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Finding Reflective Insertion Loss Noise and Reflectionless Insertion Loss

Track 7. Optimizing High-Speed Serial Design

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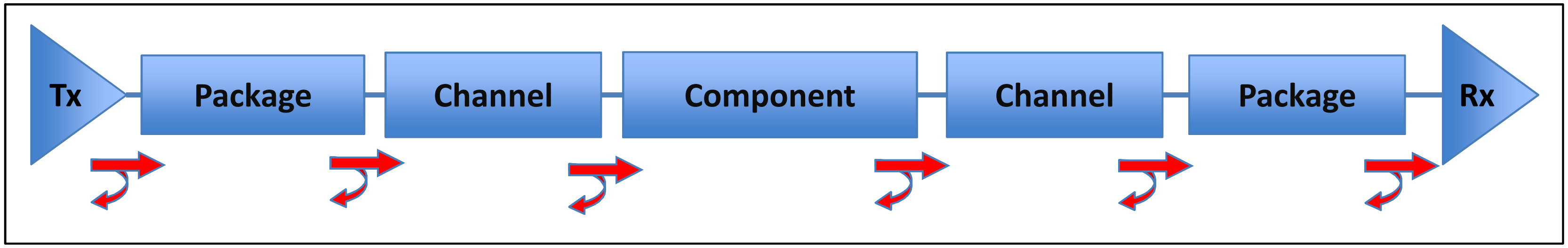
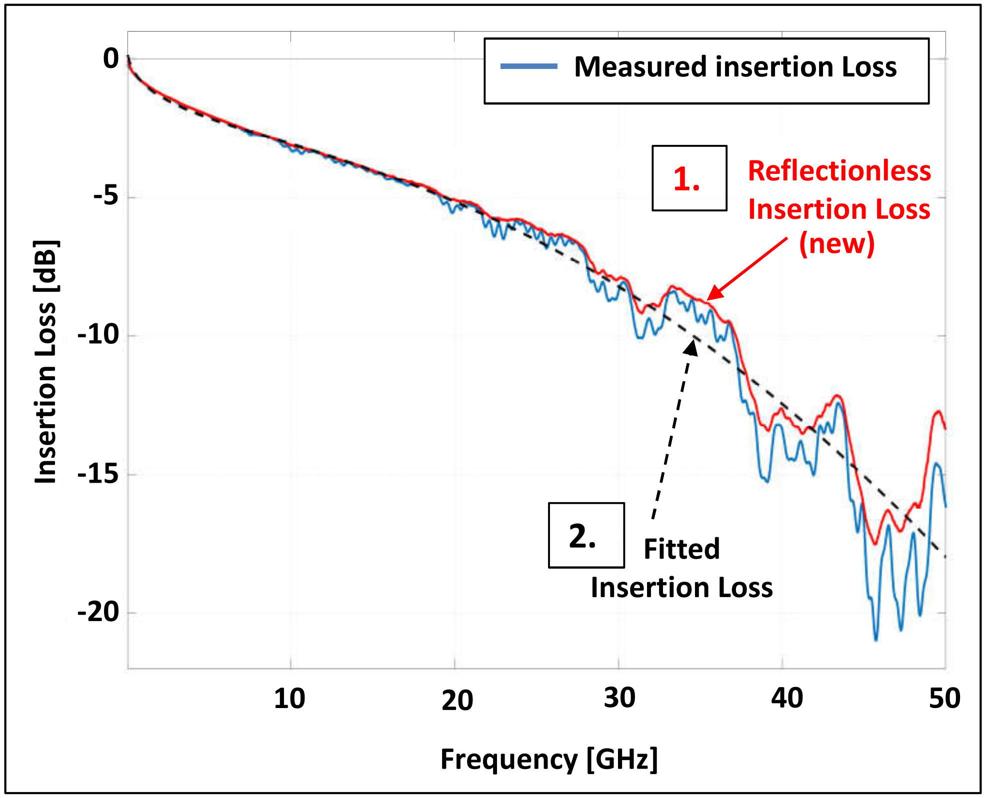
Background



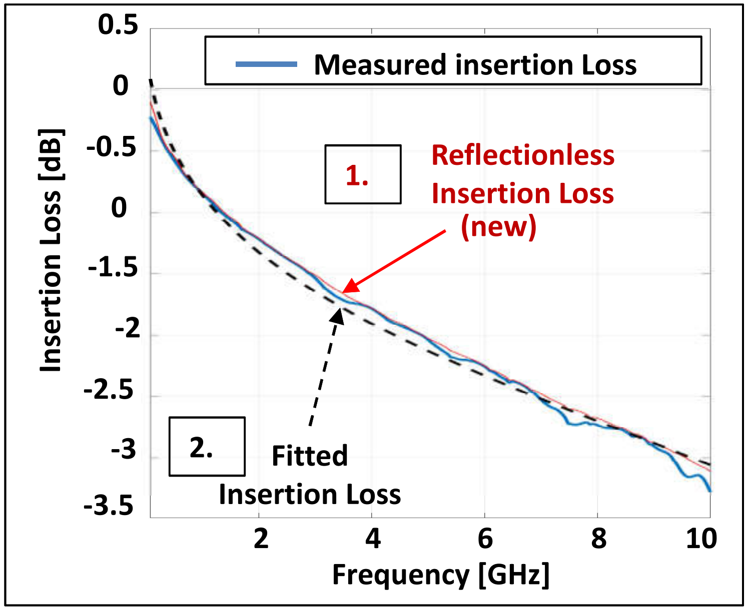
- Inter-symbol interference (ISI) & crosstalk are crucial concerns for signaling.
- This is more so for 50 Gbps and higher PAM4 signaling (than 25 Gbps NRZ).
- PAM4 is about 3.4dB more sensitive to ISI than NRZ for the same data rate.
- Reflections at component degrade system performance.
- The identification and quantification of ISI is not new.
- Insertion loss deviation (ILD) vs. frequency & corresponding figure of merit of ILD (FOM_{ILD}) as quality factor are used in specification like in IEEE and OIF standards.

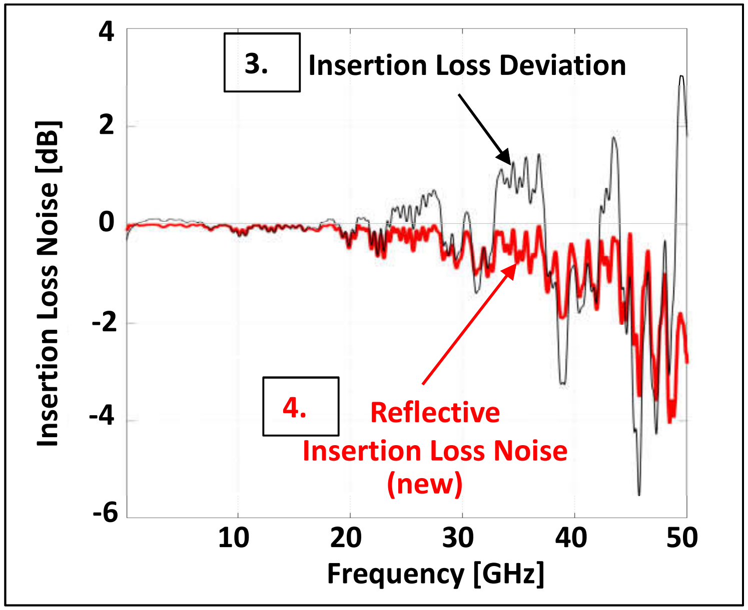
Problem statement

- Insertion loss deviation (ILD(f)) is based on a fit to an insertion loss (IL) curve (specified in IEEE802.3 Annex 69B).
- ILD(f): the difference between the measured and fitted IL.
- The purpose is to be the basis of an ILD quality factor.
- This quality factor is supposed to be a measure of the reflections.
- These may have been sufficient of the 2005 manufacturing and signaling technology but not for today's.



Problems with ILD



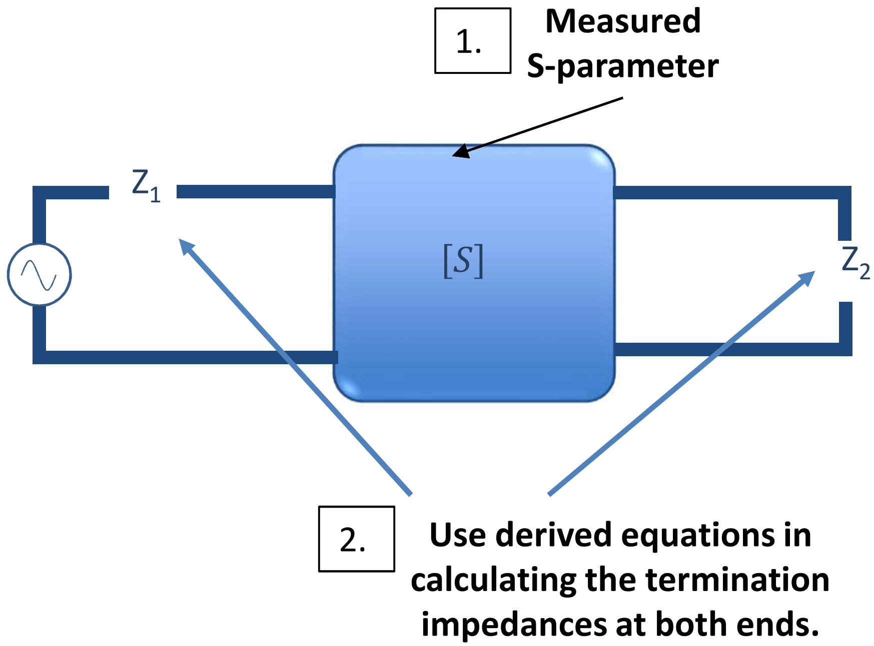


- Fitting at low frequency may have gain.
- This may be caused when skin effect dominates the insertion loss.
- In high frequency ILD(f) may have disproportionate perturbations.
- Reflection loss should always be negative.

Proposal: Reflective insertion loss noise (RILN)

- Reflectionless insertion loss (RIL(f)) is the insertion loss if the component (or DUT) termination is reflectionless at all frequencies.
- Reflective insertion loss noise (RILN(f)) is the insertion loss noise only due to the reflection and not the material (heat) loss of the component.

Zeroing out of reflections at both ends



$$\begin{aligned}&\widehat{\rho_1}^2\left(\widetilde{Z_1}^*\right)(-S_{11}+S_{11}S_{22}S_{22}^*-S_{12}S_{21}S_{22}^*)+\\&\widehat{\rho_1}\left(\widetilde{Z_1}^*\right)(1+S_{11}S_{11}^*+S_{11}S_{22}S_{12}^*S_{21}^*-S_{12}S_{21}S_{12}^*S_{21}^*-\\&S_{11}S_{22}S_{11}^*S_{22}^*+S_{12}S_{21}S_{11}^*S_{22}^*-S_{22}S_{22}^*)+\\&+(-S_{11}^*-S_{22}S_{12}^*S_{21}^*+S_{22}S_{11}^*S_{22}^*)=0\end{aligned}$$

$$\begin{aligned}&\widehat{\rho_2}^2\left(\widetilde{Z_2}^*\right)(-S_{22}+S_{22}S_{11}S_{11}^*-S_{12}S_{21}S_{11}^*)+\\&\widehat{\rho_2}\left(\widetilde{Z_2}^*\right)(1+S_{22}S_{22}^*+S_{11}S_{22}S_{12}^*S_{21}^*-S_{12}S_{21}S_{12}^*S_{21}^*-\\&S_{11}S_{22}S_{11}^*S_{22}^*+S_{12}S_{21}S_{11}^*S_{22}^*-S_{11}S_{11}^*)+\\&+(-S_{22}^*-S_{11}S_{12}^*S_{21}^*+S_{11}S_{11}^*S_{22}^*)=0\end{aligned}$$

This will lead to two solutions for $\widehat{\rho_1}\left(\widehat{Z_1}\right)$ and $\widehat{\rho_2}\left(\widehat{Z_2}\right)$ and the right solution is chosen based on the requirement that $\left|\widehat{\rho_1}\left(\widehat{Z_1}\right)\right| < 1$ and $\left|\widehat{\rho_2}\left(\widehat{Z_2}\right)\right| < 1$ given the real part of the impedance is to be positive. By knowing the reflection coefficient the corresponding impedance can be found.

And the Answer is…

- **Insert the two solutions to determine reflectionless insertion loss (RIL(f))**

$$RIL(f) = S21' = \frac{\left(\dfrac{1-\widehat{\rho_1}^*\left(\widehat{Z_1}^*\right)}{\left|1-\widehat{\rho_1}\left(\widehat{Z_1}^*\right)\right|}\sqrt{\left|1-\widehat{\rho_1}\left(\widehat{Z_1}^*\right)\widehat{\rho_1}^*\left(\widehat{Z_1}^*\right)\right|}\right)^*}{\dfrac{1-\widehat{\rho_2}^*\left(\widehat{Z_2}^*\right)}{\left|1-\widehat{\rho_2}\left(\widehat{Z_2}^*\right)\right|}\sqrt{\left|1-\widehat{\rho_2}\left(\widehat{Z_2}^*\right)\widehat{\rho_2}^*\left(\widehat{Z_2}^*\right)\right|}} \cdot$$

$$\frac{(S_{21})\left(1-\widehat{\rho_2}\left(\widehat{Z_2}^*\right)S_{22}\right)+\left(S_{22}-\widehat{\rho_2}^*\left(\widehat{Z_2}^*\right)\right)\left(\widehat{\rho_2}\left(\widehat{Z_2}^*\right)S_{21}\right)}{\left(1-\widehat{\rho_2}\left(\widehat{Z_2}^*\right)S_{22}\right)\left(1-\widehat{\rho_1}\left(\widehat{Z_1}^*\right)S_{11}\right)-\widehat{\rho_1}\left(\widehat{Z_1}^*\right)\widehat{\rho_2}\left(\widehat{Z_2}^*\right)S_{12}S_{21}}$$

See paper for details…

What is RILN?

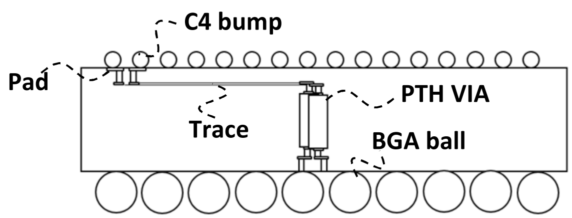
- **RILN(f): reflective insertion loss noise**
  - **Compute <u>reflectionless insertion loss (RIL(f))</u> by zeroing out the reflections at both ports of the network.**
  - **Subtract <u>reflectionless insertion loss (RIL(f))</u> from the <u>measured insertion loss (IL(f))</u>.**
- **ILD(f) vs. RILN(f): a mathematical fitting vs. a physics context by zeroing out reflections.**

$$RILN(f) = IL(f) \quad RIL(f)$$

“Find termination impedances for zero return loss at both ends”

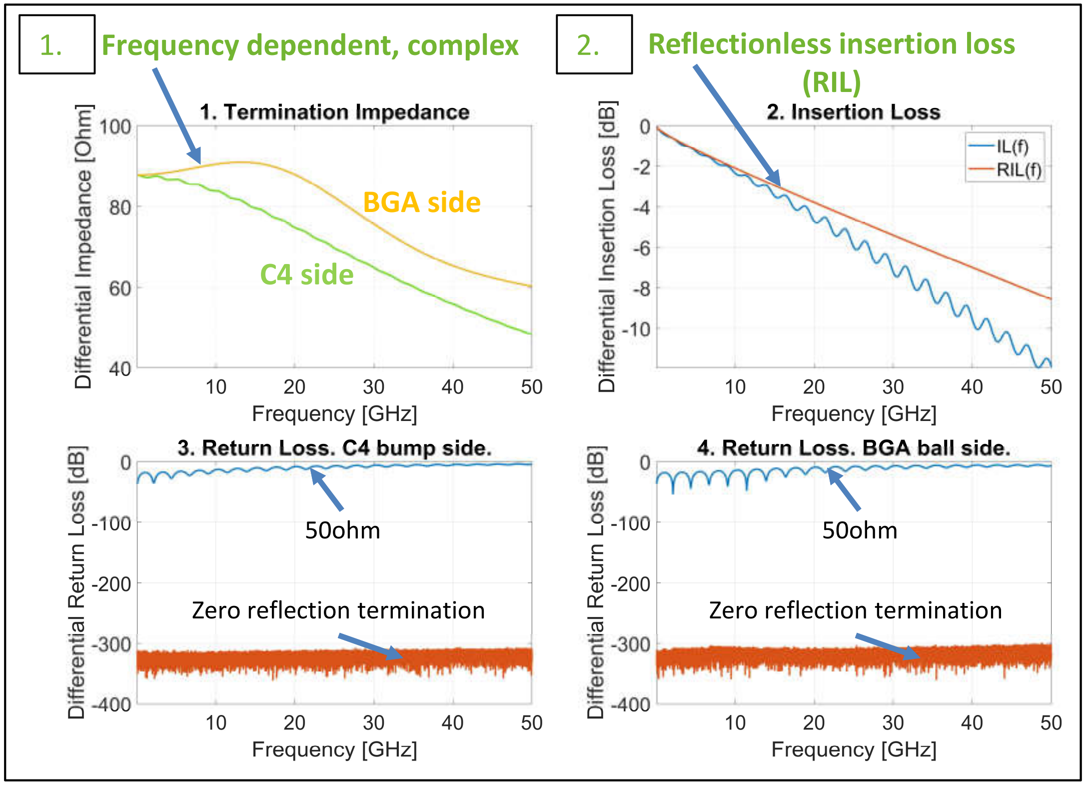
- **Frequency dependent complex impedances**
- **Different values at each end**
- **Zero return loss (renormalized)**

Verification on zeroing out the reflections



- Trace length/Zo – 30mm/ 87.5 Ω
- PTH – 1.8mm/ 92.5 Ω
- 110 *fF* C4 bump & 80 *fF* BGA ball

- **Reference package model defined by the IEEE 802.3 specification.**
- **Possible to dissect loss and reflections from a measured S-parameter insertion loss.**
- **This will help to partition the loss and reflections.**



What is FOM_{RILN}?

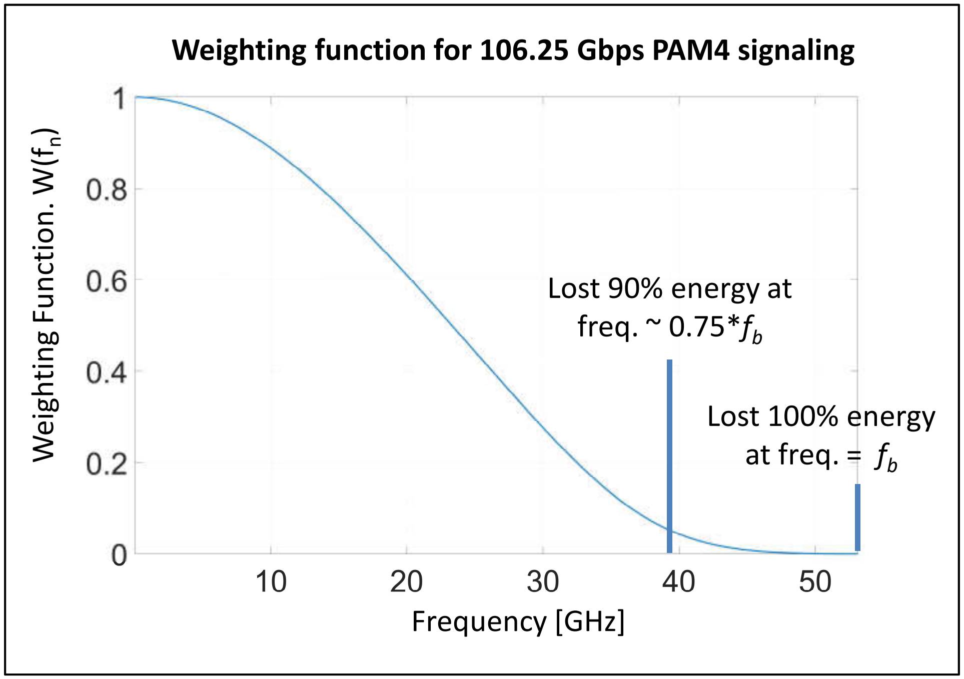
- **Defined FOM_{RILN} similar to FOM_{ILN} to quantify the reflections at a data rate.**
- **Quality factor for the amount of reflections.**
- **Integration of RILN(f) over frequency by using a weighting function $W(f_n)$.**
- **Unit: decibel [dB].**

$$FOM_{RILN} = \left[\frac{1}{N}\sum_{n} \underbrace{W(f_n)}_{Unitless}\ \underbrace{RILN^2(f_n)}_{dB^2}\right]^{1/2}$$

dB

What is weighting function?

- **Weighting function $W(f_n)$: the power spectral density of a digital transmission with the signalling rate (f_b).**
- **Weighting function $W(f_n)$ represents**
  1. **The power spectral density of Random Bit Sequence $\left(sinc^2(f_n/f_b)\right)$.**
  2. **Transmitter output bandwidth derived from the rise and all time $\left(\frac{1}{(1+(f_n/f_t))^4}\right)$.**
  3. **Receiver noise filter bandwidth $\left(\frac{1}{(1+(f_n/f_r))^8}\right)$.**
- **Representation of signaling condition with sinc², TX filter & RX filter.**



Example: IEEE 802.3cd Mated Test Fixture

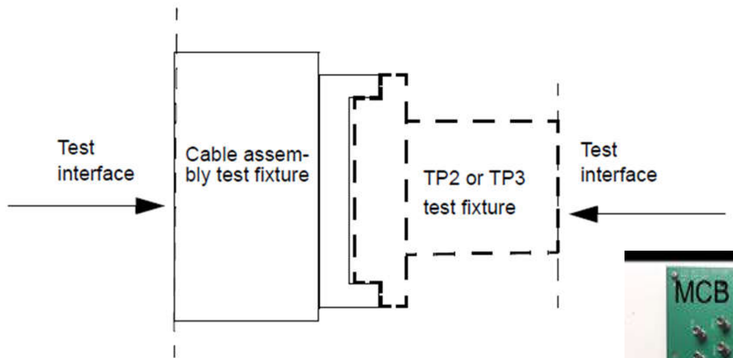
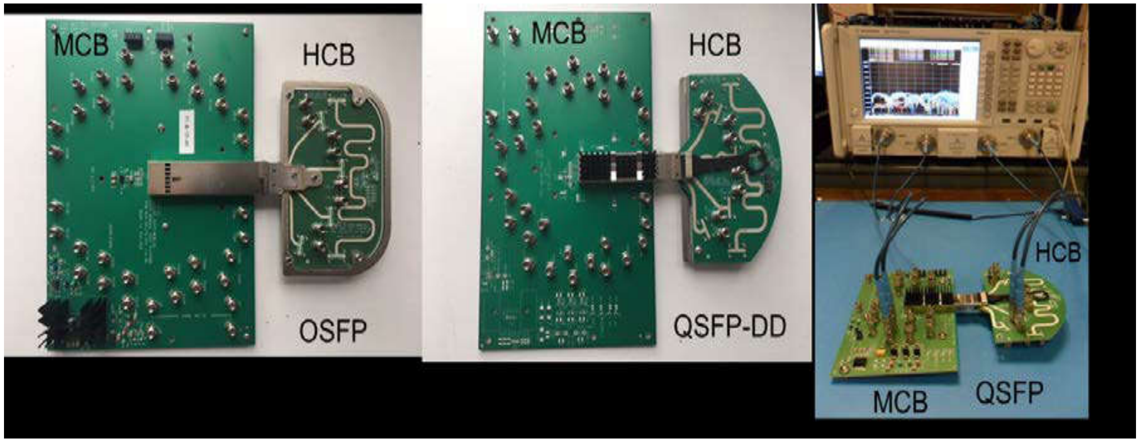


Figure 92–18—Mated test fixtures

MCB= Module Compliance Board
HCB= Host Compliance Board



"Practical Implementation of Testing 50-Gbps per Lane Effective Return Loss (ERL)", DiMinico et al., DesignCon 2019

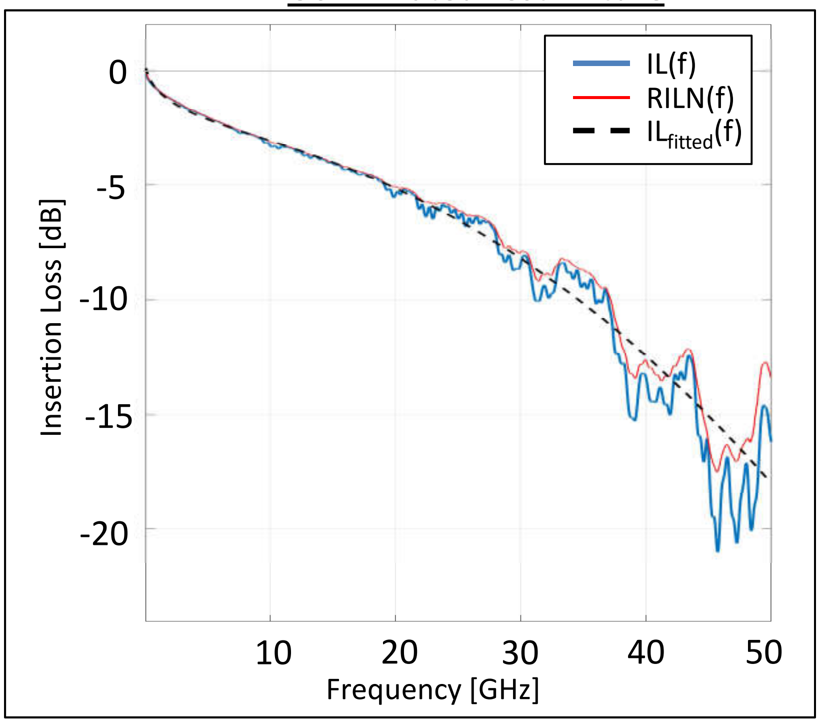
FOM_{RILN} Contrasted to FOM_{ILD}

- IEEE 802.3cd copper twin axial cable specification uses FOM_{ILD}.
- The example will contrast of FOM_{RILN} to FOM_{ILD} for mated test fixture (MTF) in accounting for reflections.

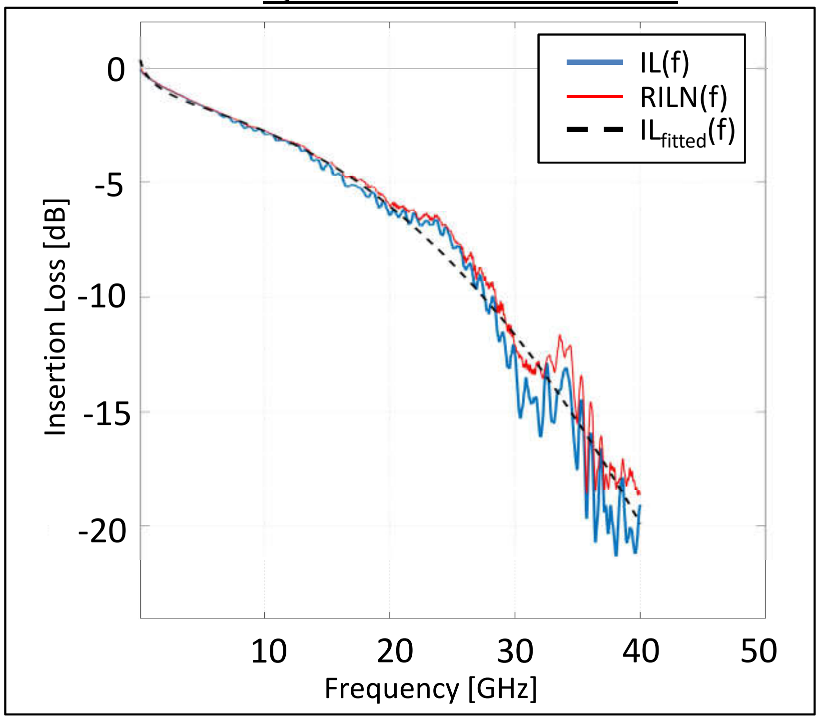
OSFP and QSFP28 MTF evaluation for reflections

Contrast between IL, fitted IL and RIL

1. OSFP Mated Test Fixture



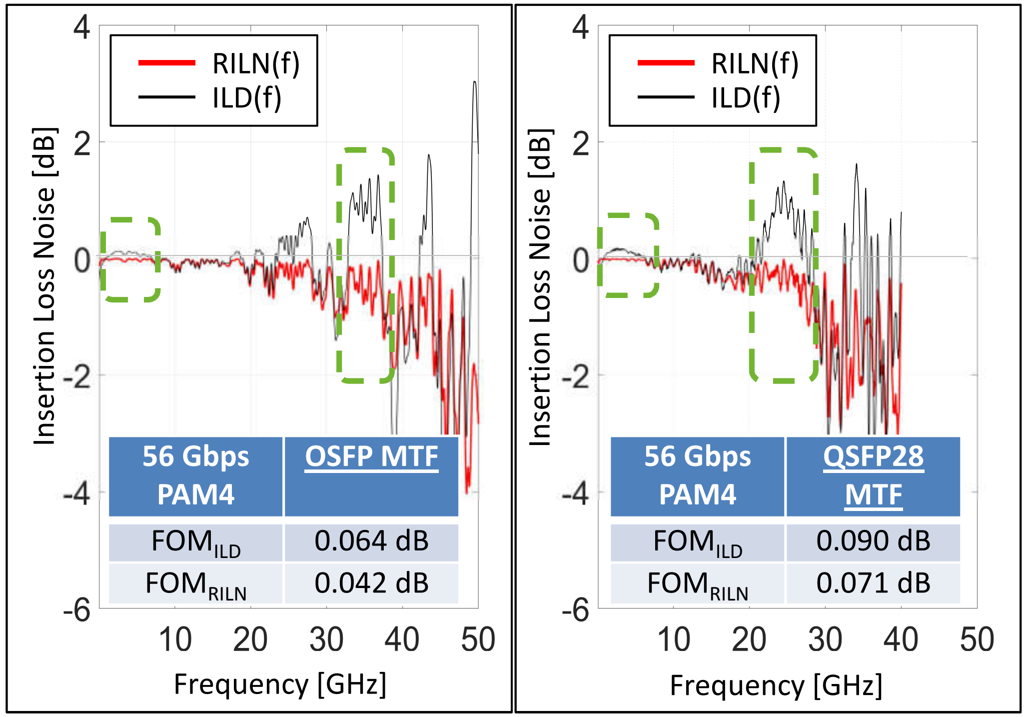
2. QSFP28 Mated Test Fixture



OSFP and QSFP28 MTF evaluation for reflections

- **ILD(f)**
  - **ILD(f) predicts high noise in low and high frequency region.**
  - **ILD(f) has positive and negative dB values.**
- **RILN(f)**
  - **RILN(f) has only negative dB values.**
  - **RILN(f) has more physics context.**

RILN(f) vs. ILD(f)

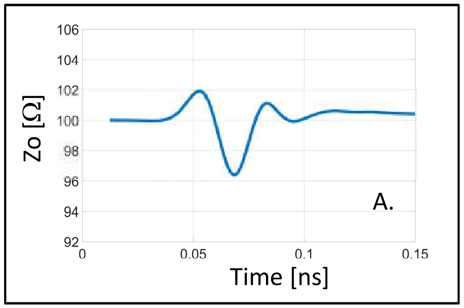


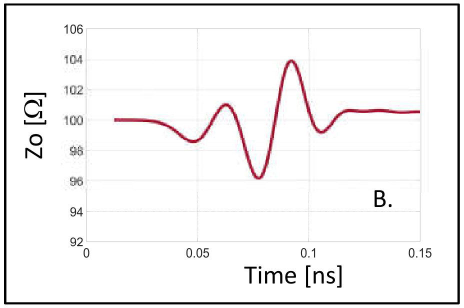
Example: Via Optimization for Reflections

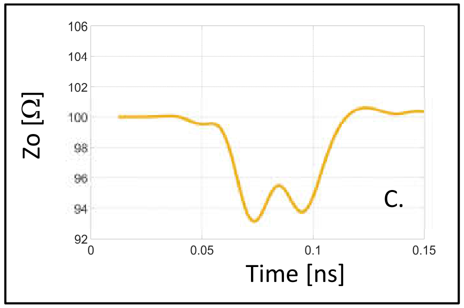
- **Component level (via or connector) optimization involves return loss (RL) and time domain reflectometry (TDR) verification.**
- **RL and TDR are not tied to a data rate.**
- **Pulse response shows very minor differences.**
- **This example shows that FOM_{ILD} does not correlate with via optimization pertaining to lower reflections while FOM_{RILN} does correlate.**

Via optimization using FOM_{RILN} quality metric

TDR plot



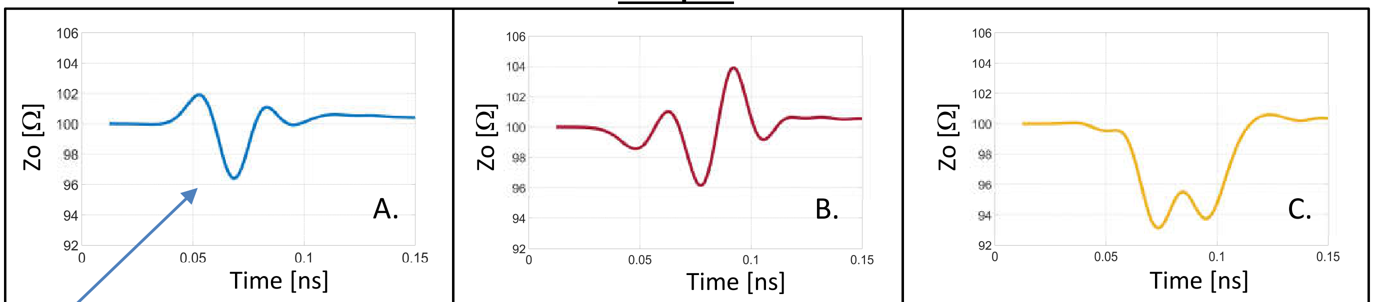




- **The above three via optimizations are evaluated for reflections.**
  - **Compare FOM_{RILN} and FOM_{ILD} for 25, 56 and 106.25 Gbps PAM4 data rate.**

Via optimization using FOM_{RILN} quality metric

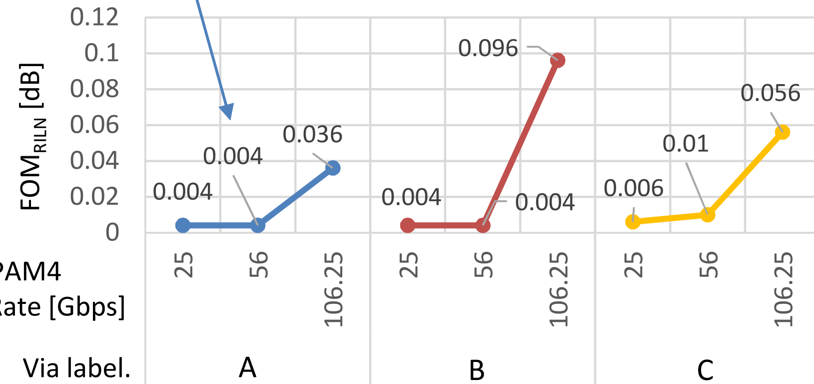
TDR plot



1.

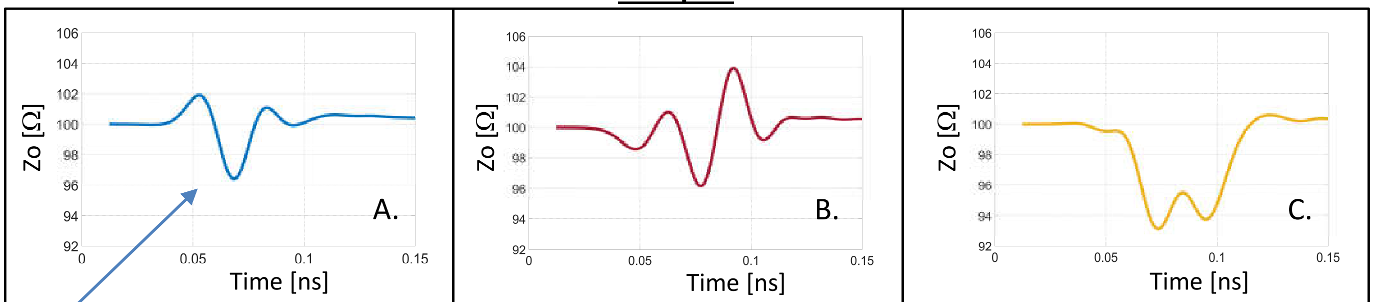
Via A appears to have relatively lower reflections

FOM_{RILN} vs. data rate



Problem with FOM_{ILD}

TDR plot



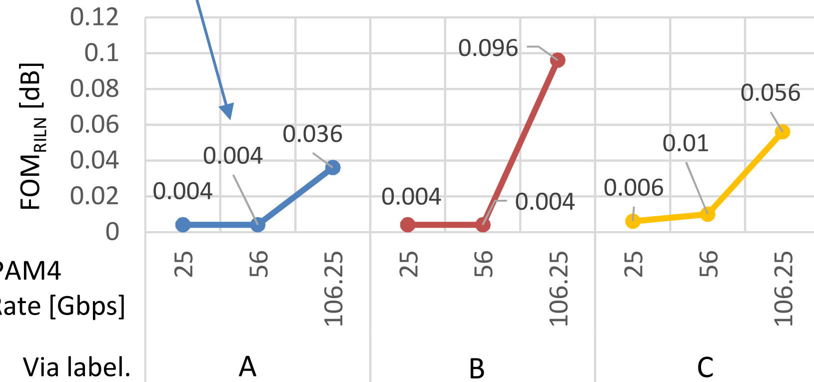
1.

Via A appears to have relatively lower reflections

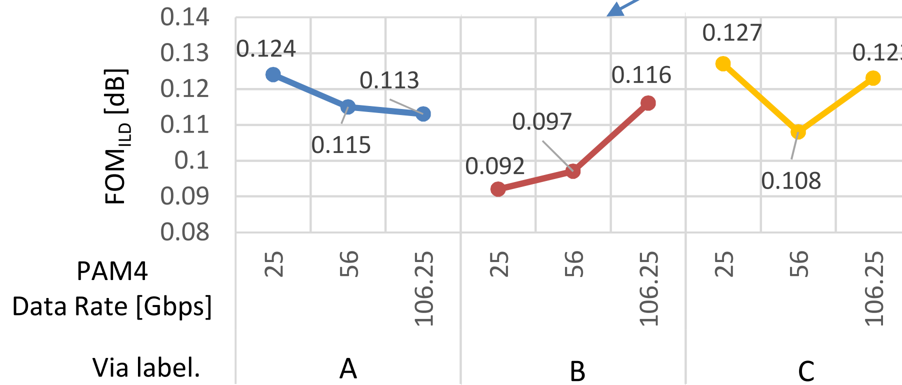
2.

FOM_{ILD} does not trend well with data rate

FOM_{RILN} vs. data rate



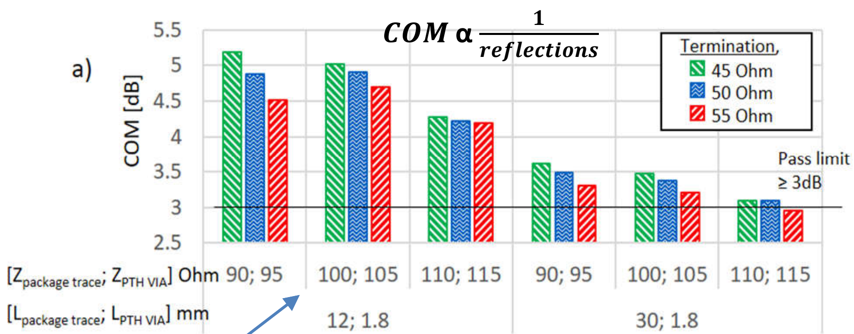
FOM_{ILD} vs. data rate

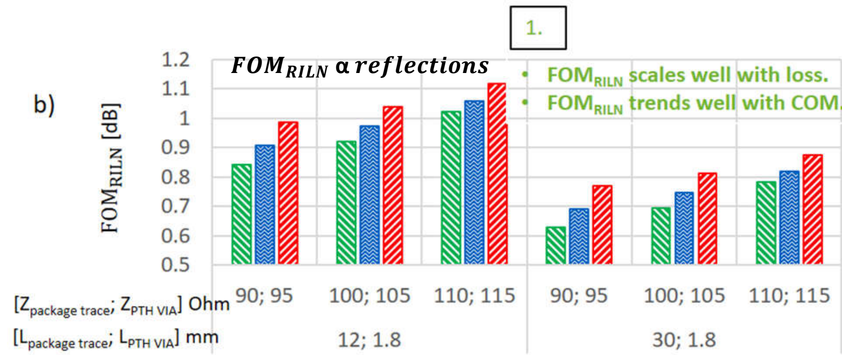


FOM_{RILN} correlation to COM

FOM$_{RILN}$ correlation to COM

Cabled BP Channel, 106.25 Gbps PAM4





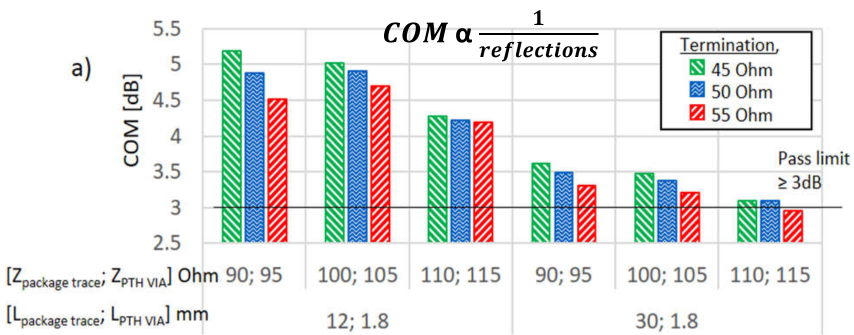
Varied the following.

1. **Package trace length: 12mm and 30mm**
2. **Package trace impedance: 90, 100 and 110 Ohm**
3. **PTH impedance: 95, 105, 115 Ohm**
4. **On-die resistive termination: 45, 50 and 55 Ohm**

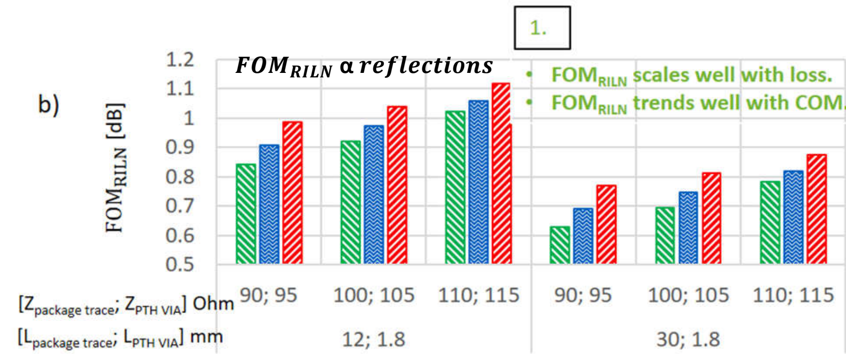
Problem with FOM_{ILD}

Cabled BP Channel, 106.25 Gbps PAM4

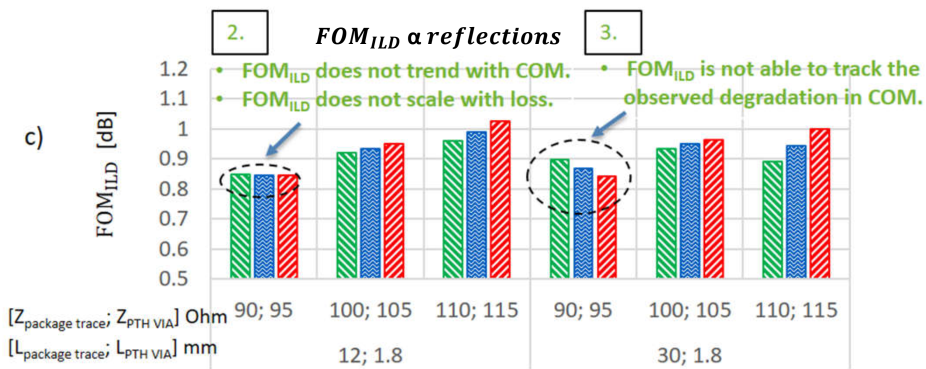
a)



b)



c)



Summary

- A methodology which finds termination impedances for zero return loss at both ends.
- Reflectionless Insertion Loss (RIL(f)) and Reflective Insertion Loss Noise (RILN(f)) are closed form equations.
- Introduced a quality factor called the figure of merit of reflective Insertion Loss Noise (FOM_{RILN}) to quantify reflections as a function of data rate.
- Application show promise for the evaluation of reflections based on experiments.
    i. IEEE802.3 reference package
    ii. IEEE 802.3cd mated test fixtures
    iii. PCB VIA optimizations
- RILN(f) & FOM_{RILN} are better quality factors for DUT reflections compared to ILD(f) & FOM_{ILD}.
- FOM_{RILN} tracks COM.

Take away

- This is a reasonable method to specify small components.
- Single value quality metric.

Thank you!

QUESTIONS?