PCB의 Signal Integrity 측정과 분석 세미나

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High Speed Characteristics of Interconnects

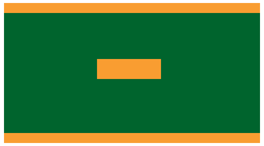
- **Characteristic Impedance**
- TDR and DK measurement
- Speed of Signal and Skew
- Insertion/Return Loss, or S-parameters
- Differential Signal & Mode Conversion
- Crosstalk

Transmission Line

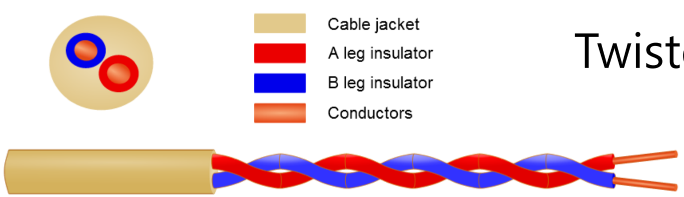
PCB

Microstrip Line

Coaxial Cable



Strip Line



Twisted Pair Cable

Coupled Microstrip

Ideal Transmission Line

No Reflection!

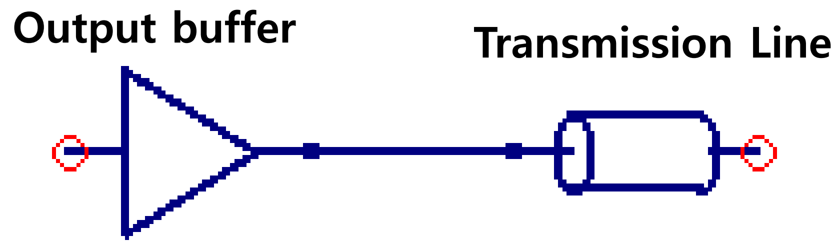
No Loss!

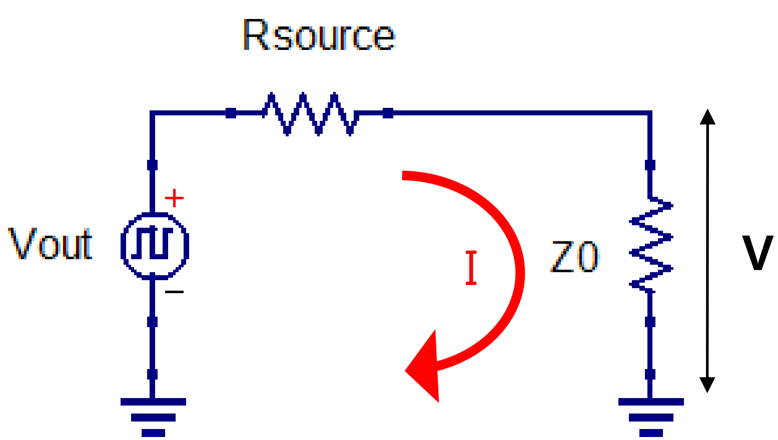
No Crosstalk!

No Mode conversion!

No Timing error!

Input Impedance of Transmission Line





$$Z_0 = \frac{V}{I}$$

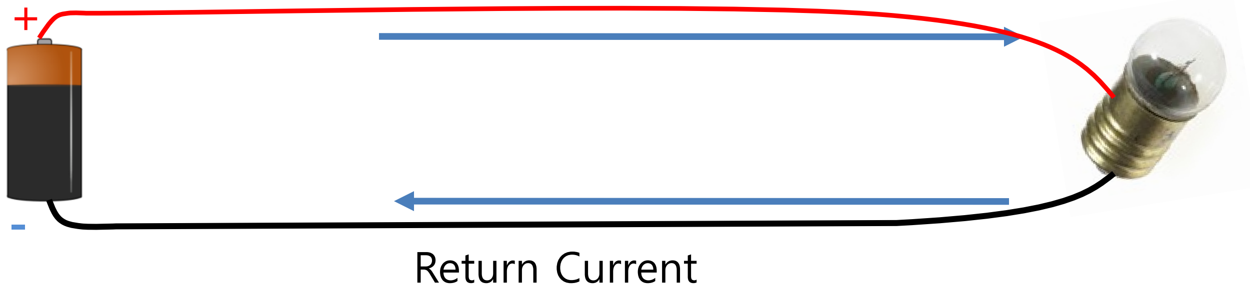
$$V = Vout \frac{Z_0}{Z_0 + Rsource}$$

Z_0 : Input Impedance of Tline

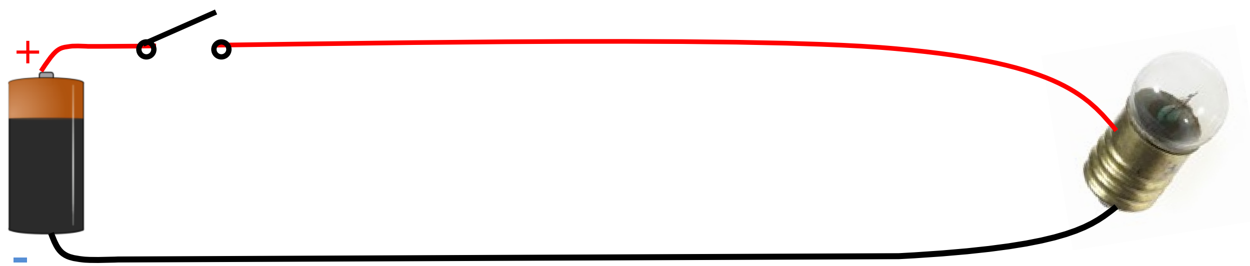
Characteristic Impedance of Tline

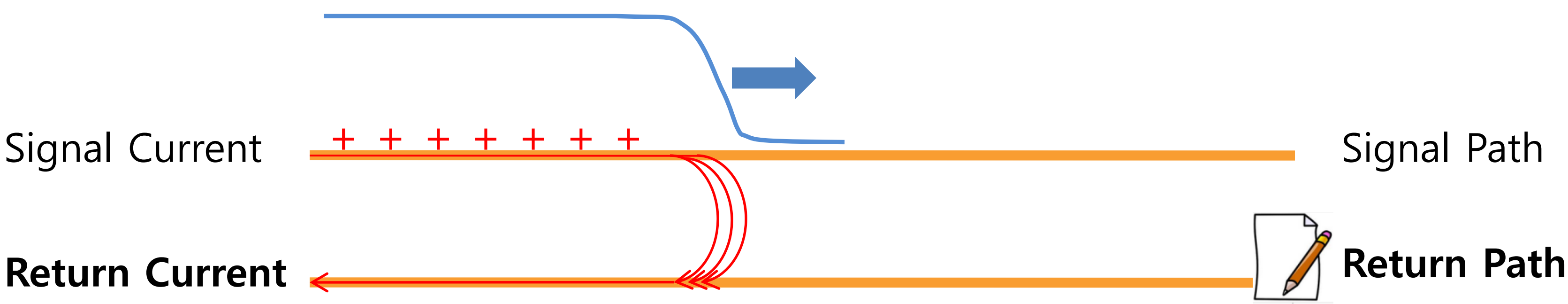
Current Flow in the Circuit

DC

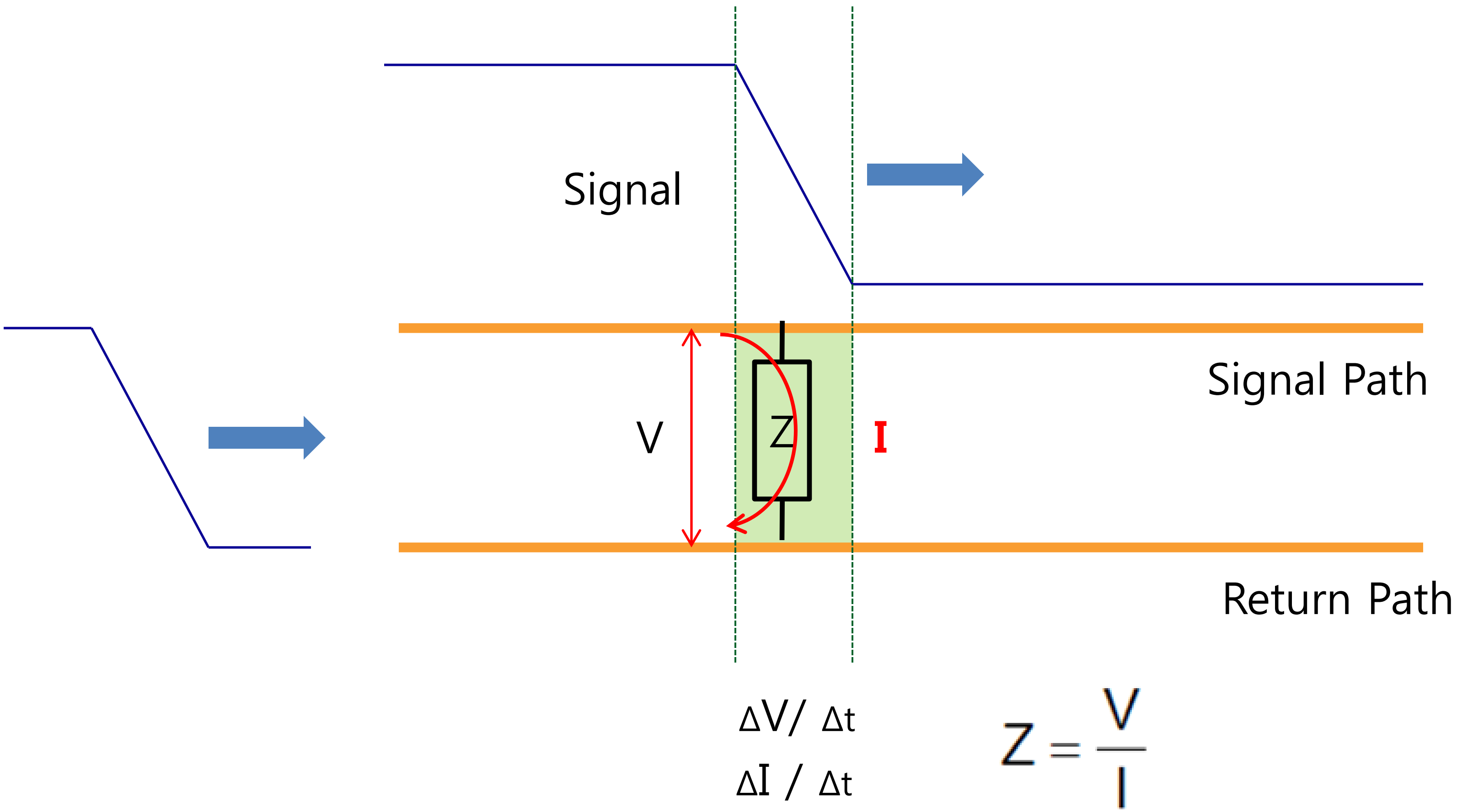


Transient or AC





Instantaneous Impedance



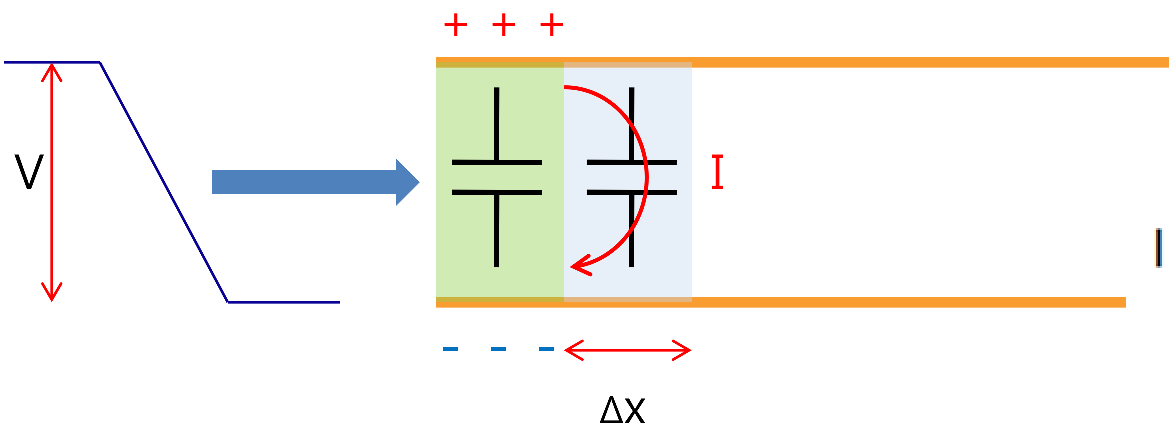
$$Z = \frac{V}{I}$$

Impedance of a Transmission Line

$$Z = \frac{V}{I}$$

$$I = \frac{\Delta Q}{\Delta t} \qquad C = C_L \, \Delta x$$

$$\Delta Q = CV, \quad \Delta t = \frac{\Delta x}{v}$$



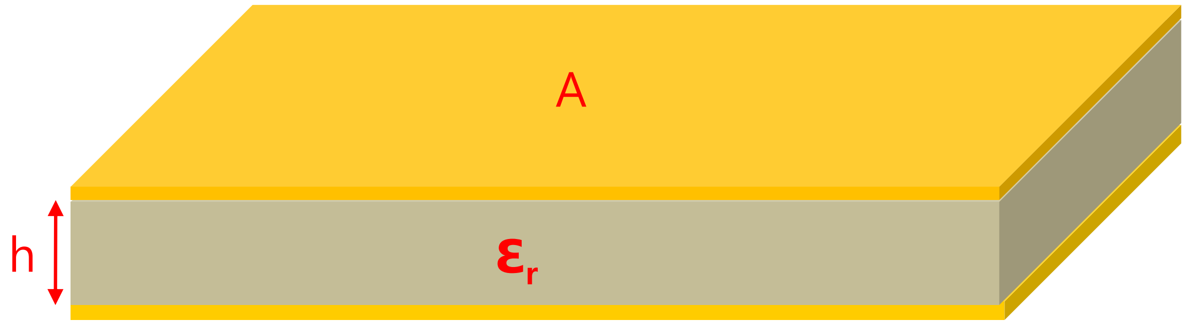
$$I = \frac{\Delta Q}{\Delta t} = \frac{v C_L \Delta x V}{\Delta x} = v C_L V$$

$$Z = \frac{V}{I} = \frac{V}{v C_L V} = \frac{1}{v C_L}$$

Q: charge, V: Voltage of the signal, I: current from the signal
C: capacitance
v: speed of signal in the material

Equation from <Eric Bogatin, Signal and Power Integrity>

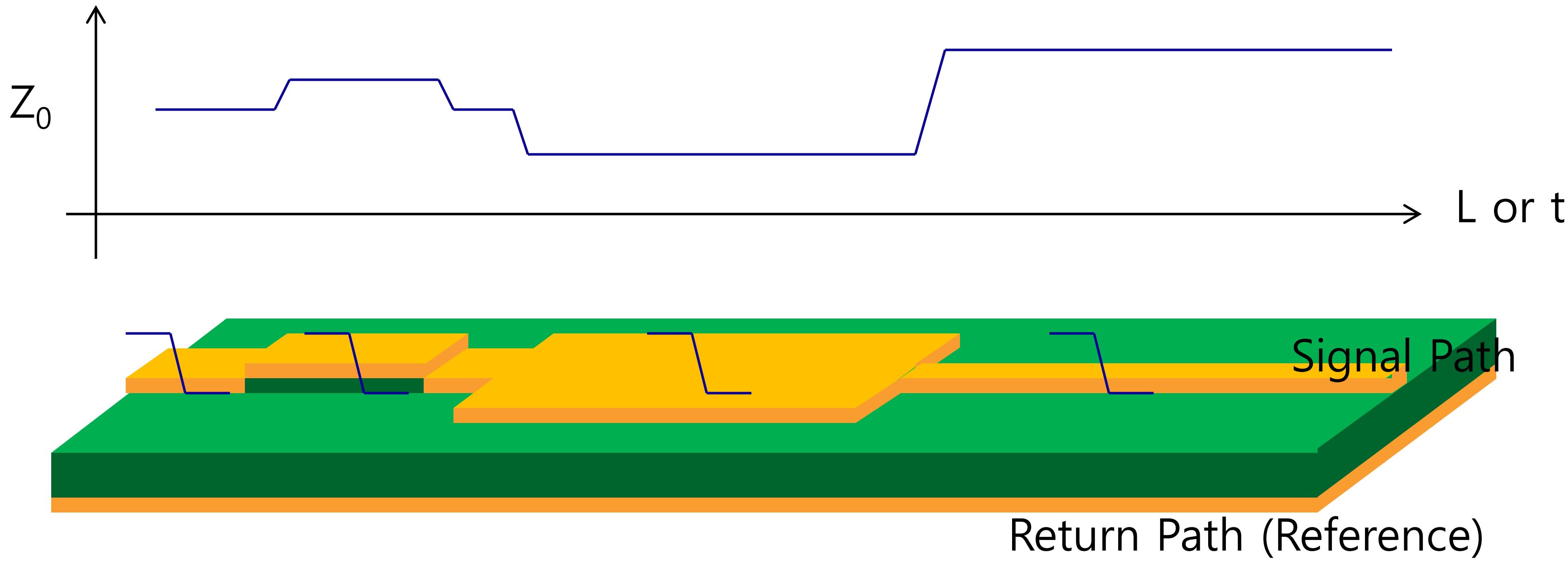
Capacitance

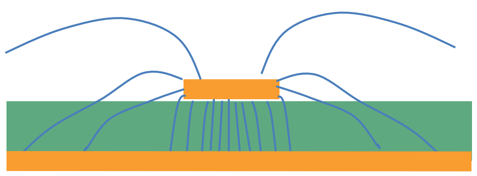


$$C = \varepsilon_0 \varepsilon_r \frac{A}{h}$$

C: capacitance of the plane, in pF
ε_0: permittivity of free space, 0.089pF/cm or 0.225pF/inch
ε_r: relative dielectric constant, typically ~ 4 in FR4
A: area of the plane, in inches
h: distance between the planes, in inches

Change of Instantaneous Impedance



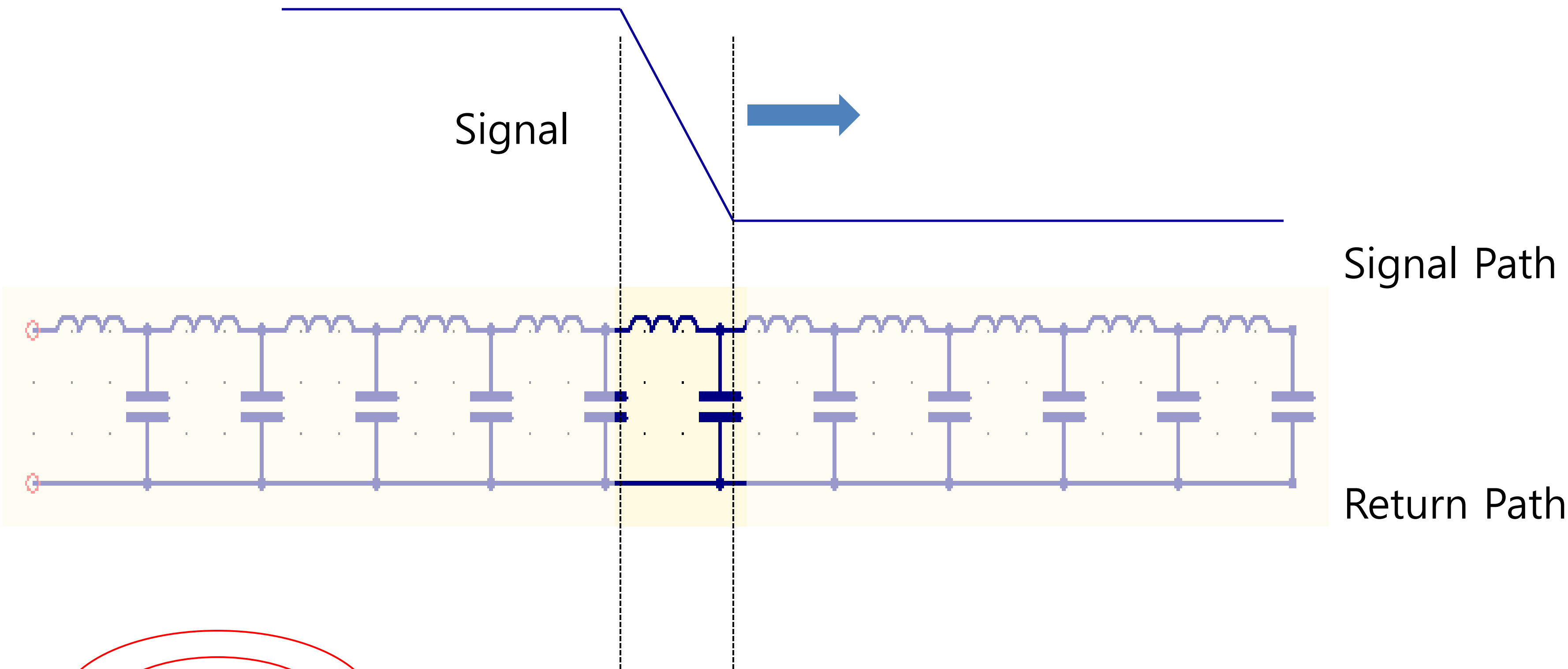


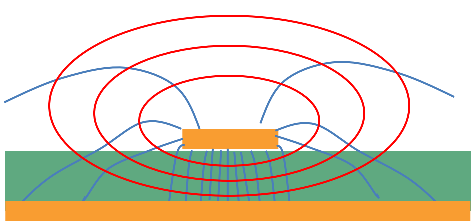
Electric Field Lines

$$Z_0 = \frac{1}{v\,C_L} = \frac{83}{C_L}\sqrt{\varepsilon_r}$$

v: the speed of light in the material
ε_r: dielectric constant of the material

Model of Transmission Line, LC



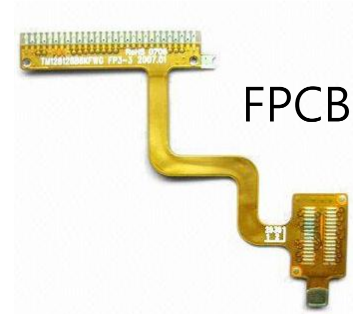


$$Z_0 = \sqrt{\frac{L_L}{C_L}}$$

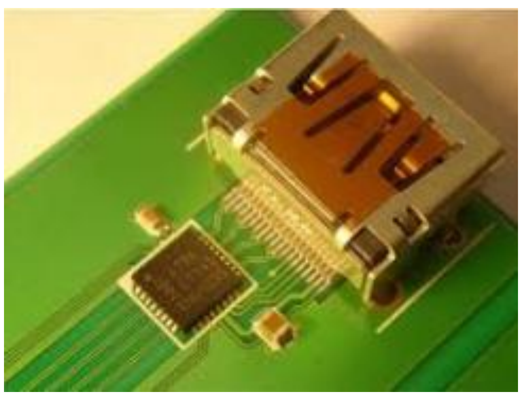
Characteristic Impedance, Z_0

Coaxial
Cable

FFC



FPCB



PCB

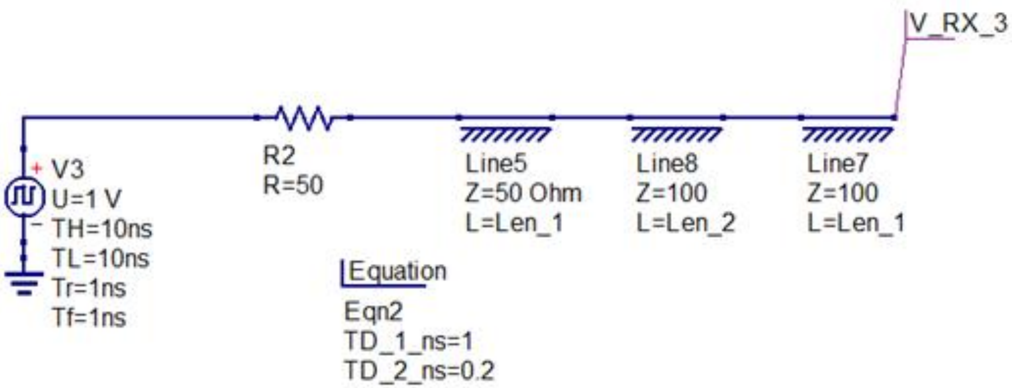
Uniform Transmission Line

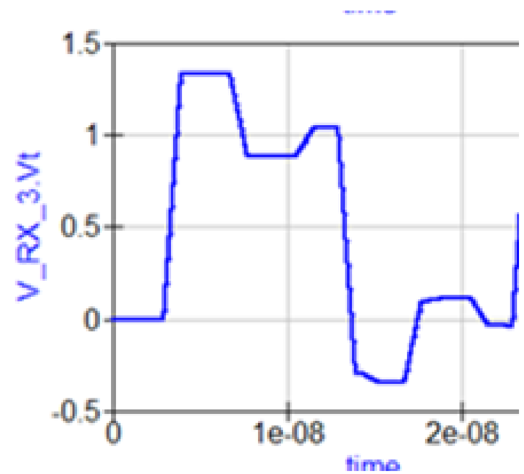
$$Z_0 = \sqrt{\frac{L_L}{C_L}}$$

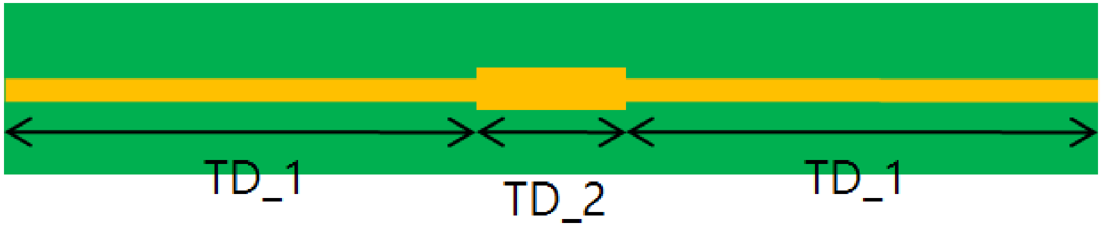
Instantaneous Impedance is same through the Uniform Transmission Line
→ **Controlled Impedance**

✓**Characteristic Impedance** is **One Number** representing the Impedance of Transmission Line

Waveform distortion by reflection







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- Characteristic Impedance
- **TDR and DK measurement**
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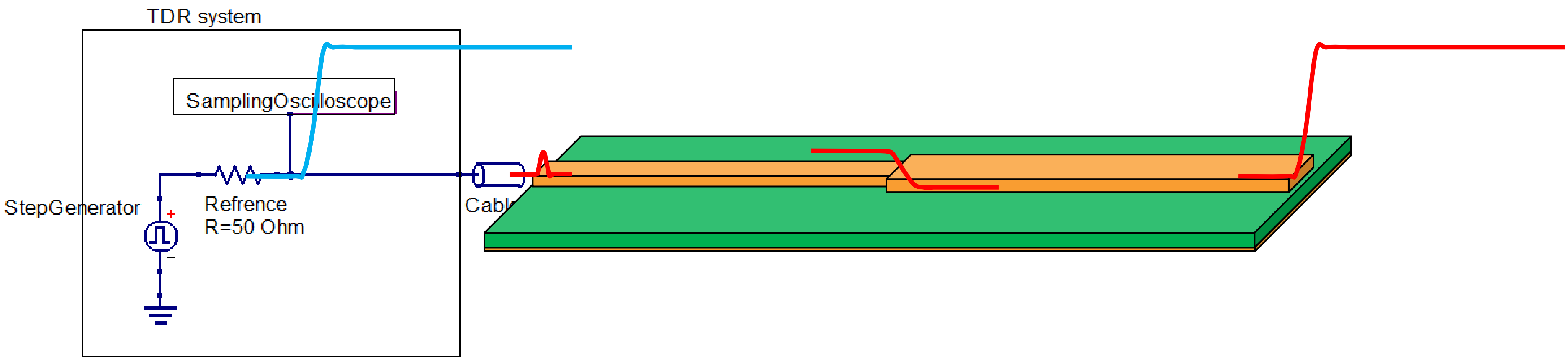
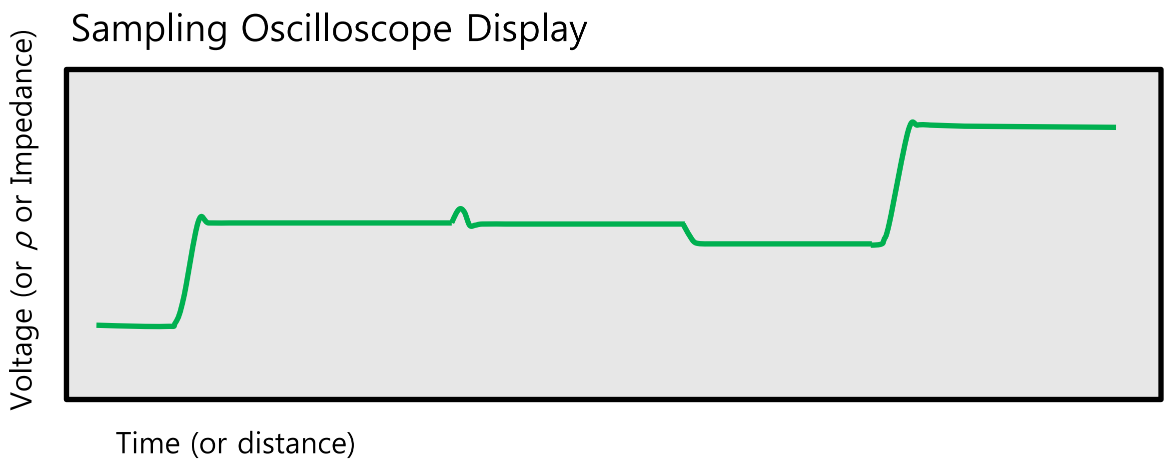
- Differential Signal & Mode Conversion
- Crosstalk

How does TDR works?



$$\rho = \frac{V_{reflected}}{V_{incident}} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

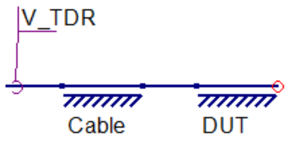
$$Z_L = Z_0 \text{ x } \frac{(1 + \rho)}{(1 - \rho)}$$

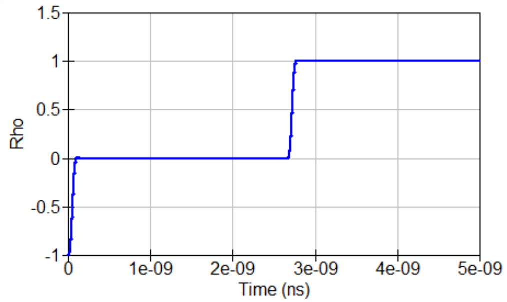


ρ = reflection coefficient, rho
Z_0 = reference Impedance
Z_L = DUT Impedance

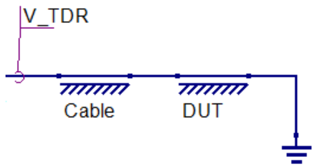
Typical TDR waveforms

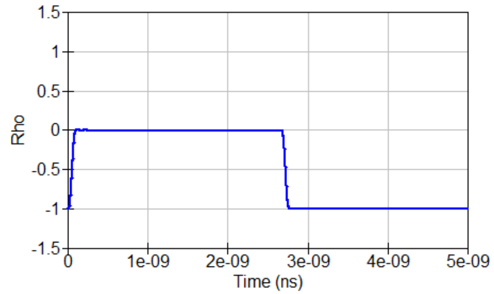
Open



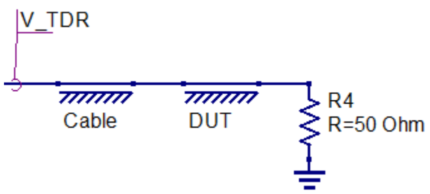


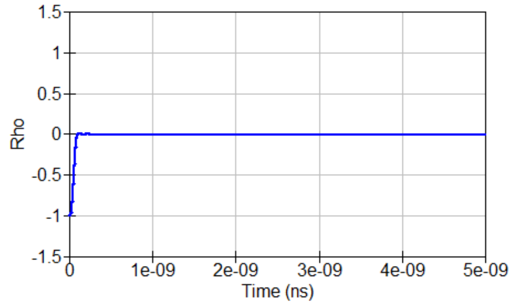
Short





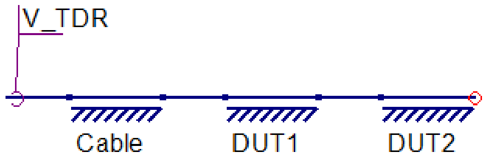
Load

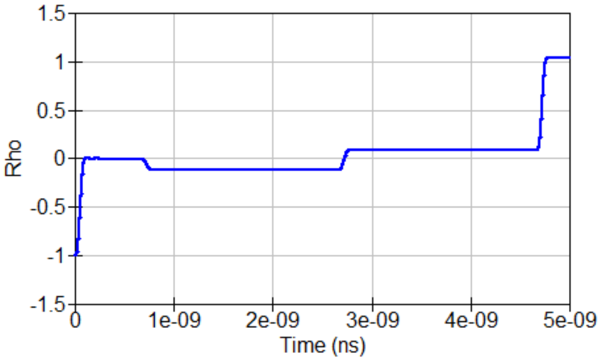




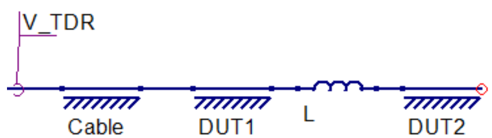
Typical TDR waveforms

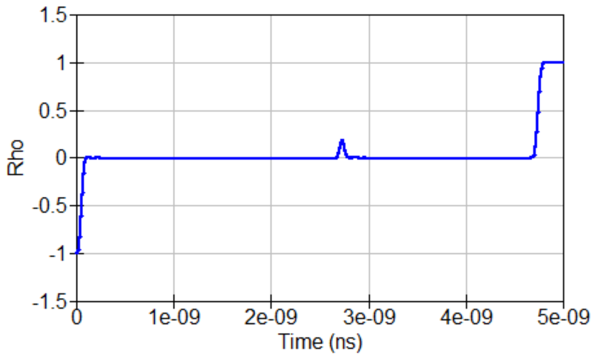
Impedance change



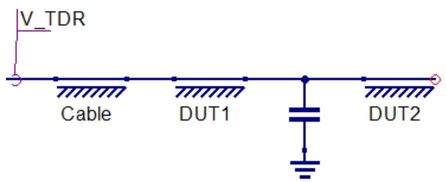


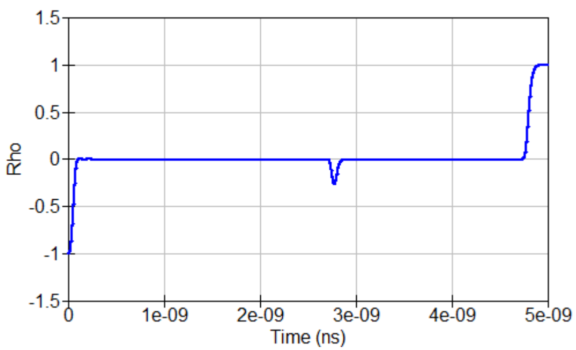
Inductive discontinuity



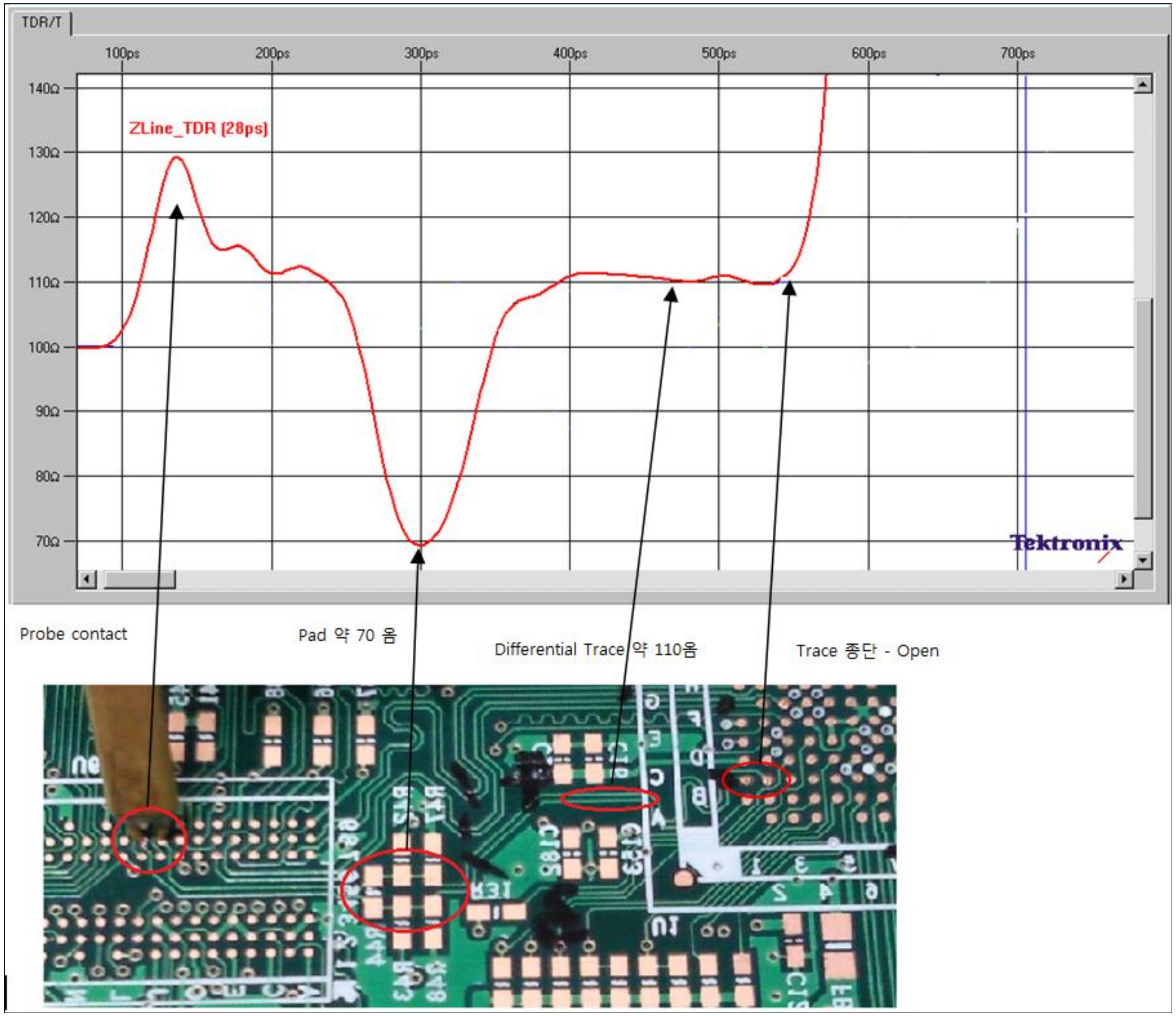


Capacitive discontinuity





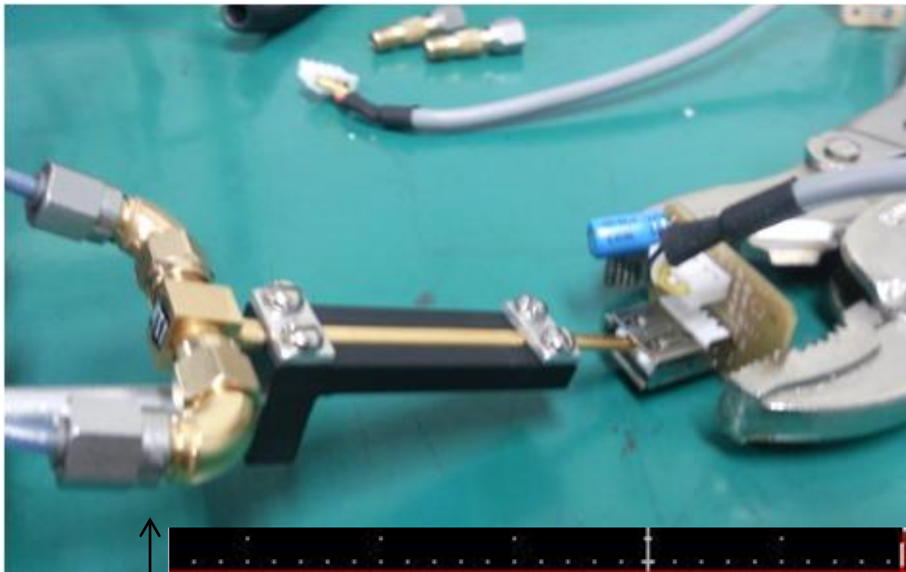
Capacitive Low Impedance

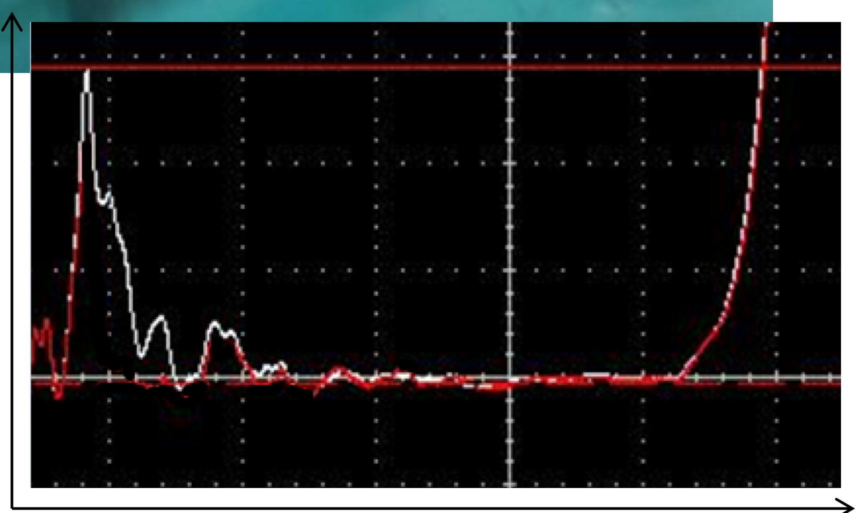


Capacitive Discontinuities

- Decoupling capacitor Pads
- Termination resistor Pads
- Filter Pads
- Connector and Pads
- Stubs
- Vias
- etc.

Inductive High Impedance





TDR plot

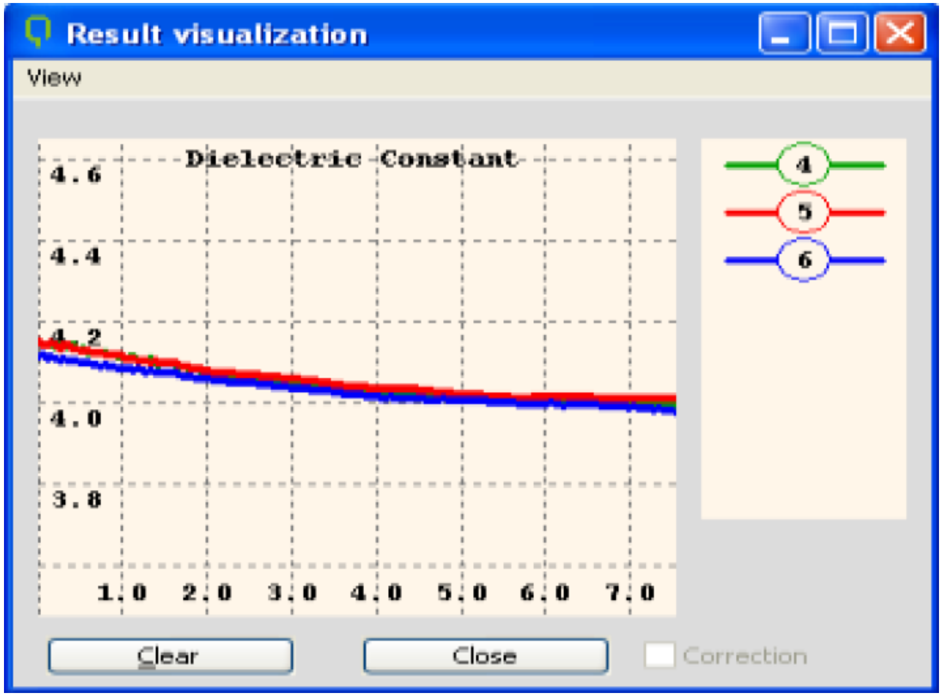
Inductive Discontinuities

- Connectors
- Joint of cable assembly
- Slit of Ground(Return) plane
- Differential Trace near Pads
- Vias
- etc.

Frequency dependant Dk Measurement

Measuring TDR of two transmission lines for determining the frequency dependent dielectric constant

Display of frequency dependant dielectric constants in the software



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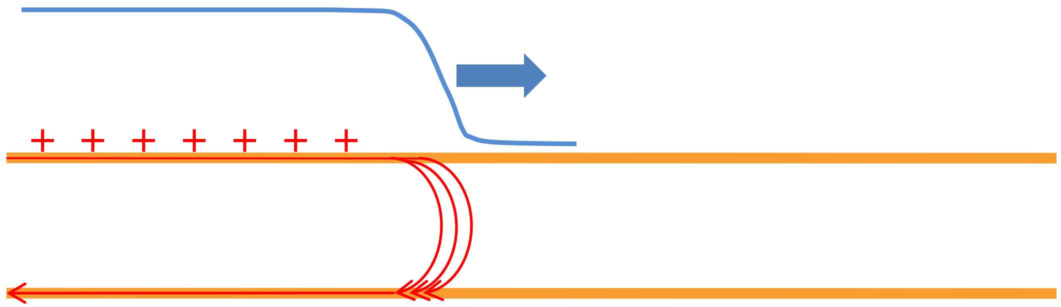
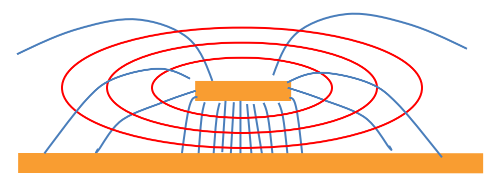
Speed of Signal





Electric Field Lines
Magnetic Field Lines in Microstrip

$$v = \frac{1}{\sqrt{\varepsilon_0 \varepsilon_r \mu_0 \mu_r}}$$

v= speed of signal
ε_0 = permittivity of free space=8.89×10^{-12}F/m
εr =relative dielectric constant of the material
μ_0 =permeability of free space=$4\pi \times 10^{-17}$H/m
μ_r =relative permeability of the material

✓ In air,

$$v = \frac{2.99 \times 10^8}{\sqrt{\varepsilon_r \mu_r}} \frac{m}{secs} = \frac{11.9}{\sqrt{\varepsilon_r \mu_r}} \frac{inches}{nsecs}$$

✓In FR4, if μ_r is 1, ε_r is 4

$$v = \frac{11.9}{\sqrt{4}} \frac{inches}{nsecs}$$

approximation

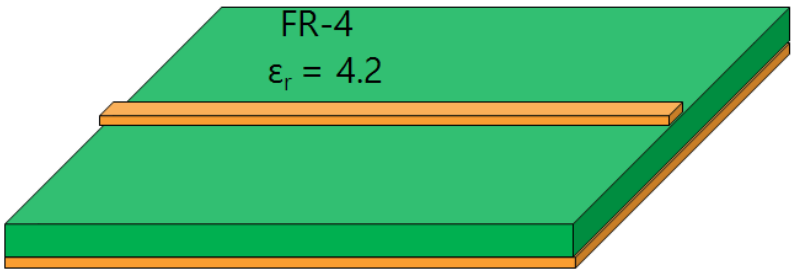
6inch / 1ns (@FR-4 PCB)

Propagation Velocity, Time Delay

$$v = \frac{C}{\sqrt{\varepsilon_r}}$$

$$PD = \frac{1}{v} = \frac{\sqrt{\varepsilon_r}}{C}$$

$$TD = \frac{x\sqrt{\varepsilon_r}}{C}$$



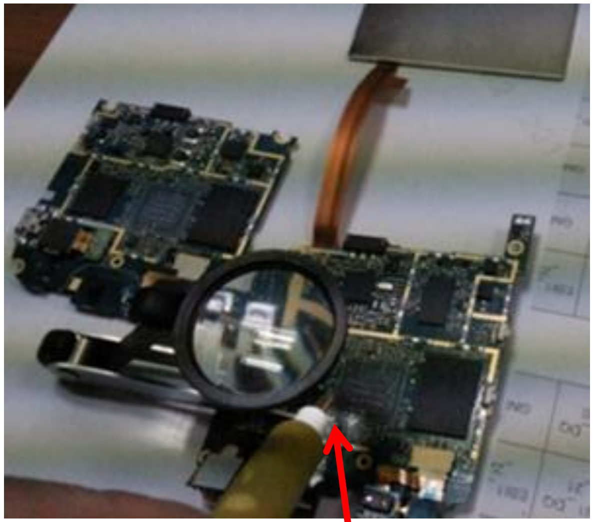
$$TD = \sqrt{L\,C}$$

- v=propagation velocity, in meters/sec
- C = speed of light in a vacuum (3×10^8 m/s)
- ε_r = dielectric constant
- PD= propagation delay, in seconds per meter
- TD = time delay for a signal to propagate down a transmission line of length x
- x = length of transmission line, in meters

L= total series inductance for the length of the line
C= total shunt capacitance for the length of the line

✓Higher Dielectric constant, Inductance, Capacitance make signal slower in Tline.

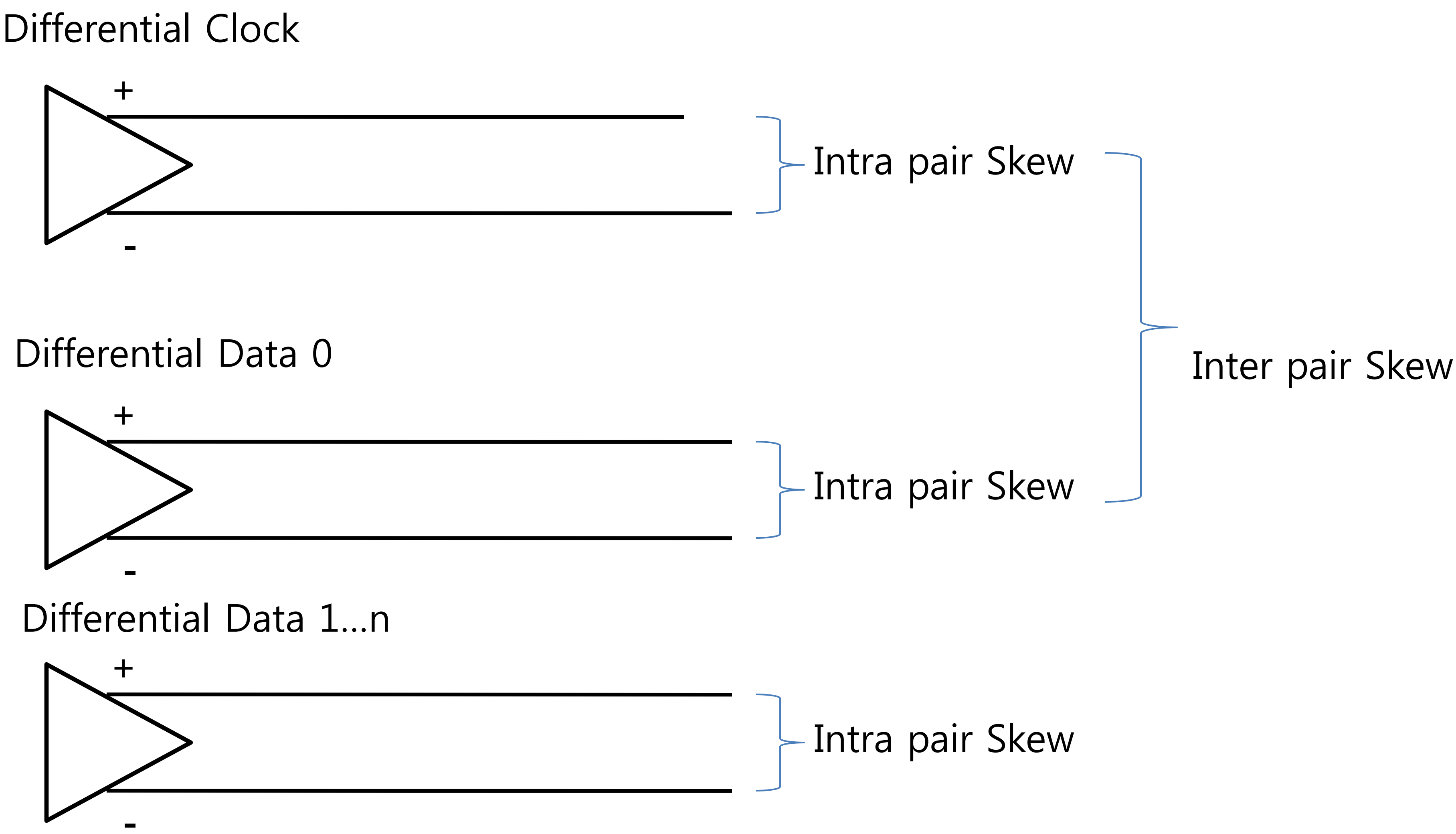
Skew Measurement example (TDR method)



TDR method: Skew and Impedance
TDT method: Skew and Loss

Probe on Pad of Processor

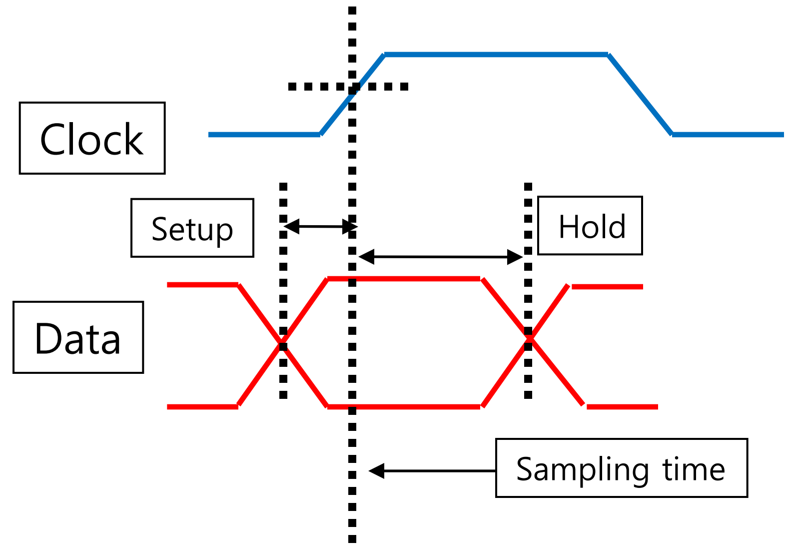
Skews in differential lines



Problems Created by Digital Timing Issues

All Analog Deviation of Clock and Data affect Digital Timing issues

- **Bus contention**
- **Setup and hold violations**
- **Metastability**
- **Undefined conditions**



Setup and hold timing diagram

Reasons of Skew

✓Physical Length

✓Structure (Microstrip or Stripline)

✓Serpentine

✓Differential or Single

✓Discontinuity

✓Different Dk caused by Weave

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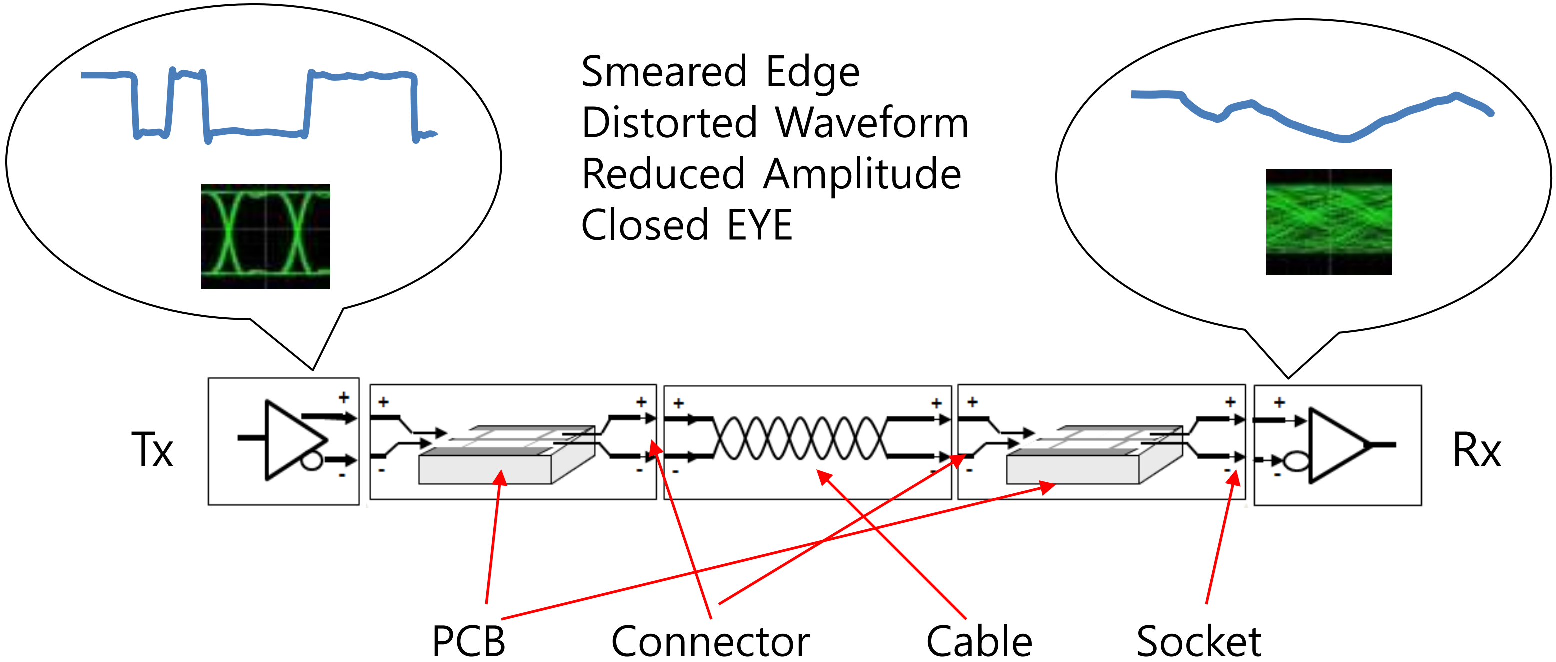
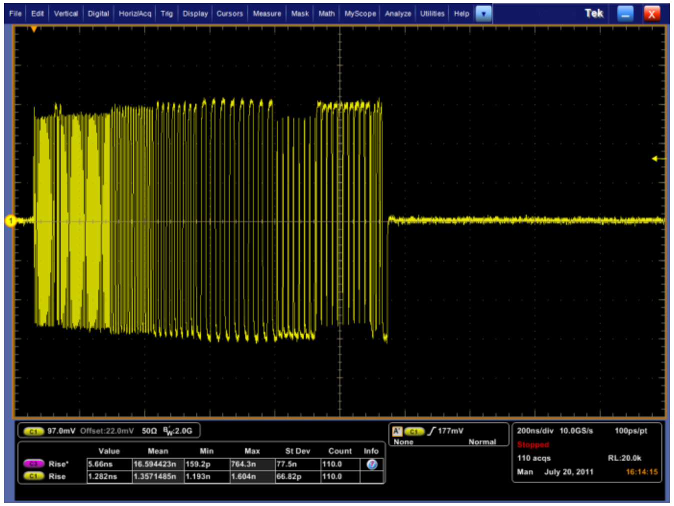
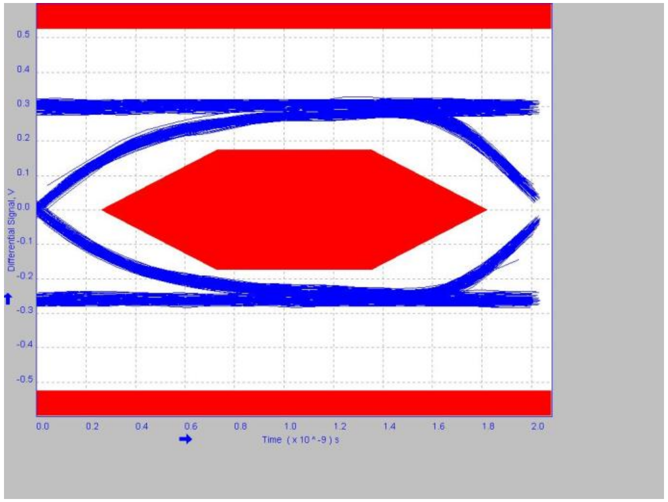
Loss of Transmission Line



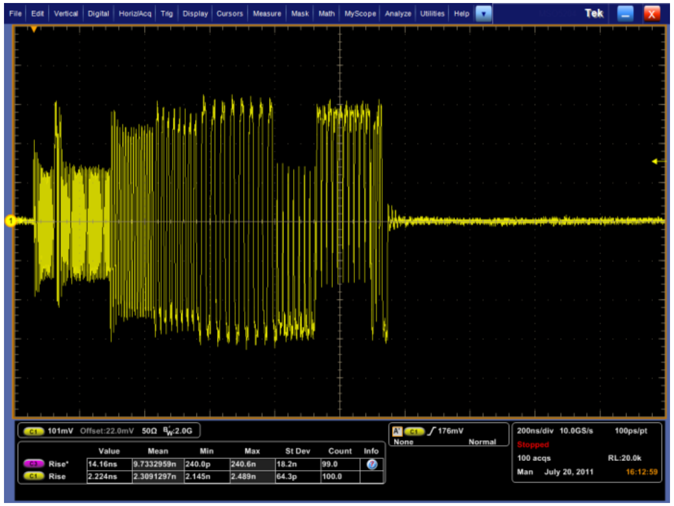
✓ Loss influences more on the closed EYE in Gpbs.

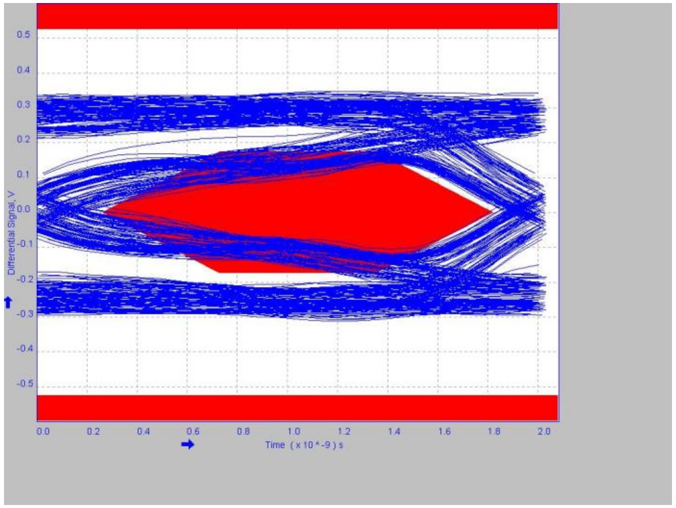
Example of Loss: Waveform and EYE diagram





Frequency dependant Loss!



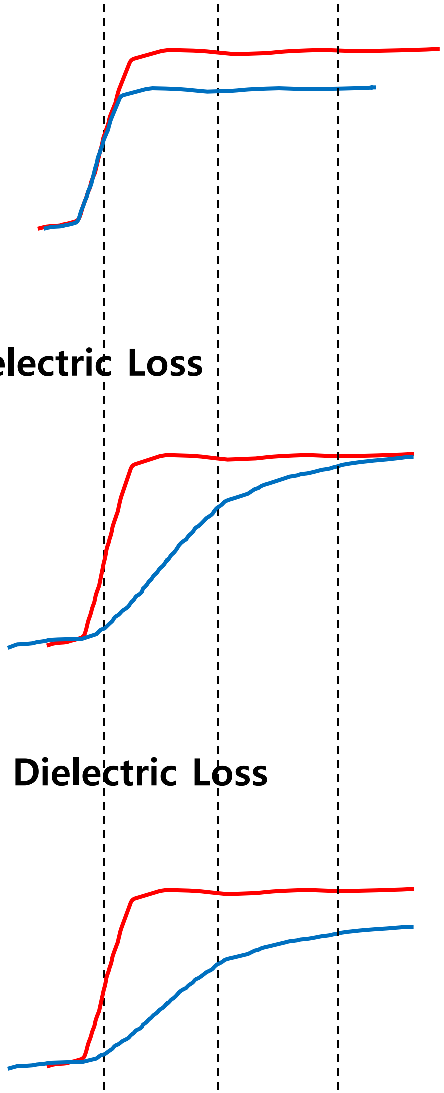


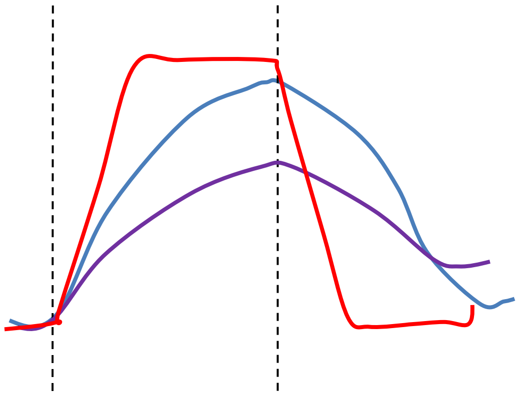
Time domain Waveforms with source of Loss

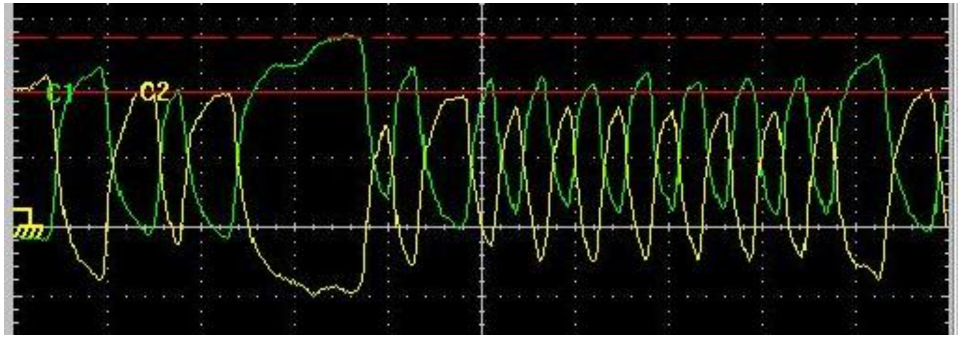
DC conductor Loss

AC conductor Loss + Dielectric Loss

DC AC conductor Loss + Dielectric Loss

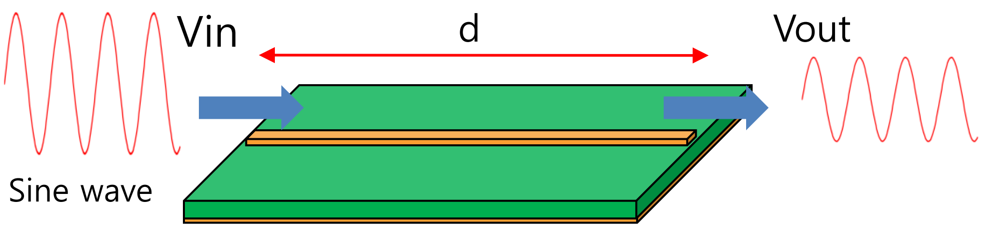






Loss in Frequency domain

Attenuation



$$V_{out} = V_{in}\exp(-A_n) = V_{in}\exp(-d \times \alpha_n)$$

V_{out}= the voltage at the end of the line
d= the distance of the line, in inch
V_{in}= the amplitude of the input voltage
A_n =the total attenuation, in neper
α_n =the attenuation per length, in neper/inch

✓**The attenuation increases exponentially with distance.**

Loss in Frequency domain

Attenuation in dB

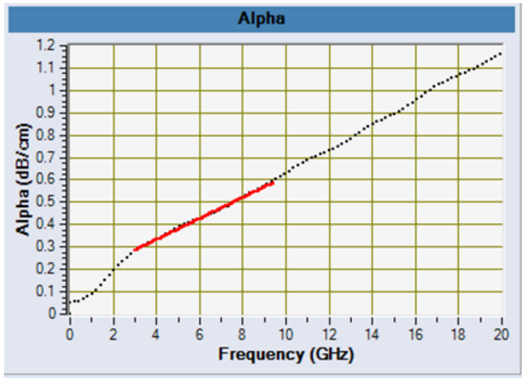
$$V_{out} = V_{in}10^{-\frac{A_{dB}}{20}} = V_{in}10^{\left(-d \times \frac{\alpha_{dB}}{20}\right)}$$

A_{dB} =the total attenuation, in dB
α_{dB} =the attenuation per length, in dB/inch
20= the factor to convert dB into amplitude

$$\text{Ratio(dB)} = 10 \times \log \frac{P_1}{P_0} = 10 \times \log\left(\frac{V_1^2}{V_0^2}\right) = 20\log\left(\frac{V_1}{V_0}\right)$$

$$\text{Ratio} = \frac{V_1}{V_0} = 10^{\frac{\text{ratio}_{dB}}{20}}$$

V_0 = reference voltage
V_1 = measured voltage



<measured α_{dB} in FR4 PCB, in dB/cm>

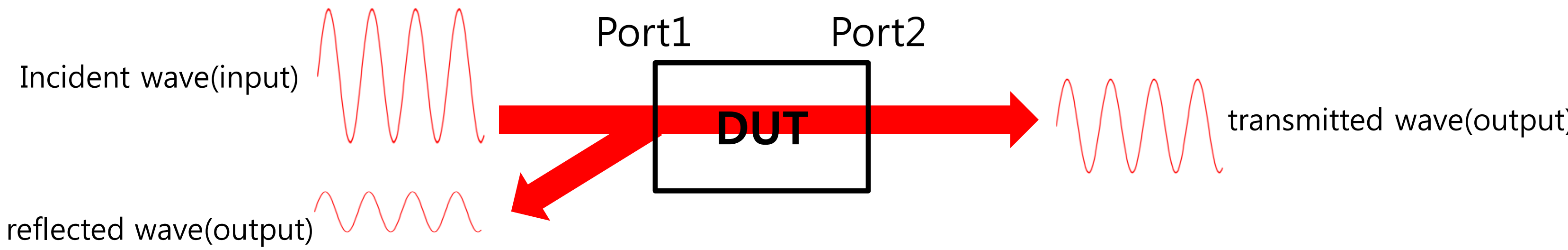
dB	Power ratio	Voltage ratio
30	1000	100
20	100	10
10	10	3.16
6	4	2
3	2	1.4
0	1	1
-3	0.5	0.7
-6	0.25	0.5
-10	0.1	0.316
-20	0.01	0.1
-30	0.001	0.01

✓**In dB, the attenuation increases linearly with frequency.**

Loss in Frequency domain

S-parameters

"Scattering-parameters"
Origins in RF world, this technique has been widely used to describe the behavior of any interconnects in time domain in the digital world.



✓Incident wave scatter back into the source, reflected wave: **S11 or Return Loss**

✓Incident wave scatter through the device, transmitted wave: **S21 or Insertion Loss**

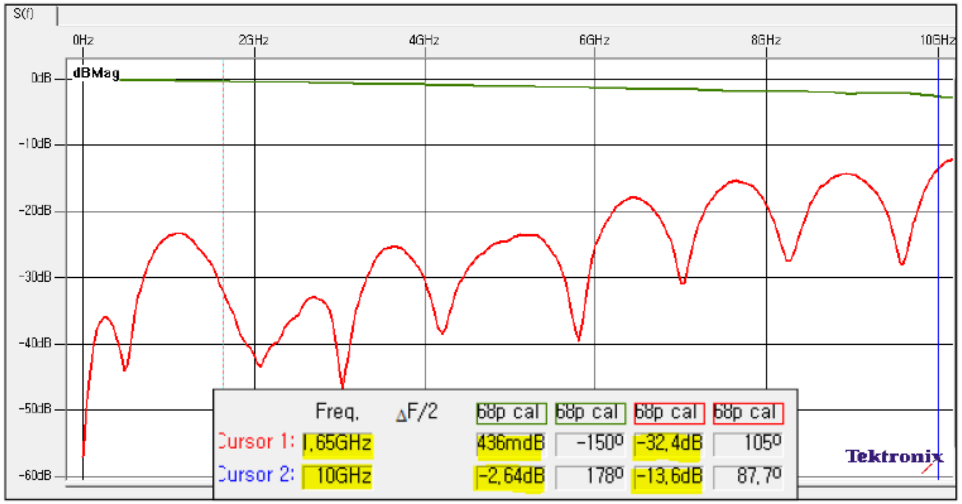
$$\text{mag}(S) = \frac{\textbf{amplitude of output sine wave}}{\textbf{amplitude of input sine wave}}$$

$S_{dB} = 20\log(\text{mag}(S))$

Phase(S)= Phase(output sine wave) – Phase(input sine wave)

S-parameters

<50ohm Transmission line, FR4, 5cm>



<Measured S21 and S11 plot. Measured with Tektronix DSA8300/80E04. Calculated and displayed with I-Connect SW>

In all linear, passive devices, S21=S12. S11=S22.

S21(Insertion Loss) describes how big the transmitted signal will be, at each frequency.

Ex) 1V, 10GHz, sine wave will be reduced to 0.738V(-2.64dB) at the output port.

This Frequency is the appx. **Bandwidth(-3dB) of this device**.

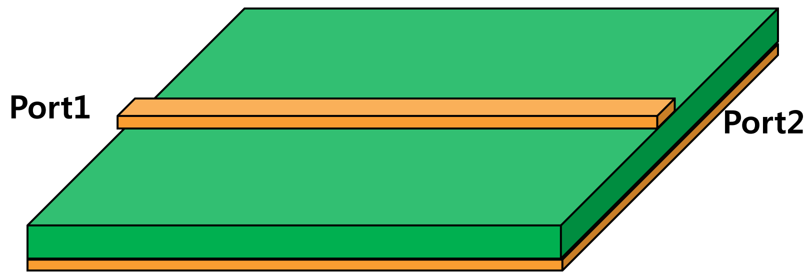
$$\text{Ratio} = \frac{V_1}{V_0} = 10^{\frac{\text{ratio}_{dB}}{20}}$$

S11(Return Loss) describes how small the reflected signal will be, at each frequency.

Ex) 0.2V(-13.6dB) out of 1V, 10GHz, sine wave will be returned back to the source.

S-parameters of Single & Differential T.line

Single-end Line

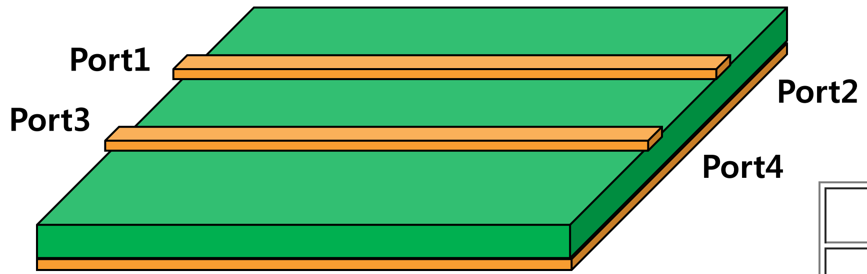


2Port S-parameters

S11 S12
S21 S22

→ **Touchstone file: .S2P**

Differential Line



4Port S-parameters

S11 S12 S13 S14
S21 S22 S23 S24
S31 S32 S33 S34
S41 S42 S43 S44

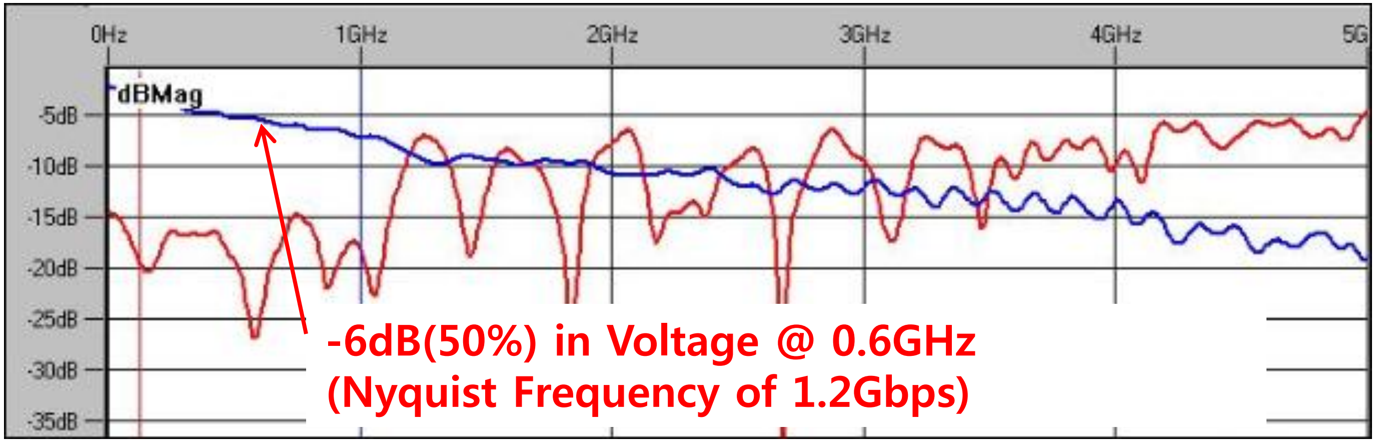
→ **Touchstone file: .S4P**

4Port Mixed-Mode S-parameters

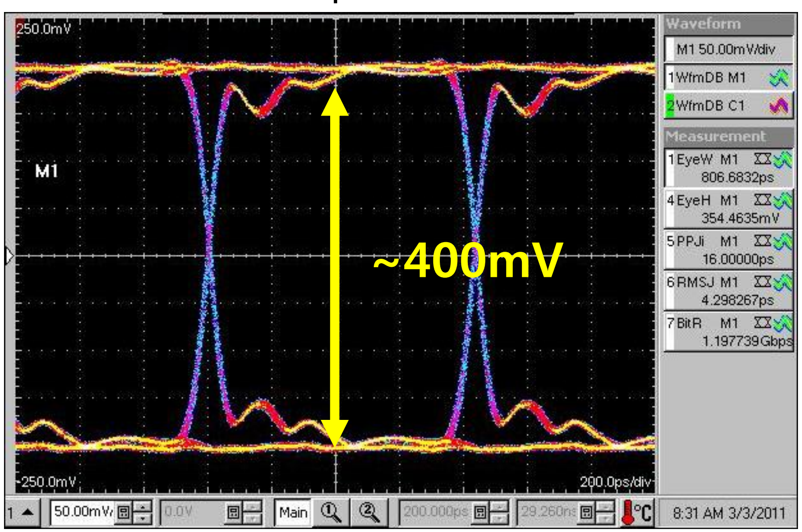
			Stimulus			
			Differential		Common Mode	
			Port 1	Port 2	Port 1	Port 2
Response	Differential	Port 1	SDD11	SDD12	SDC11	SDC12
		Port 2	SDD21	SDD22	SDC21	SDC22
	Common Mode	Port 1	SCD11	SCD12	SCC11	SCC12
		Port 2	SCD21	SCD22	SCC21	SCC22

Measured Example of Lossy Transmission Line

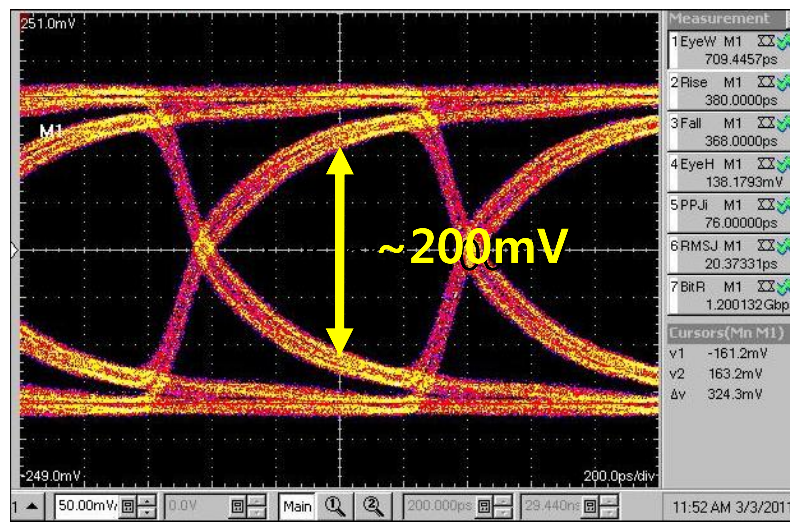
Frequency Domain: Insertion Loss, or S21 and EYE opening



In 1.2Gbps, 400mV



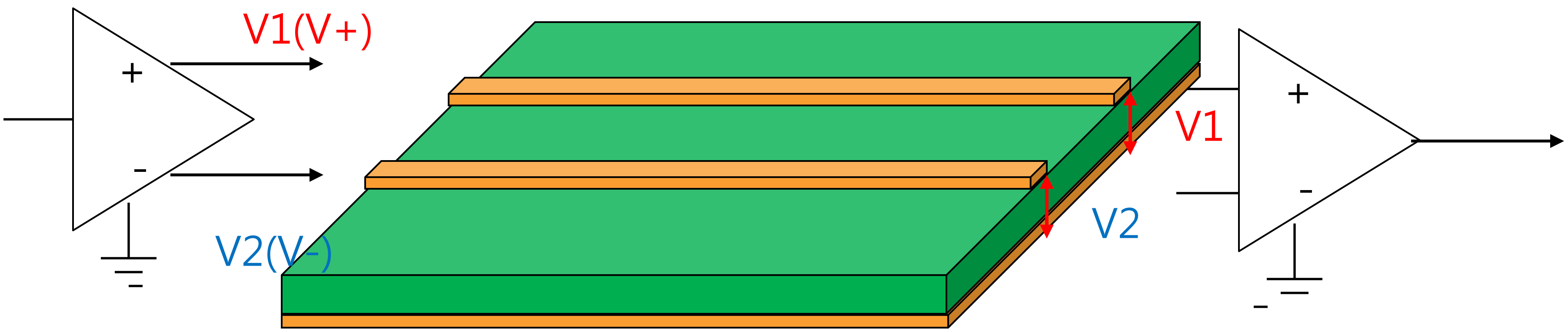
Out

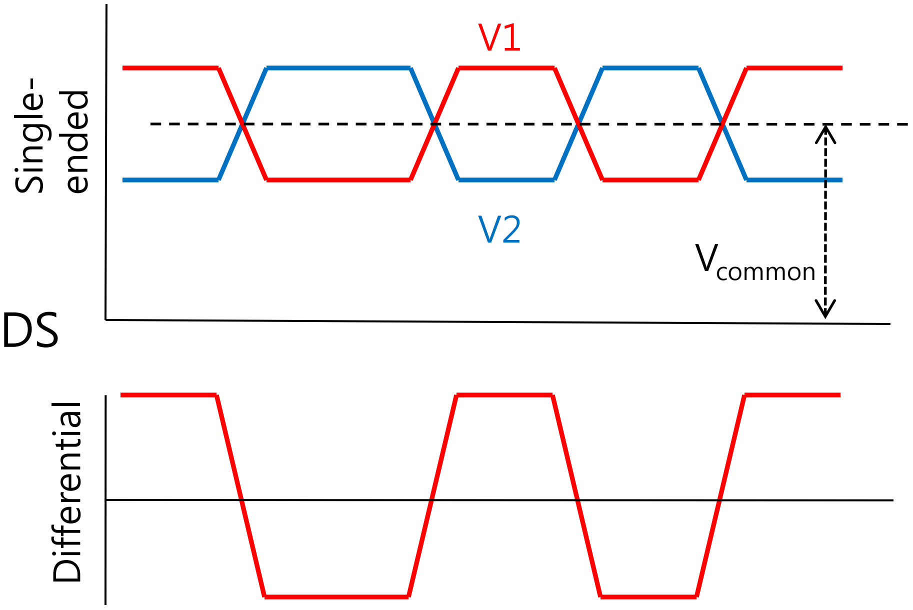


High Speed Characteristics of Interconnects

- Characteristic Impedance and TDR
- Speed of Signal and Skew
- Insertion/Return Loss, or S-parameters
- **Differential Signal & Mode Conversion**
- Crosstalk

Differential Signaling





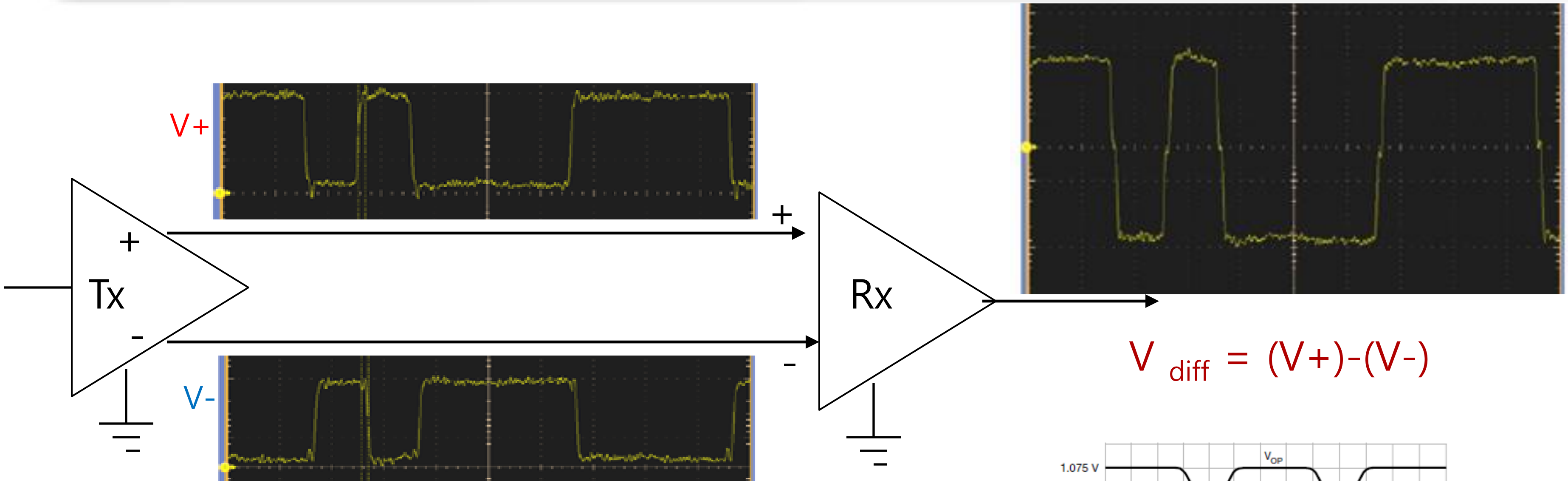
ex) LVDS

$V_{differential}$ = V1-V2

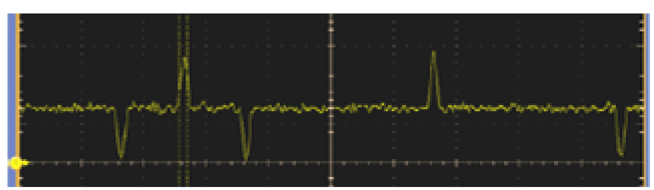
V_{common} = (V1+V2) /2

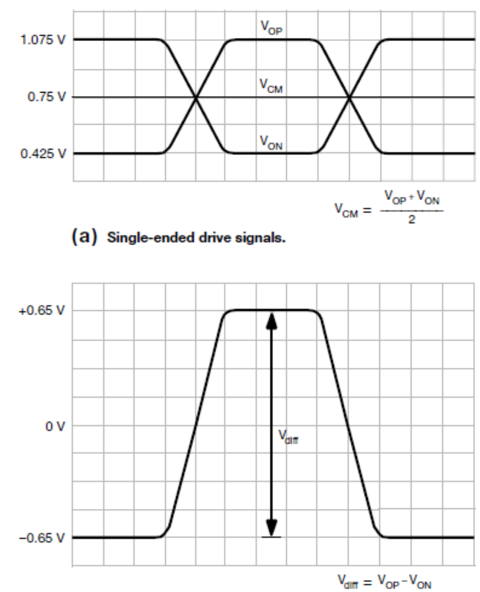
In AC coupled signal, V_{common} is 0

Mode conversion



$V_{diff} = (V+)-(V-)$





(a) Single-ended drive signals.

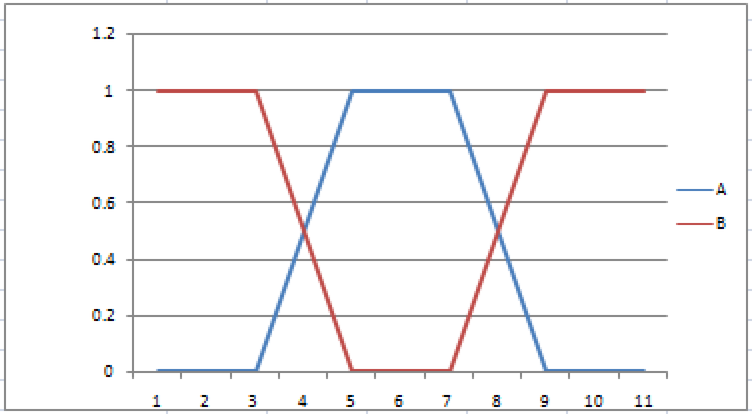
(b) Differential drive signal.

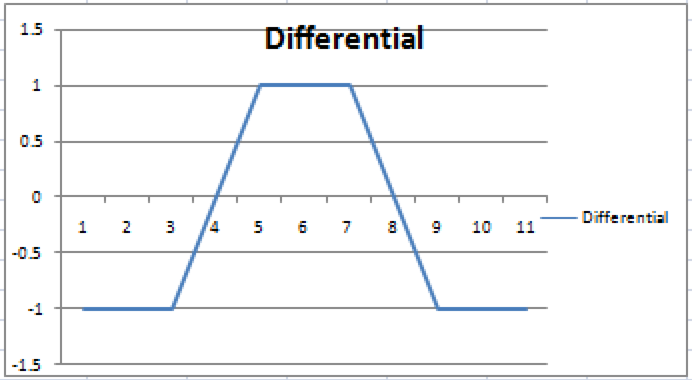
$V_{cm} = (V+)+(V-) /2$

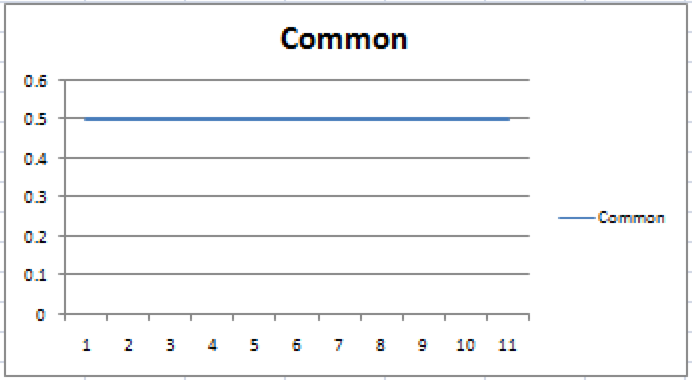
Differential to Common mode noise → EMI
Common to Differential Mode → Jitter, Noise

Mode Conversion

A	0	0	0	0.5	1	1	1	0.5	0	0	0
B	1	1	1	0.5	0	0	0	0.5	1	1	1
A-B(diff)	-1	-1	-1	0	1	1	1	0	-1	-1	-1
(A+B)/2(comm)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

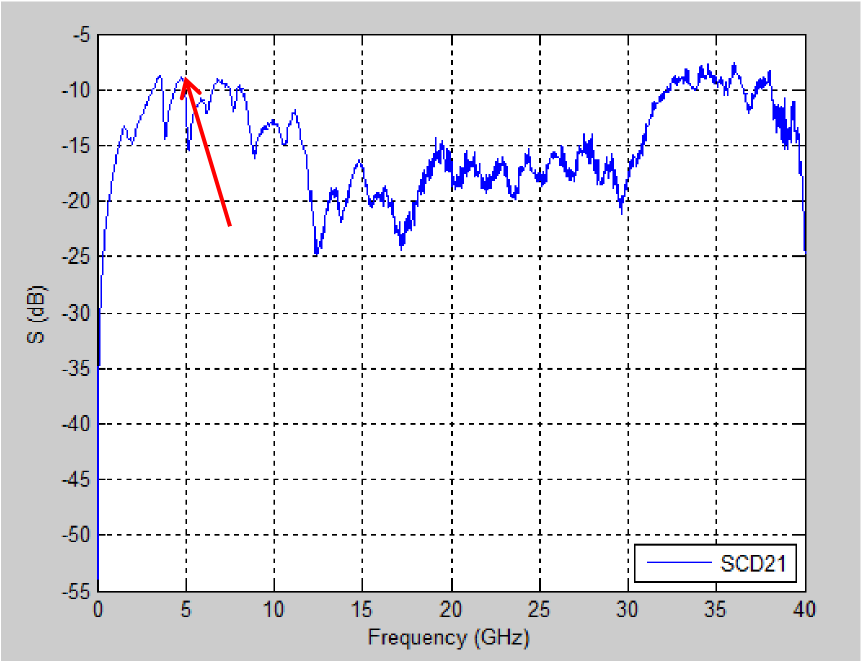


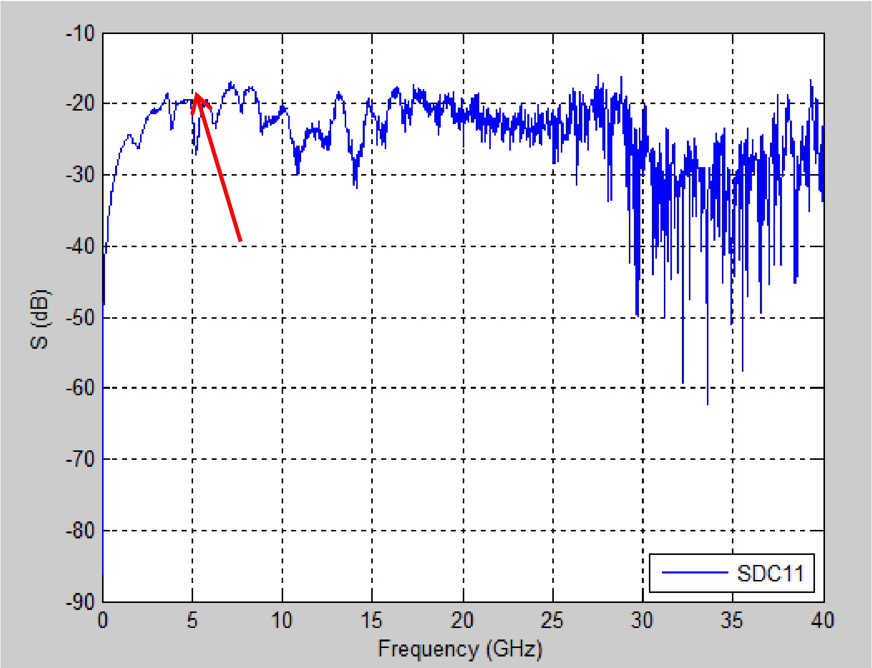




1. Edge mismatch
2. abberation one line
3. skew
4. amplitude mismatch

Mode Conversion in Frequency Domain





Differential to Common mode noise → EMI

@10Gbps, Nyquist 5GHz, -10dB (30%)
1Vdiff → 0.3Vcomm

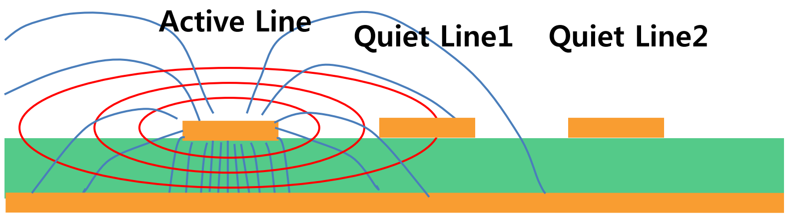
Common to Differential Mode → Jitter, Noise

@5GHz, -20dB (10%)
0.3Vcomm → 0.03Vdiff

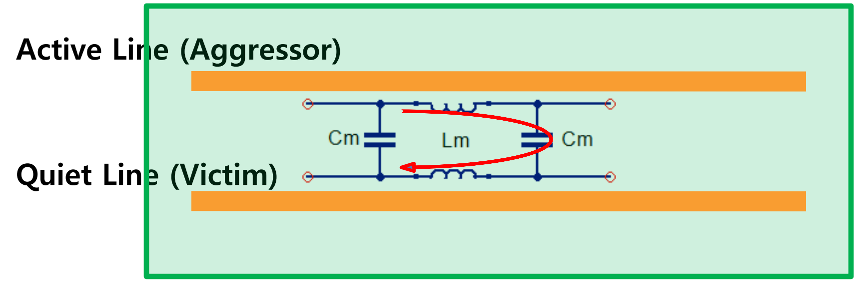
High Speed Characteristics of Interconnects

- Characteristic Impedance and TDR
- Speed of Signal and Skew
- Insertion/Return Loss, or S-parameters
- Differential Signal & Mode Conversion
- **Crosstalk**

Cause of Crosstalk



Electric Field Lines
Magnetic Field Lines in Microstrip

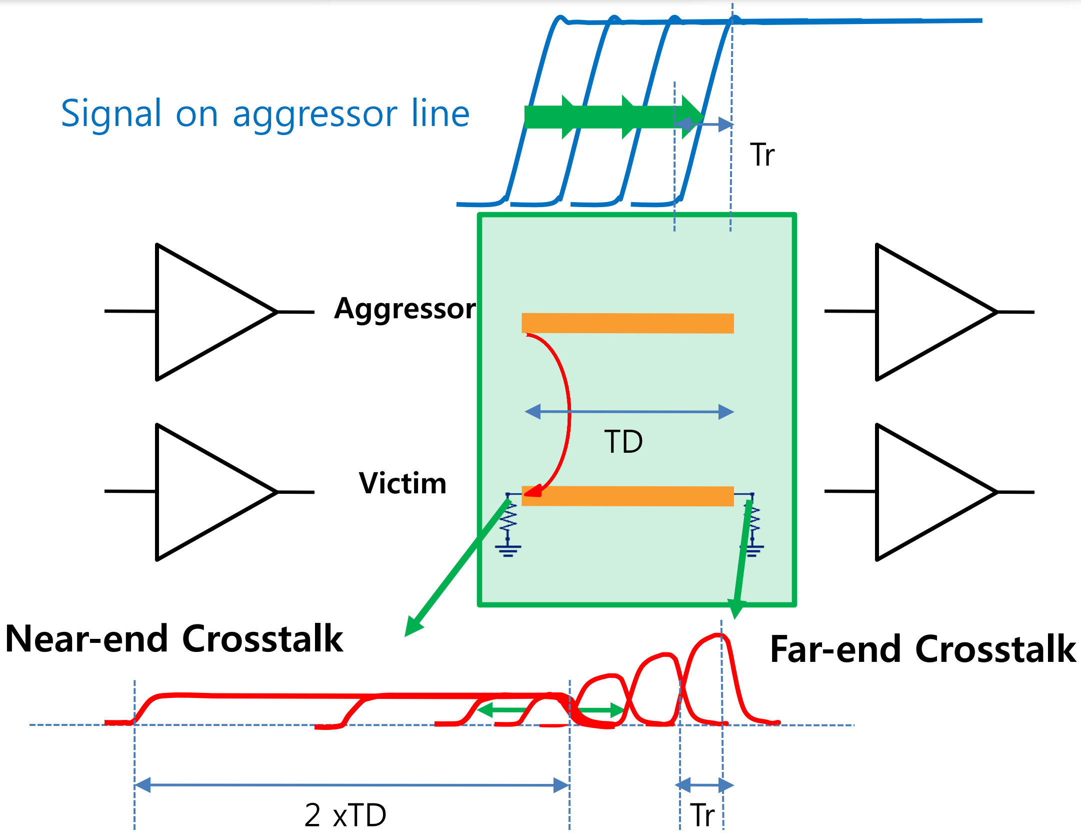


Capacitive coupling from Electric field → Mutual Capacitance (Cm)

Inductive coupling from Magnetic field → Mutual Inductance (Lm)

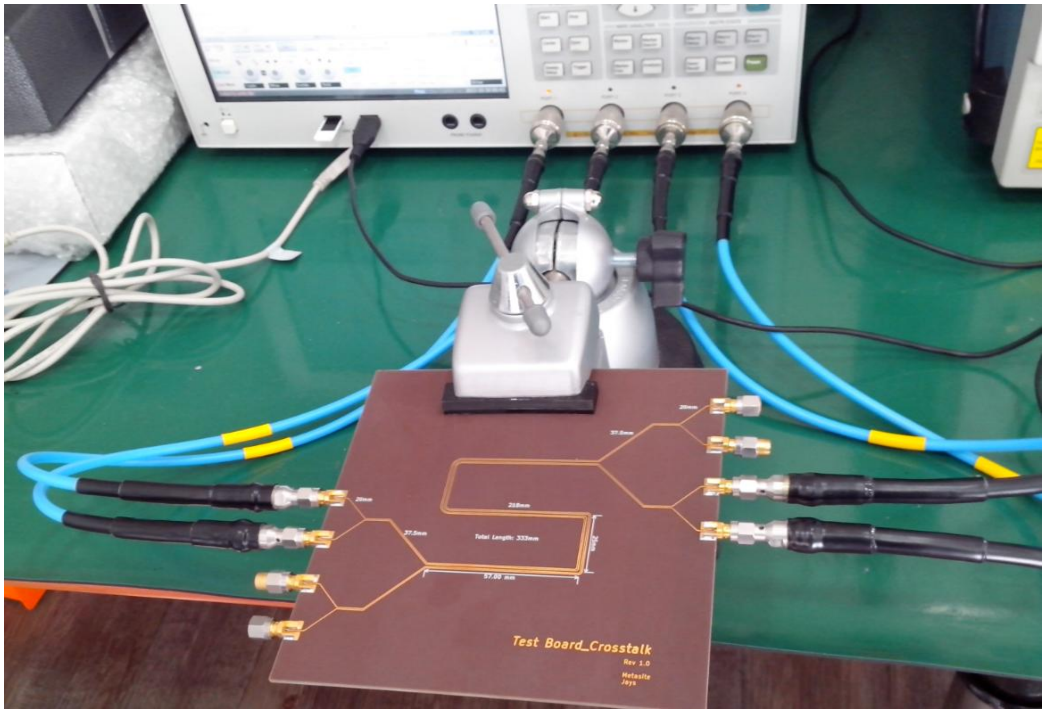
$$I_{noise,\ Cm} = C_m \times \frac{dV_{driver}}{dt} \qquad V_{noise,\ Lm} = L_m \times \frac{dI_{driver}}{dt}$$

Near and Far end Crosstalk

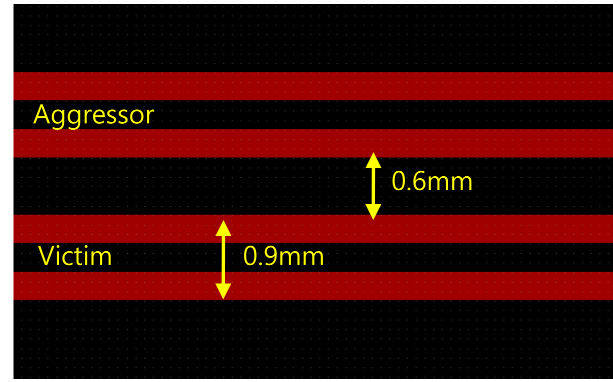


Crosstalk induced noise on victim line can affect on the signal integrity at near-end and far-end.

Crosstalk measurement Setup



<The setup for Far-end Crosstalk measurement, differential>

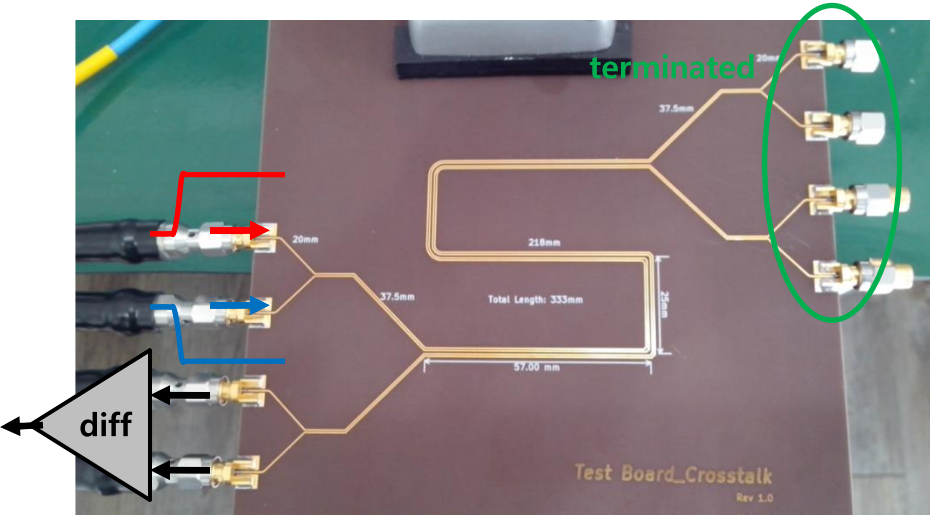


Two tightly coupled differential lines, 0.3x0.3x0.3mm
Space between differential lines: 0.6mm

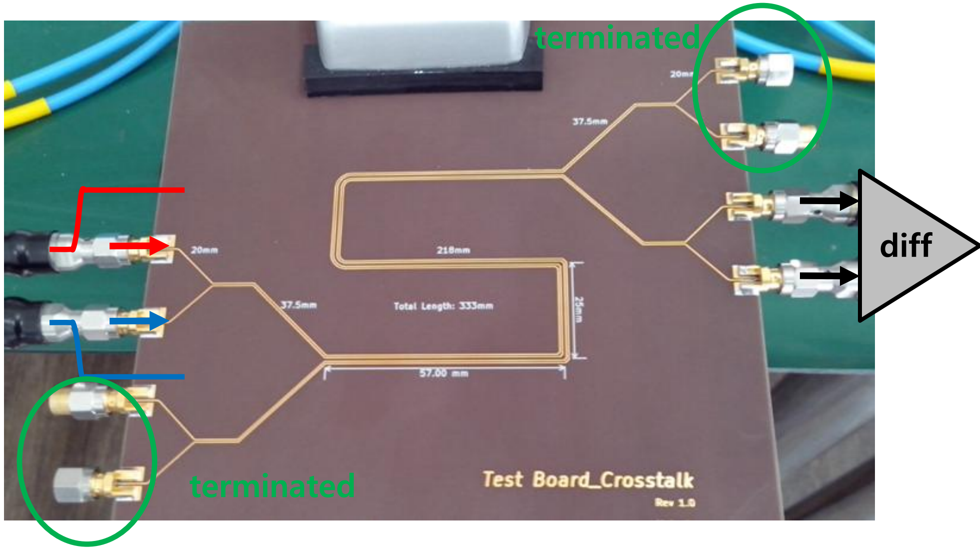
Coupled lines length: 220mm (8.67inch)
Total length: 333mm (13.1inch)

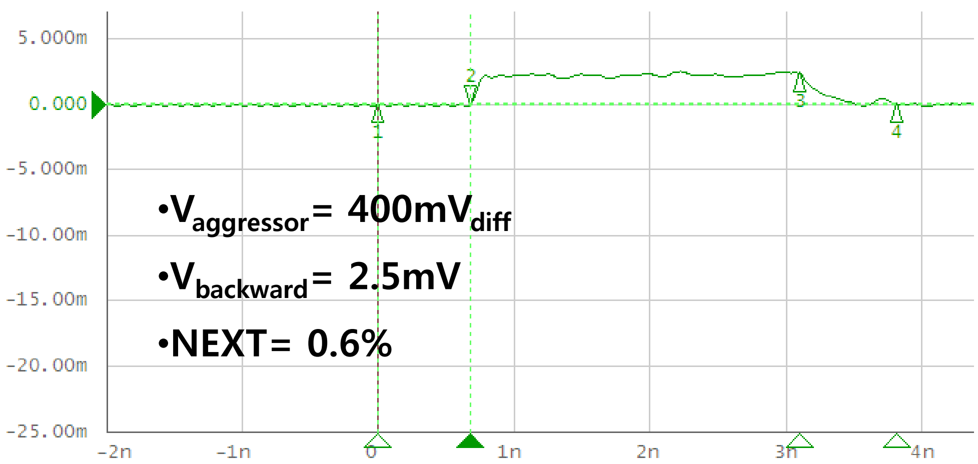
Crosstalk Measurement

Setup for NEXT measurement

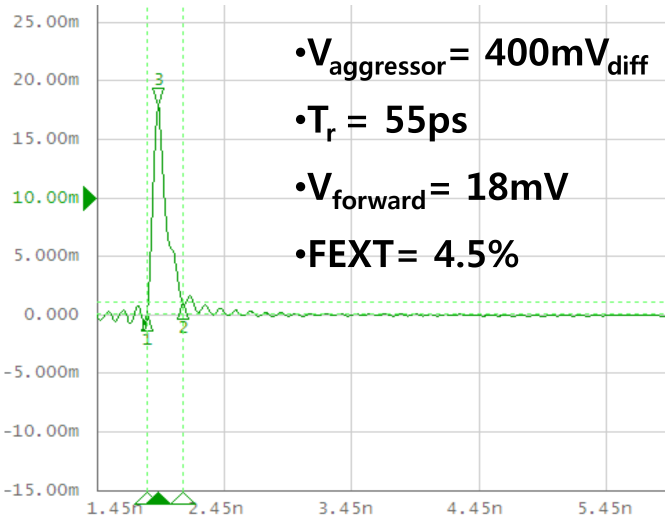


Setup for FEXT measurement



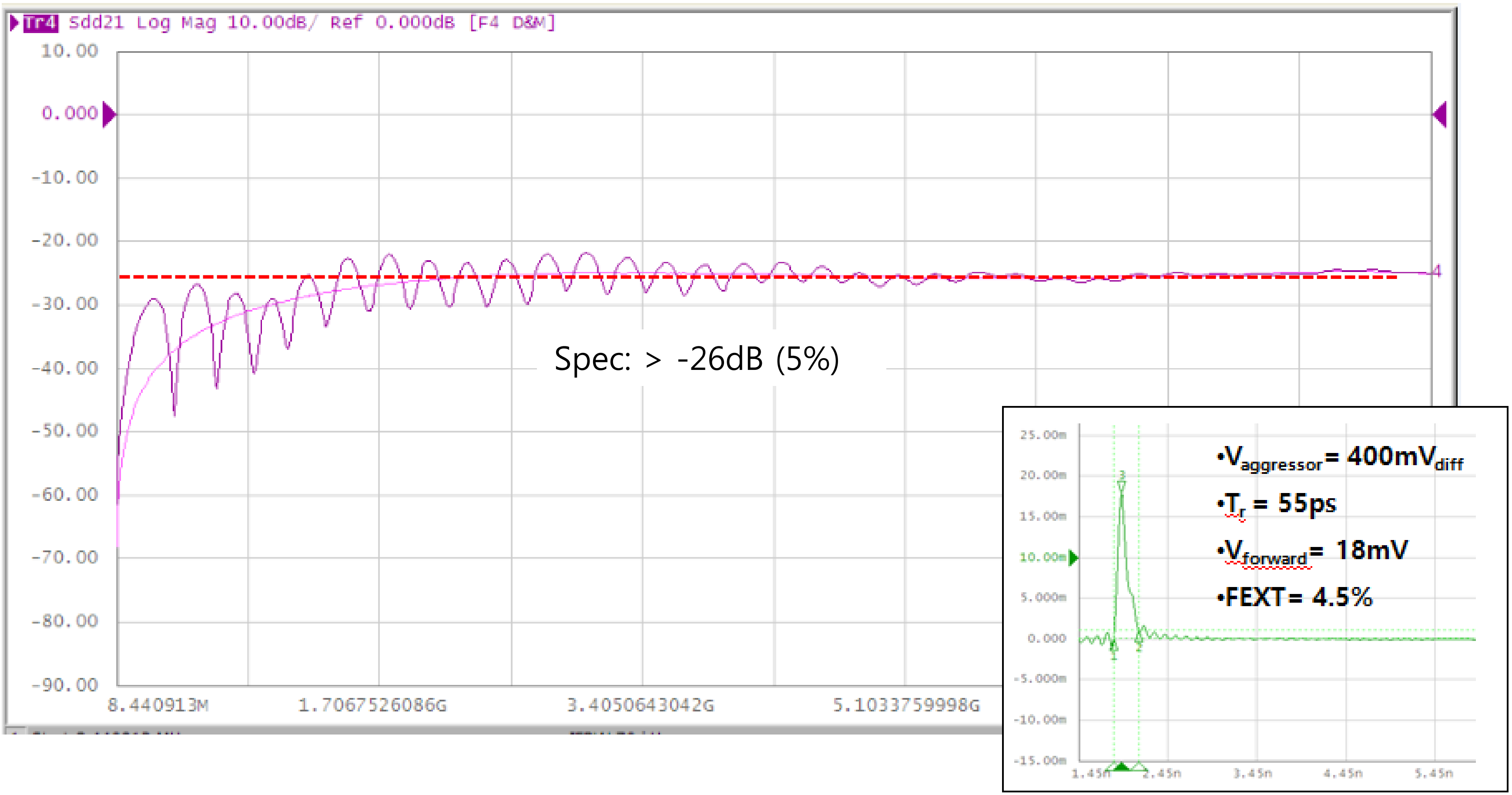


- $V_{aggressor}$ = 400mV_{diff}
- $V_{backward}$ = 2.5mV
- NEXT= 0.6%



- $V_{aggressor}$ = 400mV_{diff}
- T_r = 55ps
- $V_{forward}$ = 18mV
- FEXT= 4.5%

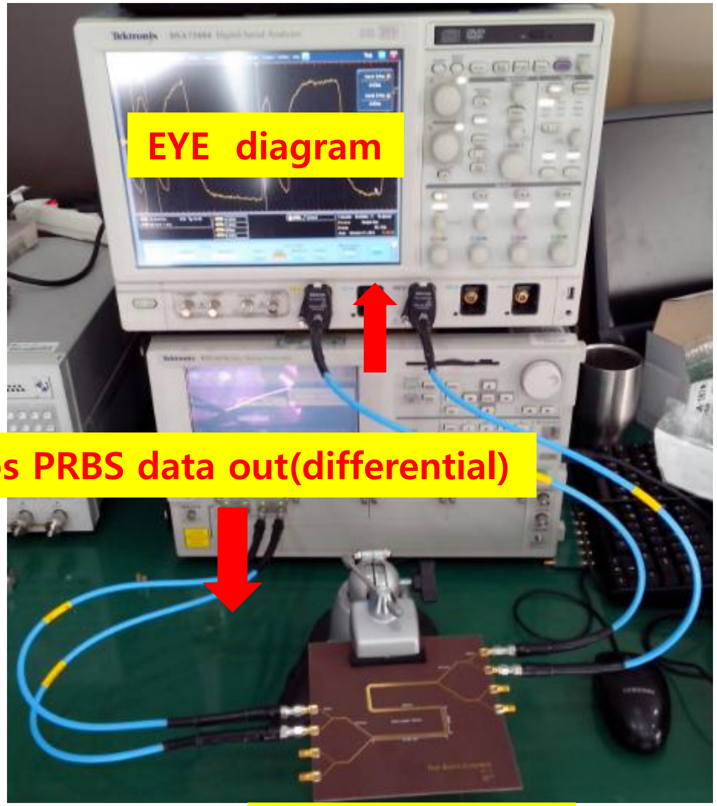
Example of Crosstalk in Frequency domain

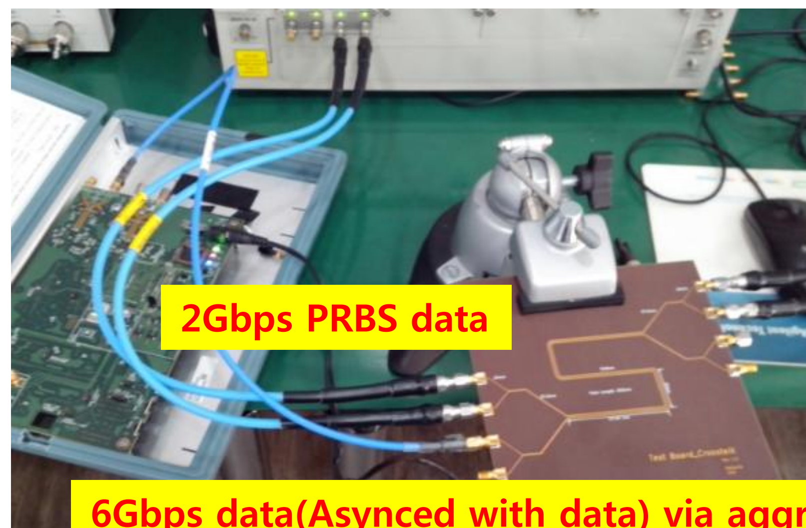


✓Far-end Noise(Xtalk) with and without termination, test board

✓Far-end noise(Xtalk) spec. of Displayport standard(1.1)

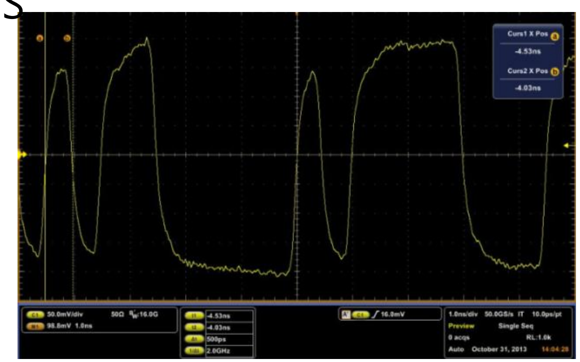
FEXT affect on EYE diagram



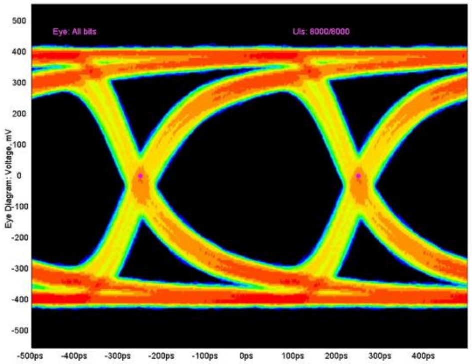


Example of Xtalk on EYE diagram

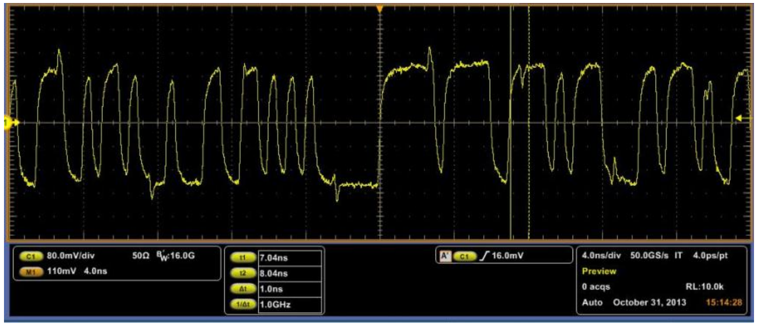
2Gbps PRBS



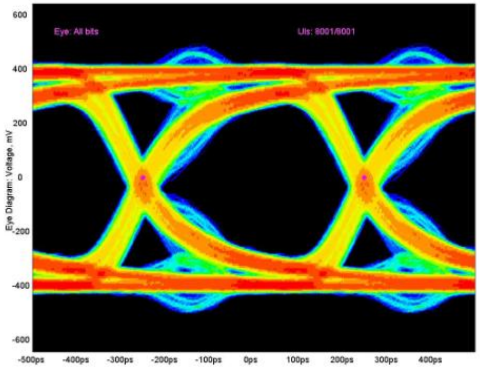
TJ= 106ps



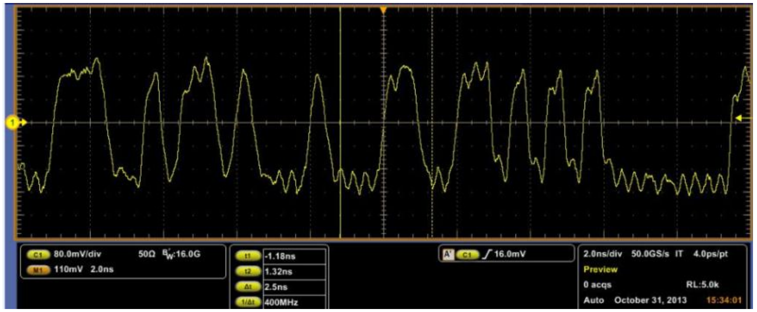
w. 200MHz Sync clock on aggressor



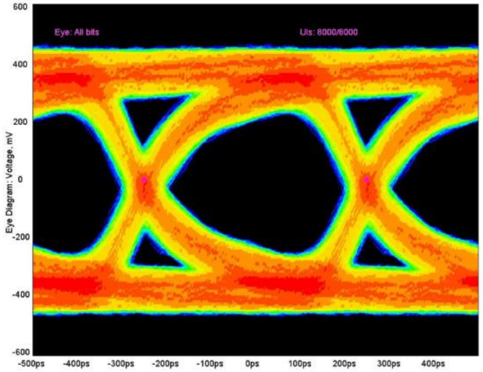
TJ= 146ps



w. 6Gbps Async data on aggressor

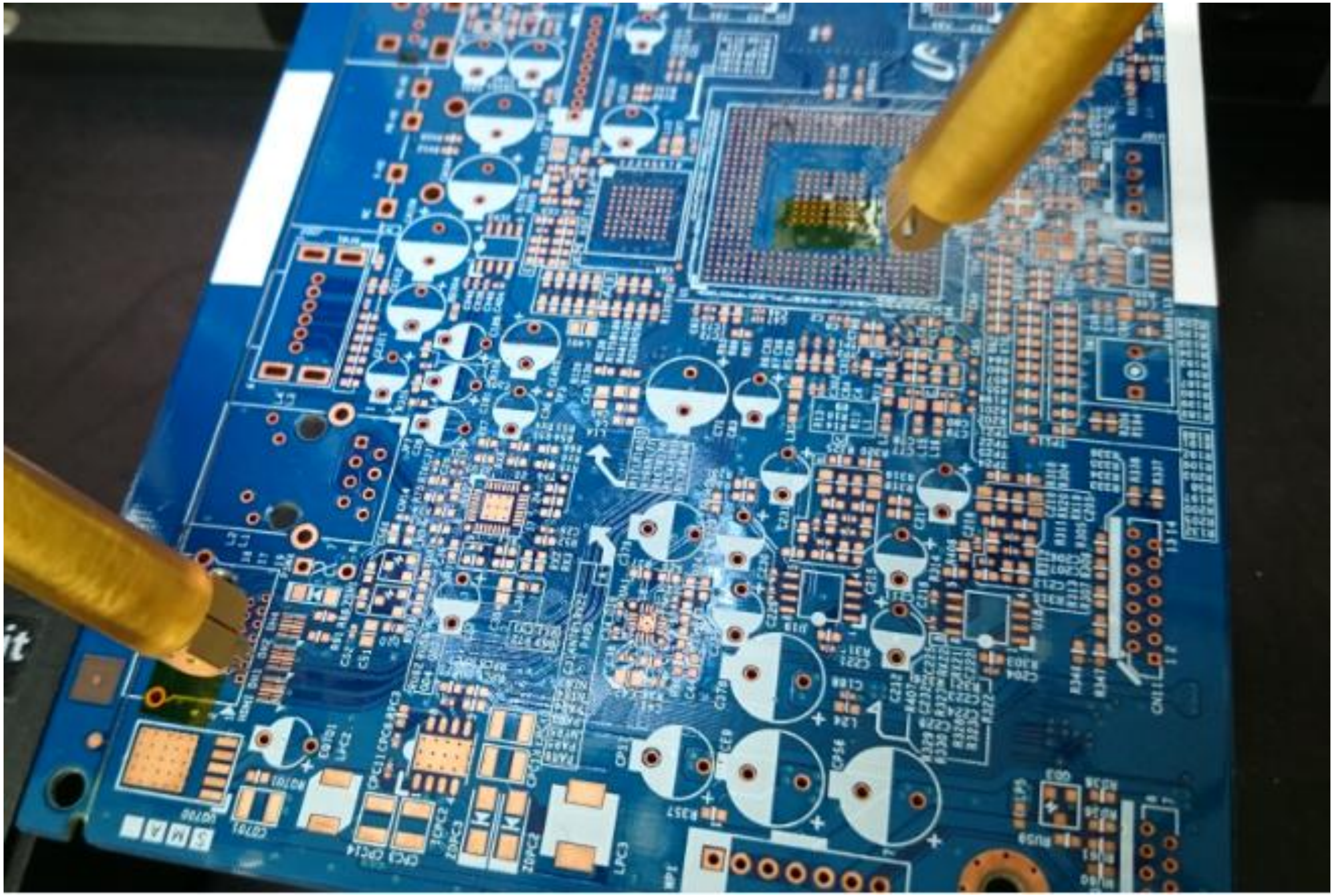


TJ= 184ps

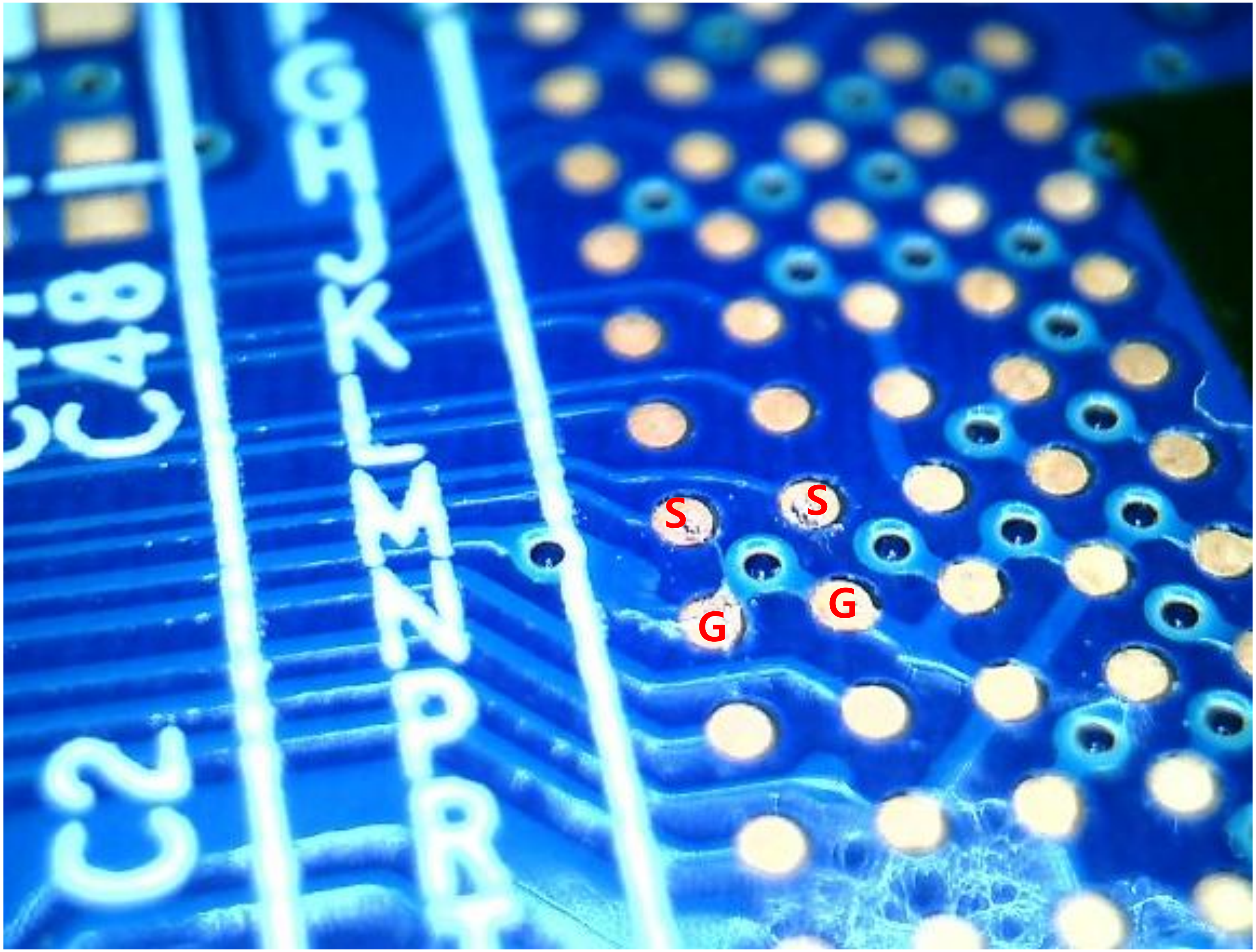


Measurement Setup

Probing on the real board

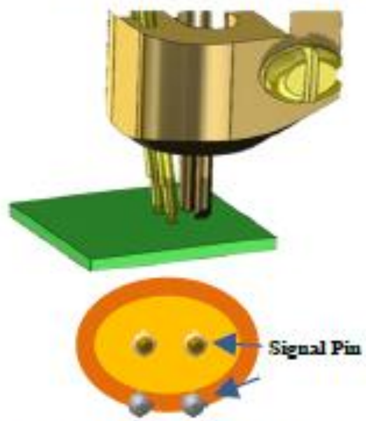


Test Pad (BGA)



Different types of Ground pin configuration

DVT40-GC-1MM-H

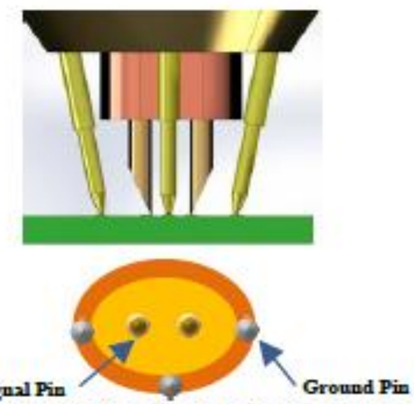


Ground Collar is reversible.
Pins can be place behind signal pins

DVT40 GHz GigaProbes

Replaceable Ground Collar

DVT40-GC-1MM-L



View of Probe tips from bottom of probe

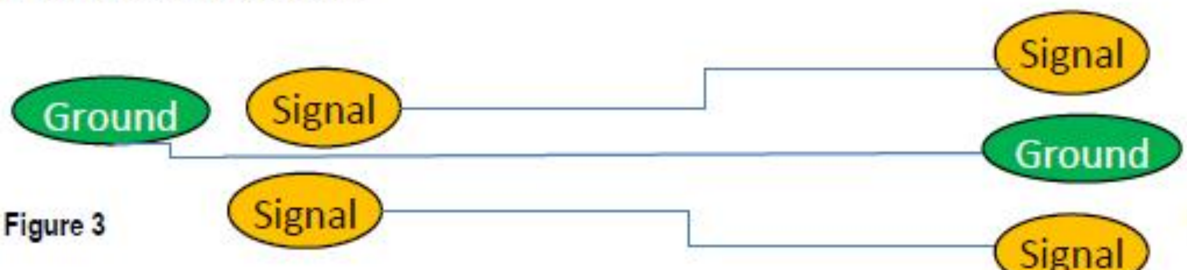


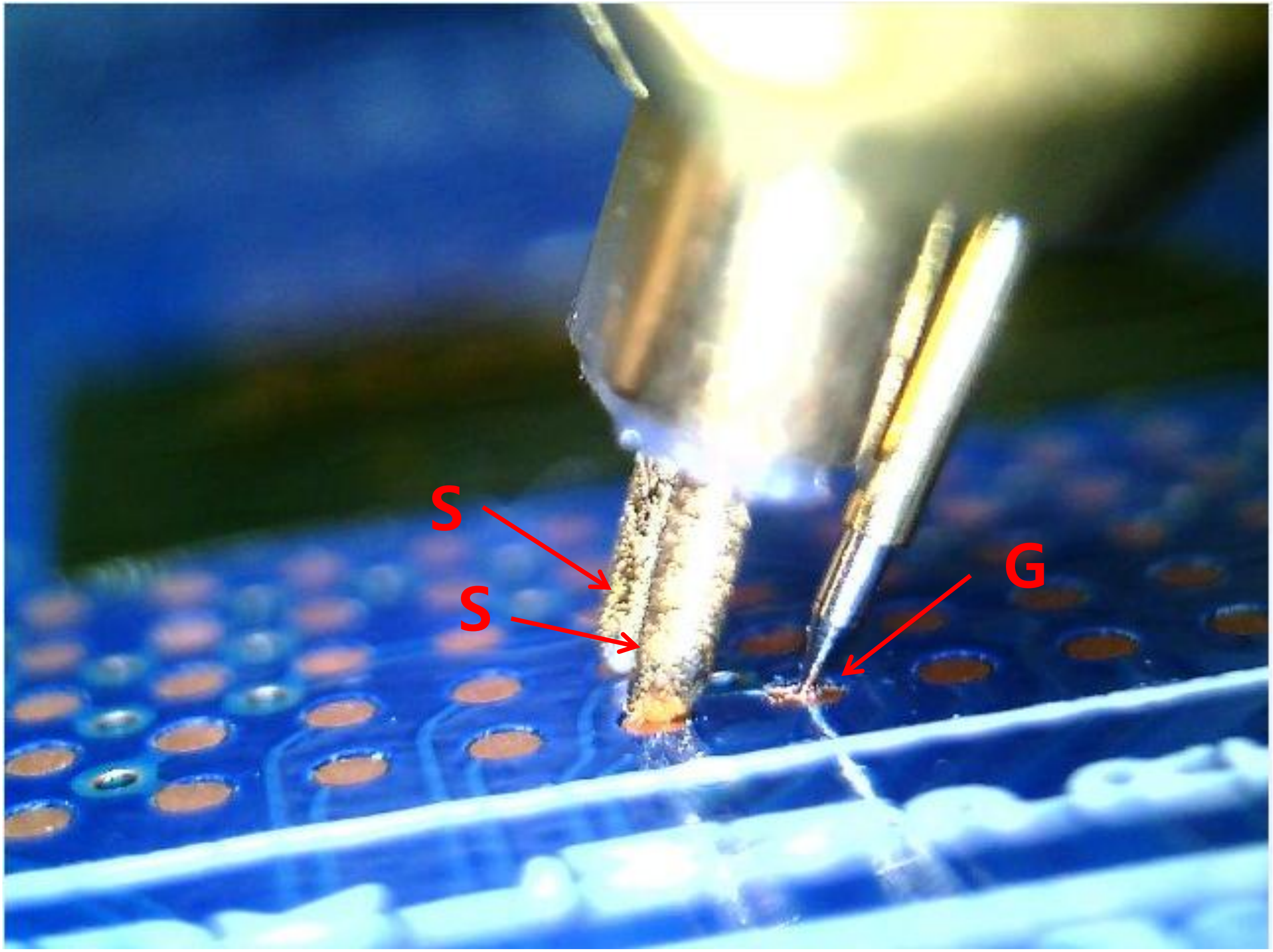
Figure 3

Figure 4

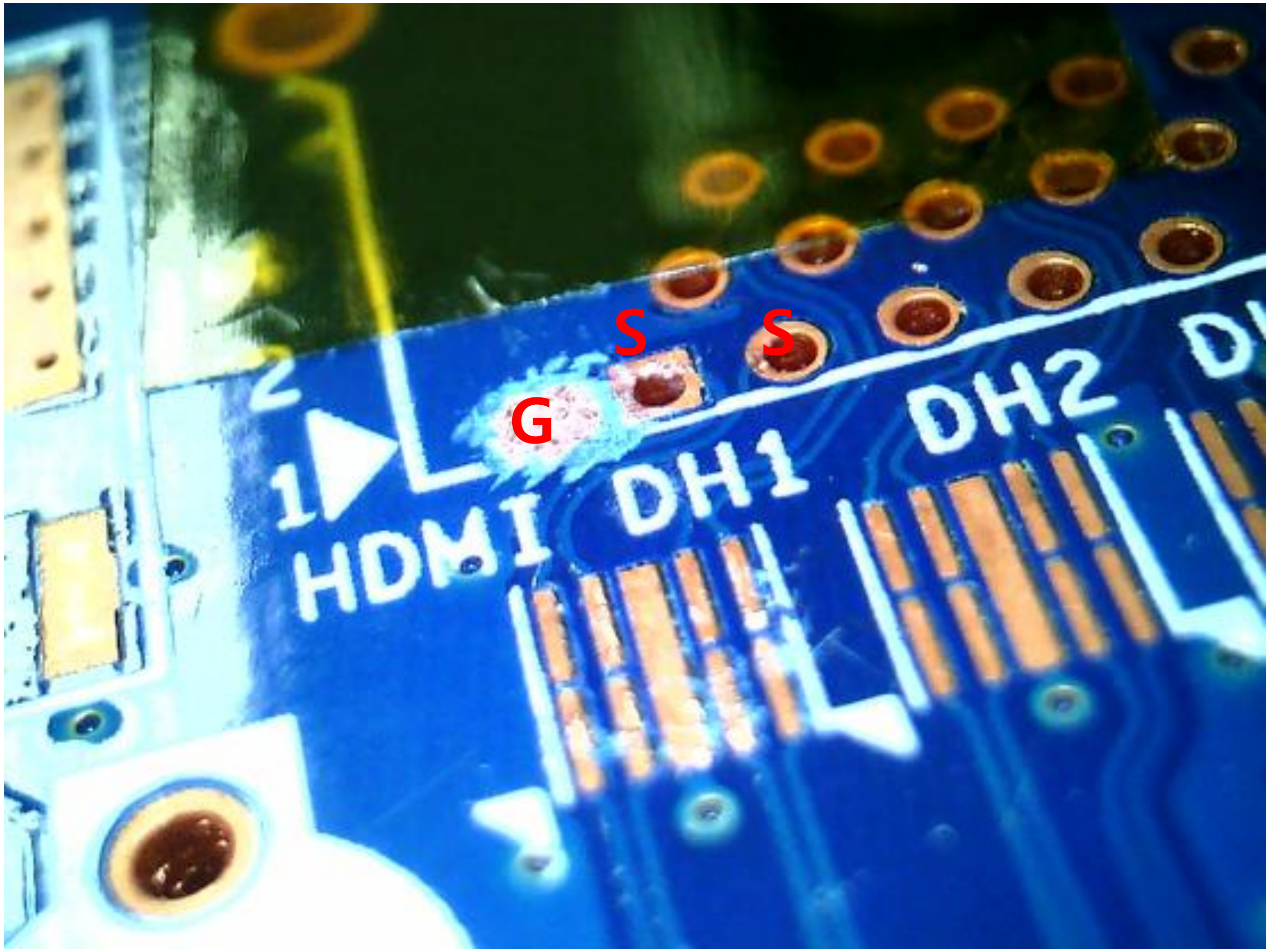
Use **DVT40-GC-1MM-H** ground collar when ground pin is <u>behind/front</u> signal pin

Use **DVT40-SPARAM In-Line** ground collar when ground pin is <u>next or in-line</u> to signal pin

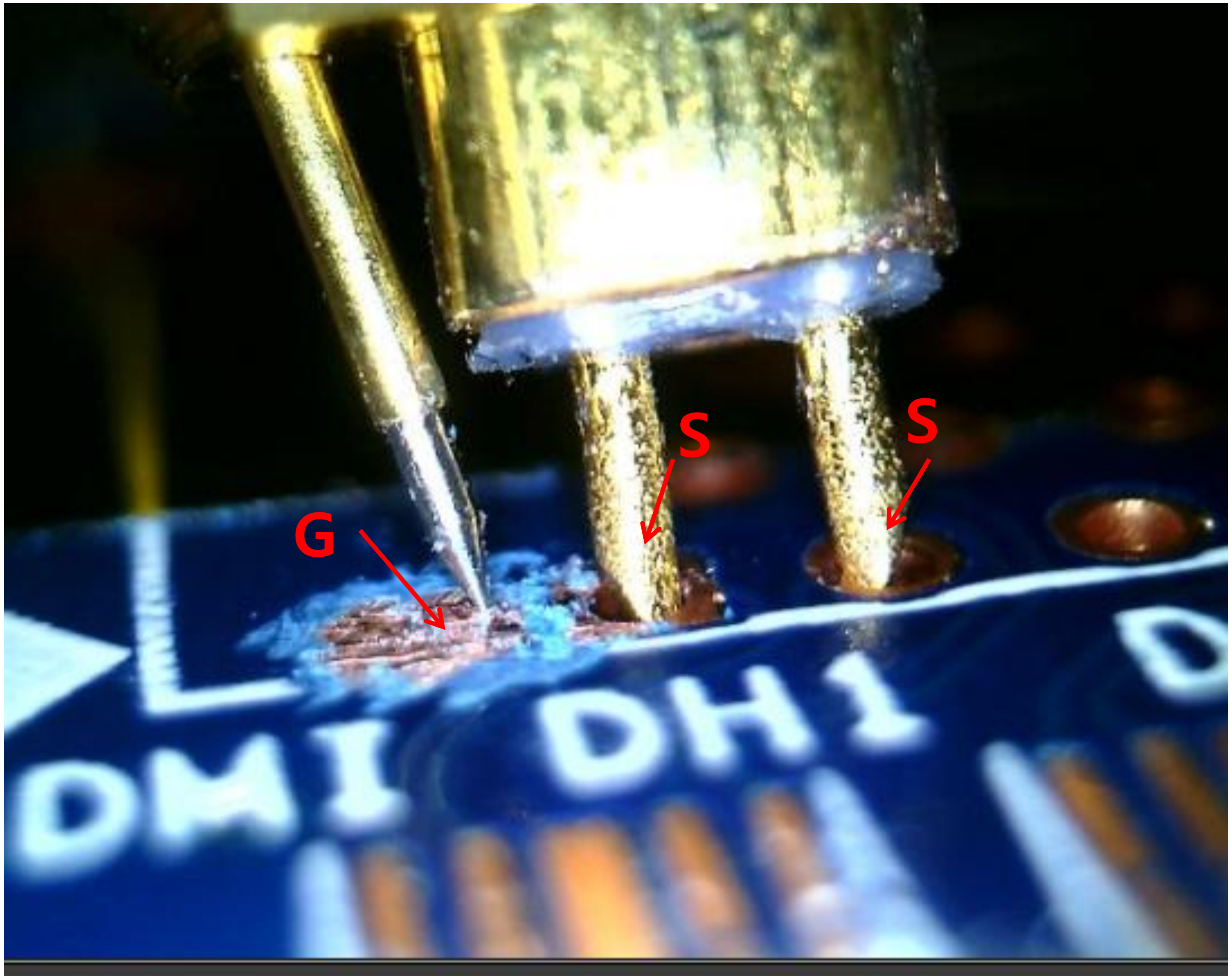
Probing on BGA



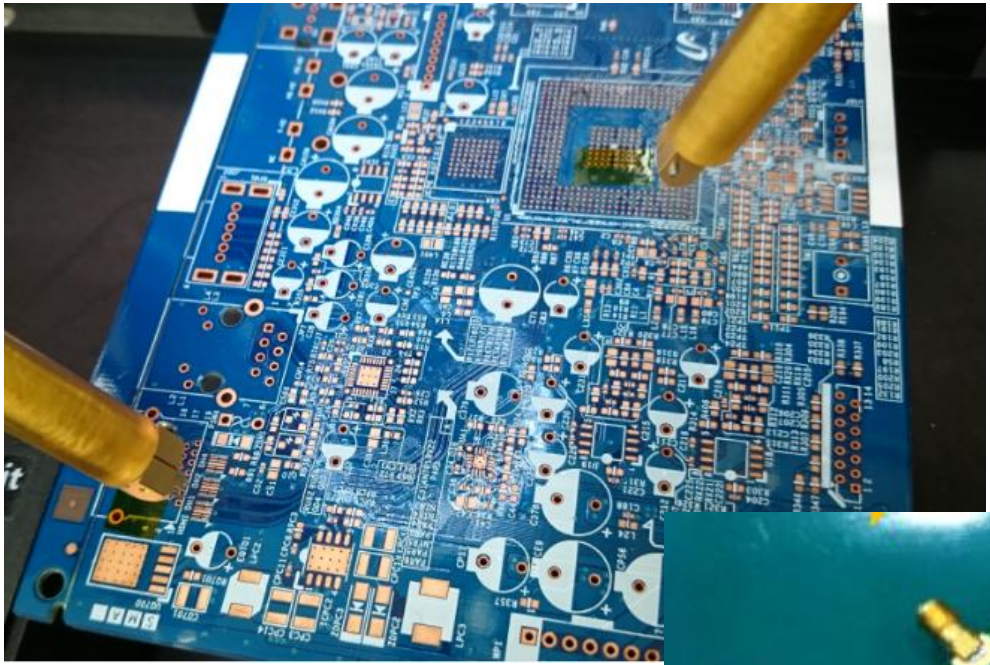
Test Pad (through hall)

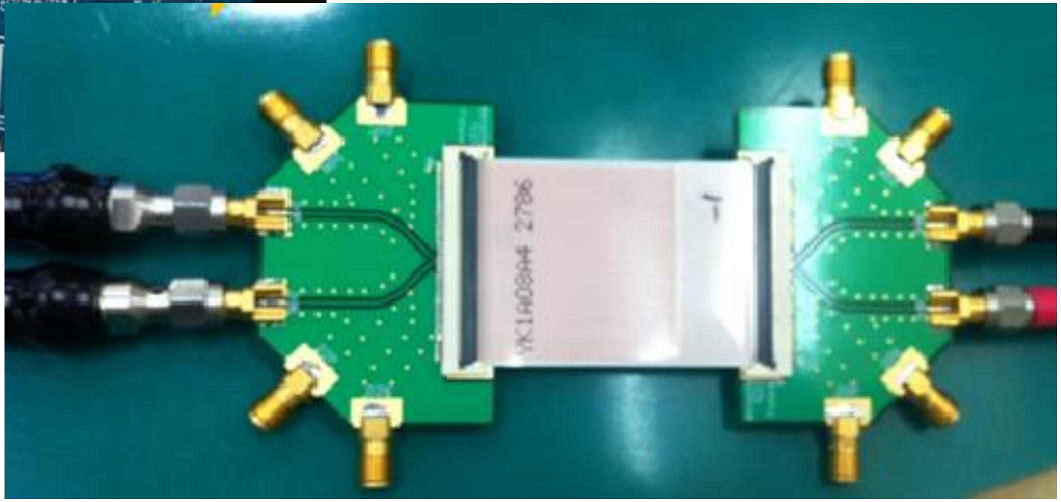


Probing on through hall

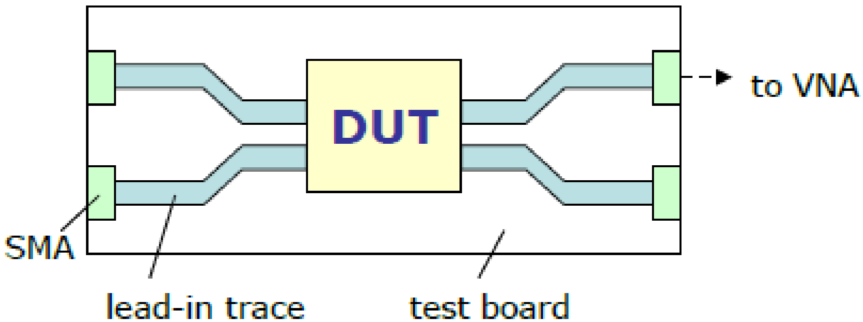


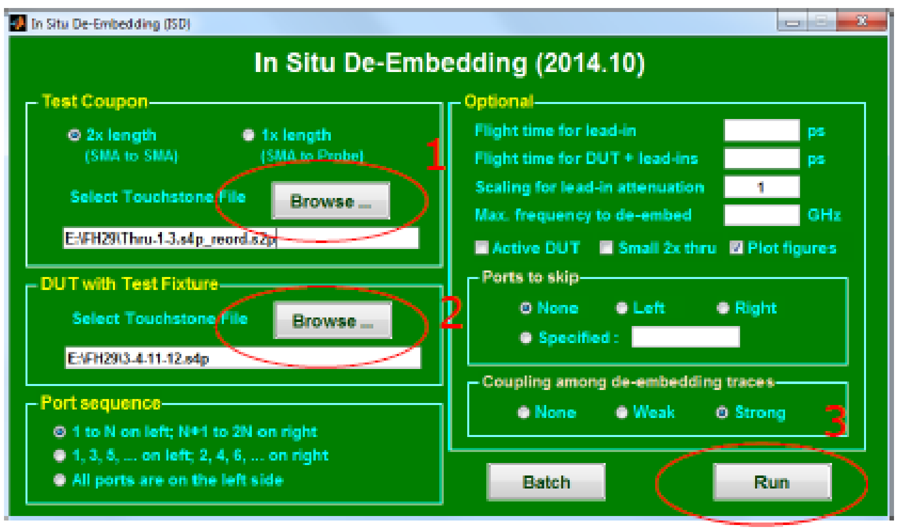
Fixture, Probe de-embedding





In-Situ De-embedding (ISD)
More accerate than TRL and AFR

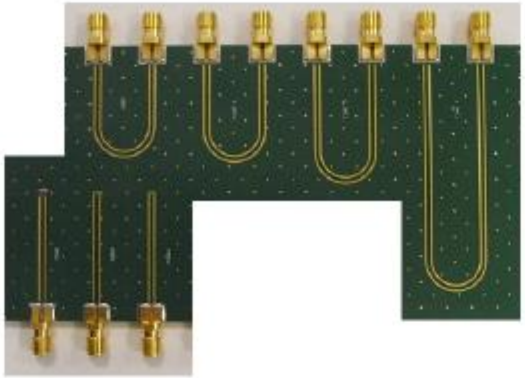




- The goal is to de-embed the fixture effect and extract DUT
- De-embedding is made easy as 1-2-3
  - Measure 2X thru coupon and DUT board and run ISD
- Through optimization in both time and frequency, ISD matches the fixture's exact impedance to extract DUT
- Save SMAs, board material and time
- Used by many companies
  - Cisco, Hirose, others

Why ISD is more accurate and saves $$$

TRL calibration board

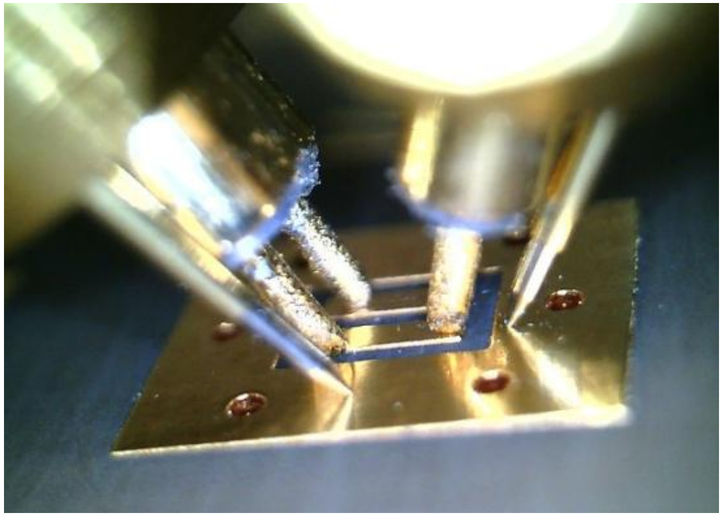


- More board space - Multiple test coupons are required
- Test coupons are used directly for de-embedding
- All differences between test coupons and actual DUT board get piled up into DUT results
- Expensive SMAs, board materials (Roger) and tight-etching-tolerance are required
  - Impossible to guarantee all SMAs and traces are identical (consider weaves, etching, ...)
- Time-consuming manual calibration is required
  - Reference plane is in front of DUT

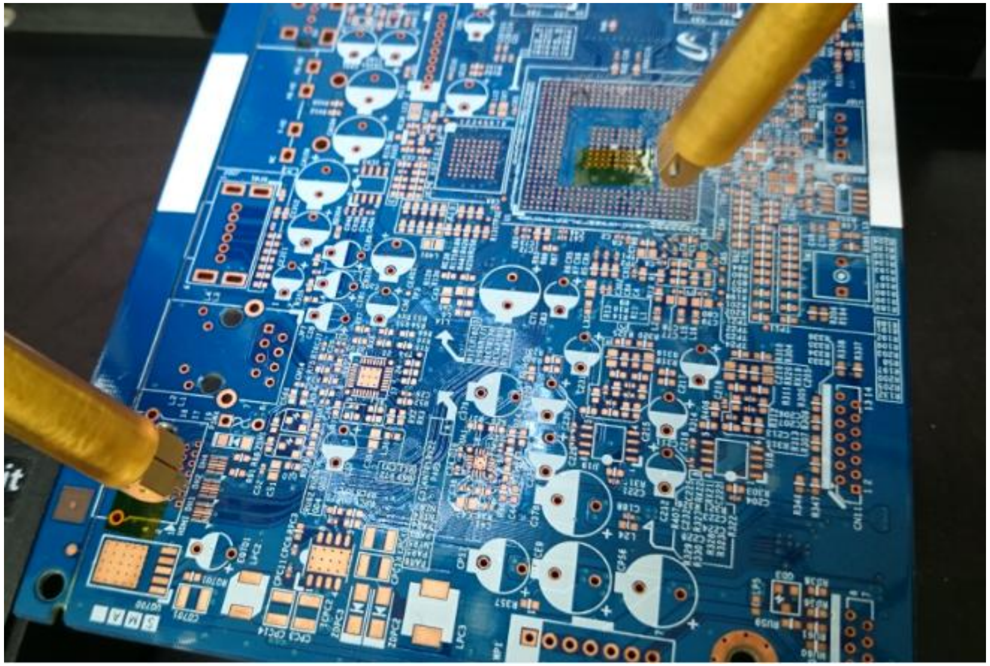
ISD test coupon

- Only one 2x thru test coupon is needed
- Test coupon is used only for reference, not for direct de-embedding
- Actual DUT board impedance is de-embedded
- Inexpensive SMAs, board materials (FR4) and loose-etching-tolerance can be used
- ECal can be used for fast SOLT calibration
  - Reference plane is in front of SMA
  - De-embedding is made easy as 1-2-3 with only two input files: 2x thru and DUT board (SMA-to-SMA) Touchstone files
  - More information: Both de-embedding and DUT files are provided as outputs

Measuring 2of S-parameters for ISD



Measure S4P of through left/right probes



Measure S4P of Board + Probes