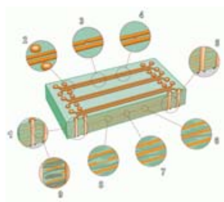
Agilent Technologies

TDR, S-Parameters & Differential Measurements



Agenda

Introduction

TDR theory of operation

Real Example: Samtec Golden Standard Board

- Single Ended Impedance
- Coupling Effects
- Odd & Even Modes
- Differential Impedance

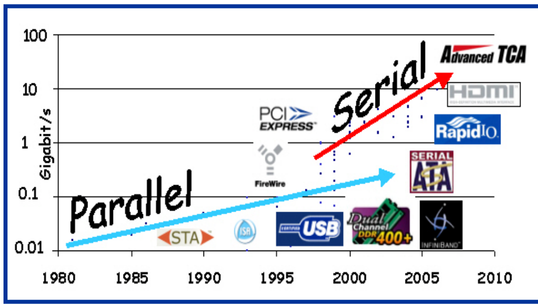
Relating TDR/TDT & S-Parameters

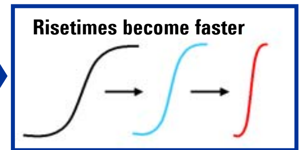
- TDR – more than reflections
- 4-Port Single Ended vs 2-Port Mixed Mode (Differential)

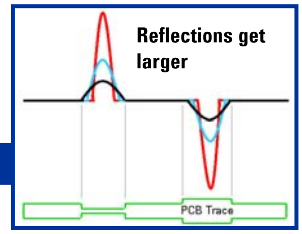
Important Factors in DTDR Accuracy

Signal Integrity Challenge

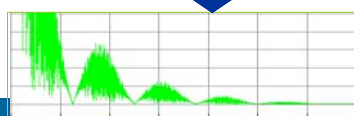
Data Rates Increase >1Gbps





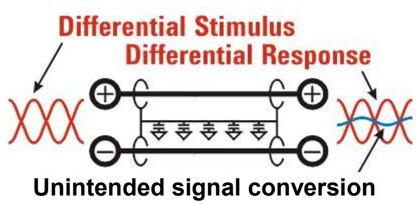


Frequency Domain Data is Now Required



Trend to Differential Topologies

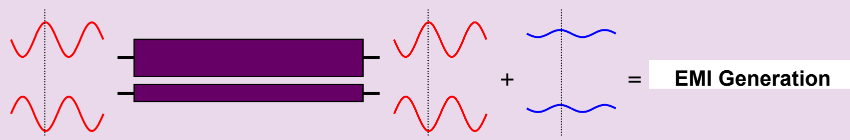
- **Ideal differential devices**
  - Low voltage requirements
  - Noise and EMI immunity
  - Virtual grounding
- **Non-ideal devices are not symmetric**
  - Can be identified by signal-conversions
    - Differential → Common
    - Common → Differential
- **Differential signal integrity design tools are needed**



What About Non-Ideal Devices?

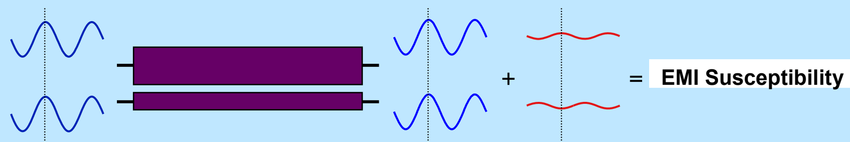
Undesirable signal conversions cause emission or susceptibility problems

- **Differential-stimulus to common-response conversion**



Imperfectly matched lines mean the electromagnetic fields of the signals are not as well confined as they should be – giving rise to generation of interference to neighboring circuits.

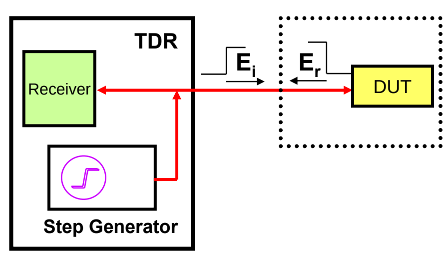
- **Common-stimulus to differential-response conversion**



Imperfectly matched lines mean that interfering signals do not cancel out completely when subtraction occurs at the receiver. Measured by stimulating common-signal to simulate interference.

Theory of Operation - TDR

Impedance



Time Domain Reflectometer (TDR)

Impedance Mismatch Terms

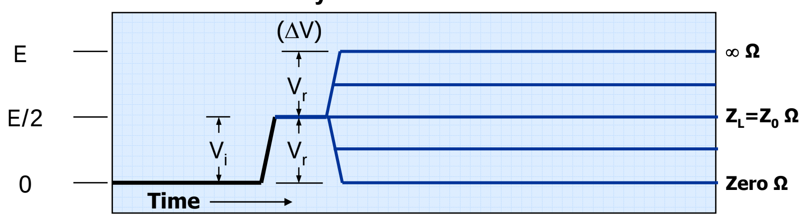
$$Z_L = Z_0 \frac{1+\rho}{1-\rho}$$

Impedance Calculated from Source Impedance and Reflection Coefficient.

$$\rho = \frac{V_r}{V_i}$$

Reflection Coefficient, rho: How much was reflected?

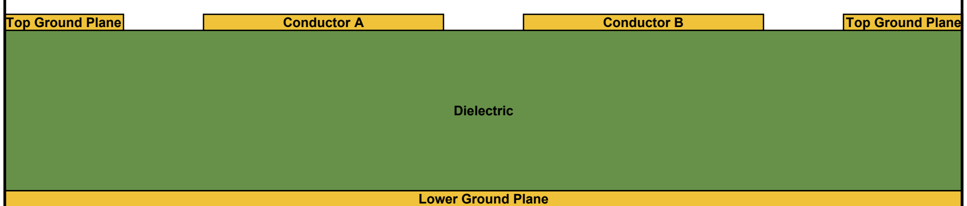
What is the value of Z_{load}?
The DCA automatically calculates this for us.



The Samtec Golden Standard Reference Board

Details on www.samtec.com

Samtec Board Cross Section



Basic Microstrip Example

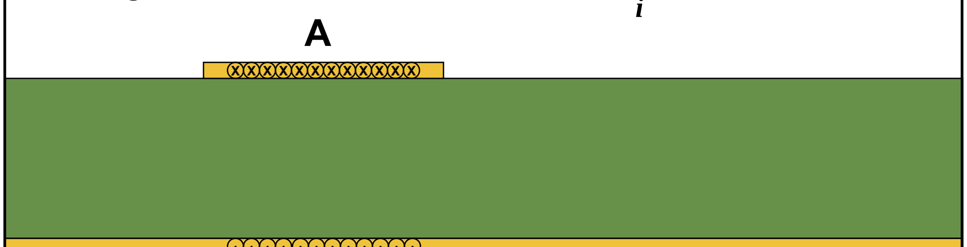
⊗ = Current into page
⊙ = Current out of page

•As Positive Voltage Step is launched into conductor, positive charge is added to the conductor creating a current.

•Impedance is defined by the geometry and material properties – *independent of the voltage applied*.

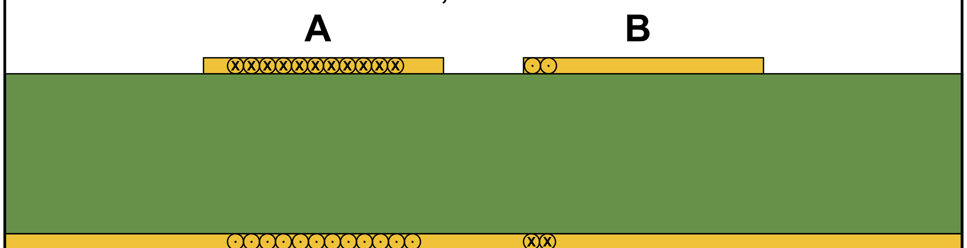
•Wider conductor or thinner dielectric increases capacitance, decreases impedance $Z \propto \frac{1}{C}$

•If Voltage is doubled, current is doubled, $Z = \frac{v}{i}$



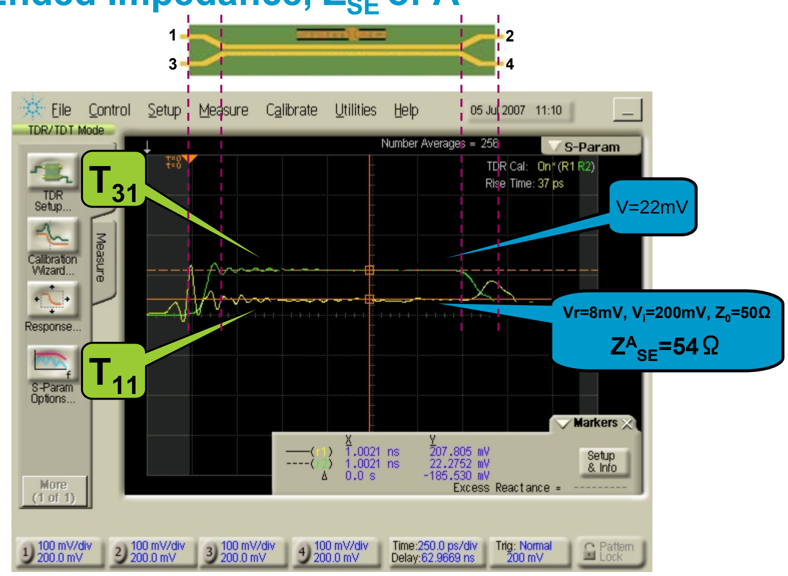
Coupling Effect on Single Ended Impedance

- Adding other nearby conductors causes field lines to couple to the other conductor instead of the return path
- Capacitance to ground is reduced slightly
- Single Ended Impedance of primary conductor is increased slightly
- Induced Voltage & Currents on adjacent conductor create Near and Far End Crosstalk, NEXT/FEXT



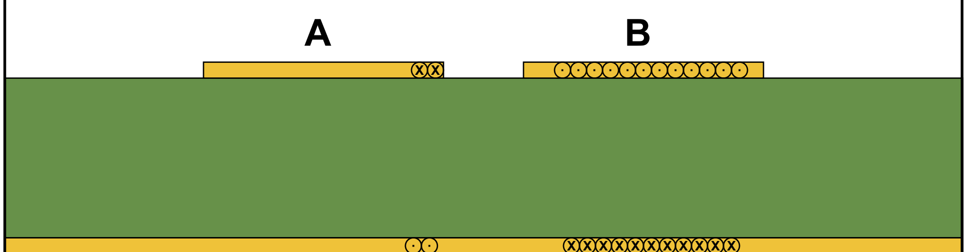
Single Ended Impedance, Z_{SE} of A

- Stimulus on Port 1 only



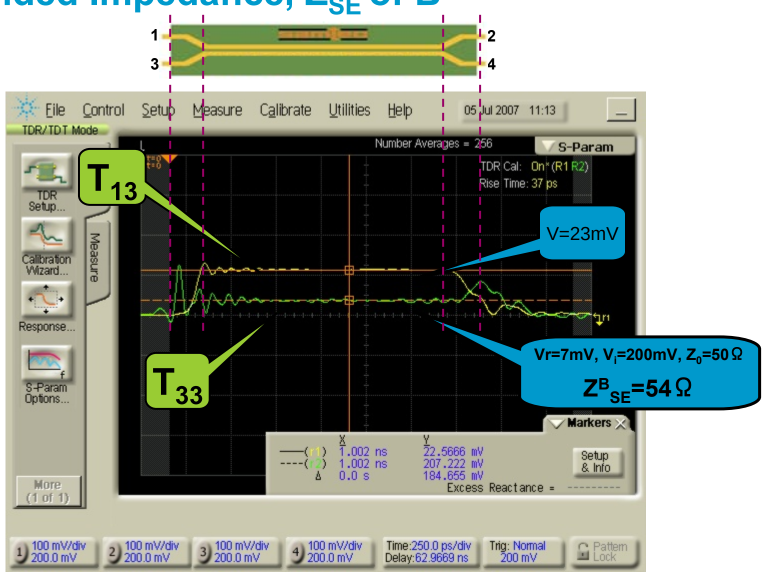
Single Ended Impedance of B

- Exactly same as A
- Can be measured with either positive or negative voltage step at various amplitudes (linear)

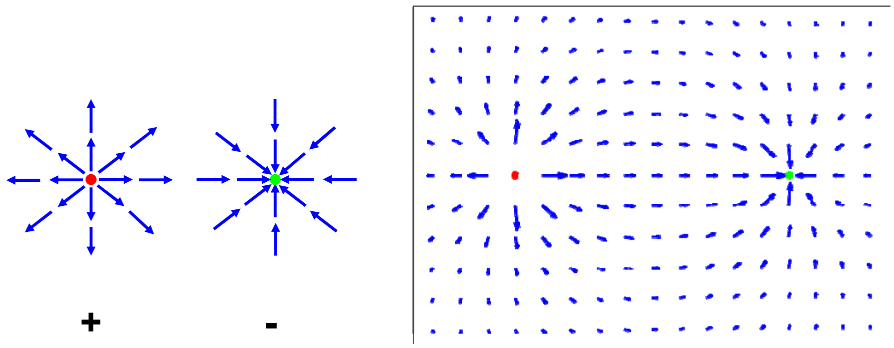


Single Ended Impedance, Z_{SE} of B

- Stimulus on Port 3 only



Vector Addition of Field Lines



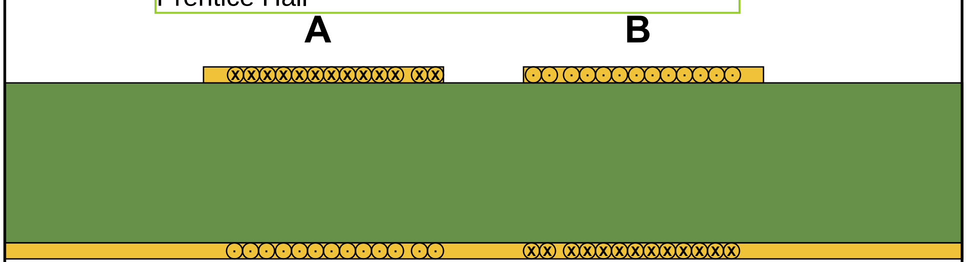
Simultaneous Stimulation

- **Since the voltages/currents add/cancel, results can be calculated from independent measurements**

"The amount of voltage that might couple onto a quiet net from an active net is completely independent of the voltage that might already be present on the quiet net"

Dr. Eric Bogatin – Signal Integrity Simplified

Prentice Hall



Differential Circuit Terminology

•Odd Mode Impedance
- Impedance of a single line, while the pair is driven in the odd mode (only differential signal, no common signal).

•Even Mode Impedance
- Impedance of a single line, while the pair is driven in the even mode (only common signal, no differential).

•Differential Impedance
- Impedance the differential part of a signal will see. (Sum of the Odd Mode Impedances)

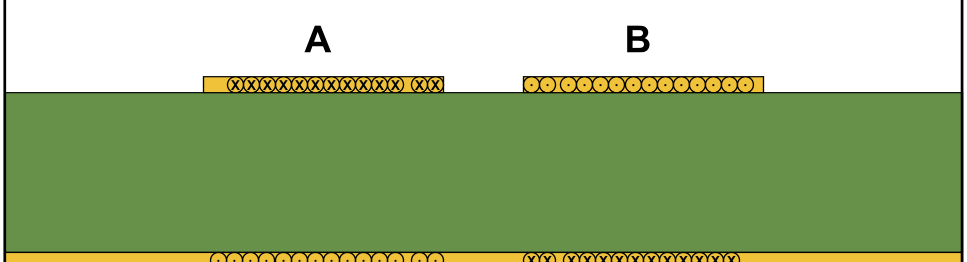
•Common Impedance
- Impedance the common part of a signal will see. (Sum of Even Mode Impedances/4)

Odd Mode Impedance

•Defined as Impedance of a single line when voltage on A is opposite polarity of voltage on B

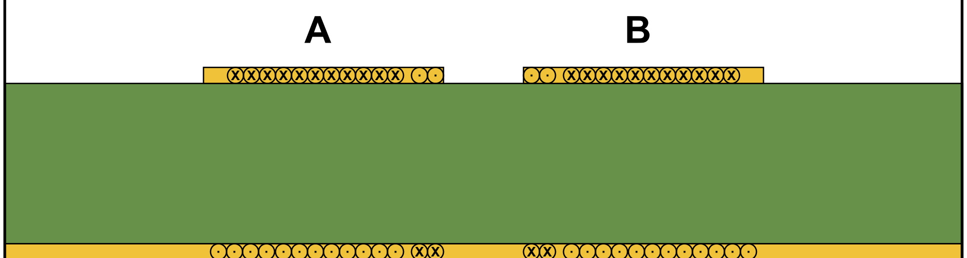
•Can be measured either by stimulating both lines simultaneously OR combining currents/voltages from independent measurements

•Z_{odd} is less than Z_{SE} due to induced currents combining (more current = less impedance)

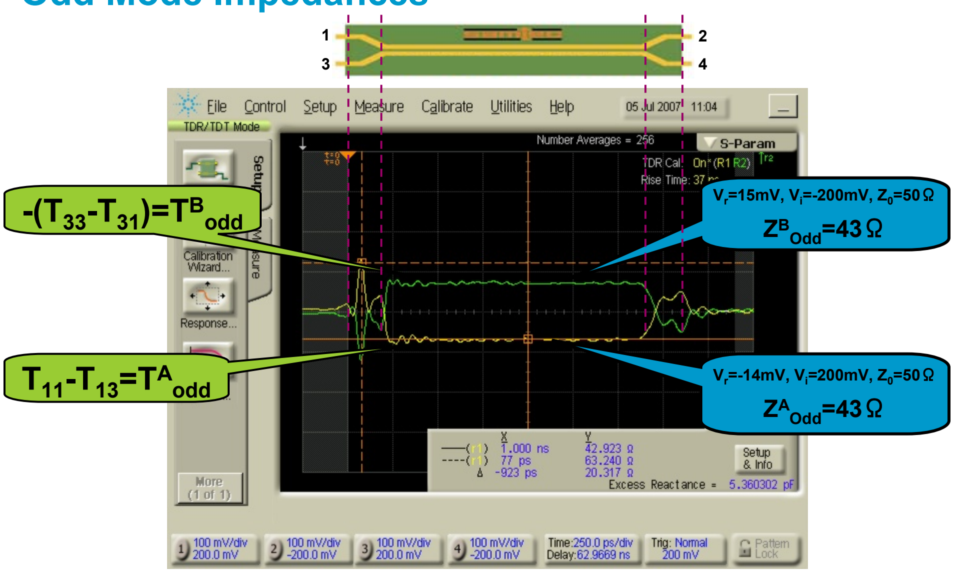


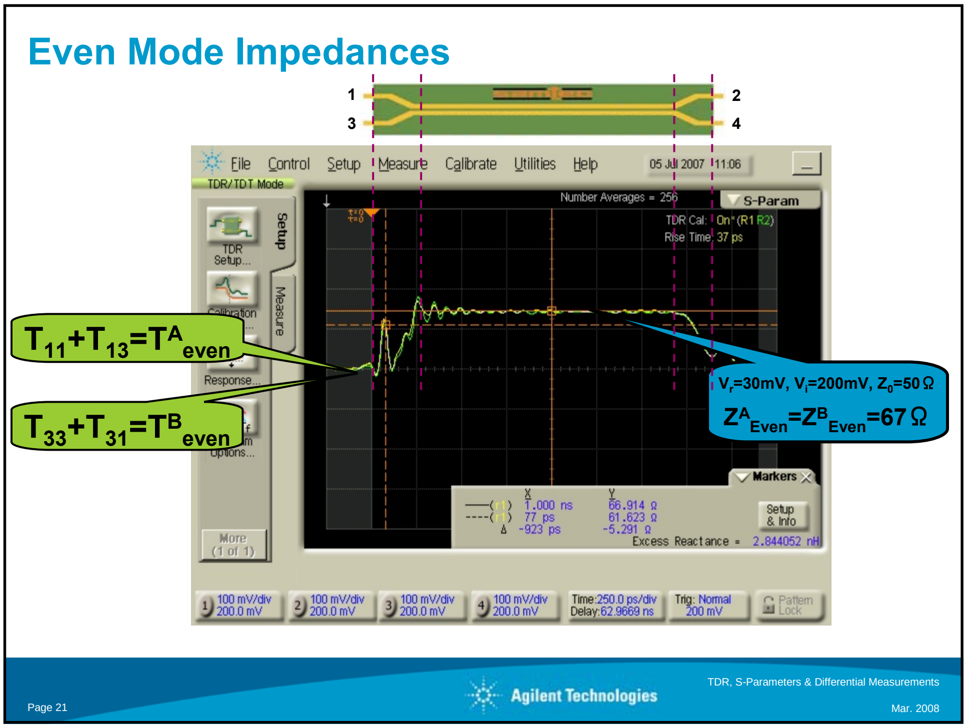
Even Mode Impedance

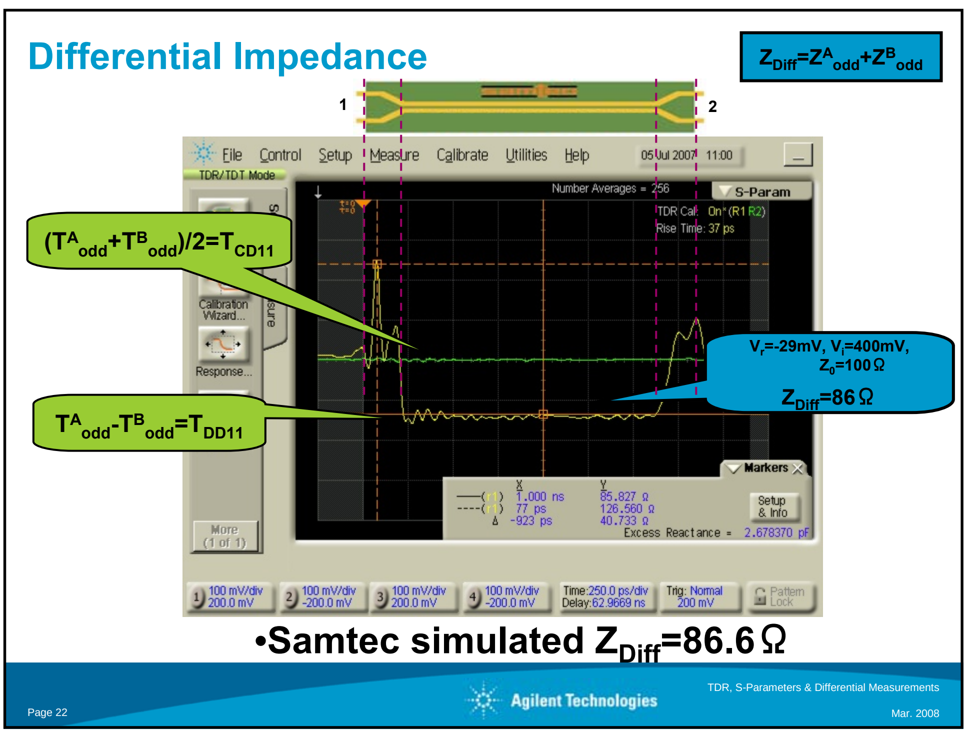
- Defined as Impedance of a single line when voltage on A is identical to voltage on B
- Can be measured either by stimulating both lines simultaneously OR combining currents/voltages from independent measurements
- Z_{even} is more than Z_{SE} since induced currents oppose each other (less current = more impedance)



Odd Mode Impedances




Even Mode Impedances
1
3
2
4
T11+T13=TAeven
T33+T31=TBeven
Vr=30mV, Vi=200mV, Z0=50 Ω
ZAEven=ZBEven=67 Ω
Number Averages = 256
S-Param
TDR Cal: On* (R1 R2)
Rise Time: 37 ps
Markers
1.000 ns
77 ps
-923 ps
66.914 Ω
61.623 Ω
-5.291 Ω
Excess Reactance = 2.844052 nH
Page 21
Agilent Technologies
TDR, S-Parameters & Differential Measurements
Mar. 2008


Differential Impedance
ZDiff=ZAodd+ZBodd
1
2
(TAodd+TBodd)/2=TCD11
TAodd-TBodd=TDD11
Vr=-29mV, Vi=400mV,
Z0=100 Ω
ZDiff=86 Ω
Number Averages = 256
S-Param
TDR Cal: On* (R1 R2)
Rise Time: 37 ps
Markers
1.000 ns
77 ps
-923 ps
85.827 Ω
126.560 Ω
40.733 Ω
Excess Reactance = 2.678370 pF
•Samtec simulated ZDiff=86.6 Ω
Page 22
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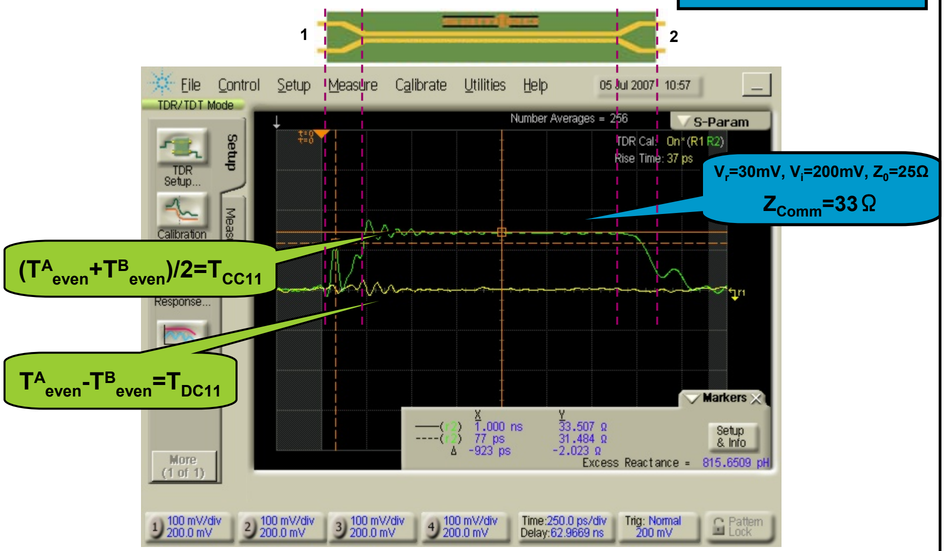
TDR, S-Parameters & Differential Measurements
Mar. 2008

Common Impedance

$Z_{Comm}=(Z^A_{even}+Z^B_{even})/4$



"Try using your single-ended TDR to make any two of the following measurements. From these measurements, you can work out the true differential impedance:

•The impedance of one trace while the other is reasonably well-terminated at both ends.

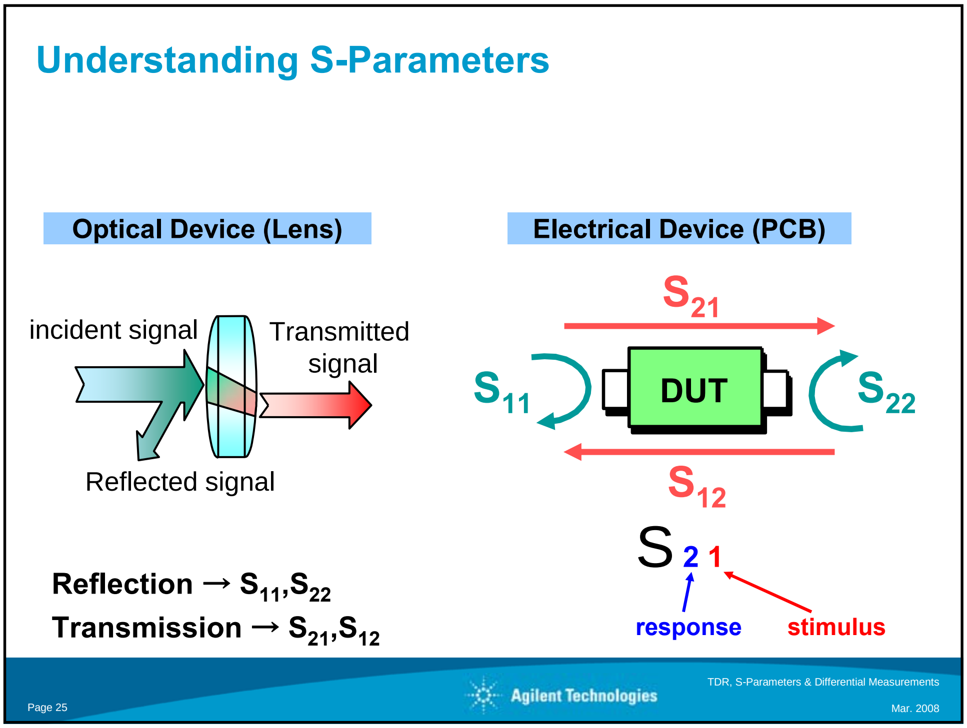
•The impedance when both traces are ganged together in parallel.

•The near-end crosstalk induced on the second trace when the first is driven.

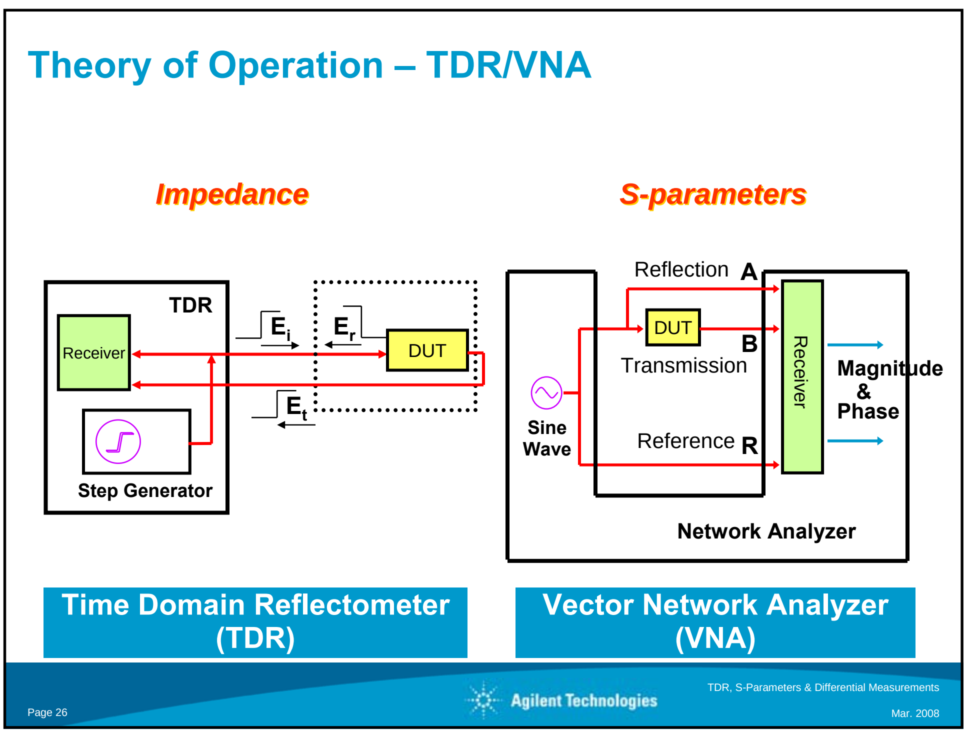
The necessary equations are pretty hairy, but you don't have to know them."

Howard Johnson, PhD – EDN Article, 8/22/2002

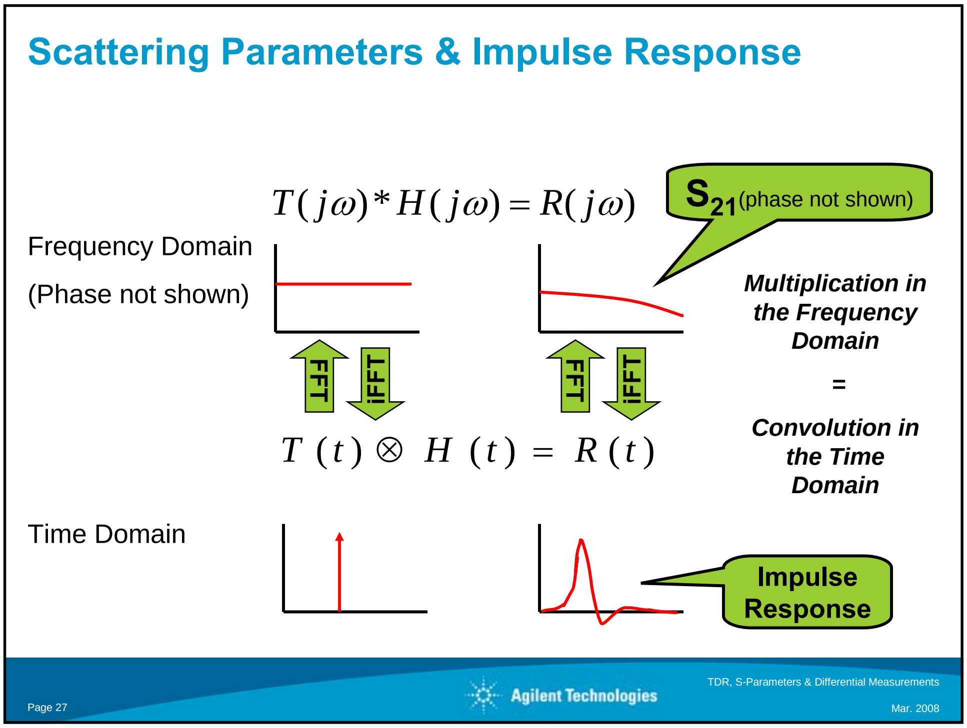
http://www.edn.com/article/CA238428.html

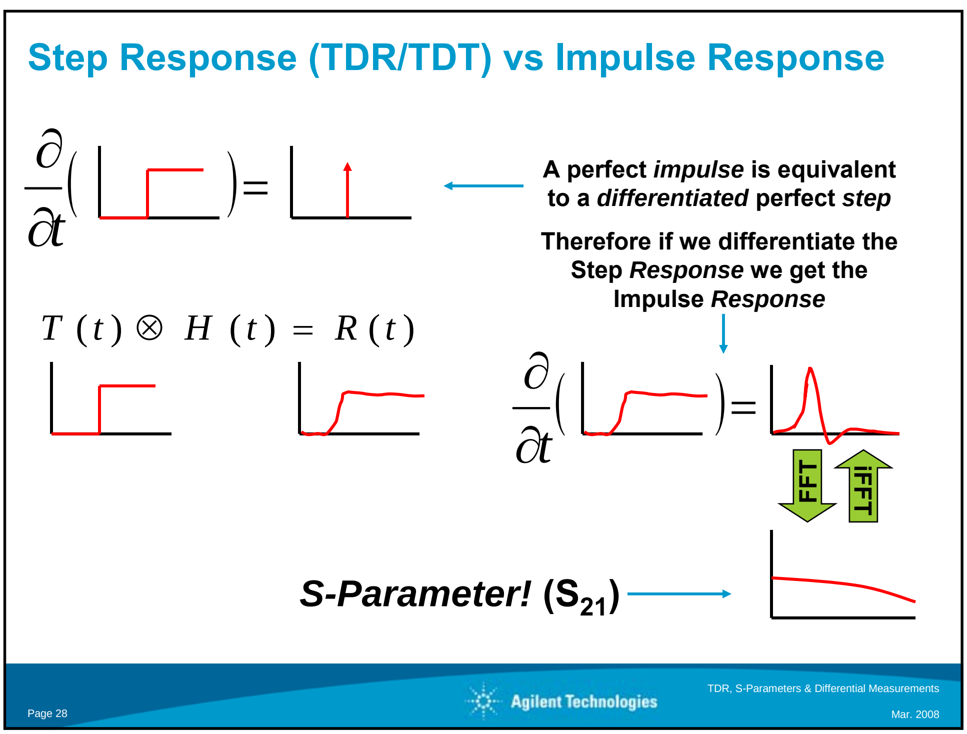


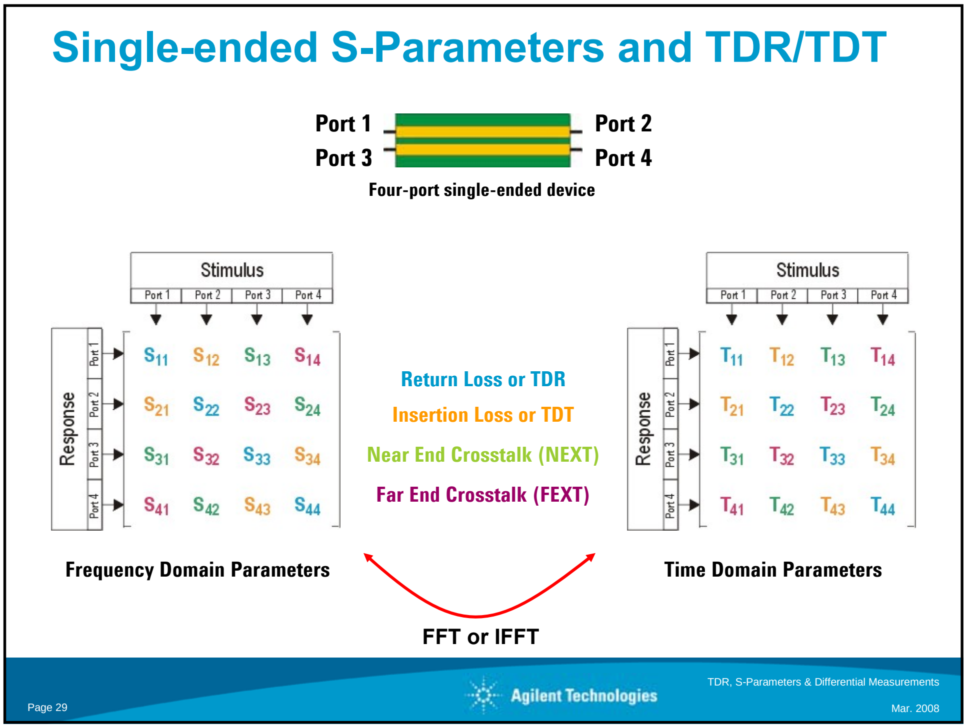
Understanding S-Parameters
Optical Device (Lens)
Electrical Device (PCB)
incident signal
Transmitted signal
Reflected signal
S_{21}
S_{11}
DUT
S_{22}
S_{12}
Reflection → S_{11},S_{22}
Transmission → S_{21},S_{12}
S 2 1
response
stimulus
Page 25
Agilent Technologies
TDR, S-Parameters & Differential Measurements
Mar. 2008

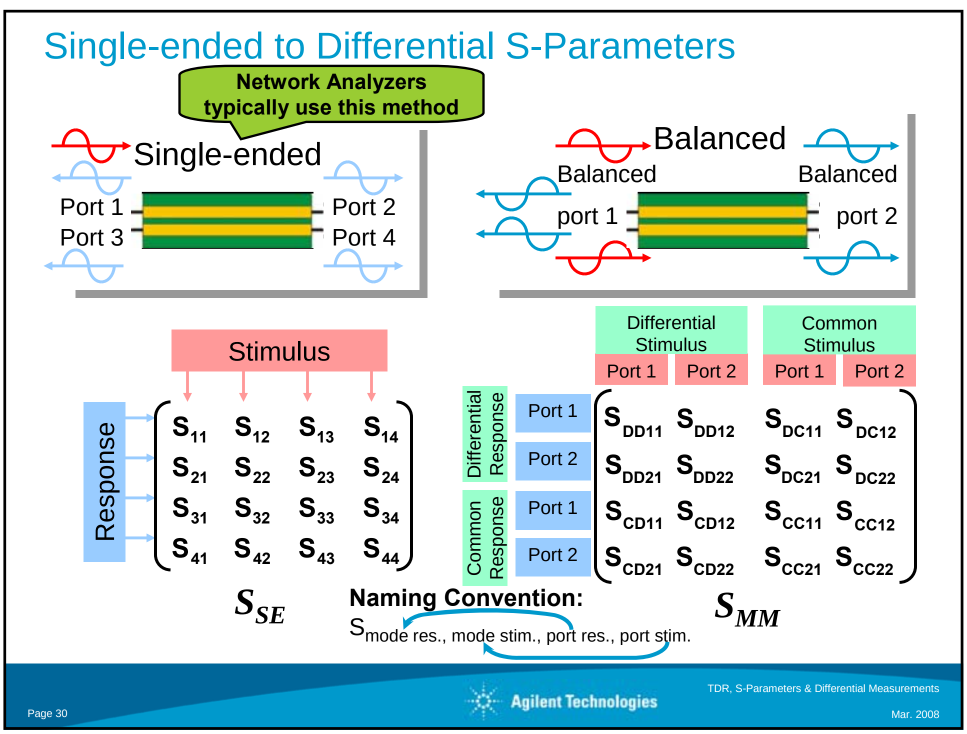


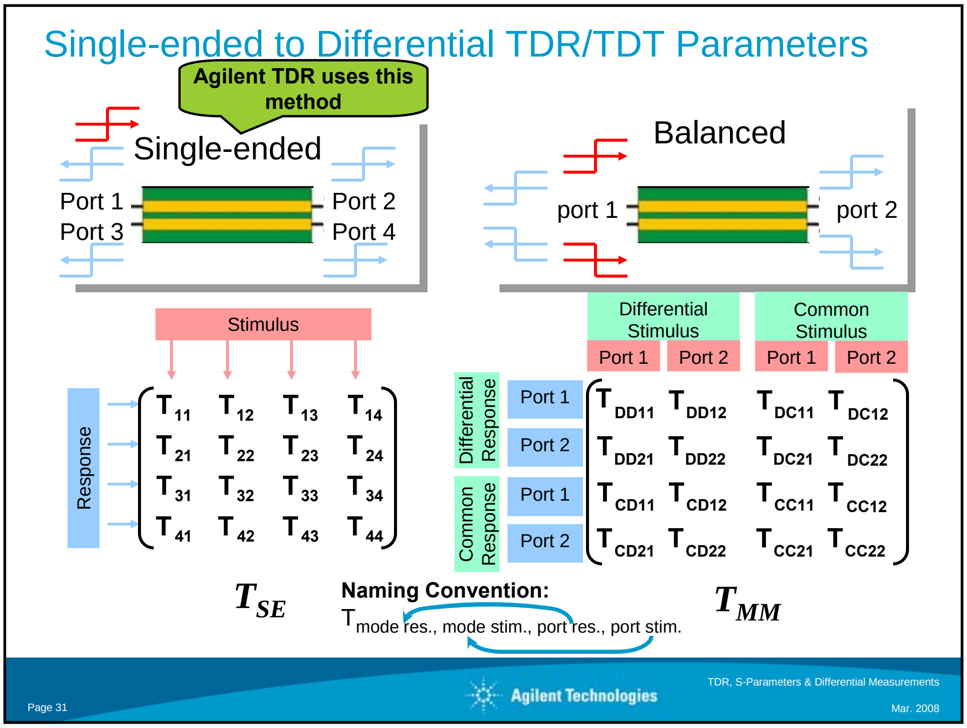
Theory of Operation – TDR/VNA
Impedance
S-parameters
TDR
Receiver
Step Generator
E_i
E_r
E_t
DUT
Reflection A
DUT
B
Transmission
Sine Wave
Reference R
Receiver
Magnitude & Phase
Network Analyzer
Time Domain Reflectometer (TDR)
Vector Network Analyzer (VNA)
Page 26
Agilent Technologies
TDR, S-Parameters & Differential Measurements
Mar. 2008

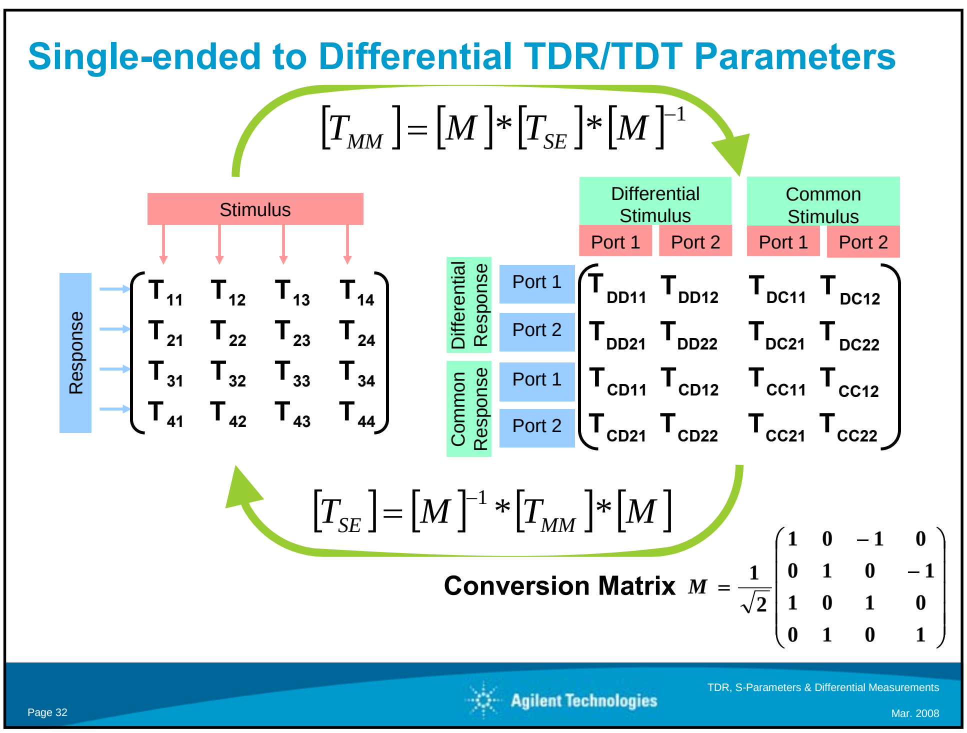

Scattering Parameters & Impulse Response
$T(j\omega) * H(j\omega) = R(j\omega)$
S_{21} (phase not shown)
Frequency Domain
(Phase not shown)
FFT
iFFT
FFT
iFFT
Multiplication in the Frequency Domain
=
Convolution in the Time Domain
$T(t) \otimes H(t) = R(t)$
Time Domain
Impulse Response
Page 27
Agilent Technologies
TDR, S-Parameters & Differential Measurements
Mar. 2008


Step Response (TDR/TDT) vs Impulse Response
$\frac{\partial}{\partial t}$
A perfect *impulse* is equivalent to a *differentiated* perfect *step*
Therefore if we differentiate the Step *Response* we get the Impulse *Response*
$T(t) \otimes H(t) = R(t)$
$\frac{\partial}{\partial t}$
FFT
iFFT
S-Parameter! (S_{21})
Page 28
Agilent Technologies
TDR, S-Parameters & Differential Measurements
Mar. 2008


Single-ended S-Parameters and TDR/TDT
Port 1
Port 3
Port 2
Port 4
Four-port single-ended device
Stimulus
Response
S11 S12 S13 S14
S21 S22 S23 S24
S31 S32 S33 S34
S41 S42 S43 S44
Return Loss or TDR
Insertion Loss or TDT
Near End Crosstalk (NEXT)
Far End Crosstalk (FEXT)
T11 T12 T13 T14
T21 T22 T23 T24
T31 T32 T33 T34
T41 T42 T43 T44
Frequency Domain Parameters
Time Domain Parameters
FFT or IFFT
Page 29
Agilent Technologies
TDR, S-Parameters & Differential Measurements
Mar. 2008


Single-ended to Differential S-Parameters
Network Analyzers typically use this method
Single-ended
Port 1
Port 3
Port 2
Port 4
Balanced
Balanced port 1
Balanced port 2
Stimulus
Response
S11 S12 S13 S14
S21 S22 S23 S24
S31 S32 S33 S34
S41 S42 S43 S44
SSE
Differential Stimulus
Common Stimulus
Port 1 Port 2 Port 1 Port 2
Differential Response
Common Response
SDD11 SDD12 SDC11 SDC12
SDD21 SDD22 SDC21 SDC22
SCD11 SCD12 SCC11 SCC12
SCD21 SCD22 SCC21 SCC22
SMM
Naming Convention:
Smode res., mode stim., port res., port stim.
Page 30
Agilent Technologies
TDR, S-Parameters & Differential Measurements
Mar. 2008


Single-ended to Differential TDR/TDT Parameters
Agilent TDR uses this method
Single-ended
Port 1
Port 3
Port 2
Port 4
Balanced
port 1
port 2
Stimulus
Response
Differential Stimulus
Common Stimulus
Port 1
Port 2
Differential Response
Common Response
T11 T12 T13 T14
T21 T22 T23 T24
T31 T32 T33 T34
T41 T42 T43 T44
TDD11 TDD12 TDC11 TDC12
TDD21 TDD22 TDC21 TDC22
TCD11 TCD12 TCC11 TCC12
TCD21 TCD22 TCC21 TCC22
TSE
TMM
Naming Convention:
Tmode res., mode stim., port res., port stim.
Page 31
Agilent Technologies
TDR, S-Parameters & Differential Measurements
Mar. 2008


Single-ended to Differential TDR/TDT Parameters
[TMM]=[M]*[TSE]*[M]^-1
Stimulus
Response
Differential Stimulus
Common Stimulus
Port 1
Port 2
Differential Response
Common Response
T11 T12 T13 T14
T21 T22 T23 T24
T31 T32 T33 T34
T41 T42 T43 T44
TDD11 TDD12 TDC11 TDC12
TDD21 TDD22 TDC21 TDC22
TCD11 TCD12 TCC11 TCC12
TCD21 TCD22 TCC21 TCC22
[TSE]=[M]^-1*[TMM]*[M]
Conversion Matrix M = 1/√2 (1 0 −1 0; 0 1 0 −1; 1 0 1 0; 0 1 0 1)
Page 32
Agilent Technologies
TDR, S-Parameters & Differential Measurements
Mar. 2008

The 4 Matrices of a 4-Port Device

$$\begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{pmatrix} \leftrightarrow \begin{pmatrix} S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\ S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\ S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\ S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22} \end{pmatrix}$$

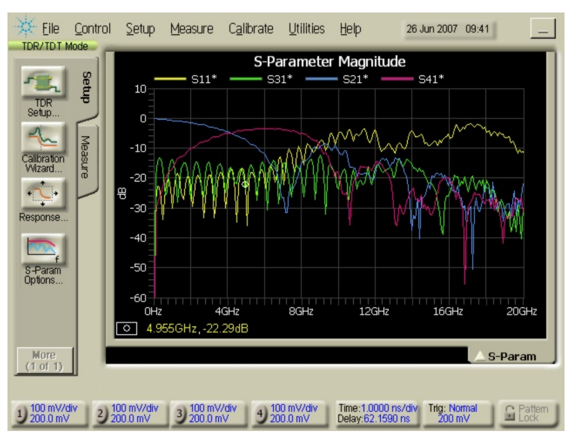
All 4 Matrices can be calculated from any 1 of the 4 Matrices

$$\begin{pmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & T_{24} \\ T_{31} & T_{32} & T_{33} & T_{34} \\ T_{41} & T_{42} & T_{43} & T_{44} \end{pmatrix} \leftrightarrow \begin{pmatrix} T_{DD11} & T_{DD12} & T_{DC11} & T_{DC12} \\ T_{DD21} & T_{DD22} & T_{DC21} & T_{DC22} \\ T_{CD11} & T_{CD12} & T_{CC11} & T_{CC12} \\ T_{CD21} & T_{CD22} & T_{CC21} & T_{CC22} \end{pmatrix}$$

DCAj – S-Parameters

Calibrated S-Parameters

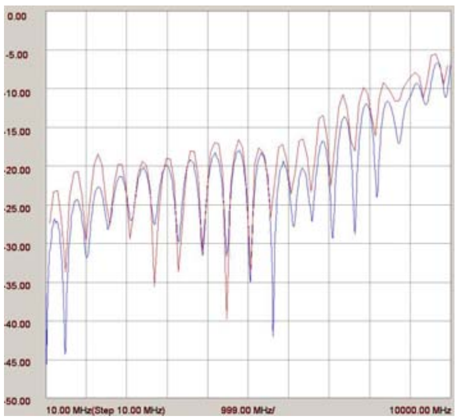
- **Real-time Update**
- **Built-in to the GUI**



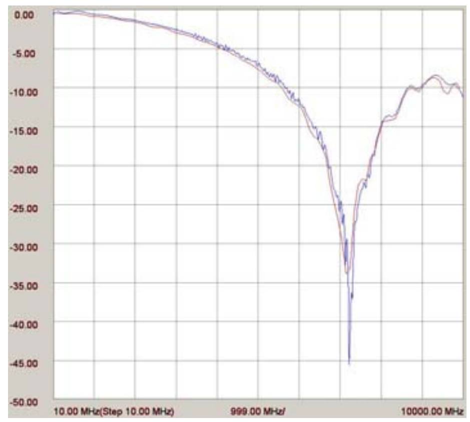
Correlation with Network Analyzer

1 2
3 GOLDEN STANDARD 4

S11



S21



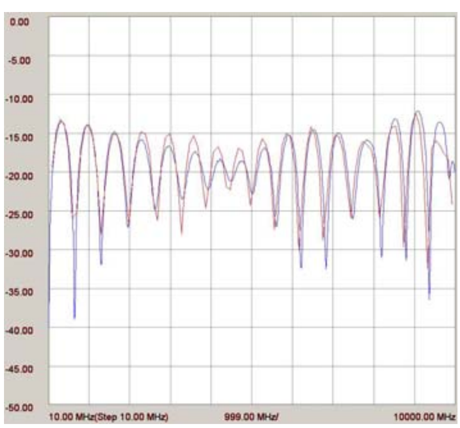
•Blue = 20GHz PNA, Red = DCAj, Data compared with PLTS

Page 35 Agilent Technologies TDR, S-Parameters & Differential Measurements Mar. 2008

Correlation with Network Analyzer

1 2
3 GOLDEN STANDARD 4

S31



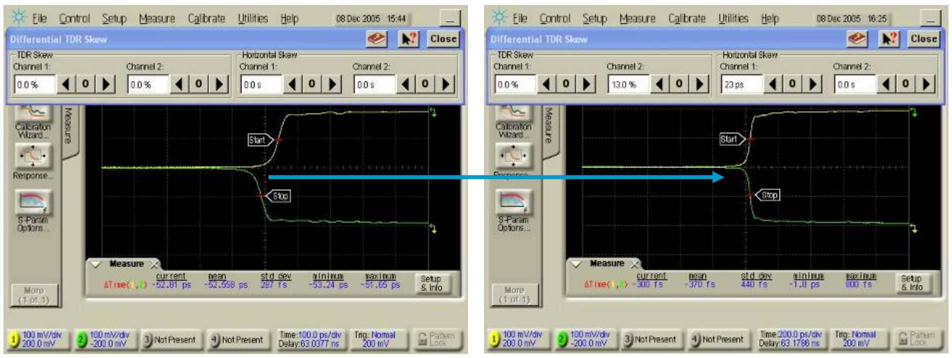
S41

•Blue = 20GHz PNA, Red = DCAj, Data compared with PLTS

Page 36 Agilent Technologies TDR, S-Parameters & Differential Measurements Mar. 2008

Differential Circuit Testing – What's Important?

- **Differential Steps must be well matched**
- **Differential Channels must be de-skewed**
  - **use the TDR De-Skew procedure prior to making measurements**



Page 37 Agilent Technologies TDR, S-Parameters & Differential Measurements Mar. 2008

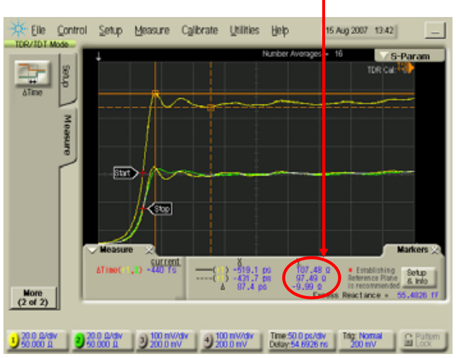
Matching the Steps

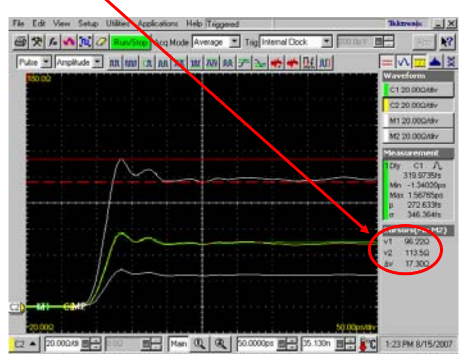
When the TDR outputs are terminated with 50 Ω standards, there is no coupling so the Differential Impedance should be 2 x 50 Ω = 100 Ω

Mismatch or overshoot will affect the resolution of the Differential Impedance measurement

DCAj has ~10 Ω (10%) variation

Tek CSA has ~17 Ω (17%) variation



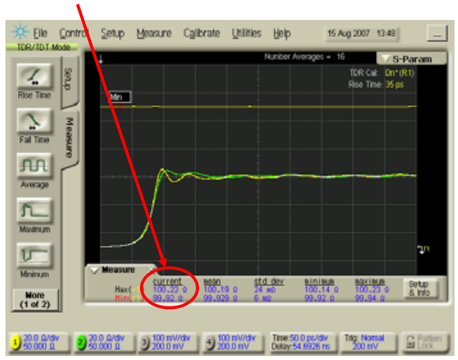


Page 38 Agilent Technologies TDR, S-Parameters & Differential Measurements Mar. 2008

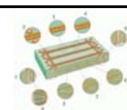
Agilent Calibration

Agilent's built-in Calibration removes the effects of imperfect steps AND fixturing to give the Truest Differential Impedance.

DCAj has <1 Ω (<1%) variation



More Information



DCAj - www.agilent.com/find/dcaj

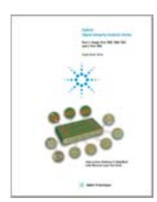
High Precision Time Domain Reflectometry (AN 1304-7)

Measuring Differential Impedance with TDR to Improve High-Speed Bus Designs, (AN 1382-5)

Improving TDR/TDT Measurements Using Normalization (AN 1304-5)

PLTS - www.agilent.com/find/plts

Signal Integrity Analysis Series



- Part 1: Single-Port TDR, TDR/TDT and 2-Port TDR - 5989-5763EN
- Part 2: 4-Port TDR/VNA/PLTS - 5989-5764EN
- Part 3: The ABCs of De-Embedding – 5989-5765EN