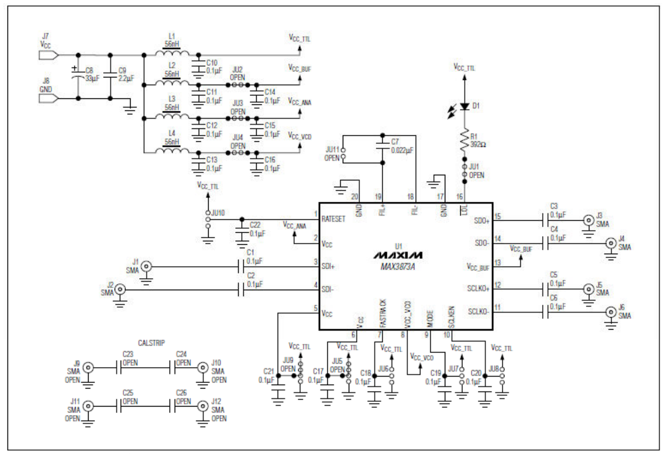
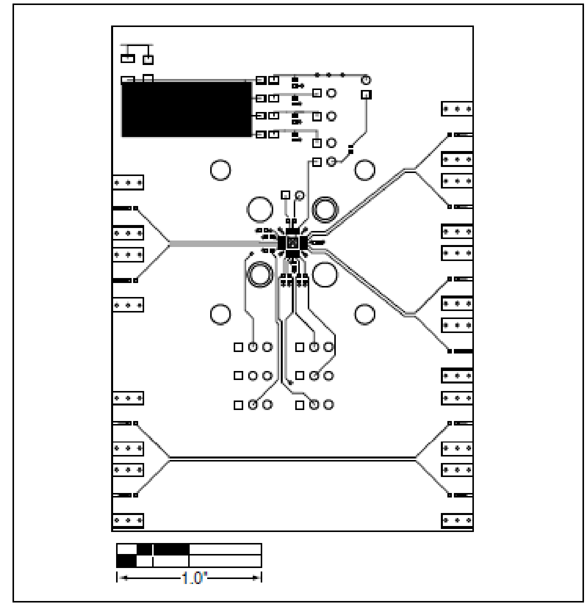


MAX3873 EV Kit Schematic



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