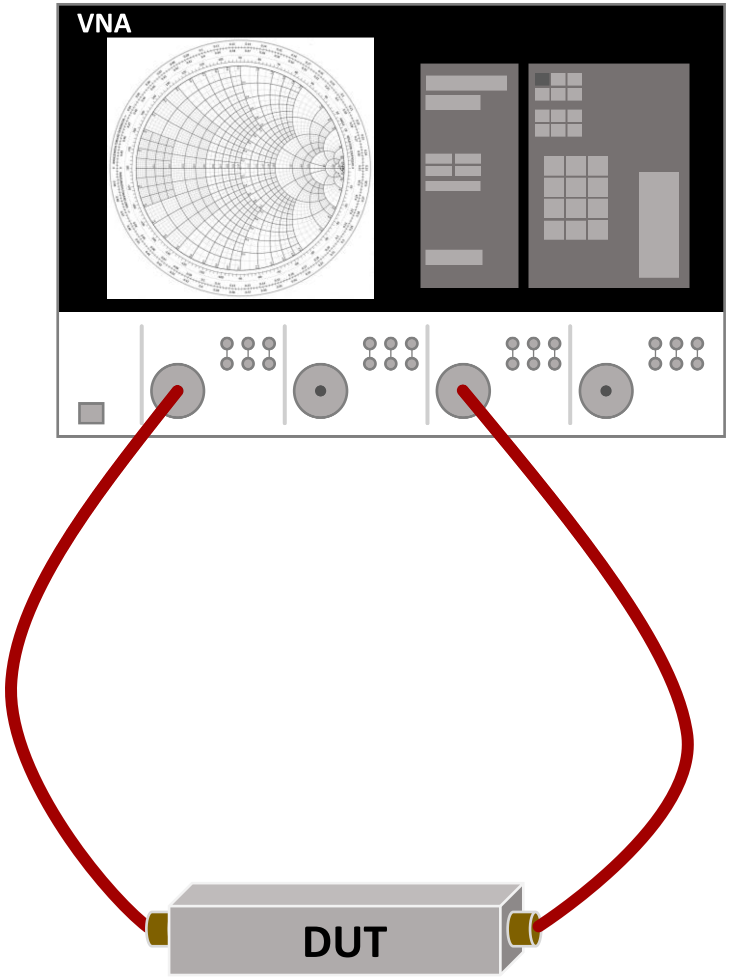
Using L-2L Method for De-embedding Structure on the PCB level

Outline

- Understanding De-embedding
- Why De-embedding methods is important?
- Introduction of De-embedding Methods
- Theoretical View of L-2L Method
  - Through de-embedding
  - Results
  - Weaknesses
- Introduction of 2x Thru De-embedding
  - TDR and Time gating method
  - Results
  - Weaknesses
- How to use the L-2L method for PCB structures
- The Structures That Can be De-embedded with this method
  - Advantage
  - Weaknesses
- Conclusion
- Future work
- References

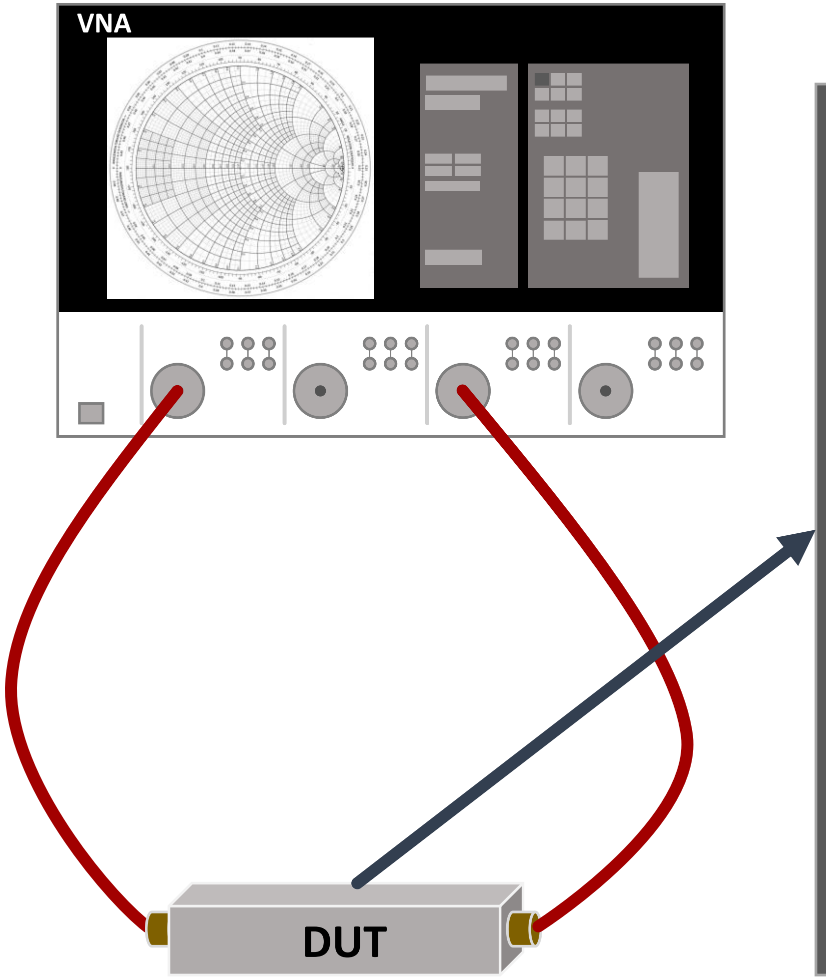
Understanding De-embedding

- Standard **RF cables** are used to **connect** the ports of **the VNA to the DUT**.

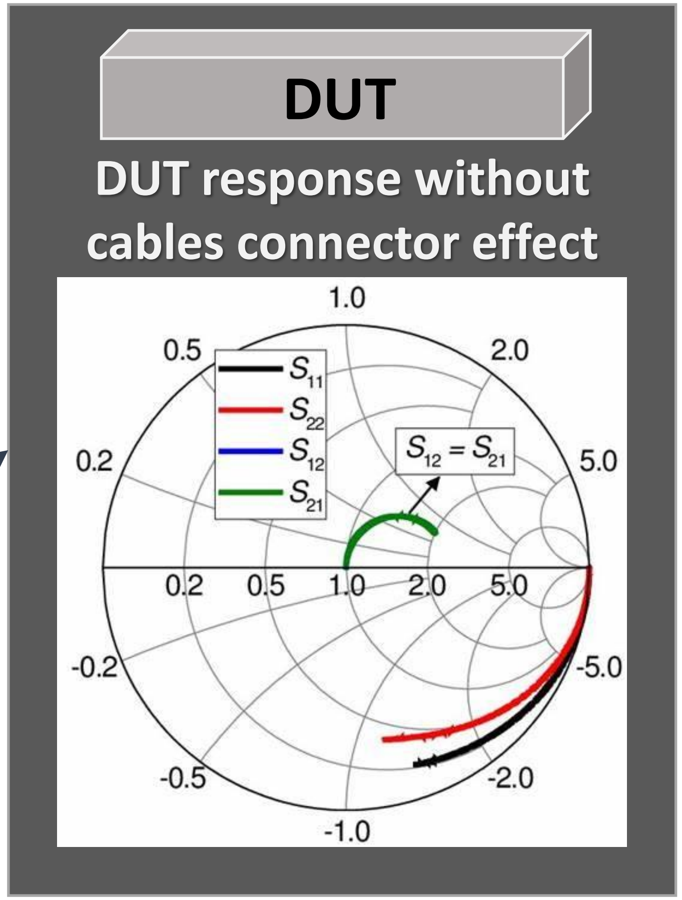


Understanding De-embedding

- Standard **RF cables** are used to **connect** the ports of **the VNA to the DUT**.
- By **calibrating/de-embedding** at the end of these **cables can be removed**.
- Standard **calibration** methods:
  - **TRL**
  - **SOLT**
  - **LRL**
  - **2x Thru**



By Calibration

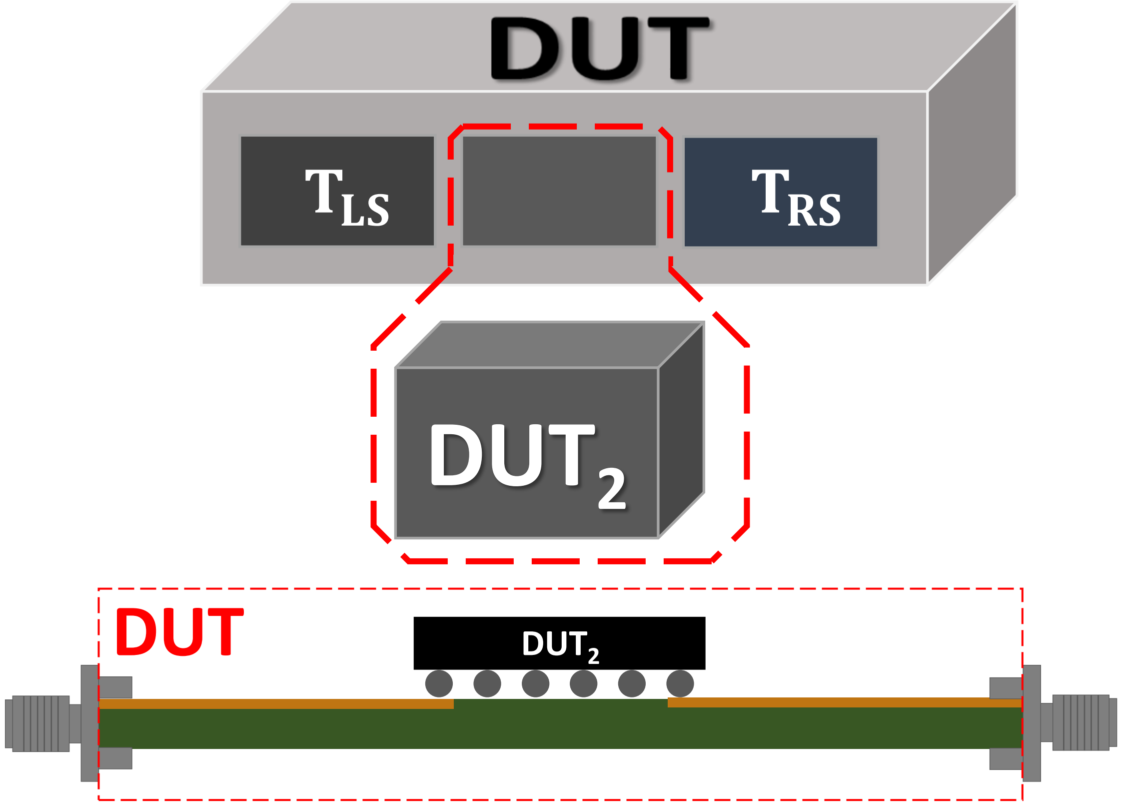


Why De-embedding methods is important?

- **The extreme importance of accurate parasitic** de-embedding techniques to RF device characterization has already been established.

- In general, the parasitic contributions of device-under-test (DUT) structures mainly arise from **probe pads**, **the interconnection lines connected to the intrinsic on-chip DUT structure**.

- **The most important purpose of mathematical-based de-embedding is to access the inside of the DUT.**



$$T_{DUT} = [T_{LS}] \times [T_{DUT_2}] \times [T_{RS}]$$

$$T_{DUT_2} = [T_{LS}]^{-1} \times [T_{DUT}] \times [T_{LR}]^{-1}$$

"Mike Resso: Senior engineer in the Keysight company, Author of Signal Integrity Characterization Techniques, 2019"

[1] Ref: H. Cho, "A Novel Transmission-Line De-embedding Technique for RF Device Characterization," in IEEE Transactions on Electron Devices, vol, 2009

Introduction of De-embedding Methods

De-embedding techniques can be classified as three groups:

- The first group is called the **lumped equivalent circuit model based** technique for short DUT structures:

  The largest dimension of the structure $< 0.1\,\lambda$

  - Open method
  - Open-Short method
  - Vandamme method

- The second group is called the **cascade based with lumped equivalent circuit model based** technique for short DUT structures:

  The largest dimension of the structure $< 0.1\,\lambda$

  - **L-2L method**
  - LiLj method
  - Hybrid method

- The third group is called the **cascade based** technique for large DUT structures:

  The largest dimension of the structure $> 0.1\,\lambda$

  - TRL
  - **2X Thru**
  - 1X Fixture

[1] Ref: H. Cho, "A Novel Transmission-Line De-embedding Technique for RF Device Characterization," in IEEE Transactions on Electron Devices, vol, 2009

Theoretical View of L-2L Method

L-2L:

For the L-2L de-embedding method, the **measurement of two transmission lines is required**. The first transmission line is of **length L**, and the second transmission line is of **length 2L**. **Pads are assumed to be symmetric**.

$$\mathbf{T}_{\mathbf{meas\_L}} = [T_{LS}] \times [T_L] \times [T_{RS}]$$

$$\mathbf{T}_{\mathbf{meas\_2L}} = [T_{LS}] \times [T_{2L}] \times [T_{RS}]$$

T_{LS}: Represent the matrix of the left pad;

$T_{L\&2L}$: Represent the matrix of the lines;

T_{RS}: Represent the matrix of the right pad;

$$\mathbf{T}_{\mathbf{thru}} = [T_{meas\_L}] \times [T_{meas\_2L}]^{-1} \times [T_{meas\_L}] =$$

$$T_{LS} \times T_L \times T_{RS} \times T_{RS}^{-1} \times T_L^{-1} \times T_L^{-1} \times T_{LS}^{-1} \times T_{LS} \times T_L \times T_{RS}$$

$$= \boxed{[\boldsymbol{T_{LS}}] \times [\boldsymbol{T_{RS}}]}$$

$$\mathbf{T}_{\mathbf{2L}} = [T_{LS}]^{-1} \times [T_{meas\_2L}] \times [T_{LR}]^{-1}$$

$$\mathbf{T} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \qquad \mathbf{S} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$$

$$T_{11} = \frac{1}{S_{21}}$$

$$T_{12} = \frac{-S_{22}}{S_{21}}$$

$$T_{21} = \frac{-S_{11}}{S_{21}}$$

$$T_{21} = \frac{S_{12}S_{21} - S_{11}S_{22}}{S_{21}}$$

$$S_{11} = \frac{T_{21}}{T_{11}}$$

$$S_{12} = \frac{T_{11}T_{22} - T_{12}T_{21}}{T_{11}}$$

$$S_{21} = \frac{1}{T_{11}}$$

$$S_{22} = \frac{-T_{12}}{T_{11}}$$

$$A = B \times C \times D$$

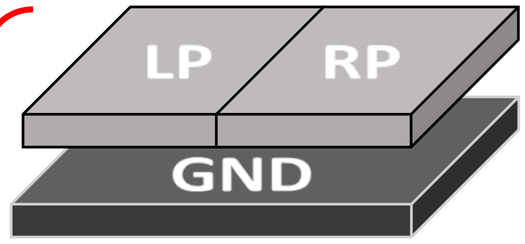
$$A^{-1} = D^{-1} \times C^{-1} \times B^{-1}$$

$$A \times A^{-1} = U$$

$$U \times A = A$$

$$U = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

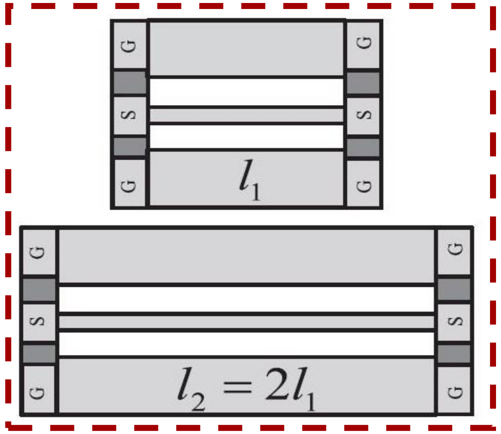
[3] Ref: Conversions between S, Z, Y, H, ABCD, and T parameters which are valid for complex source and load impedances



$$\boldsymbol{\pi - Model}$$

$$\boldsymbol{T - Model}$$

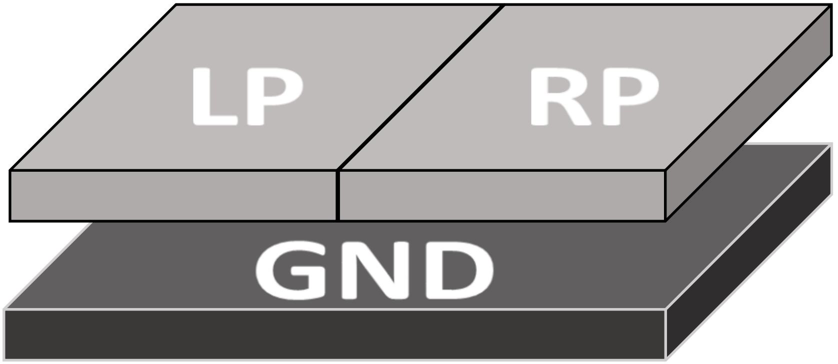
Calibration-kit



[2] Ref: De-embedding techniques for transmission lines: An exploration, review, and proposal, 2013

Separation of $[T_{LS}]$ and $[T_{RS}]$ from T_{thru}

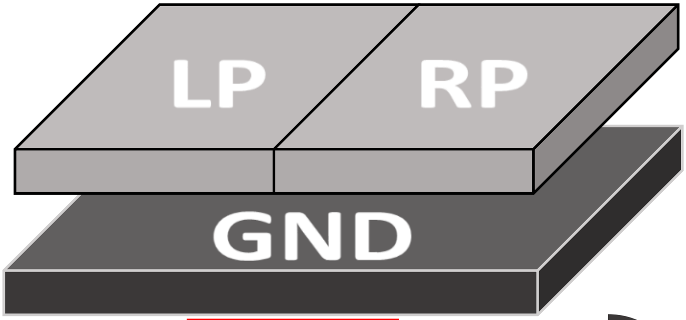
$$T_{thru} = [T_{LS}] \times [T_{RS}]$$

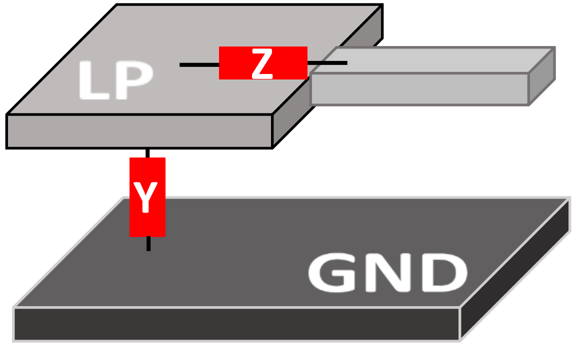


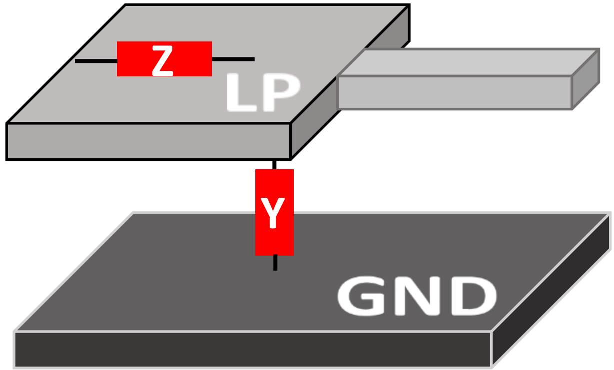
Small Scale

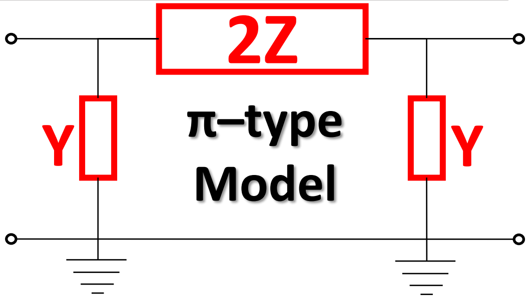
Separation of $[T_{LS}]$ and $[T_{RS}]$ from T_{thru} (Through-Only method)

$$T_{thru} = [T_{LS}] \times [T_{RS}]$$

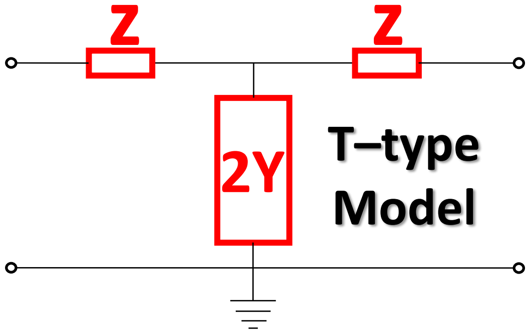








[5] Ref: Jiming Song, Feng Ling, G. Flynn, W. Blood and E. Demircan, "A de-embedding technique for interconnects," 2001



[6] Ref: S. Kawai, K. K. Tokgoz, K. Okada and A. Matsuzawa, "L-2L de-embedding method with double-T-type PAD model for millimeter-wave amplifier design," 2015

Original L-2L

$$[T_{LS}] = [T_{RS}] = \sqrt{T_{Thru}}$$

The pad is modeled with a capacitor

[4] Ref: Rautio, J.C. (1991). A de-embedding algorithm for electromagnetics. *International Journal of Microwave and Millimeter-wave Computer-aided Engineering*

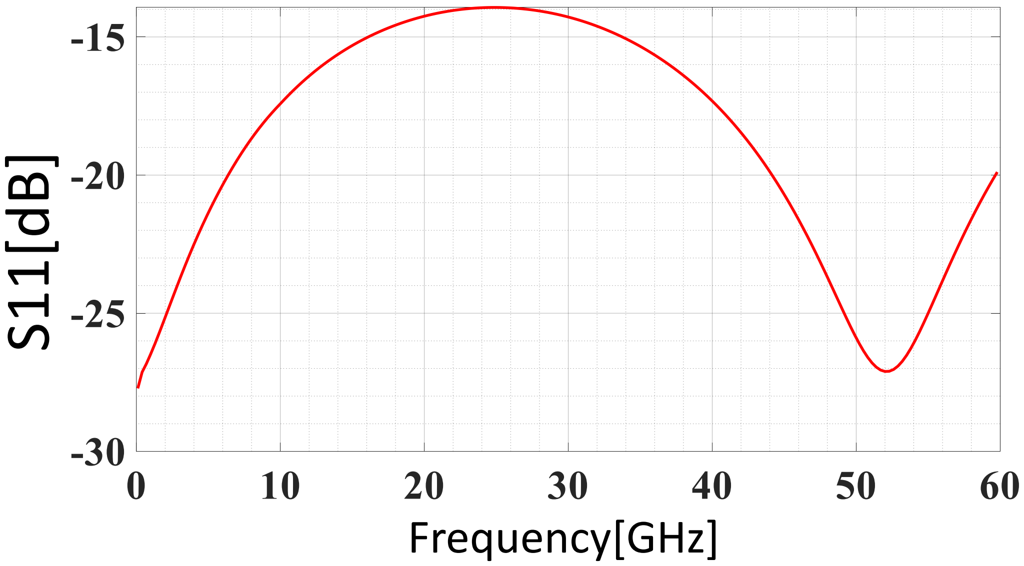
Lumped Elements

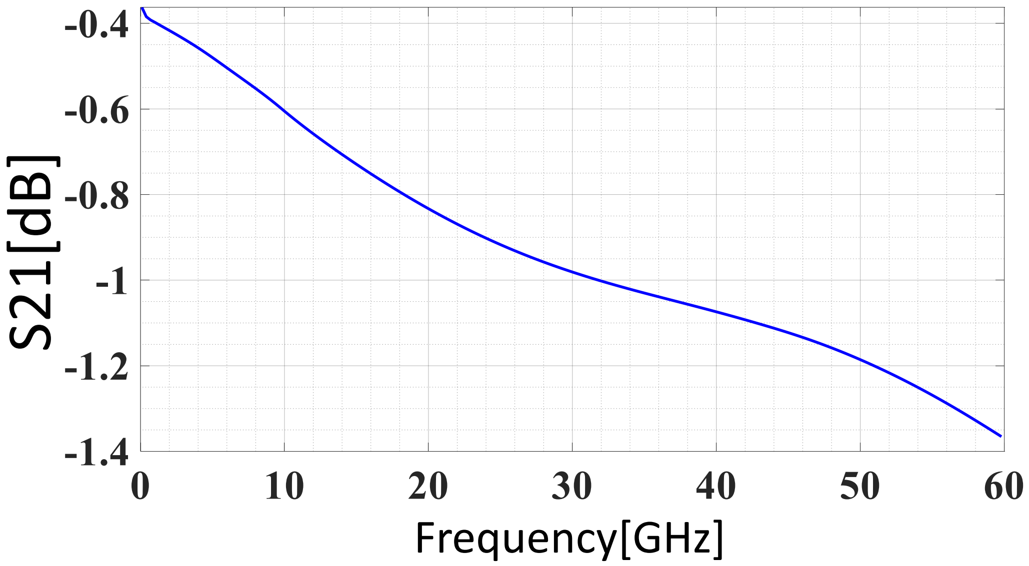
$$Z = j\omega L + R$$

$$Y = j\omega C + G$$

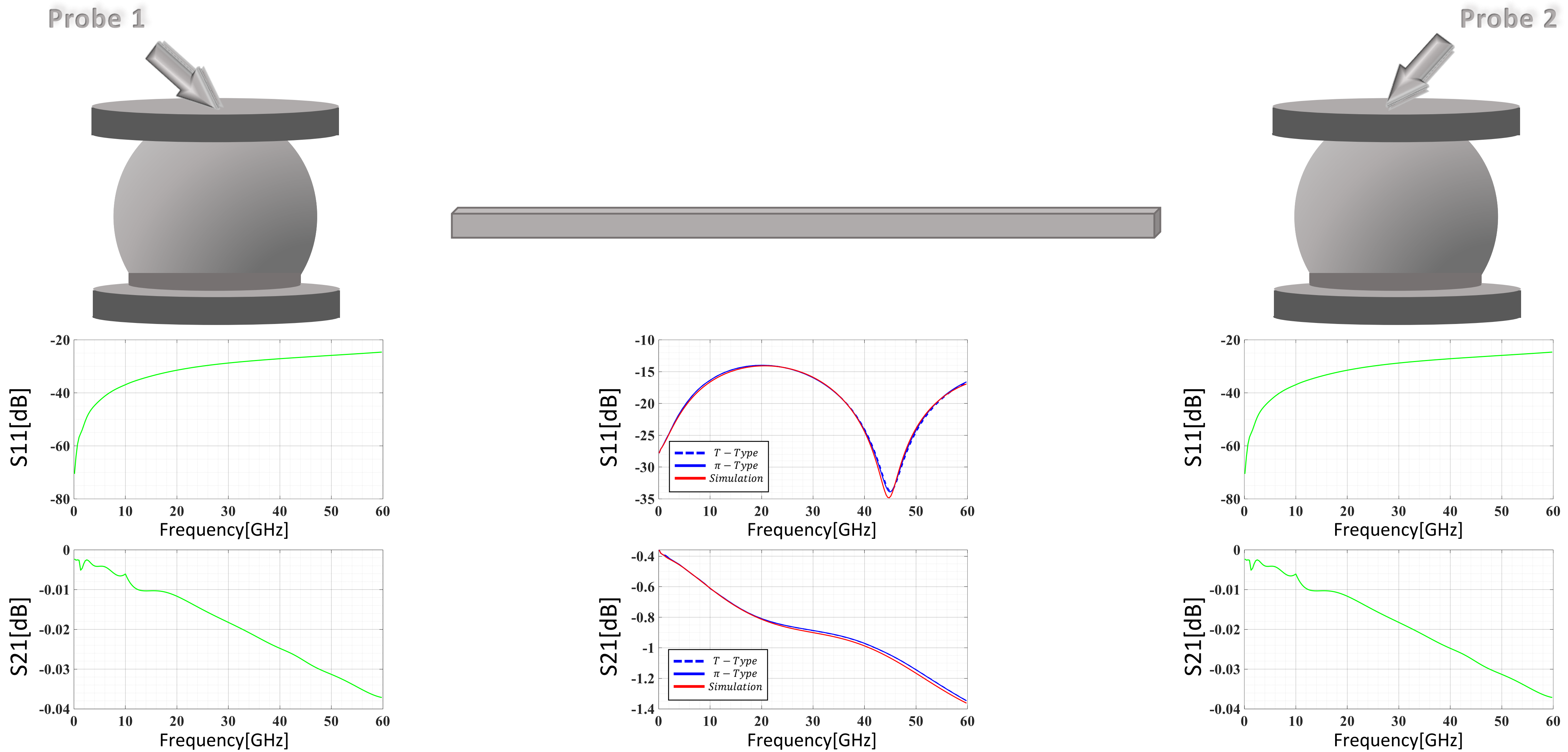
[7] Ref: Yosuke GOTO, "New On-Chip De-Embedding for Accurate Evaluation of Symmetric Devices", Japanese Journal of Applied Physic, 2008

The L-2L De-embedding Results





The L-2L De-embedding Results

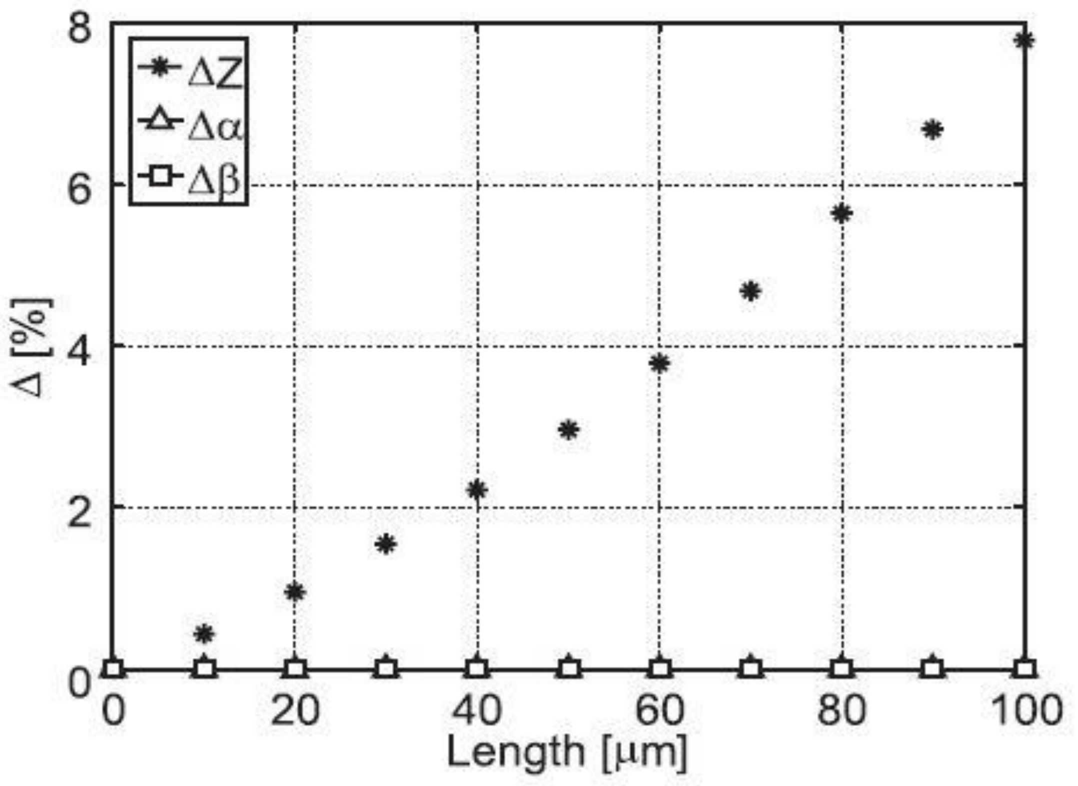


The weaknesses of L-2L Method

- By using the measured S-Parameter the parasites of the pad can be calculated which is modeled as a **π–type** or **T–type** lumped constant circuit. However, in **through-only** method, **the length of the through-line is required to be very short** to match with the π–type lumped model.

$$\Delta = \left| \frac{X^{L-2L} - X^{L}}{X^{L}} \right|$$

- **The parasitic contribution** of the extra grounded metal strip **cannot be ignored if the frequencies are high or if the device under test (DUT) structures are large**.



[8] Ref: Ning Li,” Evaluation of a Multi-Line De-Embedding Technique up to 110 GHz for Millimeter-Wave CMOS Circuit Design” , February 2010 IEICE Transactions

[1] Ref: H. Cho, "A Novel Transmission-Line De-embedding Technique for RF Device Characterization," in IEEE Transactions on Electron Devices, vol, 2009

Introduction of 2x Thru De-embedding

2X Thru:

The S11 left and right fixtures are calculated from **the time domain reflectometry (TDR)**, while the S21 and S22 fixtures are obtained from the wave peeling algorithm. **Only a 2X thru pattern is needed.**

- Symmetry in the 2x Thru is assumed.
- **Minimum spacing between discontinuities in the 2x Thru is needed.**

$$\mathbf{T_{total}} = [T_{Fixture\_A}] \times [T_{DUT}] \times [T_{Fixture\_A}]$$

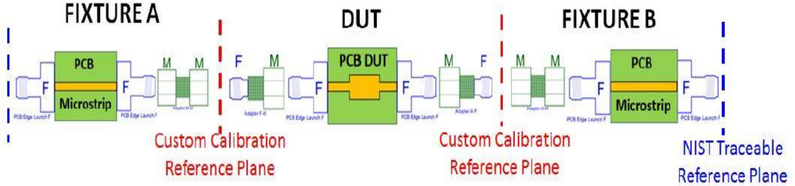
$$\mathbf{T_{2X}} = [T_{Fixture\_A}] \times [T_{Fixture\_A}]$$

$$\mathbf{T_{A}} = \textbf{\textit{FixtureRemovalAlgorithm}}(\mathrm{T_{2X}})$$

$$\mathbf{T_{DUT}} = [T_{Fixture\_A}]^{-1} \times [T_{total}] \times [T_{Fixture\_A}]^{-1}$$

Automatic Fixture Removal (AFR)

Smart Fixture De-embedding (SFD)



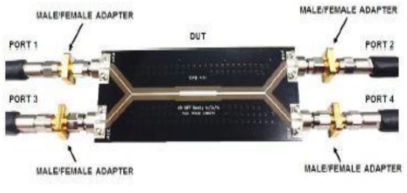
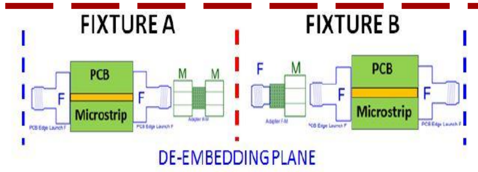


Figure 38: Setup example picture for measuring the DUT.



Cal-kit

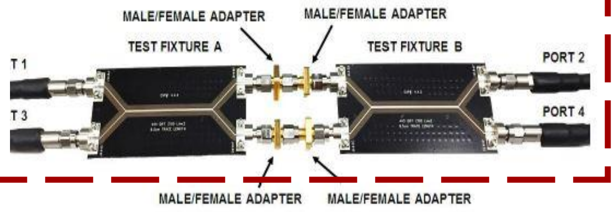


Figure 39: Setup example picture for measuring the test fixture 2x-thru.

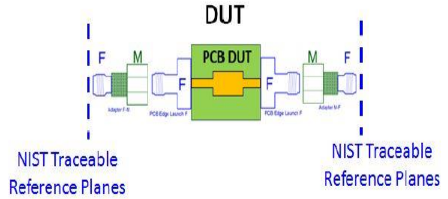


Figure 40: Setup example picture for measuring the open/short 1x-reflect (short on the picture).

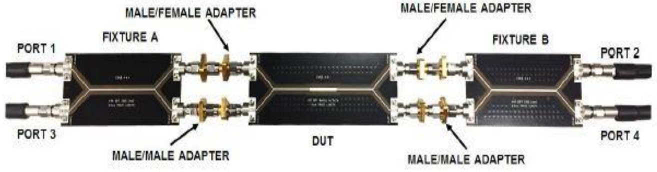
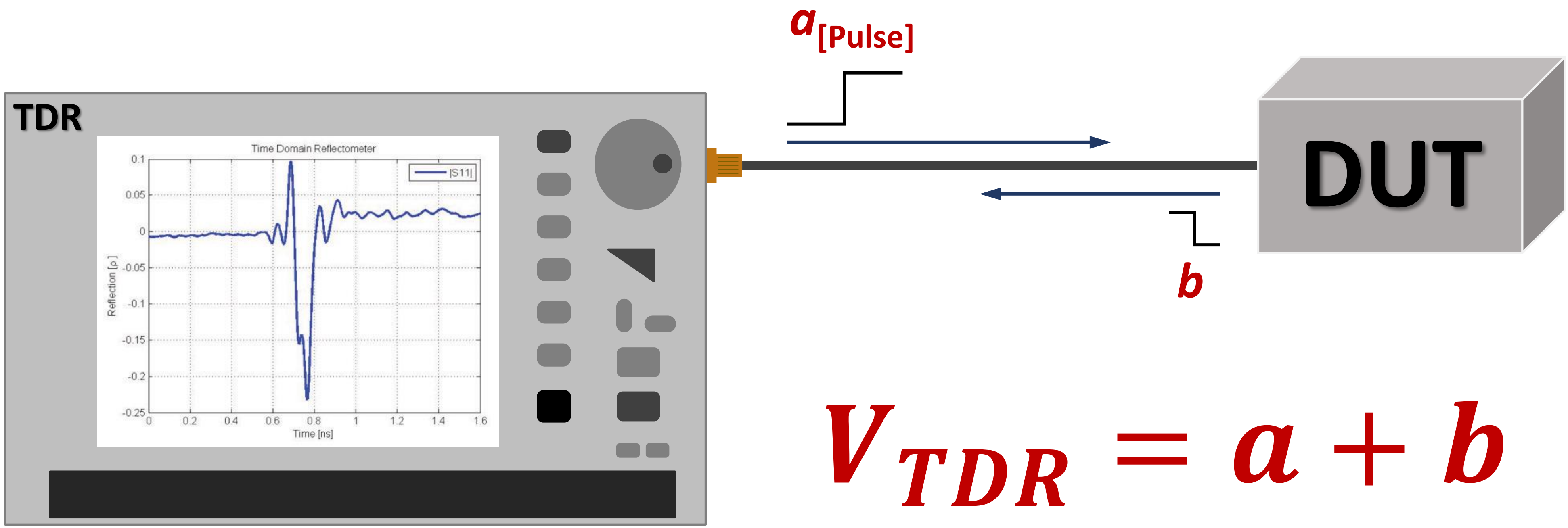


Figure 41: Setup example picture for measuring the DUT plus the test fixture.

[9] Ref: Verifying the accuracy of 2x-Thru de-embedding for unsymmetrical test fixtures, 2017 IEEE 26th Conference on Electrical Performance of Electronic Packaging and Systems (EPEPS).

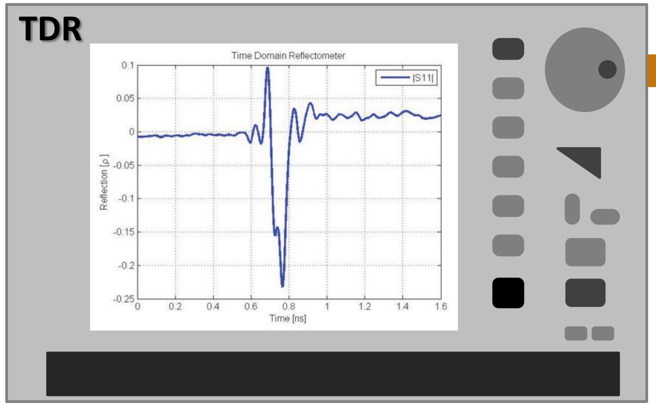
Time Domain Reflectometer (TDR)

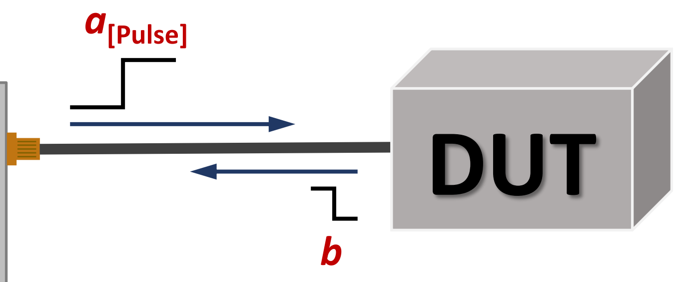
- An **instrument used to determine the characteristics of transmission line** by observing the **reflected waveforms**



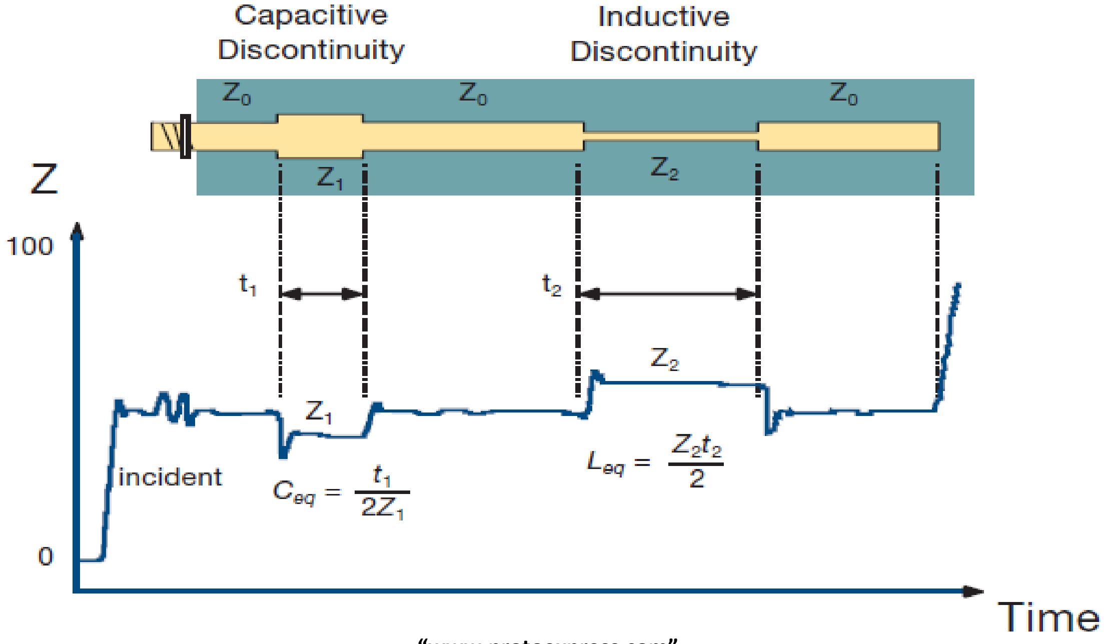
$$V_{TDR} = a + b$$

Time Domain Reflectometer (TDR)

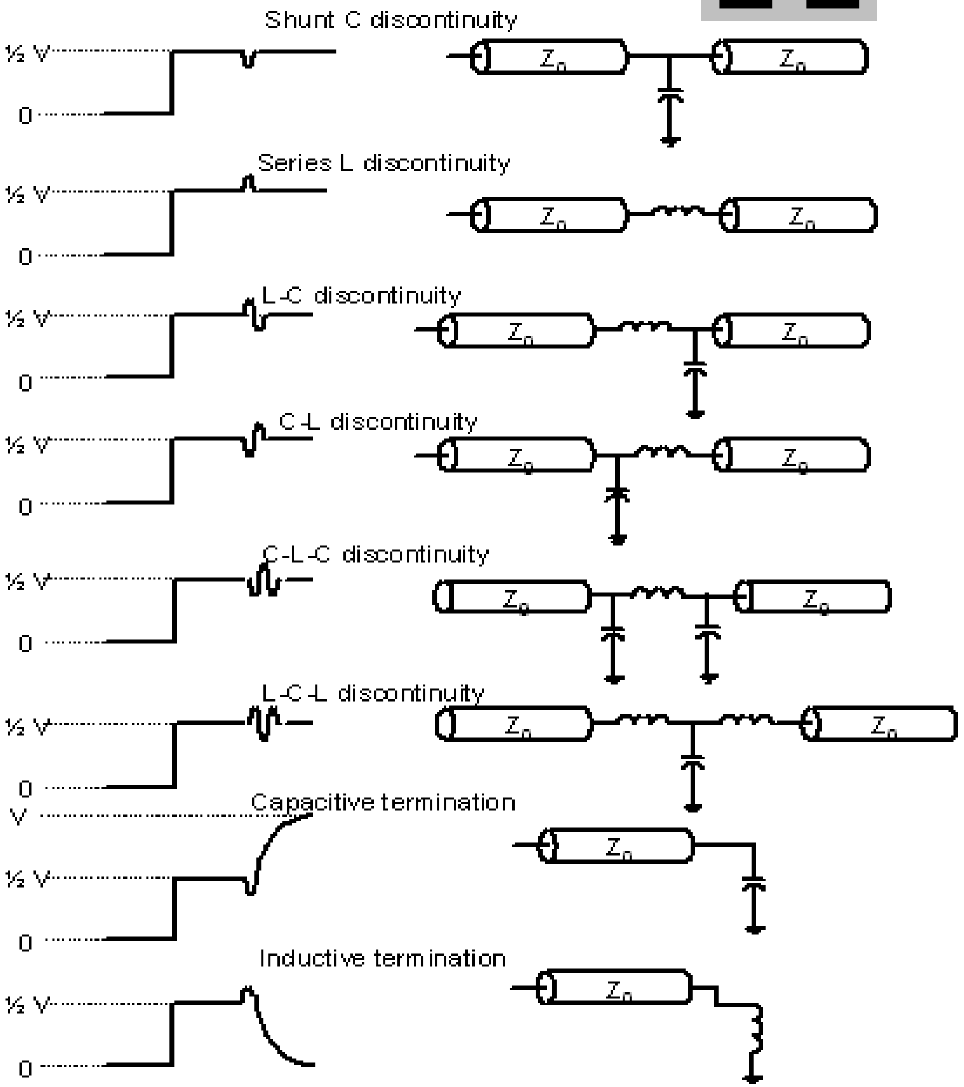




$$V_{TDR} = a + b$$



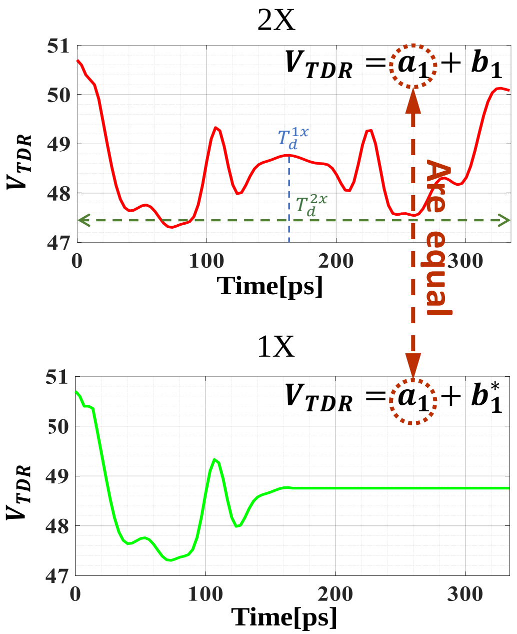
"www.protoexpress.com"

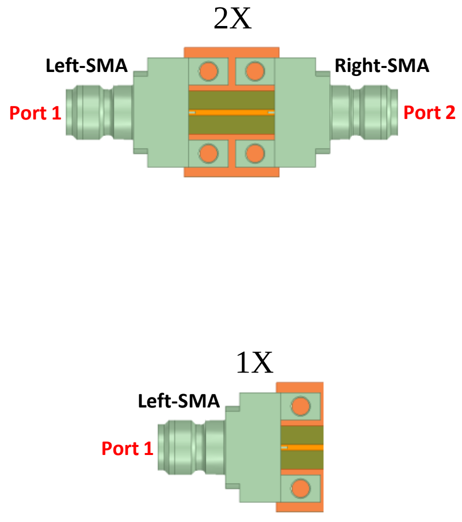


"EETimes"

The Time Domain to Separate 2X(TDR)

1. **Determine the middle time of the 2x-thru.**
2. **Extract the impedance of the 2x-thru at the middle using the TDR or *ifft(S_{11})*.**
3. Renormalize the 2x-thru from the reference impedance of the S-parameters to the measured impedance of the transmission line from step 2 (2x-thru) to satisfy Equation **($Z_{Left\_F} = Z^*_{Right\_F}$)**.
4. Extrapolate the DC point of S_{11}.
5. Convert the half-spectrum domain data into full frequency domain data by enforcing symmetry.
6. **Convert the symmetric information to the time domain.**
7. **Shift the time-domain data right by n points (where n = number of frequency points of S_{11}).**
8. Make all discrete points of the resultant time-domain data zero from the middle point to the end.
9. Shift the time-domain data left by n points.
10. **Convert the time-domain data to frequency domain.**
11. **Discard all content at negative frequencies.**
12. **Repeat steps 2 through 11 for S_{22}.**





2x thru TDR

Cutting TDR of 2xthru in Half

$$T_{d1x} = \frac{T_{d2x}}{2}$$

1x Fixture TDR

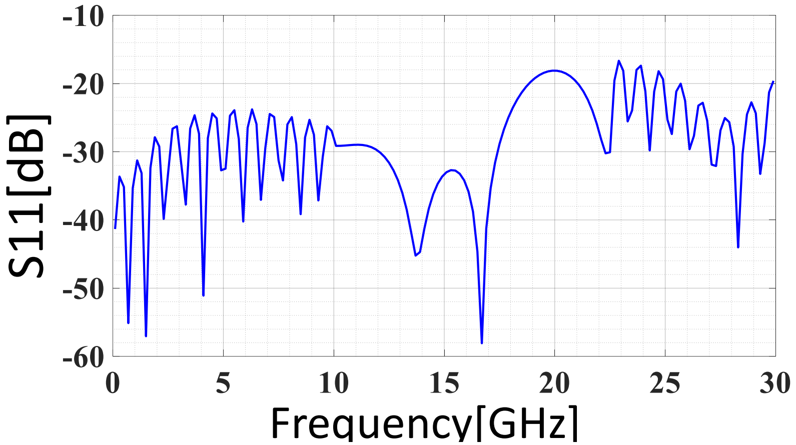
$$S11^{1x} = \frac{\mathrm{fft}(b_1^*)}{\mathrm{fft}(a_1)} \qquad S_{21}^{1x} = S_{12}^{1x} \qquad S22^{1x} = \frac{S_{11}^{2x} - S_{11}^{1x}}{S_{21}^{2x}}$$

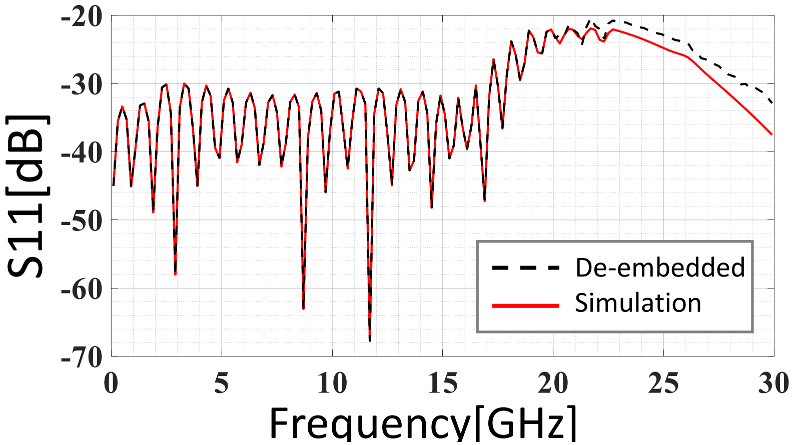
$$S22^{1x} = \frac{\mathrm{fft}(b_2^*)}{\mathrm{fft}(a_2)} \qquad S_{21}^{2x} = S_{12}^{2x} \qquad (S21^{1x})^2 = (1 - (S22^{1x})^2) \times S_{21}^{2x}$$

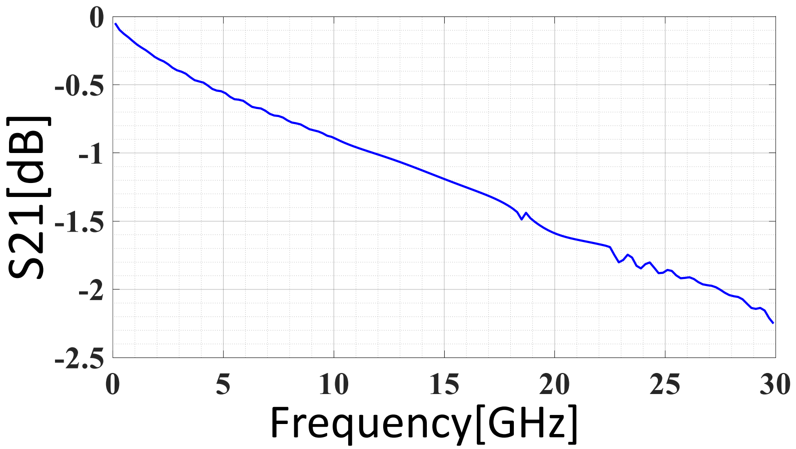
[10] Ref: Using a 2x-thru standard to achieve accurate de-embedding of measurements, 2019, Wiley

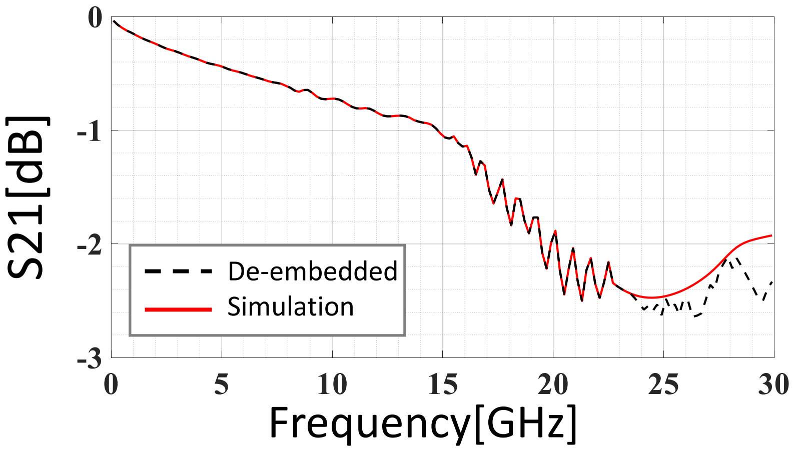
[11] Ref: Error Bounds Analysis of De-embedded Results in 2x Thru De-embedding Methods, 2017

The 2X Thru De-embedding Results









The 2X Thru Weaknesses

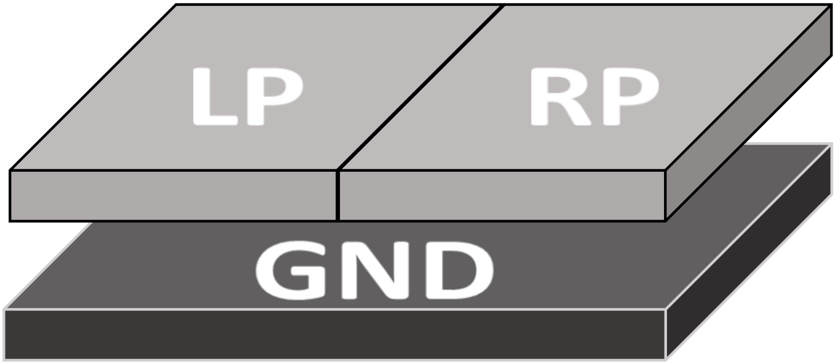
- For designing **2x thru structure** the fixtures **which are vertical cannot be connected directly.**

- It is impossible to build the correct **TDR waveform** for the 1x-fixture when there is a discontinuity at the end of the 1x fixture. **If the impedance at the middle point is 50Ω, the measured reflection ratio is equal to the return loss.**
  - This problem can be solved by adding a 50Ω transmission line which is long enough between 1x fixtures in 2x thru.

[12] Ref: C. Yoon et al., "Design Criteria and Error Sensitivity of Time-Domain Channel Characterization (TCC) for Asymmetry Fixture De-Embedding," in *IEEE Transactions on Electromagnetic Compatibility*

Separation of $[T_{LS}]$ and $[T_{RS}]$ from Each Other

$$T_{thru} = [T_{LS}] \times [T_{RS}]$$



Large Scale

The Time Domain to Separate T_{Thru}

I. Conversion of the T-parameters (T_{Thru}) to the S-parameters (S_{Thru})

II. Conversion of **$S11_{Thru}$** from frequency domain to time domain by ***ifft*** transform.

$$S_{11}^{Thru}(t) = \mathcal{F}^{-1}\left\{S_{11}^{Thru}(f)\right\}$$

III. Determine the midpoint of $S_{11}^{Thru}(t)$ response and extract impedance in the midpoint.

IV. Convert the half-spectrum domain data into full frequency domain data by enforcing symmetry.

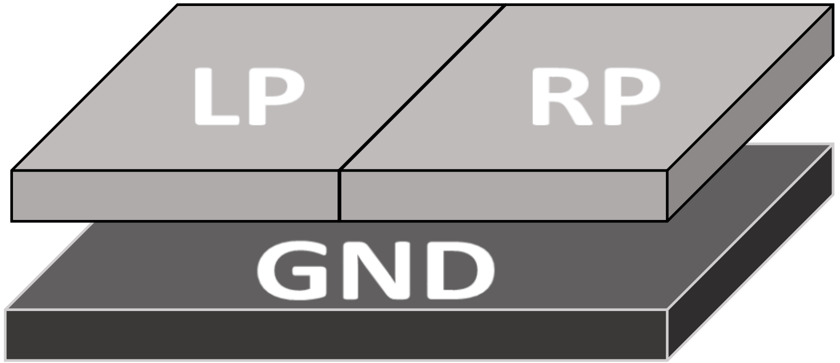
IV. Or can replace the right half-spectrum of time domain response by the midpoint.

V. Convert the time domain data to frequencies by ***fft***.

$$S_{11}^{LS}(f) = \mathcal{F}\left\{S_{11}^{LS}(t)\right\}$$

VI. Convert the S-parameter of left-structure to T-parameter

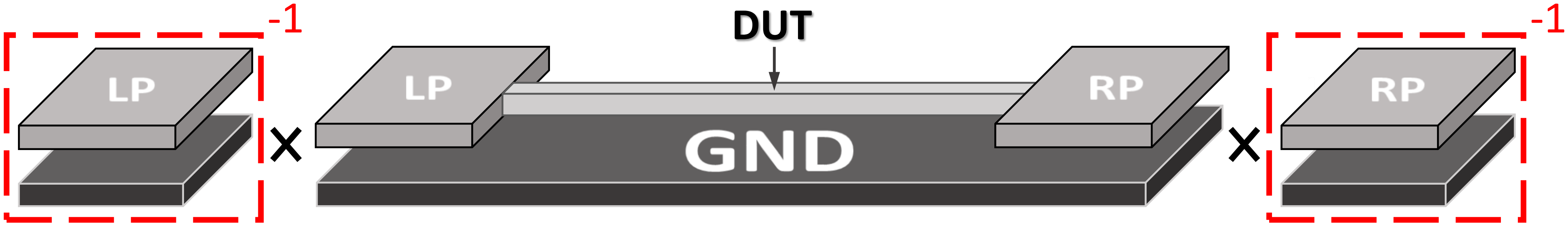
$$T_{thru} = [T_{LS}] \times [T_{RS}]$$

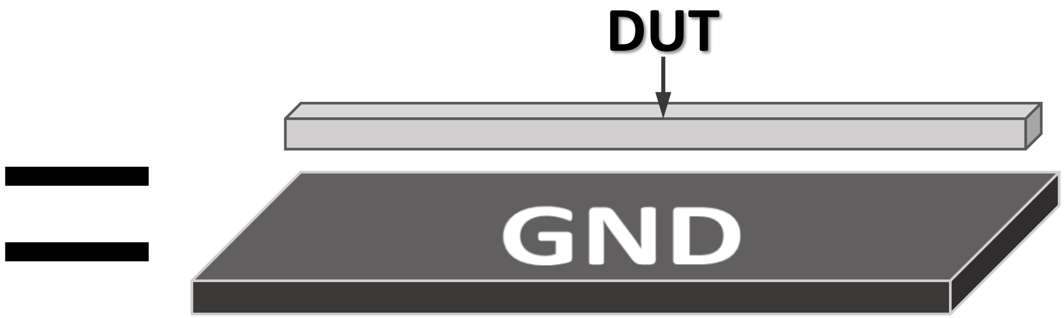


$$S_{12}^{LS} = S_{21}^{LS} \qquad S_{22}^{LS} = \frac{S_{11}^{Thru} - S_{11}^{LS}}{S_{21}^{Thru}}$$

$$S_{21}^{Thru} = S_{12}^{Thru} \qquad {S_{21}^{LS}}^2 = (1 - {S_{22}^{LS}}^2) \times S_{21}^{Thru}$$

De-embed of the DUT structure





$$\mathbf{T_{DUT}} = [T_{LS}]^{-1} \times [T_{2L}] \times [T_{LR}]^{-1}$$

Convert T-parameters of DUT to the S-parameter

The Structures That Can be De-embedded

PCB's Bump

PCB's Deferential Structure

Condition

The Structures must be symmetrical

PCB's Vias

SMA Connectors

Advantage of the Proposed Method

- ✓ This method can be used for any structure including **vertical** and **horizontal**.

- ✓ No need a **matching midline** to extract the S_{11} time response.

Weakness of the Proposed Method

- To perform **this method**, we need **two test structures** that are more **complex than** designing a calibration kit for **2x Thru de-embedding**.

- The **test structure** must be **symmetrical**.

Conclusion

- We saw that the a method has a potential to de-embed PCB's Structures.
- The calibration-kits of the proposed method are simpler than TRL and SLOT methods and are more complex than 2x Thru.
- The method could be used for de-embedding any symmetrical structures (on the PCB).
- The method has advantages and disadvantages compared to 2x thru.

Future Work

- **De-embedding simplest test structure ([Pad].[Line].[pad]) using proposed L-2L de-embedding method.**

- **Designing a GUI program (tool) for the L-2L method using Python similar to other powerful tools such as:**
    - 2X Thru AFR
    - AICC
    - AITT-AR
    - EMStar
    - IEEE Standards Association / Elec_Char / P370 · GitLab

References

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Thank you