In-Situ De-embedding (ISD)

Ching-Chao Huang
huang@ataitec.com

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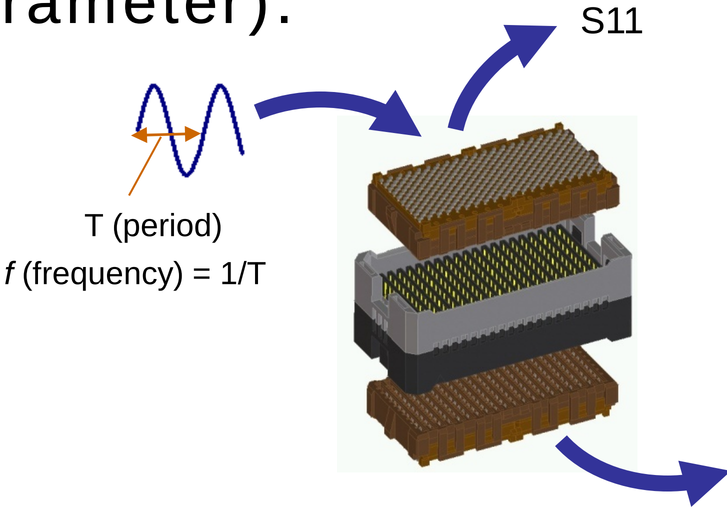
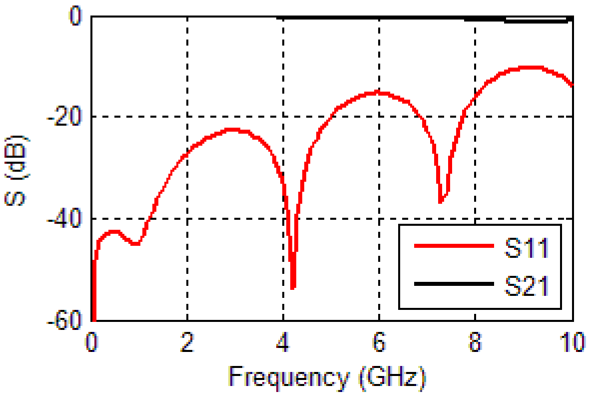
Outline

- What is causality
- What is In-Situ De-embedding (ISD)
- Comparison of ISD results with simulation and other tools
- How non-causal de-embedding affects connector compliance testing
- How to extract accurate PCB trace attenuation that is free of spikes and glitches
- How to extract a PCB's material property (DK, DF, roughness) by matching all IL, RL, NEXT, FEXT and TDR/TDT of de-embedded PCB traces

VNA and S parameter

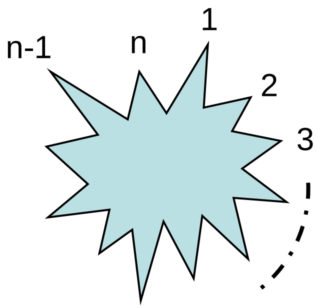
- Vector network analyzer (VNA) is an equipment that launches a sinusoidal waveform into a structure, varies the period (or frequency) of waveform, and lets us observe the transmitted and reflected wave as “frequency-domain response”.
- Such frequency-domain response, when normalized to the incident wave, is called scattering parameter (or, S parameter).





What is S parameter

- For an n-port (or I/O) device, S parameter is an n x n matrix:



$$[S_{ij}]_{n\times n} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & \ldots & S_{1n} \\ S_{21} & S_{22} & S_{23} & \ldots & S_{2n} \\ : & : & : & & : \\ S_{n1} & S_{n2} & S_{n3} & \ldots & S_{nn} \end{bmatrix}$$

- S_{ij} is called the S parameter from Port *j* to Port *i*.
- S_{ij} has a unique property that its magnitude is less than or equal to 1 (or, 0 dB) for a passive device.

$$|S_{ij}| \leq 1$$

$$S_{ij}(dB) = 20 \times \log_{10}|S_{ij}| \leq 0 \ \ dB$$

What is a Touchstone (.sNp) file

- S parameter at each frequency is expressed in Touchstone file format.

in GHz

S param

in dB and phase angle

Reference impedance

```
! Total number of ports = 4
! Total number of frequency points = 800
# GHZ  S  DB  R  50
0.025  -36.59296  48.77486  -41.40676  79.91354  -0.08648679  -6.544144  -49.50045  -105.618
       -41.39364  79.94686  -36.35592  51.52433  -49.4886  -105.5124  -0.09038406  -6.527076
       -0.08421237  -6.537903  -49.44814  -105.644  -36.0317  49.60022  -41.37105  79.91856
       -49.44393  -105.8186  -0.09834136  -6.542909  -41.36758  79.9318  -36.05645  48.98348
0.05  -32.22576  48.03161  -35.59394  74.15976  -0.1277169  -12.82876  -43.90183  -112.0995
       -35.58736  74.16304  -32.12694  50.92389  -43.90926  -112.0764  -0.132402  -12.7985
       -0.1242117  -12.82302  -43.89  -112.0248  -32.10987  50.3115  -35.56998  74.078
       -43.88424  -112.0517  -0.1381616  -12.80199  -35.56758  74.06782  -31.94136  50.49276
0.075  -29.88861  42.02766  -32.19713  68.06704  -0.1589249  -19.05252  -40.67476  -118.8188
       -32.19116  68.0941  -29.7086  45.41557  -40.63857  -118.837  -0.1635606  -19.01593
       -0.1603356  -19.0376  -40.63557  -118.8543  -29.89064  47.63852  -32.16917  67.94677
       -40.65711  -118.8021  -0.1737256  -19.02956  -32.16865  67.93389  -29.65444  46.15548

   :        :          :
```

Frequency in GHz

S11, S12, …, S44 in dB and phase angle

What is causality

cau·sal·i·ty

/kôˈzalədē/

noun

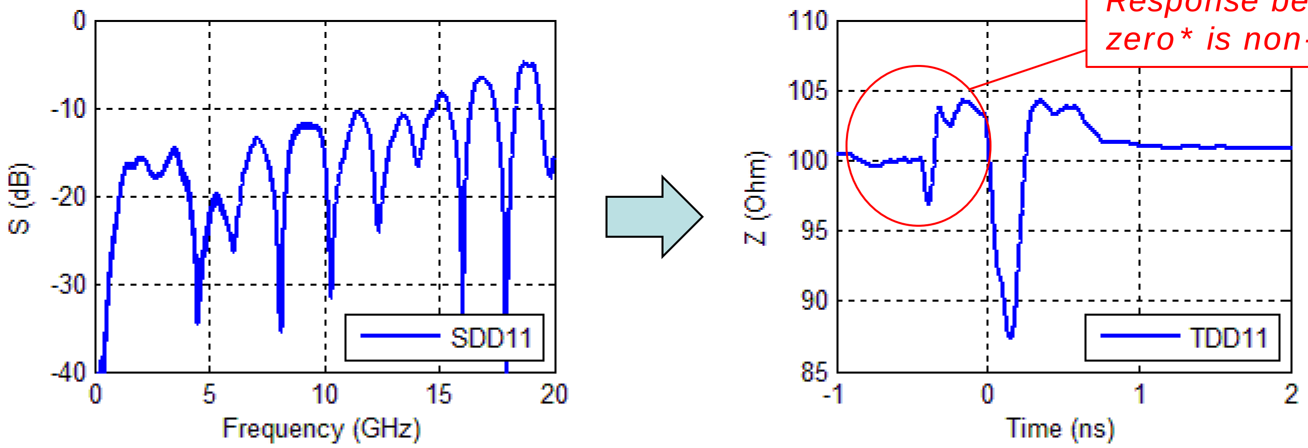
1. the relationship between cause and effect.
2. the principle that everything has a cause.

In other words:

Can not get something from nothing.

How to identify non-causal S parameter

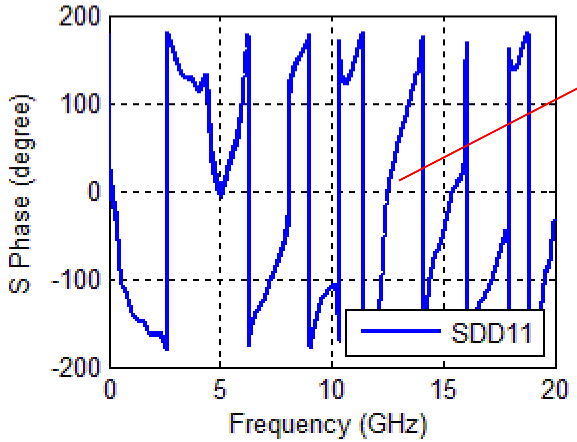
- Convert S parameter into TDR/TDT.



Response before time zero is non-causal.*

* Delay waveform by 1ns to see if tools do not show before time zero.

- Check phase angle.



Counterclockwise phase angle is non-causal.

Why does S parameter violate causality

- Measurement error (de-embedding), simulation error (material property) and finite bandwidth of S parameter all contribute to non-causality.
- Kramers-Kronig relations require that the real and imaginary parts of an analytic function be related to each other through Hilbert transform:

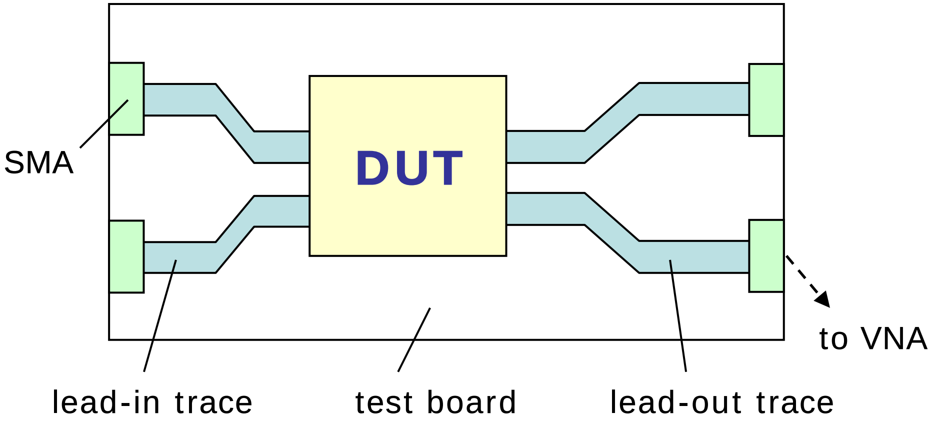
$$\Psi(\omega) = \Psi_R(\omega) + j\Psi_I(\omega)$$

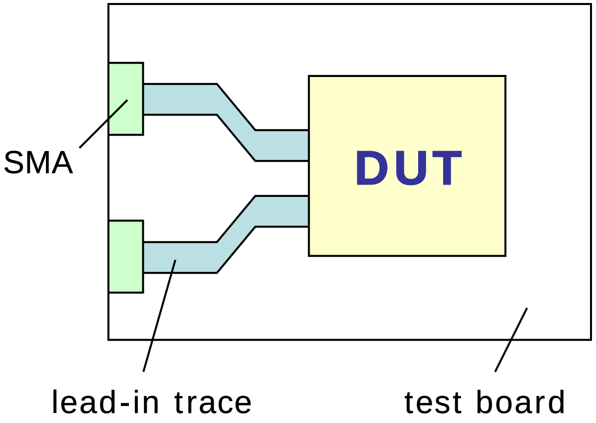
$$\Psi_R(\omega) = \frac{1}{\pi} P\int_{-\infty}^{\infty} \frac{\Psi_I(\omega')}{\omega' - \omega} d\omega'$$

$$\Psi_I(\omega) = -\frac{1}{\pi} P\int_{-\infty}^{\infty} \frac{\Psi_R(\omega')}{\omega' - \omega} d\omega'$$

What is de-embedding

- To remove the effect of fixture (SMA connector + lead-in/out) and extract the S parameter of DUT (device under test).

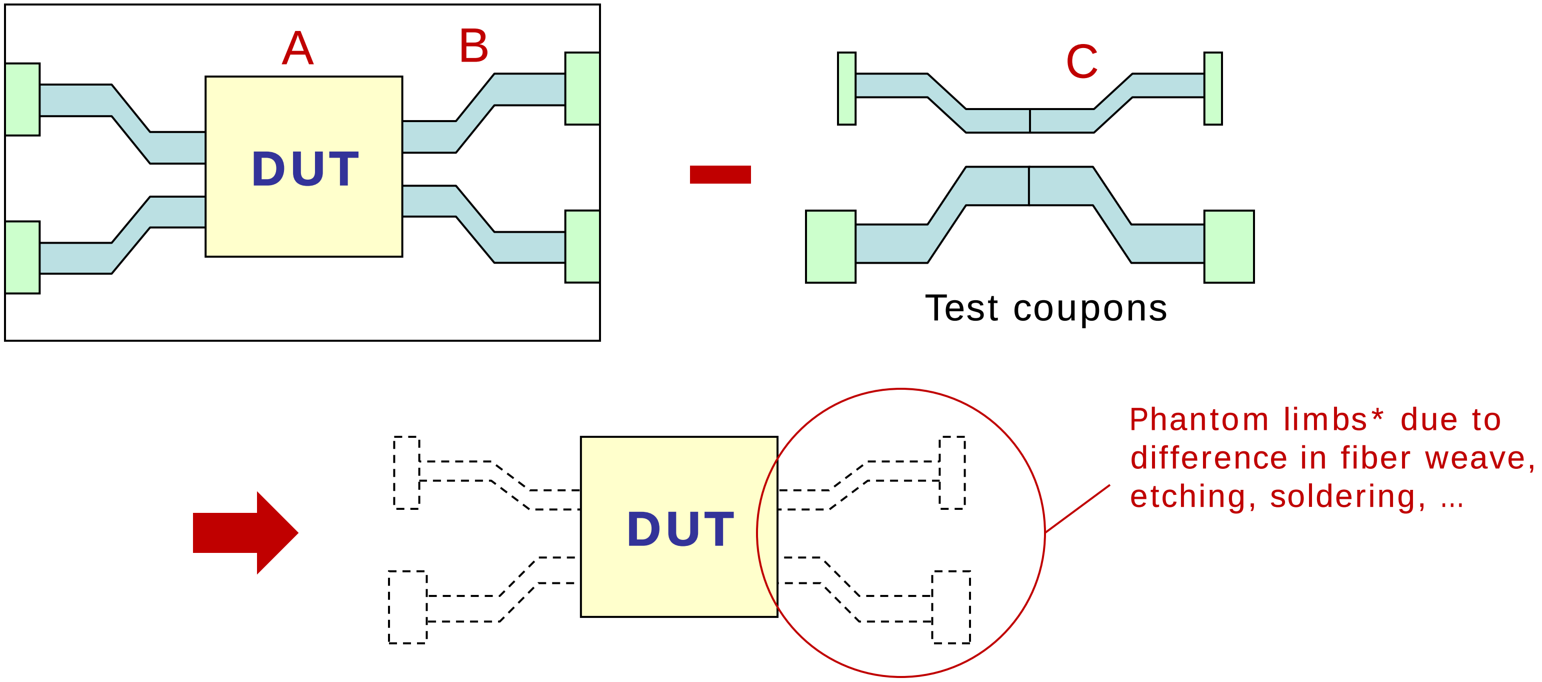




- The lead-ins and lead-outs don’t need to look the same.
- There may even be no lead-outs (e.g., package).

Why do most de-embedding tools give causality error

- Most tools use test coupons directly for de-embedding, so difference between actual fixture and test coupons gets piled up into DUT results.



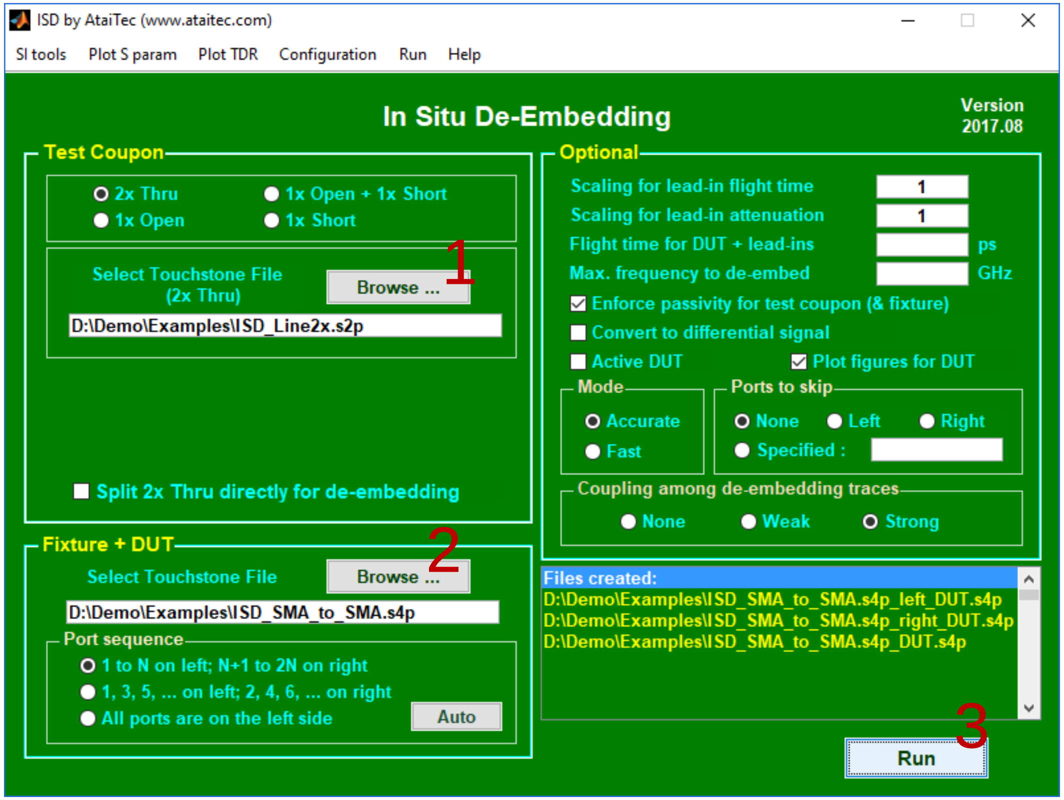
Phantom limbs* due to difference in fiber weave, etching, soldering, …

* http://www.edn.com/electronics-blogs/test-voices/4438677/Software-tool-fixes-some-causality-violations by Eric Bogatin

What is In-Situ De-embedding (ISD)

- Use “2x thru” or “1x open / 1x short” as reference and de-embed fixture’s actual impedance through numerical optimization.

In Situ



In Situ De-Embedding

Version 2017.08

Test Coupon

● 2x Thru ○ 1x Open + 1x Short
○ 1x Open ○ 1x Short

Select Touchstone File (2x Thru)
D:\Demo\Examples\ISD_Line2x.s2p

☐ Split 2x Thru directly for de-embedding

Fixture + DUT

Select Touchstone File
D:\Demo\Examples\ISD_SMA_to_SMA.s4p

Port sequence
● 1 to N on left; N+1 to 2N on right
○ 1, 3, 5, ... on left; 2, 4, 6, ... on right
○ All ports are on the left side

Optional

Scaling for lead-in flight time: 1
Scaling for lead-in attenuation: 1
Flight time for DUT + lead-ins: ps
Max. frequency to de-embed: GHz
☑ Enforce passivity for test coupon (& fixture)
☐ Convert to differential signal
☐ Active DUT ☑ Plot figures for DUT

Mode
● Accurate
○ Fast

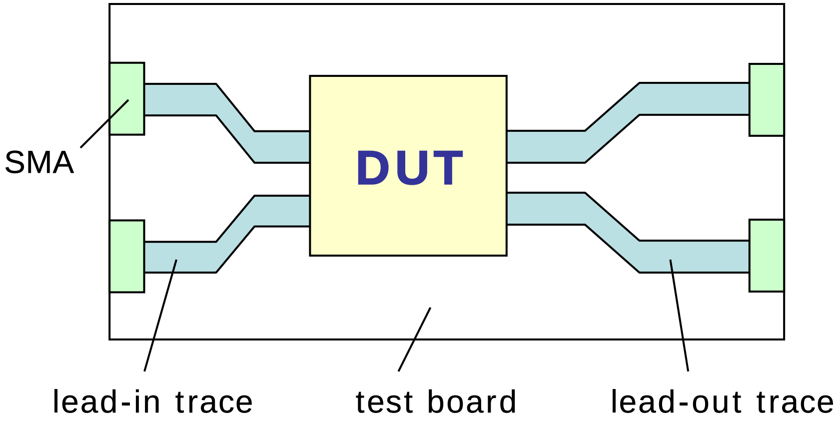
Ports to skip
● None ○ Left ○ Right
○ Specified :

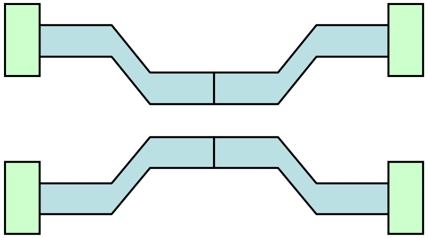
Coupling among de-embedding traces
○ None ○ Weak ● Strong

Files created:
D:\Demo\Examples\ISD_SMA_to_SMA.s4p_left_DUT.s4p
D:\Demo\Examples\ISD_SMA_to_SMA.s4p_right_DUT.s4p
D:\Demo\Examples\ISD_SMA_to_SMA.s4p_DUT.s4p

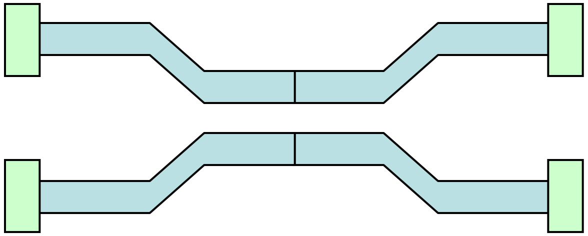
What is “2x thru”

- “2x thru” is 2x lead-ins or lead-outs.





2x thru for lead-ins

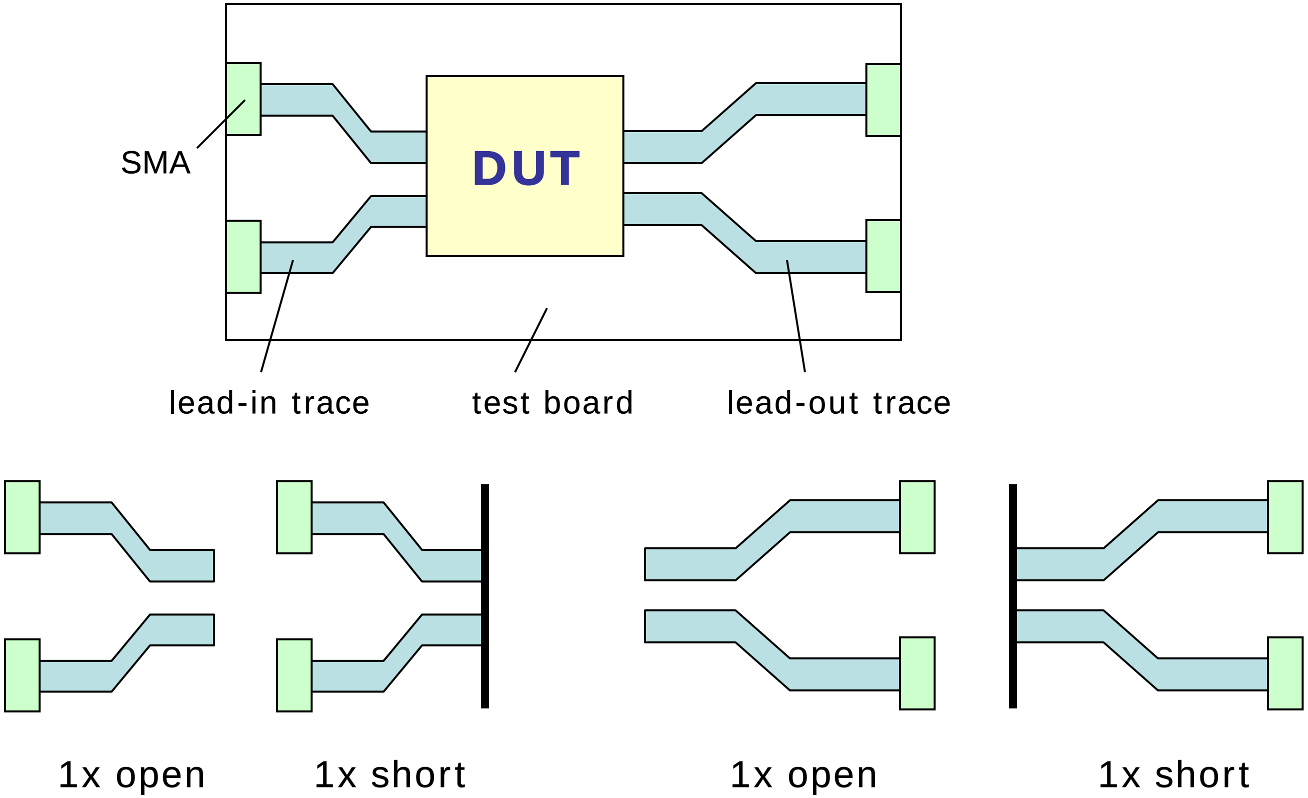


2x thru for lead-outs

2 sets of “2x thru” are required for asymmetric fixture.

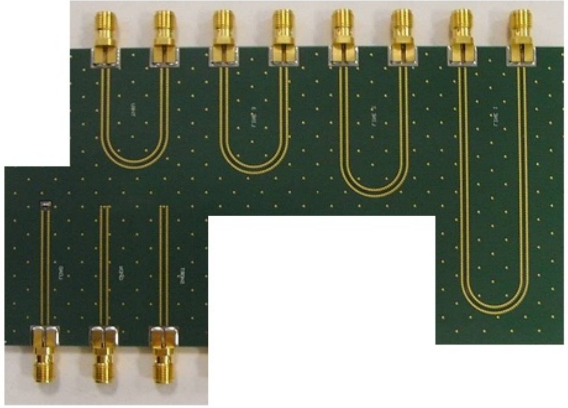
What is “1x open / 1x short”

- “1x open / 1x short” is useful when “2x thru” is not possible (e.g., connector vias, package, …).



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 difference between calibration and actual DUT boards gets 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

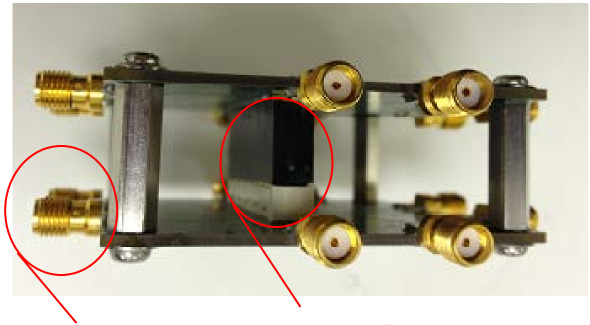
- Only one 2x thru test coupon is needed.
- Test coupon is used only for reference, not for direct de-embedding.
- Actual DUT board impedance is de-embedded.
- Inexpensive SMAs, board materials (FR4) and loose-etching-tolerance can be used.
- ECal can be used for fast SOLT calibration.
  - Reference plane is in front of SMA.
  - De-embedding requires 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.

* TRL = Thru-Reflect-Line

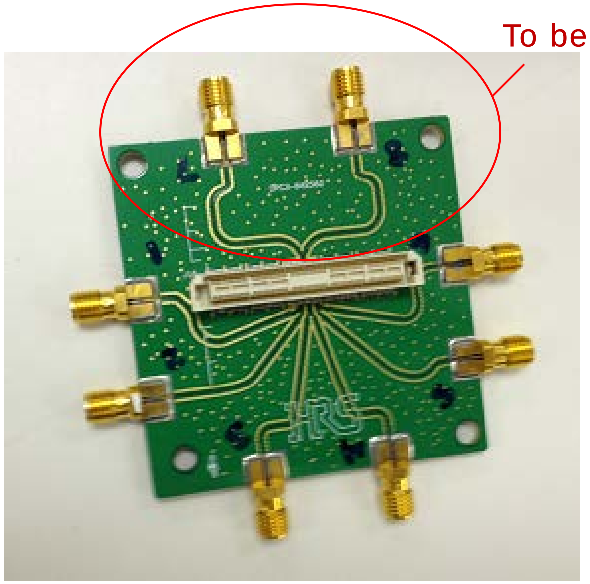
Example 1: Mezzanine connector

ISD vs. TRL

- In this example, we will use ISD and TRL to extract a mezzanine connector and compare their results.


SMA

Mezzanine connector (DUT)

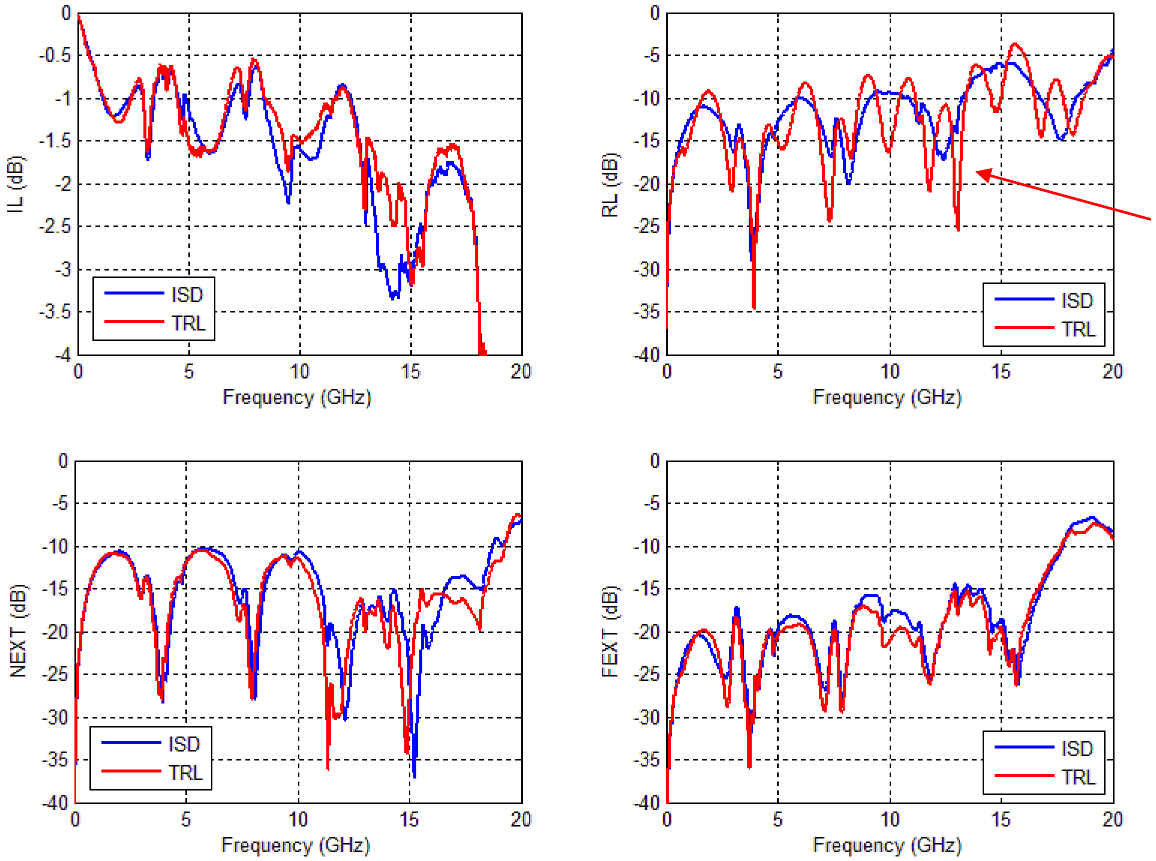

To be de-embedded

*Courtesy of Hirose Electric

DUT results after ISD and TRL

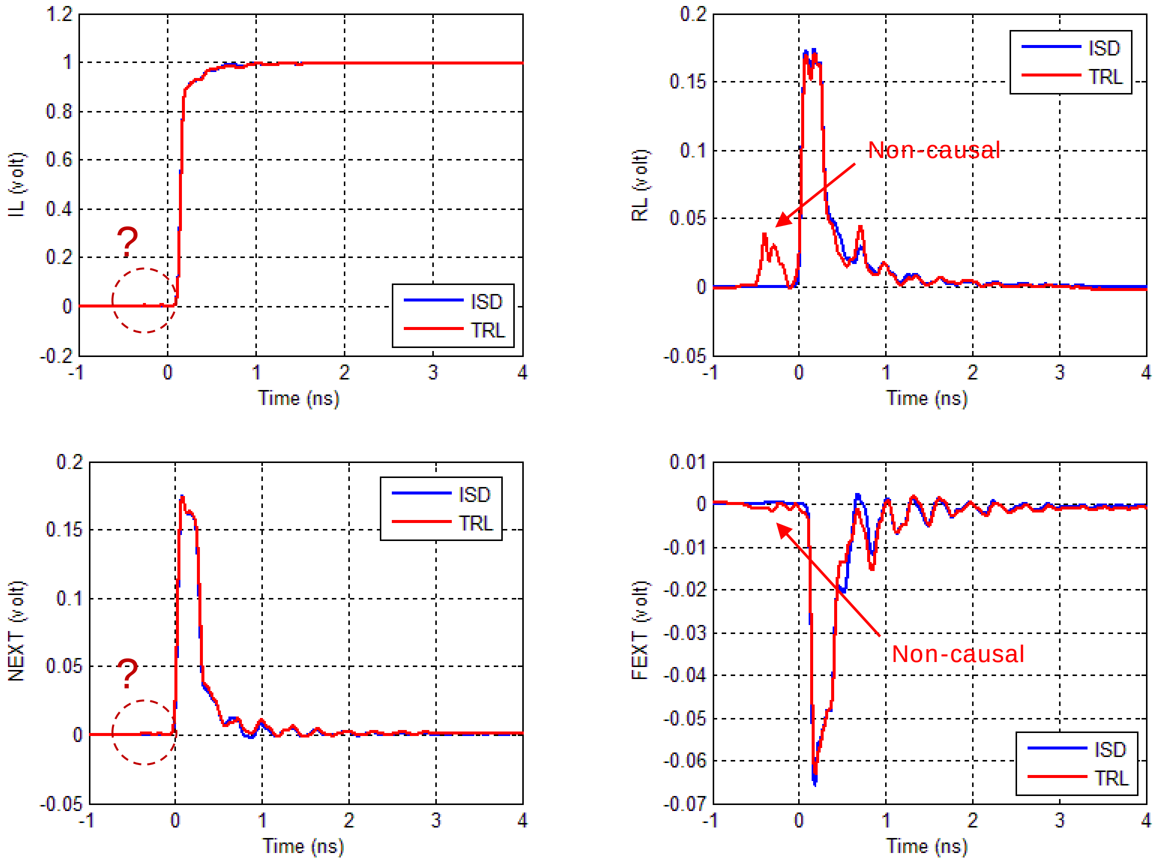
Which one is more accurate?

- TRL gives too many ripples in return loss (RL) for such a small DUT.



Non-causal ripples

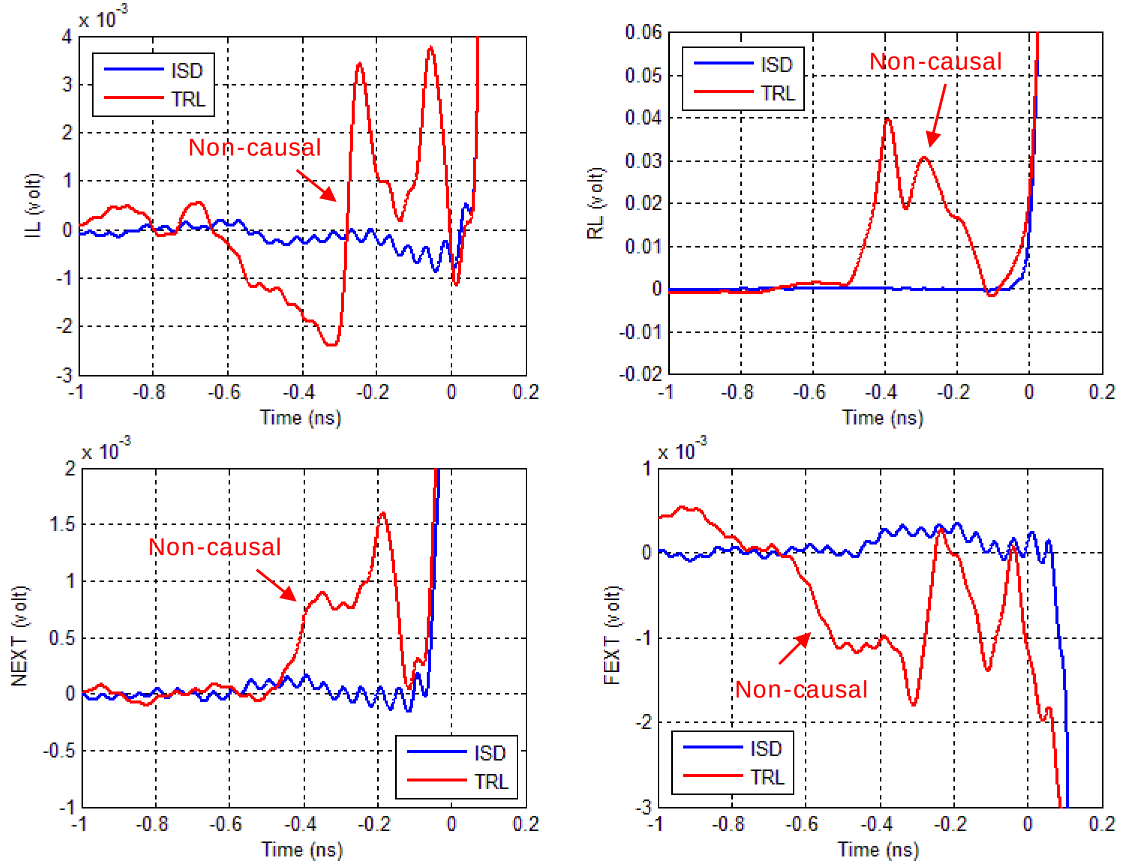
Converting S parameter into TDR/TDT shows non-causality in TRL results



Rise time = 40ps (20/80)

Zoom-in shows non-causal TRL results in all IL, RL, NEXT and FEXT

- TRL causes time-domain errors of 0.38% (IL), 25.81% (RL), 1.05% (NEXT) and 2.86% (FEXT) in this case*.

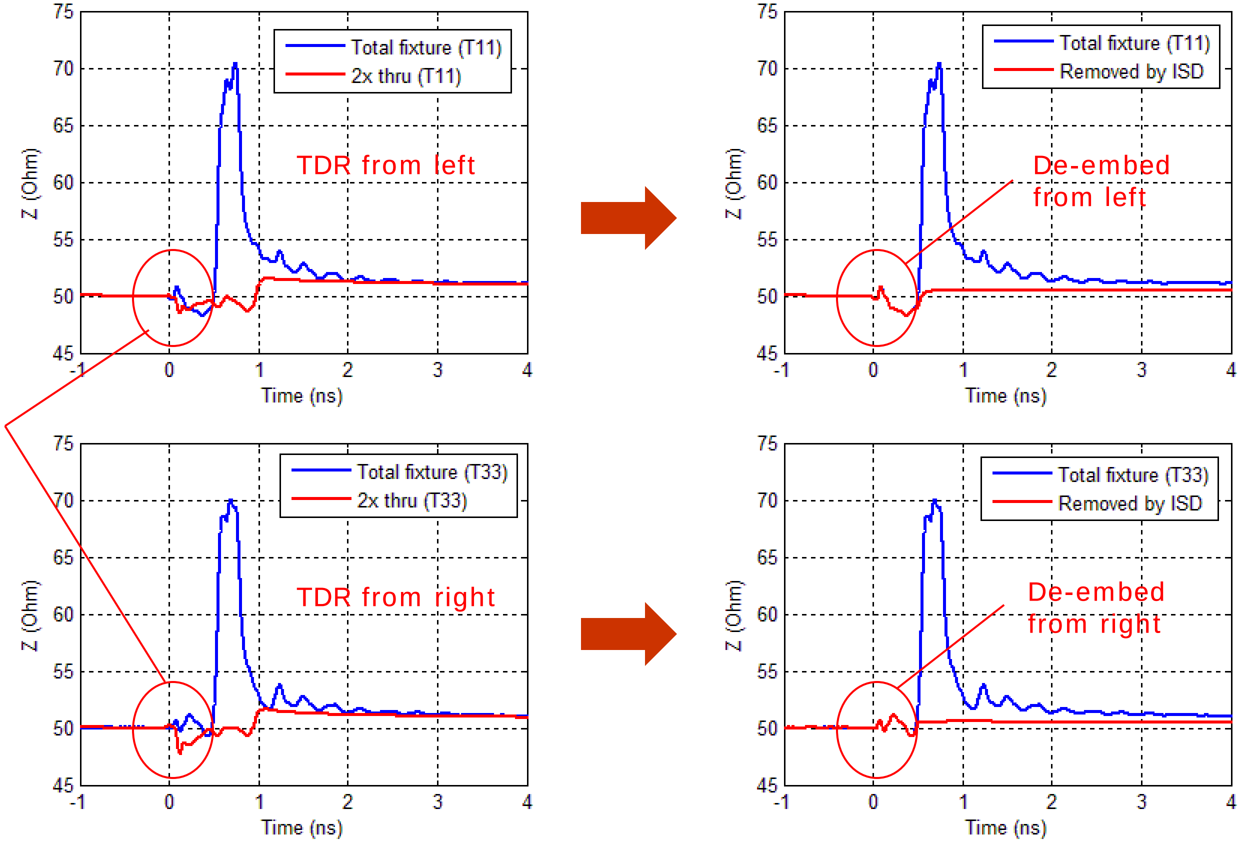


* The percentage is larger with single-bit response and/or faster rise time.

Rise time = 40ps (20/80)

How did ISD do it?

- Through numerical optimization, ISD de-embeds fixture’s impedance exactly, independent of 2x thru’s impedance.

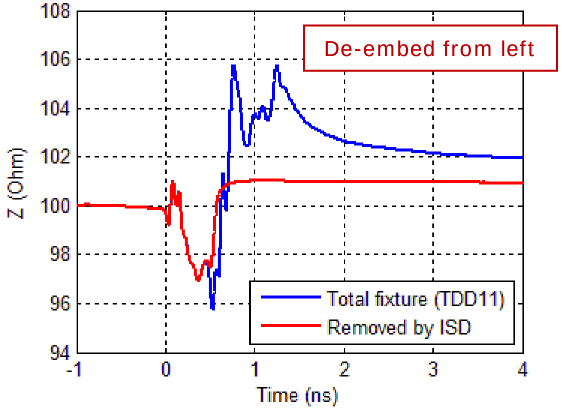


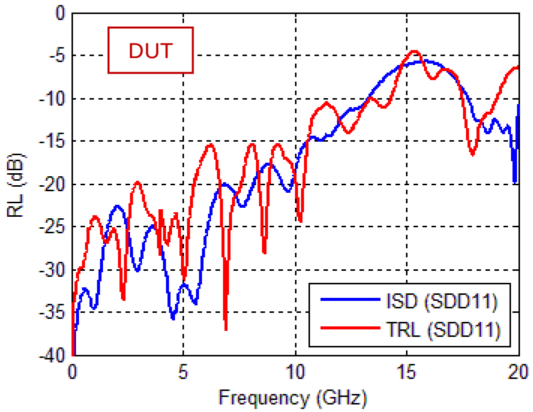
2x thru and fixture have different impedance.

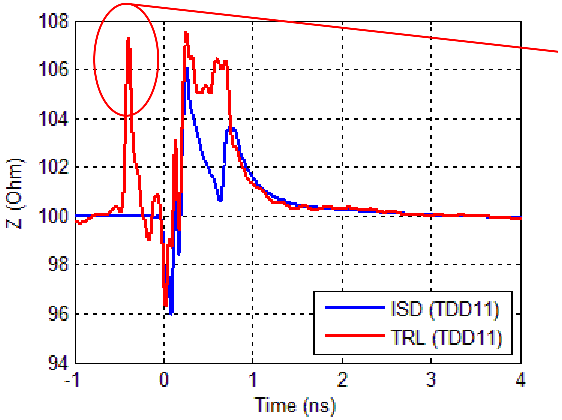
Rise time = 40ps (20/80)

TRL can give huge error in SDD11 even with small impedance variation*

- ISD is able to de-embed fixture's differential impedance with only a single-trace 2x thru.







TRL gives more than 100% error due to causality violation.

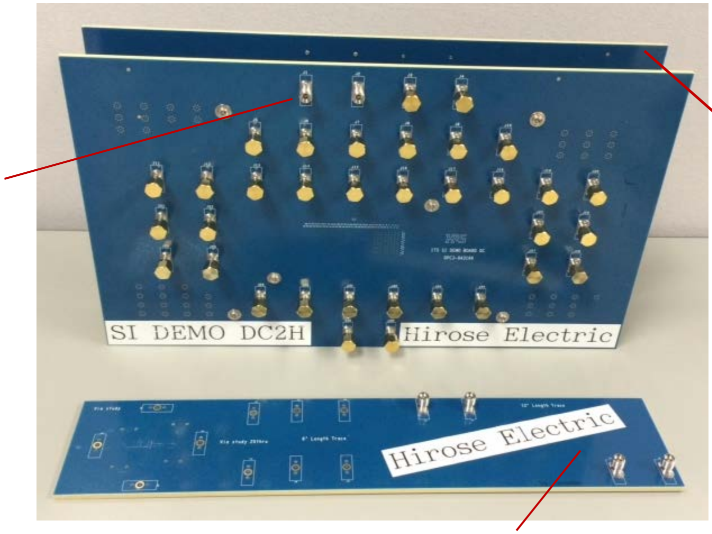
Rise time = 40ps (20/80)

* The impedance variation between 2x thru and fixture is less than 5%. (See previous slide.)

Example 2: Mezzanine connector

Extracting DUT from a large board

- TRL is impractical for de-embedding large and coupled lead-ins/outs.



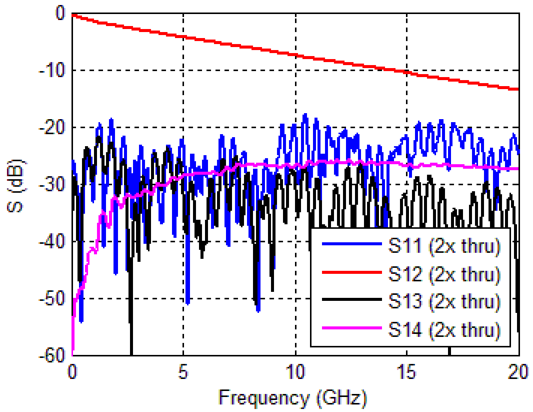
Fixture

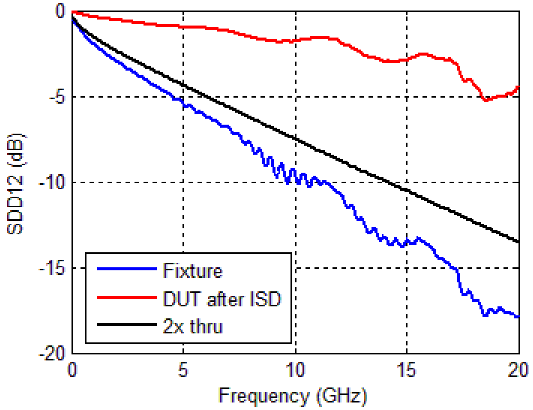
2x thru
(12” total)

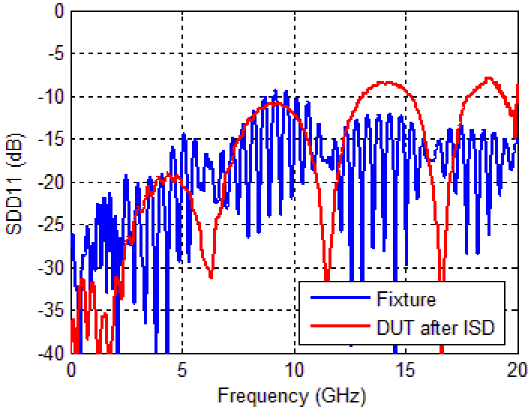
Mezzanine
connector
(DUT)

ISD can use a .s4p file of 2x thru for de-embedding

- TRL would have required many long and coupled traces.

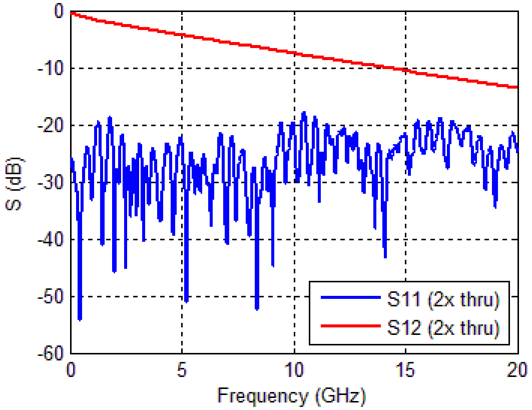


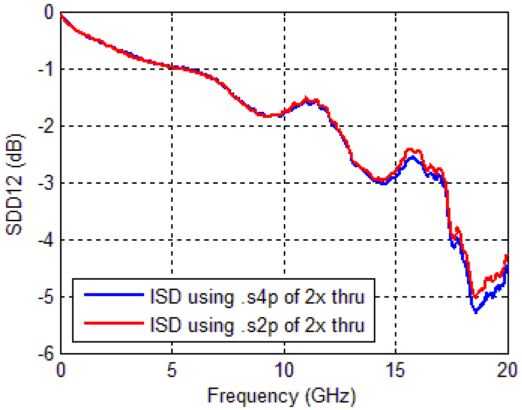


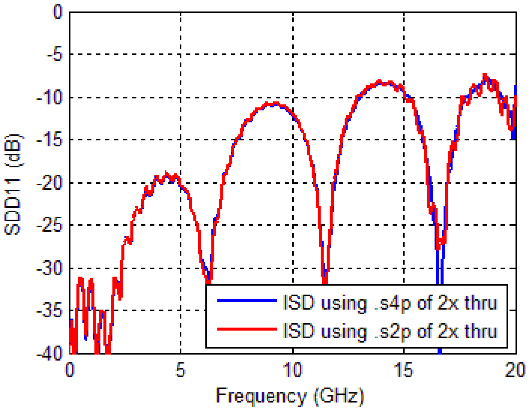


ISD can even use a .s2p file of 2x thru to de-embed crosstalk…

- And the results are similar!

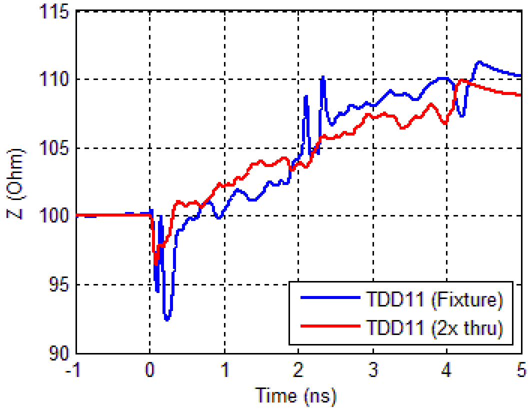


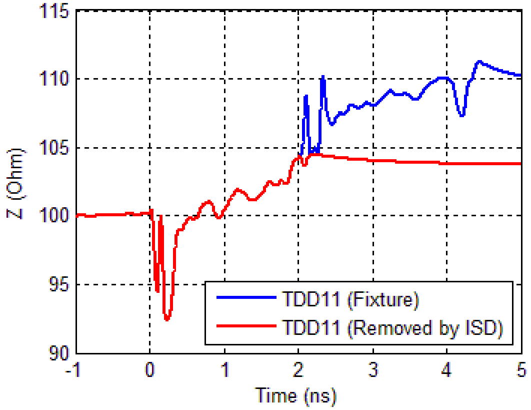


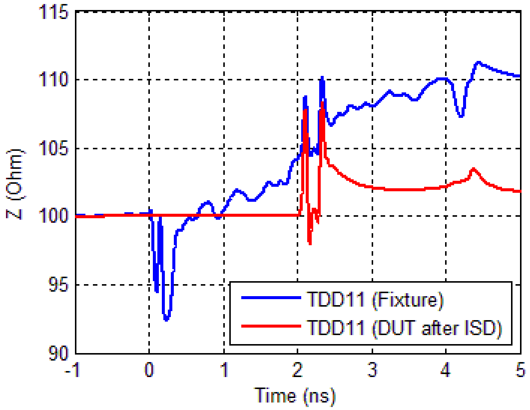


ISD allows a large demo board to double as a characterization board

- ISD de-embeds fixture's impedance regardless of 2x thru's impedance.





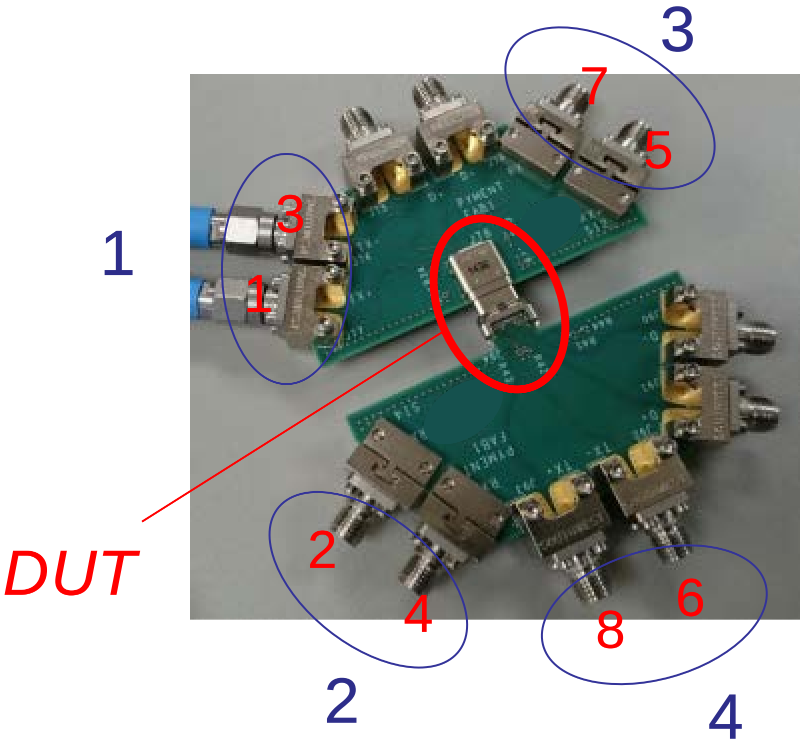


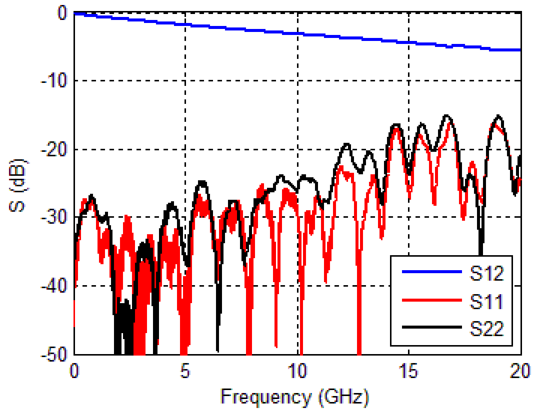
Rise time = 40ps (20/80)

Example 3: USB type C mated connector

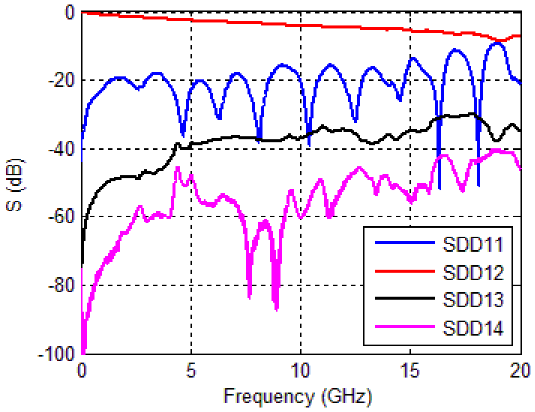
ISD vs. Tool A

- Good de-embedding is crucial for meeting compliance spec.





2x thru



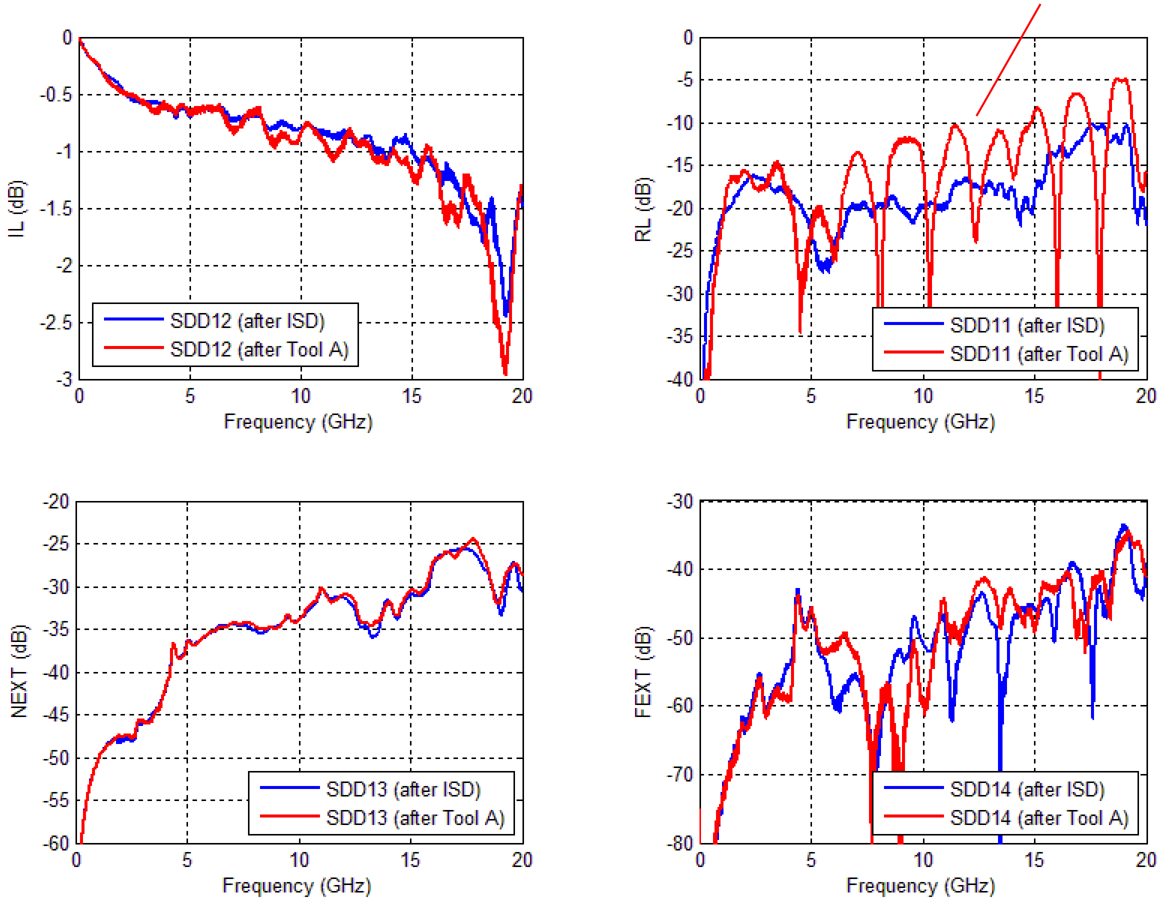
Fixture

DUT results after ISD and Tool A

Which one is more accurate?

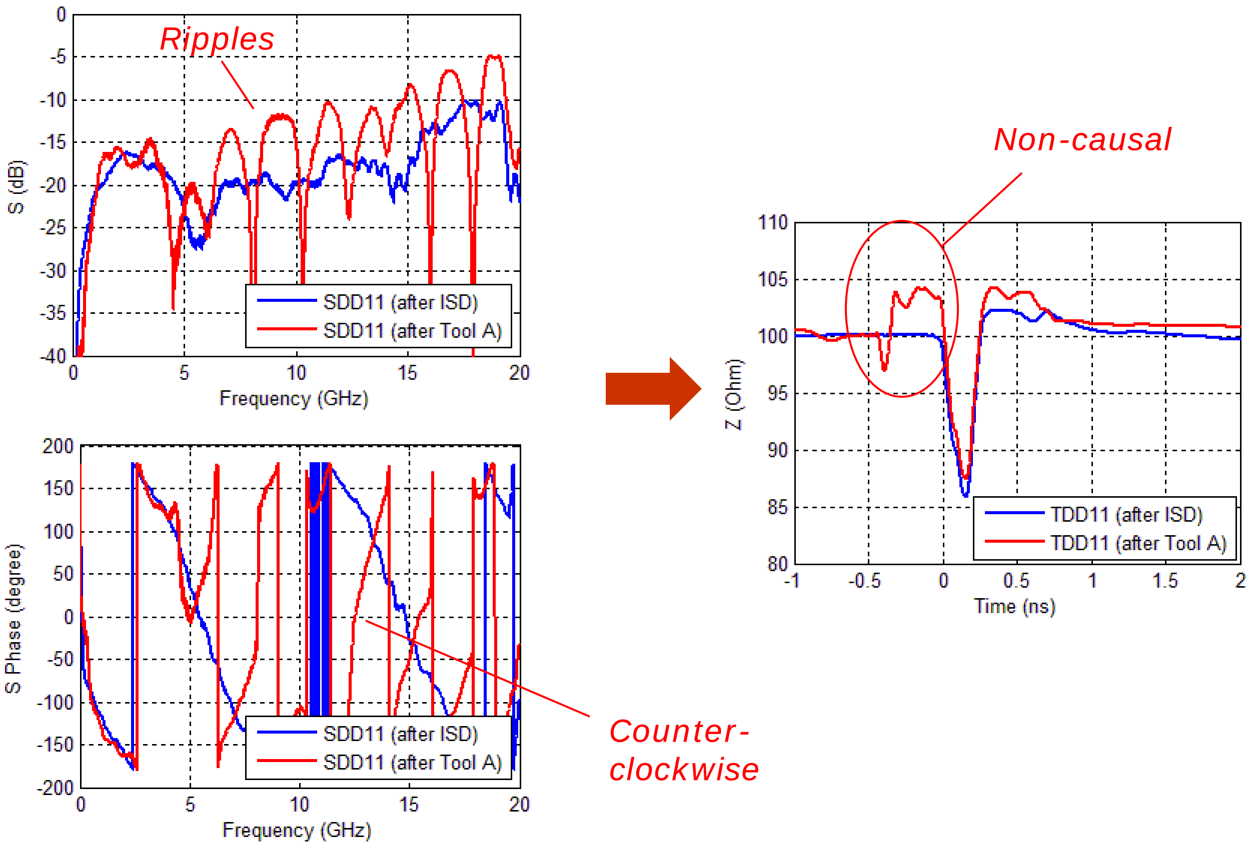
- Tool A gives too many ripples in return loss (RL) for such a small DUT.

Non-causal ripples



Converting S parameter into TDR/TDT shows non-causality in Tool A results

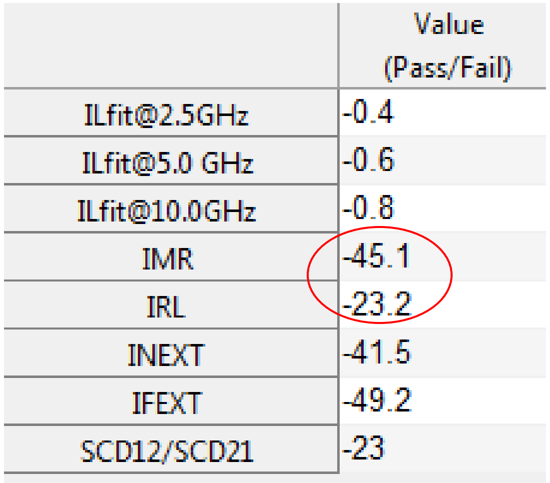
- Counter-clockwise phase angle is another indication of non-causality.



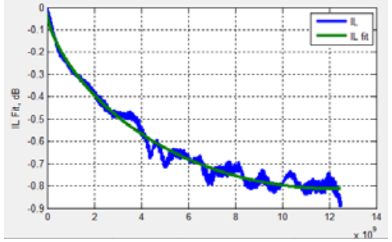
De-embedding affects pass or fail of compliance spec.

- ISD improves IMR and IRL (from compliance tool).

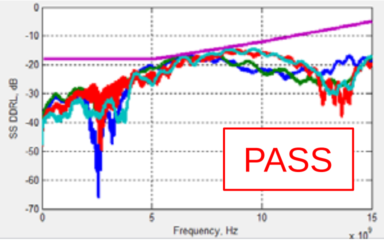
ISD



	Value (Pass/Fail)
ILfit@2.5GHz	-0.4
ILfit@5.0 GHz	-0.6
ILfit@10.0GHz	-0.8
IMR	-45.1
IRL	-23.2
INEXT	-41.5
IFEXT	-49.2
SCD12/SCD21	-23

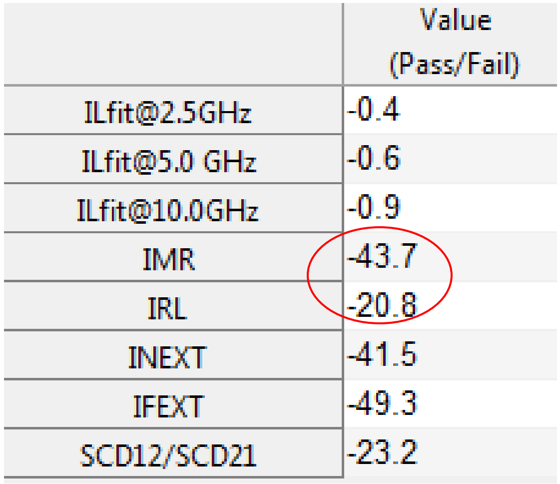


IL

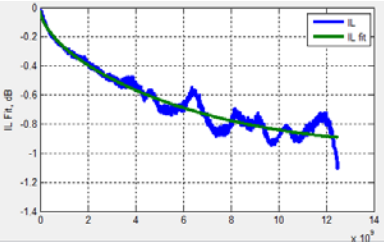


RL

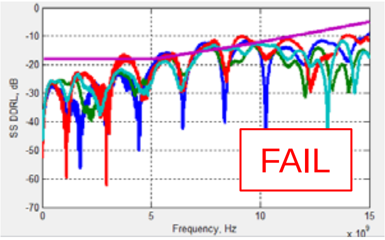
Tool A



	Value (Pass/Fail)	Spec
ILfit@2.5GHz	-0.4	-0.6
ILfit@5.0 GHz	-0.6	-0.8
ILfit@10.0GHz	-0.9	-1.0
IMR	-43.7	-40
IRL	-20.8	-18
INEXT	-41.5	-44
IFEXT	-49.3	-44
SCD12/SCD21	-23.2	



IL

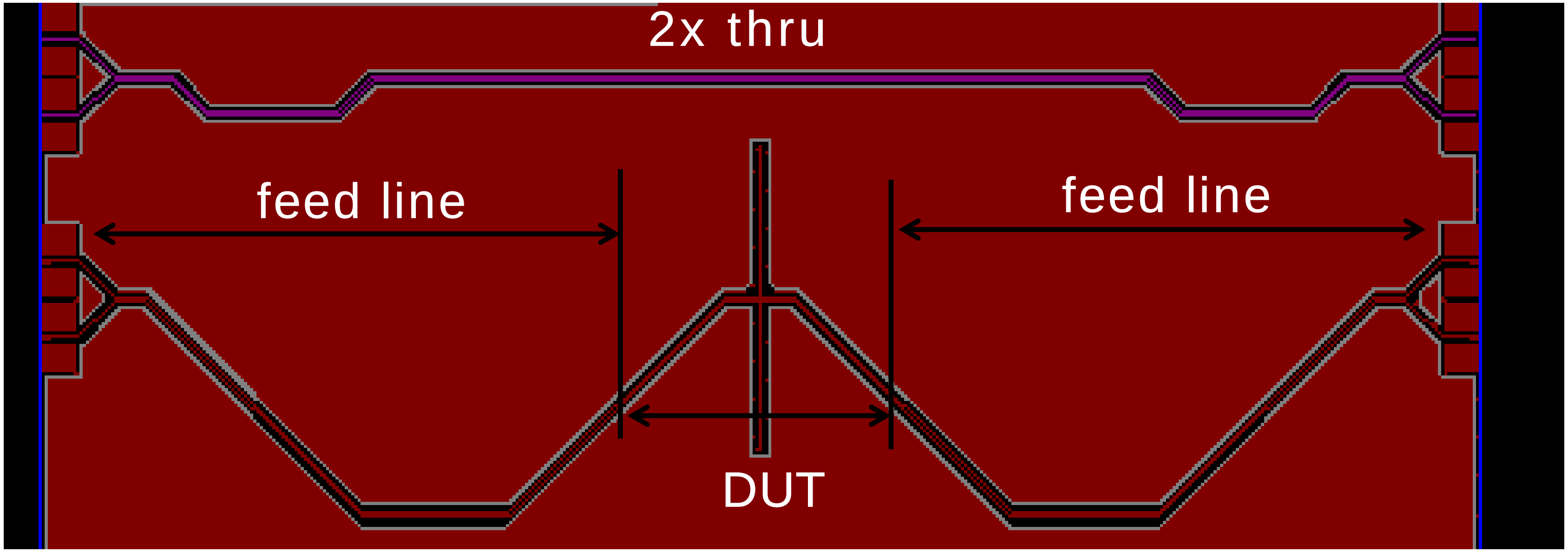


RL

Example 4: Resonator

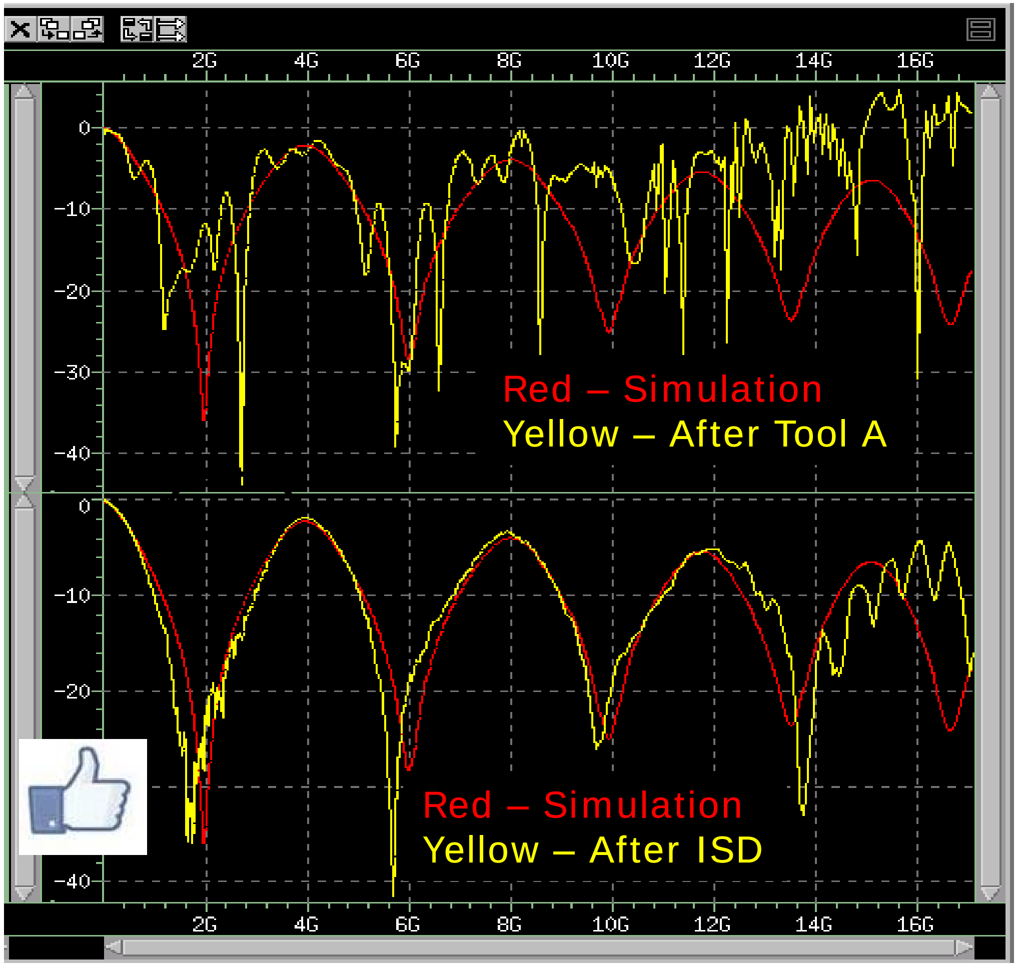
ISD vs. Tool A vs. simulation

- Good de-embedding is crucial for design verification (i.e., correlation) and improvement.



SDD11

ISD correlates with simulation



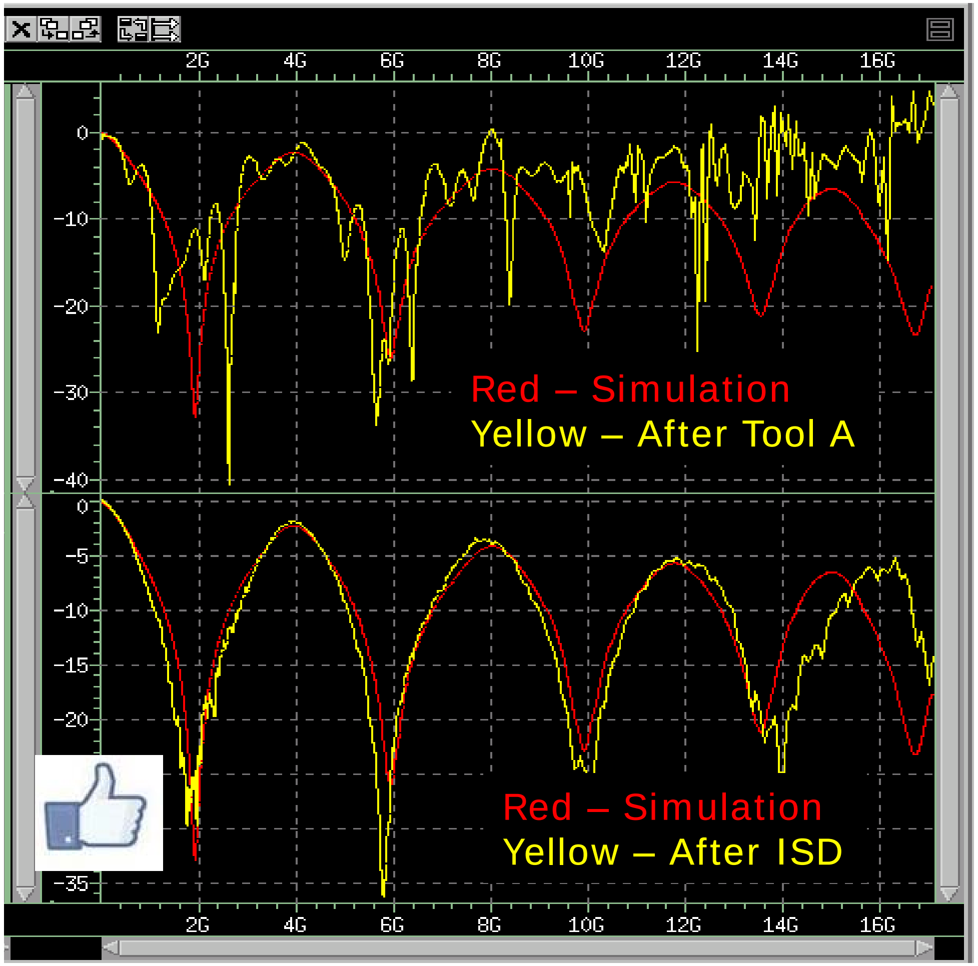
Red – Simulation
Yellow – After Tool A

Red – Simulation
Yellow – After ISD

SCC11

ISD correlates with simulation

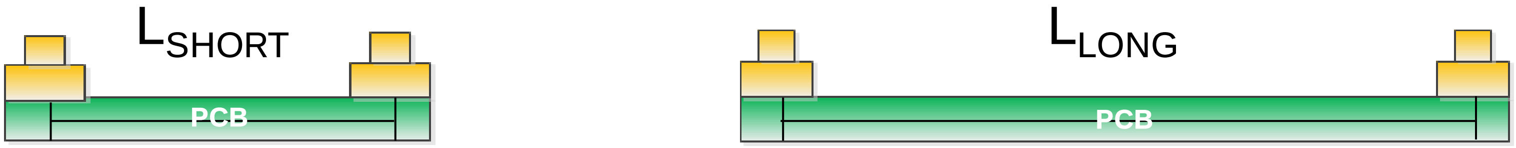
- Good correlation is crucial for design improvement.



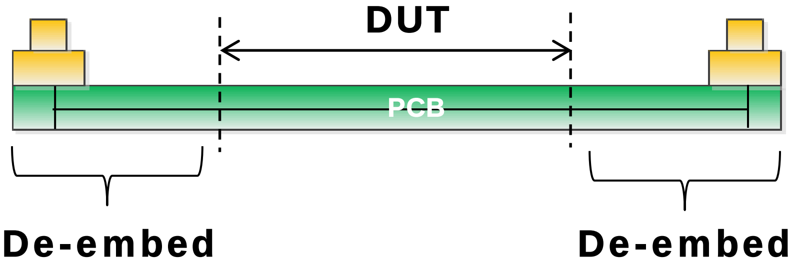
Example 5: PCB trace attenuation

ISD vs. eigenvalue (Delta-L)

- De-embed short trace (+ launch) from long trace (+ launch) to get trace-only attenuation.



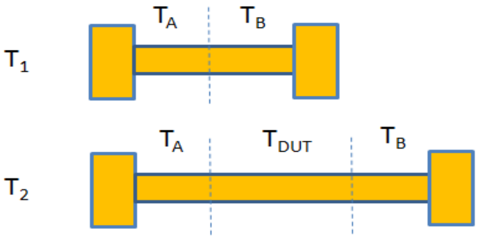
$$L_{DUT} = L_{LONG} - L_{SHORT}$$



Eigenvalue solution: not de-embedding

For calculating trace attenuation only

- Convert S to T for short and long trace structures
- Assume the left (and right) sides of short and long trace structures are identical
- Assume DUT is uniform transmission line
- Trace-only attenuation is written in one equation.



$$T_1 = T_A \cdot T_B$$

$$T_2 = T_A \cdot T_{DUT} \cdot T_B$$

$$\Rightarrow \quad T_2 \cdot T_1^{-1} = T_A \cdot T_{DUT} \cdot T_A^{-1}$$

For uniform transmission line:

$$T_{DUT} = P \cdot \begin{pmatrix} e^{-\gamma l} & 0 \\ 0 & e^{+\gamma l} \end{pmatrix} \cdot P^{-1}$$

Let $T_2 \cdot T_1^{-1} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$

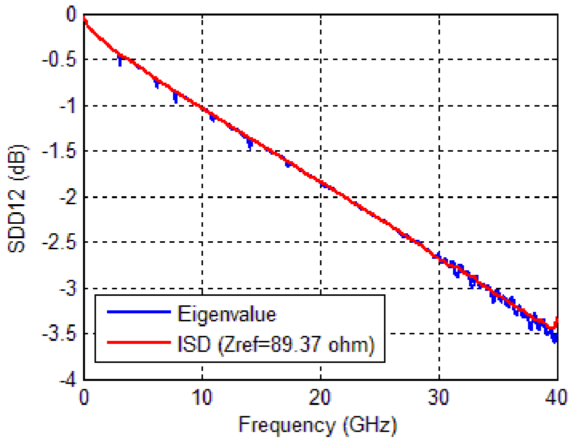
$$\Rightarrow \quad e^{-\gamma l} = \frac{(a+d) \pm \sqrt{(a-d)^2 + 4bc}}{2}$$

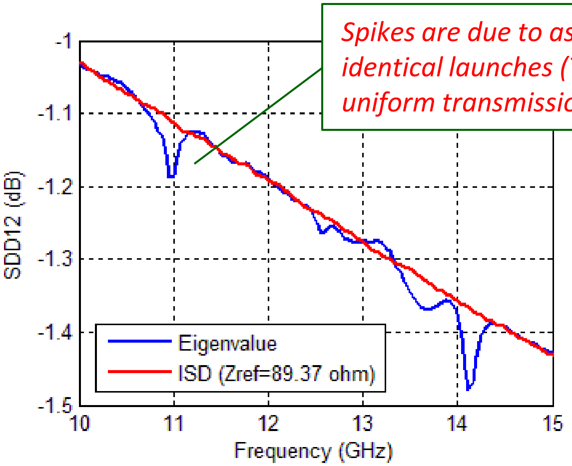
eigenvalue

modal propagation constant

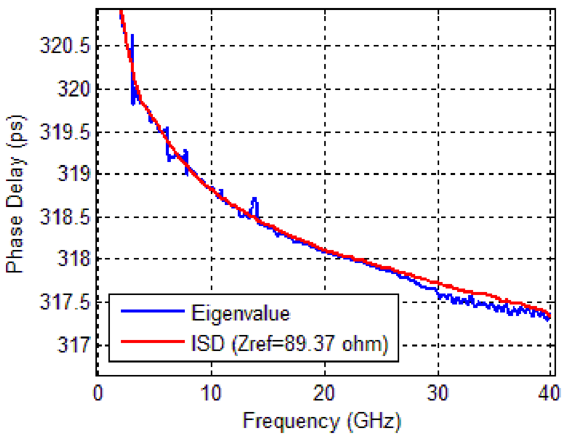
Case 1: 2” (=7”-5”) trace attenuation

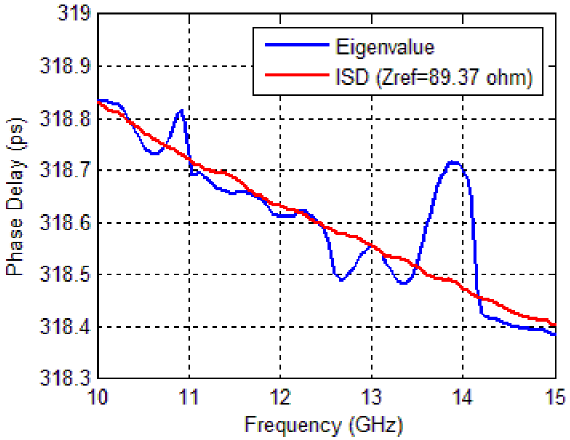
Eigenvalue solution is prone to spikes





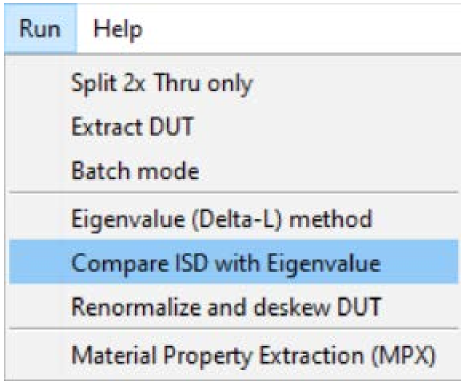
Spikes are due to assumptions of identical launches (T_A and T_B) and uniform transmission line (T_{DUT}).



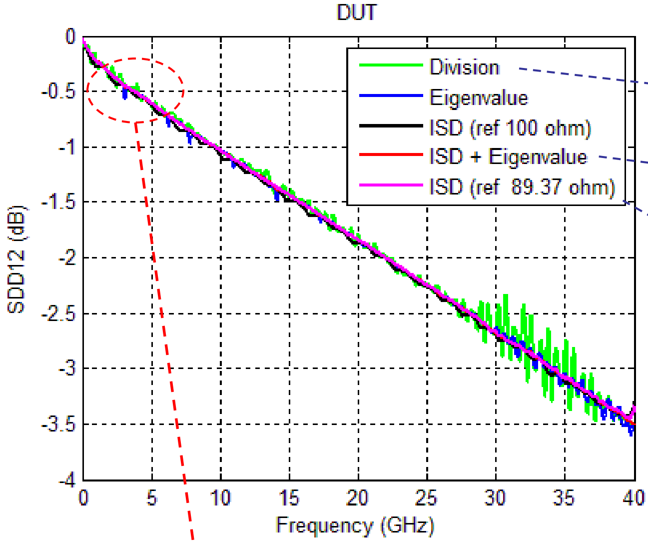


ISD’s spike-free results help DK and DF extraction later.

One click compares ISD with eigenvalue and more…



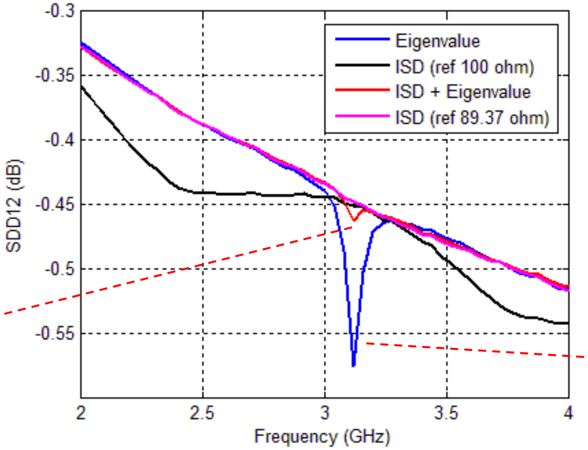
One click does it all



Direct dB subtraction

Eigenvalue of ISD results

Renormalize ISD results by trace impedance (automatically calculated)



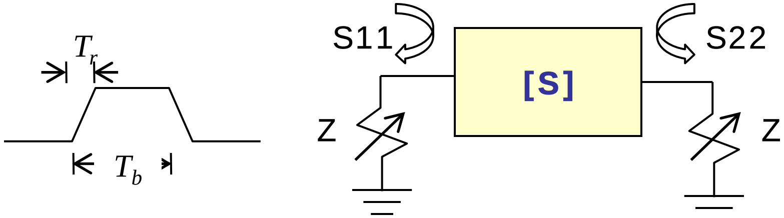
Spikes are due to assumption of uniform transmission line (T_{DUT}).

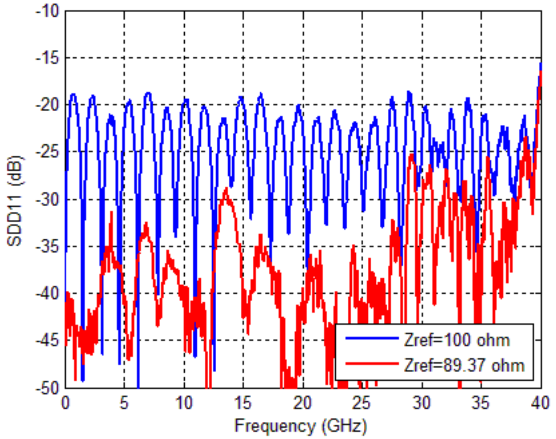
Spikes are due to assumptions of identical launches (T_A and T_B) and uniform transmission line (T_{DUT}).

How to define trace impedance

PCB trace is non-uniform transmission line

- Define impedance by minimal RL*

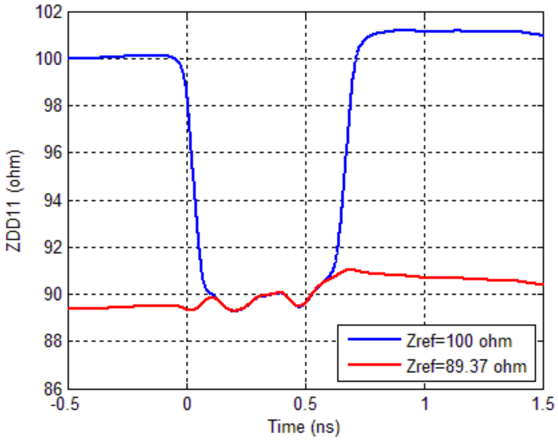




Minimize:

$$\varphi = \int_{f_{\min}}^{f_{\max}} \left\{ \left|S_{11}(f)\right|^2 + \left|S_{22}(f)\right|^2 \right\} \cdot \left|w(f)\right|^2 df$$

$$w(f) = \frac{\sin(\pi f T_r)}{\pi f T_r} \cdot \frac{\sin(\pi f T_b)}{\pi f T_b}$$



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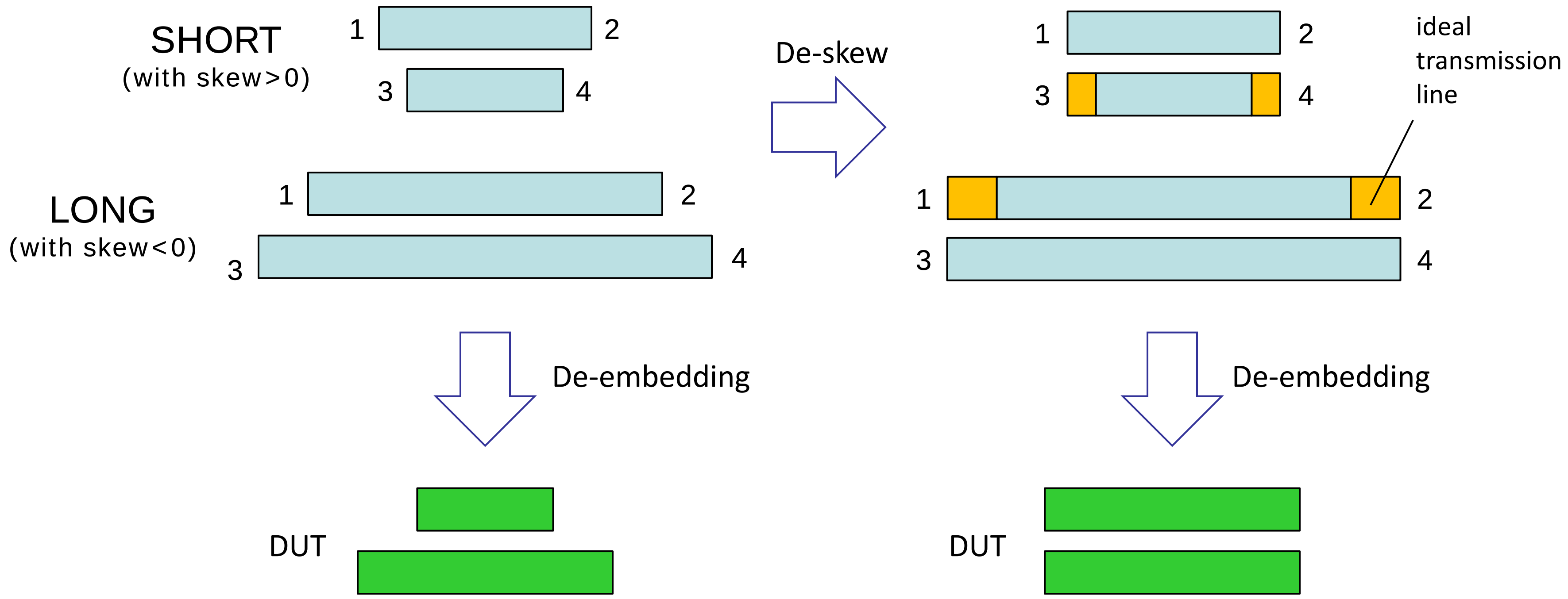
* J. Balachandran, K. Cai, Y. Sun, R. Shi, G. Zhang, C.C. Huang and B. Sen, "Aristotle: A fully automated SI platform for PCB material characterization," DesignCon 2017, 01/31-02/02/2017, Santa Clara, CA.

Skewless de-embedding

- Pad ideal transmission line to de-skew.

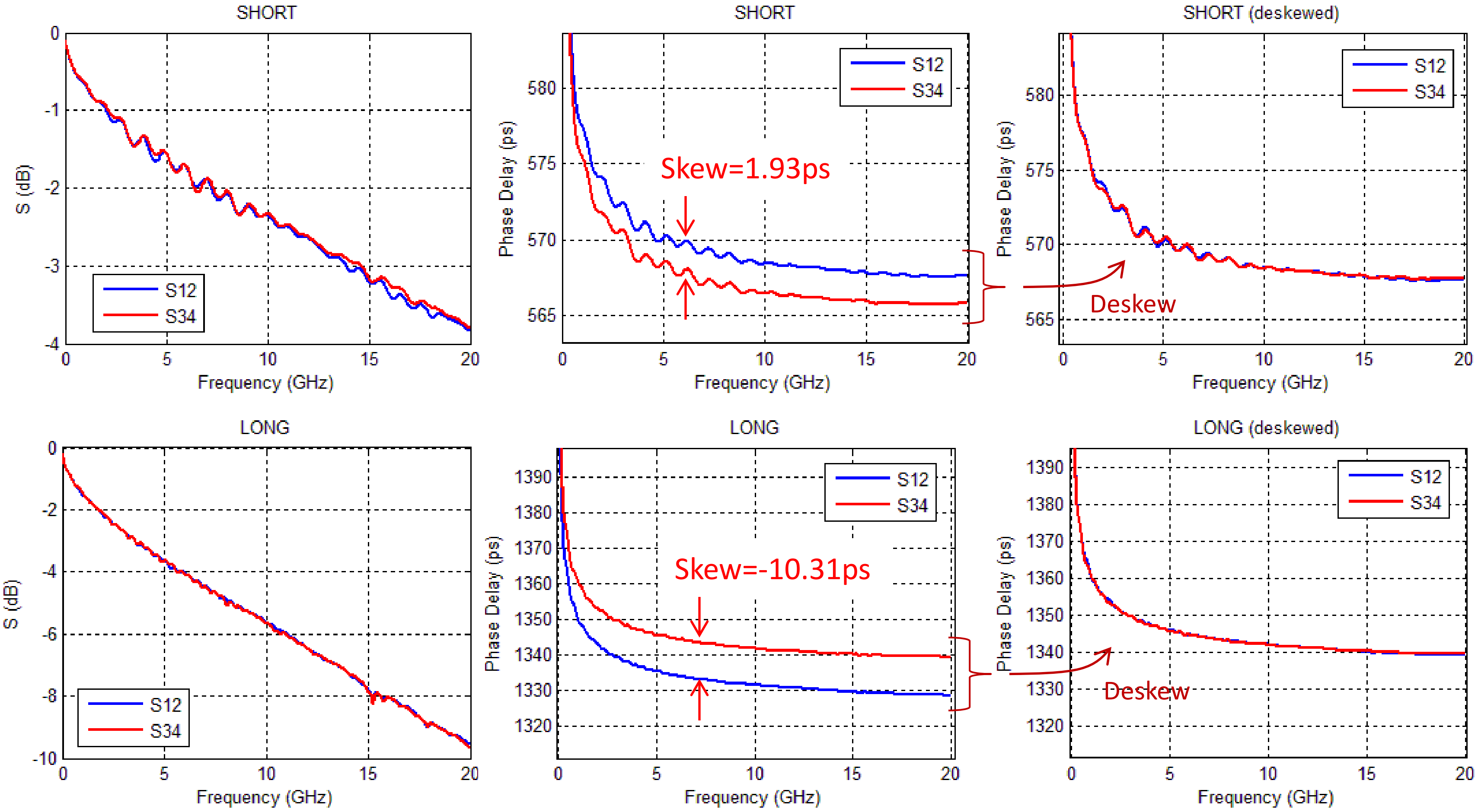


Skew<0:

DUT skew is worse when long and short diff pairs have opposite skew

Skew=0

ISD optionally automates de-skewing of raw data



Skew=1.93ps

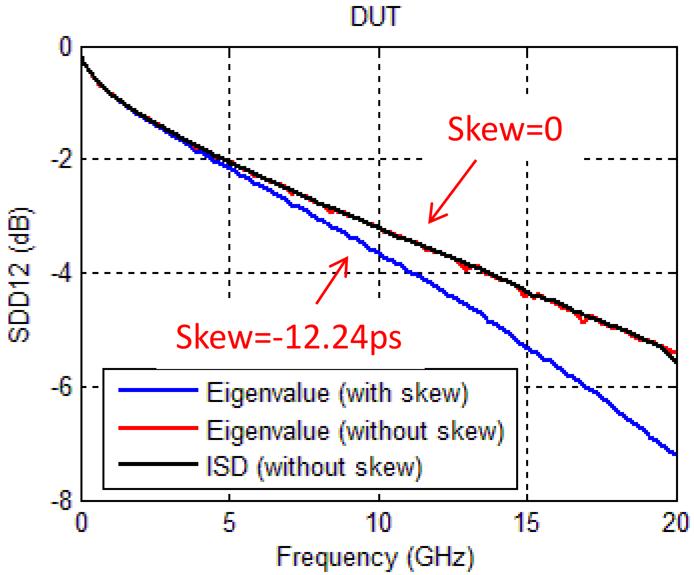
Deskew

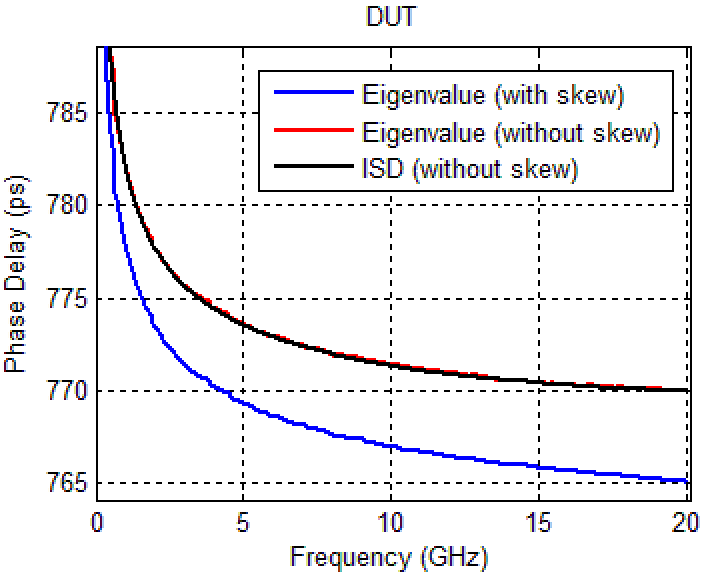
Skew=-10.31ps

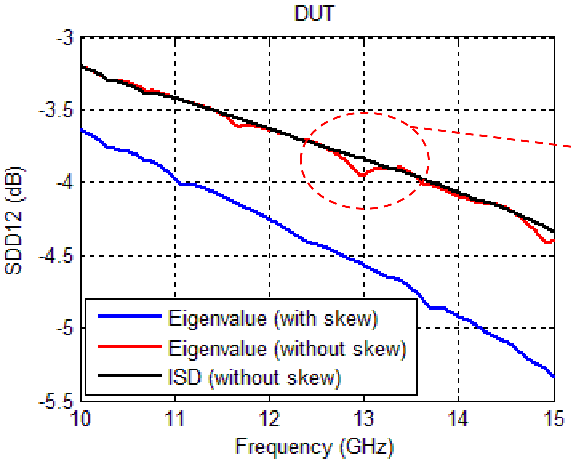
Deskew

LONG=8”
SHORT=3”

Case 2: Extracted trace attenuation can be very different with or without skew

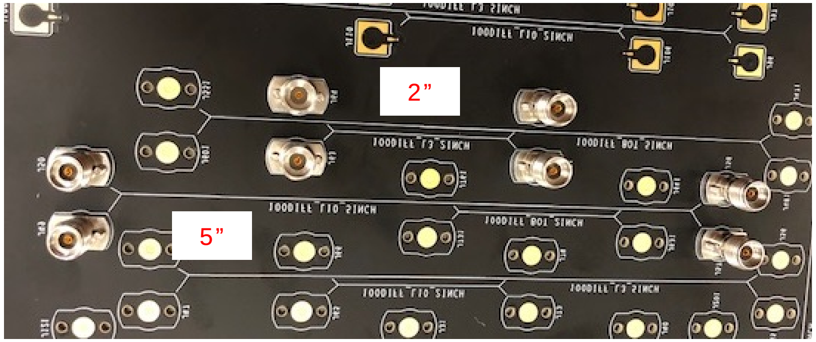


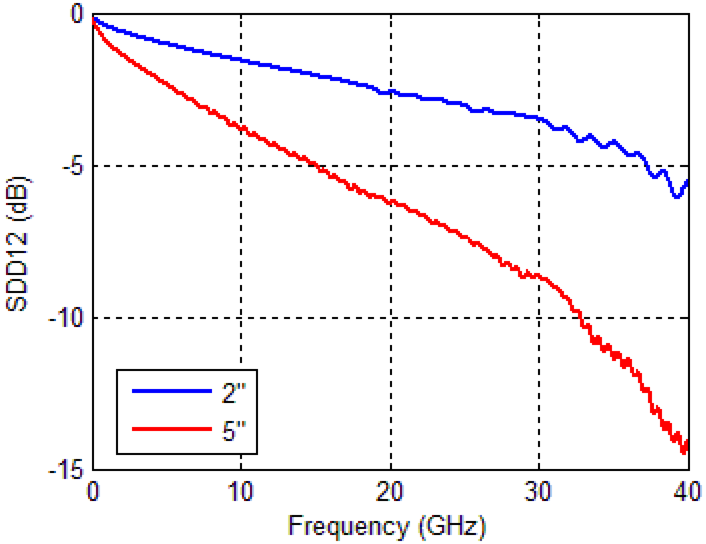


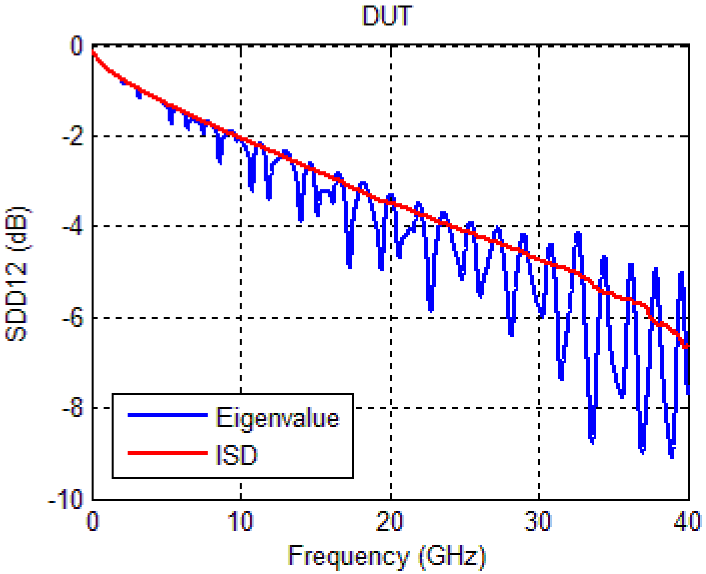


Eigenvalue solution has a dip at the frequency of interest (~12.9 GHz)

Case 3: Eigenvalue (Delta-L) solution becomes unstable in this case, but why?



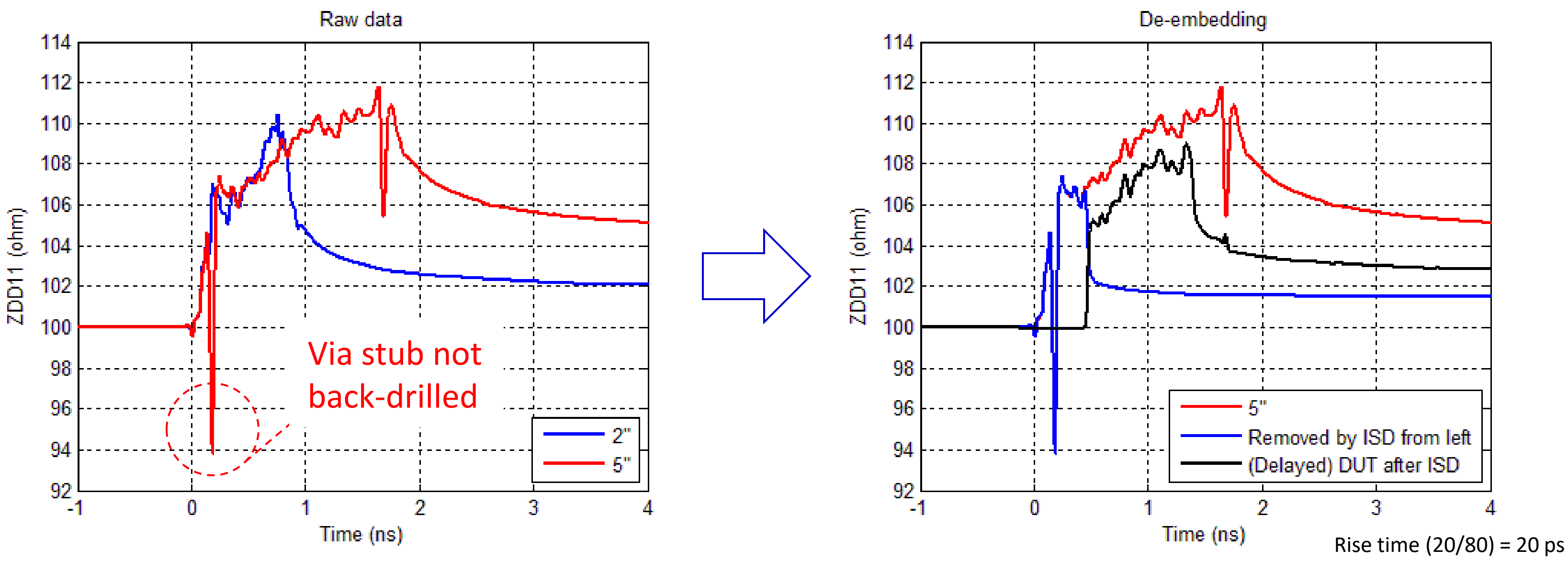




TDR of raw data reveals why…

2” structure was back-drilled but 5” was not

- Eigenvalue solution assumes 2” and 5” structures have identical launches.
- ISD de-embeds 5” structure’s launch correctly.



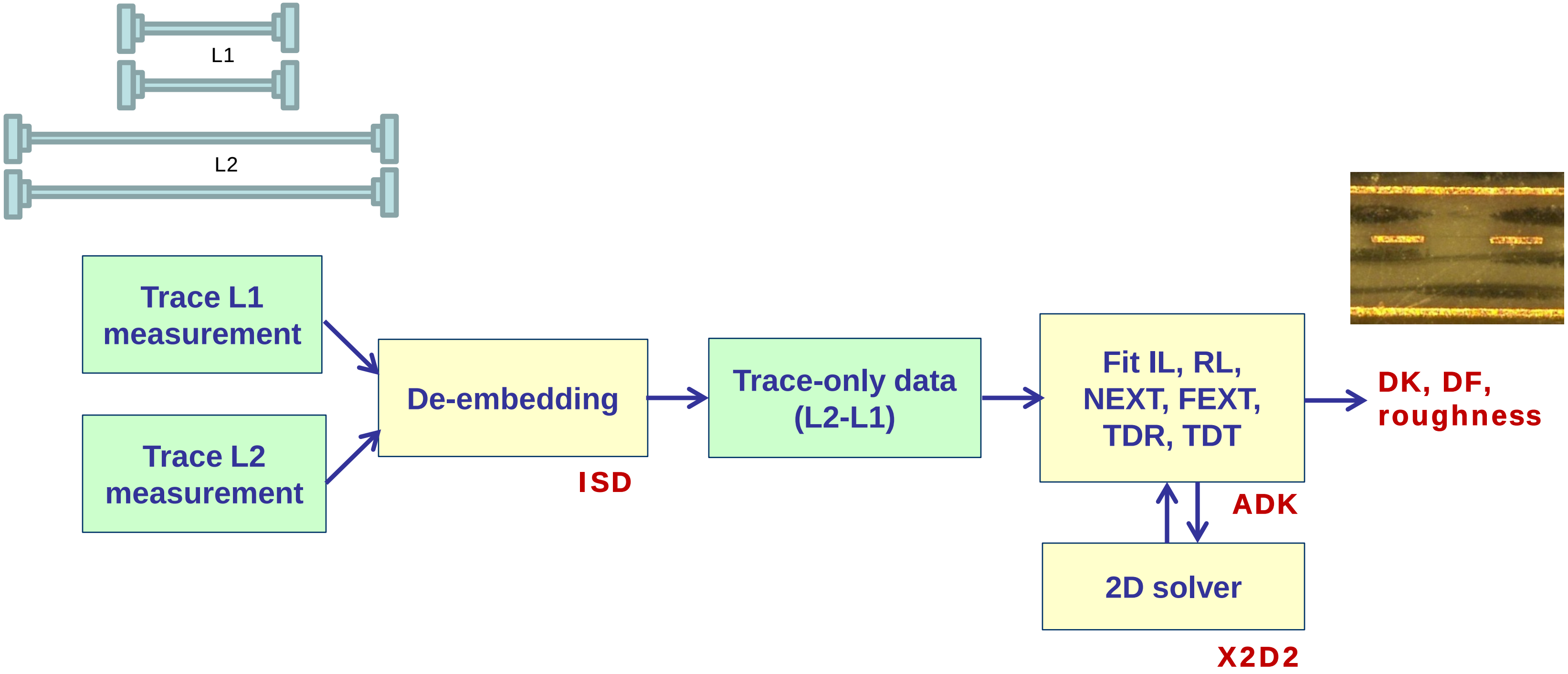
Via stub not back-drilled

Rise time (20/80) = 20 ps

ISD saves $$$ and time for not spinning another board.

Example 6: Material property extraction
DK, DF and roughness

- Self consistent approach to extract DK, DF and roughness by matching all IL, RL, NEXT, FEXT and TDR/TDT of de-embedded trace-only data.



Trace L1 measurement

Trace L2 measurement

De-embedding

ISD

Trace-only data (L2-L1)

Fit IL, RL, NEXT, FEXT, TDR, TDT

ADK

2D solver

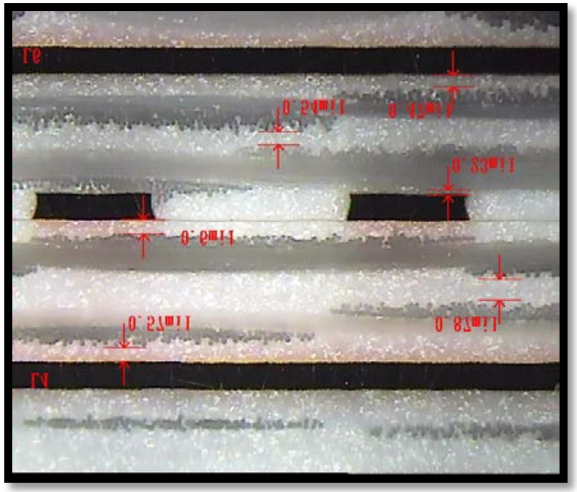
X2D2

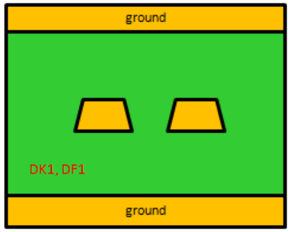
DK, DF, roughness

Automated extraction flow

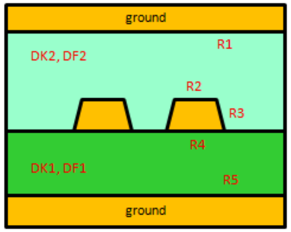
Models for cross section

Optimized variables:
DK1, DF1, DK2, DF2
R1, R2, R3, R4, R5 (roughness)
Metal width and spacing

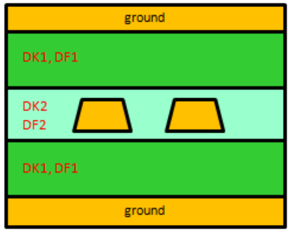




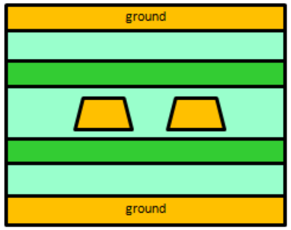
Model 1



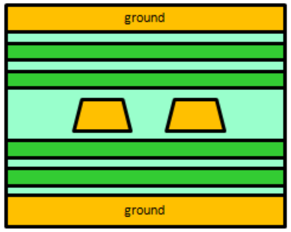
Model 2



Model 3



Model 4



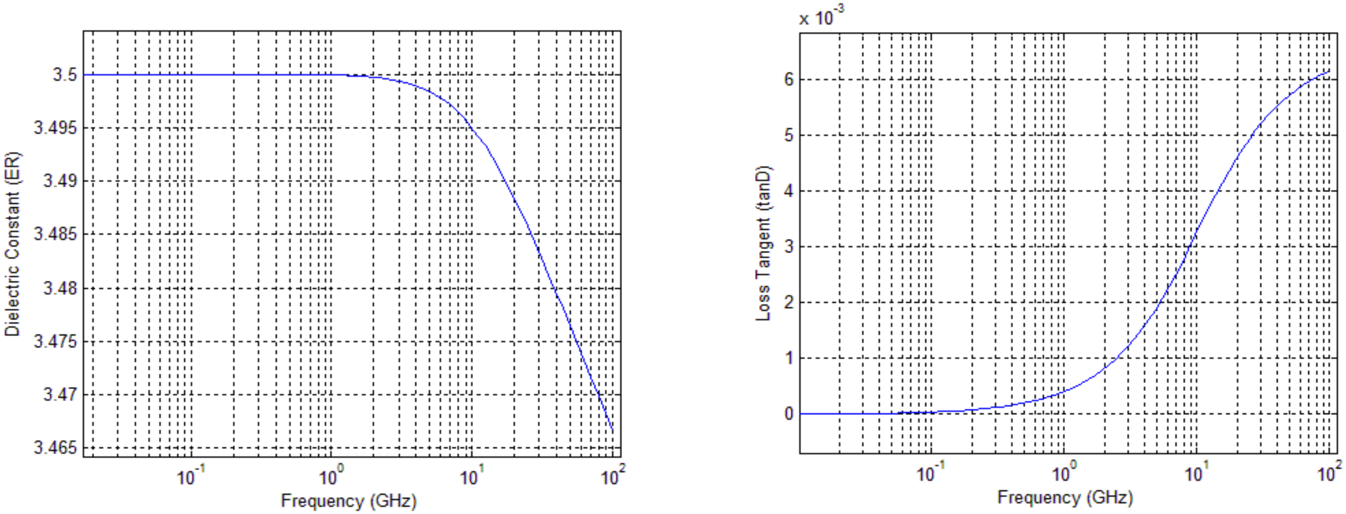
Model 5

Causal dielectric model

- Wideband Debye (or Djordjevic-Sarkar) model
  - Need only four variables: ε_∞ , $\Delta\varepsilon$, m_1 , m_2

$$\varepsilon = \varepsilon_\infty + \Delta\varepsilon \cdot \frac{1}{m_2 - m_1} \cdot \log_{10}\left(\frac{10^{m_2} + i \cdot f}{10^{m_1} + i \cdot f} \right)$$

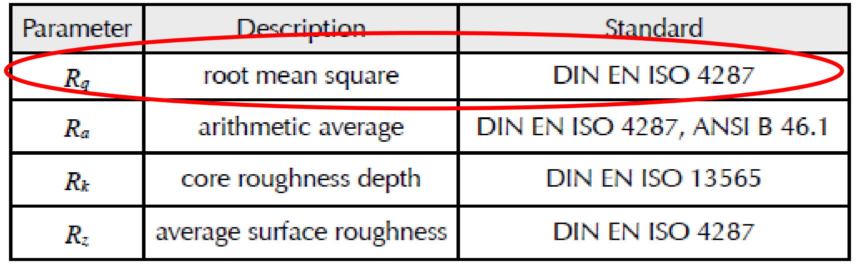
$$= \varepsilon_r \cdot (1 - i \cdot \tan\delta)$$



$$\varepsilon_\infty = 3.35 \ , \ \Delta\varepsilon = 0.15 \ , \ m_1 = 10 \ , \ m_2 = 14.5$$

Surface roughness model

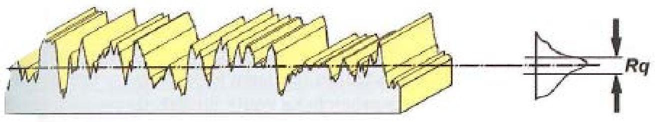
- Effective conductivity (by G. Gold & K. Helmreich at DesignCon 2014) needs only two variables: σ_{bulk} , R_q



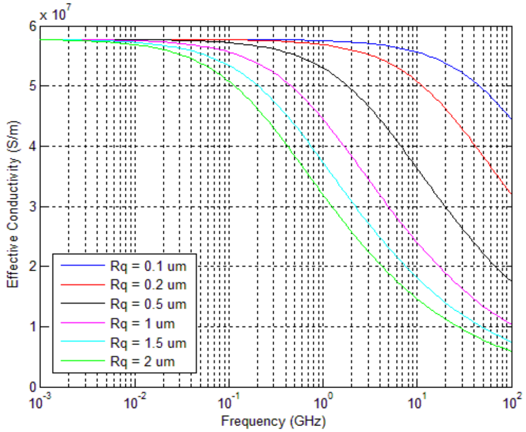
Parameter	Description	Standard
R_q	root mean square	DIN EN ISO 4287
R_a	arithmetic average	DIN EN ISO 4287, ANSI B 46.1
R_k	core roughness depth	DIN EN ISO 13565
R_z	average surface roughness	DIN EN ISO 4287

Table 1: *Statistical parameters to describe surface roughness*

$$\sigma(x)=\sigma_{bulk}\cdot CDF(x)=\sigma_{bulk}\cdot\int_{-\infty}^{x}PDF(x)du=\sigma_{bulk}\cdot\int_{-\infty}^{x}e^{-\frac{u^2}{2R_q^2}}du$$



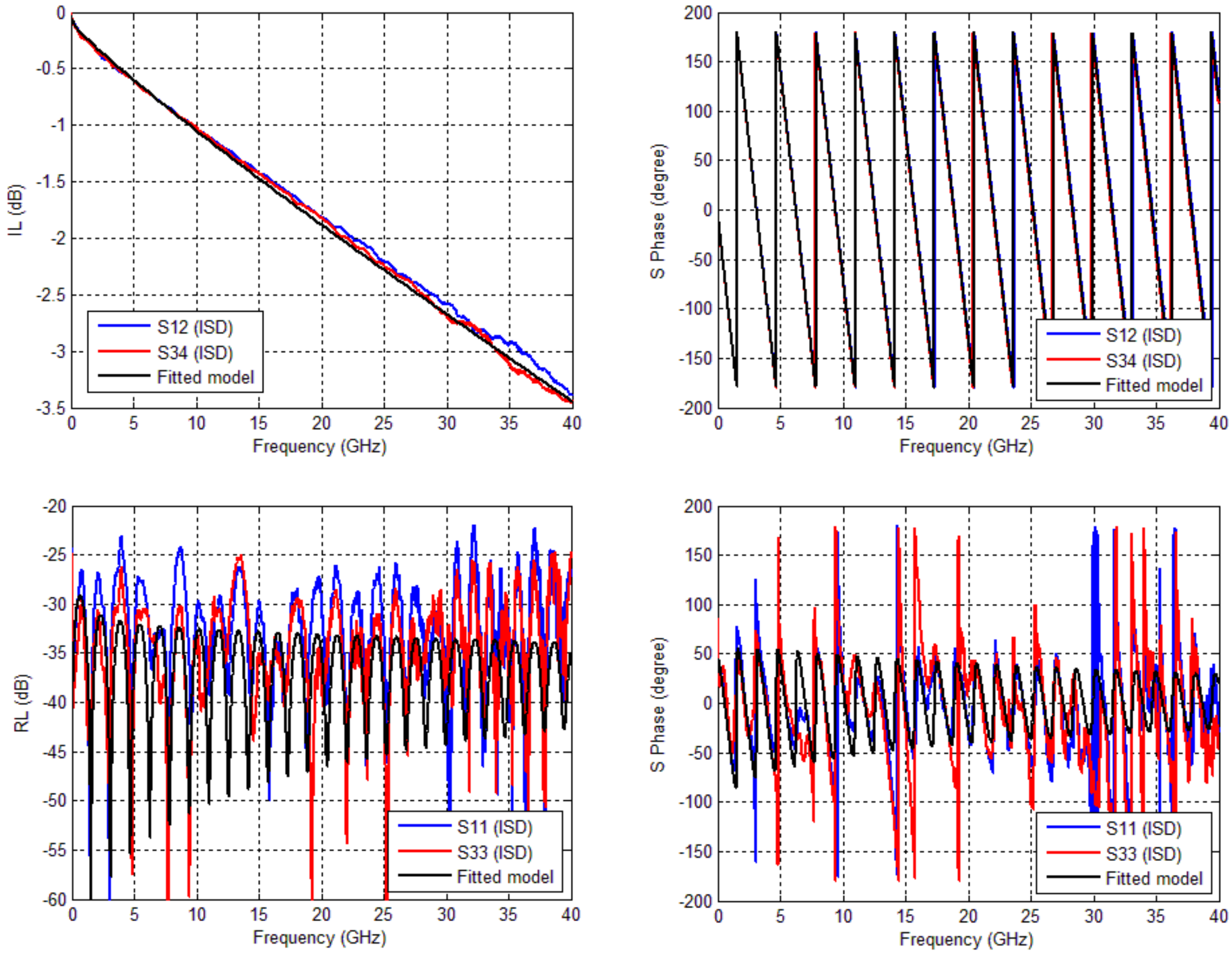
- Numerically solving $\nabla^2\overline{B}-j\omega\mu\sigma\overline{B}+\frac{\nabla\sigma}{\sigma}\times\left(\nabla\times\overline{B}\right)=0$ and equating power to that of smooth surface gives σ_{eff}



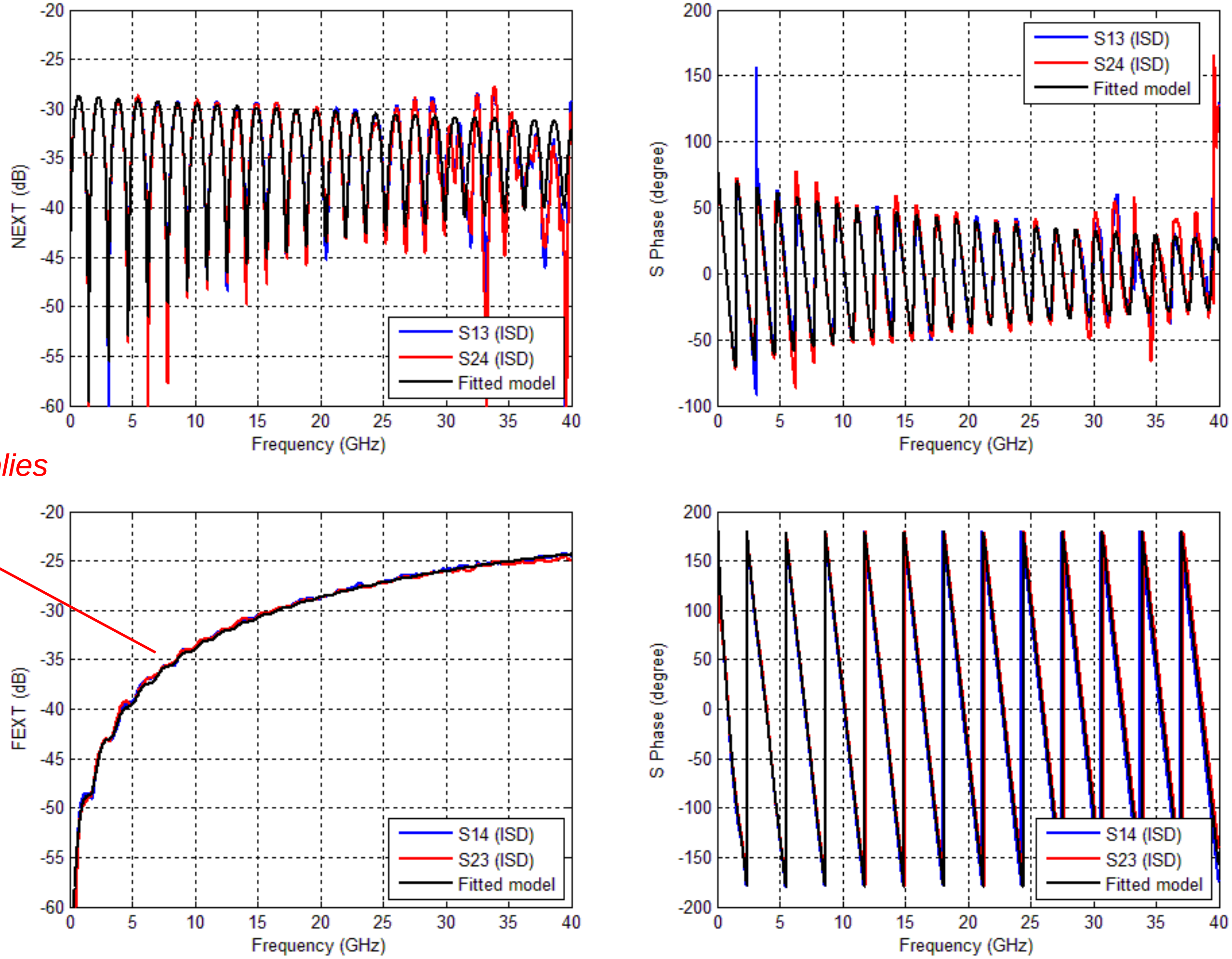
$\sigma_{bulk}=5.8\times10^7$ s/m

- ❖ Simple
- ❖ Work well with field solver
- ❖ Give effect of roughness on all IL, RL, NEXT and FEXT

Matching IL and RL

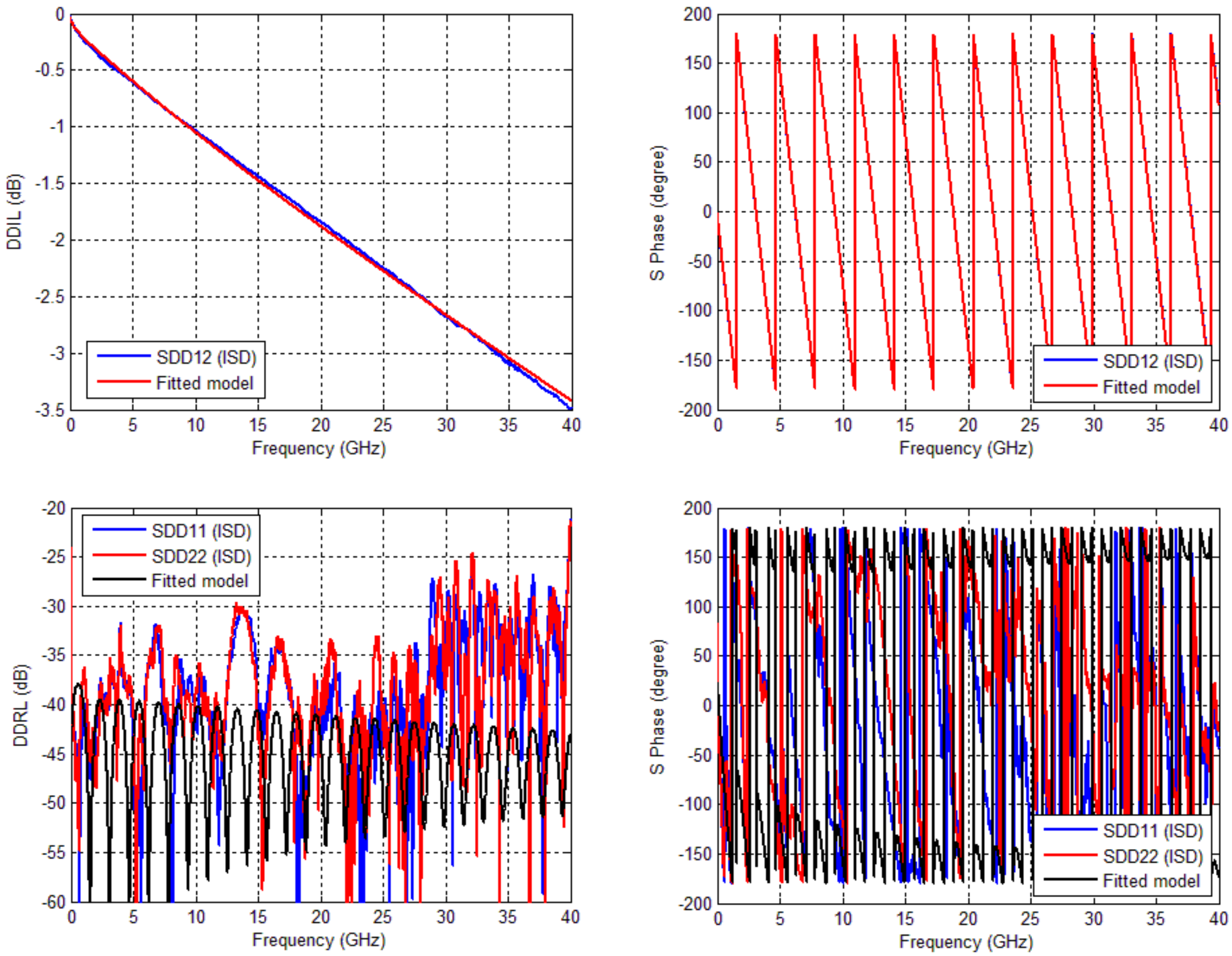


Matching NEXT and FEXT

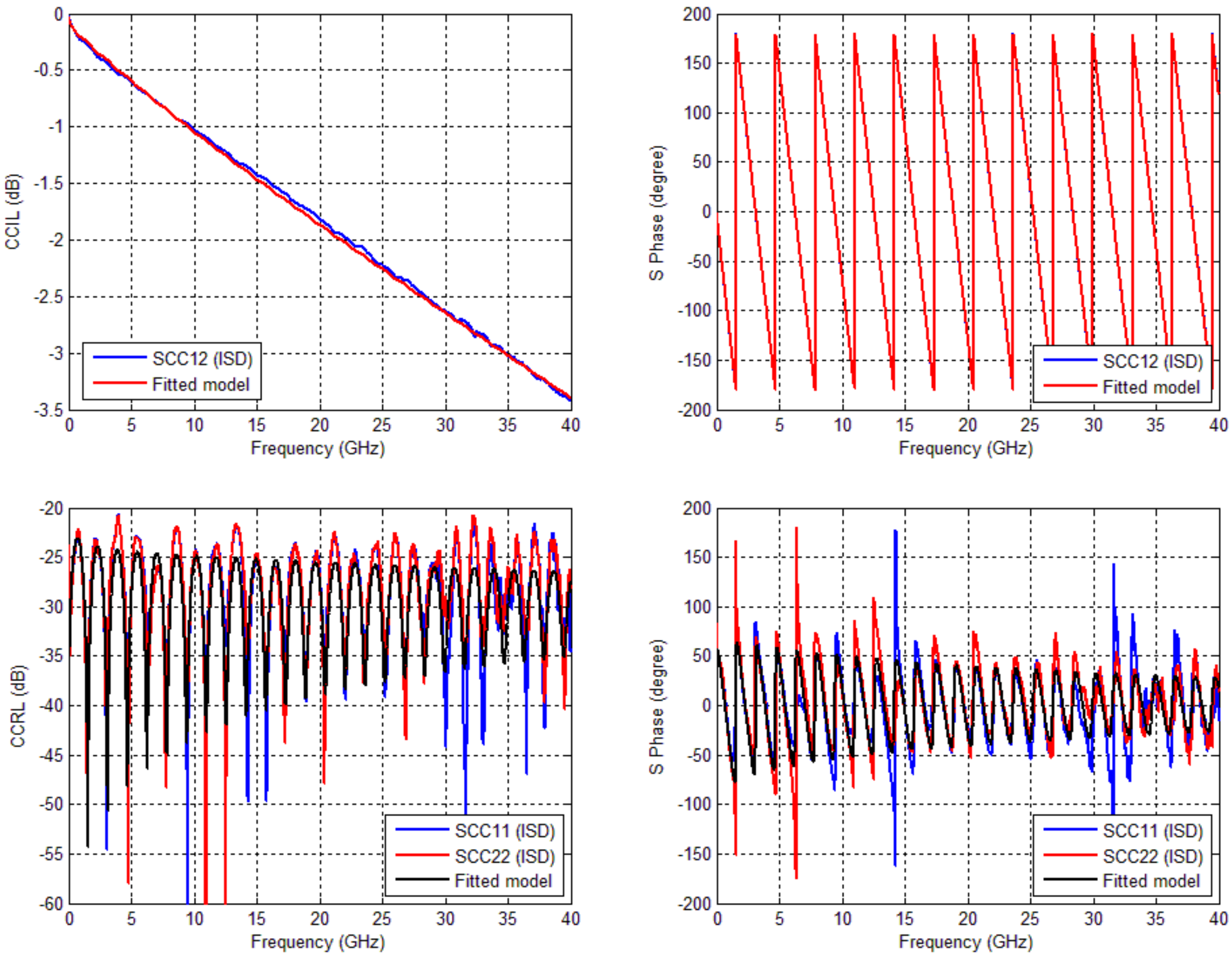


Large FEXT implies inhomogeneous dielectric

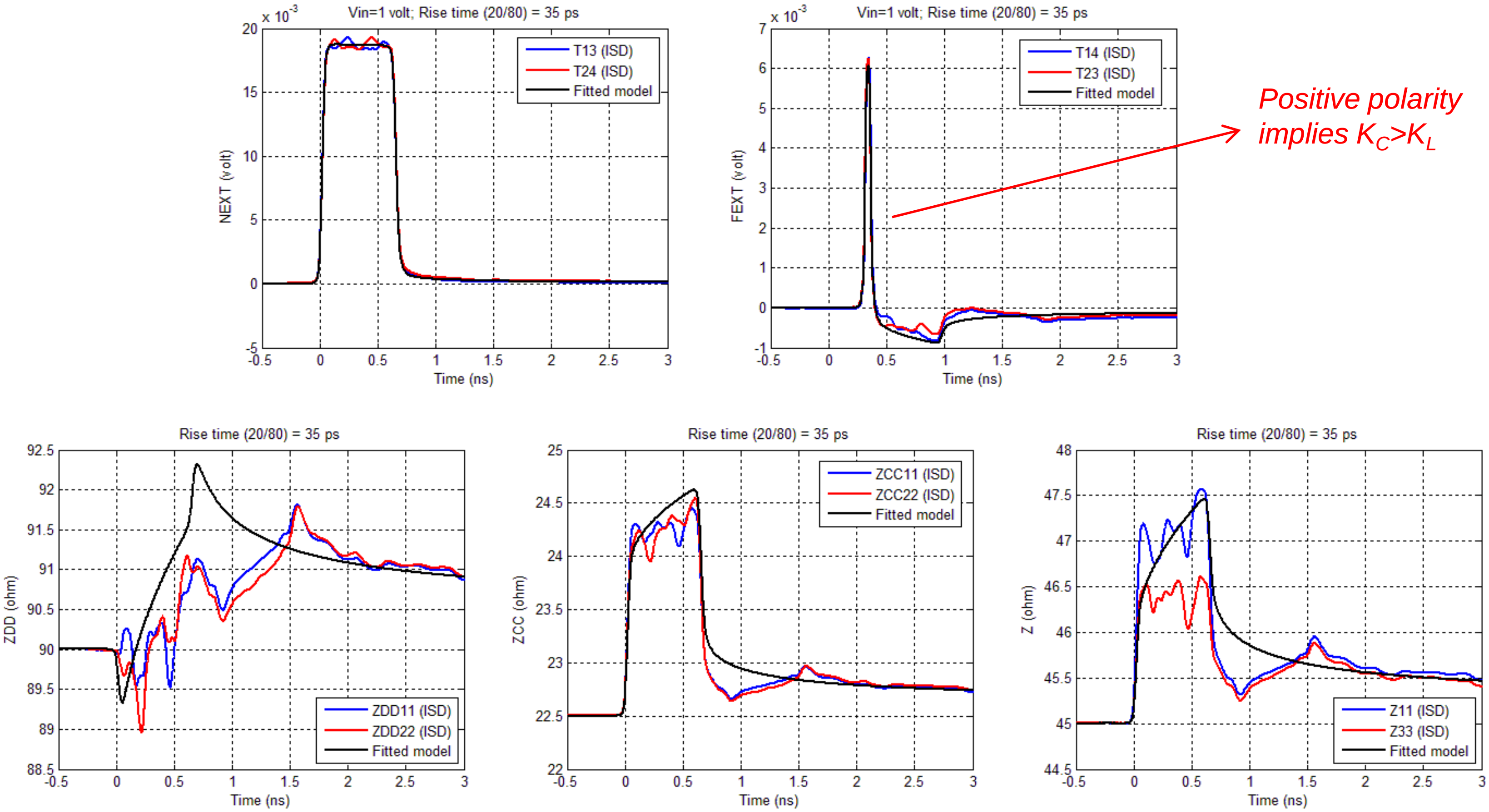
Matching DDIL and DDRL



Matching CCIL and CCRL



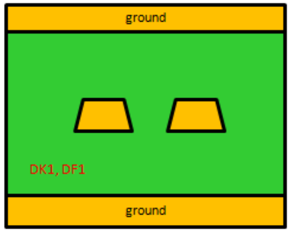
Matching TDT and TDR



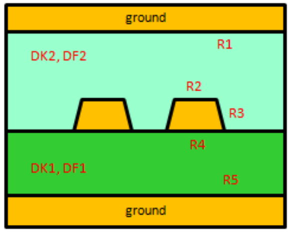
Positive polarity implies $K_C > K_L$

Comparison of Models 1 to 5

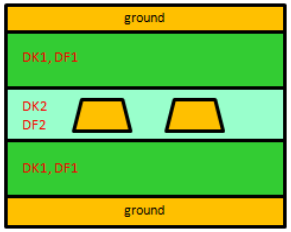
- Model 1 cannot match FEXT. Models 2 to 5 can match all IL, RL, NEXT, FEXT and TDR/TDT very well.



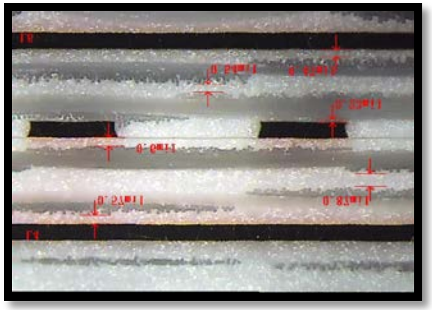
Model 1

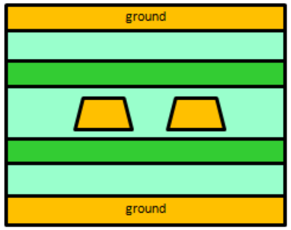


Model 2

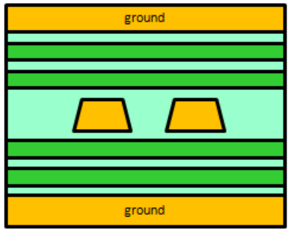


Model 3





Model 4



Model 5

🟩 DK1

▢ DK2

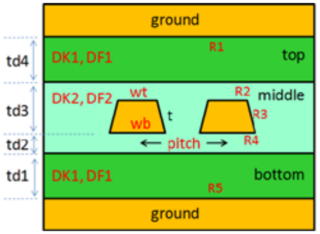
Model	DK1	DK2
1	3.510	-
2	2.444	4.294
3	3.413	3.623
4	3.863	3.360
5	3.115	3.975

At 10 GHz

DK2>DK1 because of positive-polarity FEXT

Extracted DK1 and DF1

Model 3



$$\varepsilon_\infty = 3.27929$$

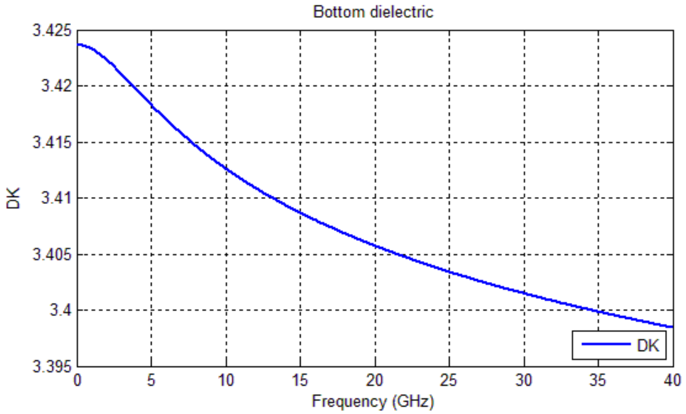
$$\Delta\varepsilon = 0.144348$$

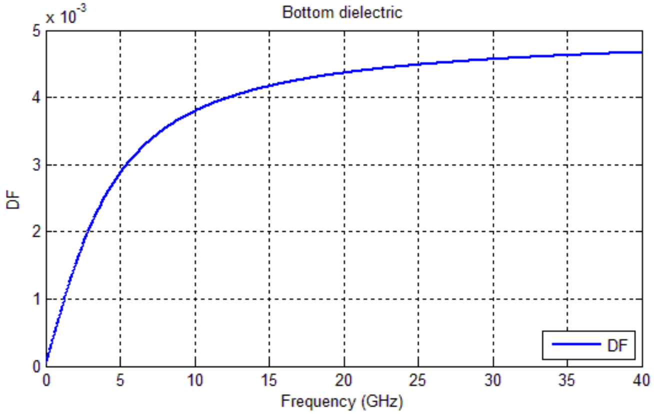
$$m1 = 9.58619$$

$$m2 = 15.4109$$

$$\varepsilon = \varepsilon_\infty + \Delta\varepsilon \cdot \frac{1}{m_2 - m_1} \cdot \log_{10}\left(\frac{10^{m_2} + i \cdot f}{10^{m_1} + i \cdot f}\right)$$

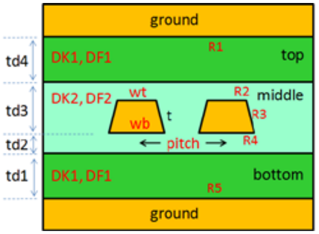
$$= \varepsilon_r \cdot (1 - i \cdot \tan\delta)$$





Extracted DK2 and DF2

Model 3



$$\varepsilon_\infty = 3.46724$$

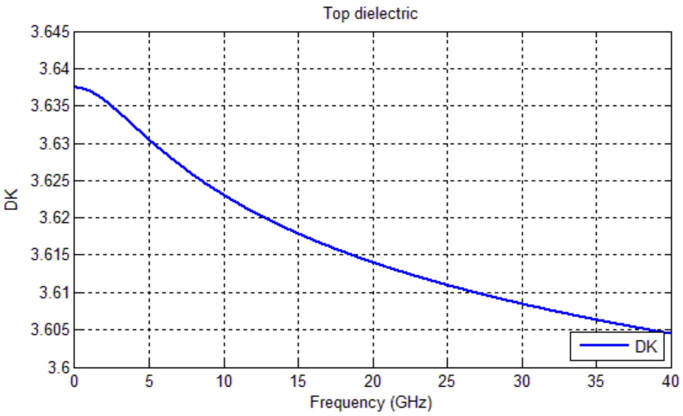
$$\Delta\varepsilon = 0.170196$$

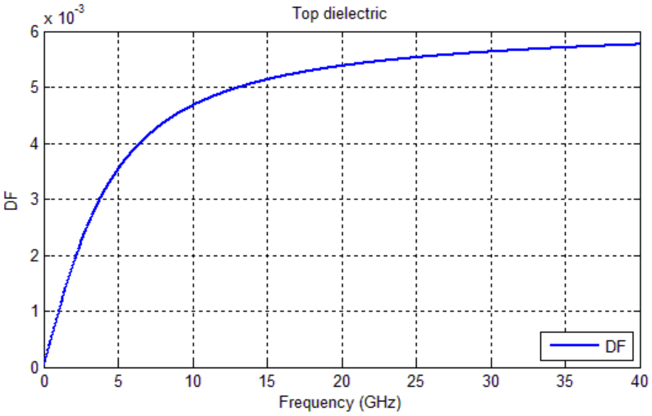
$$m1 = 9.58715$$

$$m2 = 14.8352$$

$$\varepsilon = \varepsilon_\infty + \Delta\varepsilon \cdot \frac{1}{m_2 - m_1} \cdot \log_{10}\left(\frac{10^{m_2} + i \cdot f}{10^{m_1} + i \cdot f}\right)$$

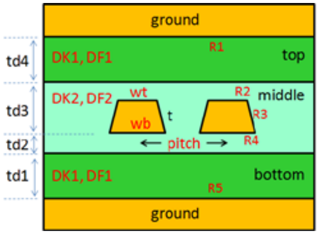
$$= \varepsilon_r \cdot (1 - i \cdot \tan\delta)$$





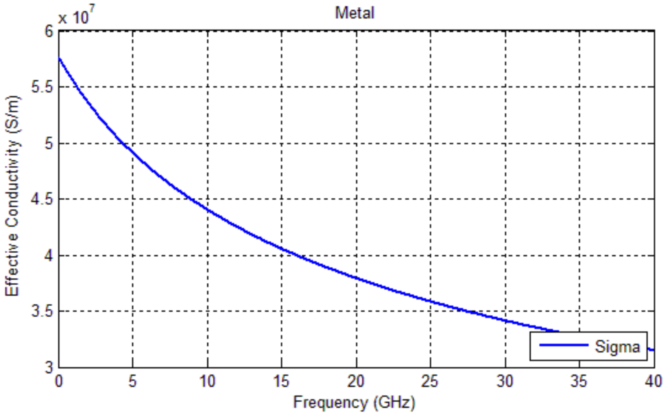
Extracted effective conductivity

Model 3

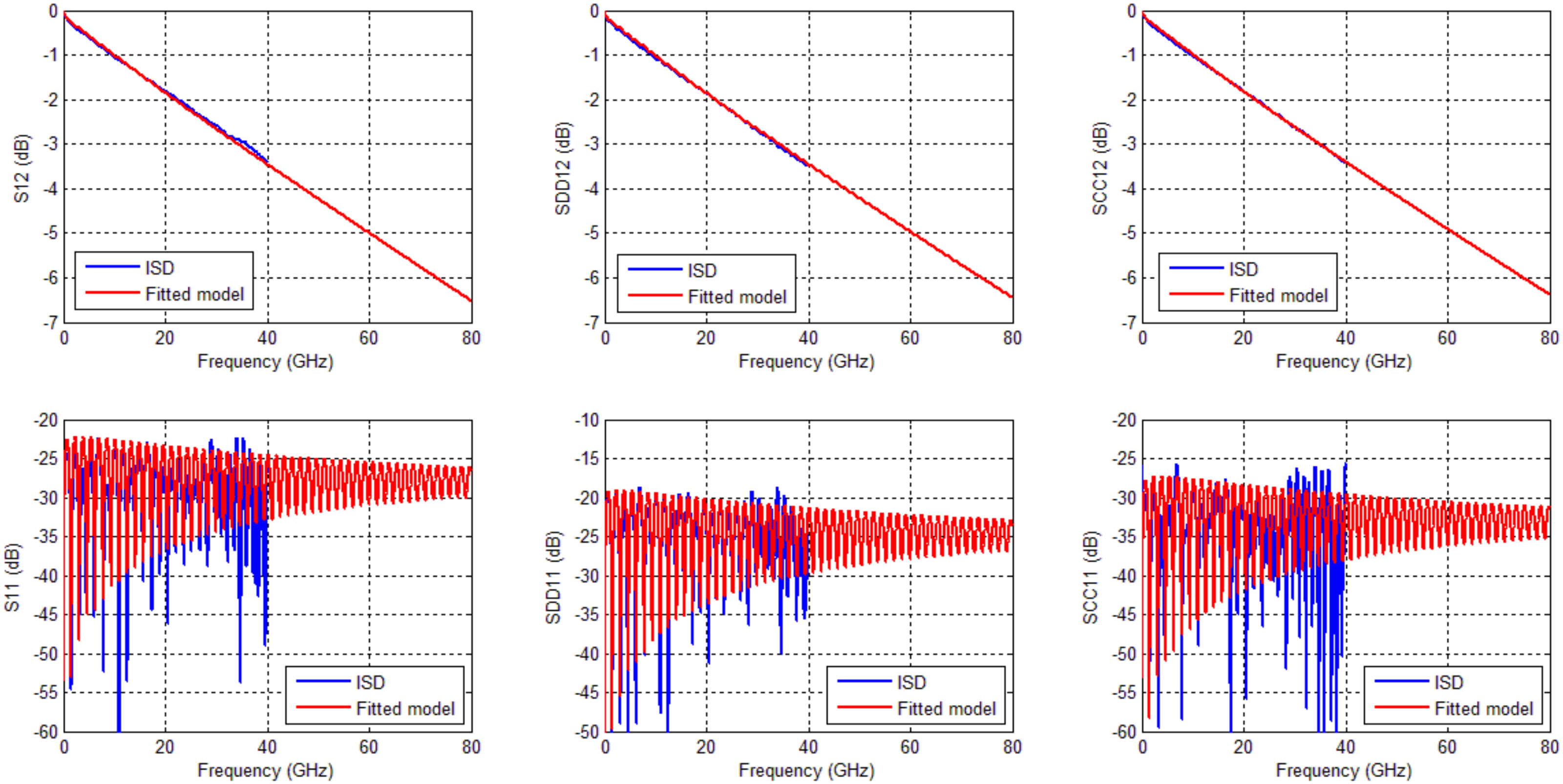


$$\sigma = 5.8\times10^{7}\ \mathrm{S/m}$$

$$R_q = 0.324321\,\mu\mathrm{m}$$



Length- and frequency-scalable models can now be created.



Summary

- Accurate de-embedding is crucial for design verification, compliance testing and PCB material property (DK, DF, roughness) extraction.
- Traditional de-embedding methods can give non-causal errors in device-under-test (DUT) results if the test fixture and calibration structure have different impedances.
- In-Situ De-embedding (ISD) addresses such impedance differences through software instead of hardware, thereby improving de-embedding accuracy while reducing hardware costs.

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