In-Situ De-embedding (ISD)

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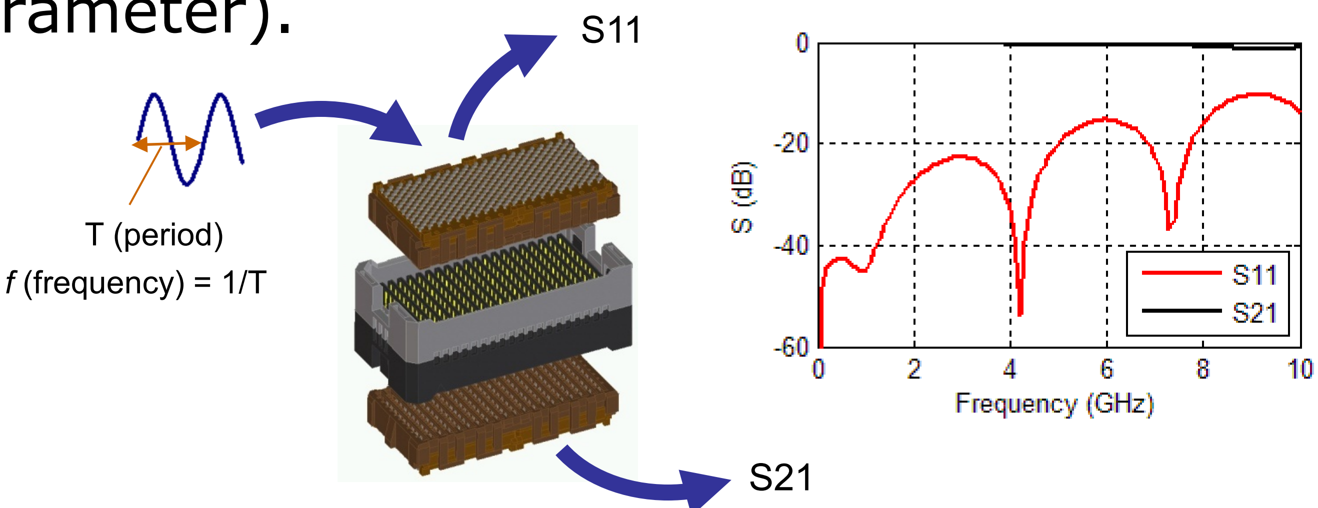
Outline

- 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

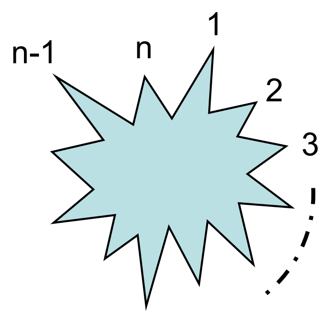
VNA and S parameter

- 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:



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

- 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.

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

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

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

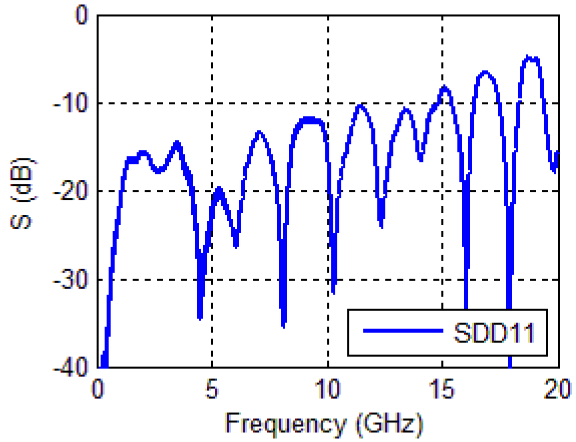
1. the relationship between cause and effect.
2. the principle that everything has a cause.

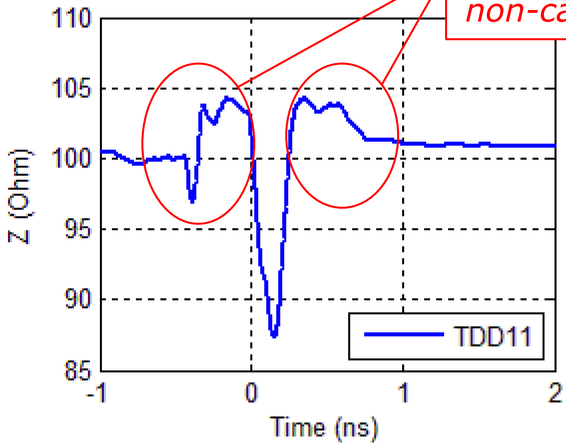
In other words:

Can not get something from nothing.

How to identify non-causal S parameter

- Convert S parameter into TDR/TDT.

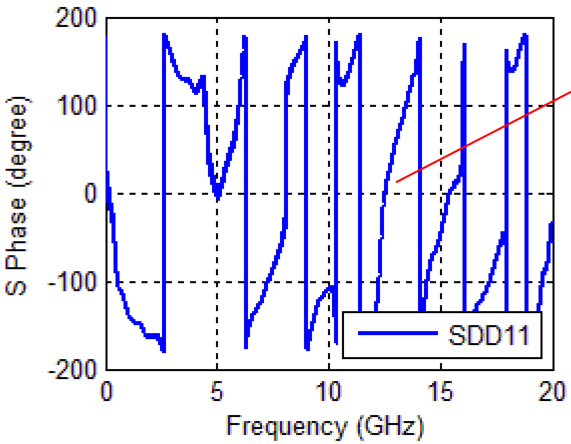




Response before time zero and/or after DUT is non-causal.*

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

- Check phase angle.



Counterclockwise phase angle is non-causal.

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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:

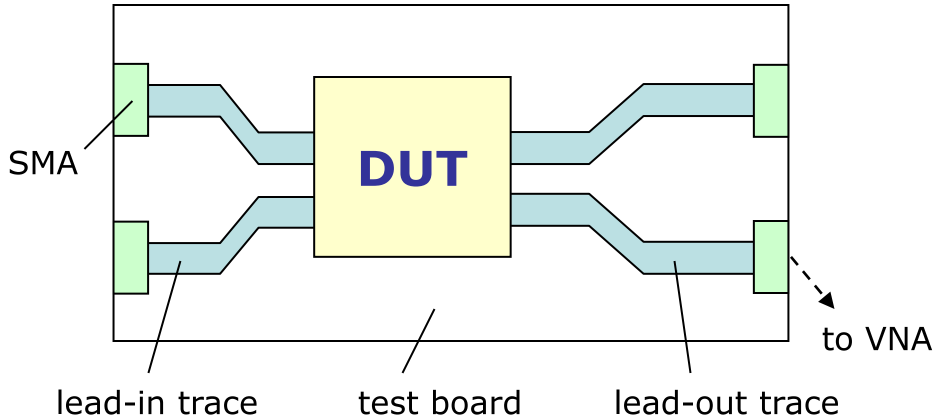
$$\Psi(\omega) = \Psi_R(\omega) + j\Psi_I(\omega)$$

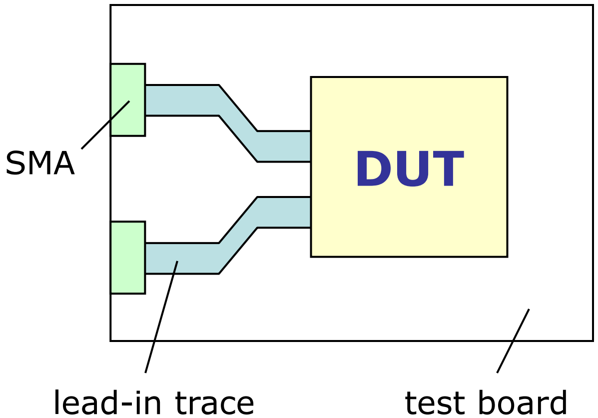
$$\Psi_R(\omega) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{\Psi_I(\omega')}{\omega' - \omega} d\omega'$$

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

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).

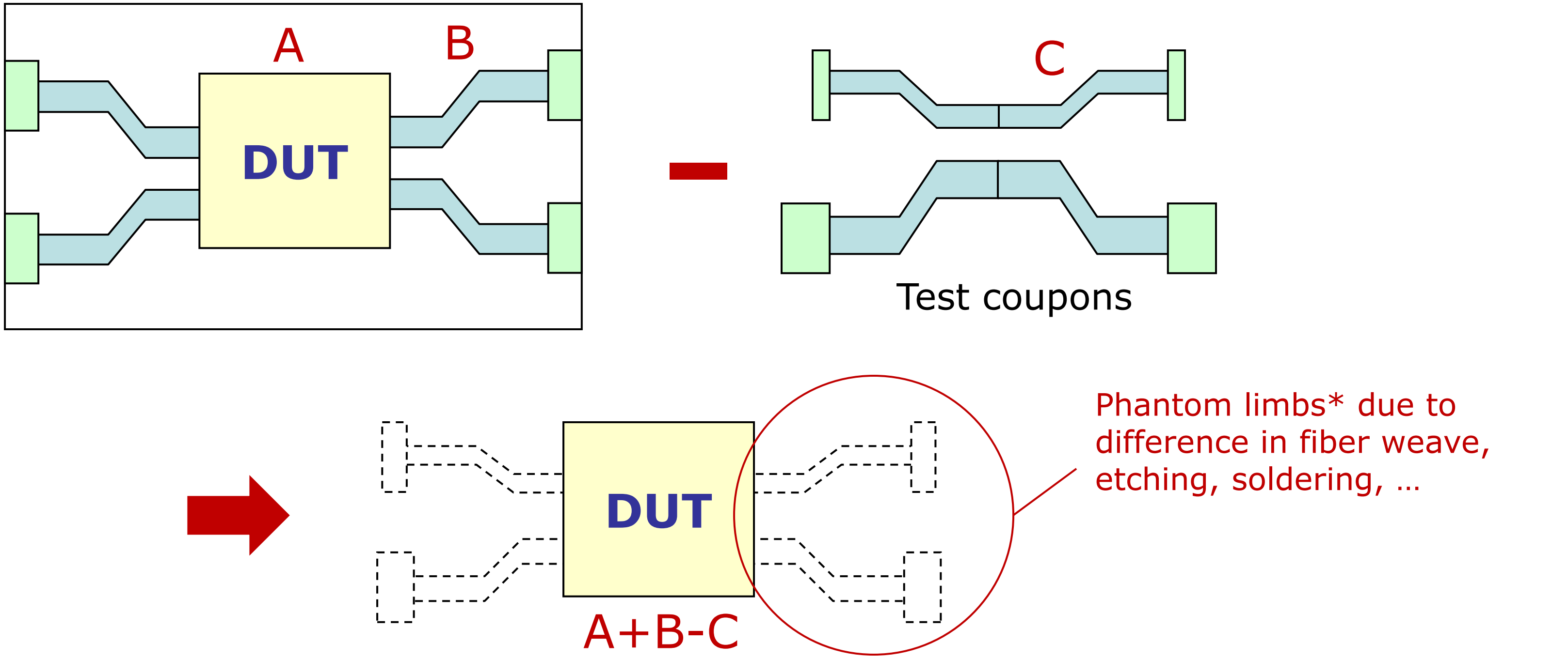




- The lead-ins and lead-outs don't need to look the same.
- There may even be no lead-outs (e.g., package).

Why do most de-embedding tools give causality error

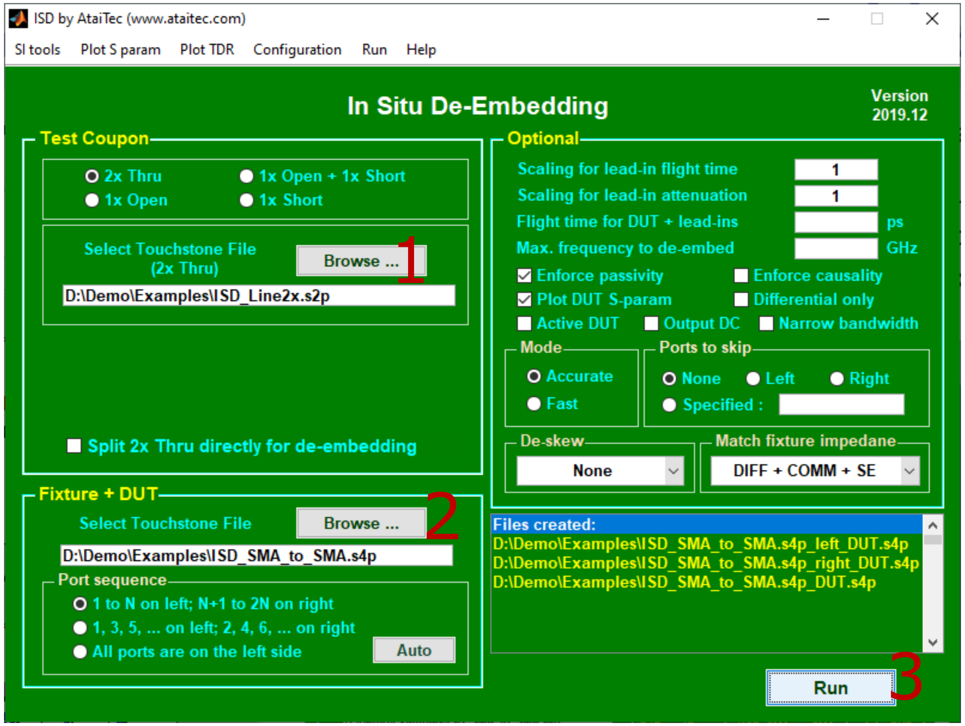
- Most tools use test coupons directly for de-embedding, so difference between actual fixture and test coupons gets piled up into DUT results.



* 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)
Introduced to address impedance variation

- ISD uses test coupon (“2x thru” or “1x open / 1x short”) as reference and de-embeds fixture’s actual impedance through numerical optimization.
- Other methods use test coupon directly for de-embedding and result in causality error when test coupon and actual fixture to be de-embedded have different impedance.
- ISD addresses impedance variation between test coupon and actual fixture through software, instead of hardware, improving de-embedding accuracy and reducing hardware cost.



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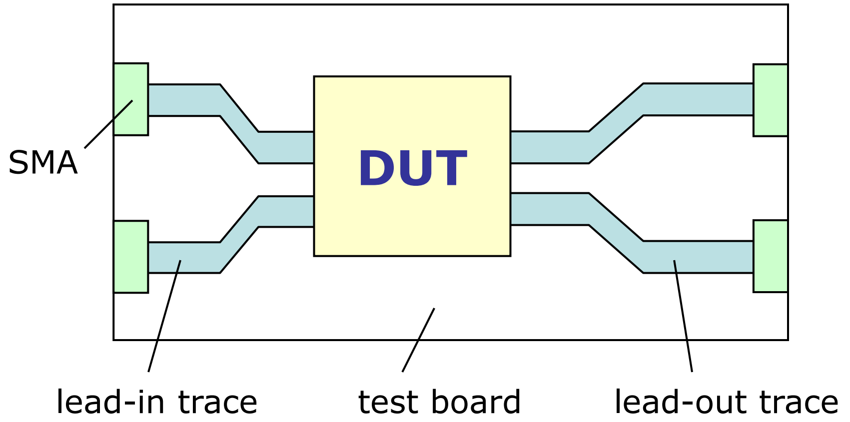
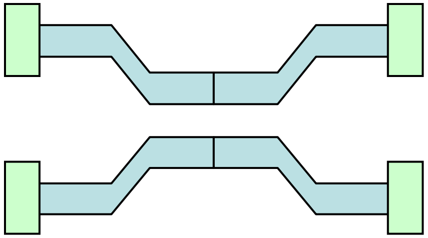
ISD is integrated into R&S ZNA, ZNB

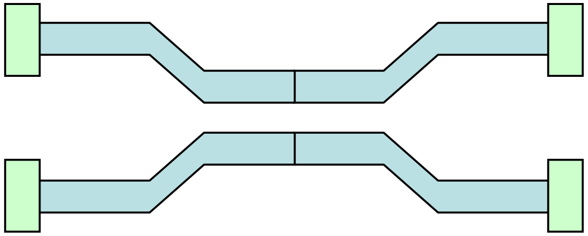
What is “2x thru”

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





2x thru for lead-ins

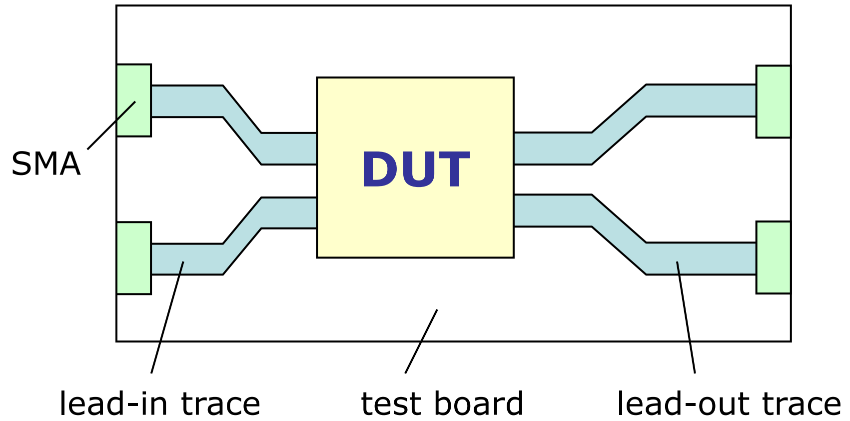


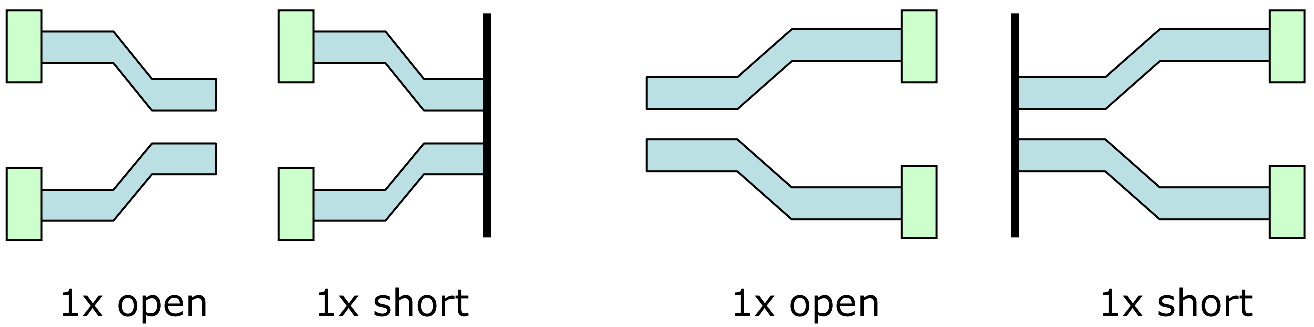
2x thru for lead-outs

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

What is "1x open / 1x short"

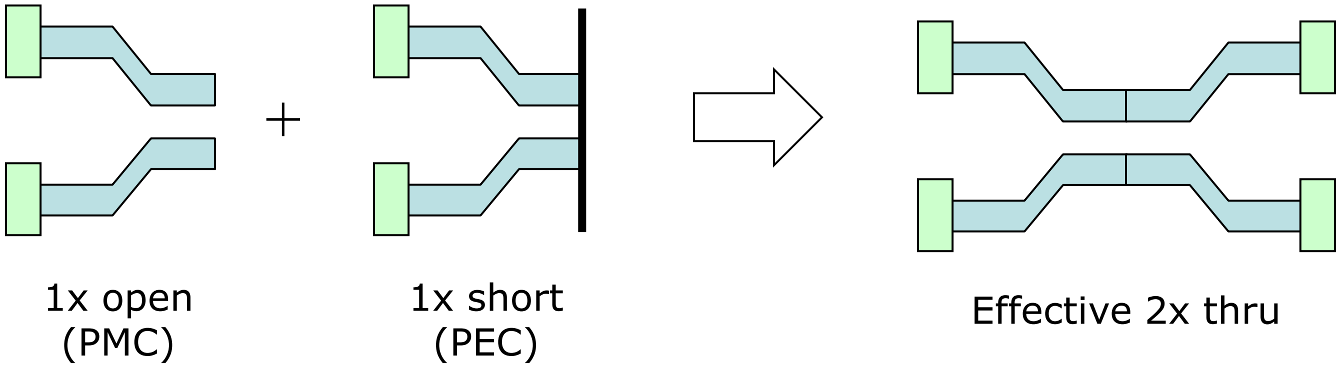
- "1x open / 1x short" is useful when "2x thru" is not possible (e.g., connector vias, package, …).





What is “1x open + 1x short”

- “1x open + 1x short” can be equated to effective* 2x thru.

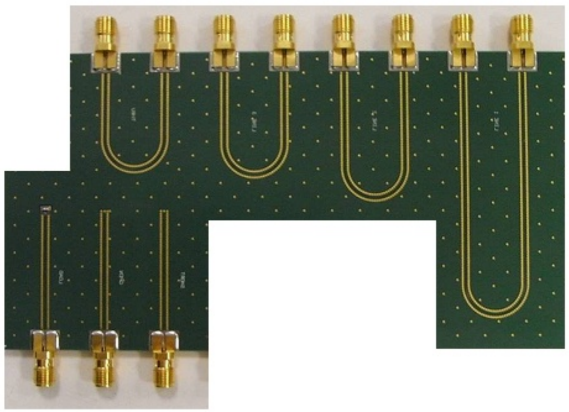


$$[S]^{2x} = \begin{bmatrix} S_{11}^{2x} & S_{12}^{2x} \\ S_{12}^{2x} & S_{11}^{2x} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} S_{11}^{open} + S_{11}^{short} & S_{11}^{open} - S_{11}^{short} \\ S_{11}^{open} - S_{11}^{short} & S_{11}^{open} + S_{11}^{short} \end{bmatrix}$$

* C.C. Huang, "Fixture de-embedding using calibration structures with open and short terminations," US patent no. 9,797,977, 10/24/2017.

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

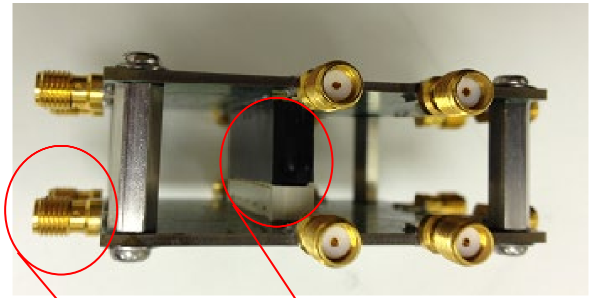
- Only one 2x thru test coupon is needed.
- Test coupon is used only for reference, not for direct de-embedding.
- Actual DUT board impedance is de-embedded.
- Inexpensive SMAs, board materials (FR4) and loose-etching-tolerance can be used.
- ECal can be used for fast SOLT calibration.
  - Reference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

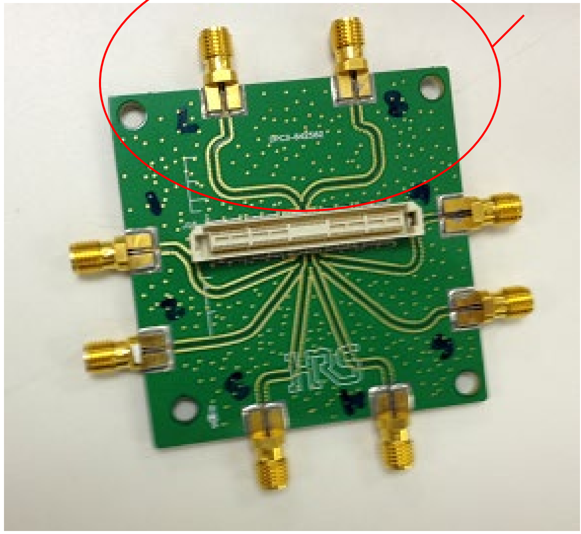
- In this example, we will use ISD and TRL to extract a mezzanine connector and compare their results.



SMA

Mezzanine connector (DUT)

To be de-embedded

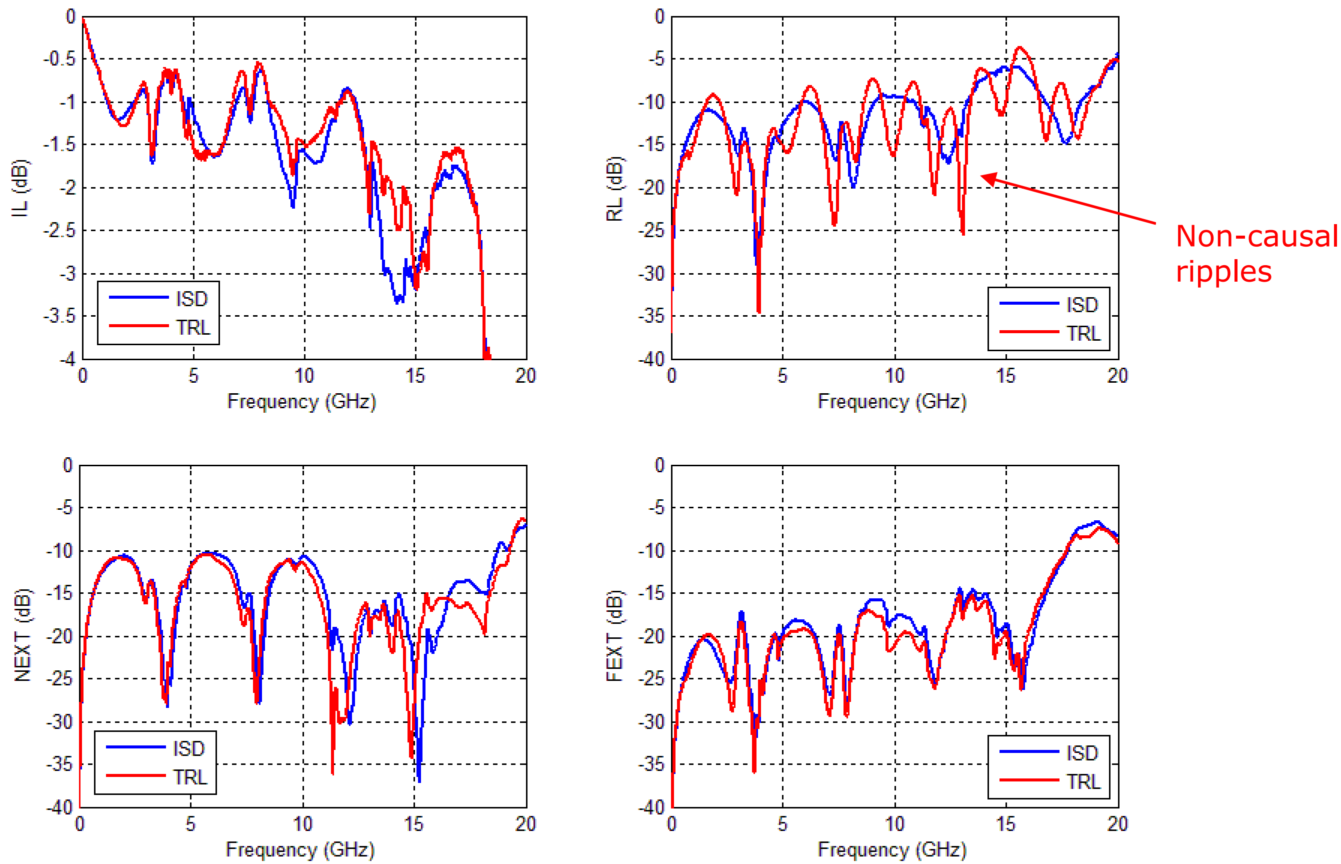


*Courtesy of Hirose Electric

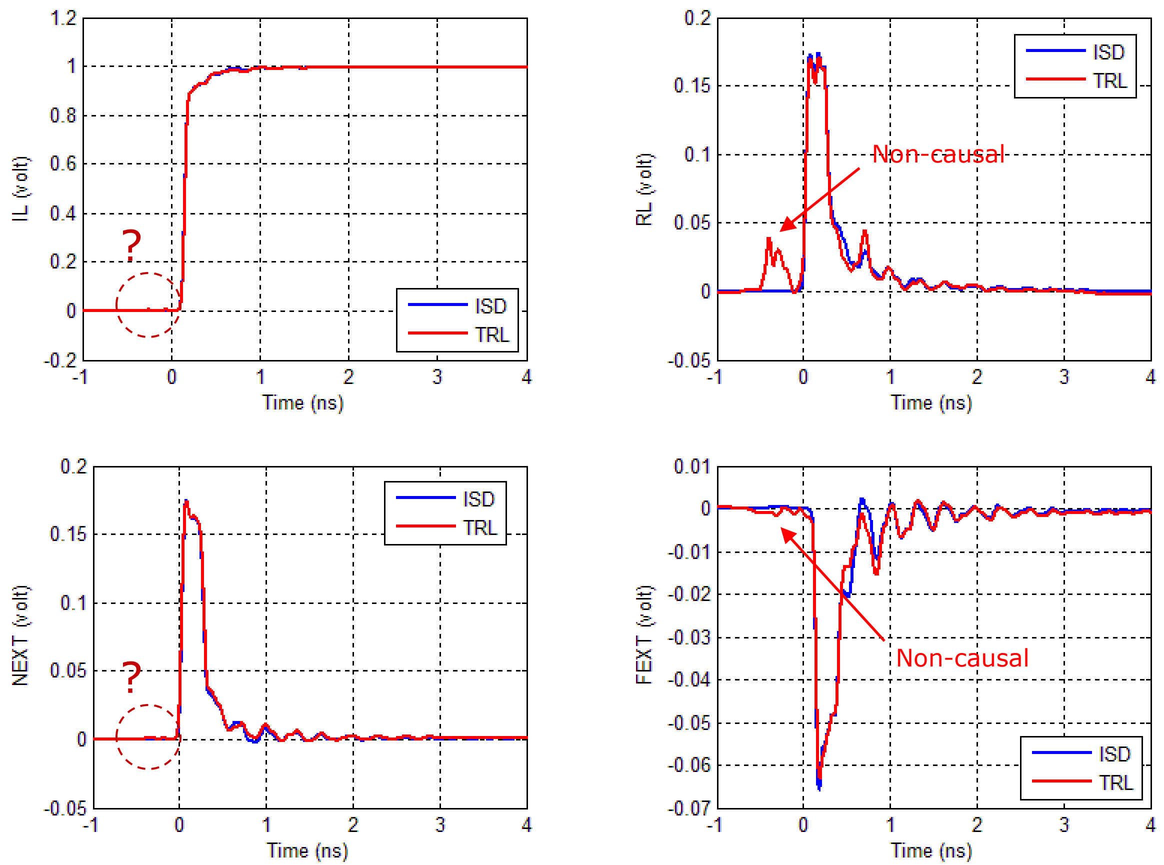
DUT results after ISD and TRL

Which one is more accurate?

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



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



Rise time = 40ps (20/80)

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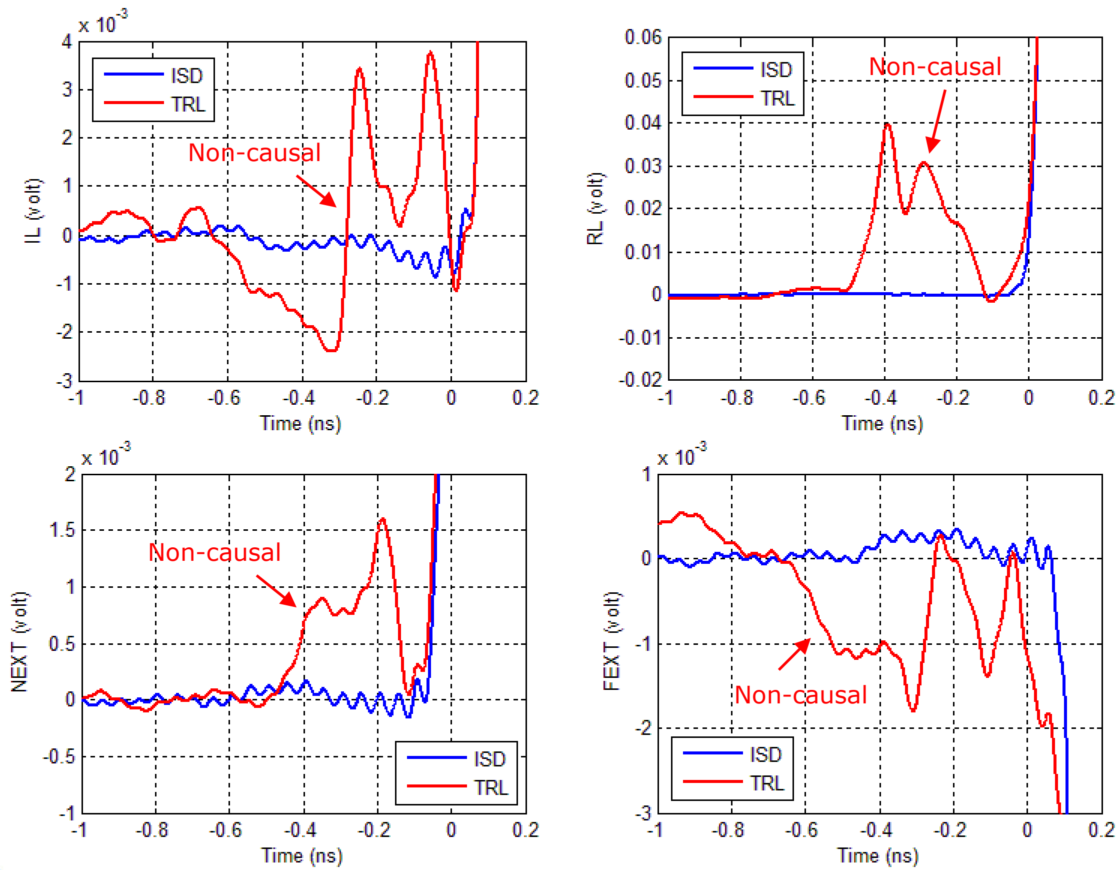
Zoom-in shows non-causal TRL results in all IL, RL, NEXT and FEXT

- 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)

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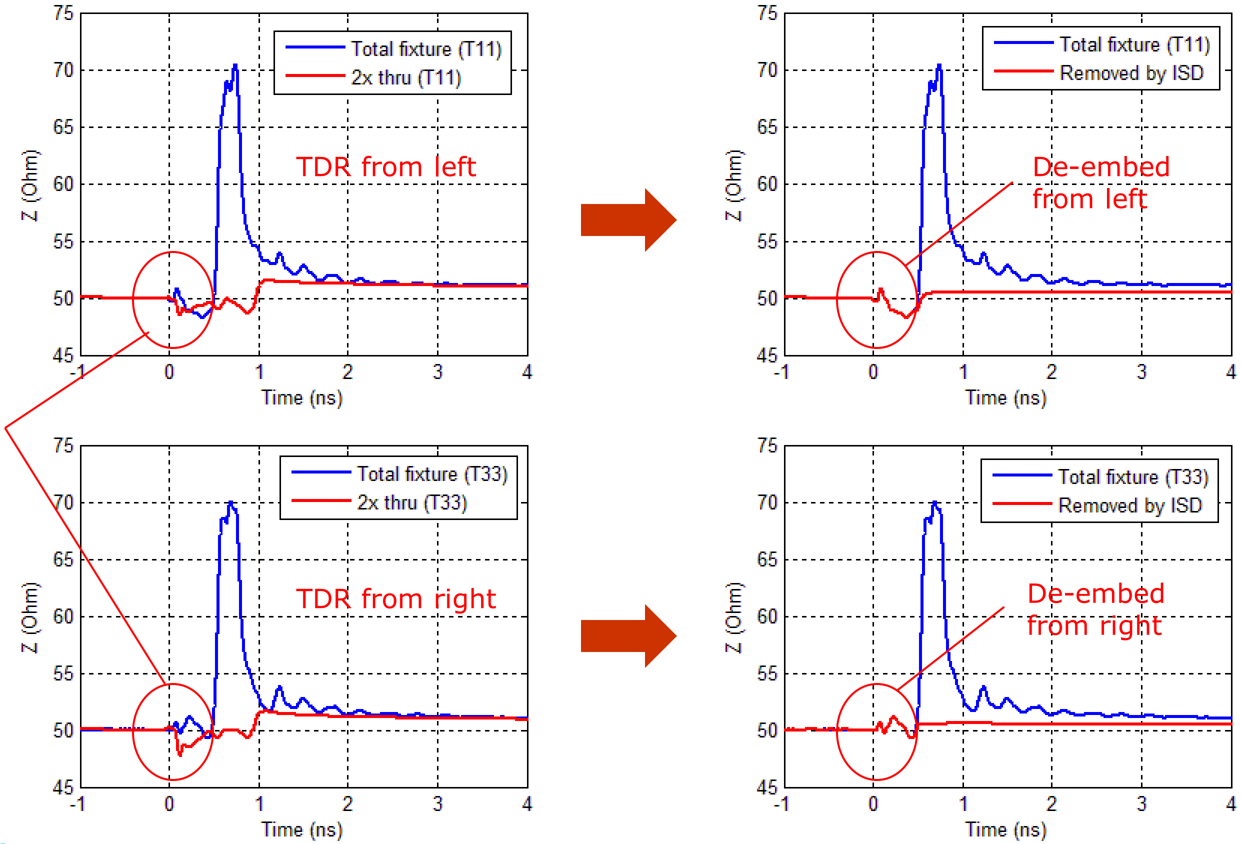
How did ISD do it?

- 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)

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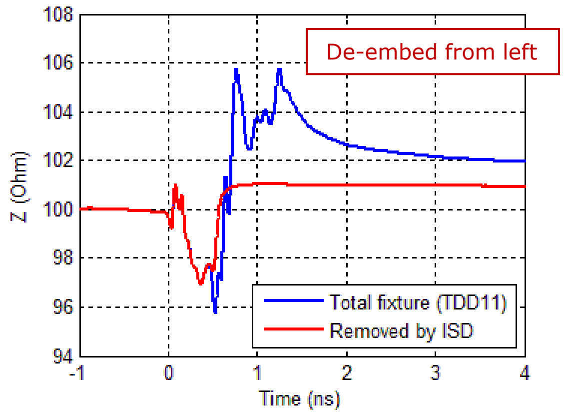
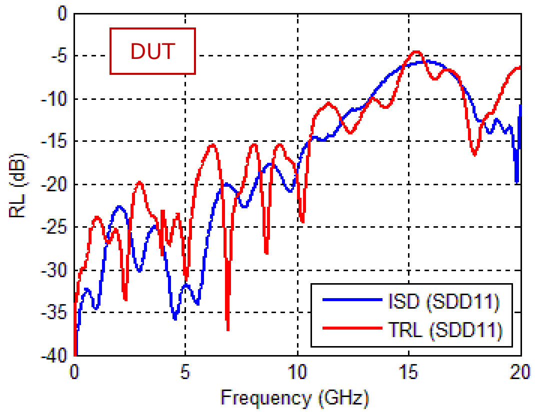
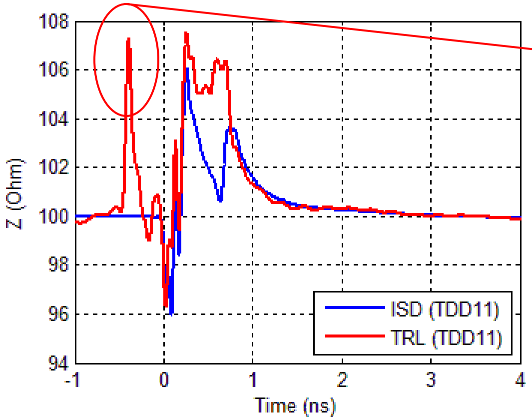
TRL can give huge error in SDD11 even with small impedance variation*

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







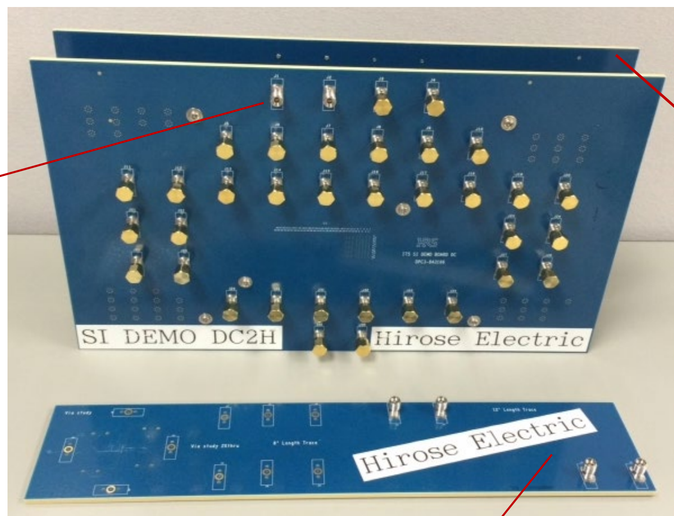
TRL gives more than 100% error due to causality violation.

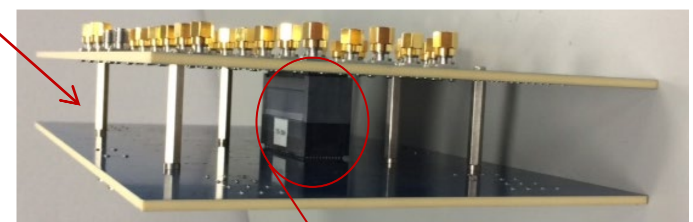
Rise time = 40ps (20/80)

* 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

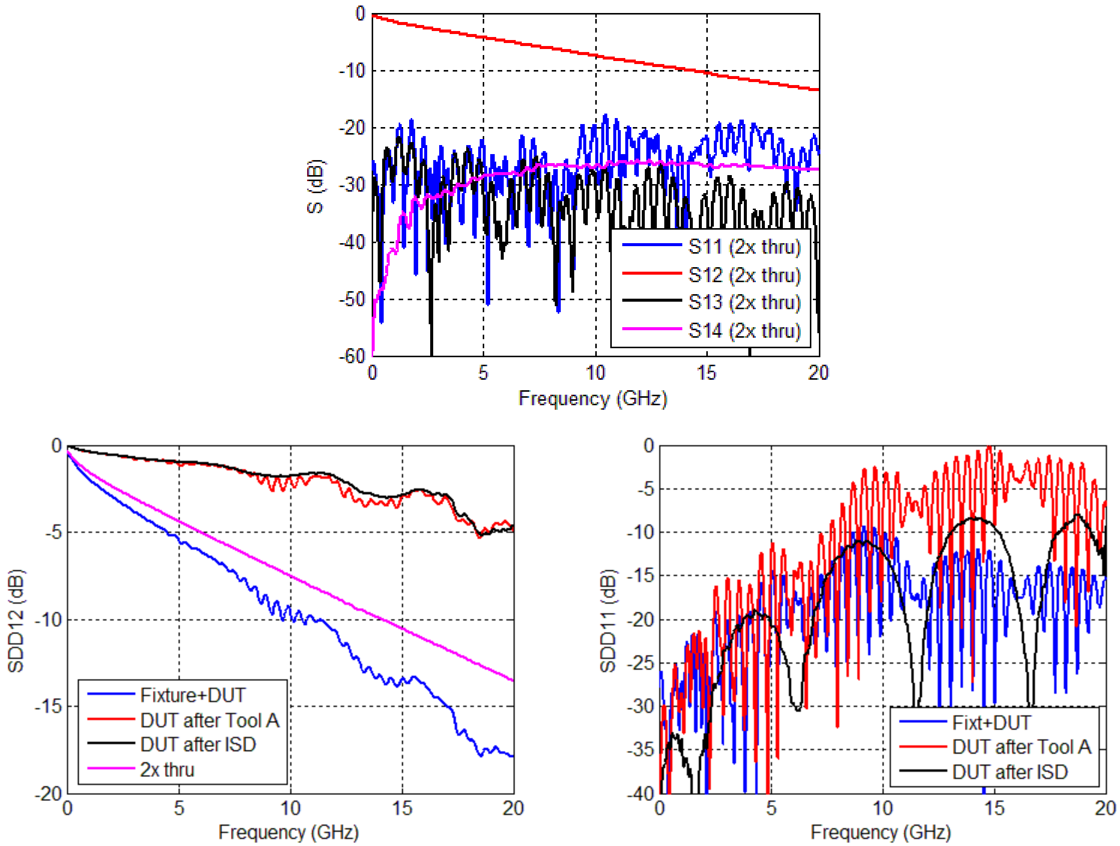
- TRL is impractical for de-embedding large and coupled lead-ins/outs.





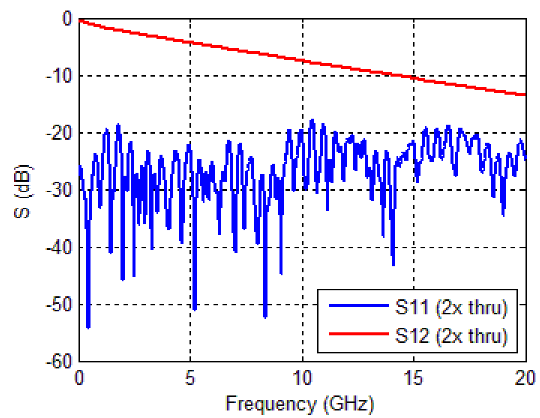
ISD can use a .s4p file of 2x thru for de-embedding

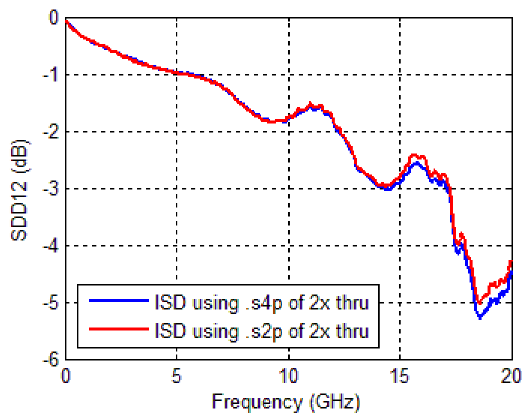
- TRL would have required many long and coupled traces. Tool A gave incorrect results.

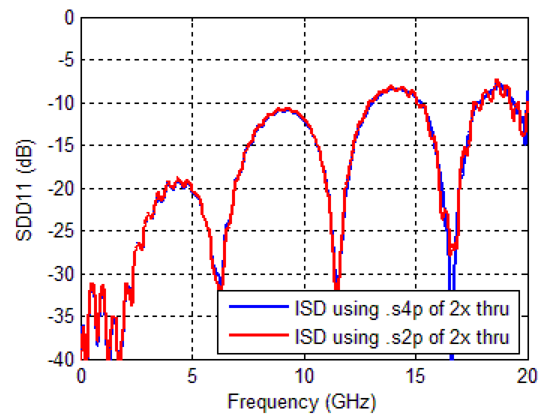


ISD can even use a .s2p file of 2x thru to de-embed crosstalk…

- And the results are similar!

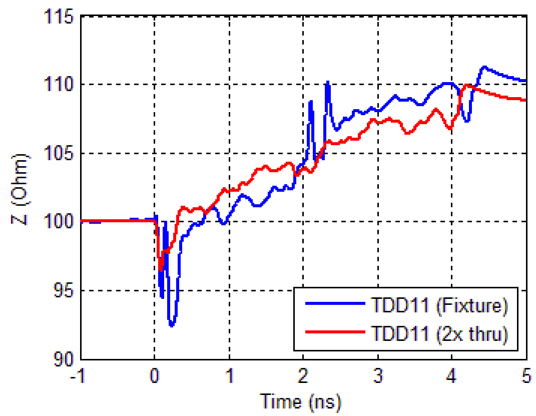


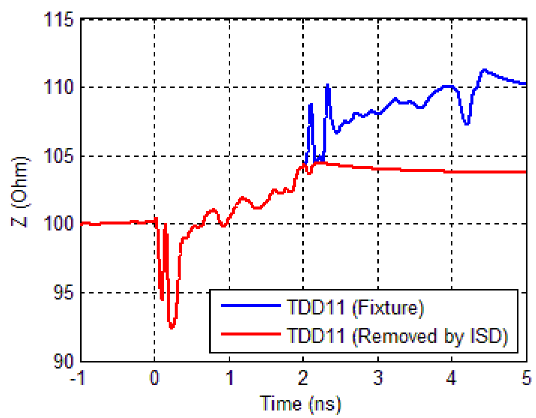


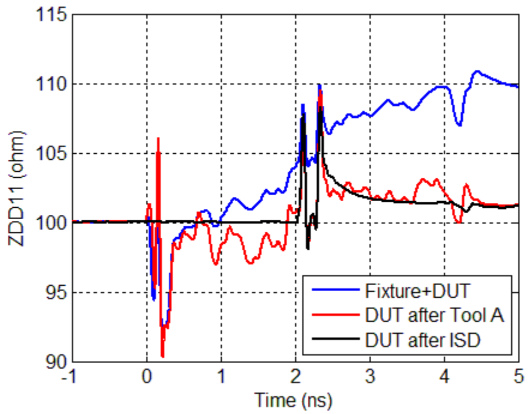


ISD allows a large demo board to double as a characterization board

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



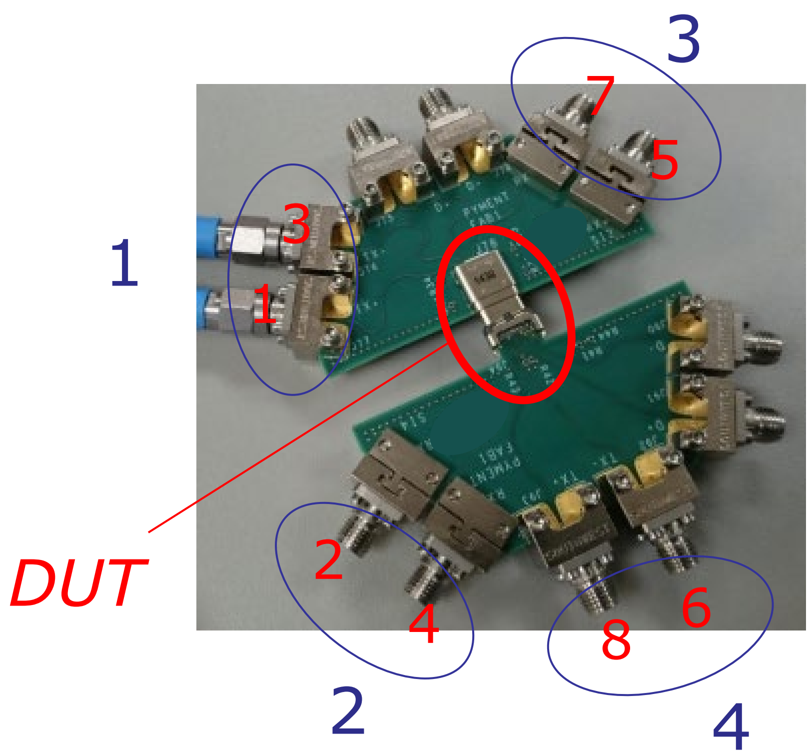


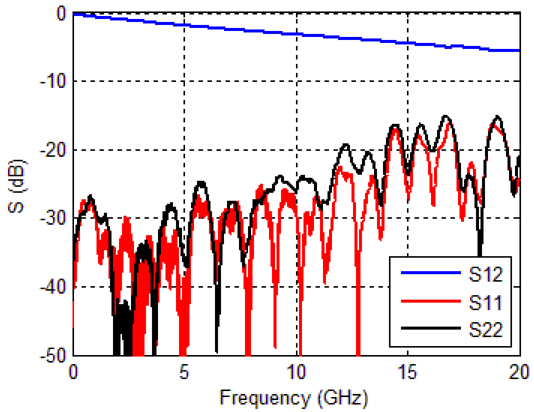


Rise time = 40ps (20/80)

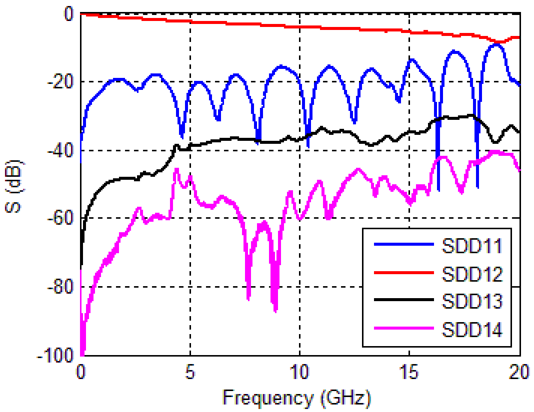
Example 3: USB type C mated connector
ISD vs. Tool A

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





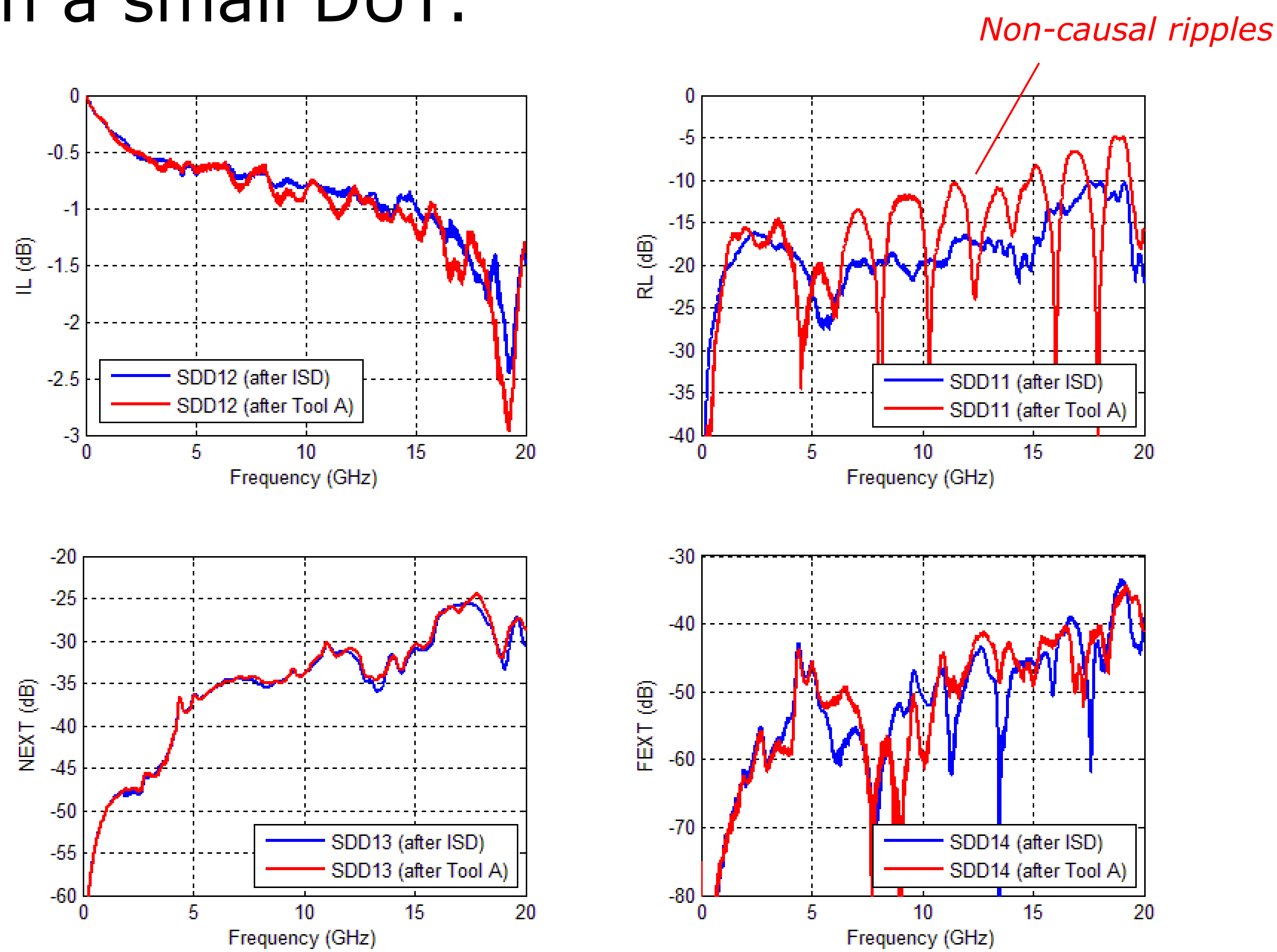
2x thru



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.



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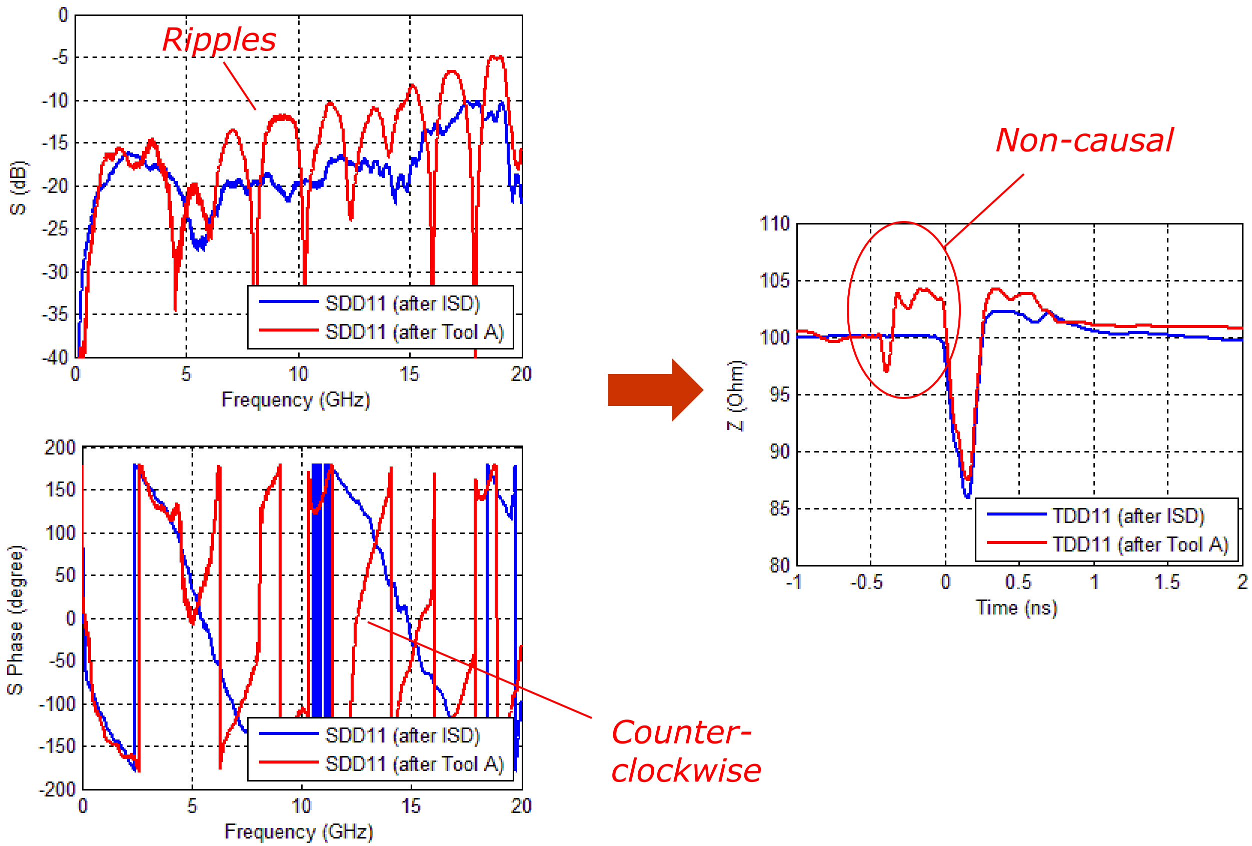
Converting S parameter into TDR/TDT shows non-causality in Tool A results

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



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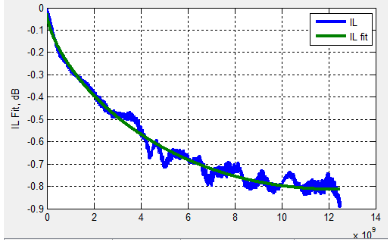
De-embedding affects pass or fail of compliance spec.

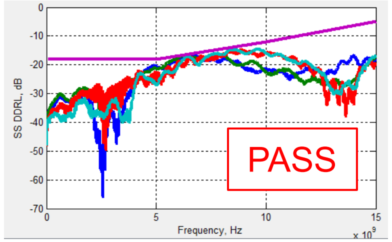
- ISD improves IMR and IRL (from compliance tool).

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



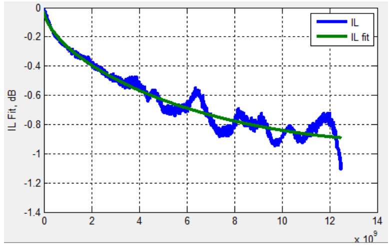
IL



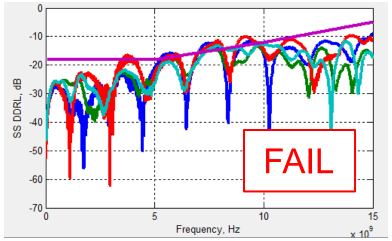
RL

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

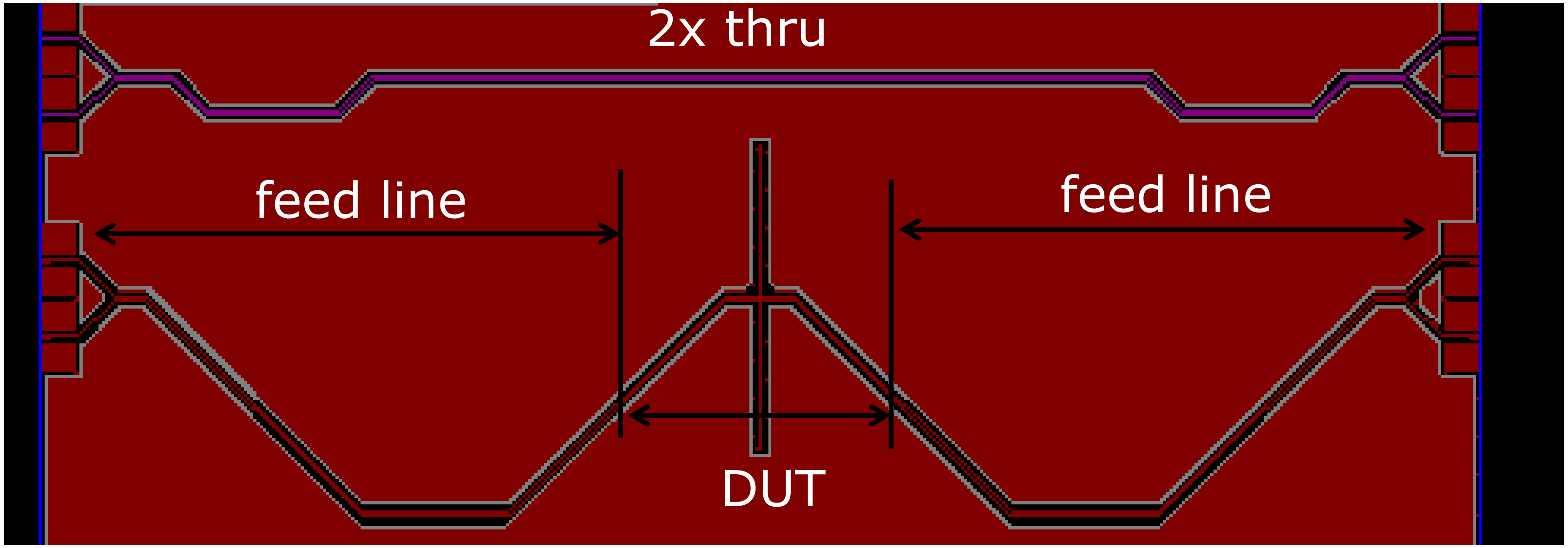


RL

Example 4: Resonator

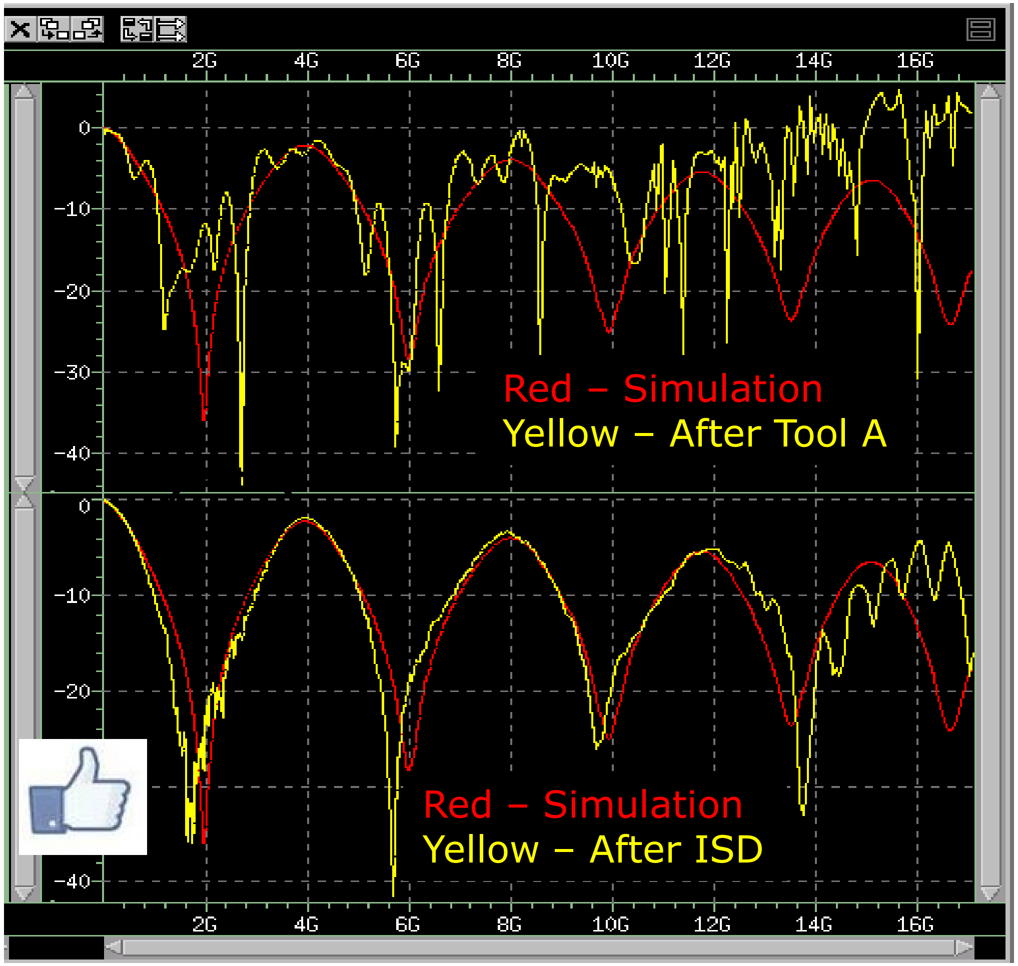
ISD vs. Tool A vs. simulation

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



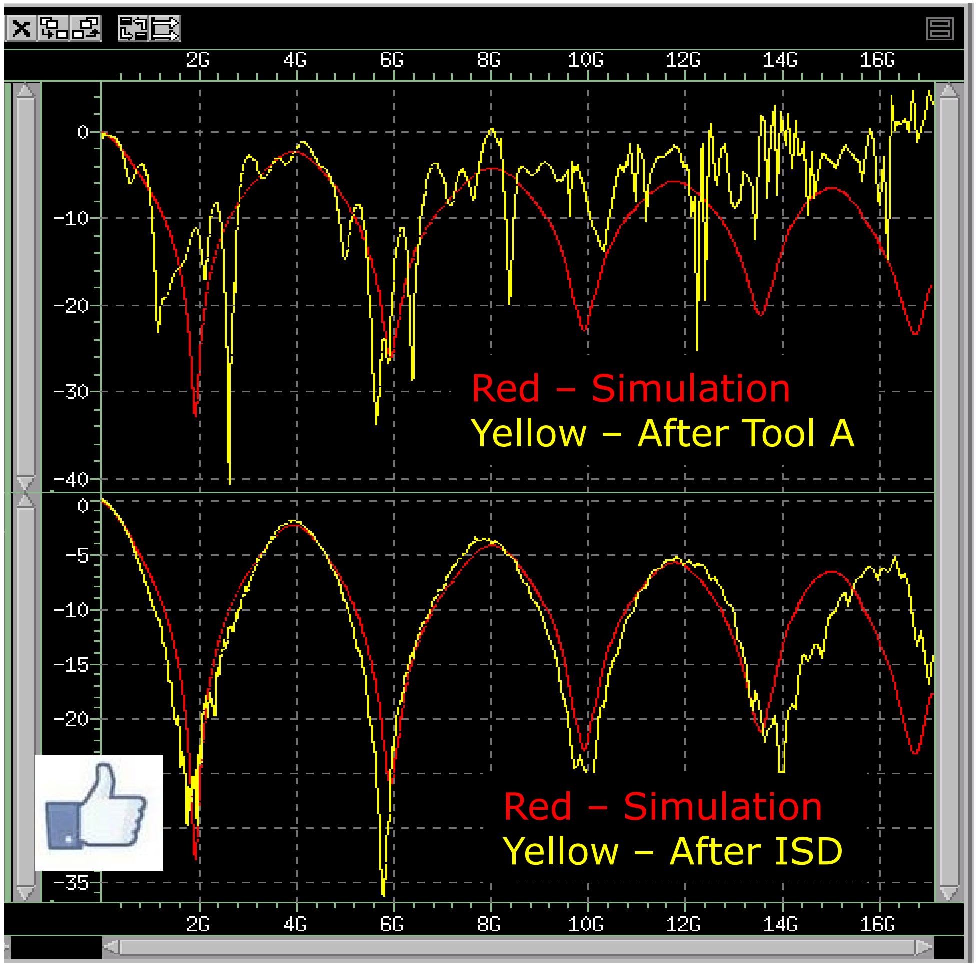
SDD11

ISD correlates with simulation



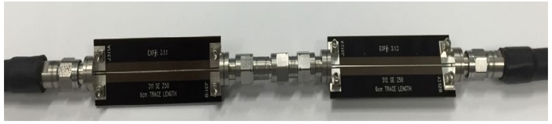
SCC11
ISD correlates with simulation

- Good correlation is crucial for design improvement.

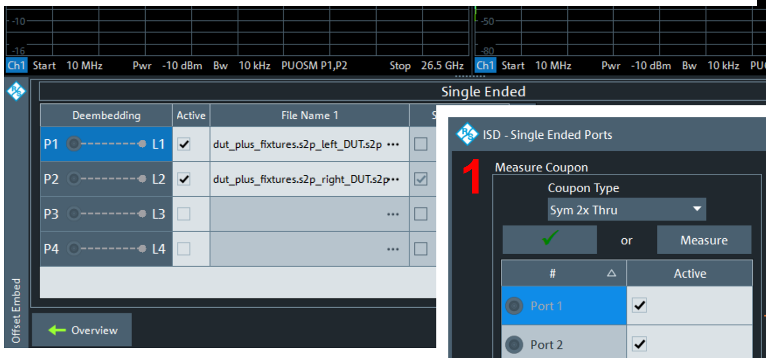


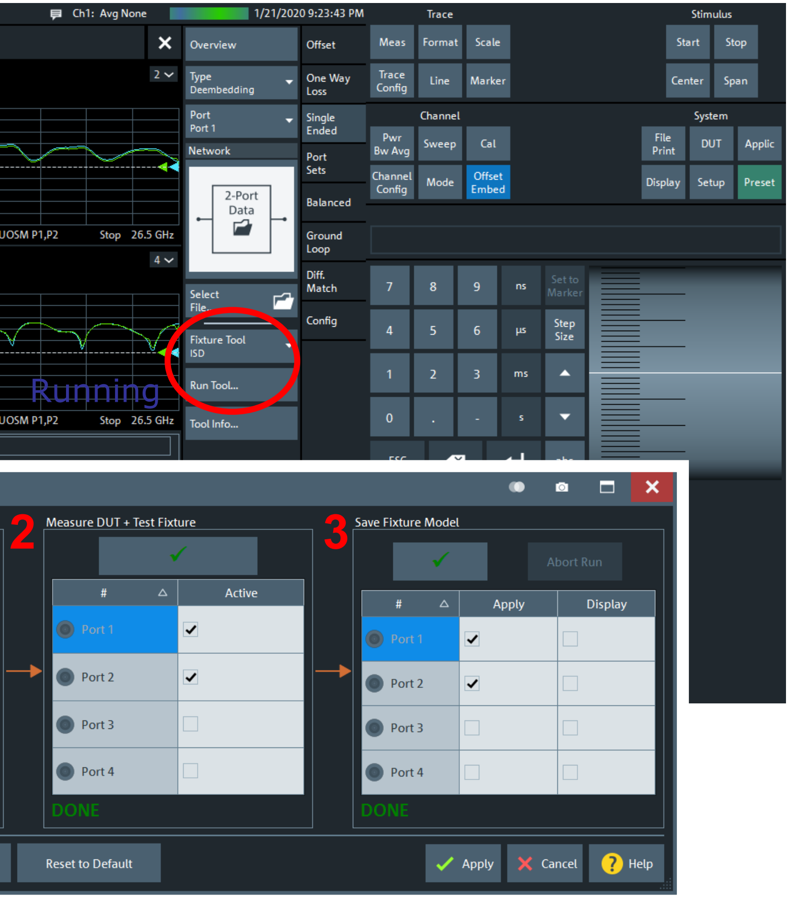
Example 5: IEEE P370 plug and play kit
Beatty standard

2x thru

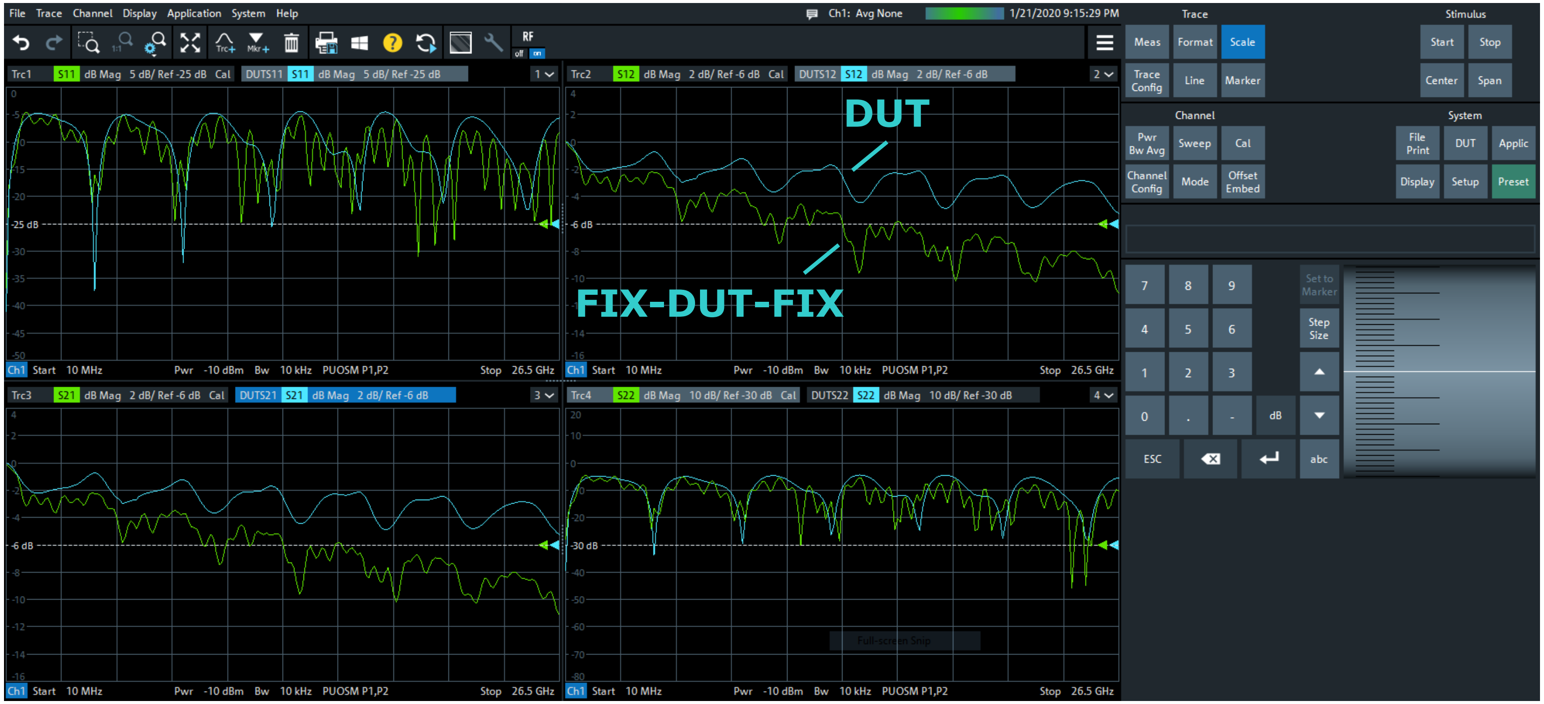


FIXTURE A — Beatty standard (DUT) — FIXTURE B





FIX-DUT-FIX vs. measured DUT



De-embedded DUT vs. measured DUT

Example 6: IEEE P370 plug and play kit
Use 45 ohm 2x thru to de-embed 50 ohm fixture*

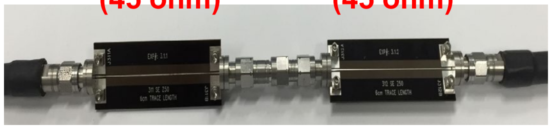
* To mimic possible PCB impedance variation

M11

exp 3.2.1 (45 ohm)

exp 3.2.2 (45 ohm)

2x thru



1.85mm M/M + M/F Adapter

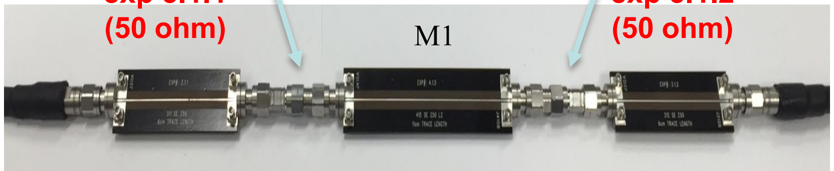
1.85mm M/M + M/F Adapter

M16

exp 3.1.1 (50 ohm)

M1

exp 3.1.2 (50 ohm)

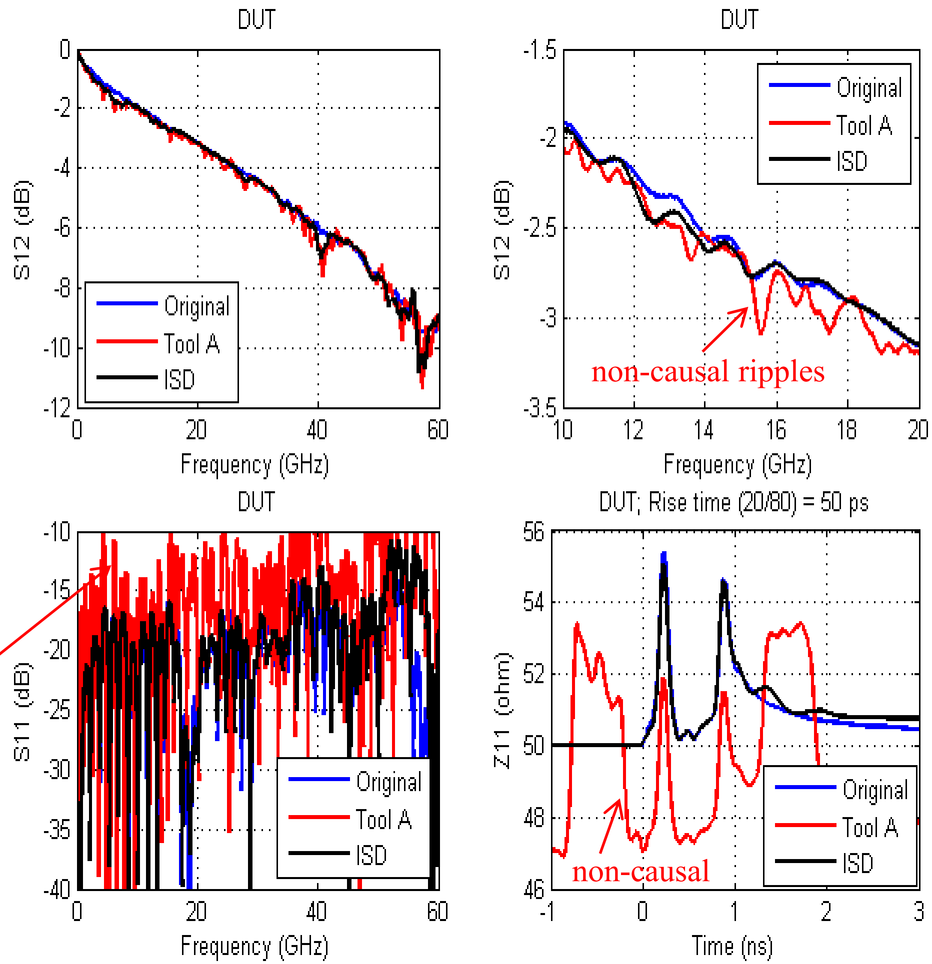


FIXTURE A

exp 4.1.1 6 cm microstrip (DUT)

FIXTURE B

Inaccurate RL is not suitable for DK/DF/SR extraction.



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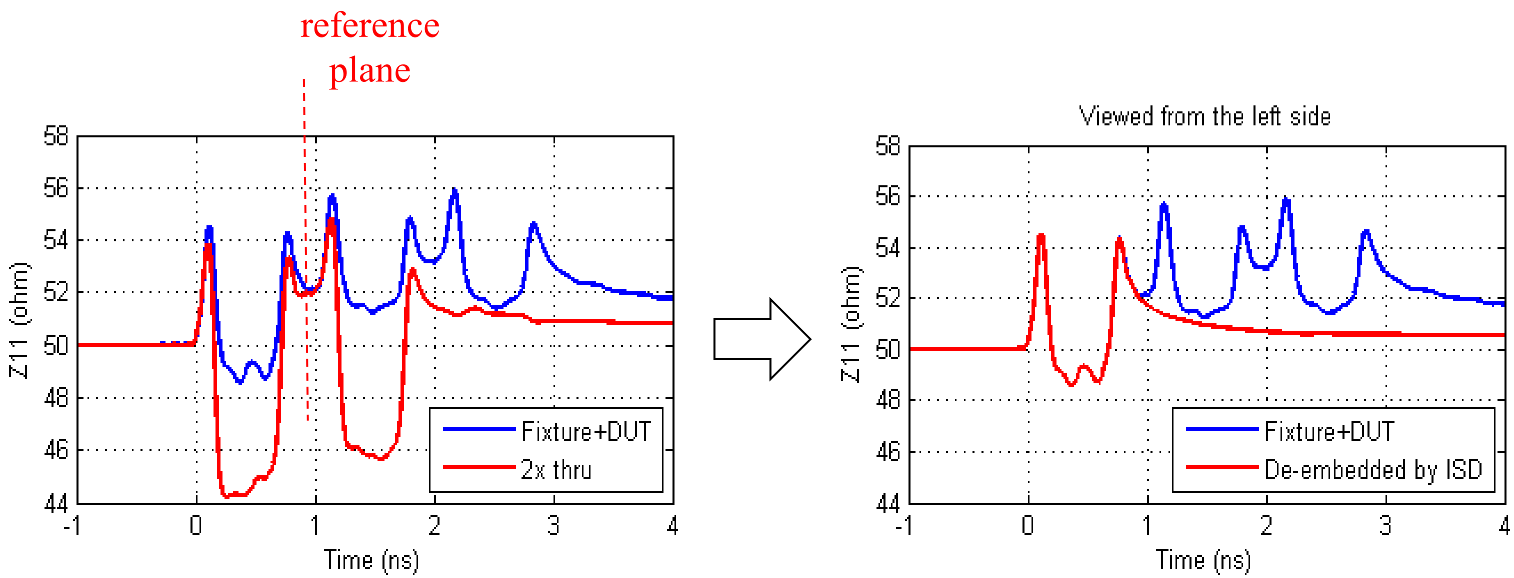
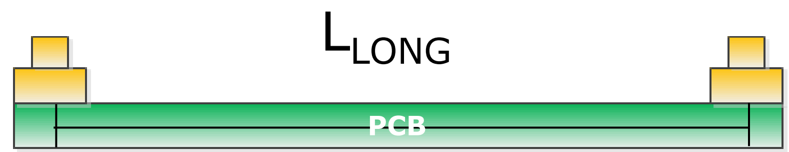
2x thru vs. fixture impedance

- ISD de-embeds fixture's impedance, not 2x thru's impedance.

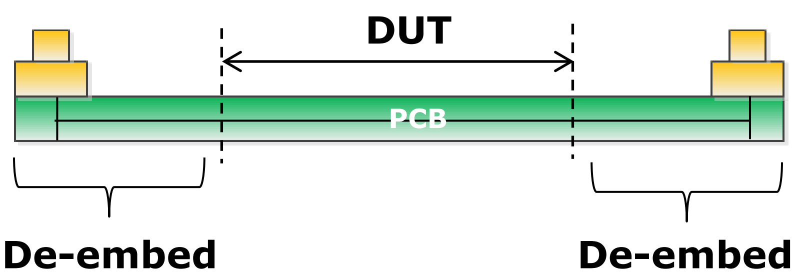


Example 7: PCB trace attenuation
ISD vs. eigenvalue (Delta-L)

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



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



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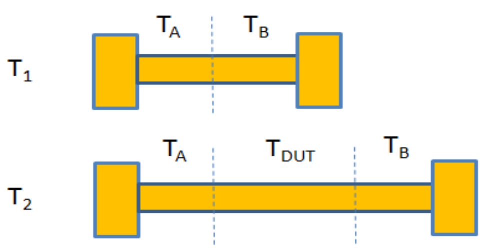
Eigenvalue solution: not de-embedding
For calculating trace attenuation only

- 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

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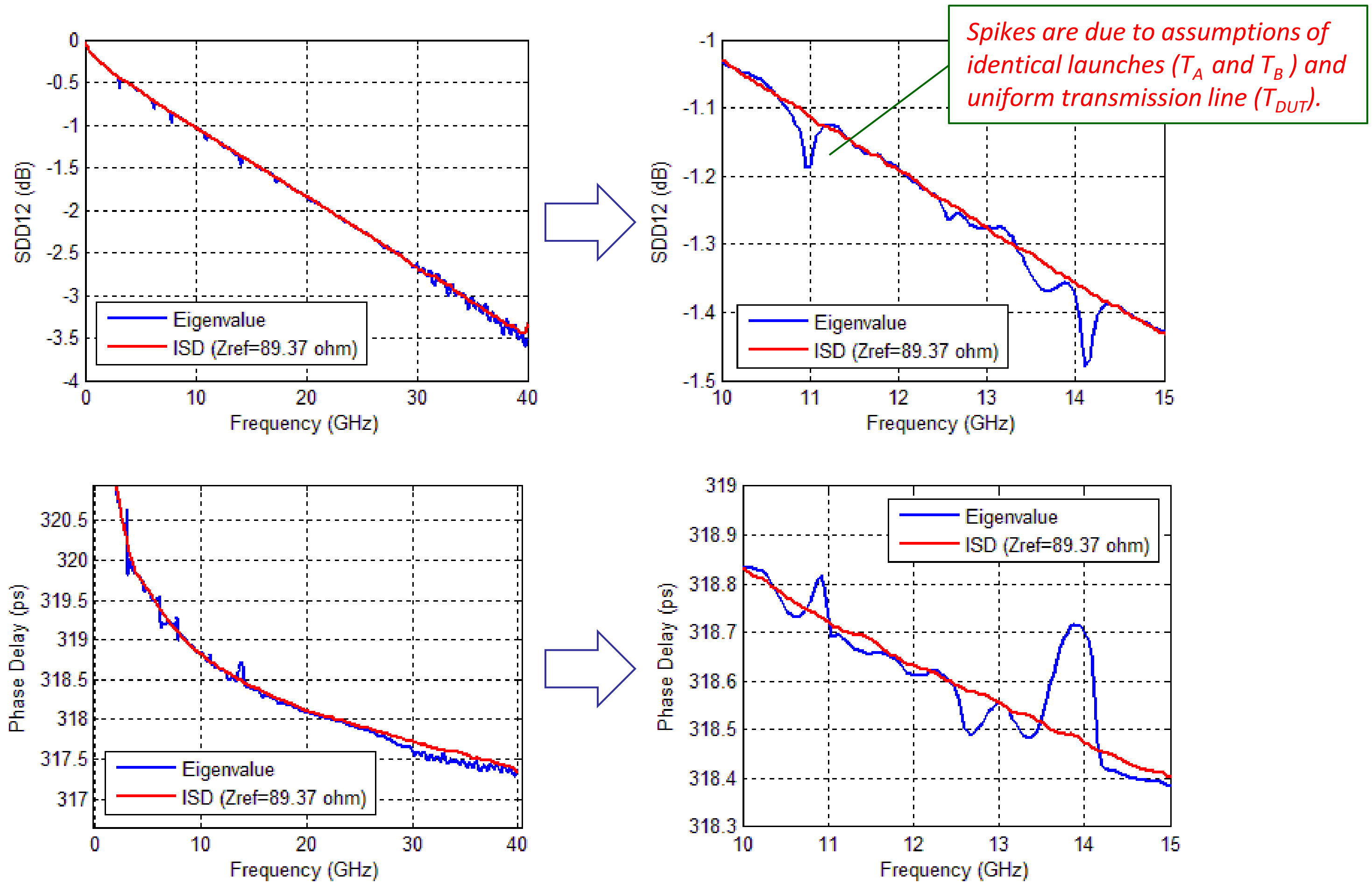
Case 1: 2” (=7”-5”) trace attenuation
Eigenvalue solution is prone to spikes



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

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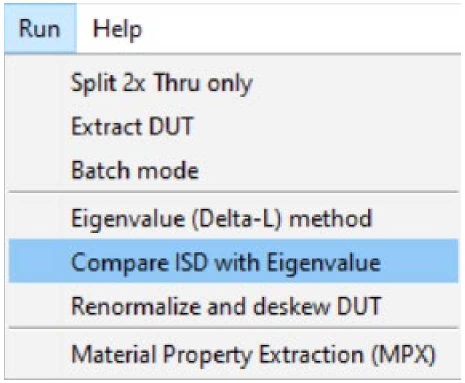
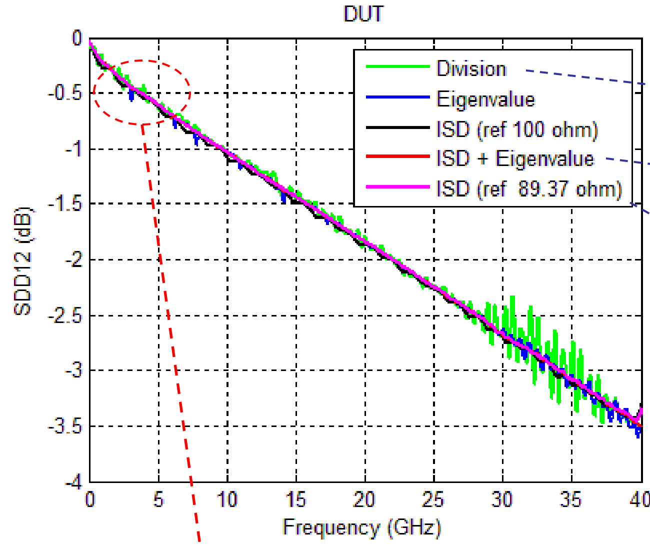
One click compares ISD with eigenvalue and more…



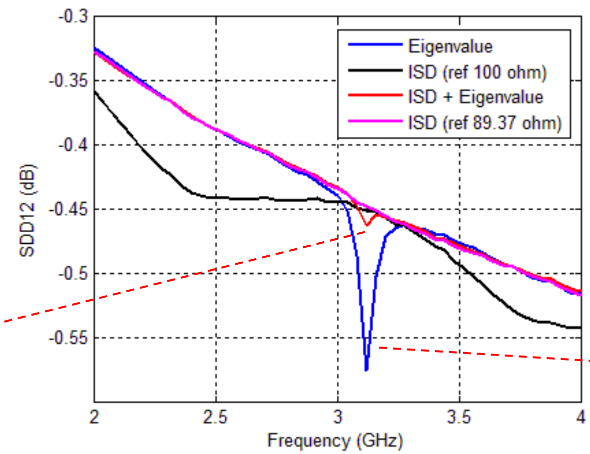
One click does it all



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}).

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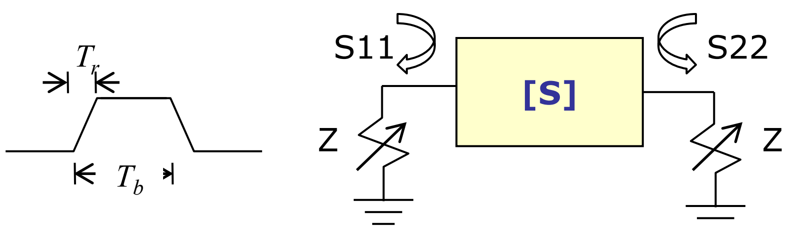
How to define trace impedance
PCB trace is non-uniform transmission line

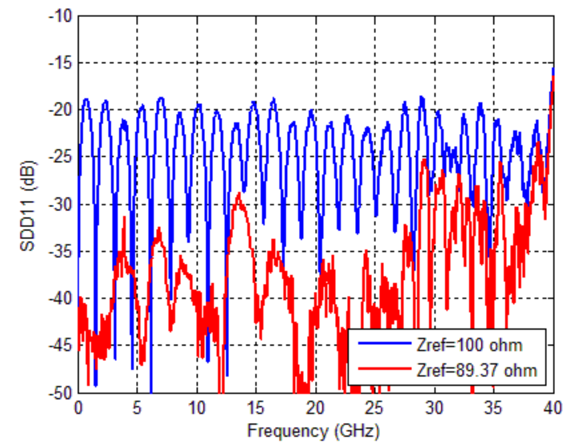
- Define impedance by minimal RL*

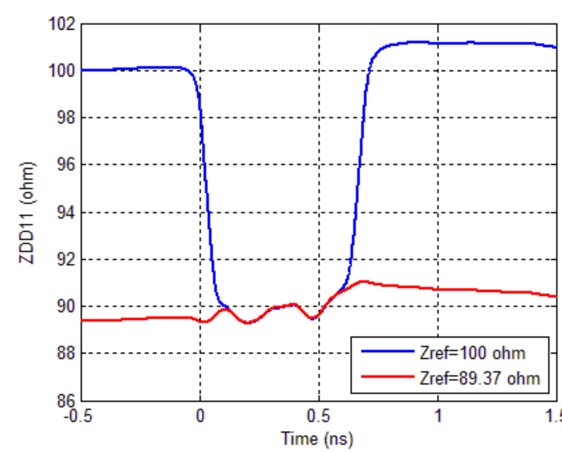


Minimize:

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

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

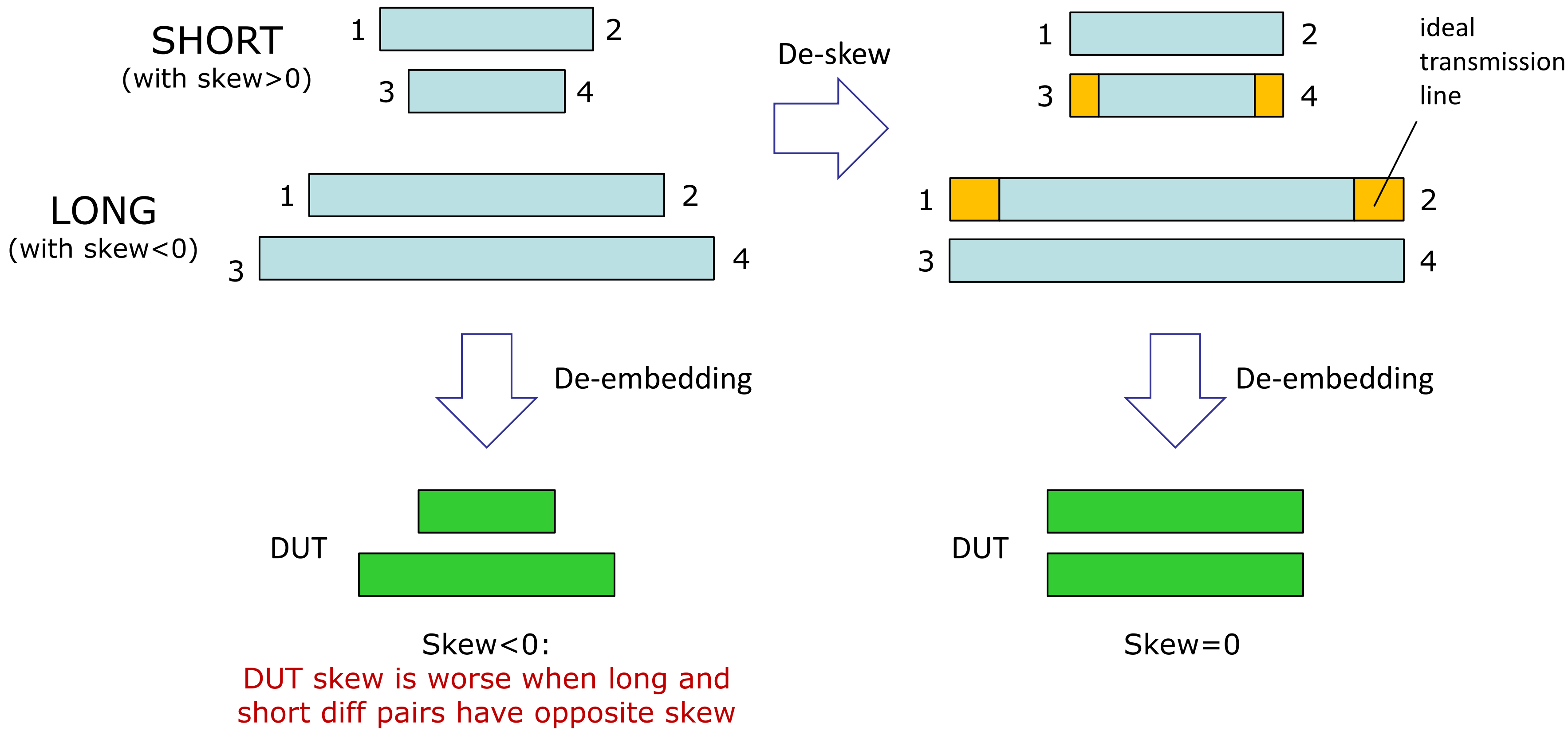




* J. Balachandran, K. Cai, Y. Sun, R. Shi, G. Zhang, C.C. Huang and B. Sen, "Aristotle: A fully automated SI platform for PCB material characterization," DesignCon 2017, 01/31-02/02/2017, Santa Clara, CA.

Skewless de-embedding

- Pad ideal transmission line to de-skew.



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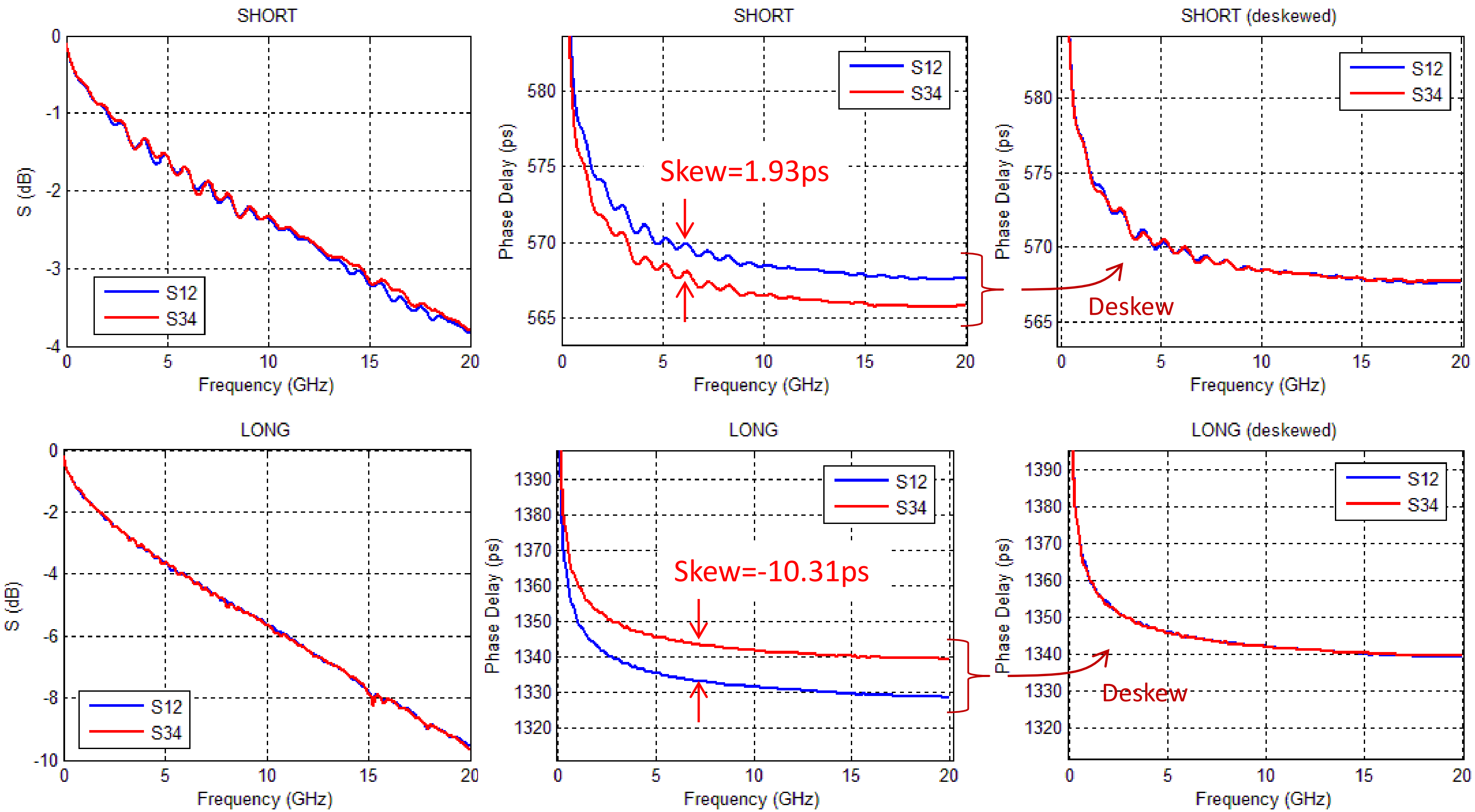
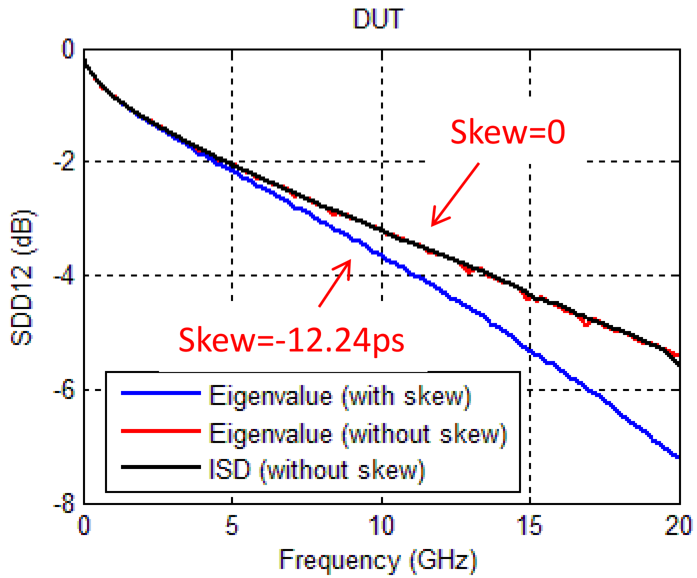
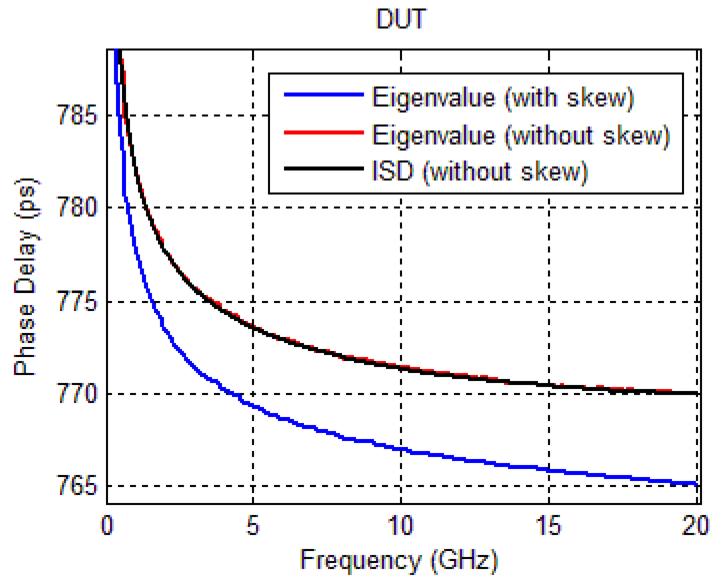
ISD optionally automates de-skewing of raw data

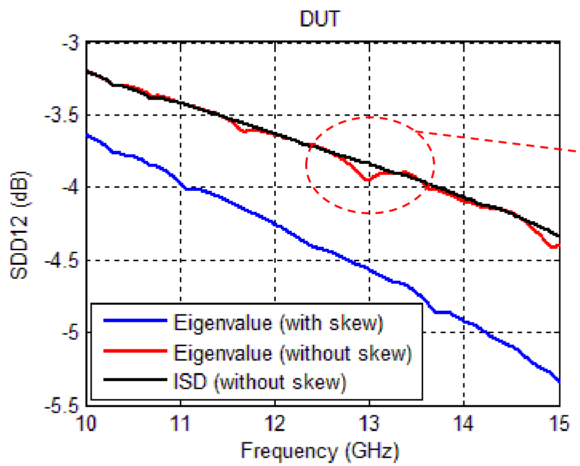


LONG=8”
SHORT=3”

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

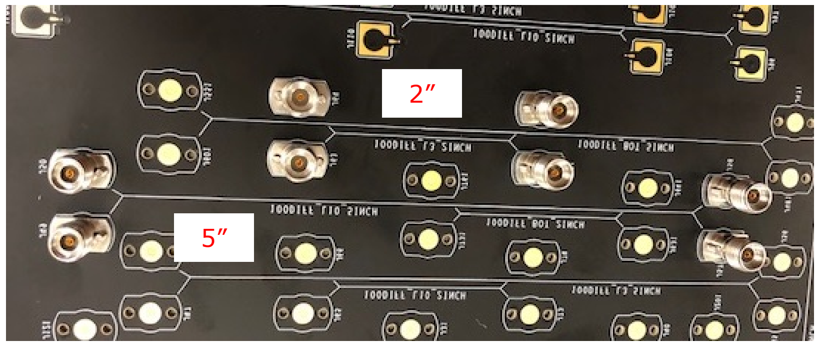


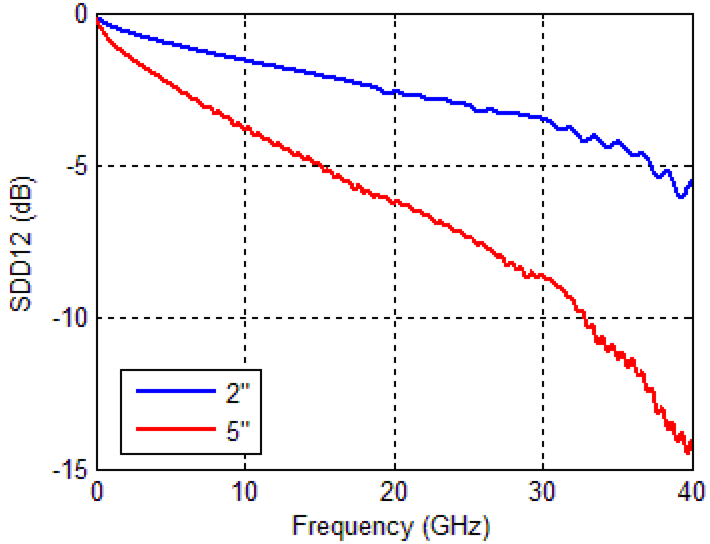


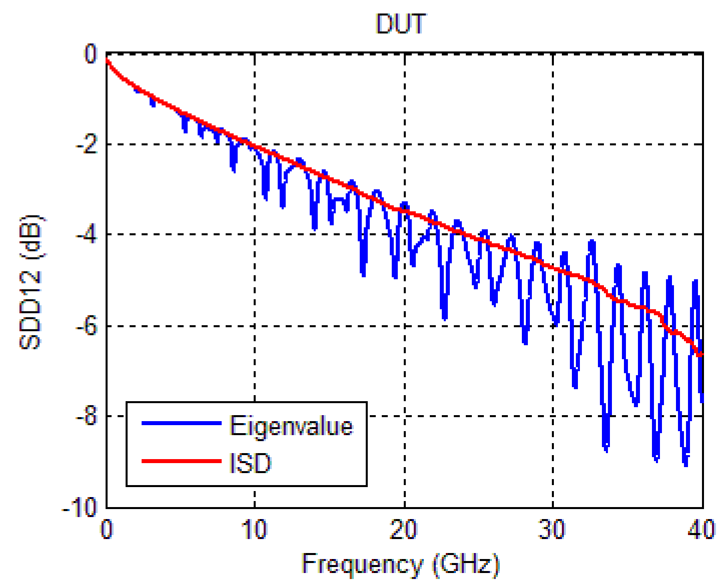


Eigenvalue solution has a dip at the frequency of interest (~12.9 GHz)

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

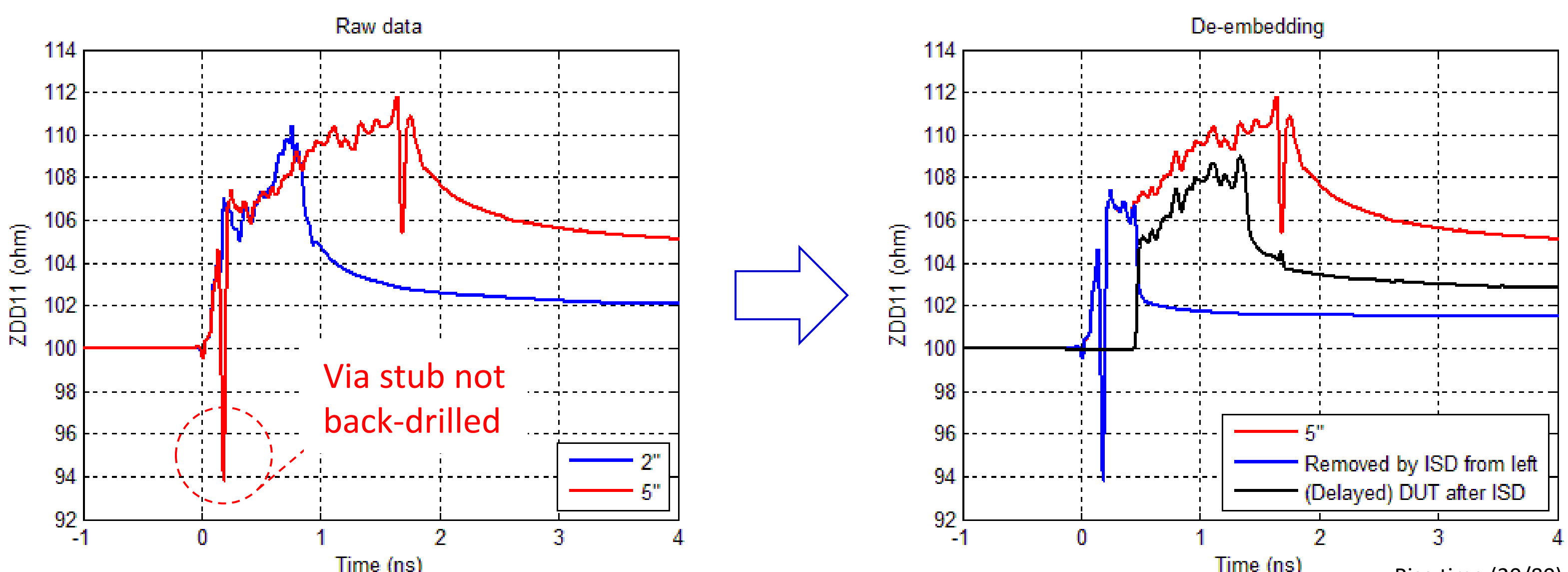






TDR of raw data reveals why…
2″ structure was back-drilled but 5″ was not

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



Rise time (20/80) = 20 ps

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

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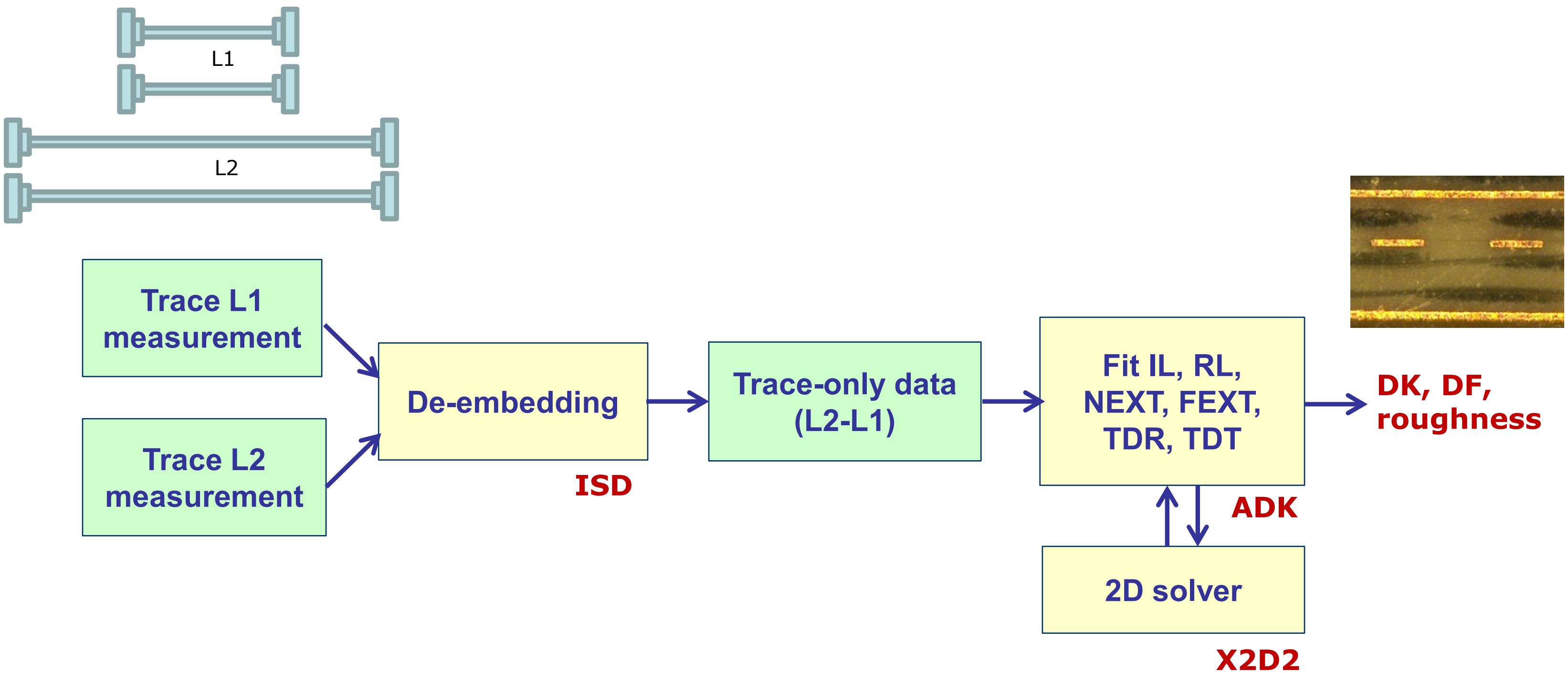
Example 8: Material property extraction
DK, DF and roughness

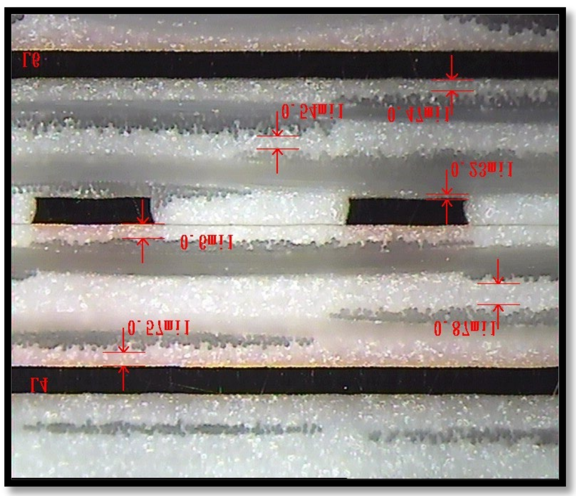
- Self consistent approach to extract DK, DF and roughness by matching all IL, RL, NEXT, FEXT and TDR/TDT of de-embedded trace-only data.

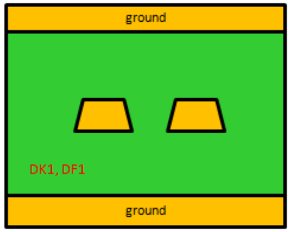


Automated extraction flow

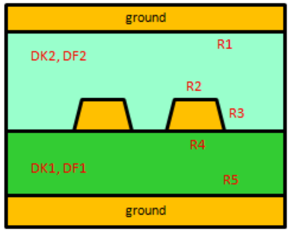
Models for cross section

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

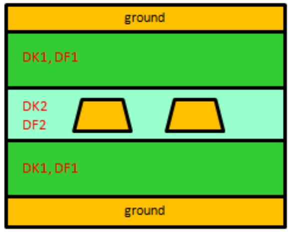




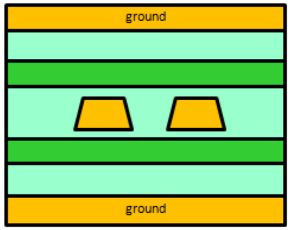
Model 1



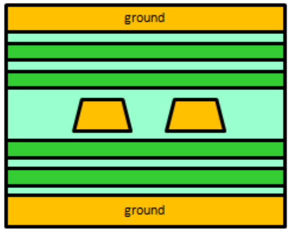
Model 2



Model 3



Model 4

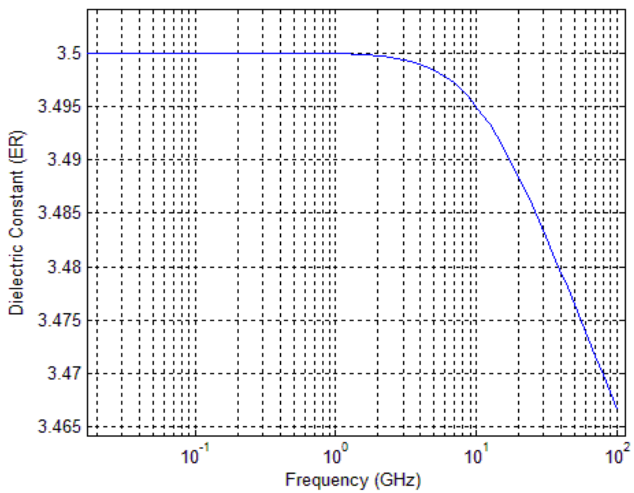


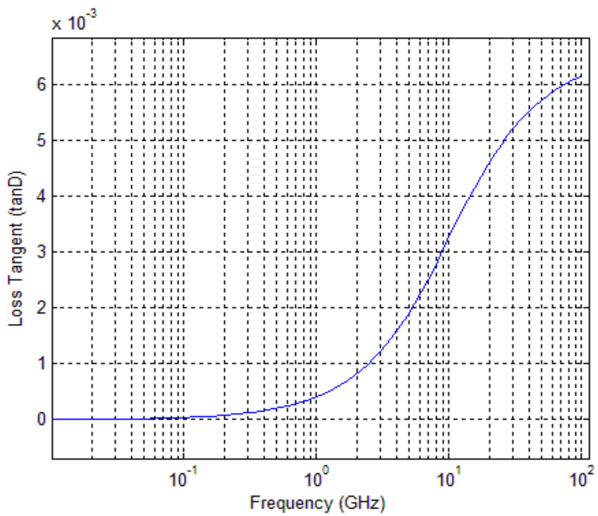
Model 5

Causal dielectric model

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

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





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

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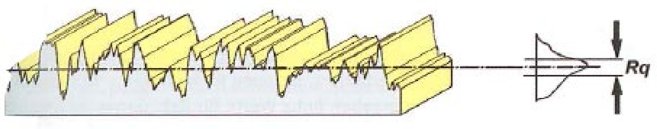
Surface roughness model

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

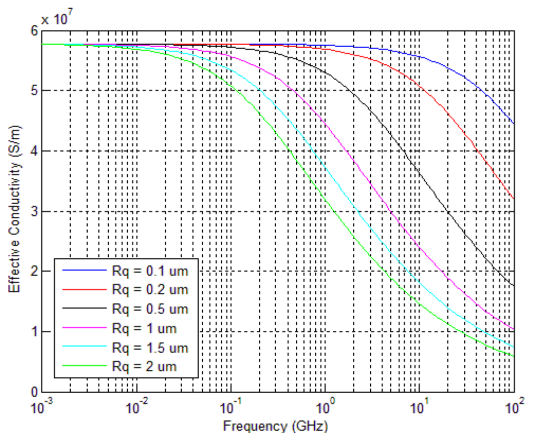
Parameter	Description	Standard
R_q	root mean square	DIN EN ISO 4287
R_a	arithmetic average	DIN EN ISO 4287, ANSI B 46.1
R_k	core roughness depth	DIN EN ISO 13565
R_z	average surface roughness	DIN EN ISO 4287

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}



$\sigma_{bulk} = 5.8 \times 10^7$ s/m

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

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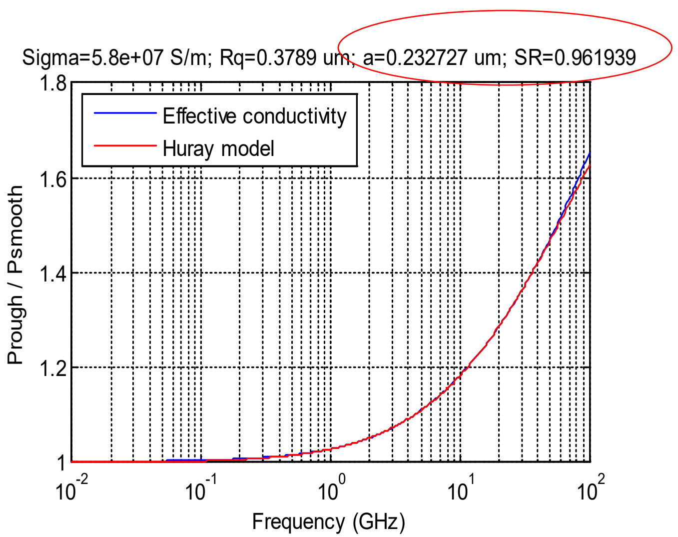
Convert effective conductivity to Huray model

- Huray model

$$\frac{P_{rough}}{P_{smooth}} \approx 1 + \frac{3}{2} \cdot SR \cdot \left(\frac{1}{1 + \frac{\delta(f)}{a} + \frac{1}{2}\left(\frac{\delta(f)}{a}\right)^2} \right)$$

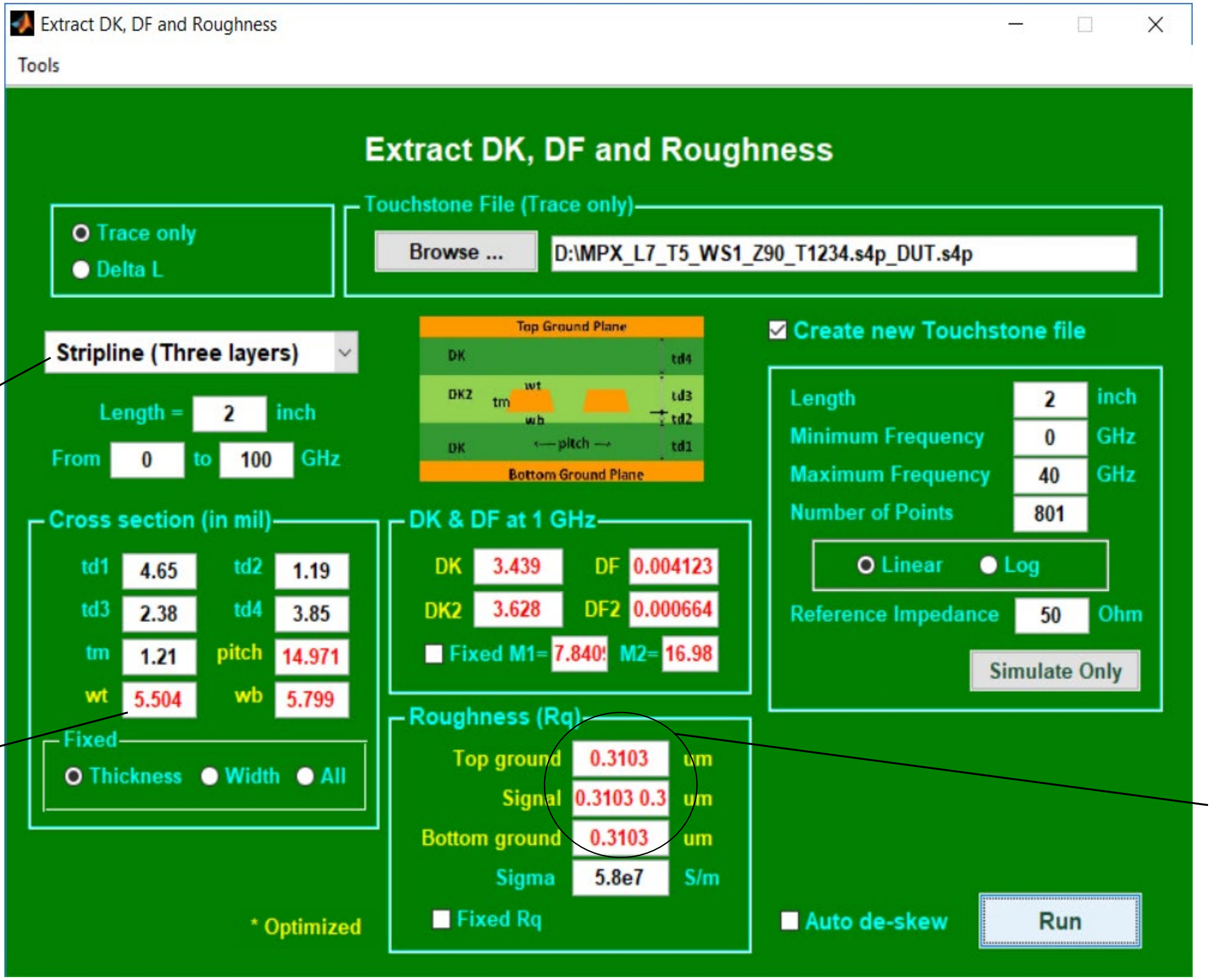
$$\delta(f) = \sqrt{\frac{1}{\pi f \mu \sigma}} \quad ; \quad a = \text{radius} \quad ; \quad SR = \text{surface ratio}$$

- Curvefit* P_{rough} / P_{smooth} to convert σ_{bulk} , R_q to a , SR



*Automated in ADK

DK/DF/SR extraction (from ADK)

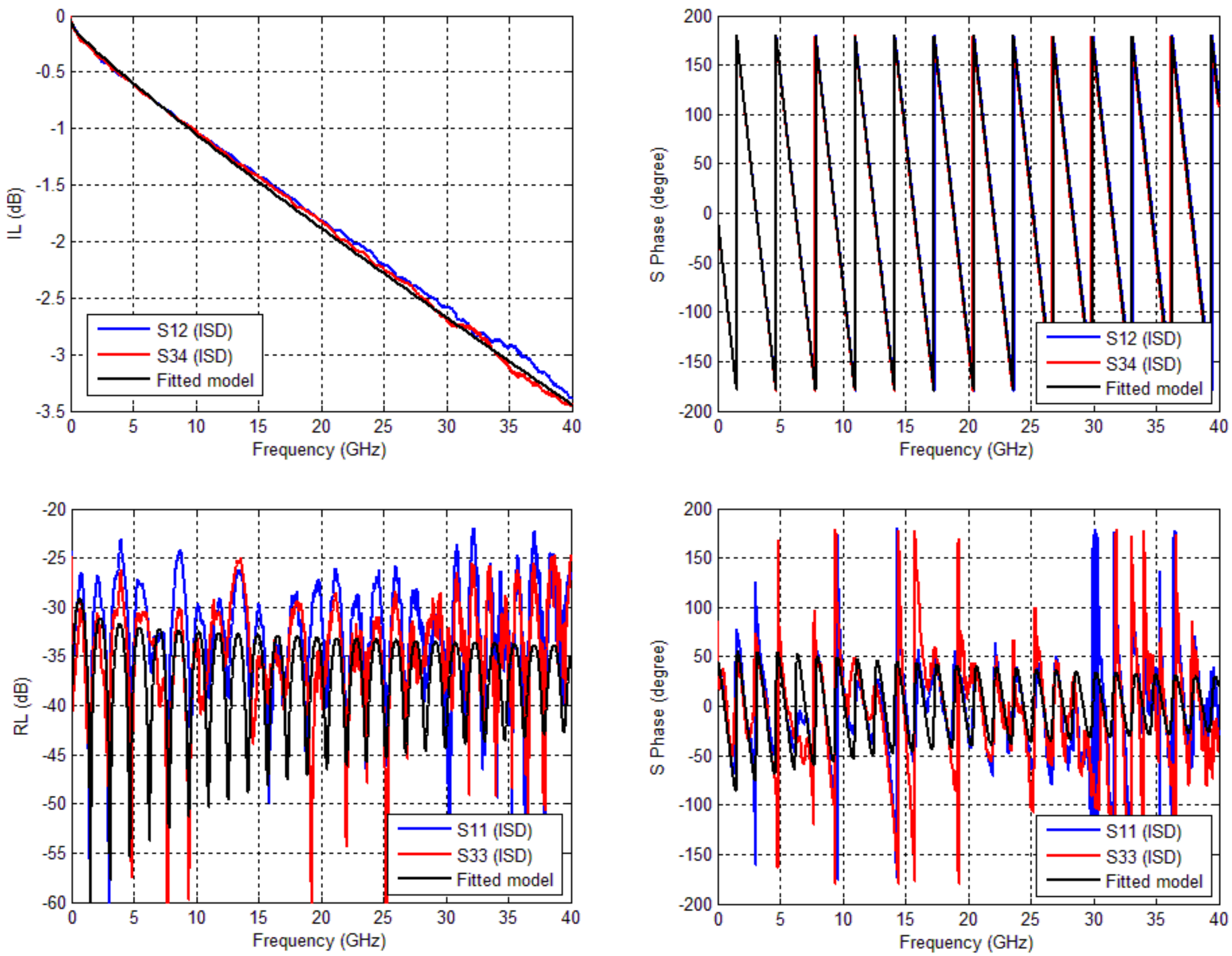


Multiple templates

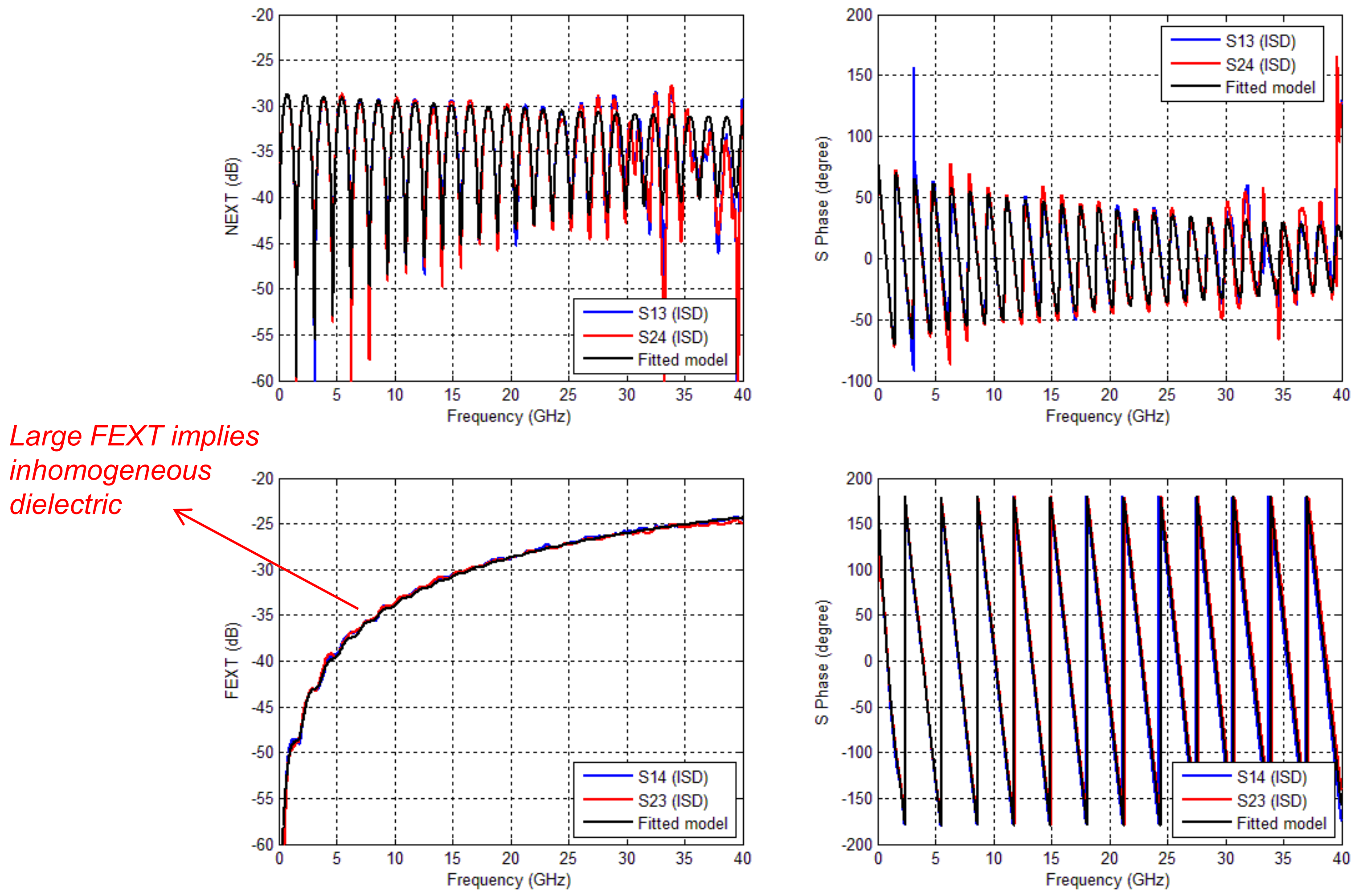
Updated after extraction

Different roughness for each surface

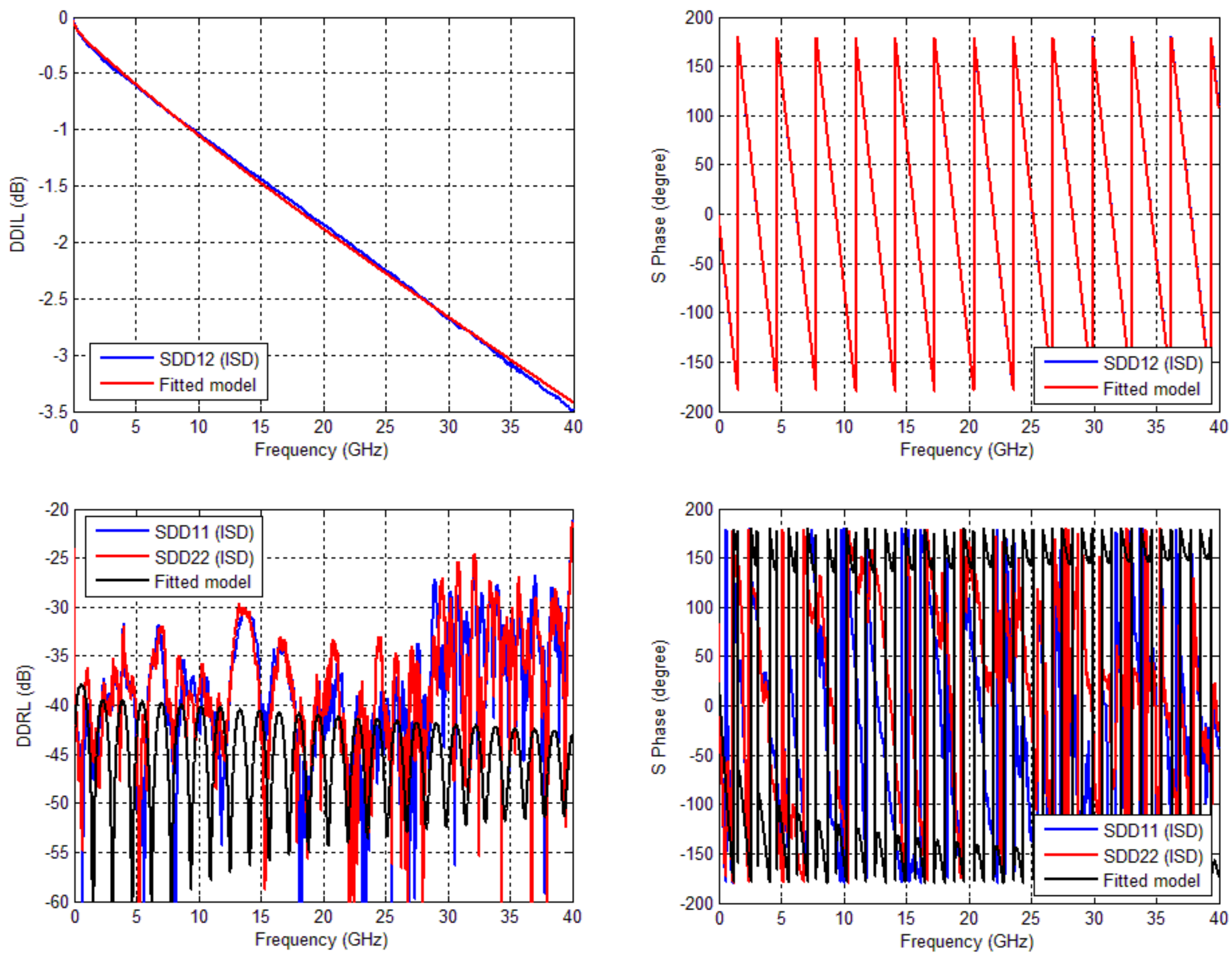
Matching IL and RL



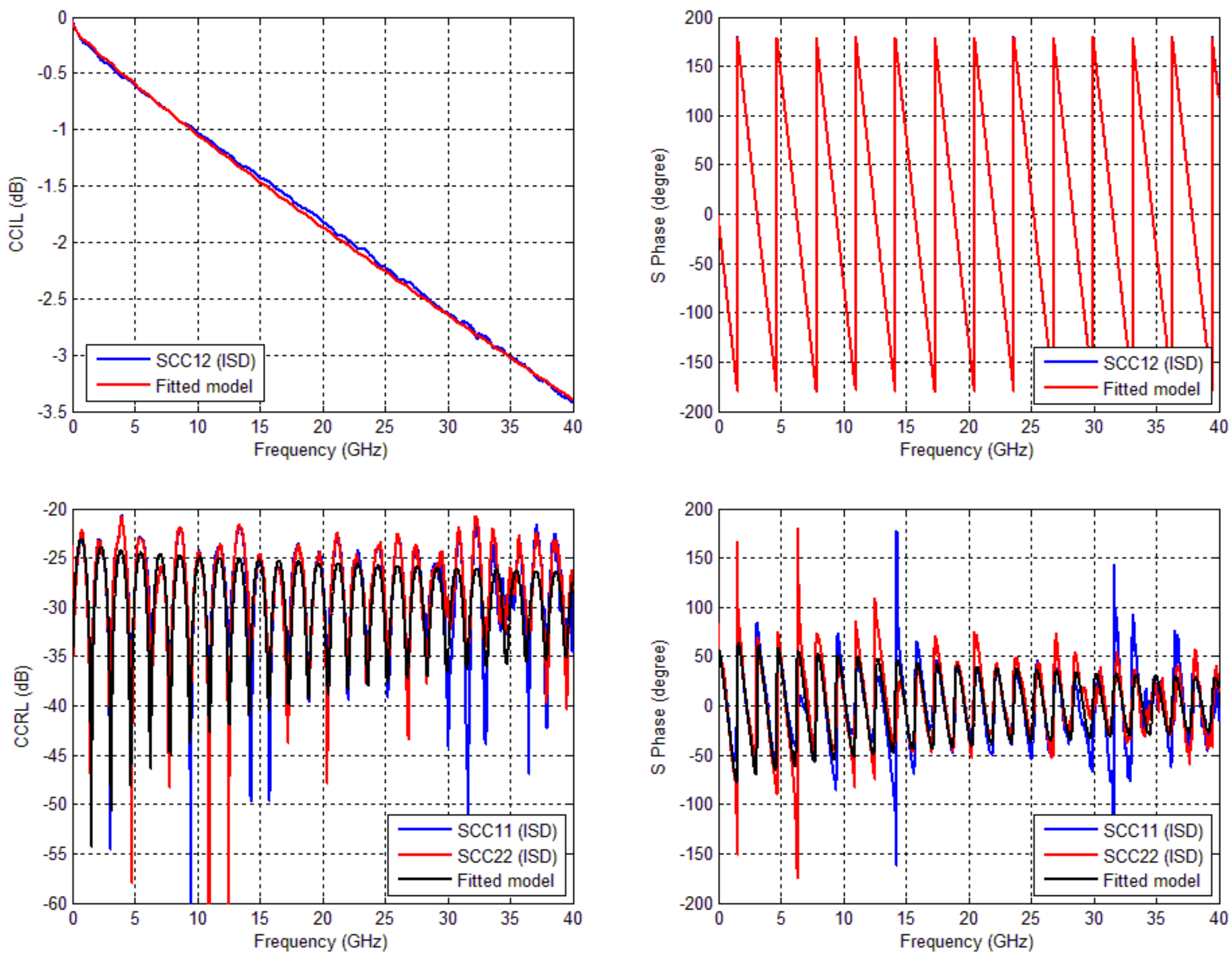
Matching NEXT and FEXT



Matching DDIL and DDRL



Matching CCIL and CCRL



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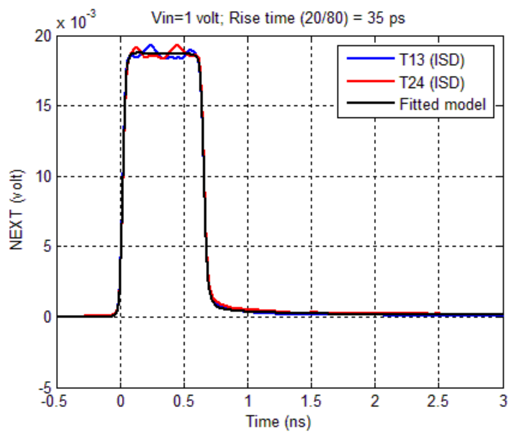
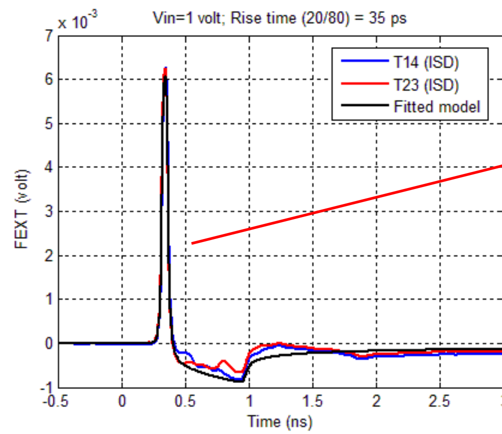
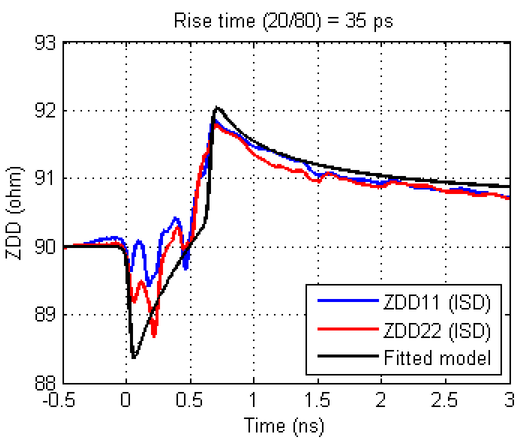
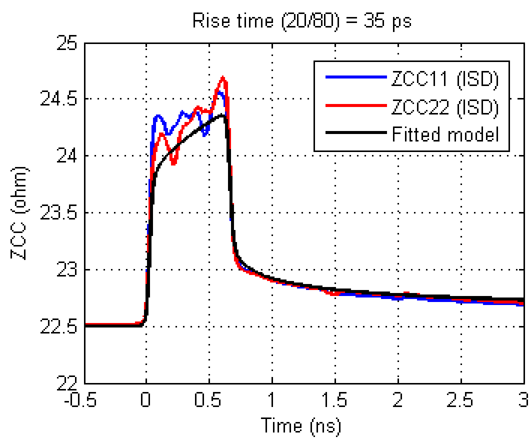
Matching TDT and TDR

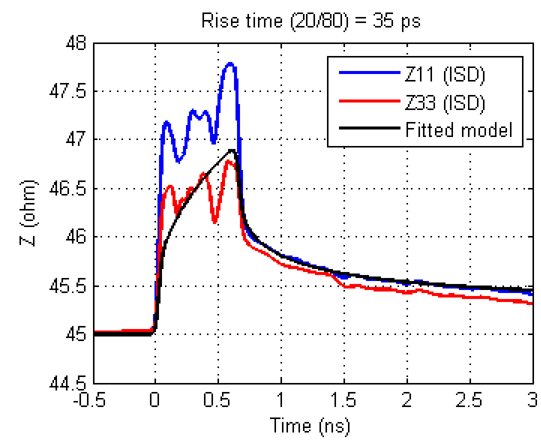




Positive polarity implies $K_C > K_L$

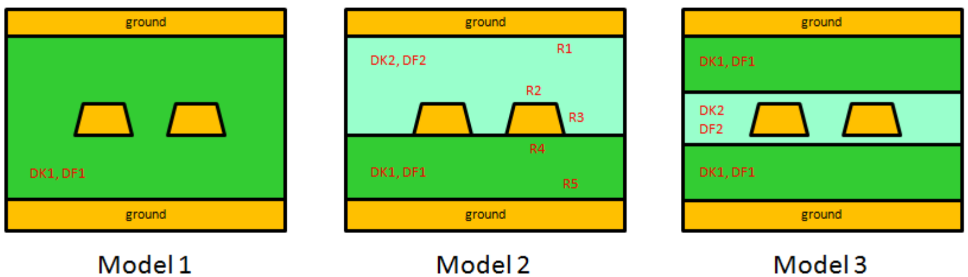


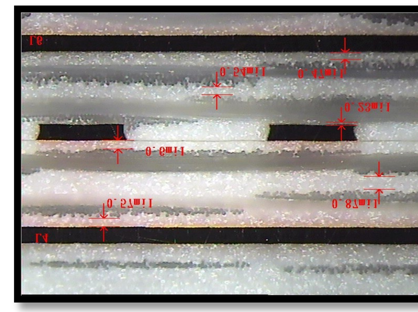


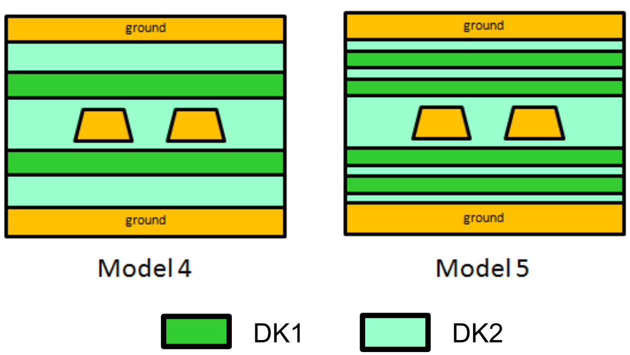


Comparison of Models 1 to 5

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





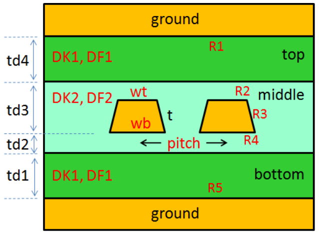


Model	DK1	DK2
1	3.510	-
2	2.444	4.294
3	3.413	3.623
4	3.863	3.360
5	3.115	3.975

At 10 GHz

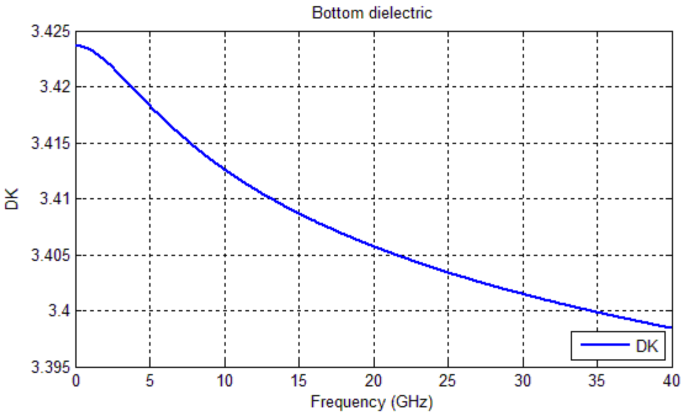
DK2>DK1 because of positive-polarity FEXT

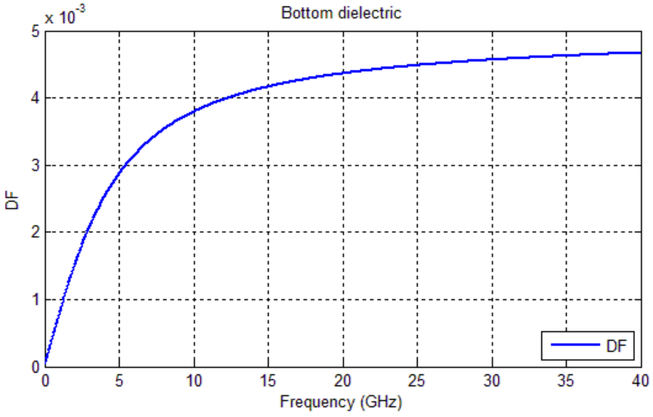
Extracted DK1 and DF1
Model 3



$$\varepsilon_\infty = 3.27929$$
$$\Delta\varepsilon = 0.144348$$
$$m1 = 9.58619$$
$$m2 = 15.4109$$

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





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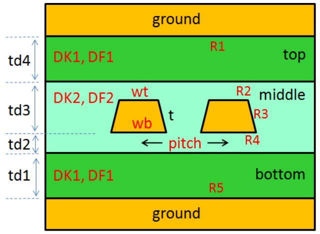
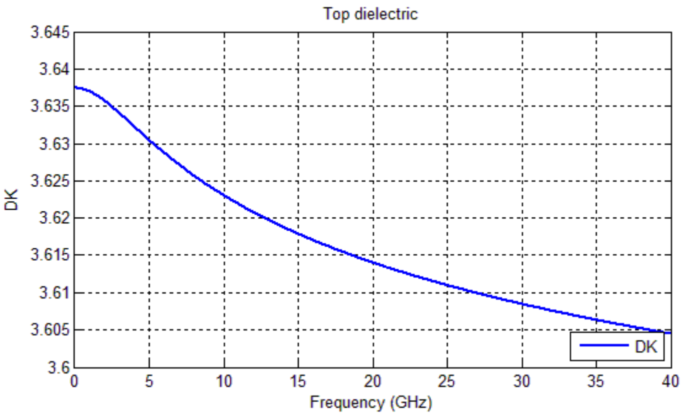
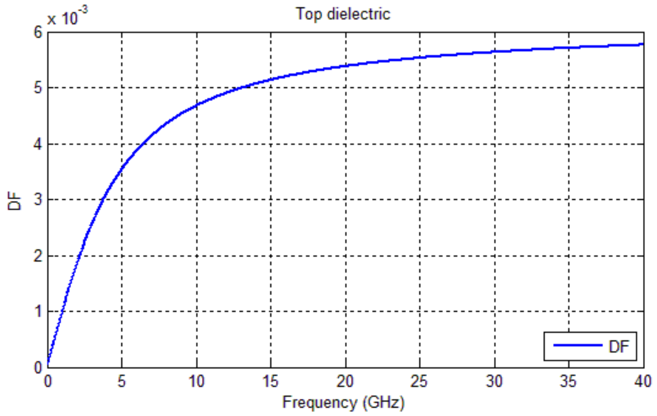
Extracted DK2 and DF2
Model 3



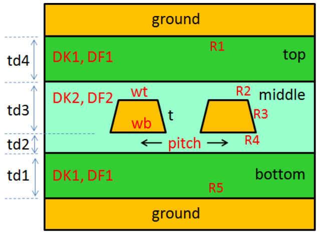
$$\varepsilon_\infty = 3.46724$$
$$\Delta\varepsilon = 0.170196$$
$$m1 = 9.58715$$
$$m2 = 14.8352$$

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



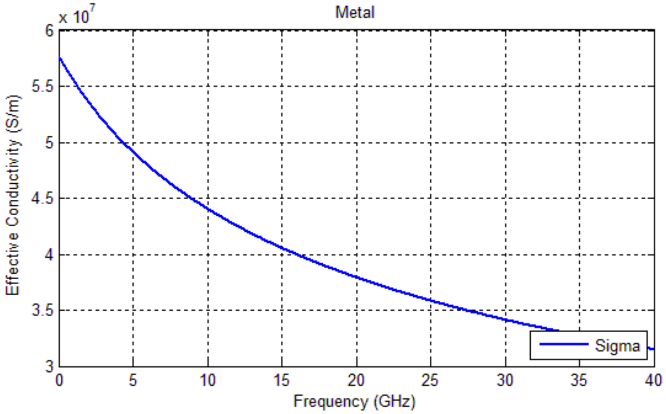


Extracted effective conductivity
Model 3

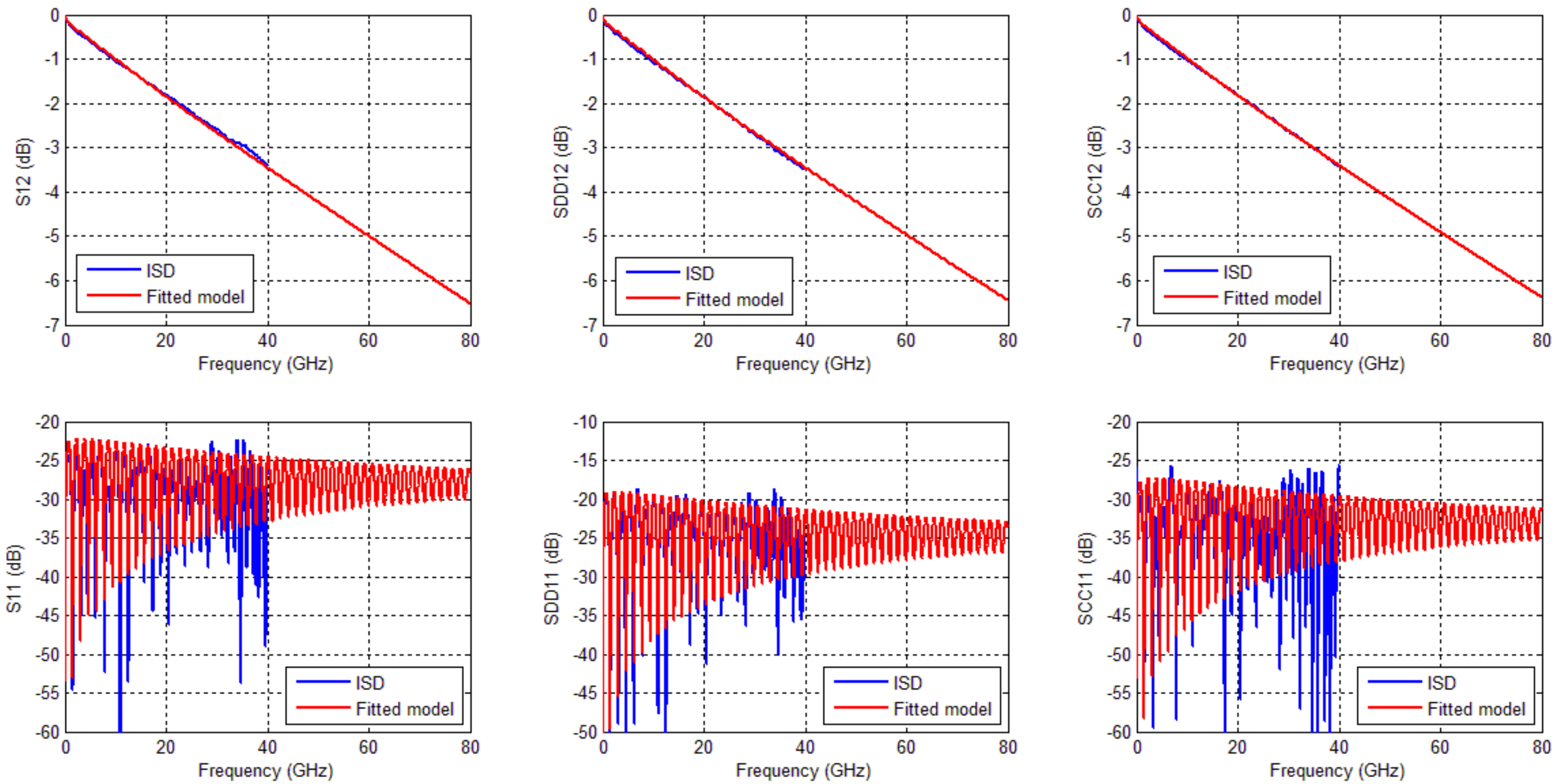


$$\sigma = 5.8 \times 10^{7}\ \mathrm{S/m}$$

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

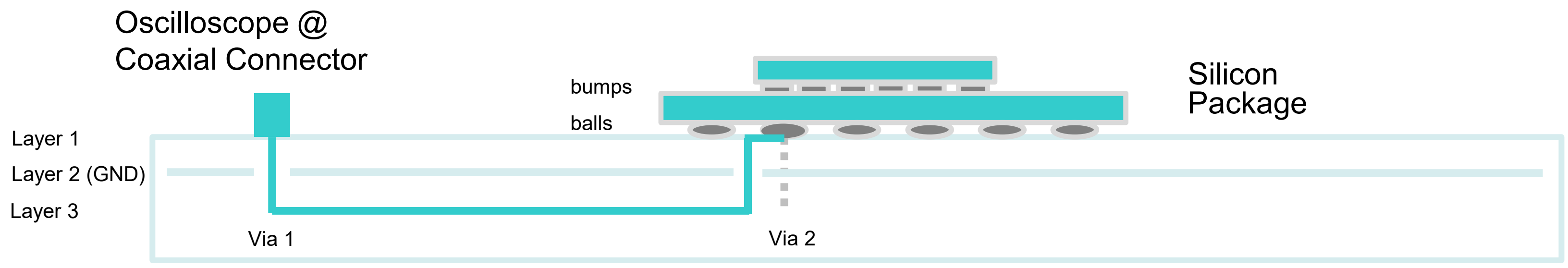


Length- and frequency-scalable models can now be created.



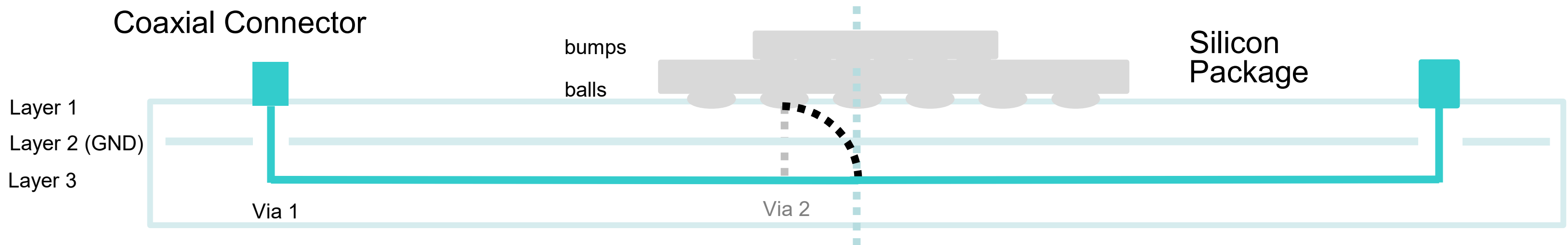
Example 9: Scope application
De-embedding to BGA interface

- Measure transmitter waveform by oscilloscope at PCB, de-embed cable connector and PCB trace and vias and display waveform at BGA balls.

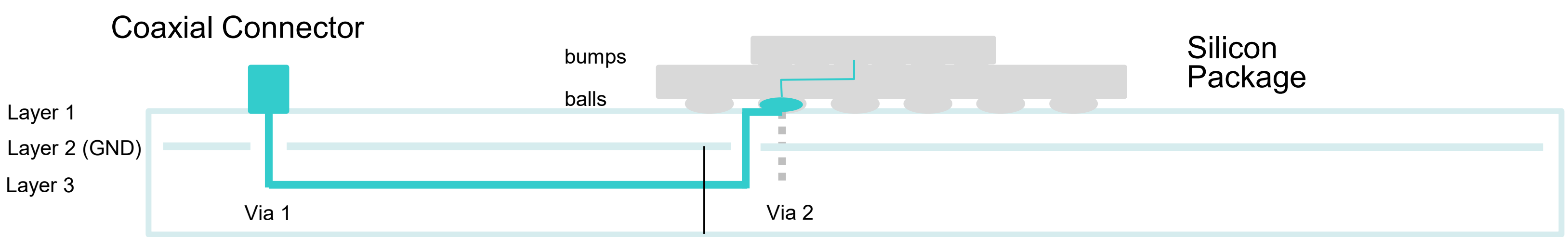


Getting de-embedding S-param for scope measurement

- Step 1: Measure 2x thru with equivalent electrical length



- Step 2: Measure RL from PCB/package/chip (power-off)



- Step 3: Run ISD to get "in-situ" de-embedding S-param (with extrapolated DC for scope) up to BGA balls.

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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.

Reference

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