In-Situ De-embedding (ISD)

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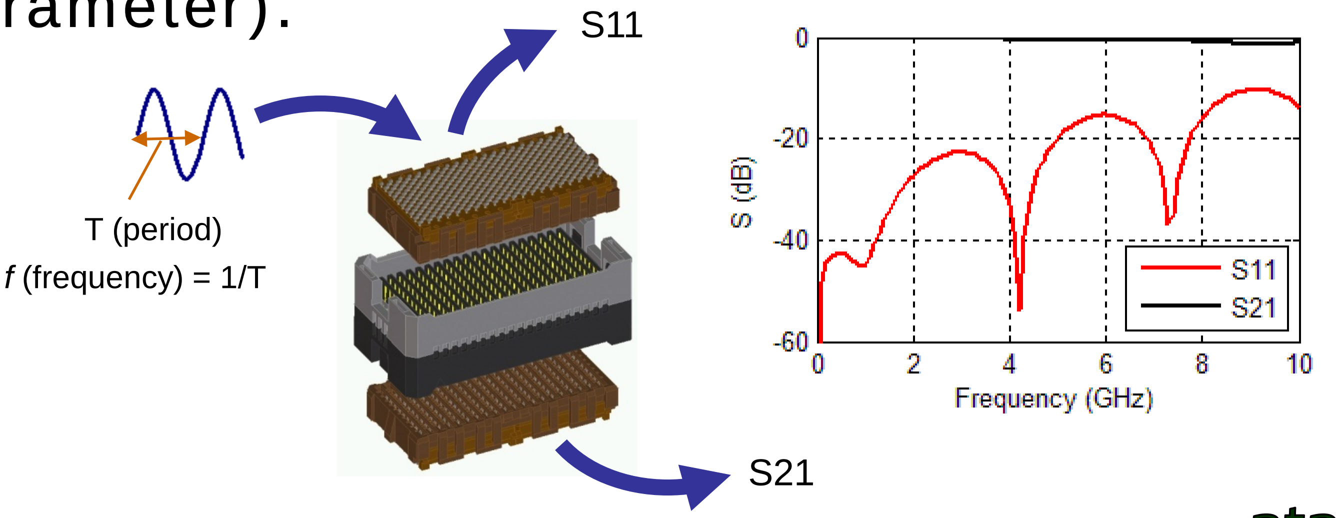
Outline

- What is causality
  - How to identify non-causal S parameter
  - Why does S parameter violate causality
- What is In-Situ De-embedding (ISD)
  - Why do other de-embedding methods give causality error
- How to use ISD to...
  - De-embed crosstalk by a single trace test coupon
  - De-embed long traces and extract a small DUT
  - Improve results for USB Type C compliance testing
- Comparison of ISD with TRL, AFR and simulation
- Mobile-apps-like SI tools: ISD, ADK and X2D2

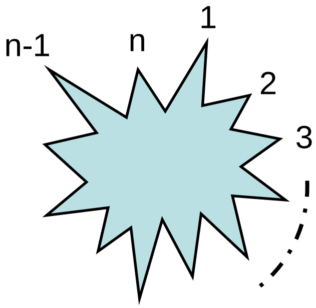
VNA and S parameter

- 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:



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

- 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.

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

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

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

noun

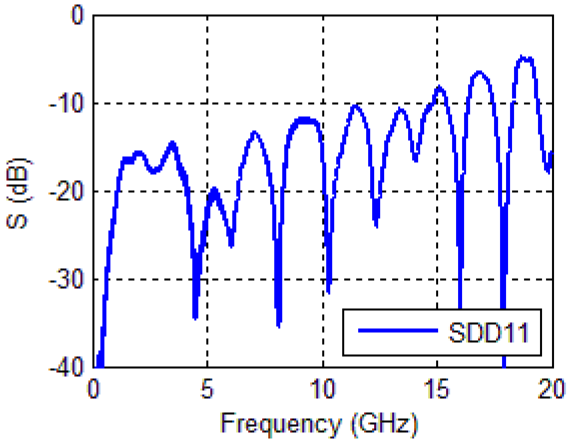
1. the relationship between cause and effect.
2. the principle that everything has a cause.

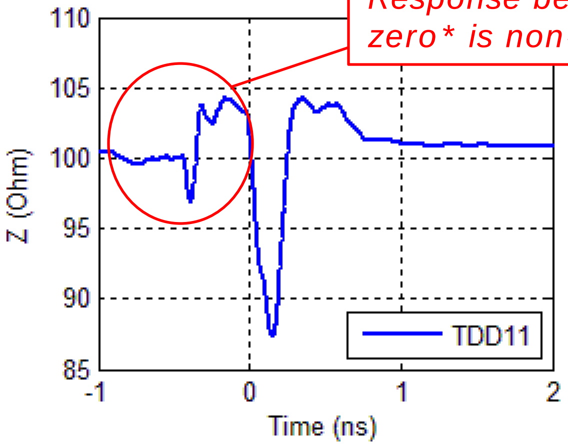
In other words:

Can not get something from nothing.

How to identify non-causal S parameter

- Convert S parameter into TDR/TDT.

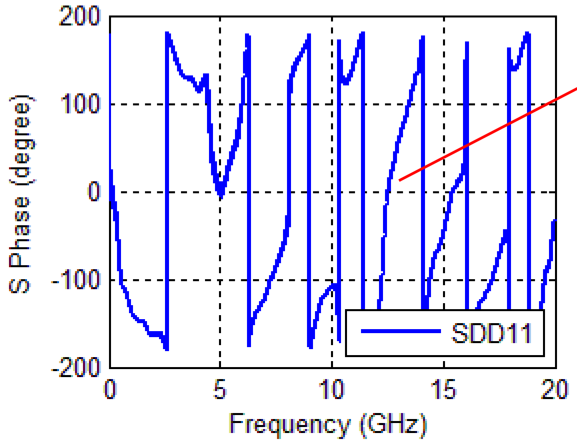




Response before time zero is non-causal.*

* 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:

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

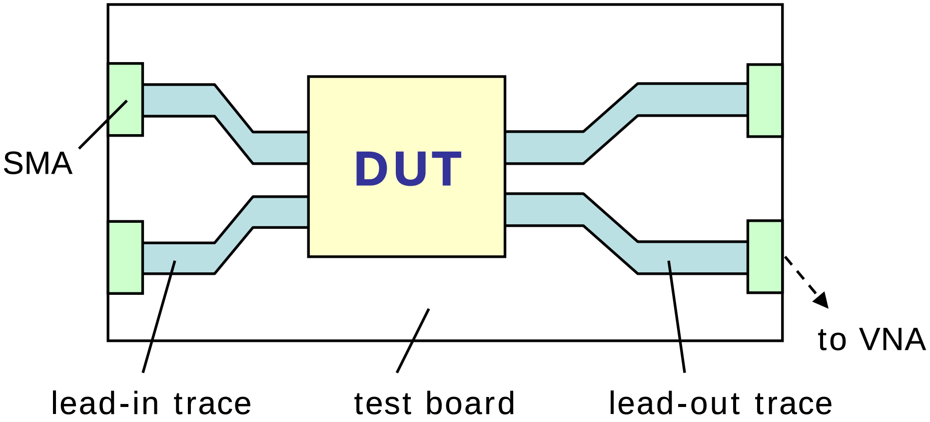
$$\Psi_R(\omega) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{\Psi_I(\omega')}{\omega' - \omega} d\omega'$$

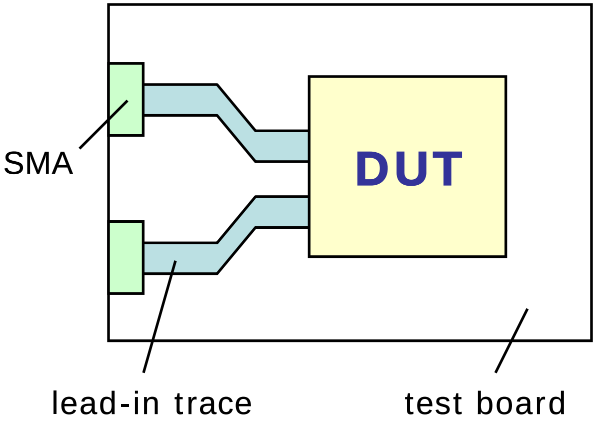
$$\Psi_I(\omega) = -\frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{\Psi_R(\omega')}{\omega' - \omega} d\omega'$$

In-Situ De-embedding (ISD) gives causal de-embedding and Advanced SI Design Kit (ADK) extracts causal material property and/or forces S parameter of finite bandwidth to give causal behavior of infinite bandwidth.

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).

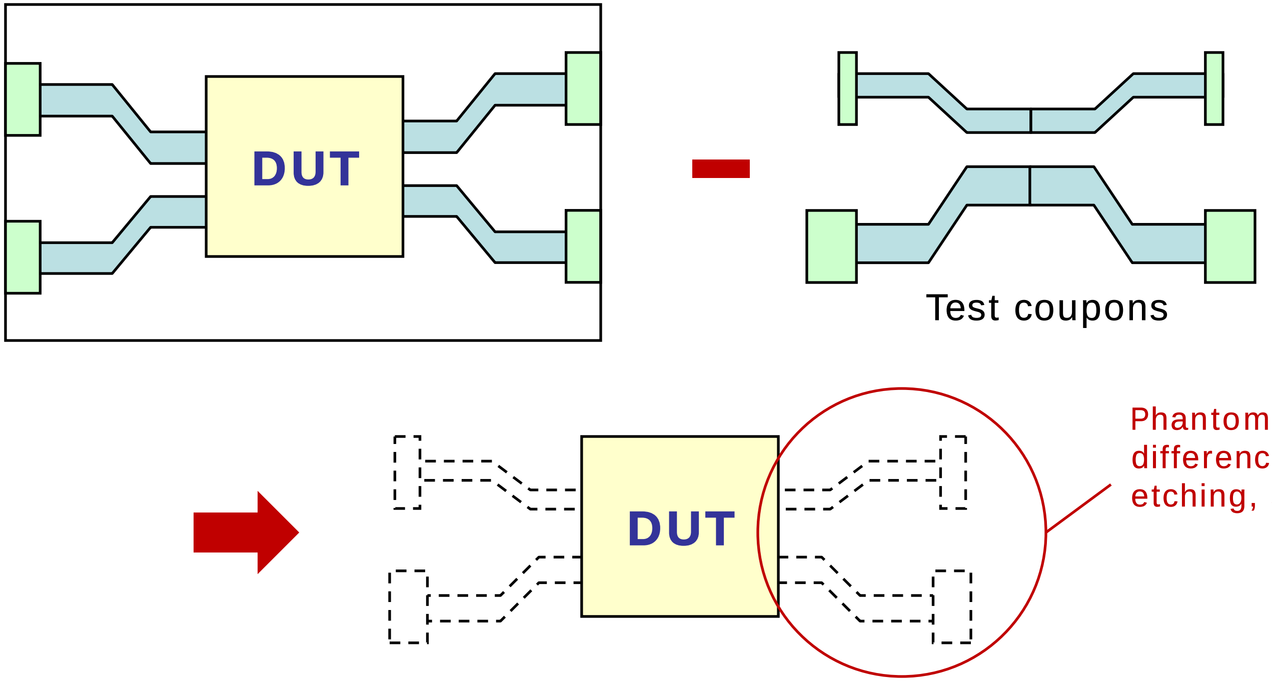




- The lead-ins and lead-outs don’t need to look the same.
- There may even be no lead-outs (e.g., package).

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, …

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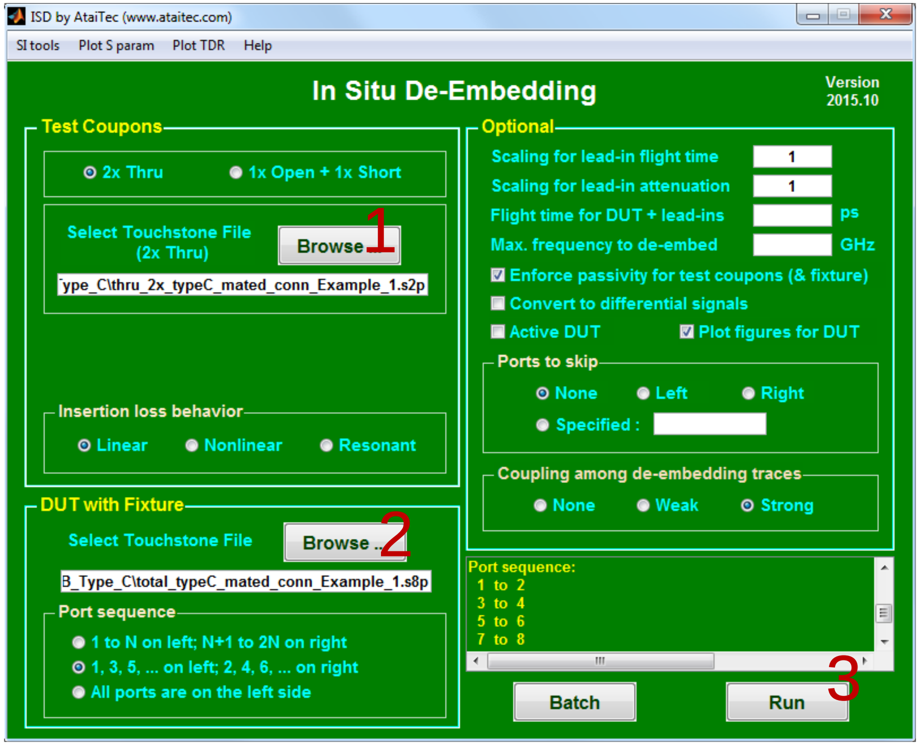
* http://www.edn.com/electronics-blogs/test-voices/4438677/Software-tool-fixes-some-causality-violations by Eric Bogatin

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 optimization.

In Situ



Test Coupons

● 2x Thru ○ 1x Open + 1x Short

Select Touchstone File (2x Thru): 'ype_C\thru_2x_typeC_mated_conn_Example_1.s2p

Insertion loss behavior: ● Linear ○ Nonlinear ○ Resonant

DUT with Fixture

Select Touchstone File: B_Type_C\total_typeC_mated_conn_Example_1.s8p

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 coupons (& fixture)
☐ Convert to differential signals
☐ Active DUT ☑ Plot figures for DUT

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

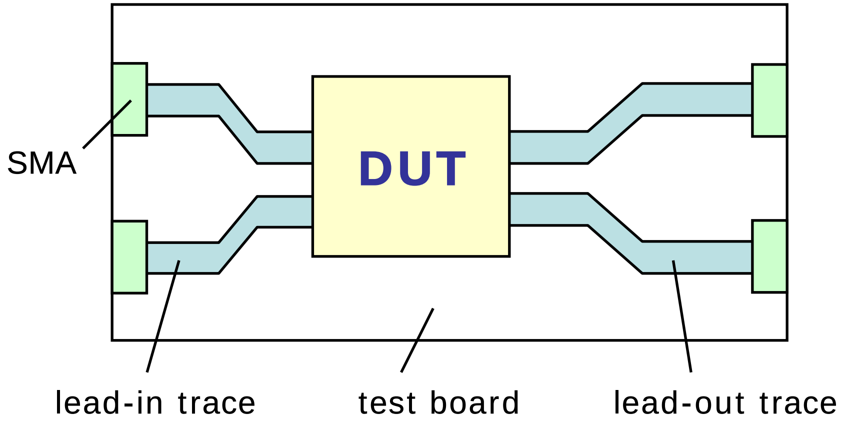
Coupling among de-embedding traces: ○ None ○ Weak ● Strong

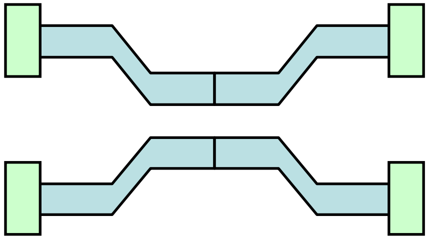
```
Port sequence:
 1  to  2
 3  to  4
 5  to  6
 7  to  8
```

- *Mobile-Apps-like SI software as easy to use as 1-2-3.*
- *Causal by construction.*

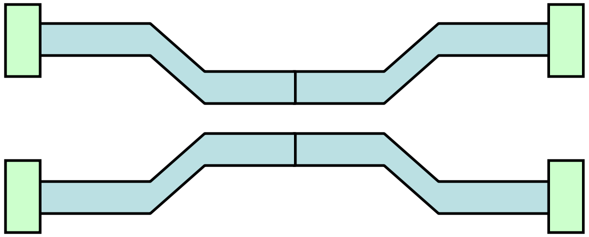
What is "2x thru"

- "2x thru" is 2x lead-ins or lead-outs.





2x thru for lead-ins

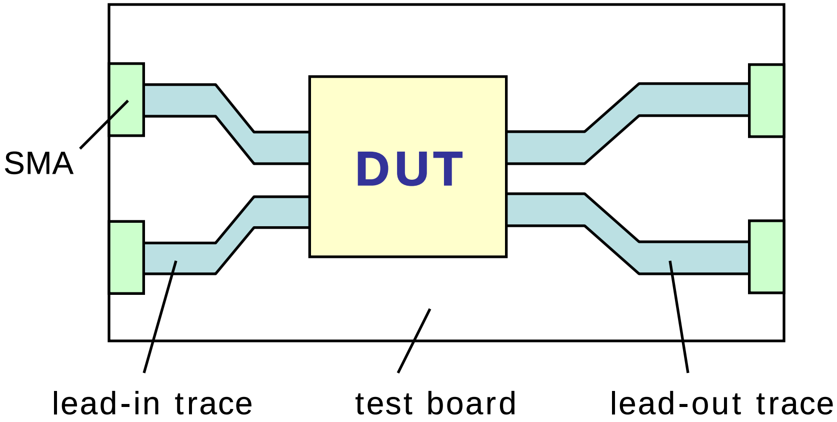


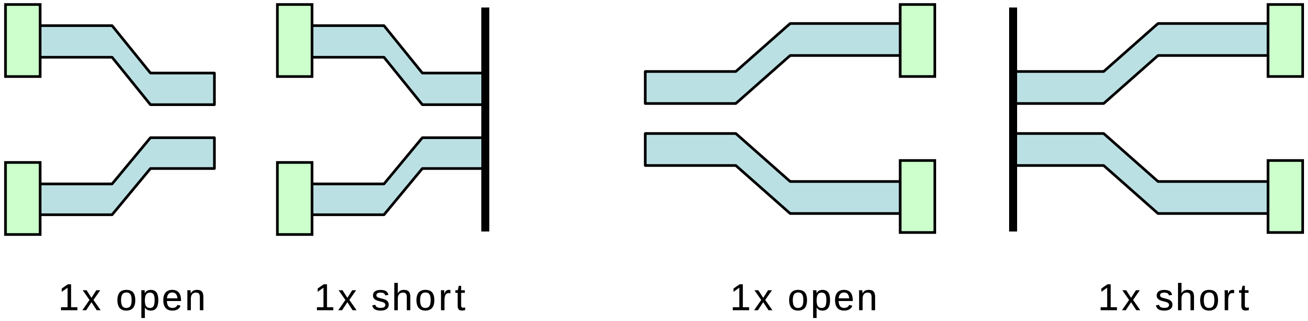
2x thru for lead-outs

2 sets of "2x thru" are required for asymmetric fixture.

What is “1x open + 1x short”

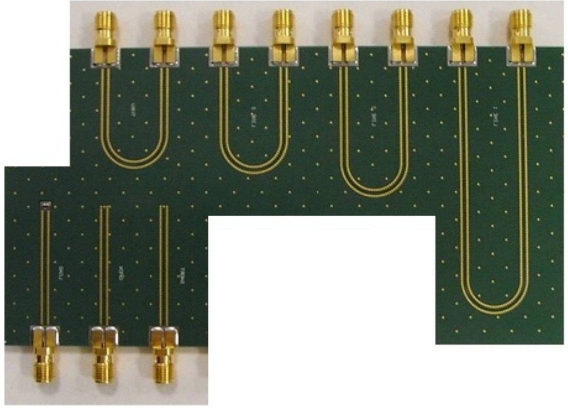
- “1x open + 1x short” is useful when “2x thru” is not possible (e.g., connector vias, package, …).





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

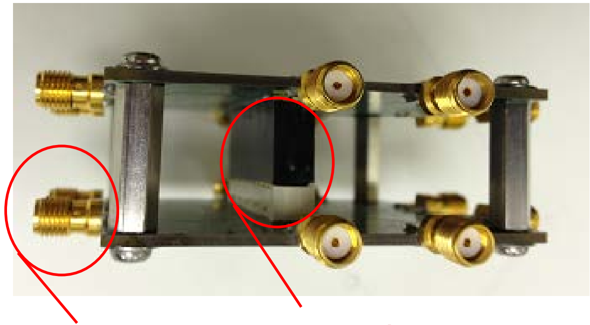
- Only one 2x thru test coupon is needed.
- Test coupon is used only for reference, not for direct de-embedding.
- Actual DUT board impedance is de-embedded.
- Inexpensive SMAs, board materials (FR4) and loose-etching-tolerance can be used.
- ECal can be used for fast SOLT calibration.
    - Reference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

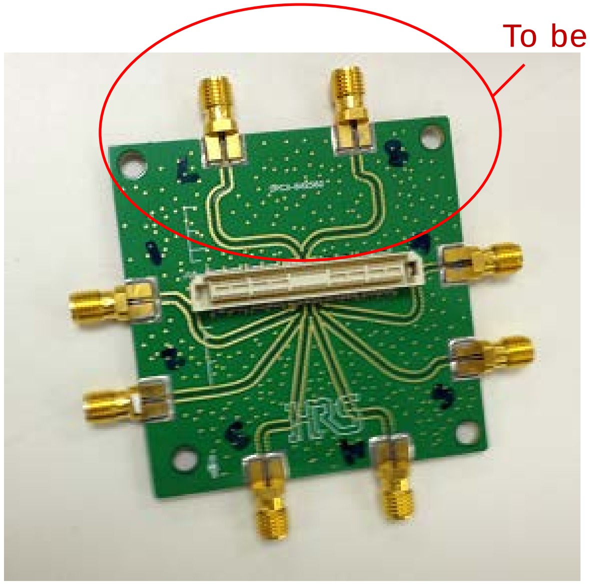
* TRL = Thru-Reflect-Line

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.



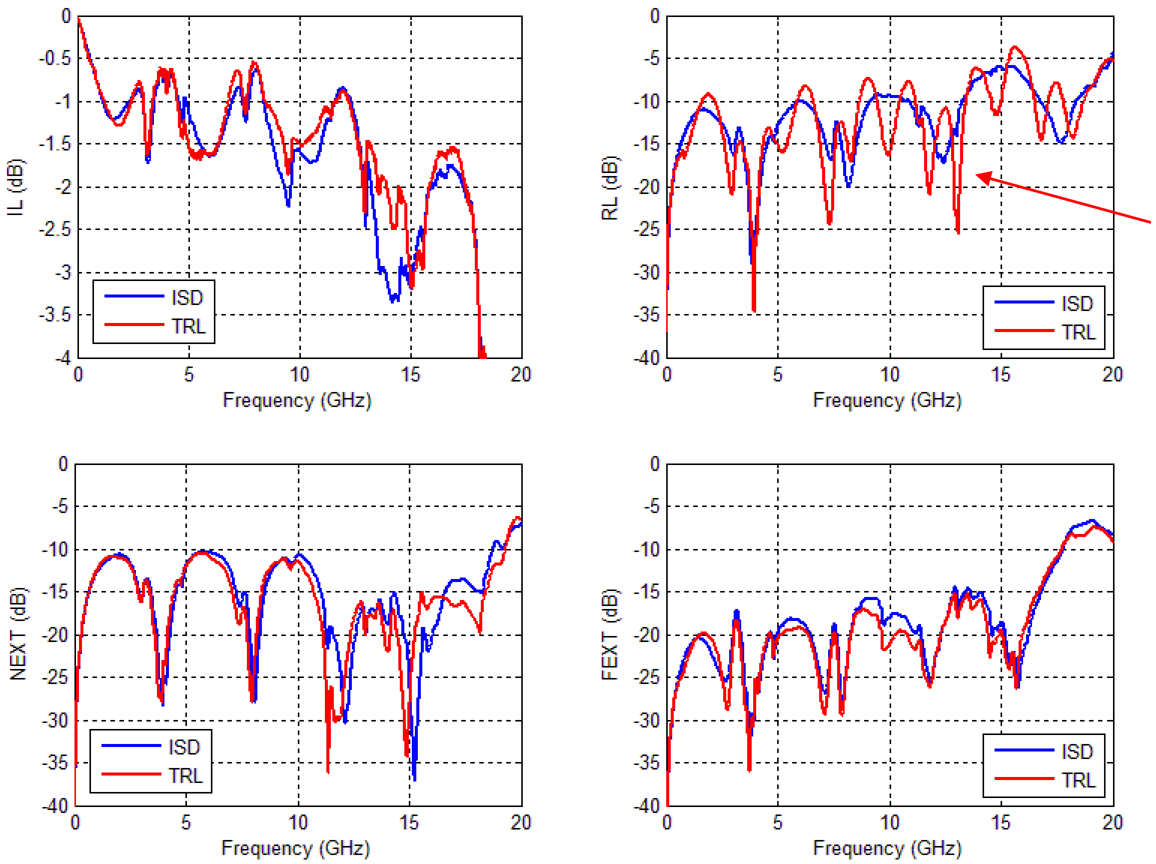


*Courtesy of Hirose Electric

DUT results after ISD and TRL

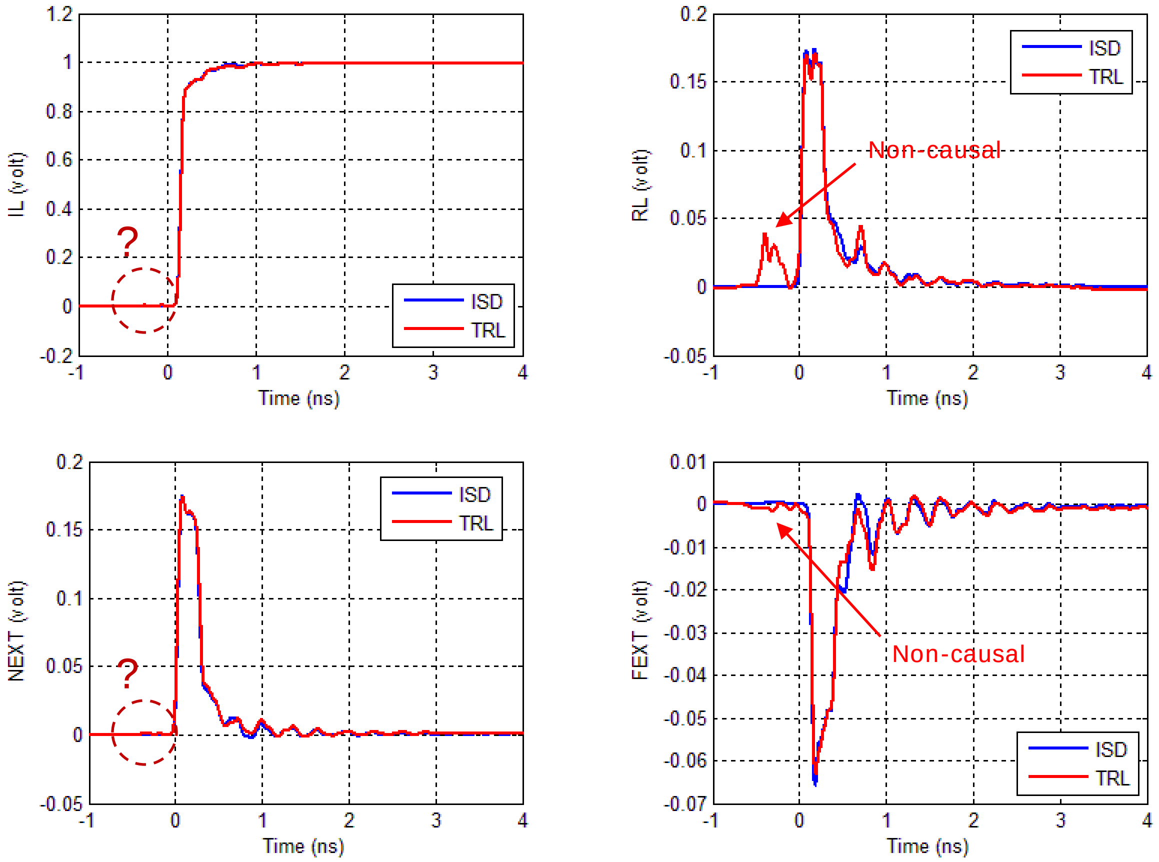
Which one is more accurate?

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



Non-causal ripples

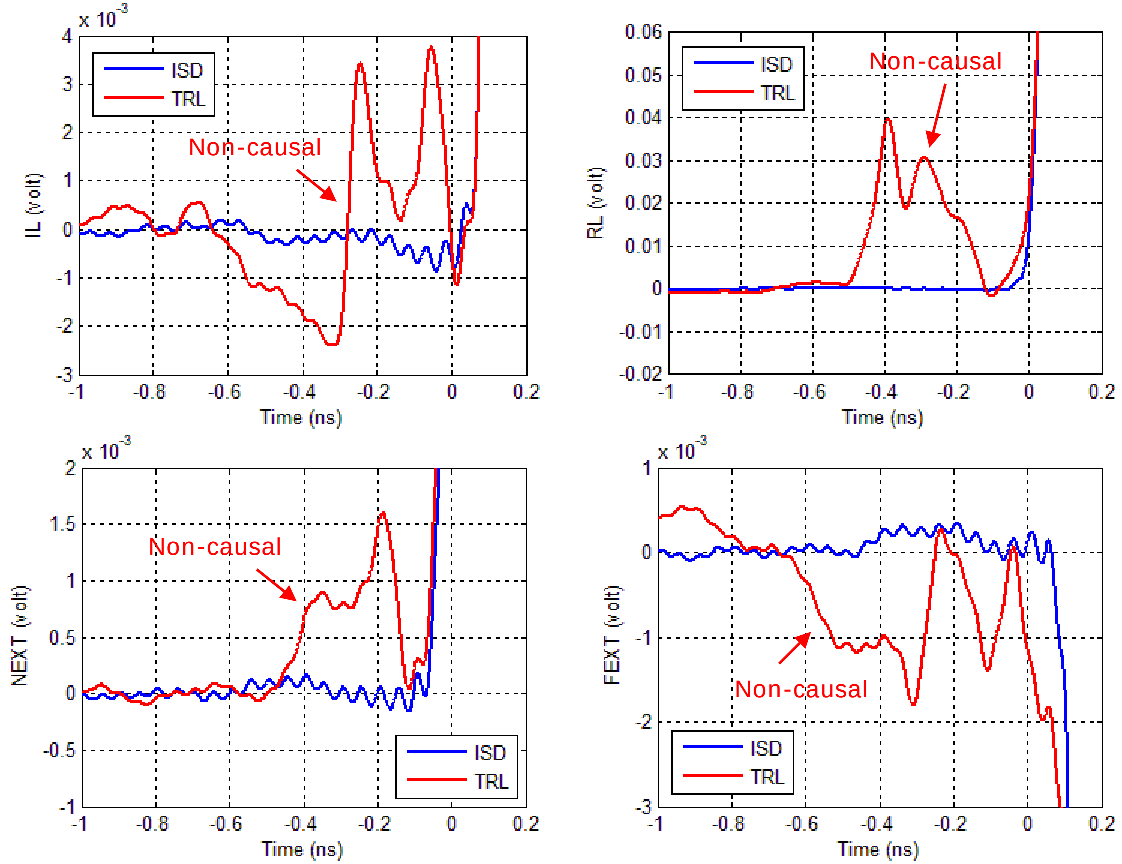
Converting S parameter into TDR / TDT shows non-causality in TRL results



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*.

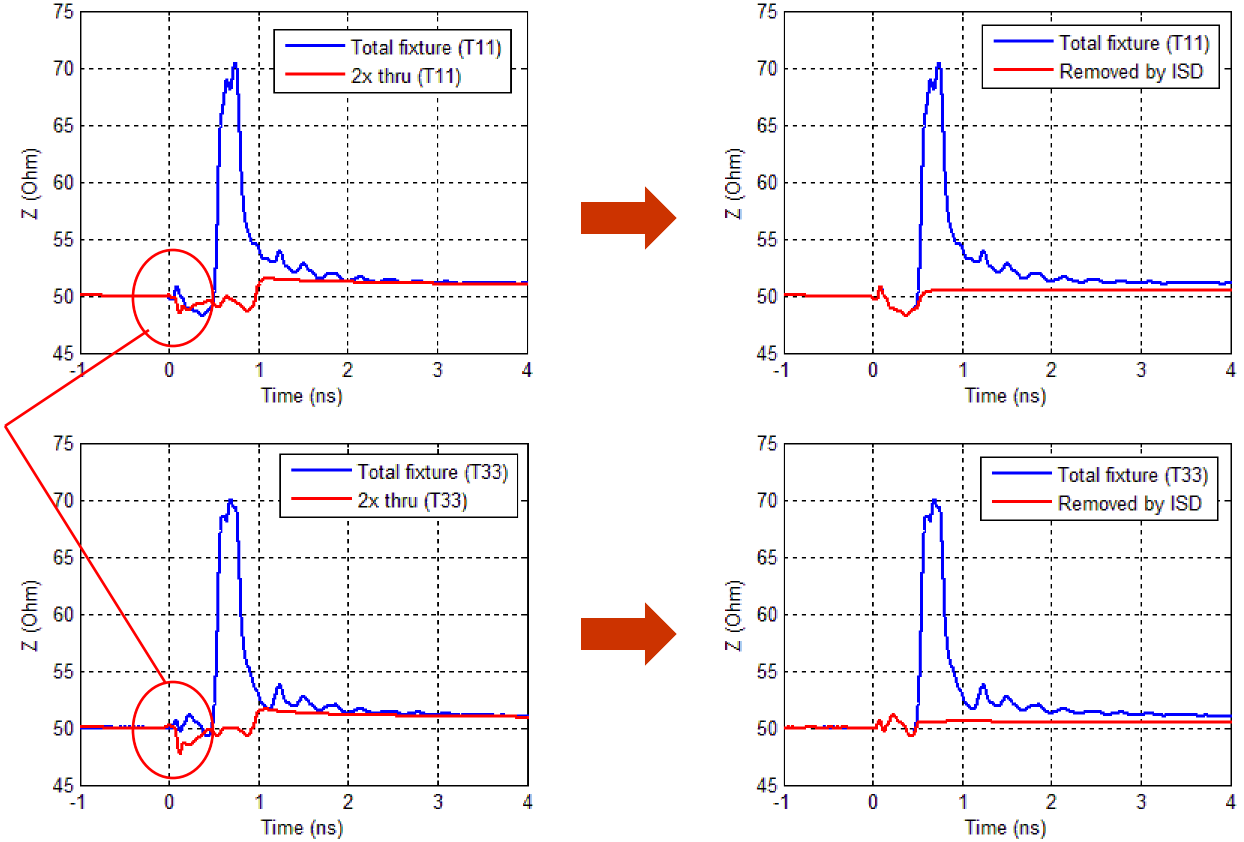


* The percentage is larger with single-bit response and/or faster rise time.

Rise time = 40ps (20/80)

How did ISD do it?

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

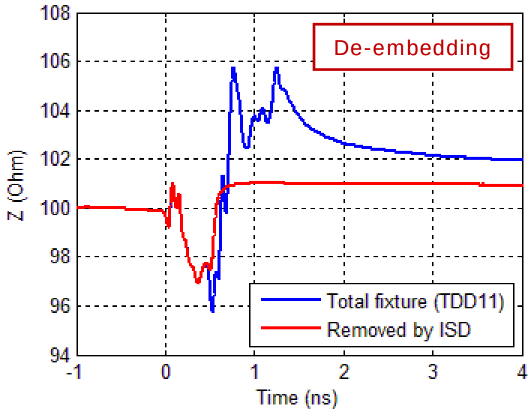


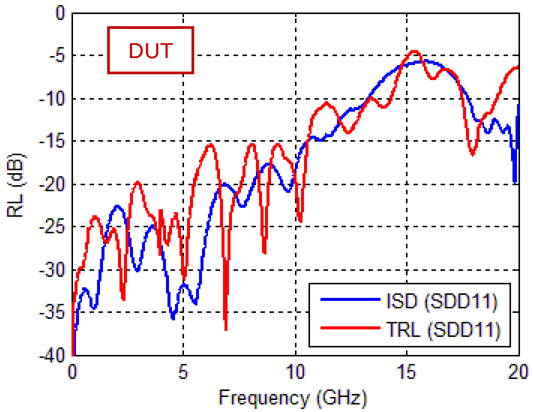
2x thru and fixture have different impedance.

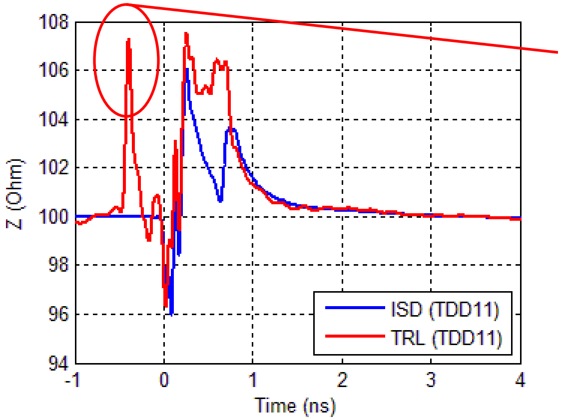
Rise time = 40ps (20/80)

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.

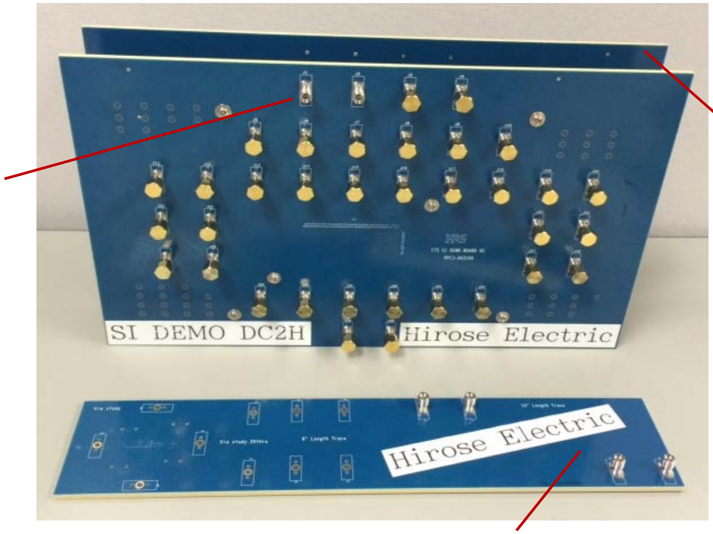
Rise time = 40ps (20/80)

* 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.



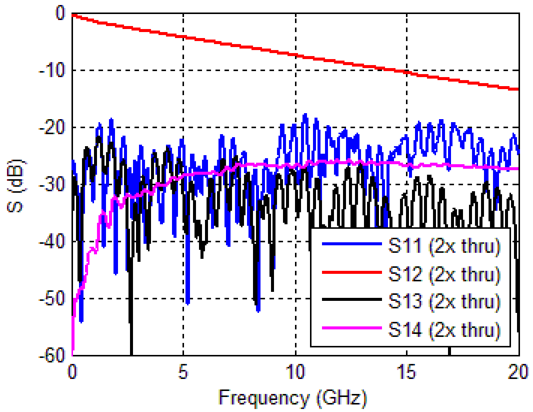
Fixture

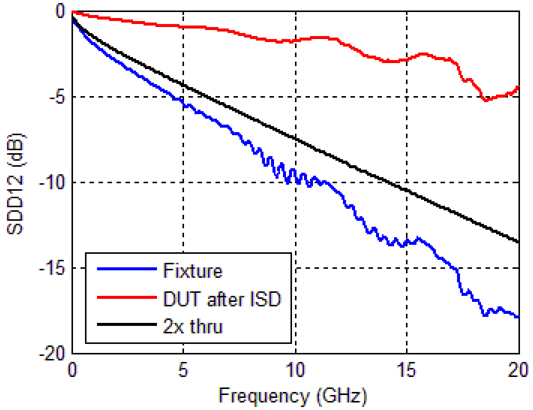
2x thru
(12” total)

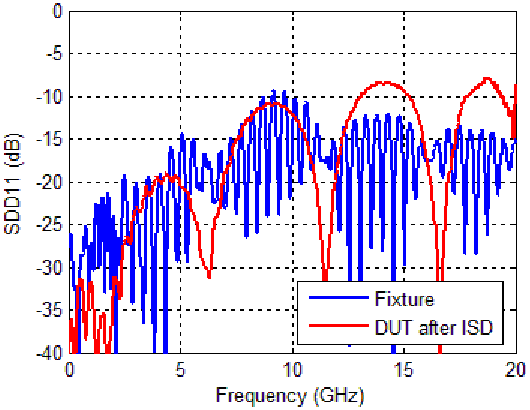
Mezzanine
connector
(DUT)

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

- TRL would have required many long and coupled traces.

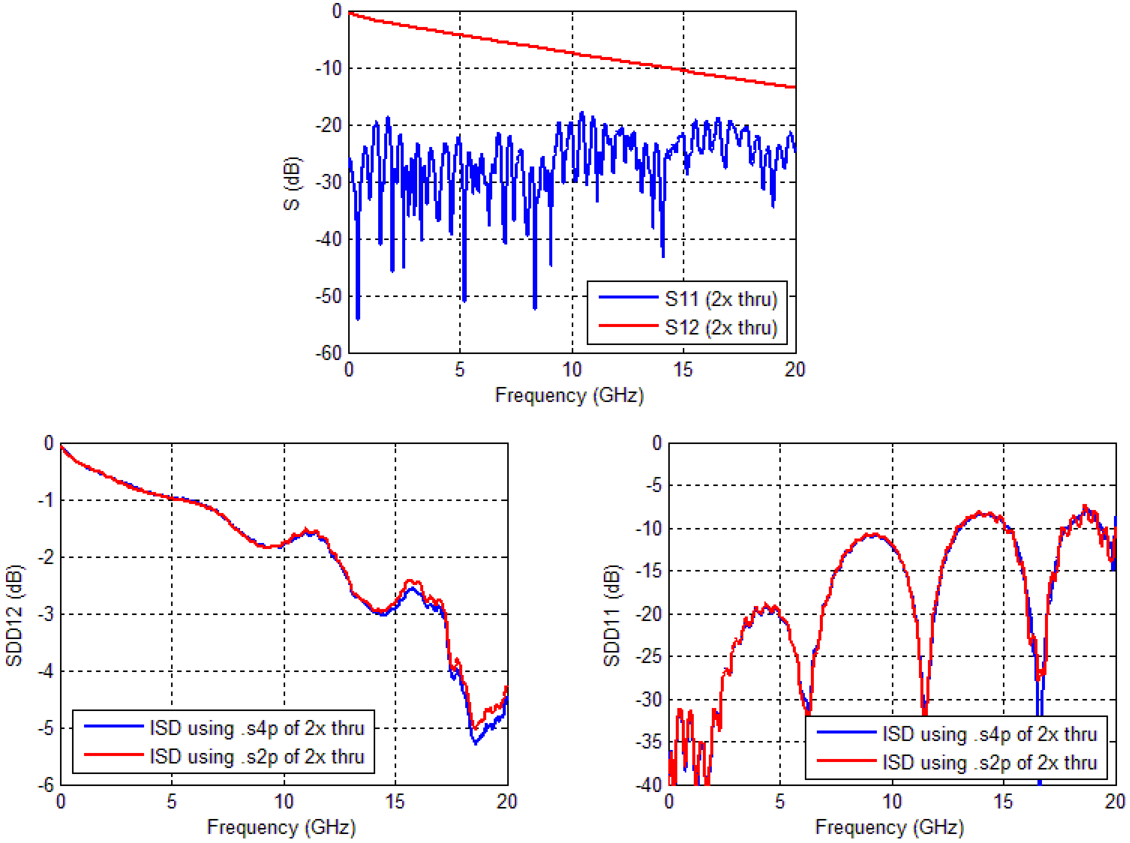






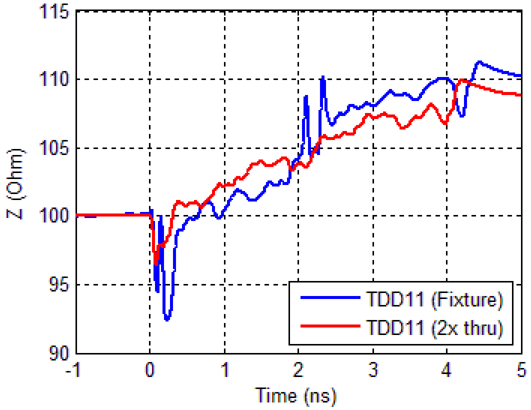
ISD can even use a .s2p file of 2x thru to de-embed crosstalk…

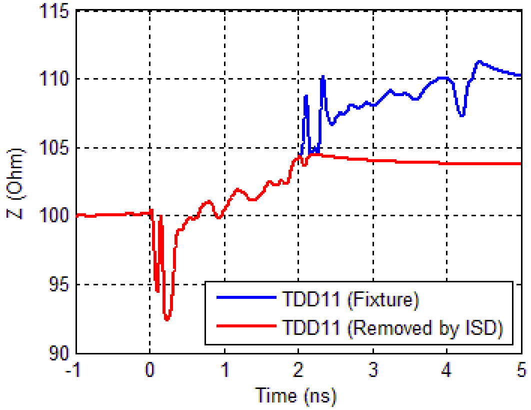
- And the results are similar!

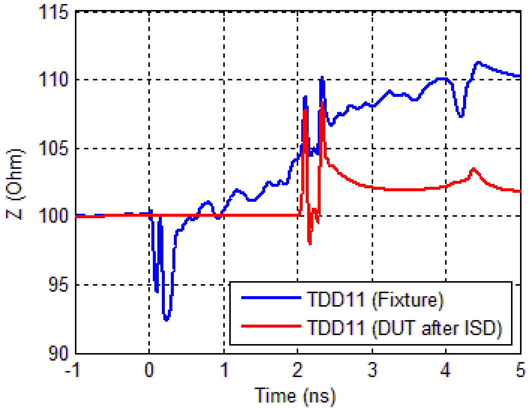


ISD allows a large demo board to double as a characterization board

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



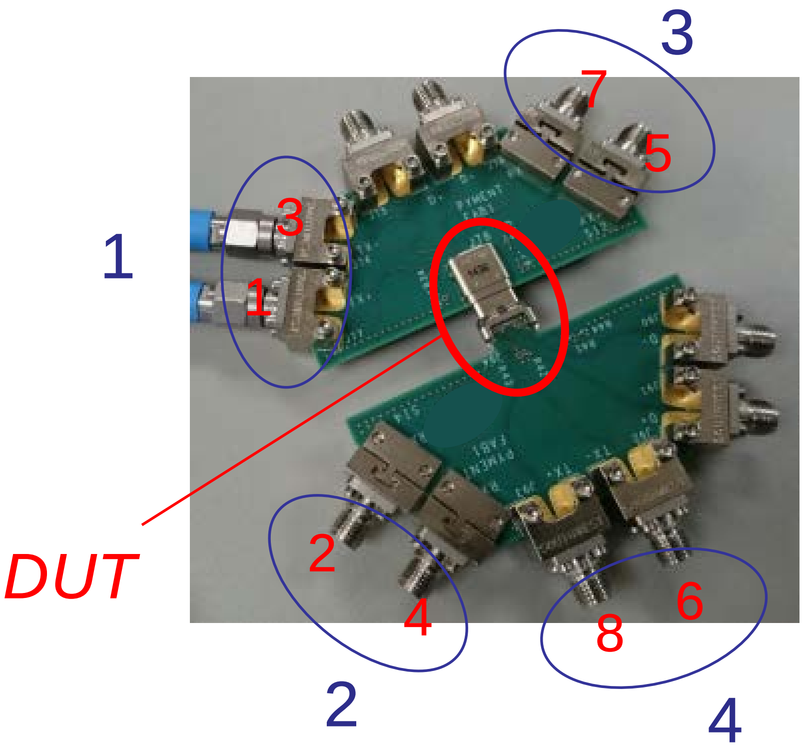


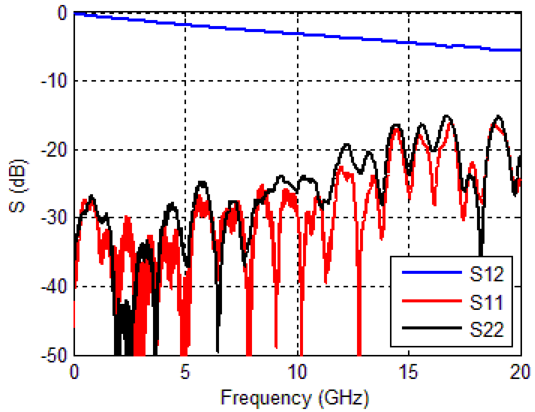


Rise time = 40ps (20/80)

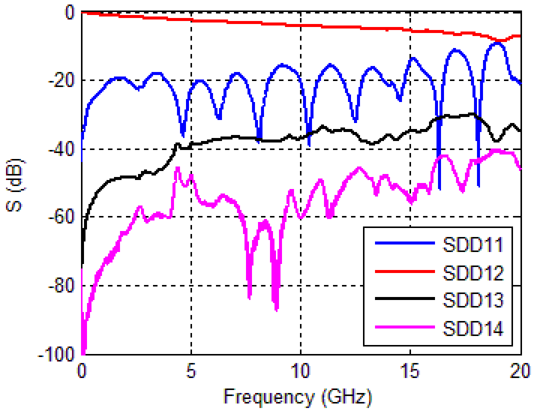
Example 3: USB type C mated connector
ISD vs. AFR

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





2x thru

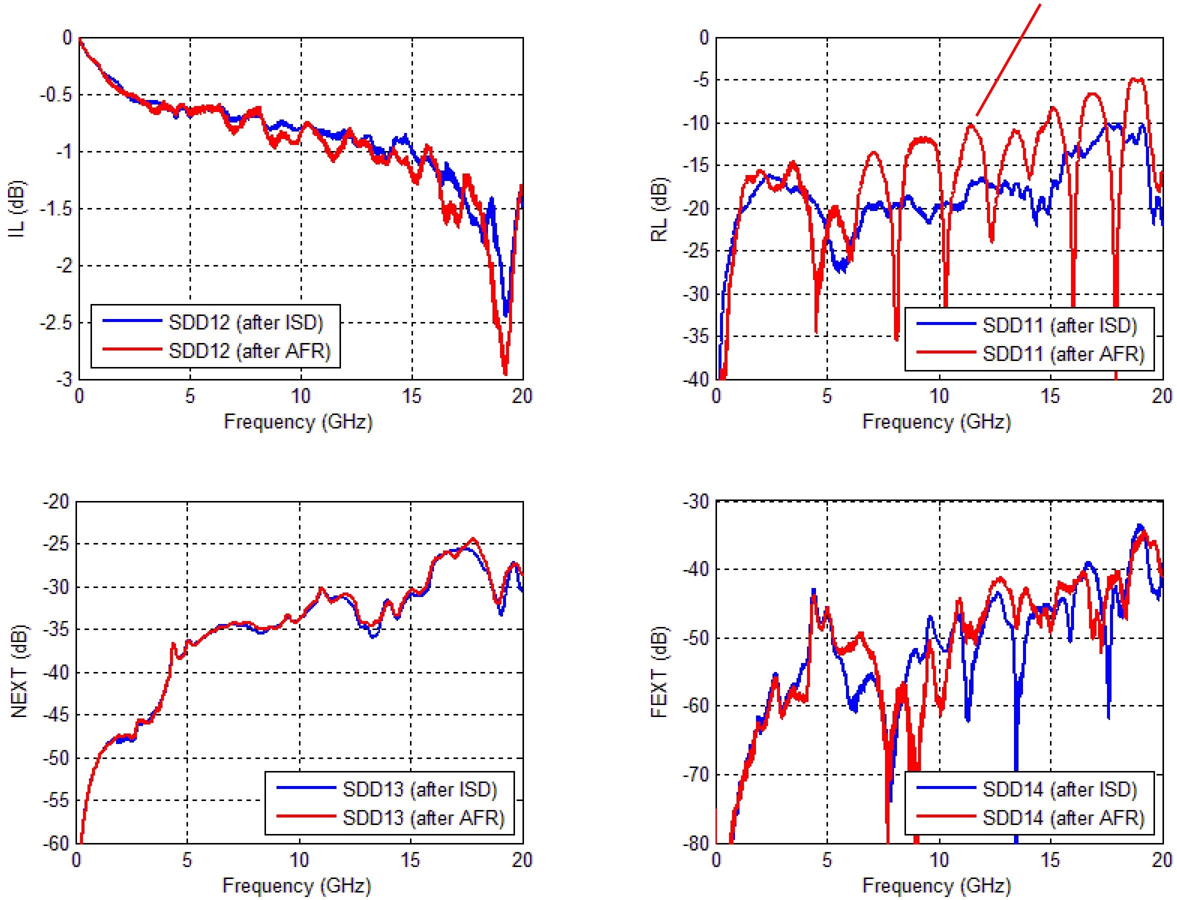


Fixture

DUT results after ISD and AFR

Which one is more accurate?

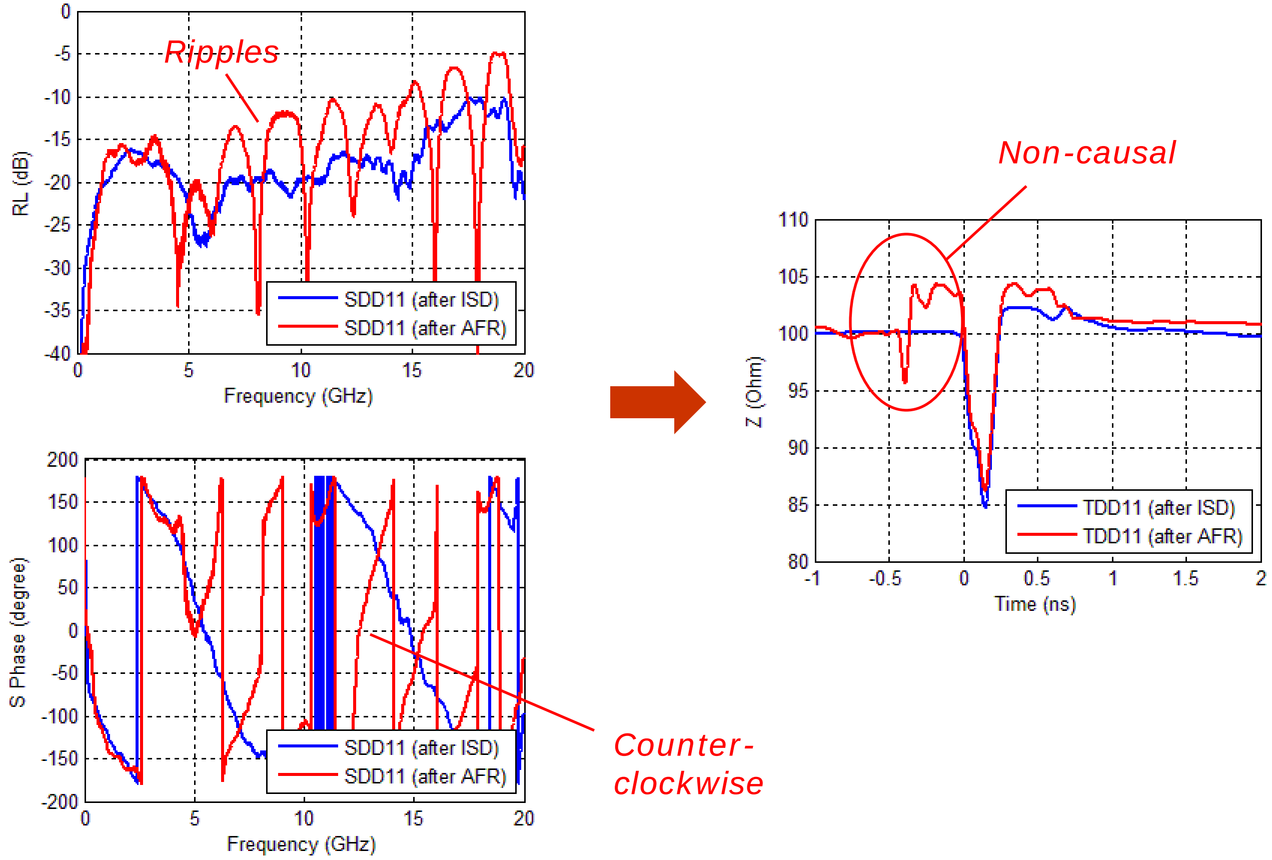
- AFR gives too many ripples in return loss (RL) for such a small DUT.



Non-causal ripples

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

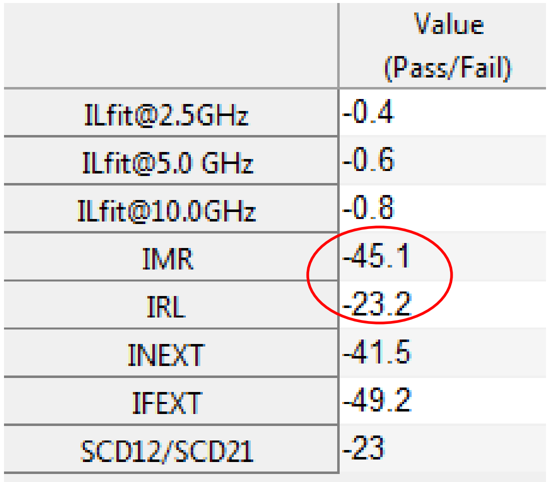
- Counter-clockwise phase angle is another indication of non-causality.



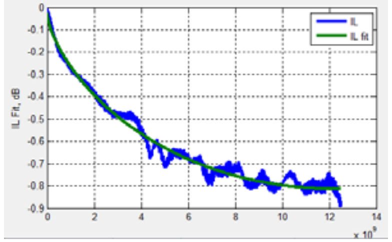
De-embedding affects pass or fail of compliance spec.

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

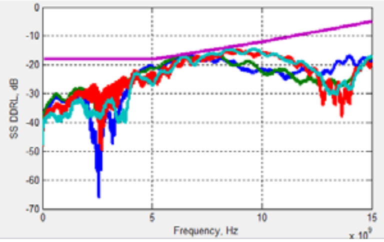
ISD



	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

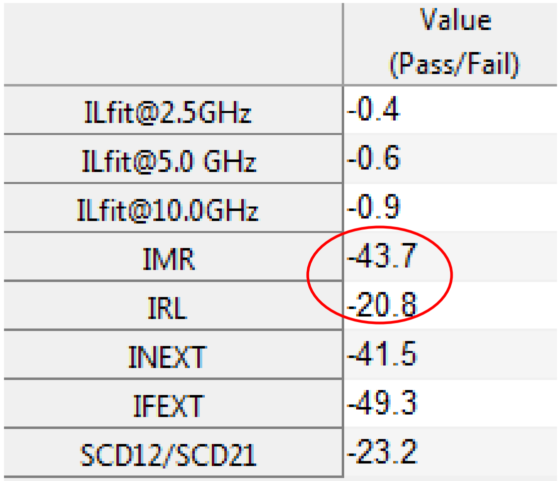


IL

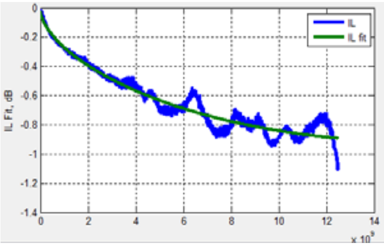


RL

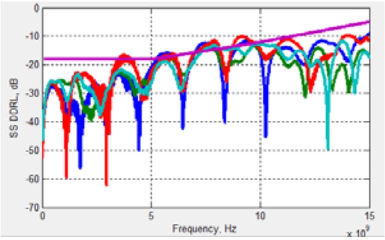
AFR



	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

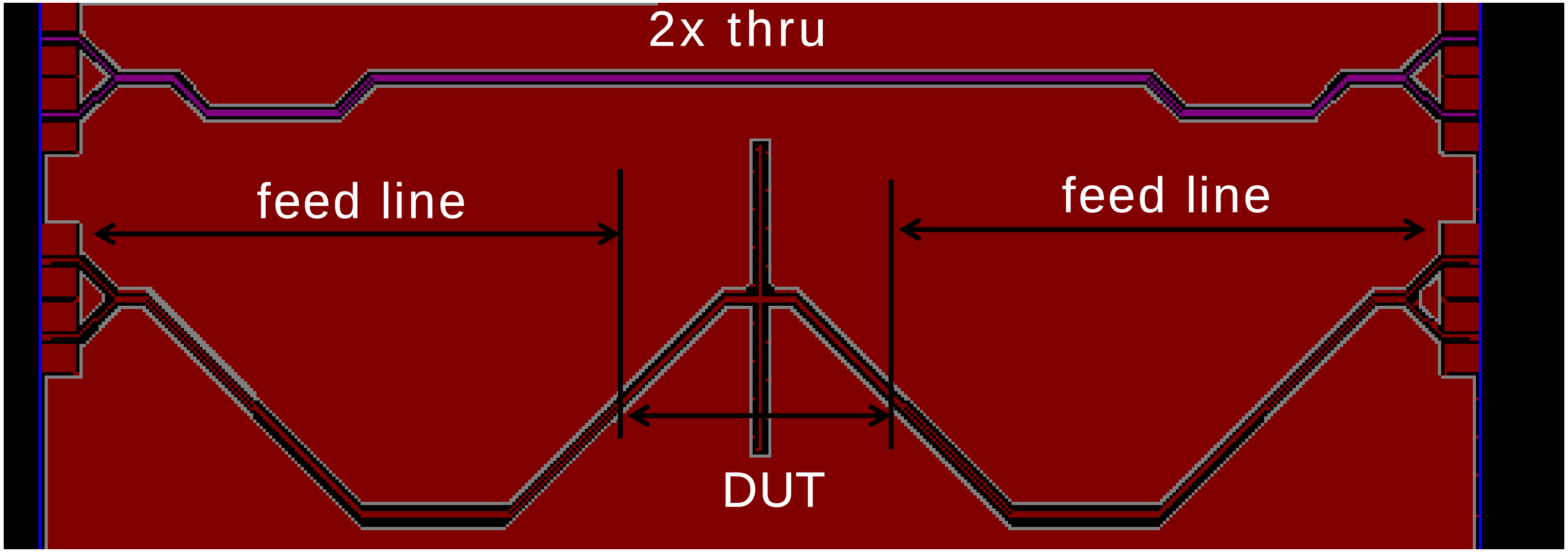


RL

Example 4: Resonator

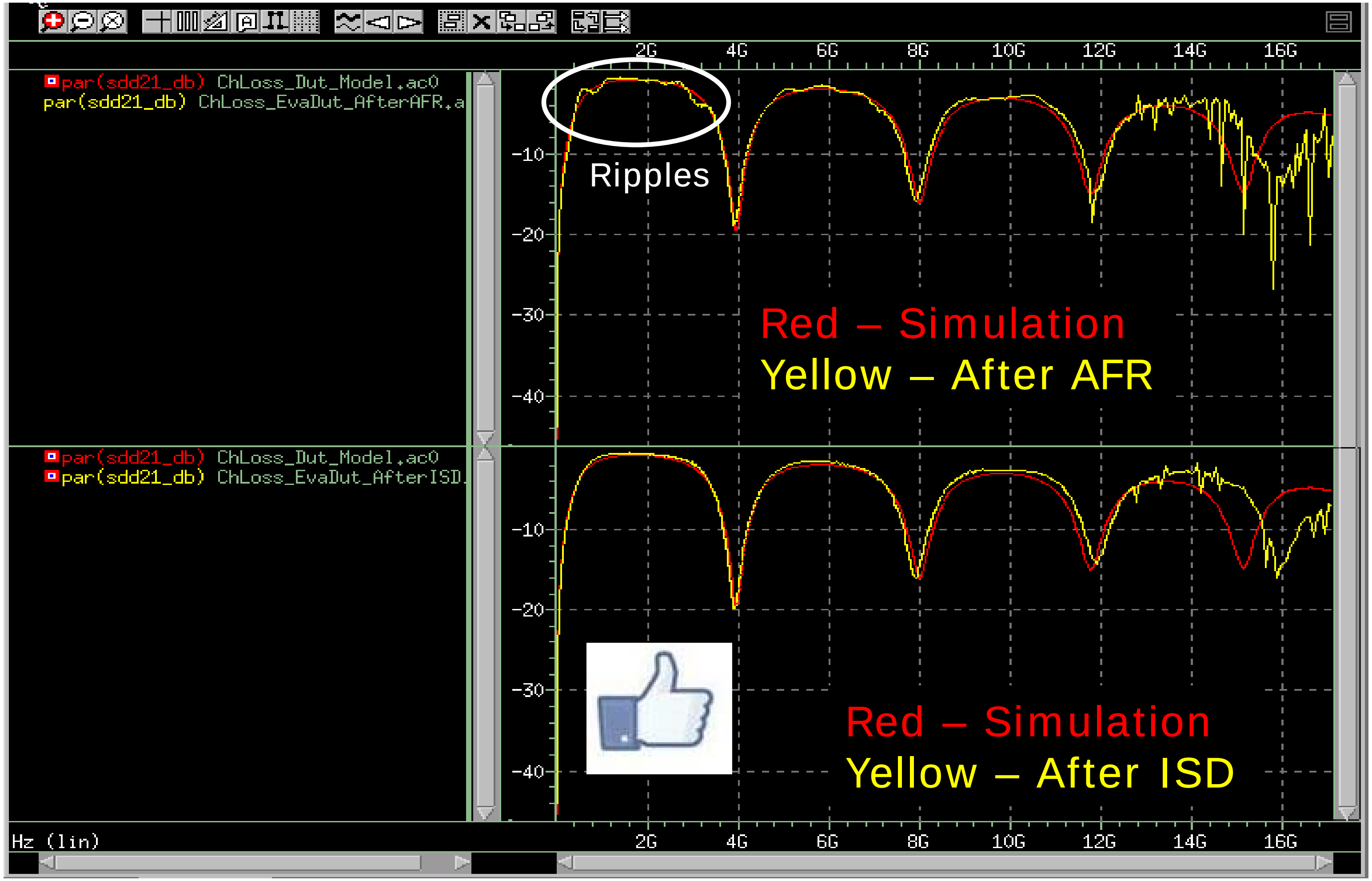
ISD vs. AFR vs. simulation

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



SDD21

ISD correlates with simulation better



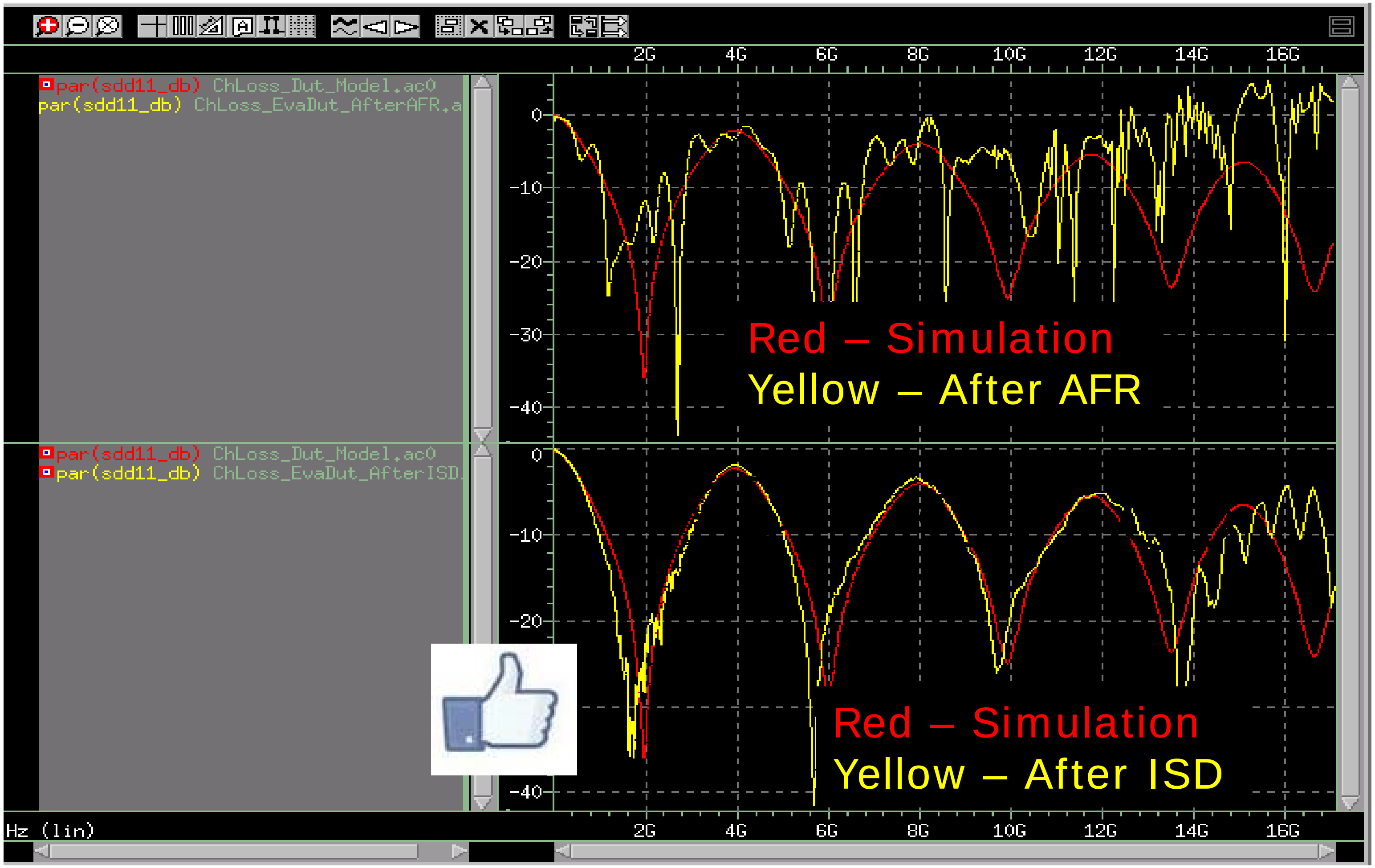
Ripples

Red – Simulation
Yellow – After AFR

Red – Simulation
Yellow – After ISD

SDD11

ISD correlates with simulation much better

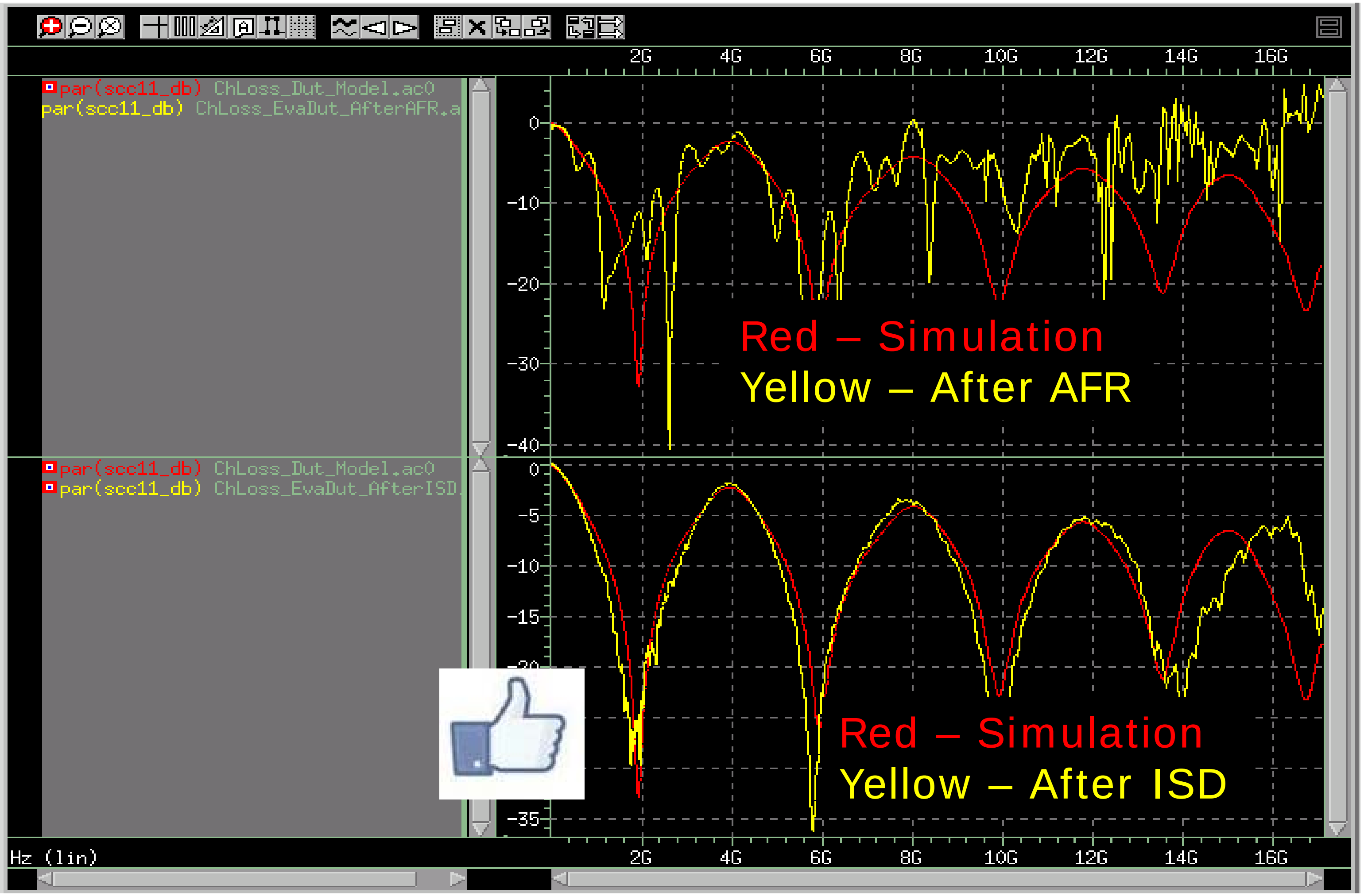


Red – Simulation
Yellow – After AFR

Red – Simulation
Yellow – After ISD

SCC11

ISD correlates with simulation much better



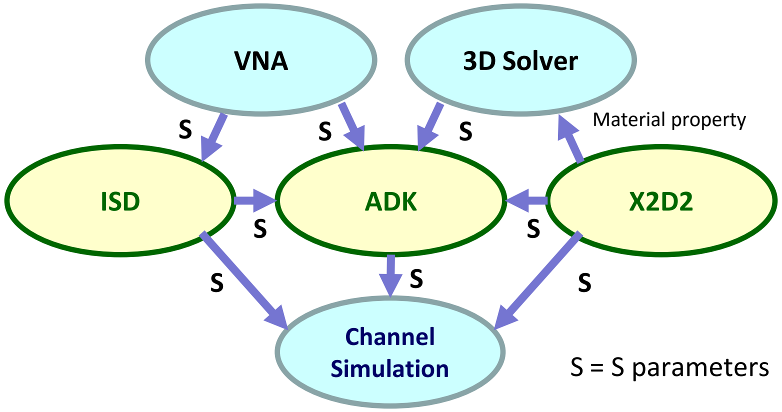
Red – Simulation
Yellow – After AFR

Red – Simulation
Yellow – After ISD

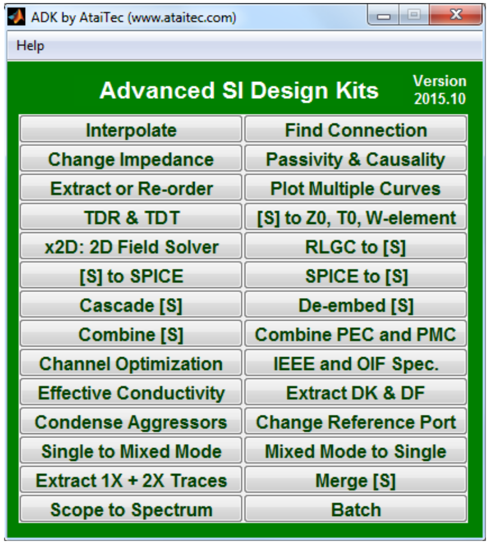
ADK and X2D2

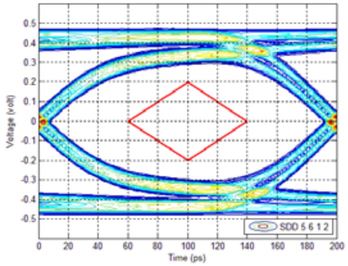
Mobile-apps-like SI tools

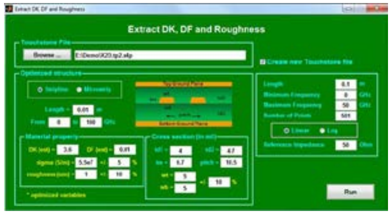
- ADK is a collection of many SI programs to convert S parameter into TDR/TDT, SPICE model or eye diagrams, compare with industry spec. (ICR, ICN, …) and extract DK, DF and roughness, …
- X2D2 models the effect of surface roughness on all IL, RL, NEXT and FEXT by effective conductivity.


VNA
3D Solver
ISD
ADK
X2D2
Channel Simulation
S
Material property
S = S parameters

AtaiTec enhanced flow







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Summary

- In-Situ De-embedding (ISD) solves the causality problem commonly encountered in de-embedding.
- ISD is causal by construction and it can...
  - give more accurate DUT results,
  - de-embed crosstalk using a single-trace coupon,
  - de-embed long traces and extract a small DUT,
  - give better DUT results for compliance testing,
  - correlate with simulation better and make design refinement possible.
- Mobile-apps-like ISD is easy to use and it helps save $$$ from board material, correlation and design cycle time, ...