Effects of PCB Technological Features on Channel Operating Margin (COM)

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Abstract

The coupling (weak vs. strong) in edge-coupled differential transmission lines on a printed circuit board (PCB) affects frequency behavior of mixed-mode S-parameters. Slightly imbalanced stripline differential pairs are considered with various technological features modeled: rectangular vs. trapezoid shape of a signal trace cross-section; copper foil roughness; and presence of an epoxy-resin " pocket " (EP) between the stripline traces (dielectric properties of the EP are different from the homogenized parameters of the ambient dielectric where these traces are embedded. The quality of the differential mode (DM), which determines SI, is associated with the frequency dispersion and loss on the line. The common mode (CM) is inevitable on differential pairs. The study is carried out using full-wave simulation and corroborated with measurement. After the differential pairs are examined, the model is used for the calculation of COM. Channel Operating Margin (COM) is an efficient method to evaluate high speed interconnects. Effects of PCB technologies on COM are studied with a 1000GBASE-KP4 link. The pulse responses of COM are validated by comparing to circuit simulations.

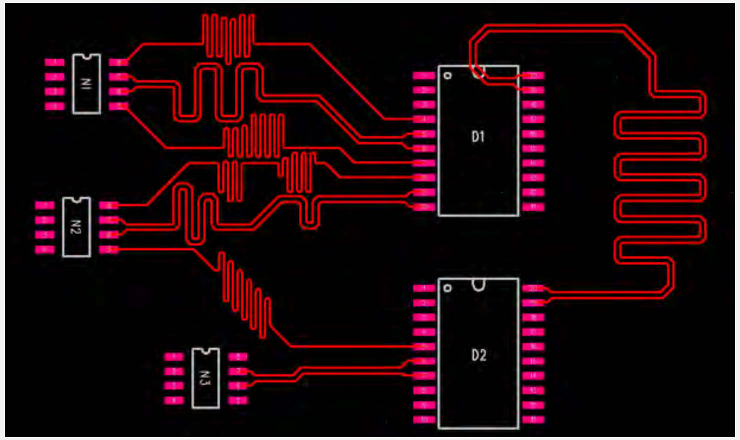
Outline

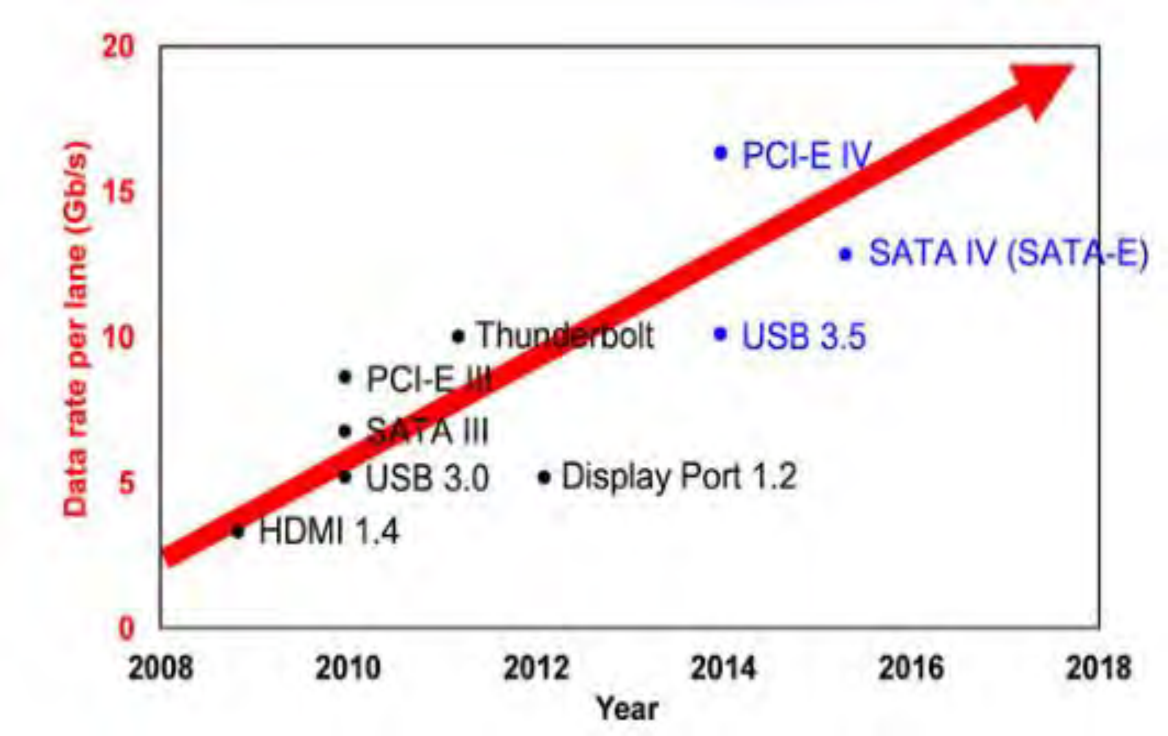
This is a two-step presentation. The first step (see below). The second step is a calculation of the COM with the same features.

The first step overview:

- ❖Motivation
- ❖What do you mean by “Technological Features”
  - ❖Discuss the features of interest
- ❖Simulated results (focus on mode conversion)
- ❖Measured results

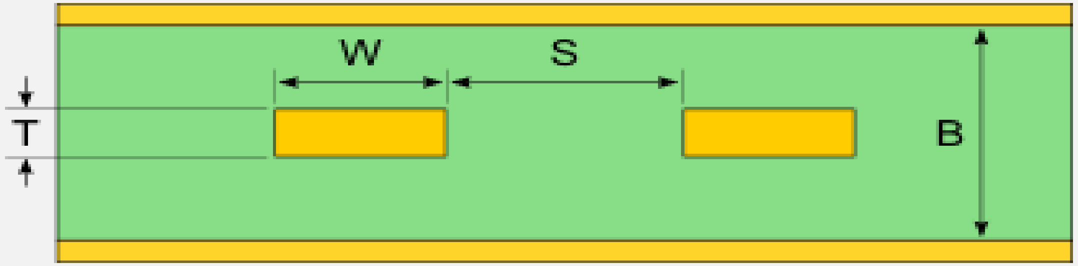
Motivation

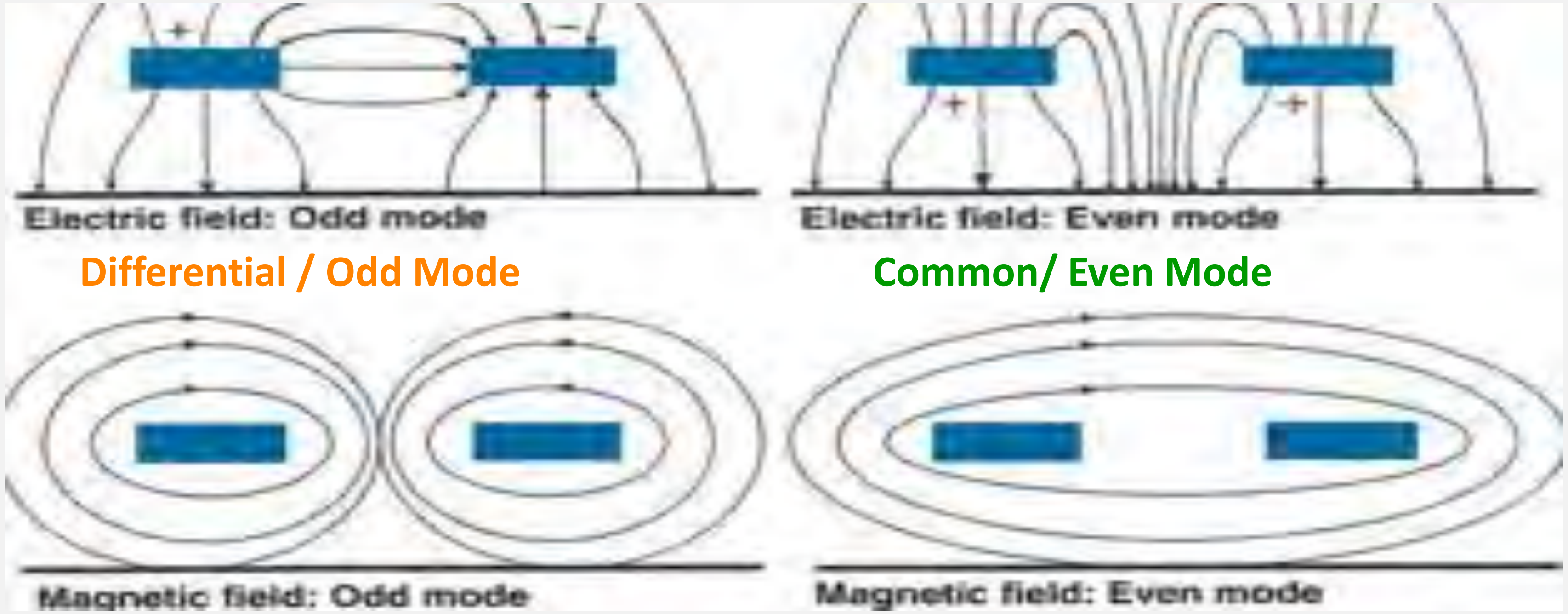




- Differential signaling plays an important part in high-speed digital design due to their high immunity, low X-talk, and potentially reduced EMI problems.
- Currently, high-speed serial link interfaces, *e.g.*, USB, Ethernet, InfiniBand, PCI Express, Serial Attached SCSI, operate in the differential signal transmission mode, and have from a few to tens gigabit-per-second data rates.
- Transmission line/net features have an impact on the mode conversion of the signals.

Modes Edge Coupled Stripline

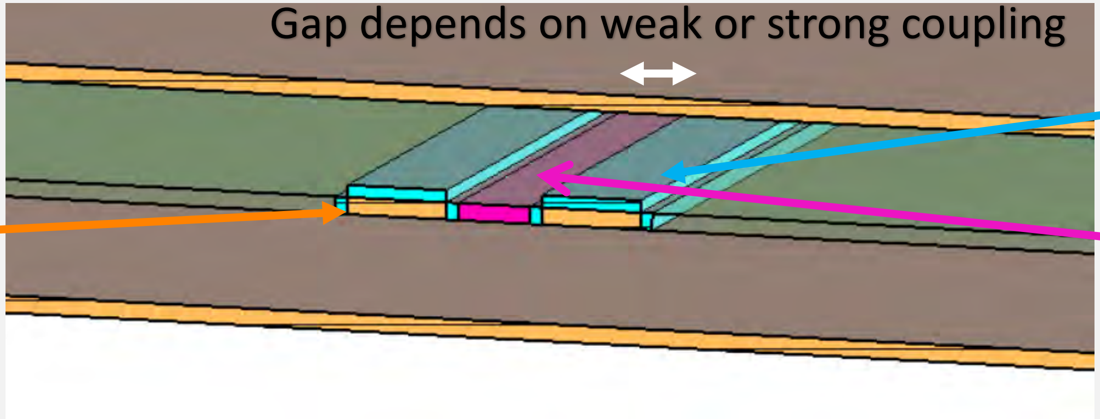




Topological features and material factors on Signal Integrity of differential pair

Stripline edge coupled differential pair were compared for

- Weak and strong coupled case
- Trace shape: Rectangular edge; trapezoid edges of 60 and 45 degrees
- With/without copper foil roughness
- With/without epoxy-resin “pocket”

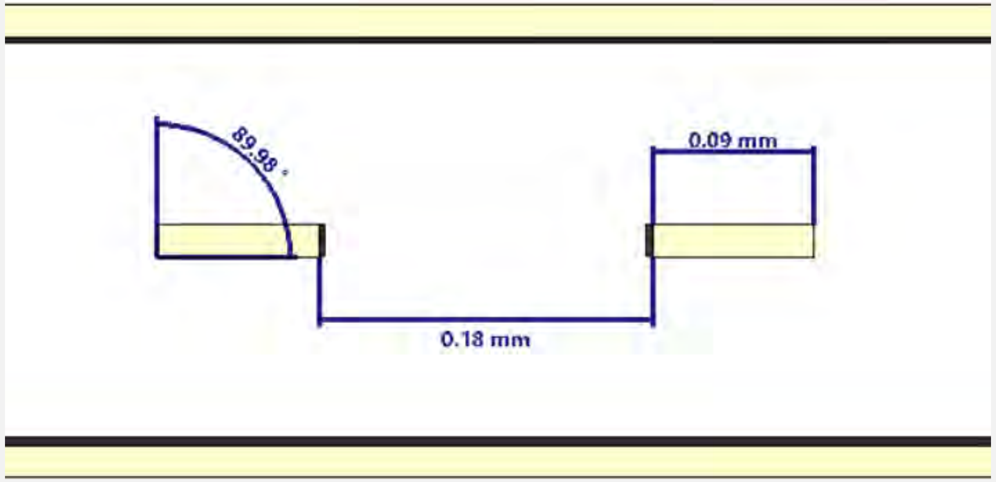


M. Koledintseva, T. Vincent, “Comparison of Mixed-mode S-parameters in Weak and Strong coupled Differential Pairs”. Conference: 2016 IEEE International Symposium on Electromagnetic Compatibility - EMC 2016

Strong vs Weak coupling metric

Weak coupled: Zdiff = 97.44, Zcom = 26.11 K= - 0.034

Strong coupled: Zdiff = 83.22, Zcom = 25.48, K= - 0.096



Example: Weak coupled

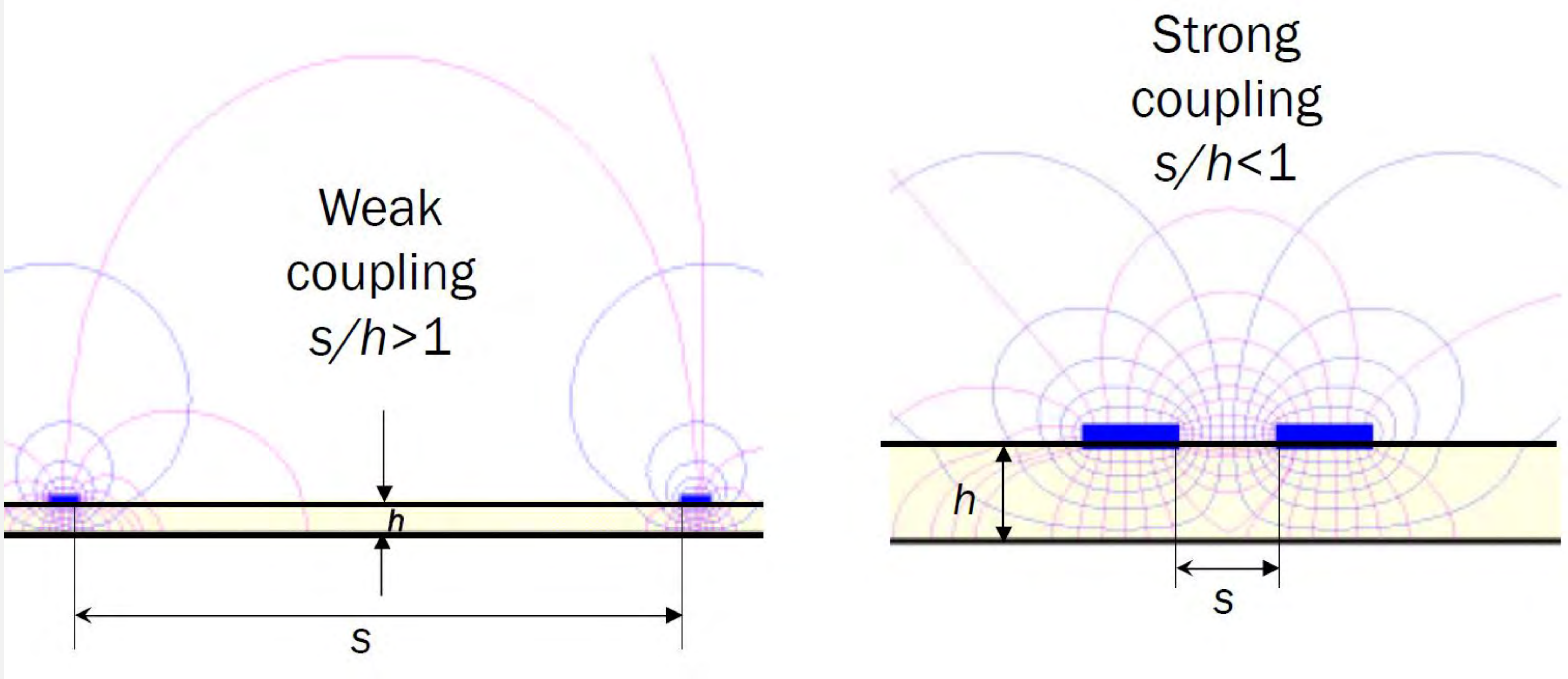
Zdiff = 2Zodd = 2Zse(1-K)

Zcom = Zeven/2=(Zse/2)(1+K)

Zdiff + 4*Zcom = 97.44+4*26.11 = 201 = 4*Zse. **Zse=50.47**

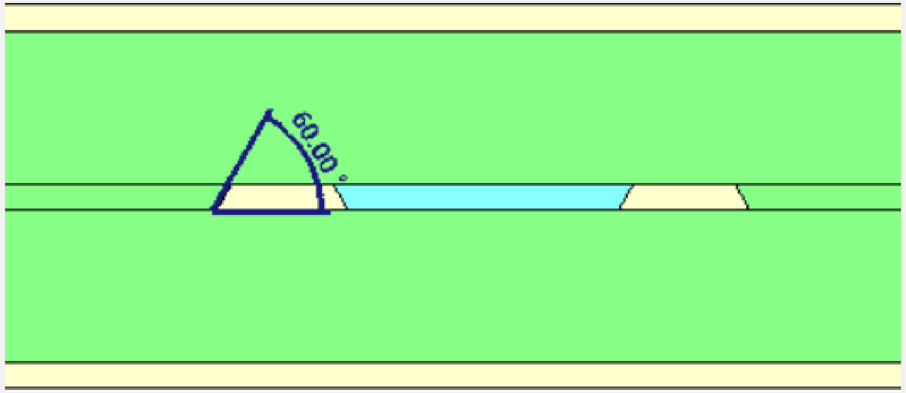
Zdiff + 4*Zcom = 83.22+4*25.48 = 185.14 = 3*Zse. **Zse=46.285**

Weak and strong coupling

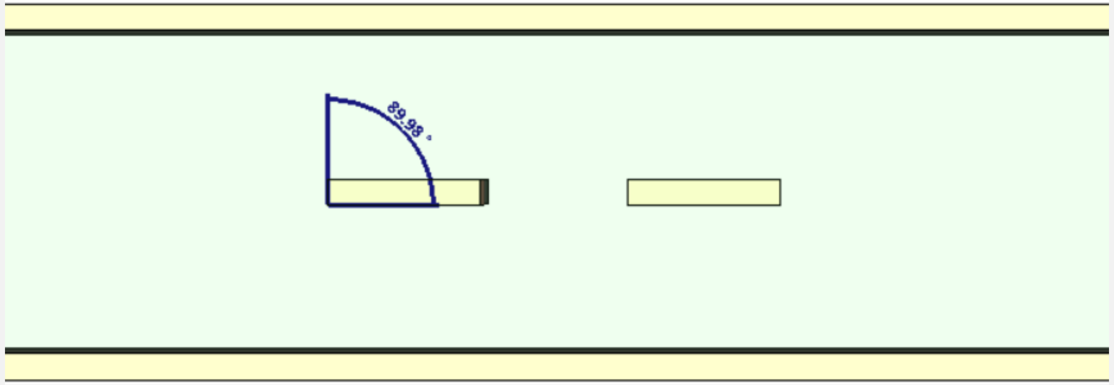


Trace edge shapes

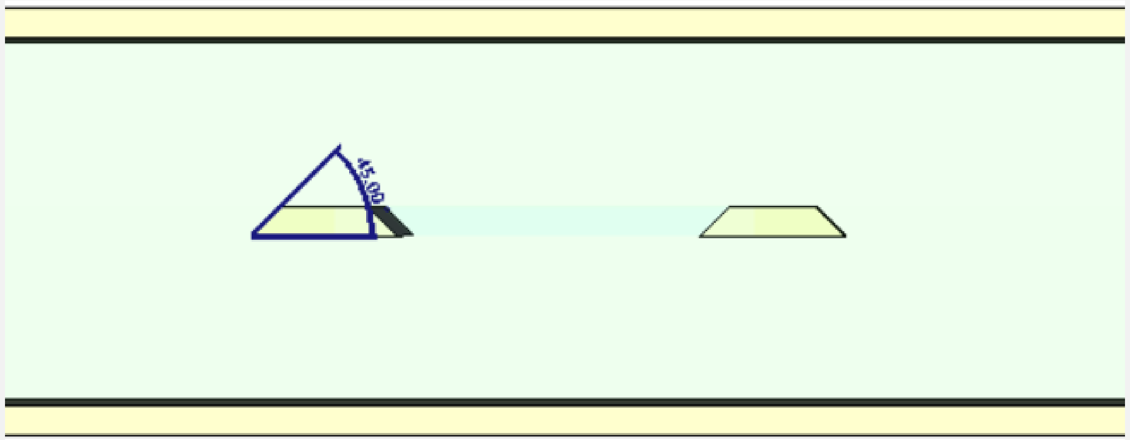
Cross section views from models showing trapezoid shape.



60 degree edge. Weak coupled, epoxy pocket.



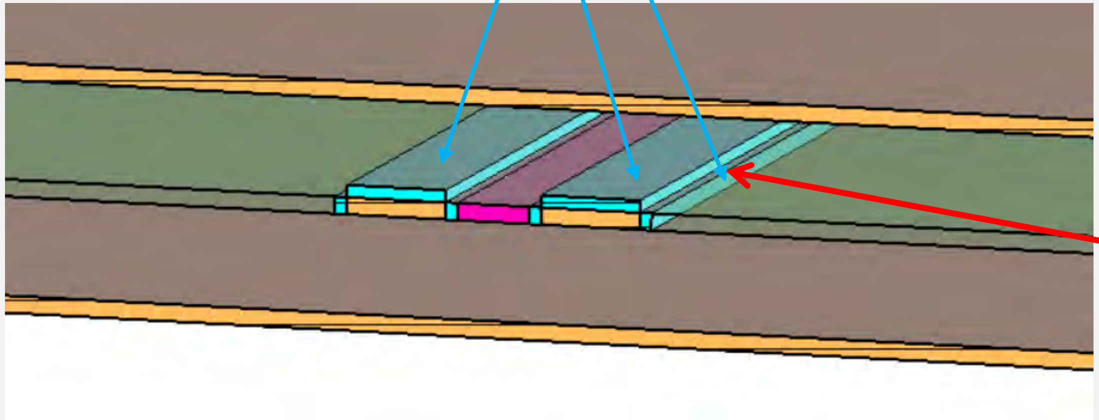
90 degree edge. Strong coupled. No other features included in this model.



45 degree edge. Weak coupled. Epoxy pocket (transparent).

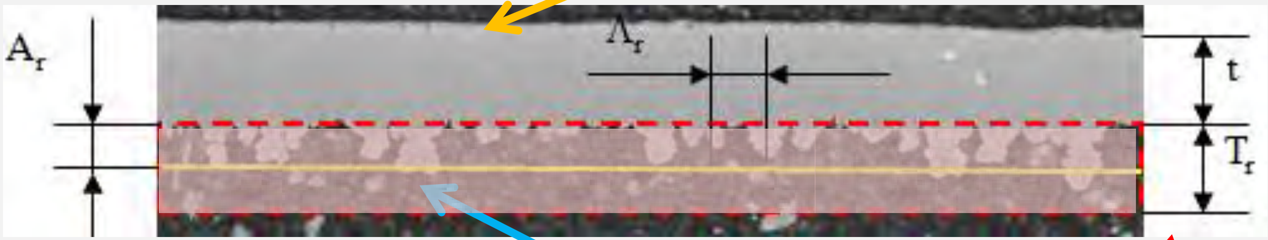
Copper foil Roughness

Surface roughness modelled as dielectric layer on traces



ERD (surface roughness). Strong coupled, rectangle edge, with epoxy pocket.

Drum, or “oxide” side



Matte, or “foil” side

This inhomogeneous interface layer “copper-dielectric” is substituted by ERD

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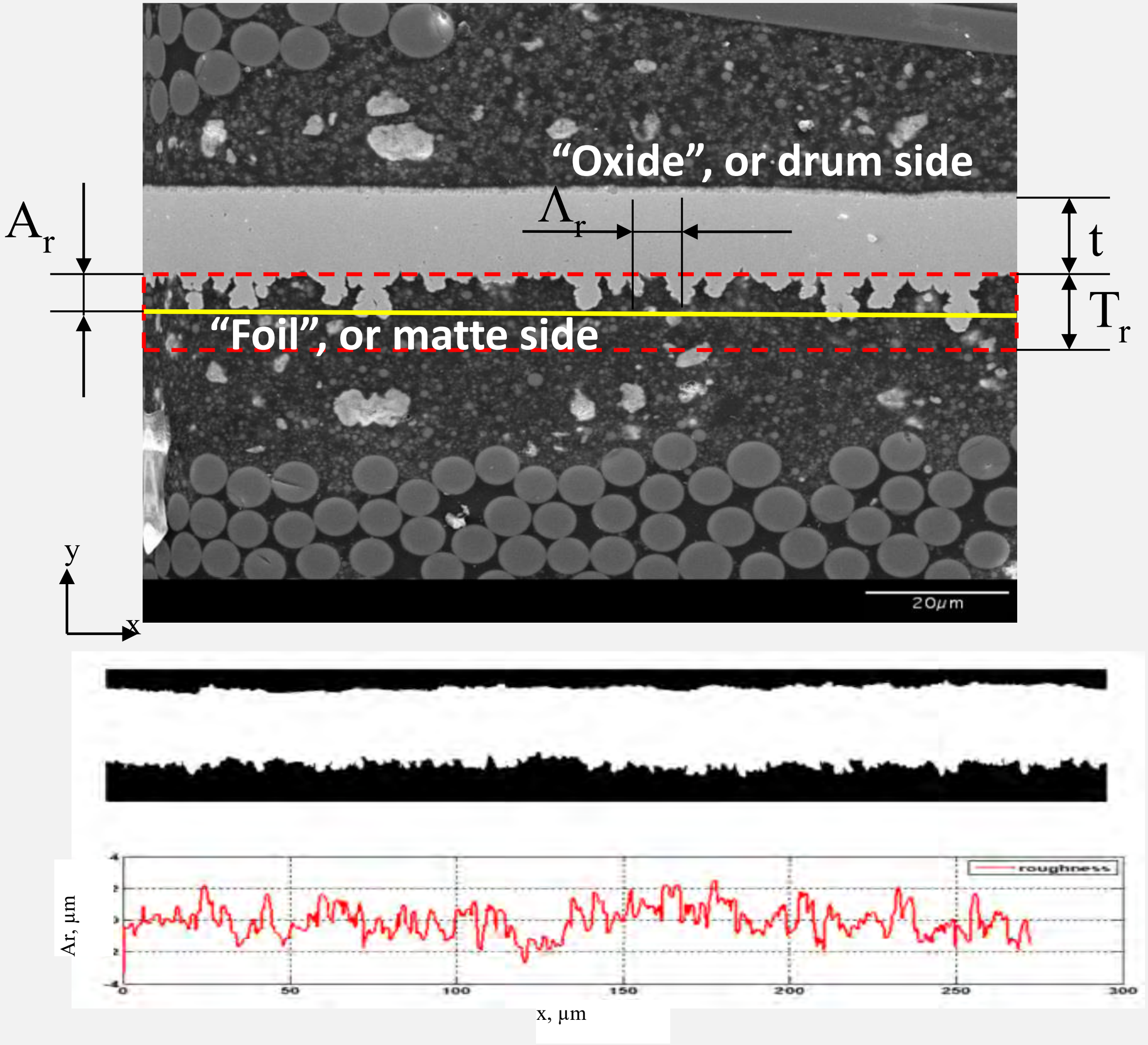
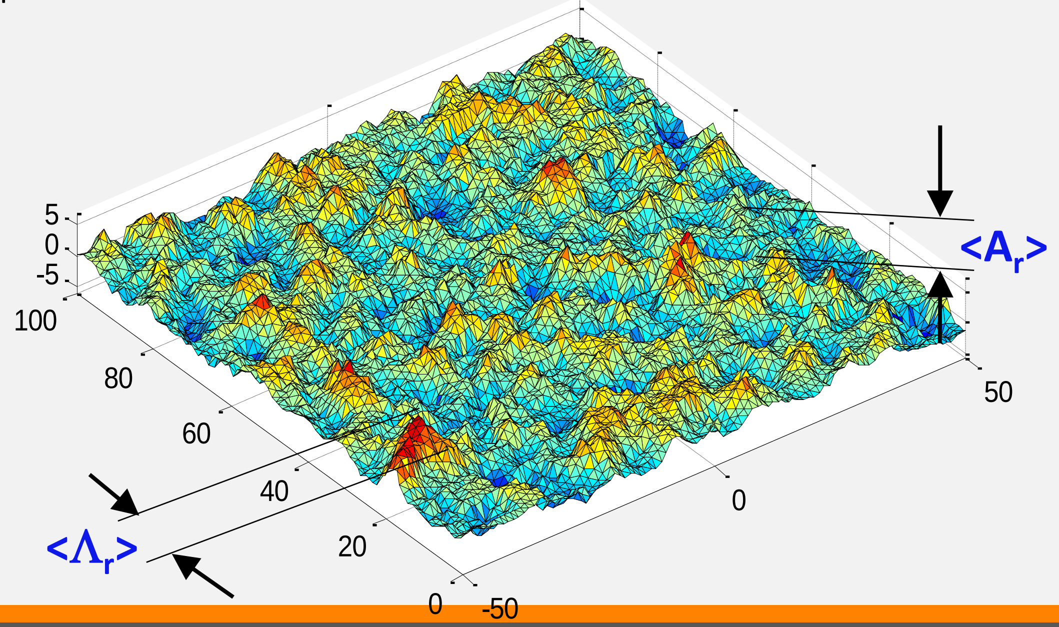
Quantification of Copper Foil Roughness Profiles

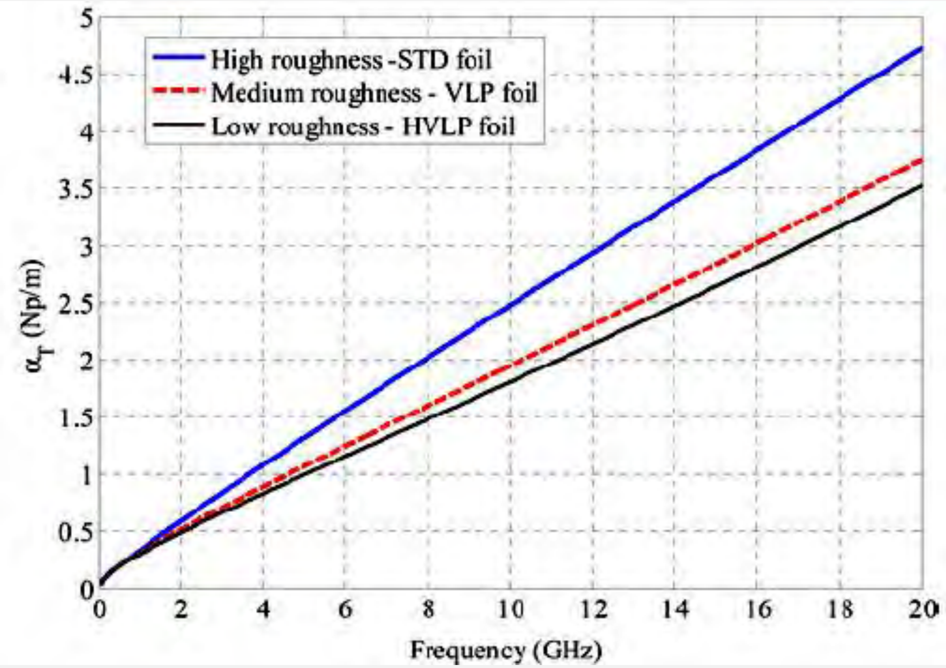


1st look at the surface measurement – and a look at a more sophisticated approach.

A_r- average peak-to-valley roughness amplitude
Λ_r – average quasi-period of roughness
QR – roughness quantification factor, QR~ A_r/Λ_r
t – copper foil thickness (at flat levels)
T_r – height of copper foil roughness layer in a model



Effective Roughness Dielectric (ERD) Parameters Extraction



Reference: Koul, Koledintseva, Hinaga, Drewniak "Differential Extrapolation Method for Separating Dielectric and Rough Conductor Losses in Printed Circuit Boards" IEEE Trans, 2012.

"smooth" conductor contribution/ skin effect

Roughness contribution

Dielectric contribution

$$\alpha_T = a\sqrt{\omega} + b\sqrt{\omega} + c\omega + d\omega^2 + e\omega + f\omega^2$$

a + b = K1 c + e = K2 d + f = K3

- Curve fitting co-efficients are generated K1 ~ $\sqrt{\omega}$, K2 ~ ω, and K3 ~ ω²
- K1(0), K2(0), and K3(0) corresponds with smooth conductor, allow separation of surface roughness loss and dielectric loss. K co-efficients relate to Ar
- Dielectric material (smooth) 3D object with extracted "roughness" parameters can be included in simulation to simulate roughness impact

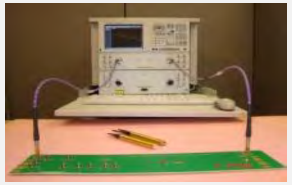
Effective Roughness Dielectric (ERD) Parameters Extraction

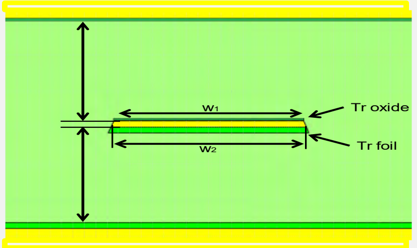
Measurements of S-parameters

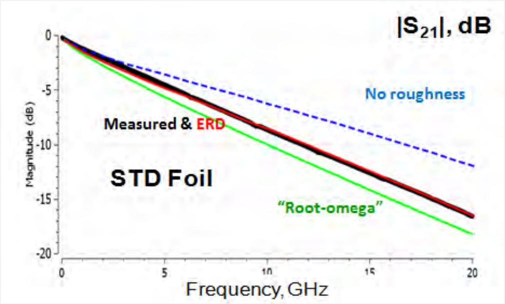
Extraction of true DK and DF of PCB dielectric (*DERM*)

2D-FEM Model

$\varepsilon_{rough} = \varepsilon'_{rough} - j\,\varepsilon''_{rough}$







Criteria for acceptable agreement of measured and modeled S_{21} (both IL & phase)

Satisfied

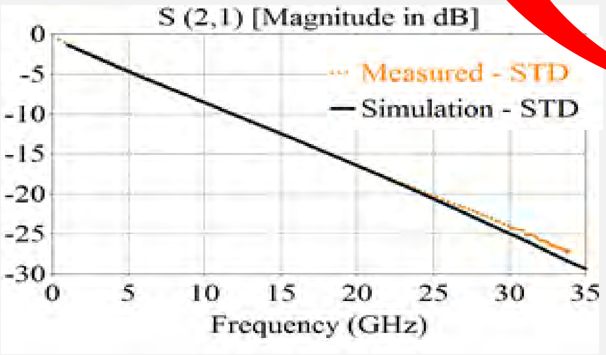
Extracted ERD $\varepsilon_{rough} = \varepsilon'_{rough} - j\,\varepsilon''_{rough}$

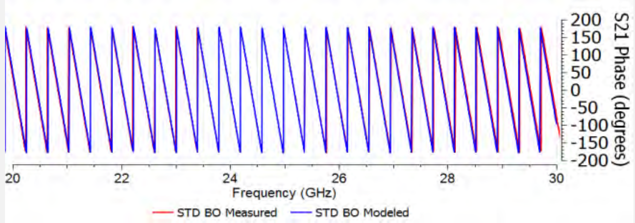
Validation by full-wave simulation

Not satisfied

Correction

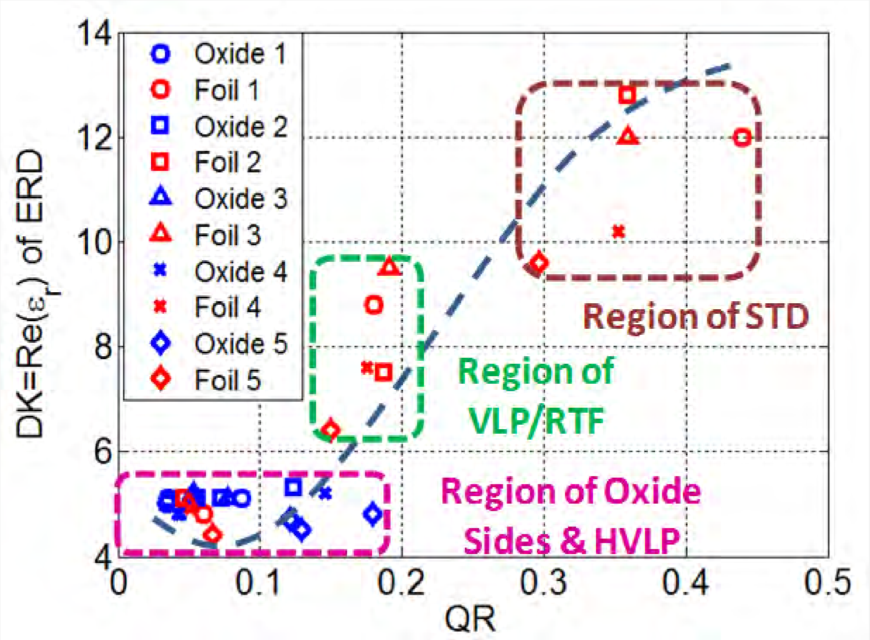
Optimization procedure uses numerical modeling in the loop for fitting S-parameters until measured and modeled results agree within some criteria.



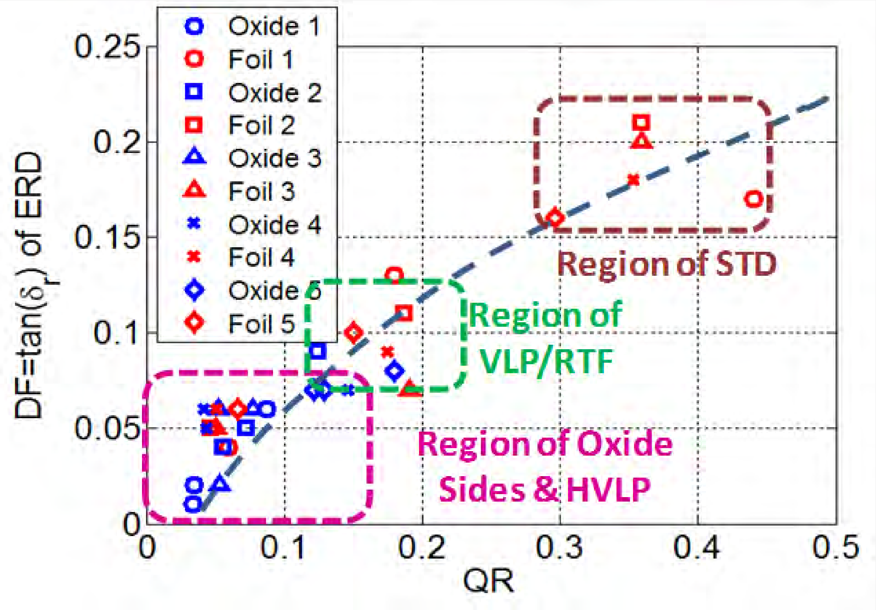


M.Y. Koledintseva, T. Vincent, A. Ciccomancini Scogna, and S. Hinaga, "Method of effective roughness dielectric in a PCB: measurement and full-wave simulation verification", IEEE Trans. Electromag. Compat., vol. 57, no. 4, Aug. 2015, pp. 807-814

Surface Roughness Model used - DERM

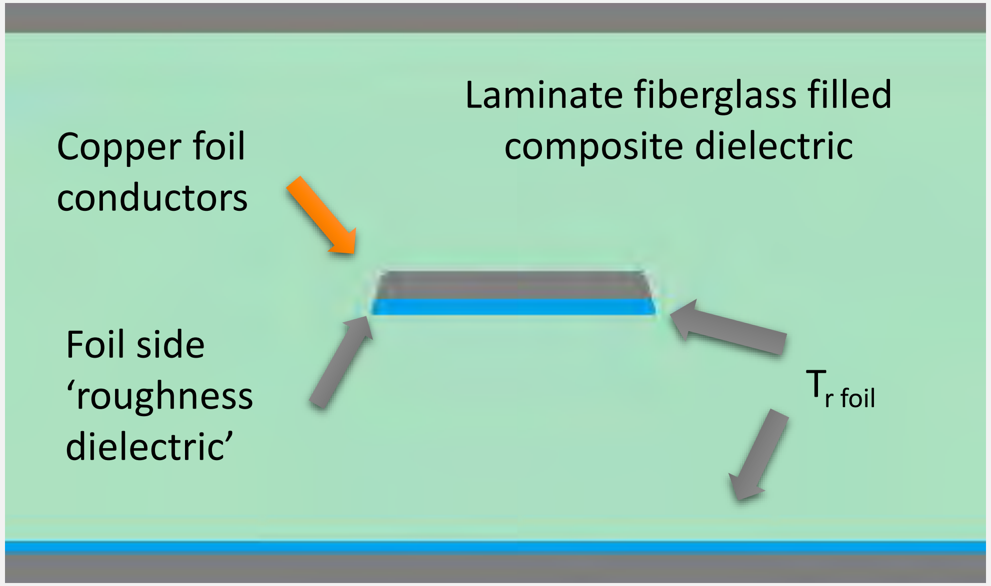


Sets 1,2,3 – **13mil** traces
Sets 4, 5 – **7 mil** traces



Thicknesses of the corresponding roughness dielectric layers in the numerical model are taken as $T_r=2\times A_r$

Simulation – layer of Dielectric

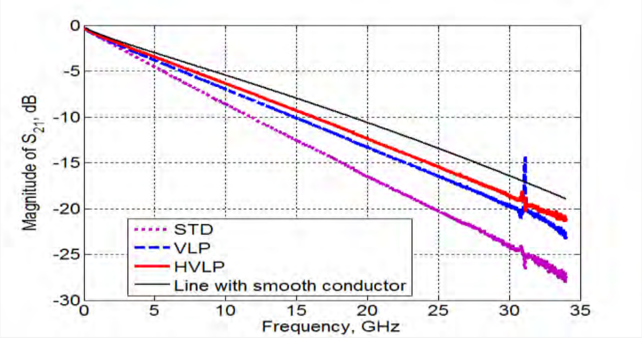


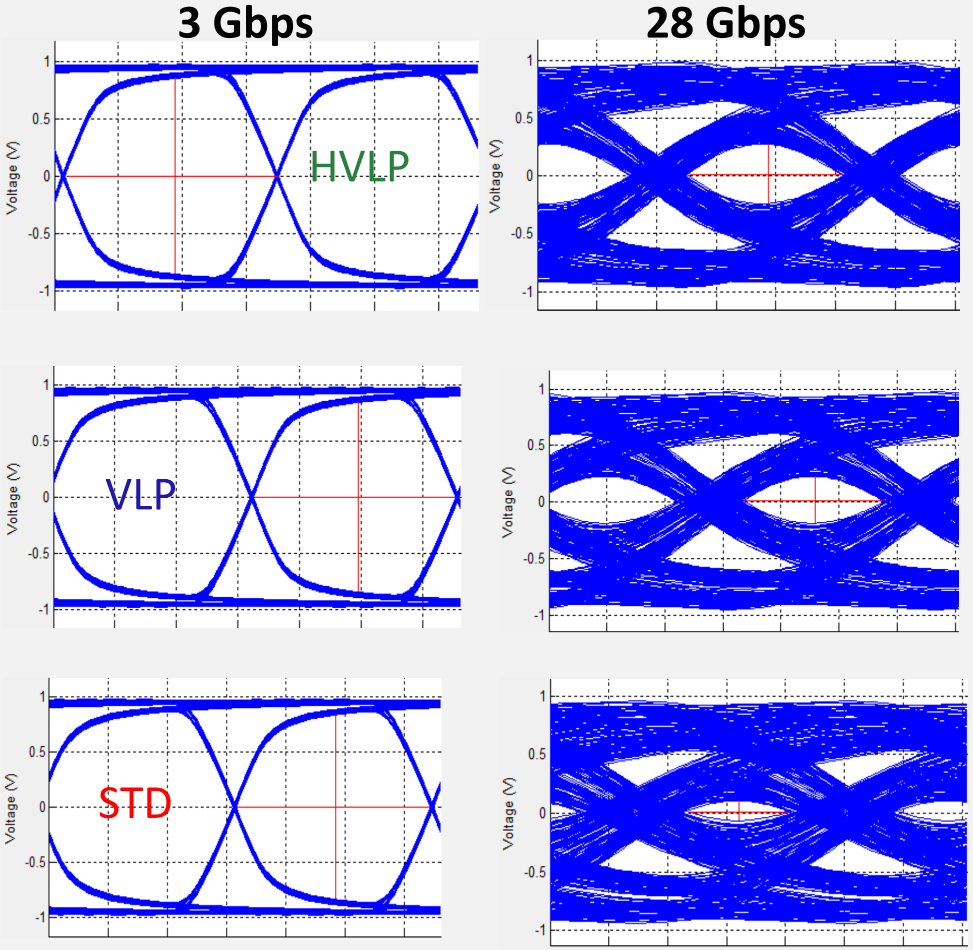
Cross section view - Not to scale for presentation purposes only

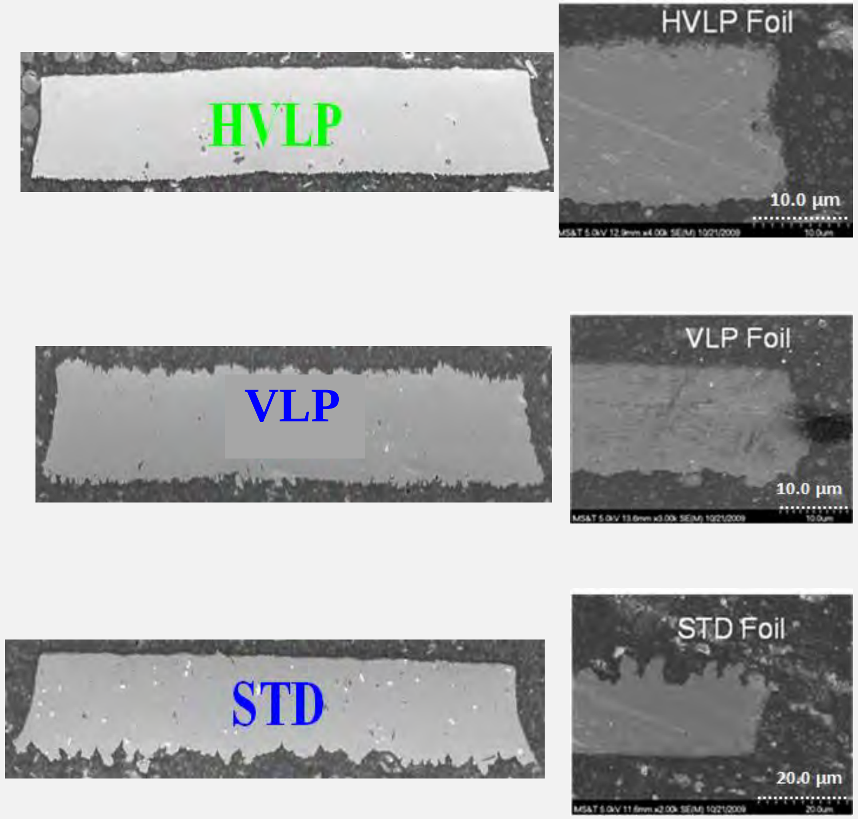
- Laminate dielectric parameters are extracted from DERM2 (for both α and β).
- Heights of ERD $T_{r\ foil}$ are taken $2A_{r\ foil}$, respectively.
- Line length for this model = 15,410 mils

Conductor Roughness in Single-Ended Lines

Conductor roughness affects both phase and loss constants in PCB transmission lines and results in eye diagram closure, especially at bit rates > 10 GBps.

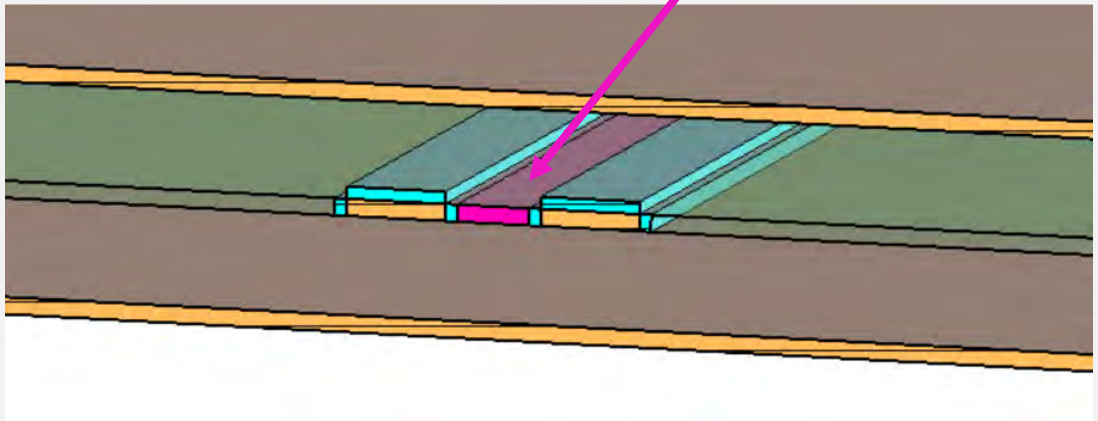




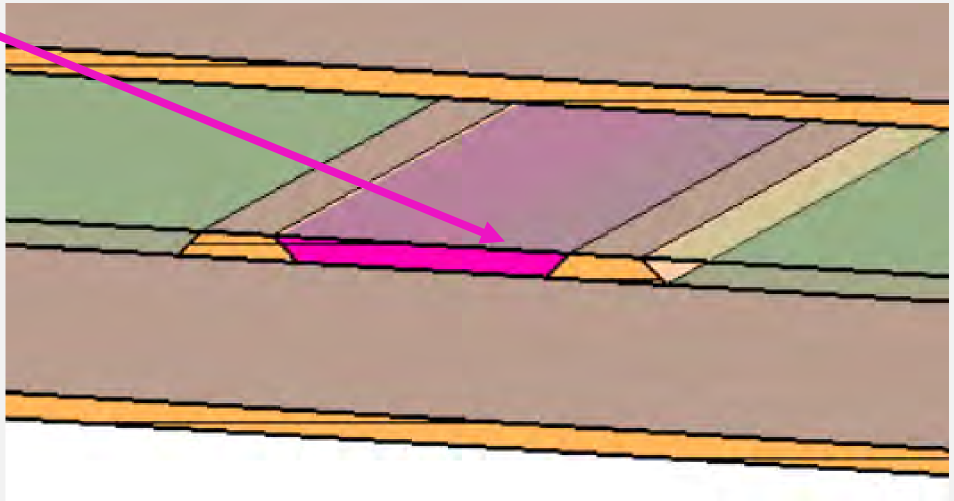


Epoxy Pocket

Epoxy pocket between traces

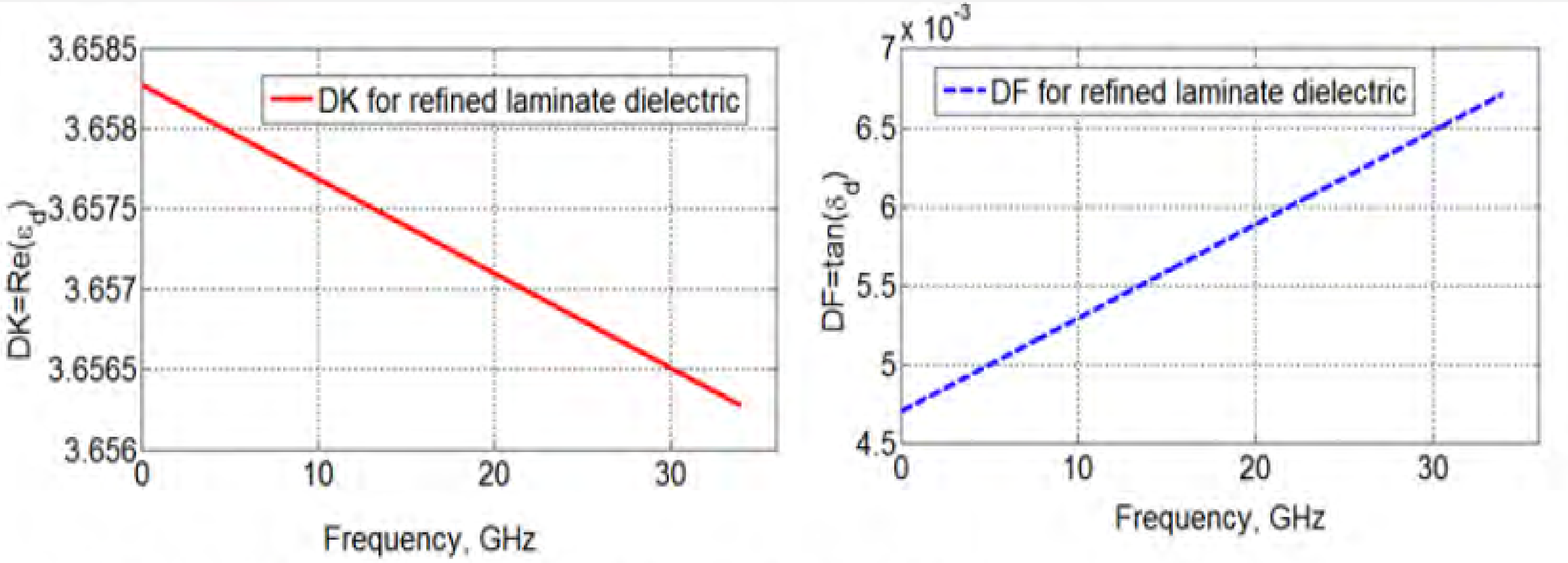


Epoxy pocket between traces. Strong coupled, rectangle edge, with ERD (surface roughness included)



Epoxy pocket shown in magenta with 60 degree edge. Weak coupled,

PCB material (matrix) properties

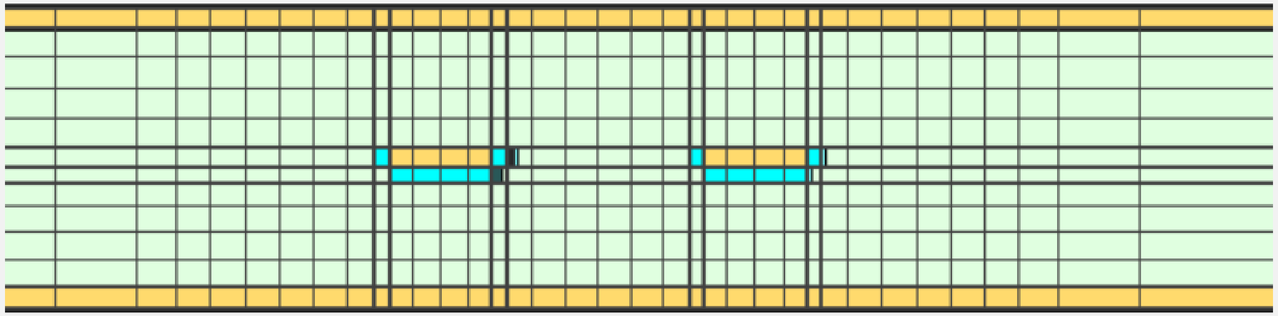


DK and DF of PPO Blend Dielectric extracted using DERM technique

M.Y. Koledintseva, A.V. Rakov, A.I. Koledintsev, J.L. Drewniak, and S. Hinaga, "Improved experiment-based technique to characterize dielectric properties of printed circuit boards", IEEE Trans. Electromag. Compat., vol. 56, no. 6, 2014, pp. 1559-1566.

Simulation

- Using time domain solver due to broad band of results 0-40 GHz and low number of ports.
- Multiple lengths, average ~100mm. For COM length the models were changed to 1meter.
- Mesh count, for 100 mm length average mesh count was 2million, for 1m long pair the mesh count average was 25 million hexahedrals.

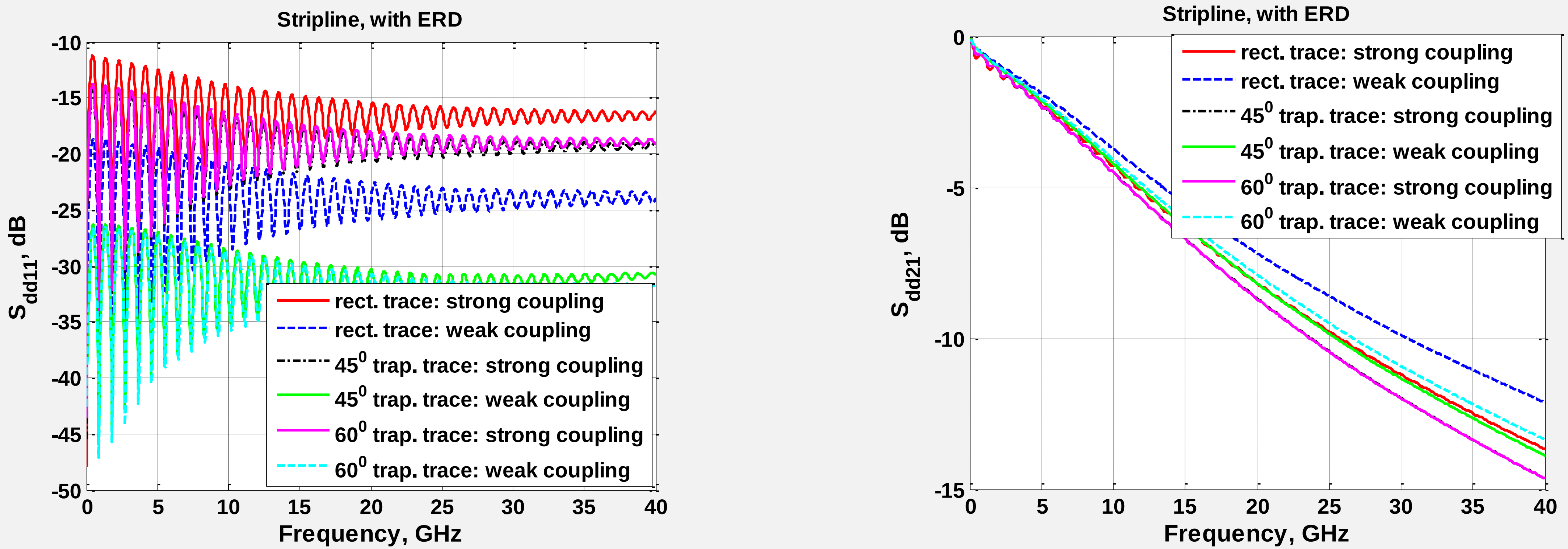


Cross section mesh view

Parameter List

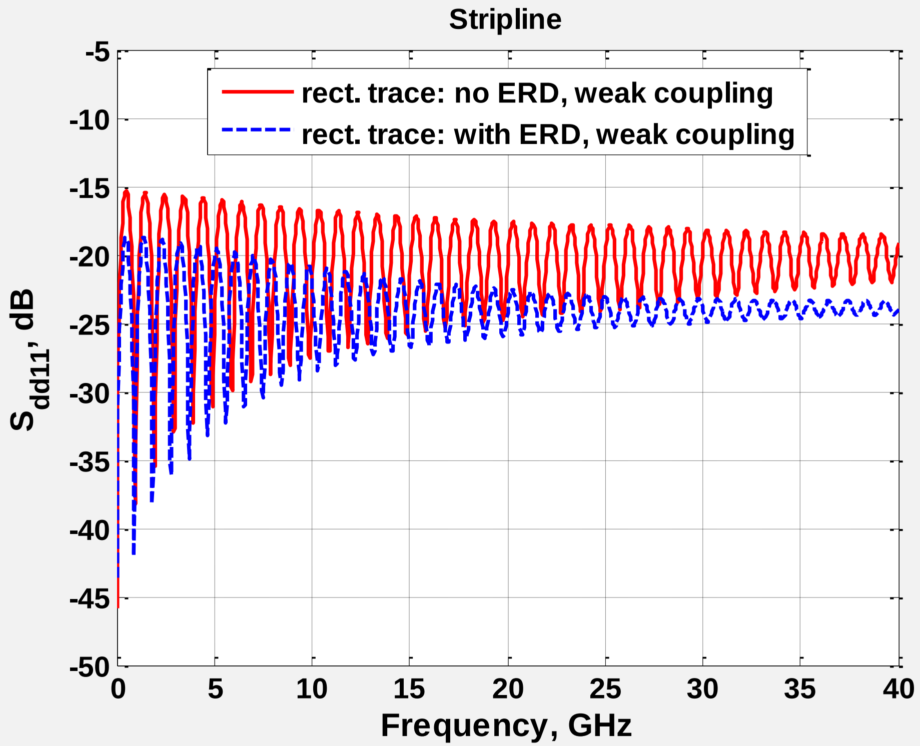
Name	Expression	Description
ERDSTD	= 0.0124	ERD layer thickness
tms	= 0.0175	thickness of microstrip trace
tgp	= .0175	thickness of ground plane
Tracetop	= TraceBot-(0.00001)	Top trace width
wt	= 0.087	width of trace (no trap)
TraceBot	= WT	Bottom trace width
d	= ((0.22-0.0175)/2)	thickness of substrate
st	= 0.18	separation of traces
a	= 0.5	determines trap angle
ht2	= 2	
ht1	= 2	distance of trace 1 to edge
subwidth	= (2*wt)+ht1+ht2+st	width of substrate
L1	= 1000	length of trace 1
L2	= 1000.127	length of trace 2
sublength	= 1004	substrate length

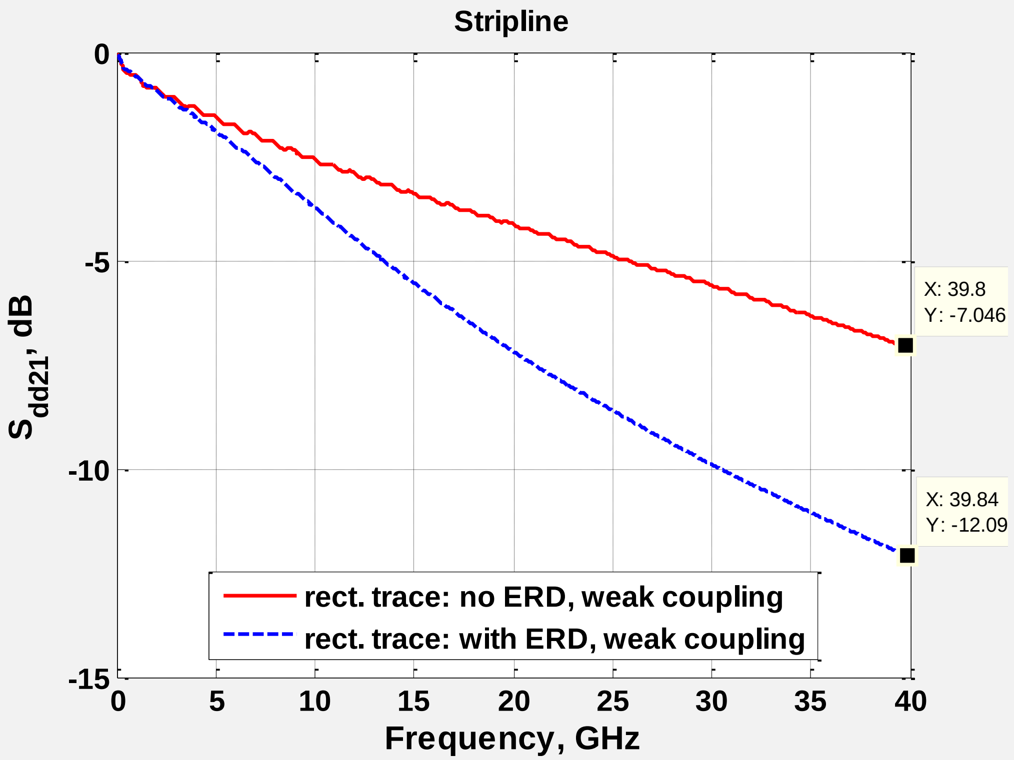
Differential-mode propagation with ERD (surface Roughness), different edge gradients



- Weak coupling provides less IL for DM than strong coupling.
- Rectangular traces provide less IL for DM than the trapezoidal traces, especially in the weak-coupled lines. IL in the 45-degree case is higher than in 60-degree case for the weak coupling.
- **IL in the 45-degree and 60-degree strong-coupled cases almost coincide, and they are higher than in the rectangular case.**

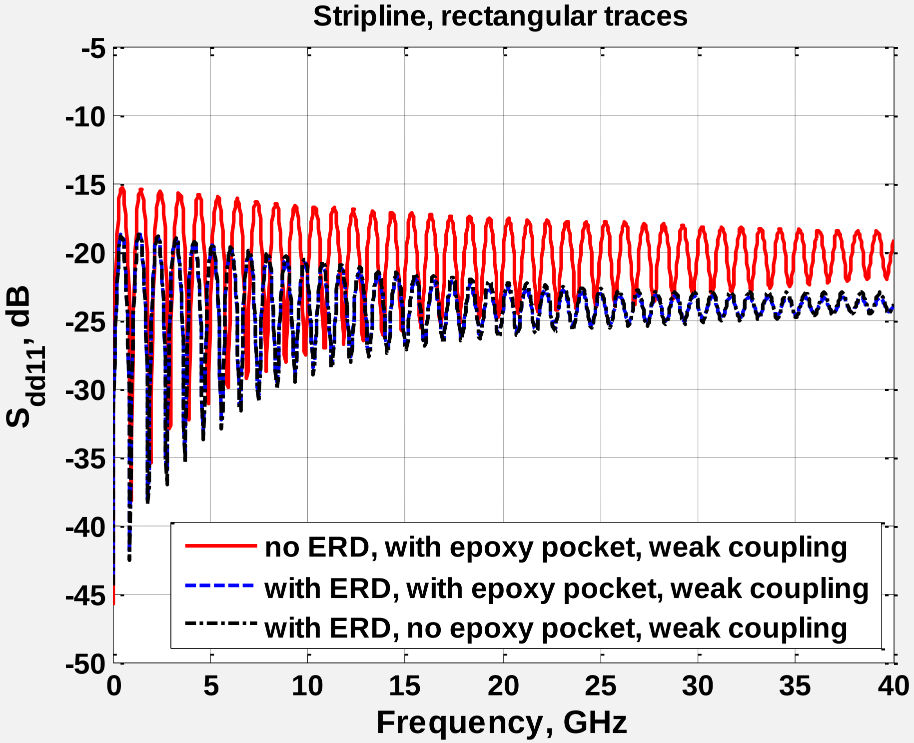
Differential-mode propagation

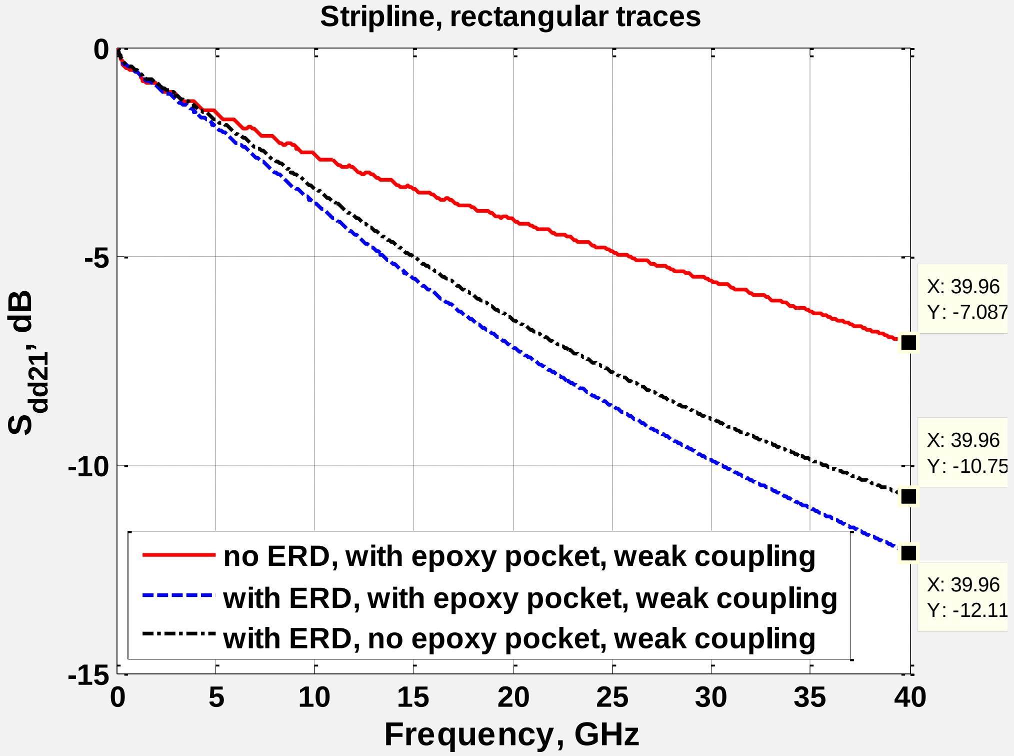




There is difference of about 5.0 dB at 40 GHz for the given lengths of the traces in the IL for the DM propagation.

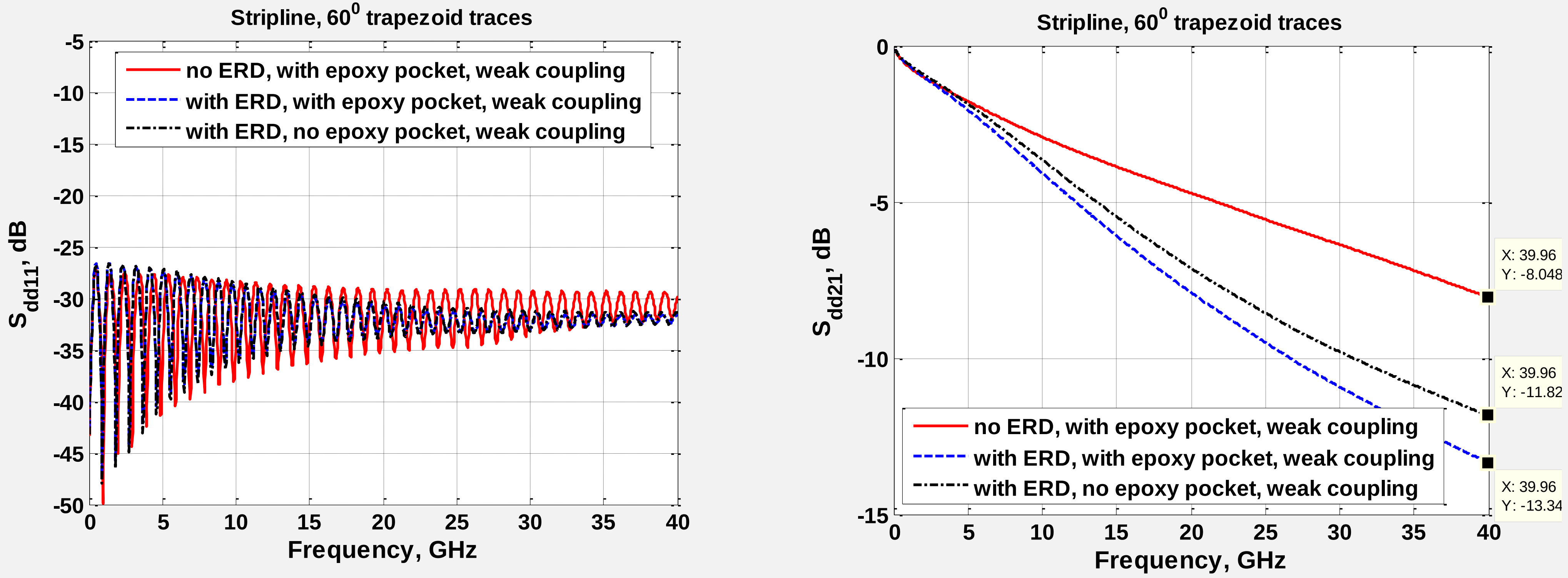
Differential-mode propagation





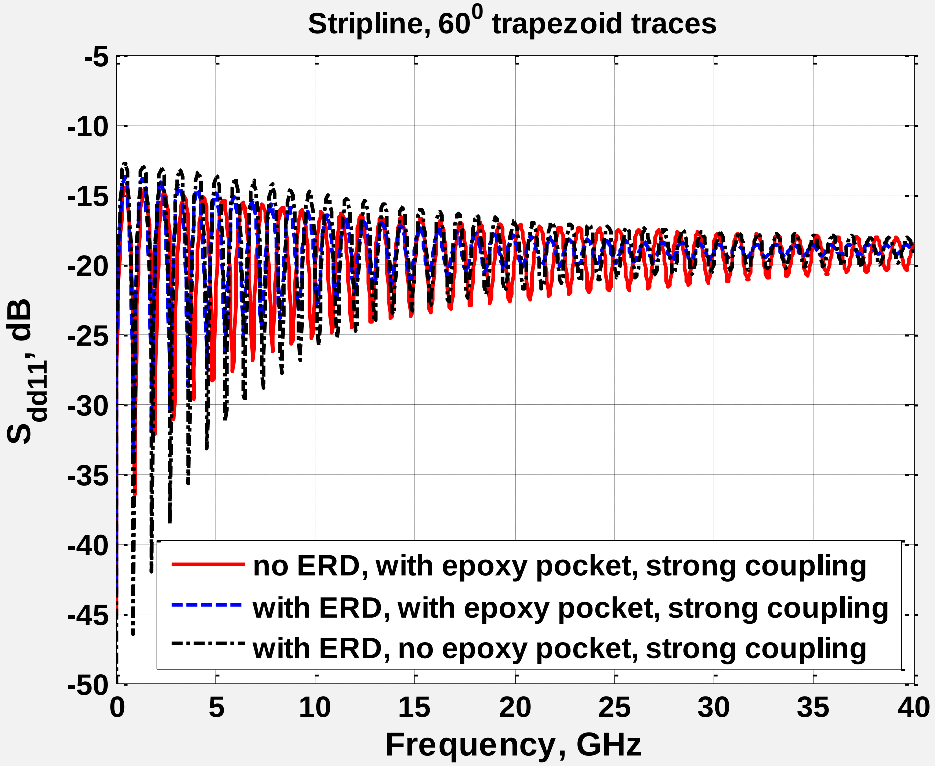
Comparing two ERD cases – with epoxy resin pockets and without, there is a difference of about 1.4 dB at 40 GHz for the given lengths of the traces in the IL for the DM propagation due to the epoxy pocket. This difference is less than for the strong-coupled case.

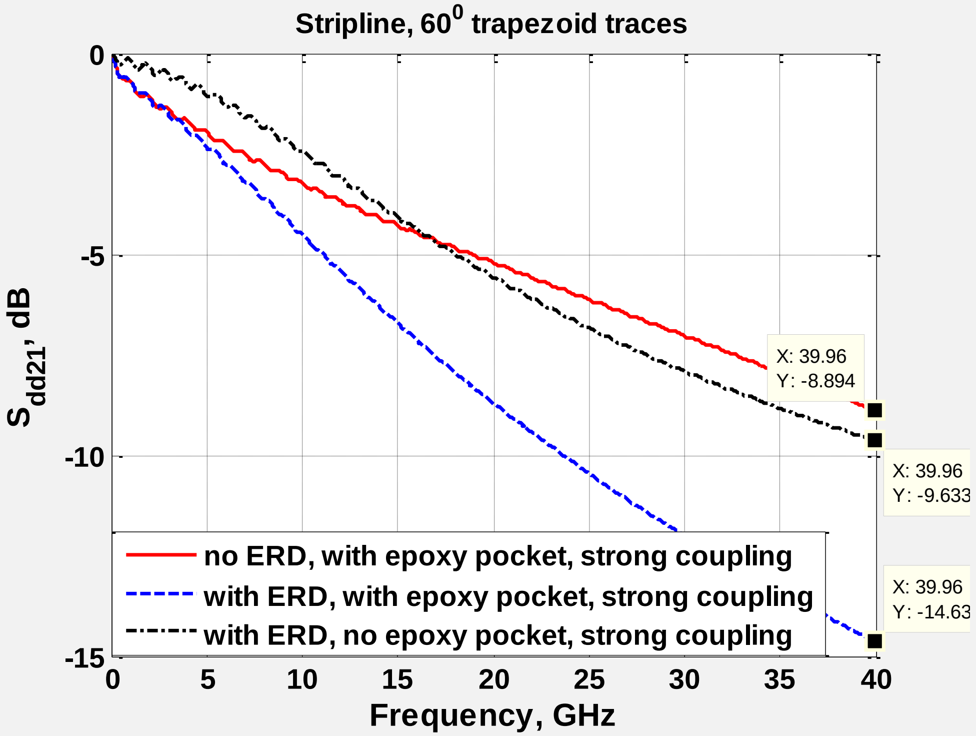
Differential-mode propagation



Comparing two ERD cases – with epoxy resin pockets and without, there is a difference of about 1.5 dB at 40 GHz for the given lengths of the traces in the IL for the DM propagation due to the epoxy pocket.

Differential-mode propagation

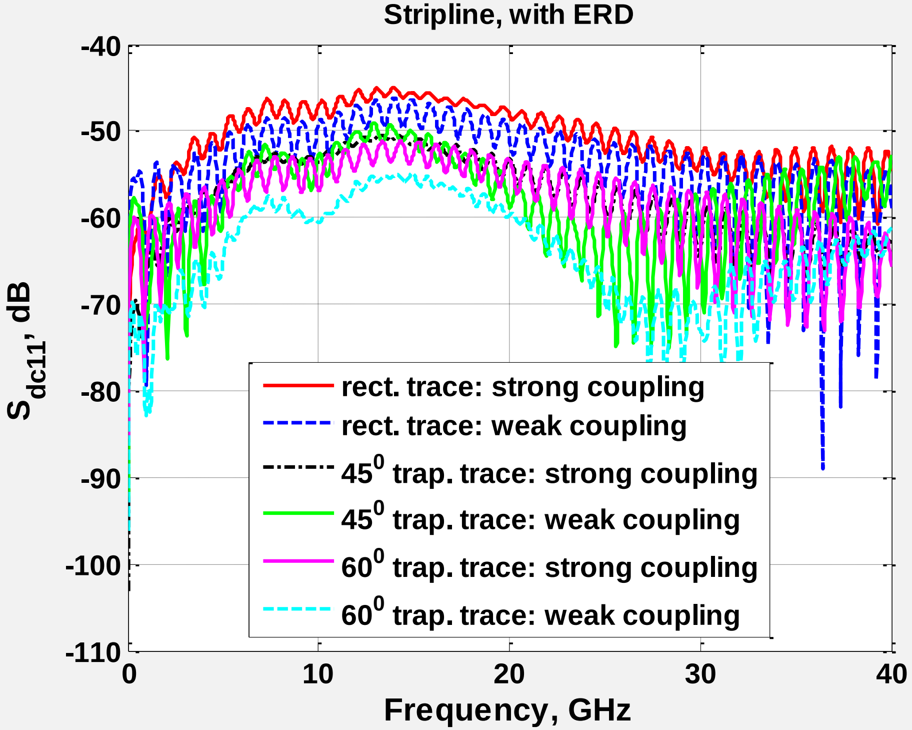


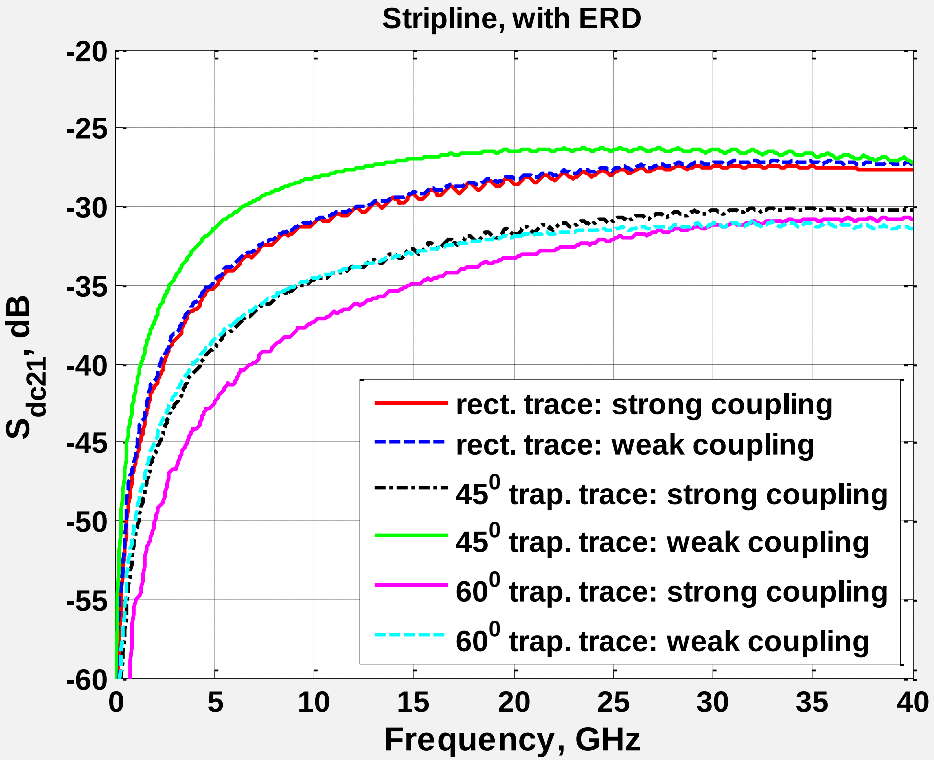


- IL for DM in the case with ERD, but no epoxy pocket is significantly less than in the cases with the epoxy pocket at lower frequencies (<17 GHz).
- After 17 GHz, the IL for DM with ERD and no epoxy pocket is higher than the case without ERD and with epoxy pocket. This means that after 17 GHz the ERD damping effect dominates.

Mode conversion

(Sdc=Scd)



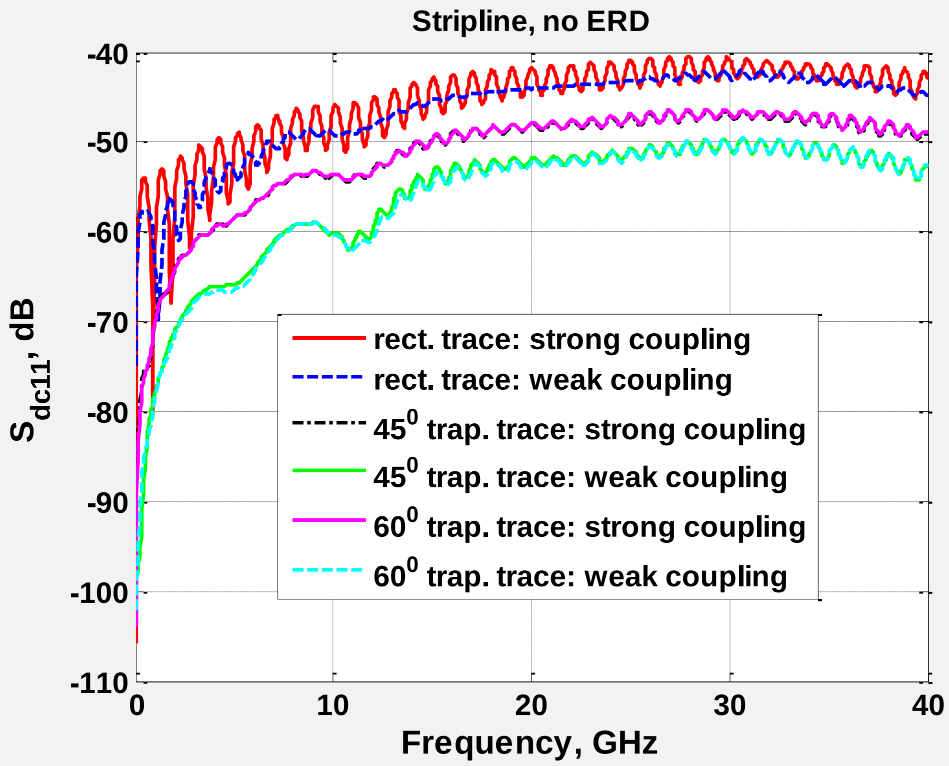


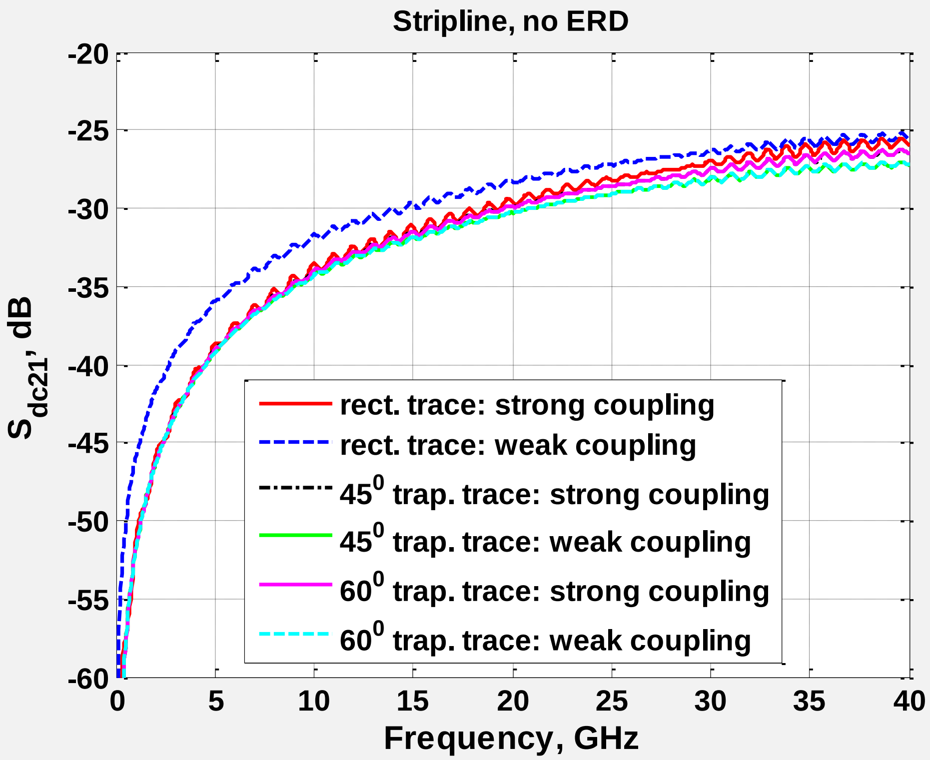
- In the strong-coupled cases, the mode conversion is reduced as compared to the weak-coupled cases.
- The weak-coupled case with 45-degree trapeziodal traces has the highest mode conversion over the entire frequency range.
- For rectangular traces, there is no significant difference in the mode conversion between the strong and weak coupling.
- **The 60-degree traces provide the least mode conversion, especially in the strong-coupled cases.**

Simulation Results

Mode conversion

(Sdc=Scd)

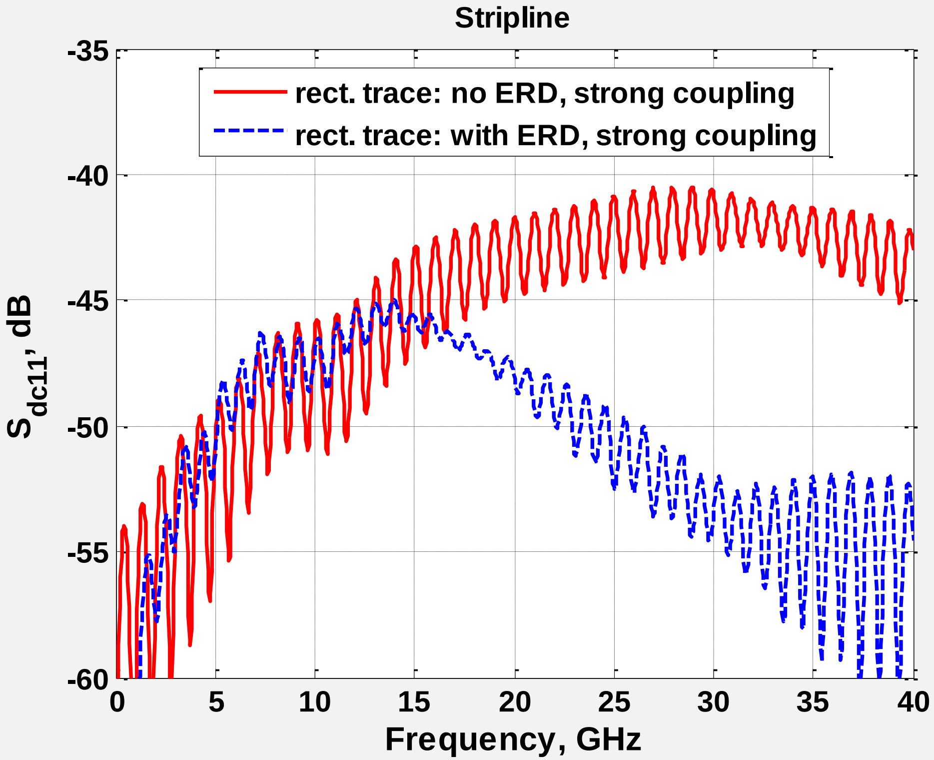


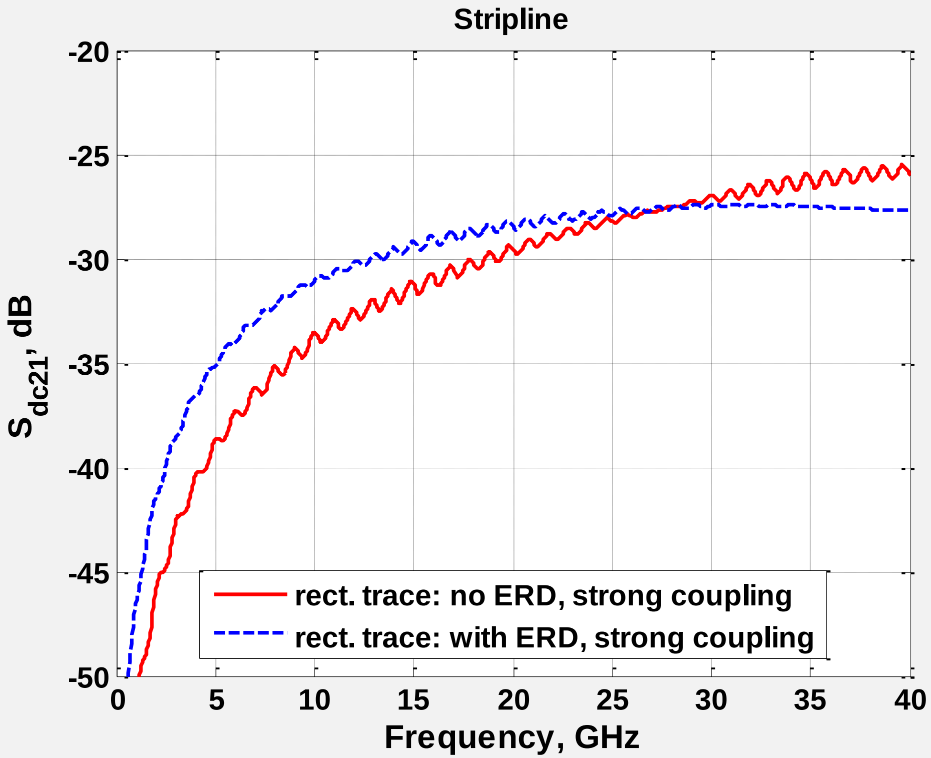


- In the strong-coupled cases, the mode conversion is reduced as compared to the weak-coupled cases. The same is seen with ERD. But without ERD, in the case with rectangular traces, strong coupling results in the higher mode conversion.
- The weak-coupled case with 60-degree trapeziodal traces has the lowest mode conversion over the entire frequency range.
- There is no much difference in the mode conversion levels for 45- and 60-degree cases in both strong-coupled and weak-coupled structures.
- **ERD looks more important for mode conversion enhancement in 45-degree weak-coupled case.**

Simulation Results

Mode conversion **(Sdc=Scd)**



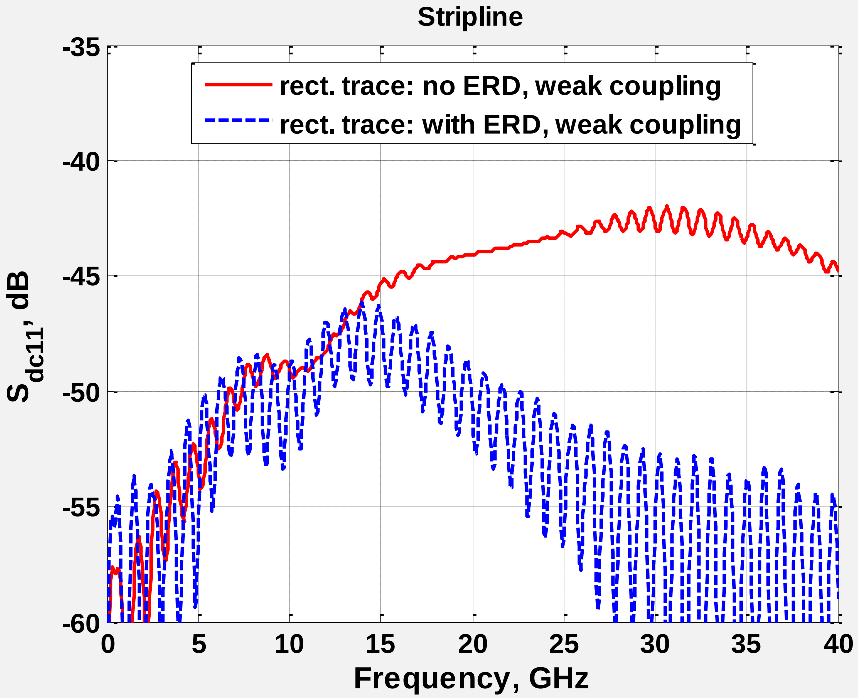


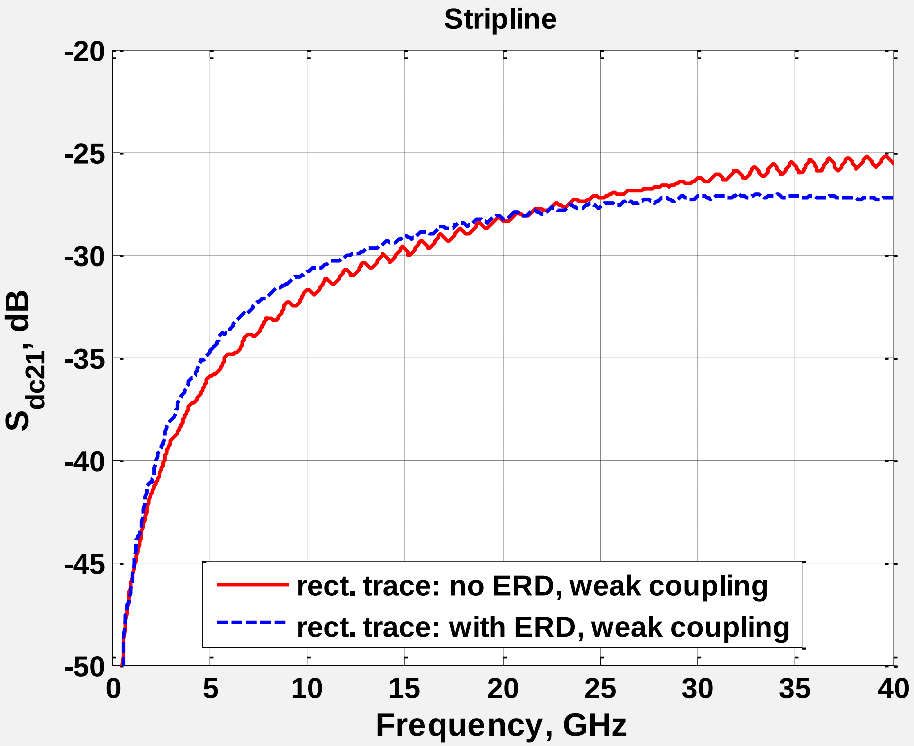
- There is a noticeable mode conversion enhancement due to ERD at the lower frequencies below 27 GHz, then ERD damps the mode conversion.

Simulation Results

(Sdc=Scd)

Mode conversion

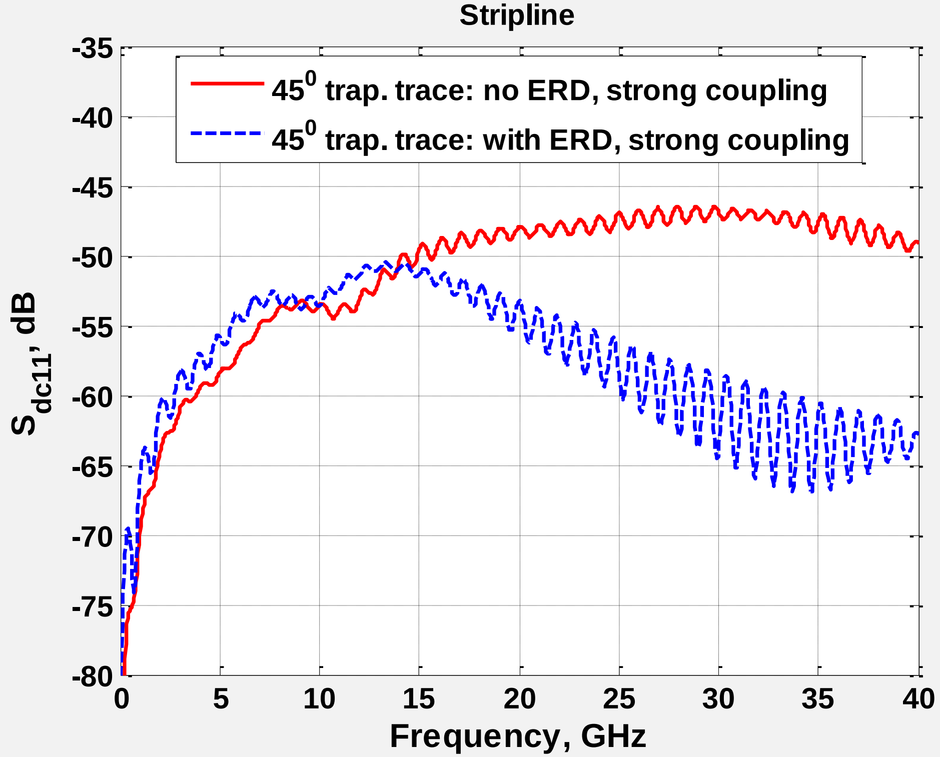


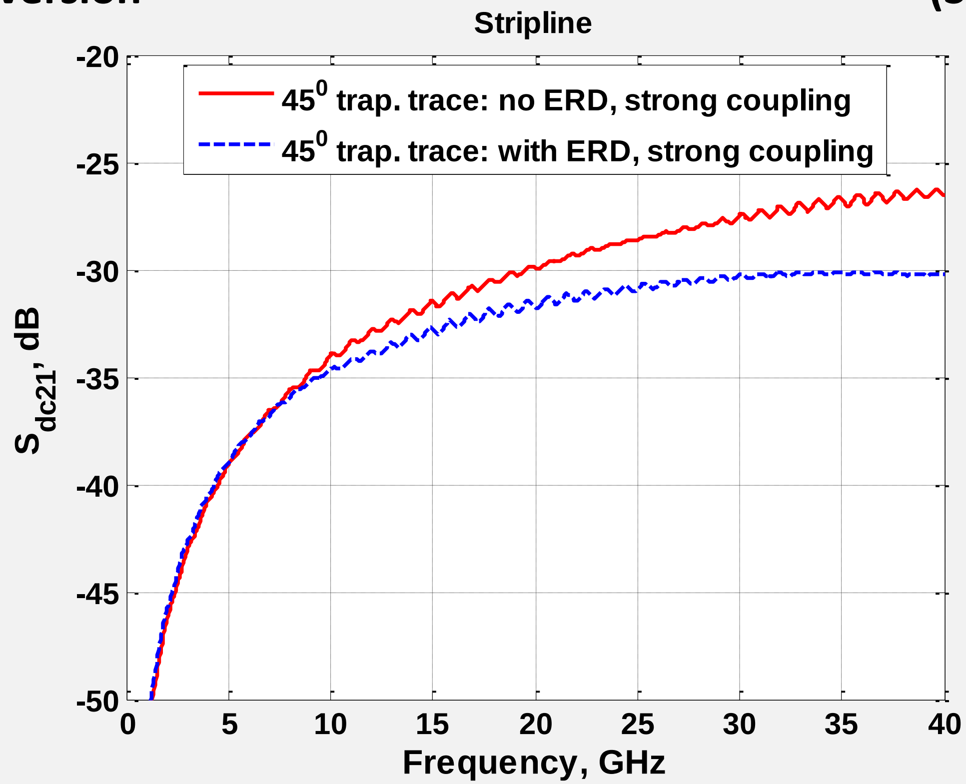


- There is a noticeable mode conversion enhancement due to ERD at the lower frequencies below 23 GHz, then ERD results in damping.
- But the observed low-frequency enhancement in the weak-coupled case is less than for the strong-coupled case.

Simulation Results

Mode conversion (Sdc=Scd)

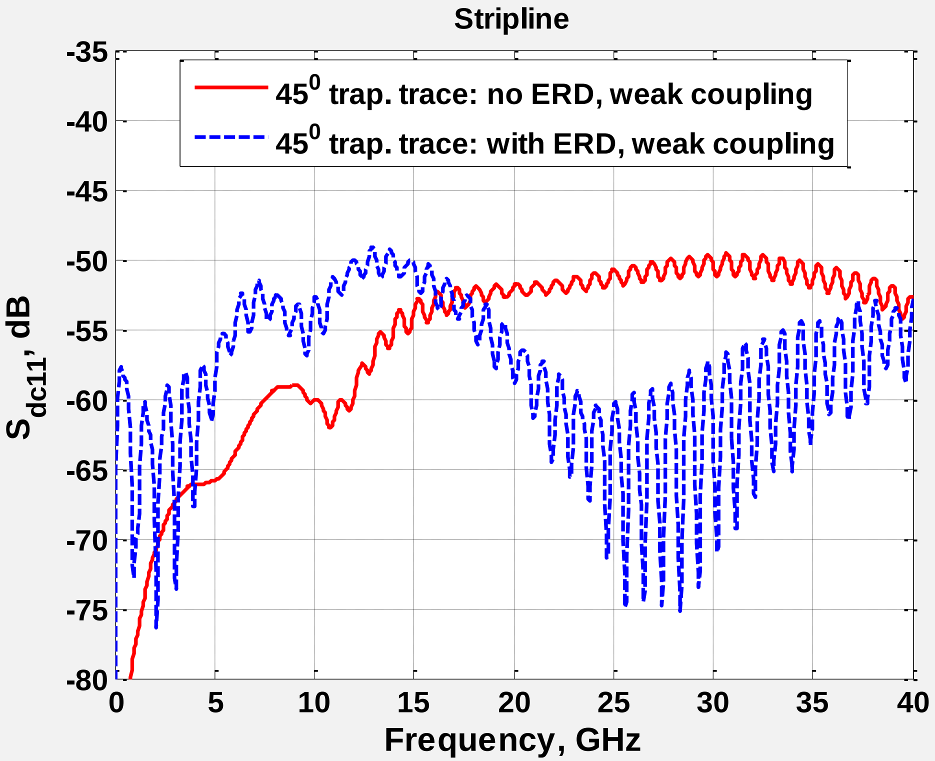


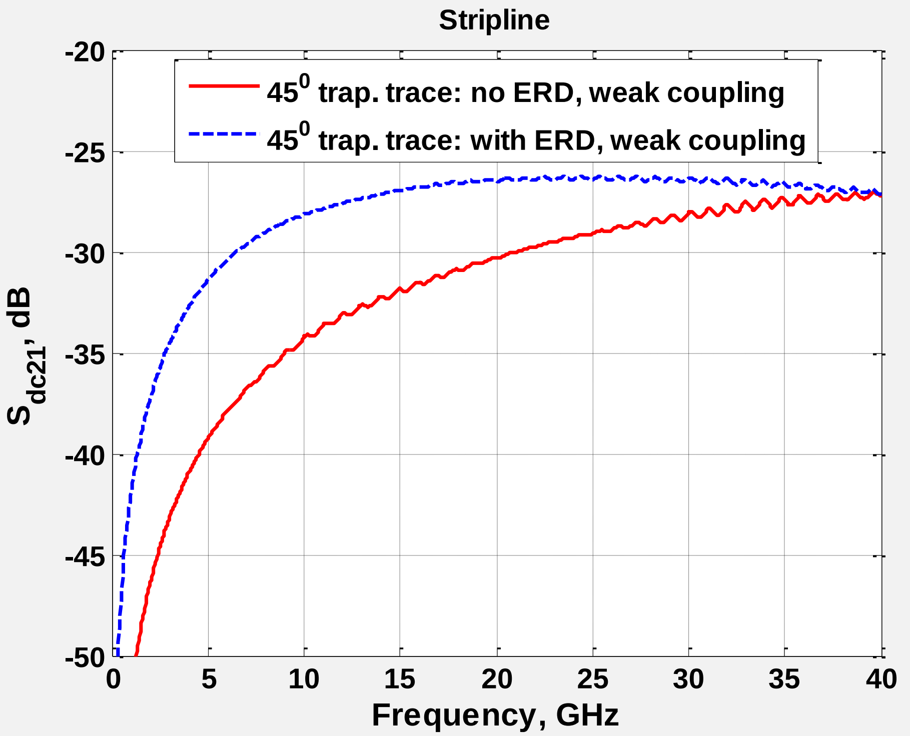


- There is damping of mode conversion by ERD over the frequency range starting from 8 GHz in the strong-coupled and 45-degree trapezoidal case.

Simulation Results

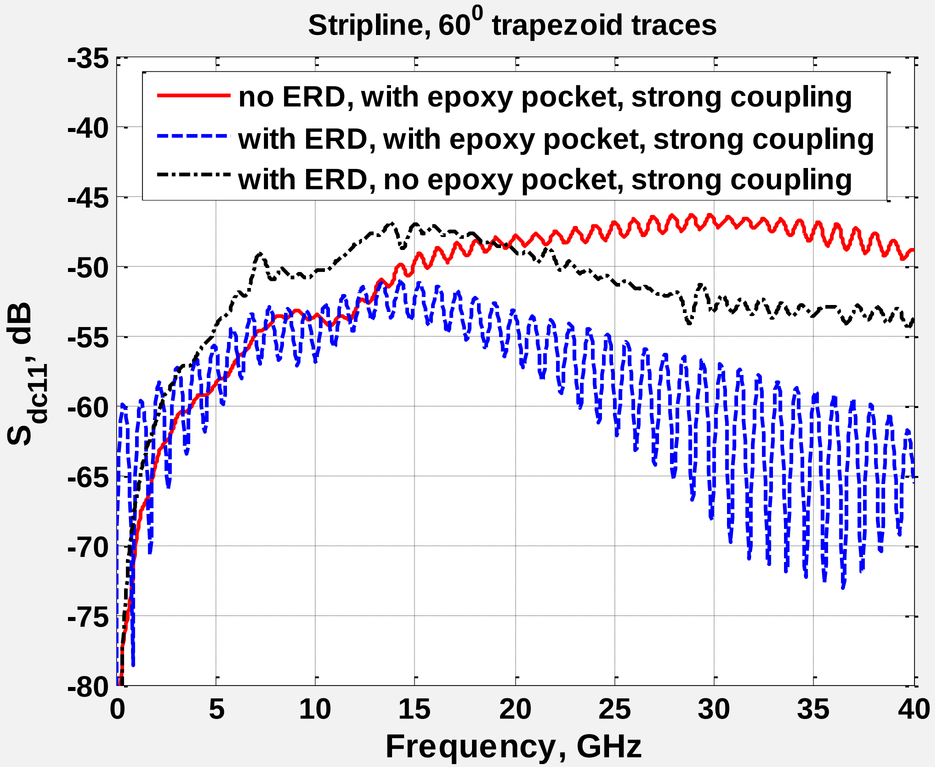
Mode conversion (Sdc=Scd)

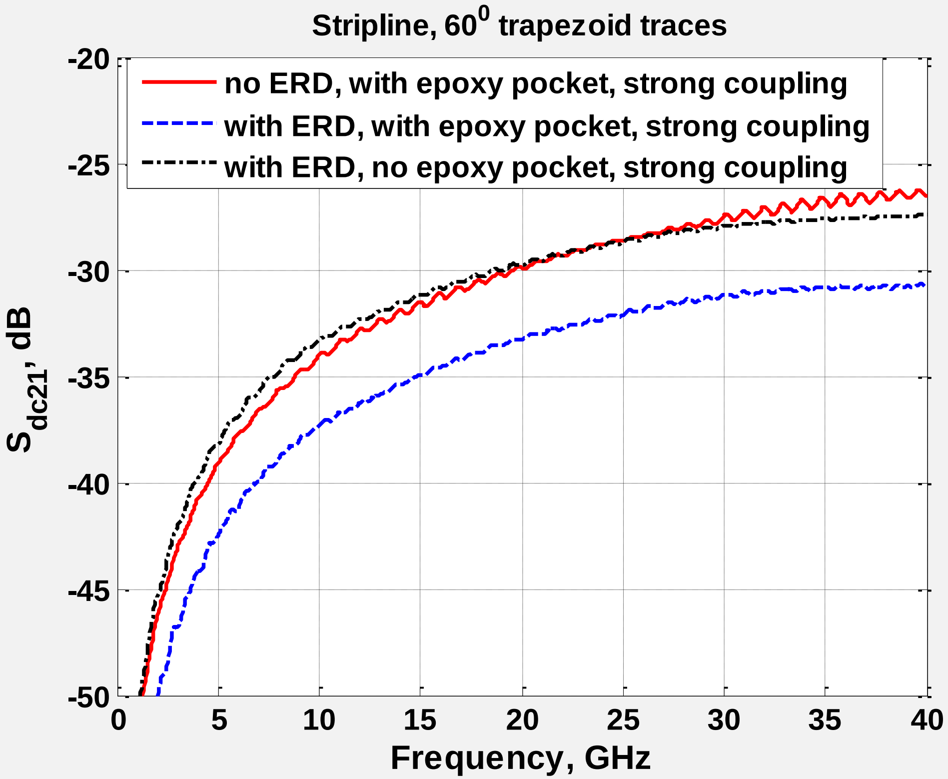




- There is significant damping of mode conversion by ERD over the entire frequency range in the weak-coupled and 45-degree trapezoidal case.

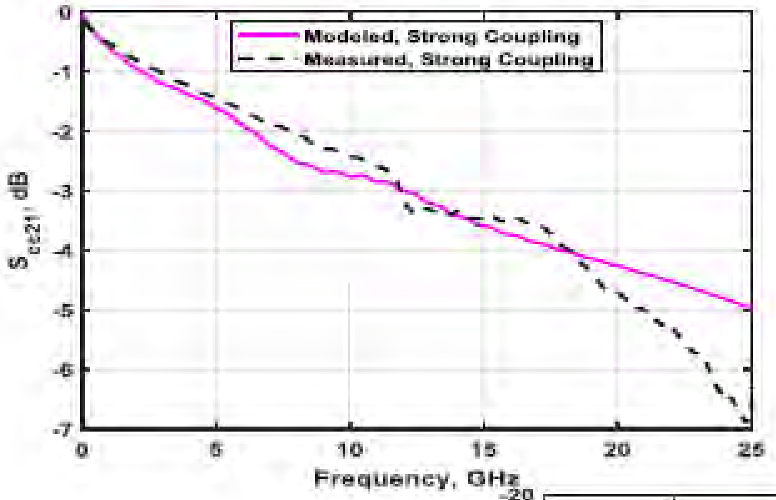
Mode conversion (Sdc=Scd)

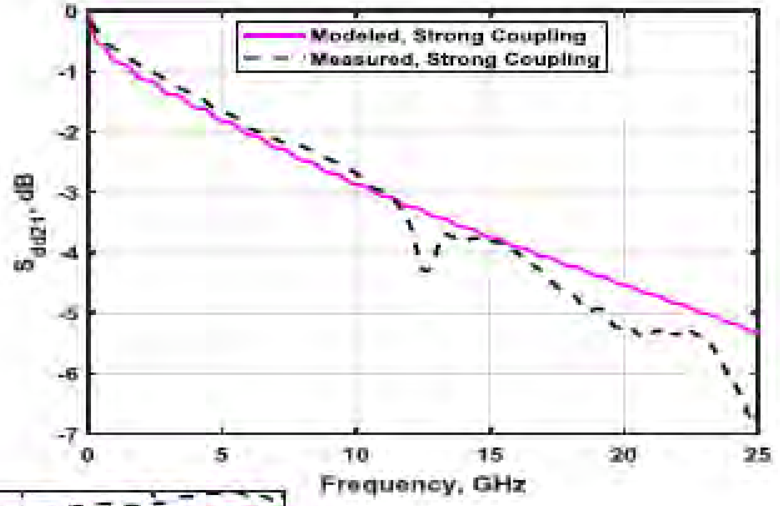




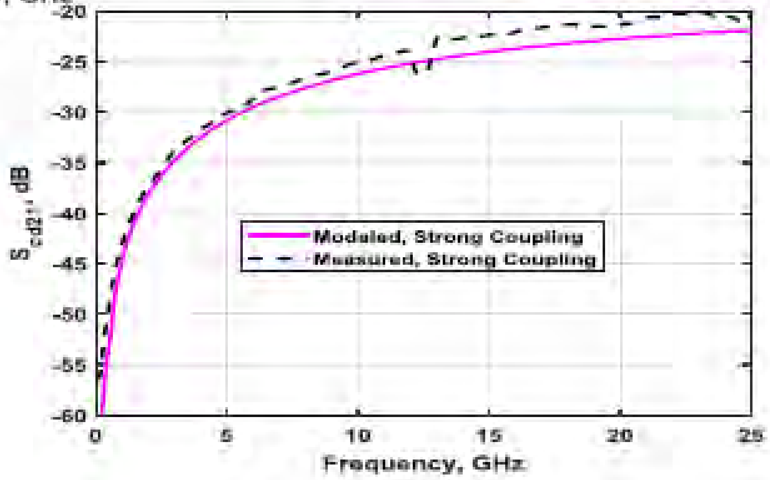
- In the ERD cases, with 60-degree traces and strong coupling, epoxy pockets damp mode conversion.
- ERD also damps mode conversion over the entire frequency range.
- However, **at the lower frequencies (<20 GHz), the ERD in the case of absence of epoxy pocket may enhance the mode conversion.**

Measured vs simulation comparison; stripline, strong coupled





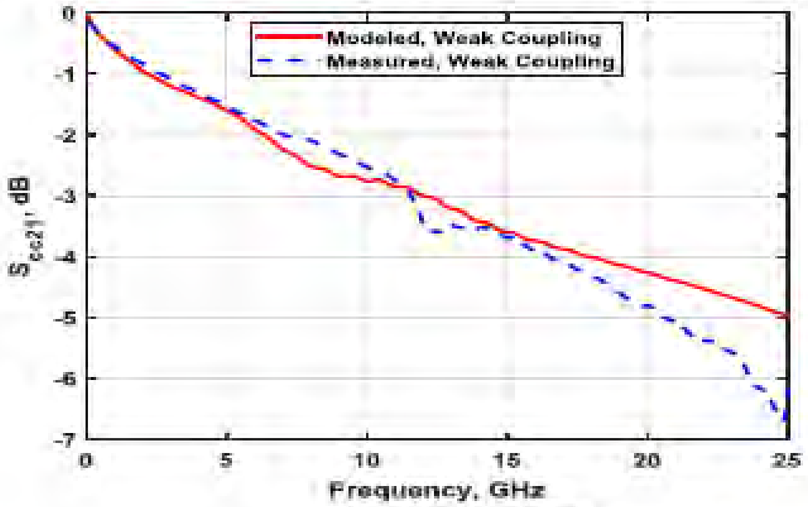
Modeled technological effects: dispersive PPO Blend, ERD, epoxy resin pocket, 60^0 trapezoid traces

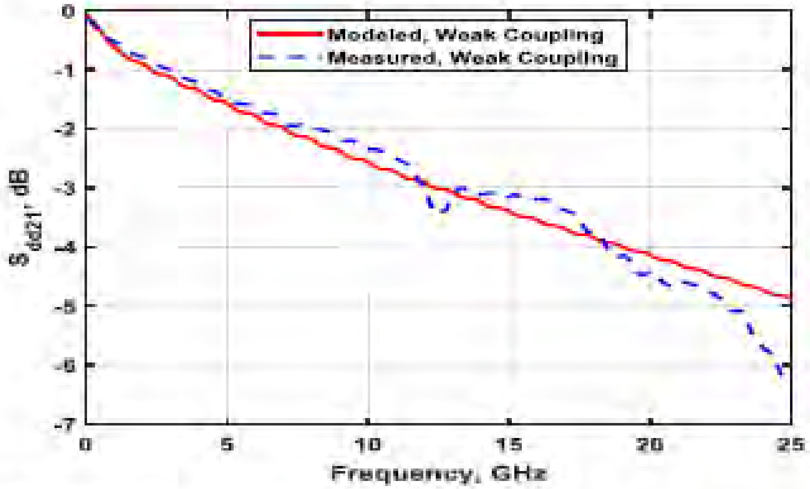


Line lengths are 80 mm and 80.254 mm (10 mil length imbalance)

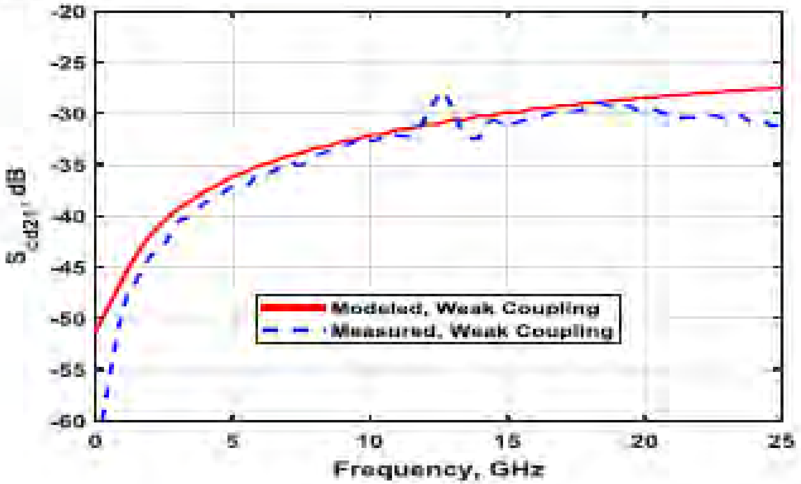
HEAVYSIDE CORPORATION

Measured vs simulation comparison; stripline, weak coupled





Modeled technological effects: dispersive PPO Blend, ERD, 60^0 trapezoid traces, Epoxy pocket



Line lengths are 80 mm and 80.127 mm (5 mil length imbalance)

Conclusion

- For differential mode insertion loss the results were as expected: ERD (surface roughness) increases IL. Weak coupling has less impact when compared to strong coupling. Sharper angles has larger impact than rectangular edge overall.
- For SI, weak coupling is preferable – as expected.
- However, mode conversion is, in general, larger in the weak-coupled than strong-coupled cases especially if the traces are trapezoid and other factors are considered.
- It seems Copper foil roughness and the epoxy-resin pocket, between the traces, enhances mode conversion.
- The mode conversion is most critical when there is weak coupling, 45-degree trapezoid traces, and significant roughness (especially at lower frequencies). Strong coupling creates mode damping.

Effects of PCB Technological Features on Channel Operating Margin (COM)

3DEXPERIENCE®

Abstract

The coupling (weak vs. strong) in edge-coupled differential transmission lines on a printed circuit board (PCB) affects frequency behavior of mixed-mode S-parameters. Slightly imbalanced stripline differential pairs are considered with various technological features modeled: rectangular vs. trapezoid shape of a signal trace cross-section; copper foil roughness; and presence of an epoxy-resin " pocket " (EP) between the stripline traces (dielectric properties of the EP are different from the homogenized parameters of the ambient dielectric where these traces are embedded. The quality of the differential mode (DM), which determines SI, is associated with the frequency dispersion and loss on the line. The common mode (CM) is inevitable on differential pairs. The study is carried out using full-wave simulation and corroborated with measurement. After the differential pairs are examined the model is used for the calculation of COM.

Channel Operating Margin (COM) is an efficient method to evaluate high speed interconnects. Effects of PCB technologies on COM are studied with a 1000GBASE-KP4 link. The pulse responses of COM are validated by comparing to circuit simulations.

Part 2: Channel Operating Margin [1][2]

- COM Introduction
- COM Results for the **Reference Model**
- Comparison of **COM Values** for Models with different PCB technological features
- Summary

100GBASE-KP4 [1]

- **100G**: Data rate is about 100 Gbps
- **BASE**: Baseband channel
- **K**: Backplane
- **P**: PAM4
- **4**: 4 differential pairs

- About 1 meter long backplane channel in the Ethernet network, including daughter boards, connectors and mother boards.

- COM parameters are provided in IEEE Std. 802.3bj-2014

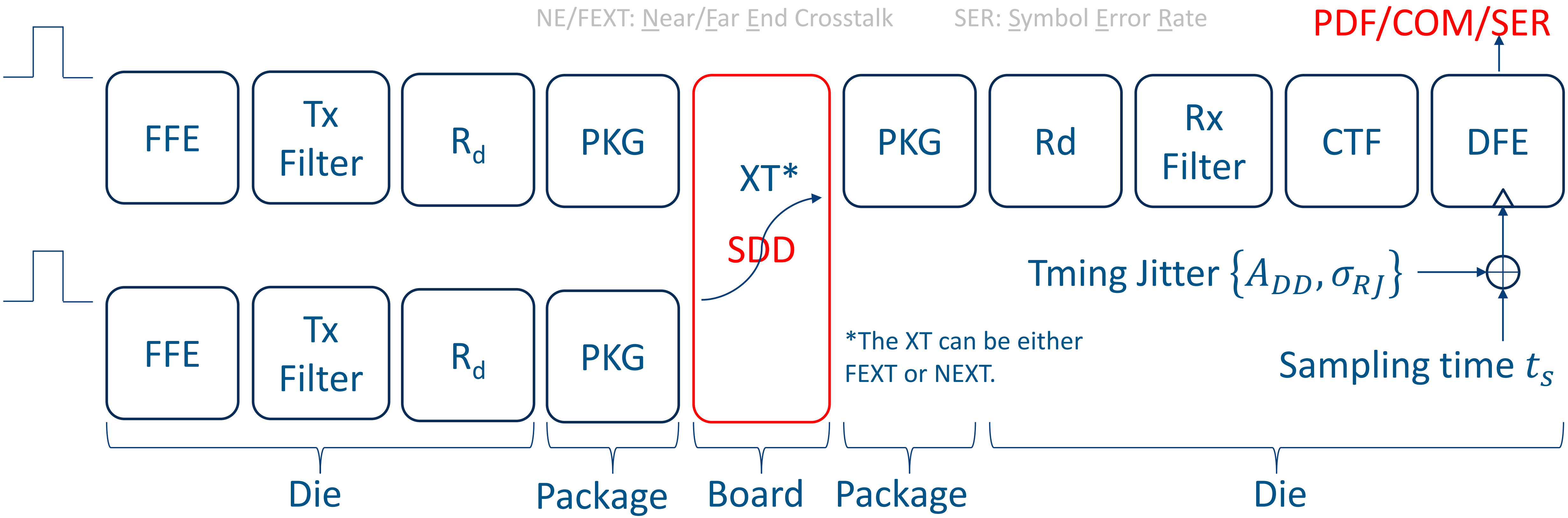
Signaling rate	f_b	13.59375 GBd
Receiver 3 dB bandwidth	f_r	$0.75 \times f_b$
Number of signal levels	L	4
⋮	⋮	⋮
Target detector error ratio	DER_0	3×10^{-4}

COM parameters

Motivation

FFE: Feed Forward Equalizer
R_d: Termination resistance
PKG: Package
SDD: Differential S-Parameter
NE/FEXT: Near/Far End Crosstalk

CTF: Continuous Time Filter
DFE: Decision Feedback Equalizer
PDF: Probability Density Function
COM: Channel Operating Margin
SER: Symbol Error Rate

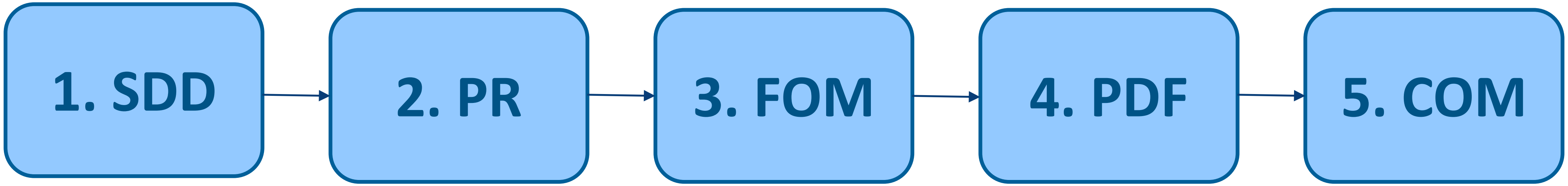


- S-parameter is not enough to estimate the performance of the entire system.
- All the blocks are analytically formulated with the given COM parameters and together with SDD, PDF/COM/SER can be calculated to give qualitative evaluation on the passive channel.

COM Workflow

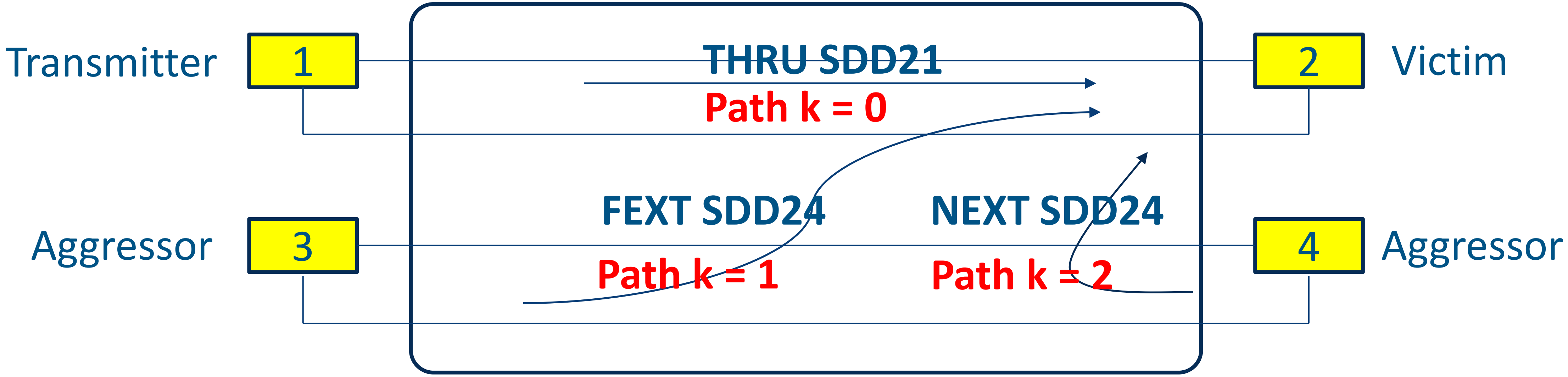
SDD: Differential S-parameter
PR: Pulse Response
FOM: Figure of Merit
PDF: Probability Density Function
COM: Channel Operating Margin

FFE: Feed Forward Equalizer
CTF: Continuous Time Filter
PDF: Probability Density Function



1. Differential S-parameter obtained from 3D simulation;
2. Pulse response can be derived from SDD, including linear package parasitics and linear filters (e.g. FFE, CTF and receiver noise filter);
3. Sweep parameters of FFE and CTF to find the best equalization setup based on FOM;
4. Calculate PDF with the optimized FFE and CTF settings at step 3;
5. Calculate COM value from the PDF obtained at step 4.

1. SDD

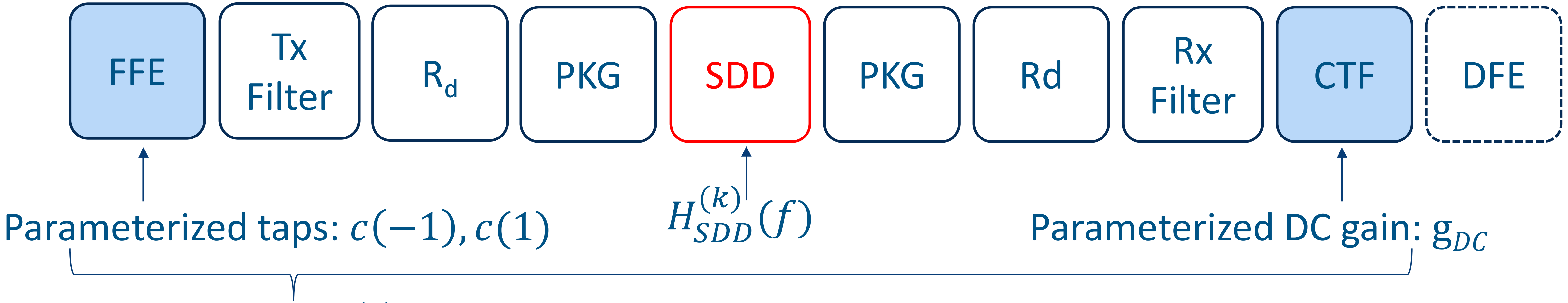


- Only differential mode is considered.
- SDD is normalized to100 Ohm.
- Linear sampled with equidistance of 0.01 GHz in the range [0, 56 GHz].
- Frequency domain response $H_{SDD}^{(k)}(f)$ for each path can be derived from S-parameter.

2. PR

PR: Pulse Response
FFE: Feed Forward Equalizer
R_d: Termination Resistance
PKG: Package

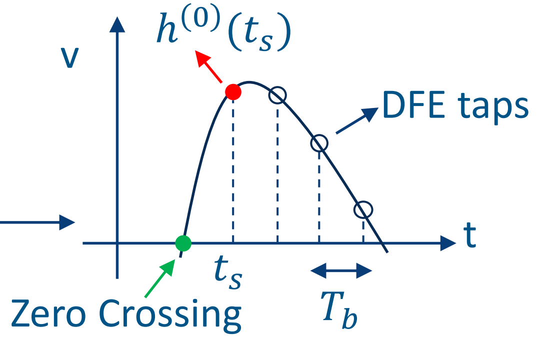
SDD: Differential S-Parameter
CTF: Continuous Time Filter
DFE: Decision Feedback Equalizer
iFFT: inverse Fast Fourier Transform



Linear part: $H^{(k)}(f)$

iFFT

Pulse Response: $h^{(k)}(t)$



$h^{(0)}(t_s)$: PR of THRU channel
t_s: the first zero crossing before the peak
T_b: Unit Interval / Bit Time

- PRs can be calculated for the linear part and DFE taps can be read from $h^{(0)}(t_s)$.
- FFE and CTF are parameterized and PRs need to be calculated for every combination of these parameters.

3. FOM

FOM: Figure of Merit
ISI: Inter Symbol Interference
XT: Crosstalk
TX: Transmitter

PR: Pulse Response
FFE: Feed Forward Equalizer
CTF: Continuous Time Filter
DFE: Decision Feedback Equalizer

$$FOM = 10\log_{10}\left(\frac{A_s^2}{\sigma_{TX}^2 + \sigma_{ISI}^2 + \sigma_J^2 + \sigma_{XT}^2 + \sigma_N^2}\right)$$

A_s: Signal Amplitude

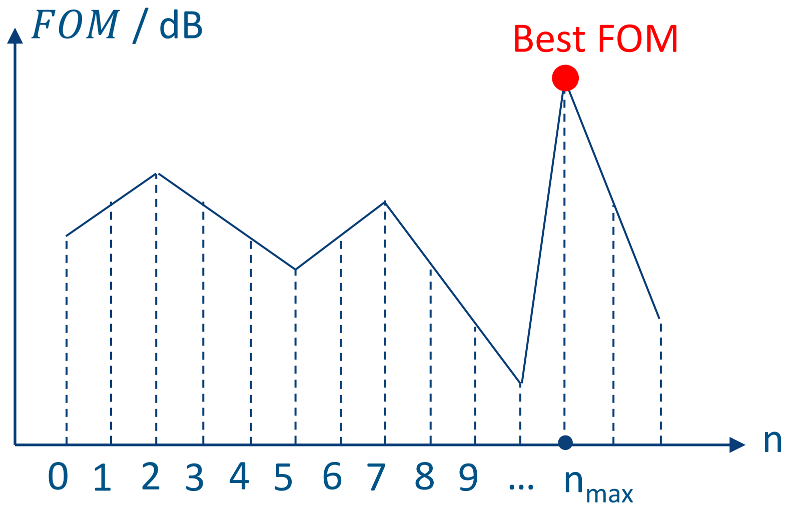
σ_{TX}^2: Transmitter Noise

σ_{ISI}^2: ISI Noise

σ_J^2: Noise due to timing jitter

σ_{XT}^2: XT Noise

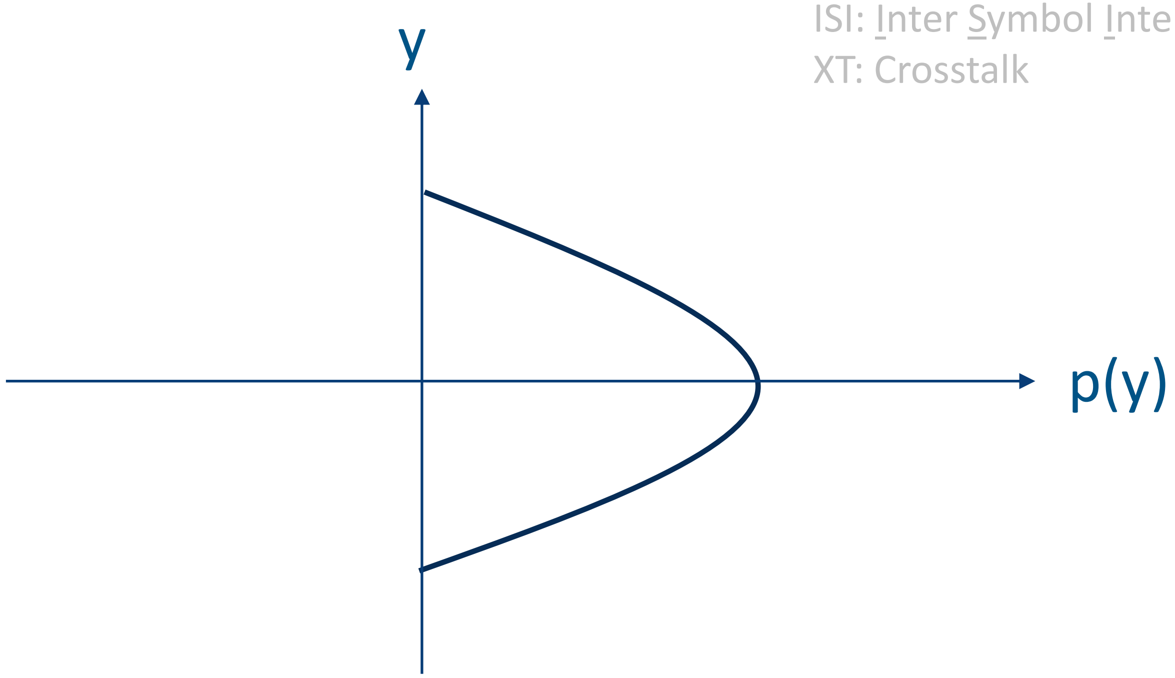
σ_N^2: Receiver Noise



n: sweep index for the parameter combination of FFE and CTF.

- FOM is defined as the formula above.
- All the variables (signal & noise) can be obtained with the given PRs and DFE taps in the previous slide.
- Parameter sweep of FFE and CTF is performed to find the largest FOM (i.e. the best FFE and CTF setting).

4. PDF



PDF p(y) is calculated by convolving DJ with RJ.

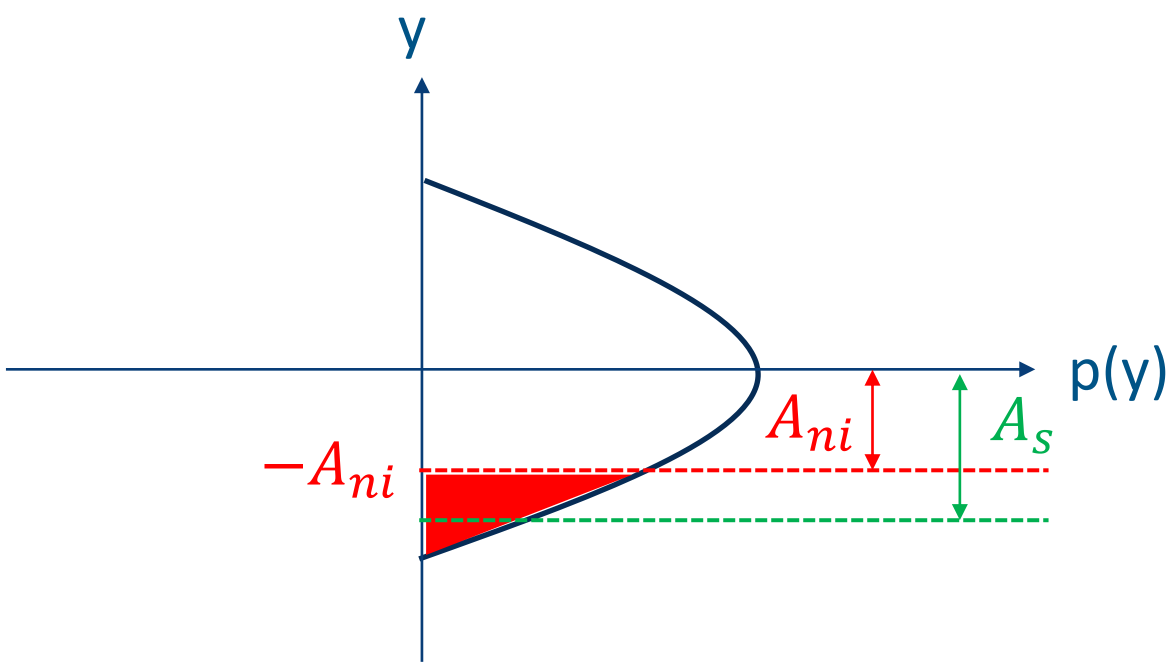
DJ: Deterministic jitter, which includes:

- **ISI**, **XT** and **deterministic timing jitter**

RJ: Random jitter following Gaussian distribution, which includes:

- **Transmitter/Receiver noise** and **random timing jitter**

5. COM



- COM value is defined as: $COM = 20\log_{10}\left(\frac{A_s}{A_{ni}}\right)$, where A_{ni} satisfies: $\int_{-\infty}^{-A_{ni}} p(y)dy = DER_0 = 3 \times 10^{-4}$.
- If COM > 3 dB, the passive channel succeeds in passing the COM test. Otherwise, it fails.

DJ & RJ

DJ: Deterministic Jitter
RJ: Random Jitter
PAM4: 4-level Pulse Amplitude Modulation
ISI: Inter Symbol Interference
XT: Crosstalk

DJ:

$$p_n(y) = \frac{1}{L}\sum_{l=0}^{L-1} \delta\left(y - \left(\frac{2l}{L-1} - 1\right) h(n)\right)$$

L= 4 for PAM4:

$$p_n(y) = \underset{\triangle}{\frac{1}{4}}\delta(y + \underline{h(n)}) + \underset{\triangle}{\frac{1}{4}}\delta\left(y + \underline{\frac{1}{3}h(n)}\right) + \underset{\triangle}{\frac{1}{4}}\delta\left(y - \underline{\frac{1}{3}h(n)}\right) + \underset{\triangle}{\frac{1}{4}}\delta(y - \underline{h(n)})$$

-------- Jitter on an arbitrary voltage level

△ Every symbol has the same probability.

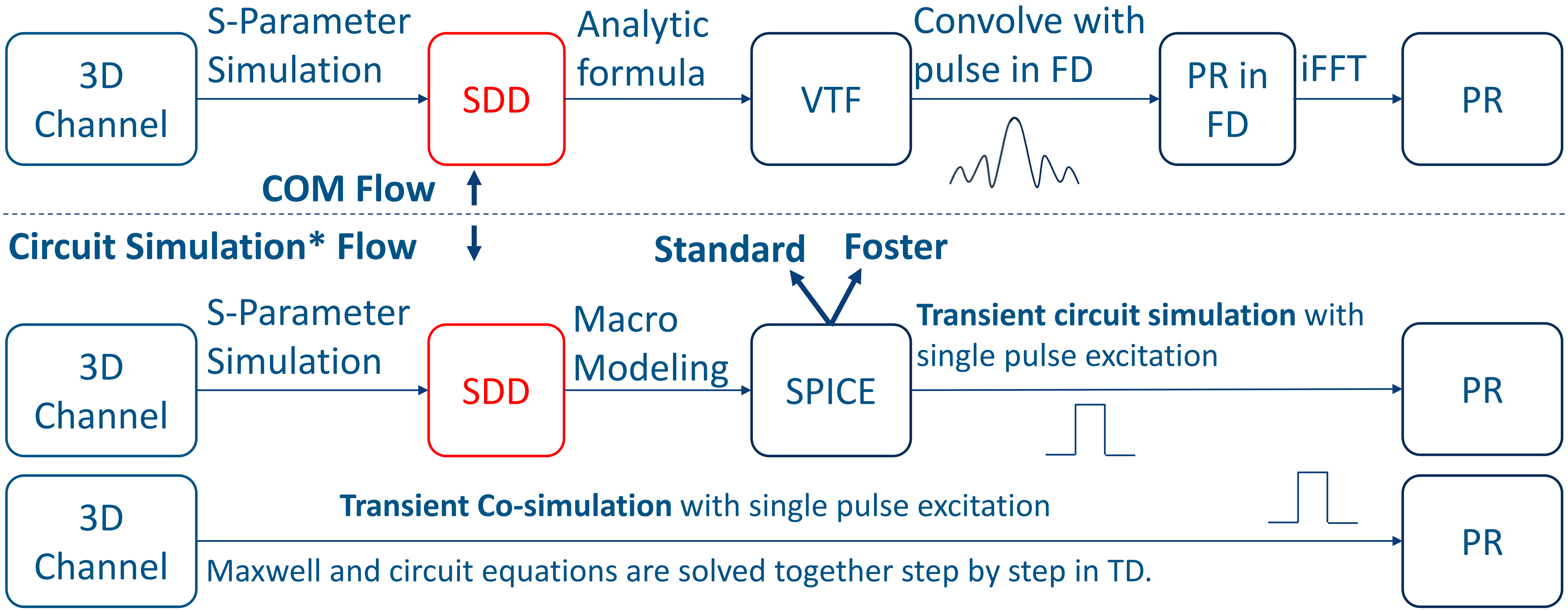
RJ:

$$p_G(y) = \frac{\exp(-y^2/(2\sigma_G^2))}{\sqrt{2\pi\sigma_G^2}}$$

Noise: **Transmitter Noise**, **Receiver Noise**, **Random Timing Jitter** and **Deterministic Timing Jitter**
Interference: **ISI** and **XT**

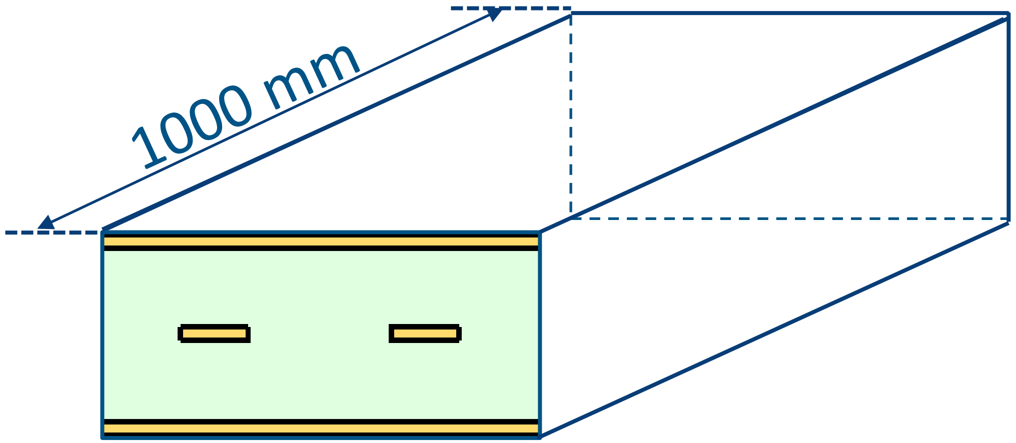
Circuit Simulations*[3]

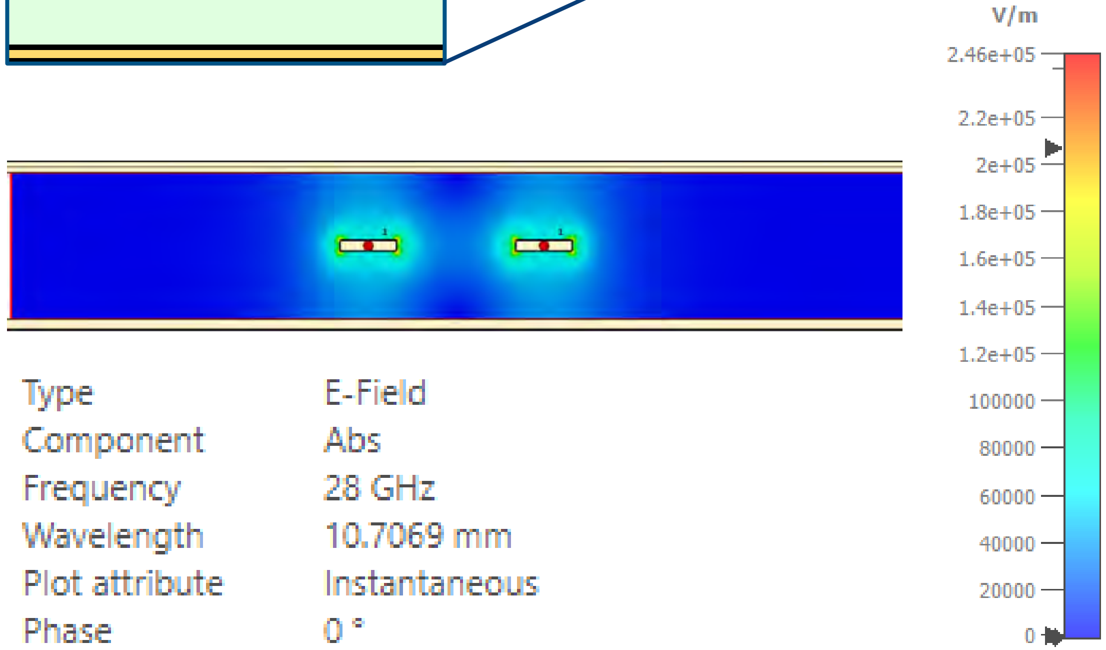
SDD: Differential S-Parameter
PR: Pulse Response
VTF: Voltage Transfer Function
FD: Frequency Domain
iFFT: inverse Fast Fourier Transform
TD: Time Domain



Ref. Model [3]

- About 1000 mm stripline
- Weak coupling with coupling coefficient K = -0.03
- Differential impedance Z_{diff} = 97.435 ohm, common impedance Z_{com} = 26.106 ohm
- Metal: electrical conductivity σ = 5.18e7 S/m
- Dielectric: Relative permittivity $\varepsilon_r = 3.56$, loss tangent tan (δ) = 0.005





Type	E-Field
Component	Abs
Frequency	28 GHz
Wavelength	10.7069 mm
Plot attribute	Instantaneous
Phase	0 °
Mode type	TEM
Line Imp.	97.435 Ω
Wave Imp.	199.984 Ω
Beta	1105.48 1/m

FFE: Feed Forward Equalizer
CTF: Continuous Time Filter
DFE: Decision Feedback Equalizer
COM: Channel Operating Margin

COM Report

SIMULIA CST COM REPORT

Report generated: Wed Feb 24 00:12:32 2021

Calculation Time

S-parameter load time: 0.12 s
Filter creation time: 149.49 s
FOM optimization time: 76.85 s
COM calculation time: 174.95 s

Total time: 413.23 s

Package model is enabled

Considered time for sigma calculation before: 10.2 ns

Noise Terms

Best FOM: 18.05952859235201
sigma_ISI: 0.0005014998067261224
sigma_J: 0.00046269707691947473
sigma_N: 0.0005159200153731885
sigma_TX: 0.0009127440062371521
sigma_XT: 0.0

Best FFE and CTF

Best FFE c(-1): -0.1
Best FFE c(0): 0.62
Best FFE c(1): -0.28
Best CTF g_DC: -12.0
Best CTF g_DC2: 0.0
CTF Pole 1: 3.3984375 GHz
CTF Pole 2: 13.59375 GHz

DFE Taps

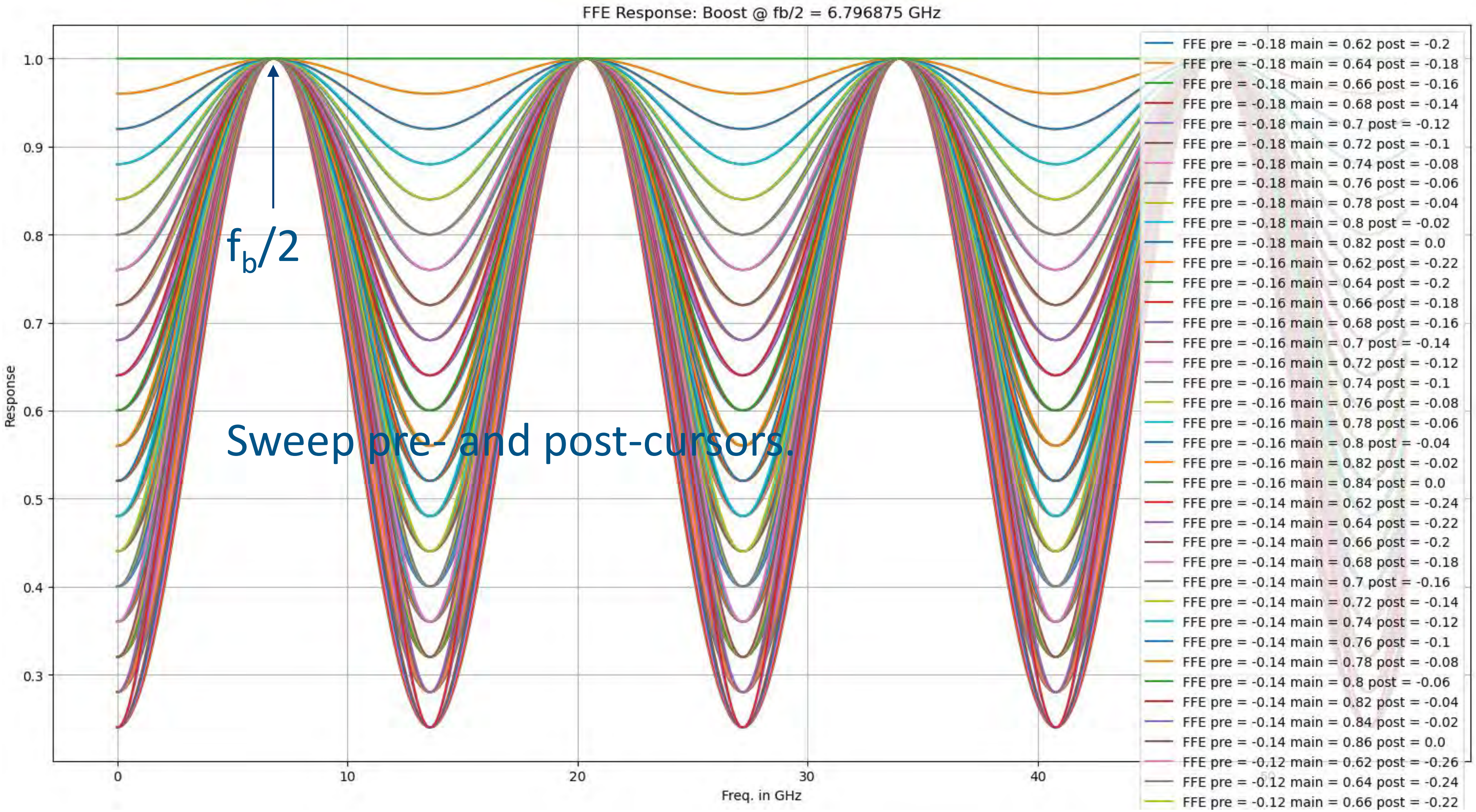
Best DFE taps:

0	1.0
1	-0.3358322705801205
2	-0.08661840062554277
3	-0.004432098413141016
4	0.011378468657579913
5	0.011152342607647959
6	0.009518705156761965
7	0.008437659903636744
8	0.007723830648089044
9	0.007196851590407687
10	0.006767672524885149
11	0.006395453674209619
12	0.006059420685933658
13	0.005746970562455649
14	0.005455720381950763
15	0.0051808779026287005
16	0.0049216282135418005

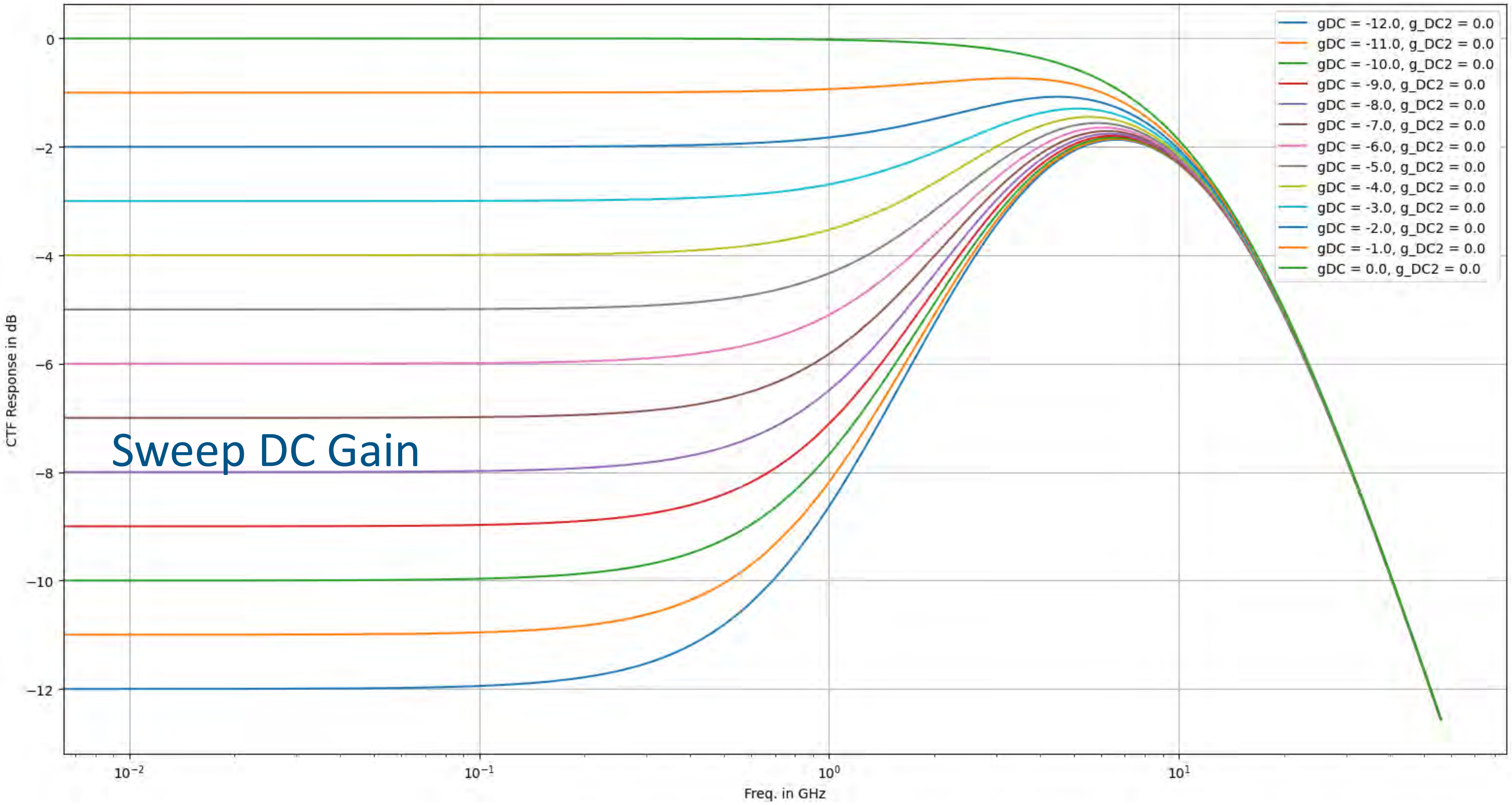
Heavy DFE taps causes error propagation [2], which is not considered in COM

As: 0.009931516360239496
DER0: 0.0003
Ani: 0.004121130489976671
COM: 7.639983925367934

FFE Sweep [4]


FFE Response: Boost @ fb/2 = 6.796875 GHz
Response
Freq. in GHz
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
10
20
30
40
$f_b/2$
Sweep pre- and post-cursors.
FFE pre = -0.18 main = 0.62 post = -0.2
FFE pre = -0.18 main = 0.64 post = -0.18
FFE pre = -0.18 main = 0.66 post = -0.16
FFE pre = -0.18 main = 0.68 post = -0.14
FFE pre = -0.18 main = 0.7 post = -0.12
FFE pre = -0.18 main = 0.72 post = -0.1
FFE pre = -0.18 main = 0.74 post = -0.08
FFE pre = -0.18 main = 0.76 post = -0.06
FFE pre = -0.18 main = 0.78 post = -0.04
FFE pre = -0.18 main = 0.8 post = -0.02
FFE pre = -0.18 main = 0.82 post = 0.0
FFE pre = -0.16 main = 0.62 post = -0.22
FFE pre = -0.16 main = 0.64 post = -0.2
FFE pre = -0.16 main = 0.66 post = -0.18
FFE pre = -0.16 main = 0.68 post = -0.16
FFE pre = -0.16 main = 0.7 post = -0.14
FFE pre = -0.16 main = 0.72 post = -0.12
FFE pre = -0.16 main = 0.74 post = -0.1
FFE pre = -0.16 main = 0.76 post = -0.08
FFE pre = -0.16 main = 0.78 post = -0.06
FFE pre = -0.16 main = 0.8 post = -0.04
FFE pre = -0.16 main = 0.82 post = -0.02
FFE pre = -0.16 main = 0.84 post = 0.0
FFE pre = -0.14 main = 0.62 post = -0.24
FFE pre = -0.14 main = 0.64 post = -0.22
FFE pre = -0.14 main = 0.66 post = -0.2
FFE pre = -0.14 main = 0.68 post = -0.18
FFE pre = -0.14 main = 0.7 post = -0.16
FFE pre = -0.14 main = 0.72 post = -0.14
FFE pre = -0.14 main = 0.74 post = -0.12
FFE pre = -0.14 main = 0.76 post = -0.1
FFE pre = -0.14 main = 0.78 post = -0.08
FFE pre = -0.14 main = 0.8 post = -0.06
FFE pre = -0.14 main = 0.82 post = -0.04
FFE pre = -0.14 main = 0.84 post = -0.02
FFE pre = -0.14 main = 0.86 post = 0.0
FFE pre = -0.12 main = 0.62 post = -0.26
FFE pre = -0.12 main = 0.64 post = -0.24
FFE pre = -0.12 main = 0.66 post = -0.22

CTF Sweep [4]



Sweep DC Gain
CTF Response in dB
Freq. in GHz
0
−2
−4
−6
−8
−10
−12
10^{-2}
10^{-1}
10^{0}
10^{1}
gDC = -12.0, g_DC2 = 0.0
gDC = -11.0, g_DC2 = 0.0
gDC = -10.0, g_DC2 = 0.0
gDC = -9.0, g_DC2 = 0.0
gDC = -8.0, g_DC2 = 0.0
gDC = -7.0, g_DC2 = 0.0
gDC = -6.0, g_DC2 = 0.0
gDC = -5.0, g_DC2 = 0.0
gDC = -4.0, g_DC2 = 0.0
gDC = -3.0, g_DC2 = 0.0
gDC = -2.0, g_DC2 = 0.0
gDC = -1.0, g_DC2 = 0.0
gDC = 0.0, g_DC2 = 0.0

FOM Sweep [4]

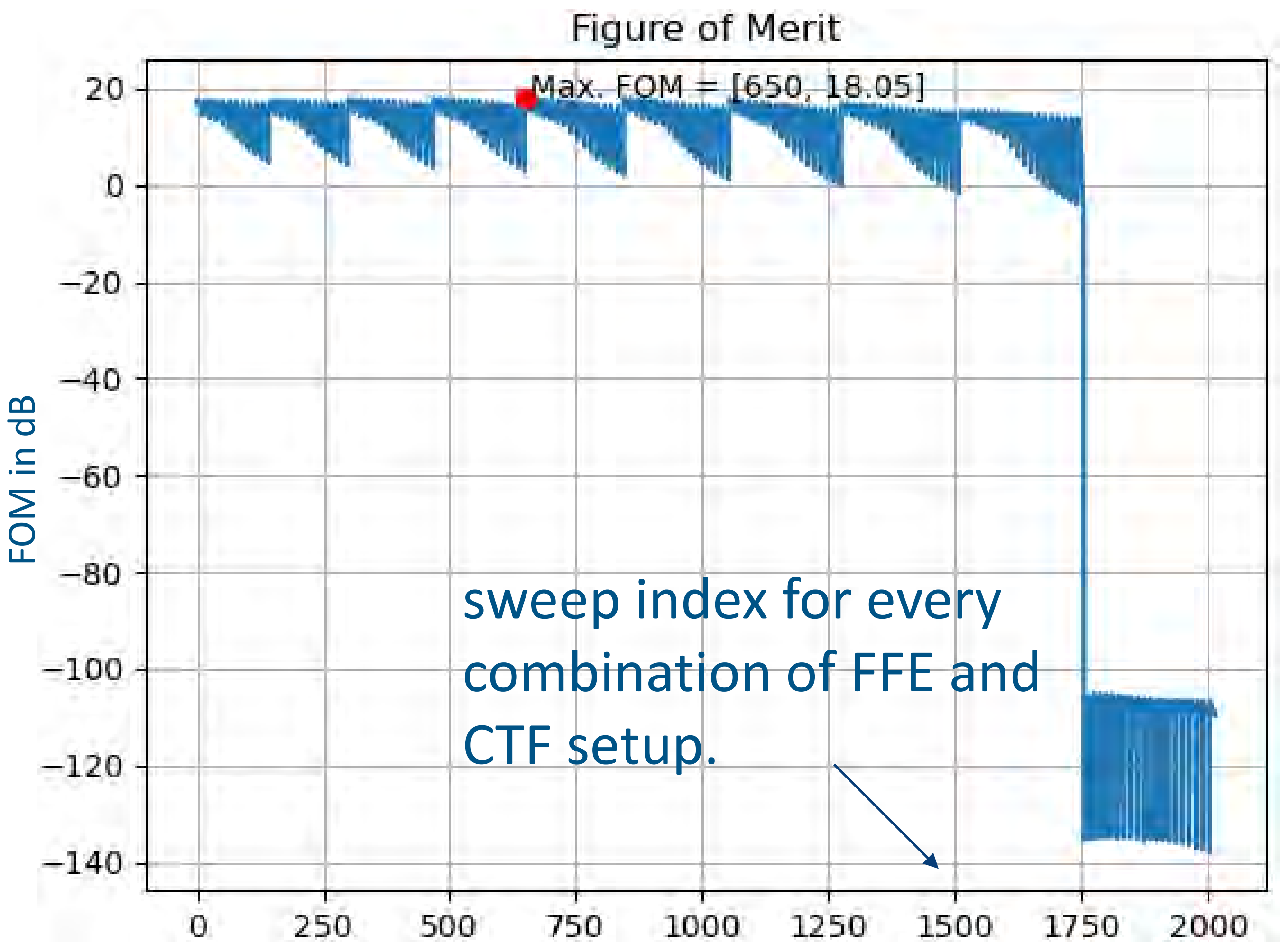
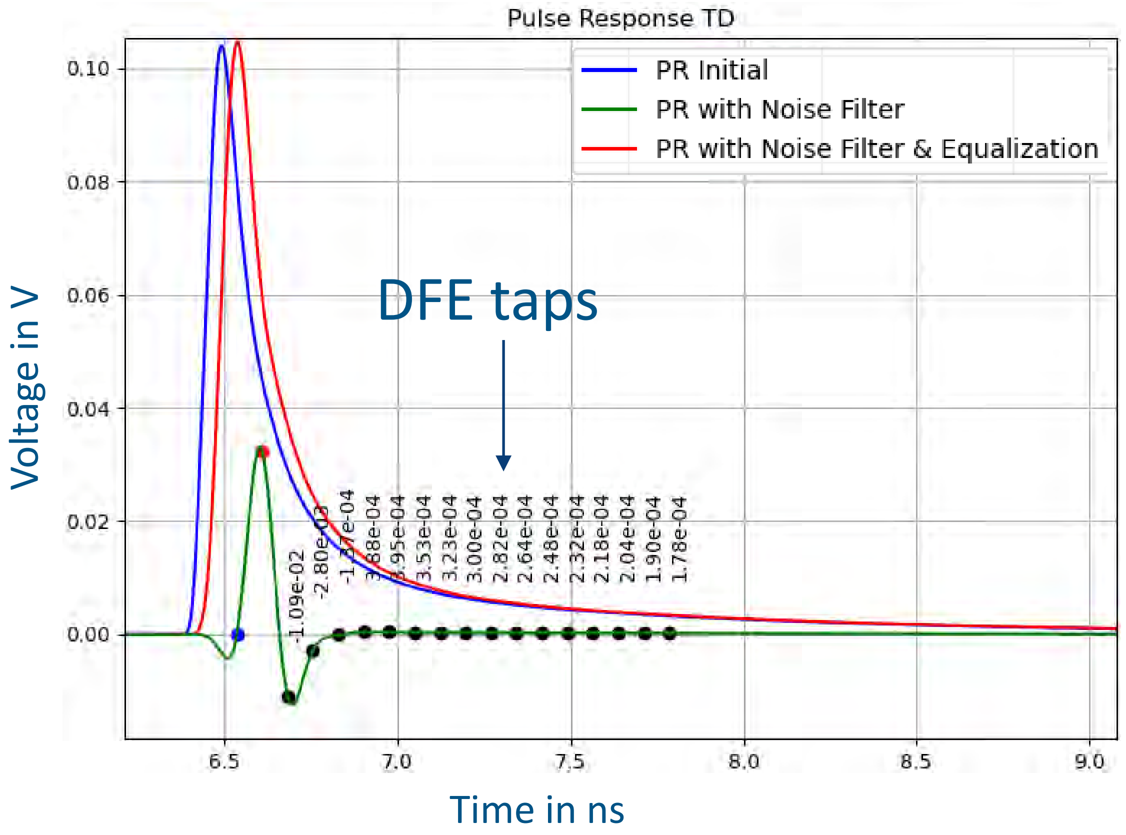
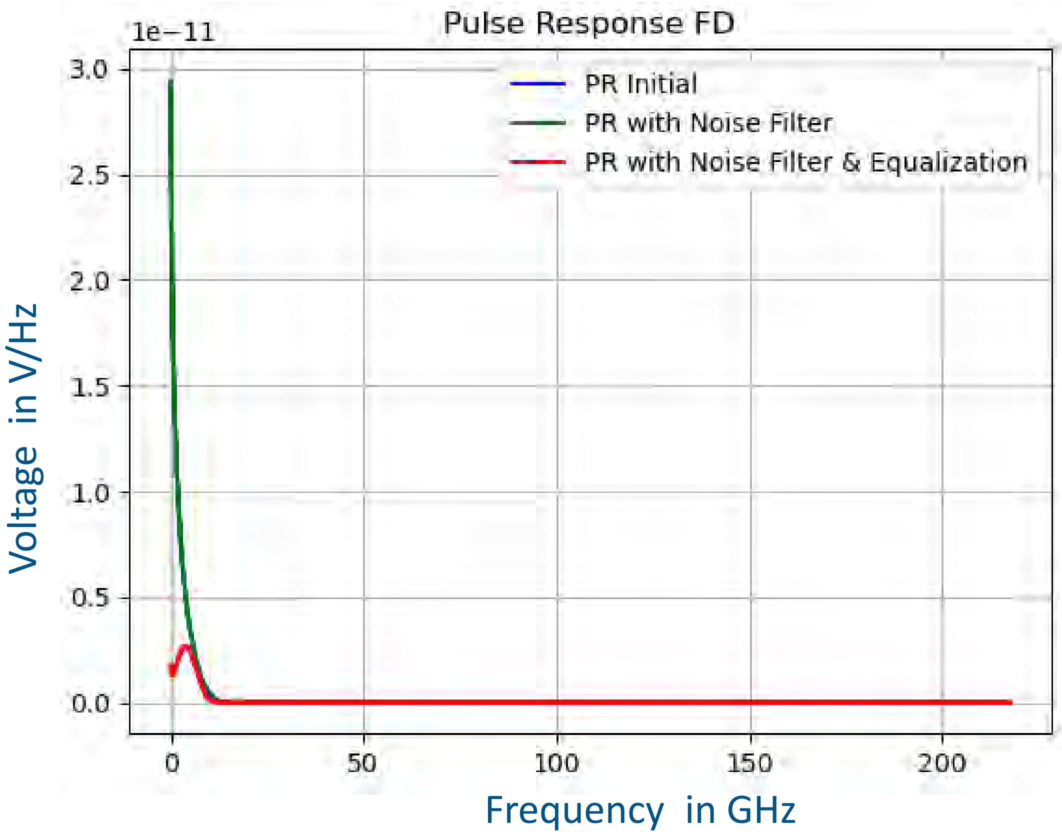


Figure of Merit
Max. FOM = [650, 18.05]
FOM in dB
20
0
−20
−40
−60
−80
−100
−120
−140
0
250
500
750
1000
1250
1500
1750
2000
sweep index for every combination of FFE and CTF setup.

PR: Pulse Response
FD: Frequency Domain
TD: Time Domain

Pulse Response (1/3) [4]

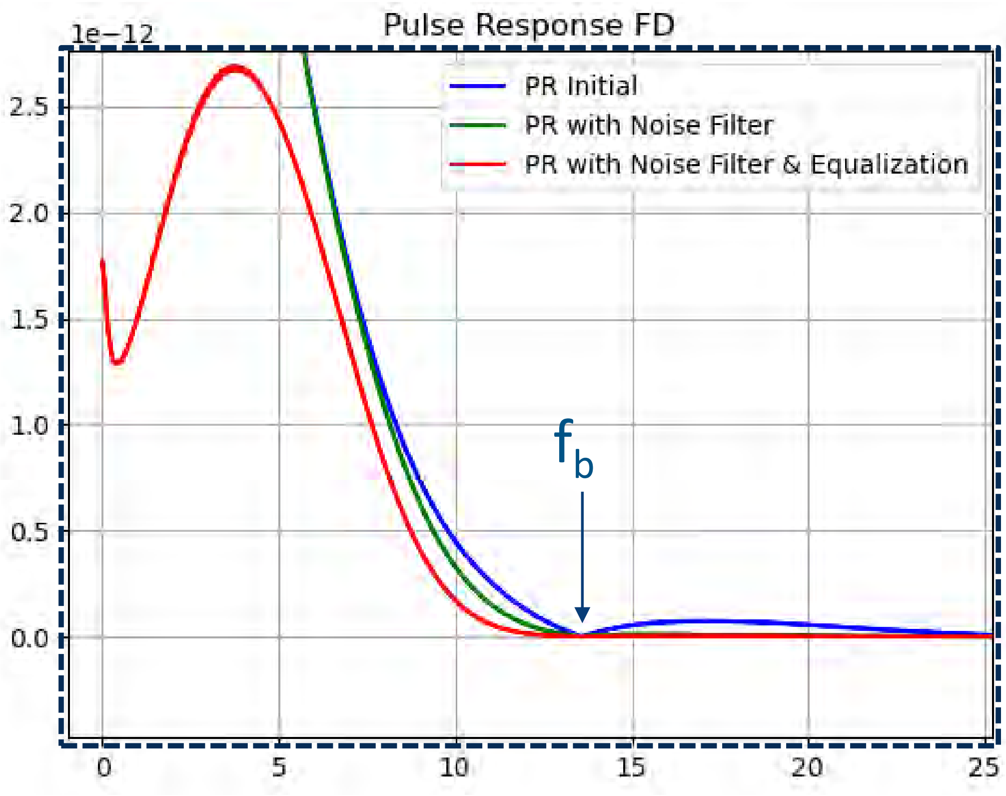


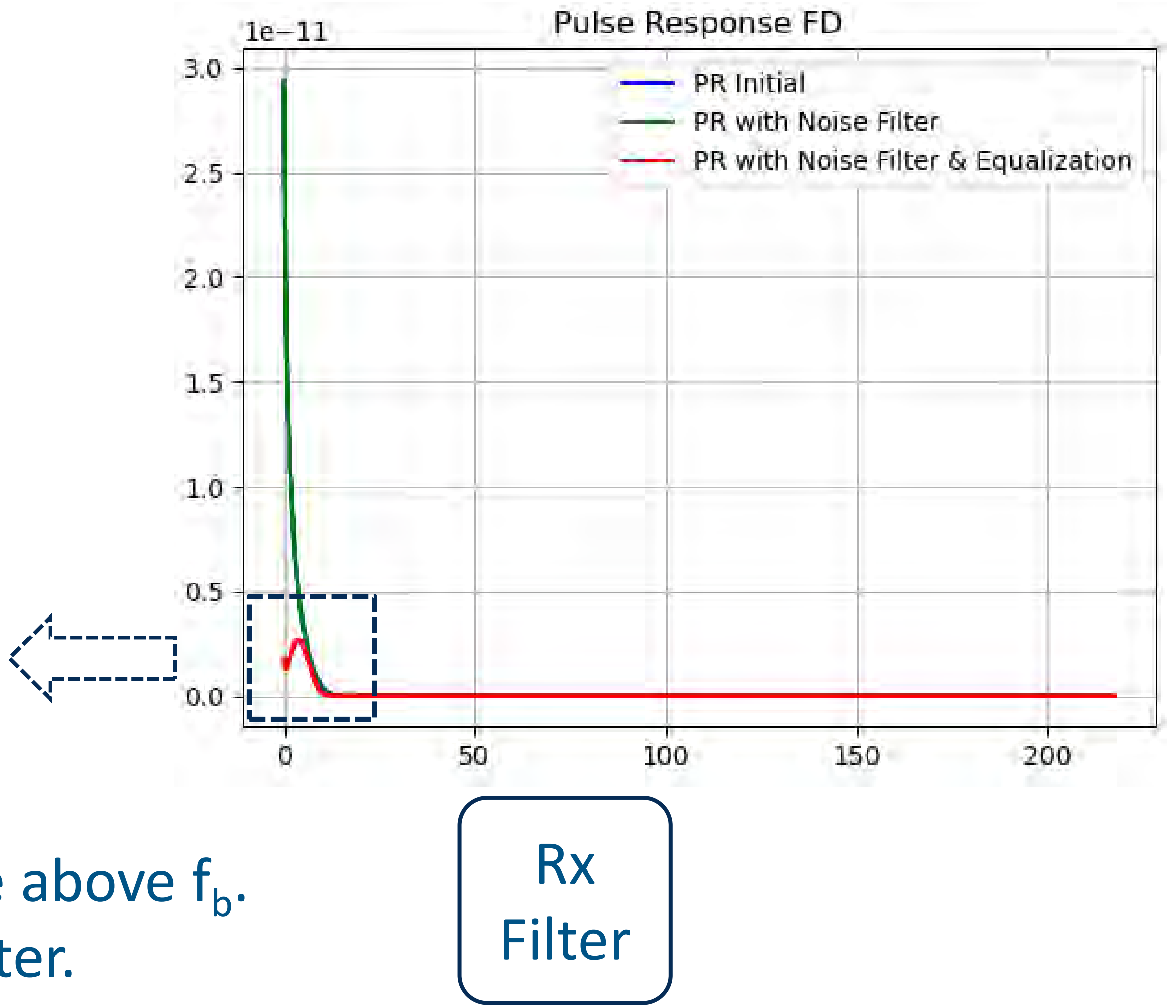


- ISI and signal amplitude is significantly reduced by equalization.

Pulse Response (2/3) [4]

PR: Pulse Response
FD: Frequency Domain
TD: Time Domain
Rx: Receiver

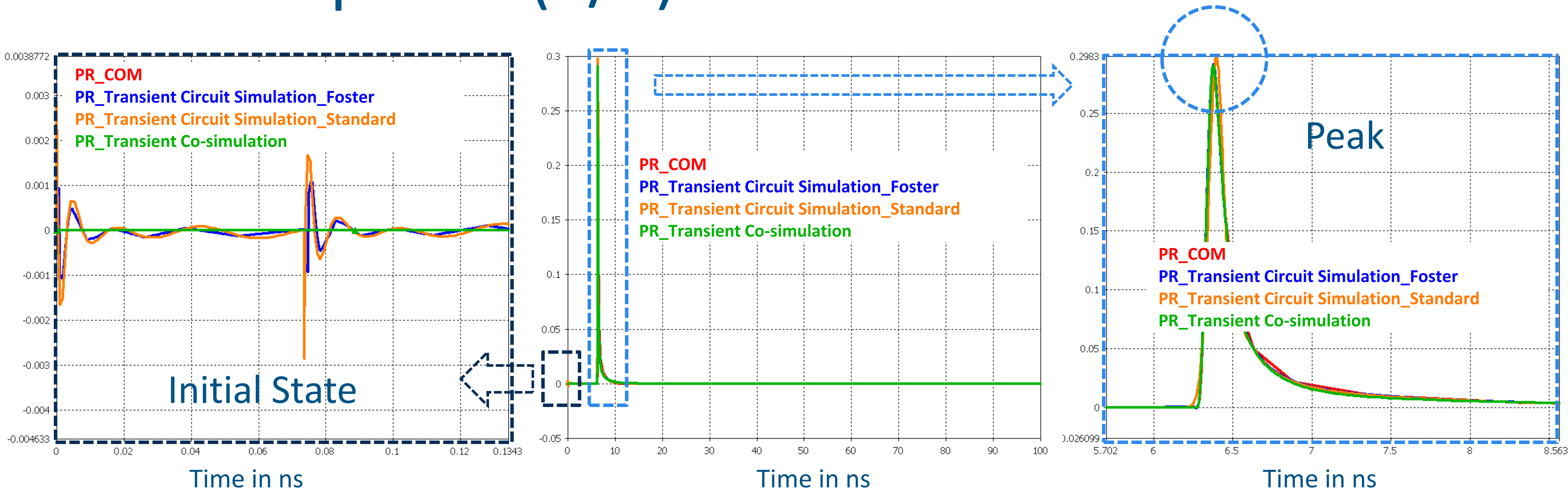




- Rx Noise Filter removes FD response above f_b.
- Equalization makes FD response flatter.

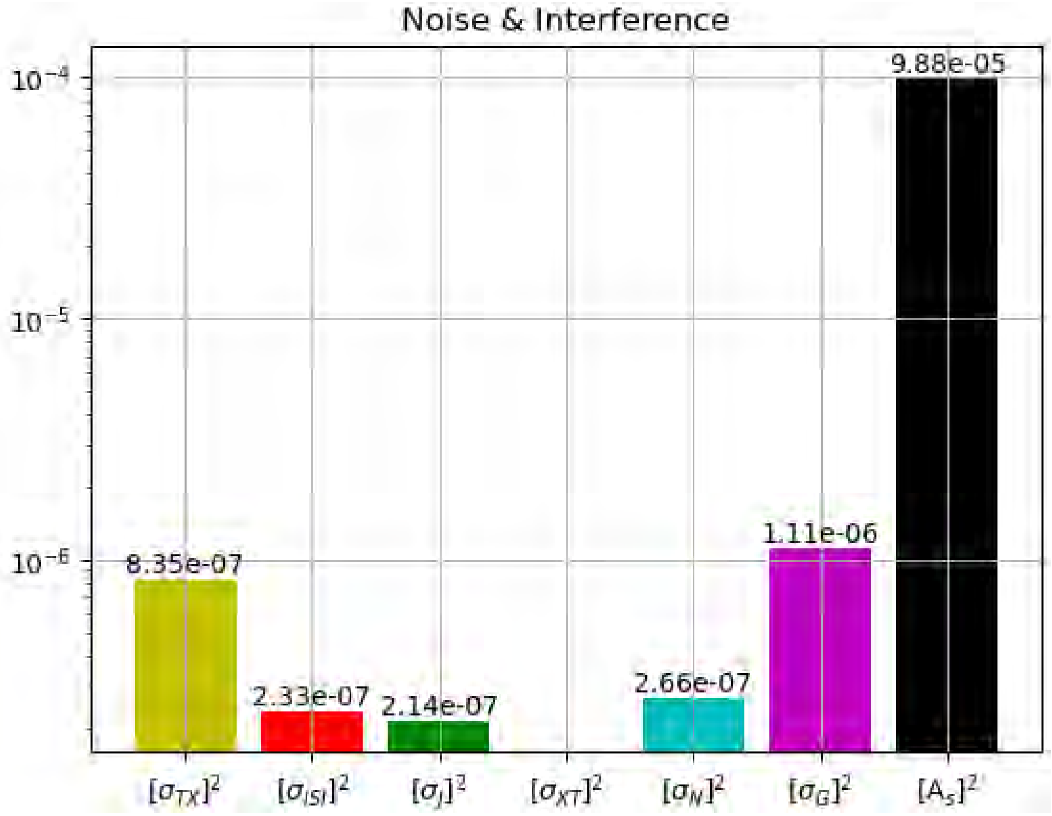
PR: Pulse Response
COM: Channel Operating Margin

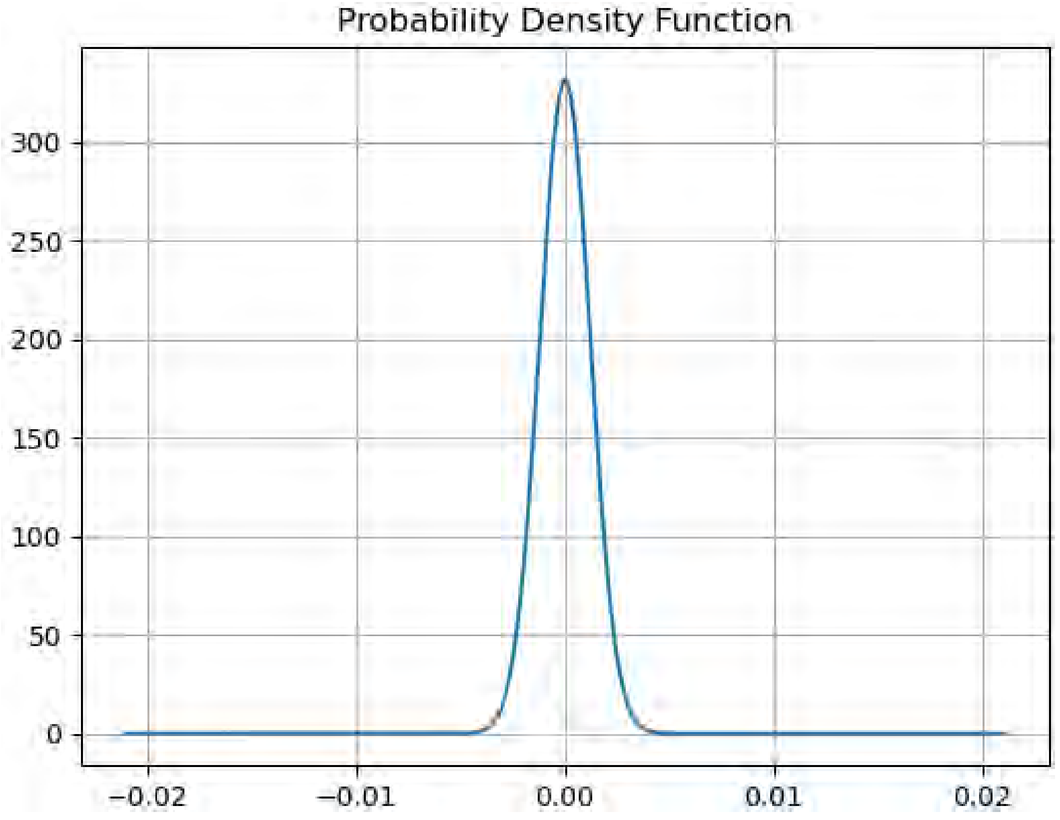
Pulse Response (3/3) [3][4]



- PR of COM can be validated by circuit simulations.
- As expected, standard macro model shows more noise at the peak and initial state than Foster because of the long propagation delay.
- Transient Co-simulation shows much less noise than macro modeling.

Noise Terms & PDF [4]



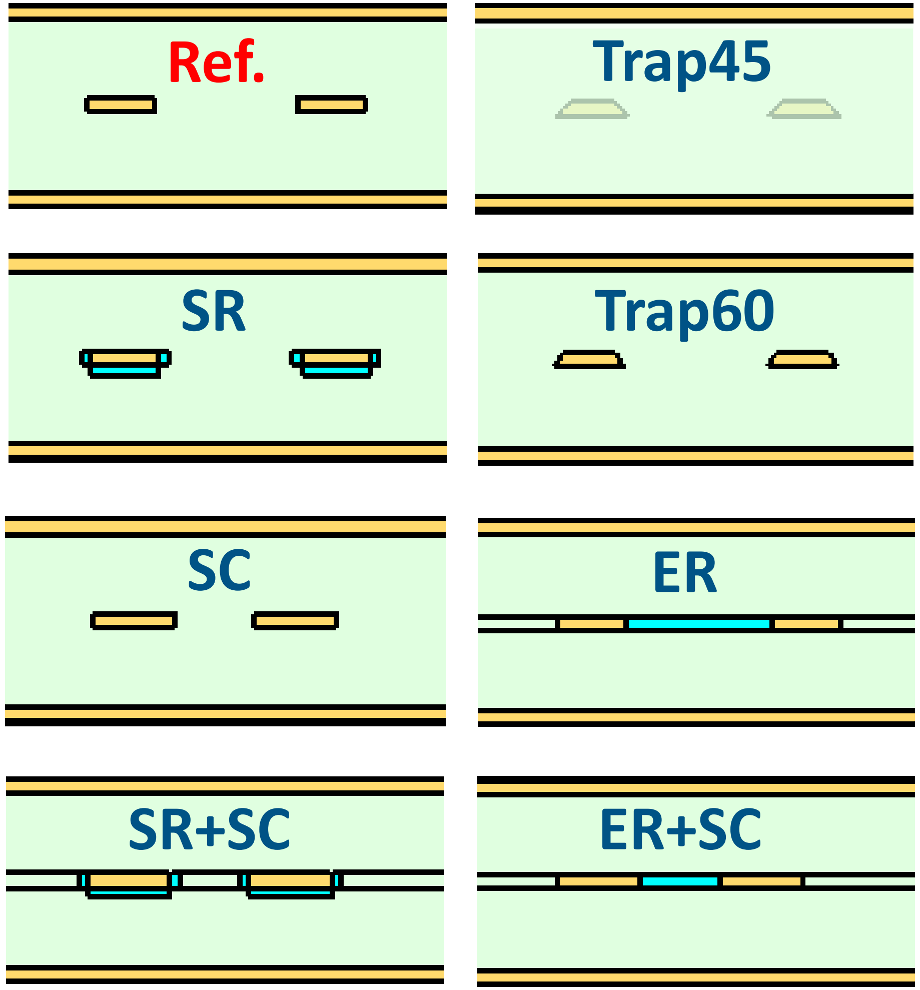


- No aggressor is simulated, so there's no XT terms.
- Tx noise is larger than ISI, which is significantly reduced by equalization.
- PDF is normalized to 1.

SR: Surface Roughness
SC: Strong Coupling
ER: Epoxy Resin

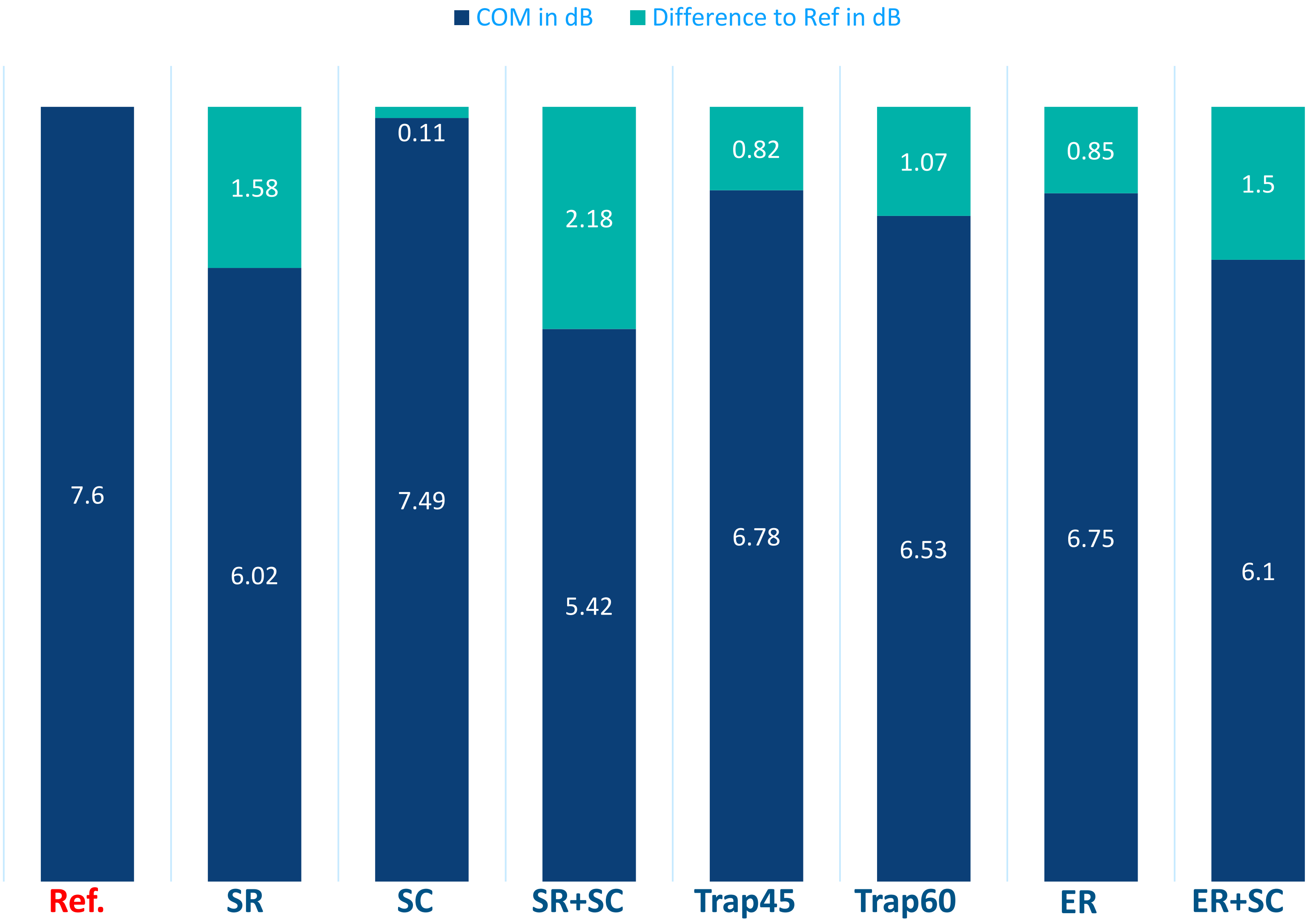
Comparison - Overview (1/6)

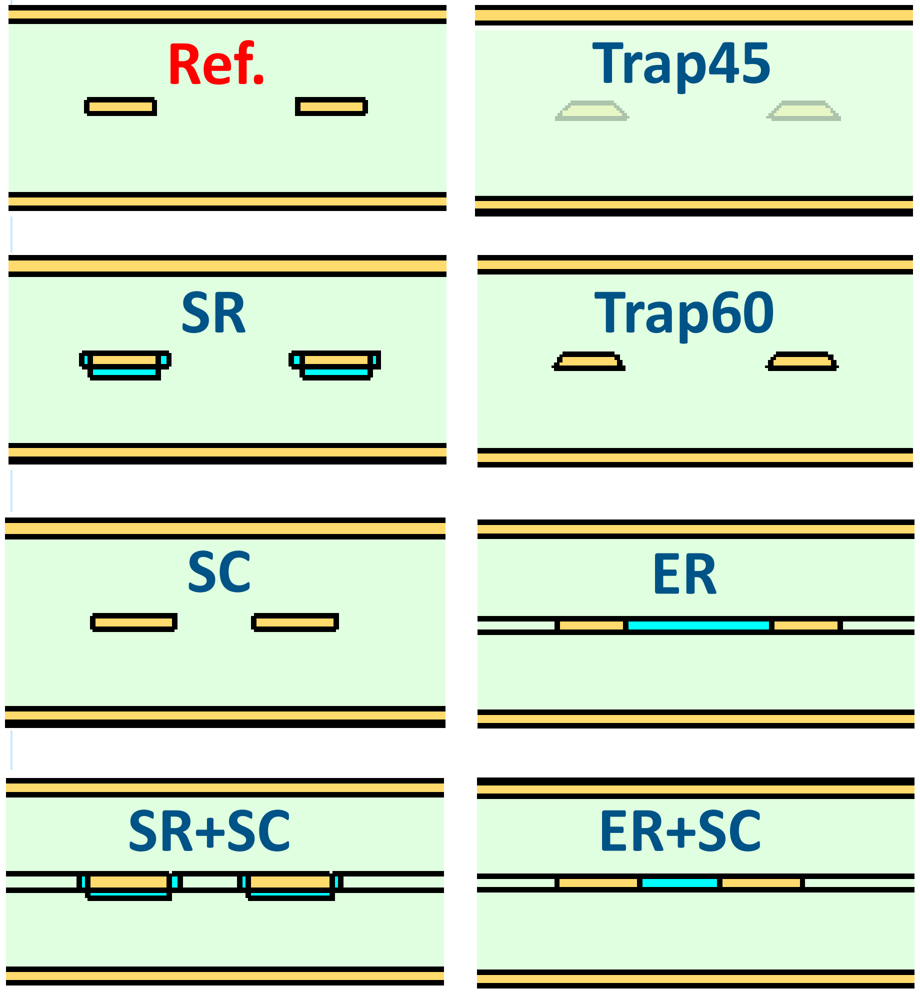
Models	Surface Roughness	Coupling	Etching	Epoxy Resin
Ref.	No	Weak	90°	No
SR	**Yes**	Weak	90°	No
SC	No	**Strong**	90°	No
SR+SC	**Yes**	**Strong**	90°	No
Trap45	No	Weak	**45°**	No
Trap60	No	Weak	**60°**	No
ER	No	Weak	90°	**Yes**
ER+SC	No	**Strong**	90°	**Yes**



SR: Surface Roughness
SC: Strong Coupling
ER: Epoxy Resin

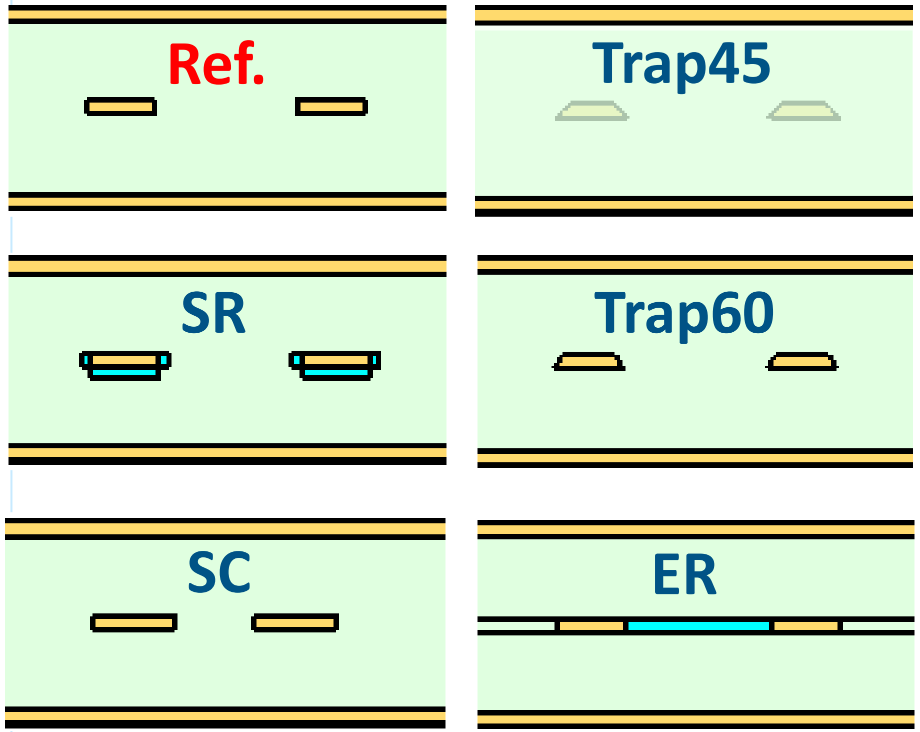
Comparison - Overview (2/6)





SR: Surface Roughness
SC: Strong Coupling
ER: Epoxy Resin
COM: Channel Operating Margin

Comparison - Individual Factors (3/6)

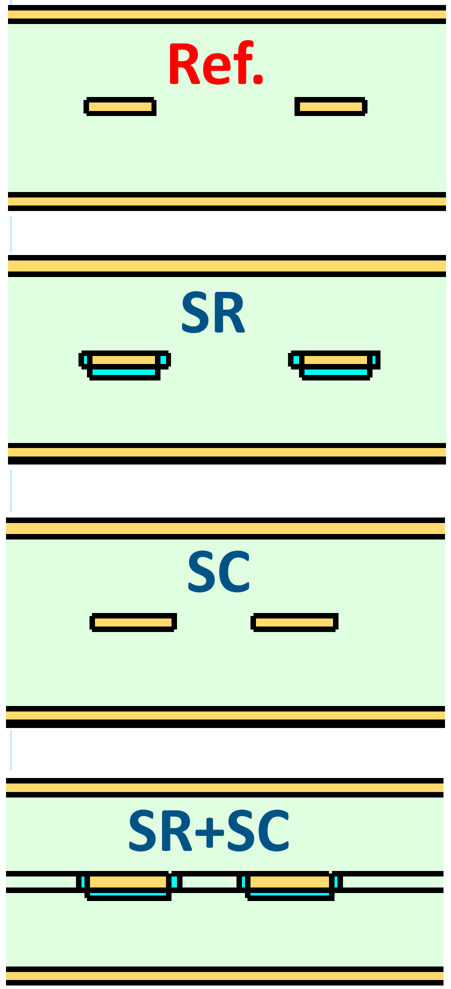


- Surface roughness is the most critical factor to consider and causes about 1.5 dB loss for COM.

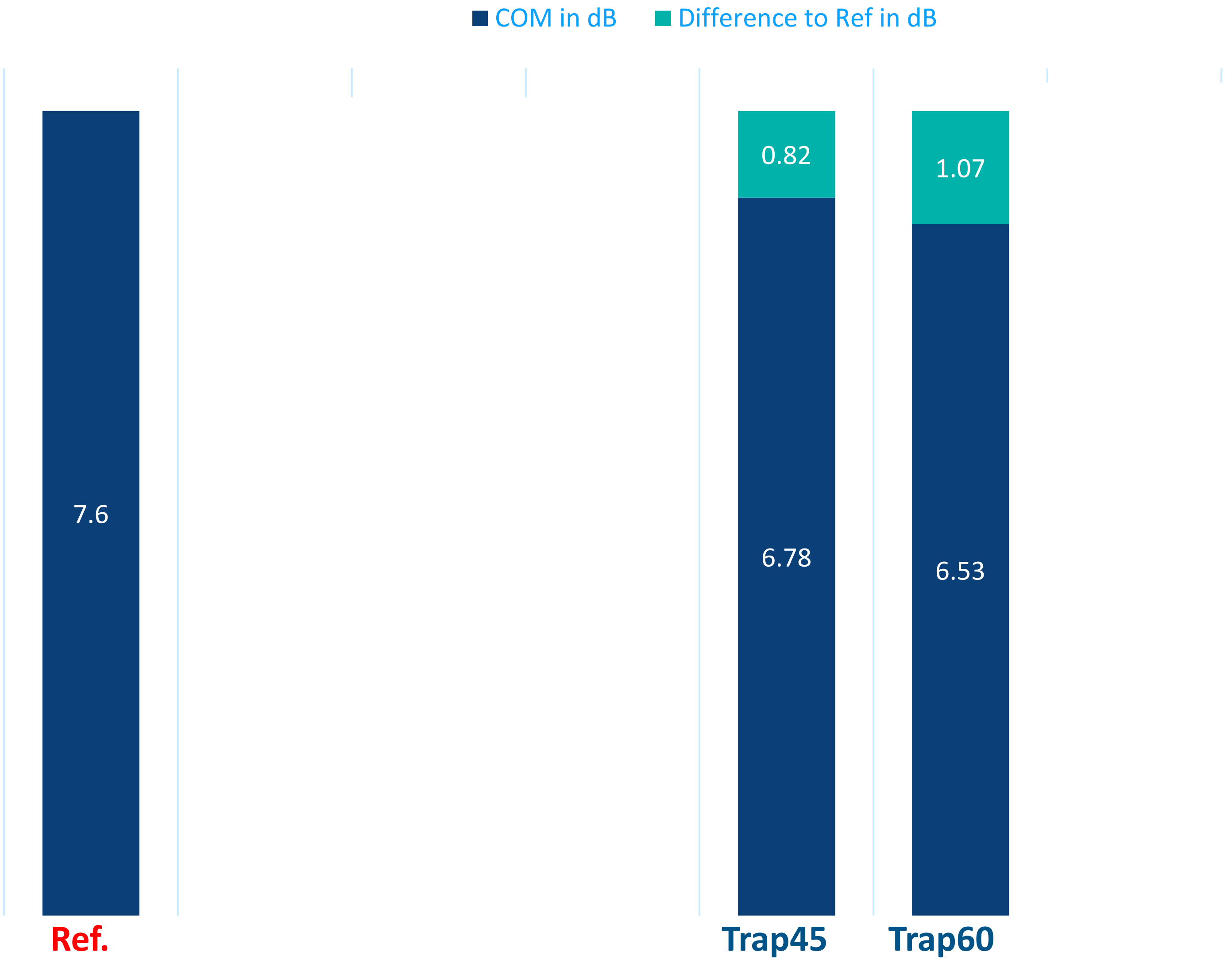
SR: Surface Roughness
SC: Strong Coupling
COM: Channel Operating Margin

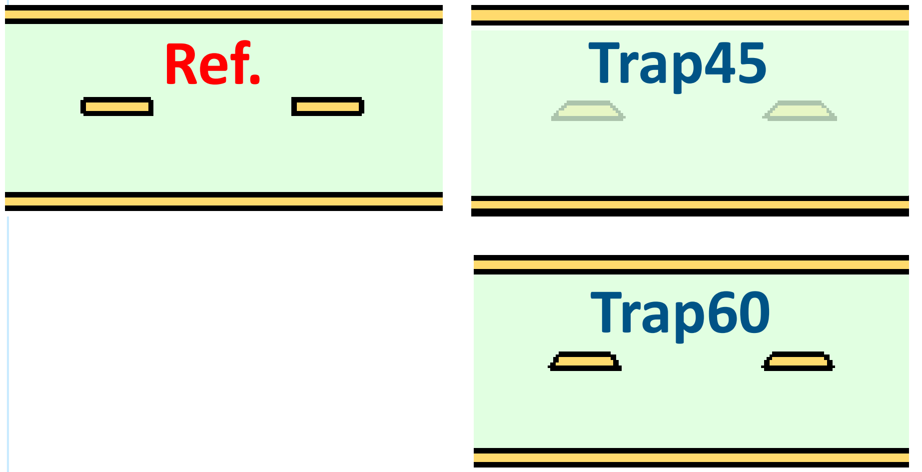
Comparison - SR (4/6)

- Strong coupling doesn’t change the results too much.
- Surface roughness has more impact on COM for the strong coupling case (in the sense 2.18 > 1.58 + 0.11 dB).



Comparison - Etching (5/6)

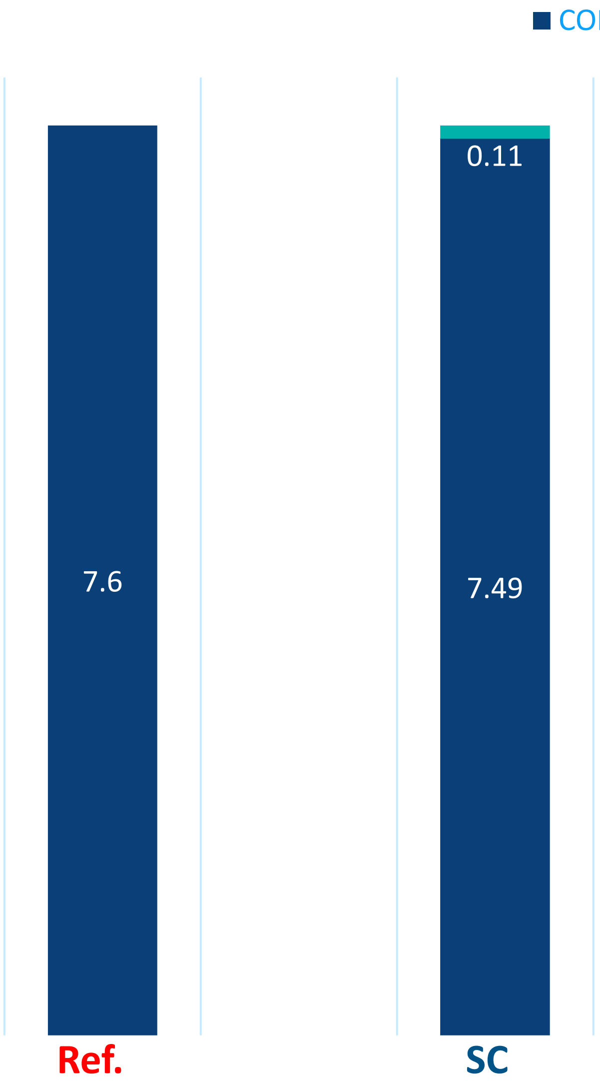




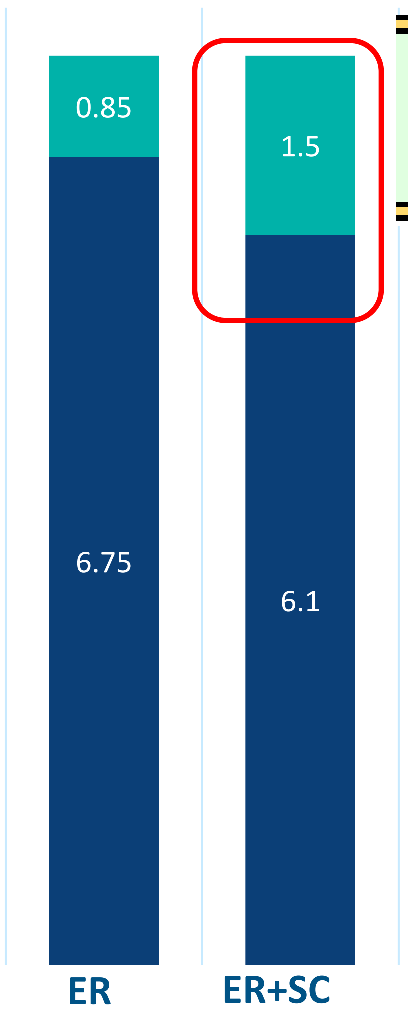
- Etch factor reduces COM about 1 dB.

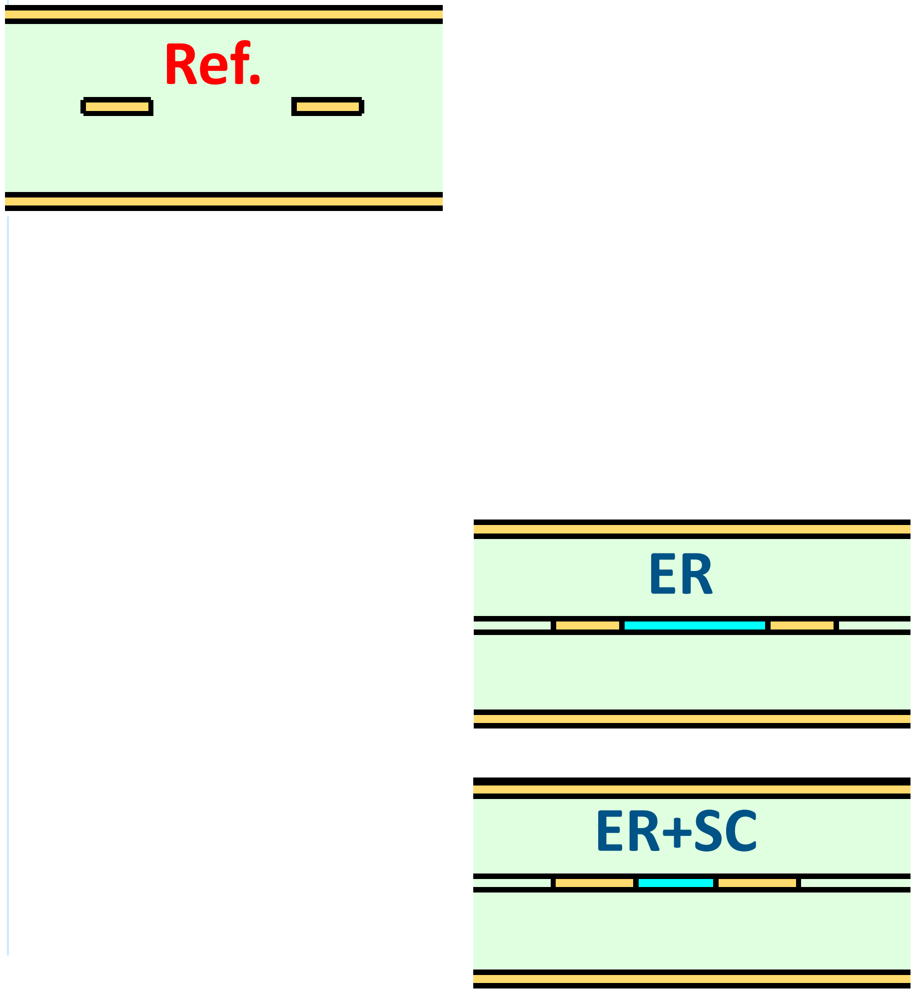
SC: Strong Coupling
ER: Epoxy Resin
COM: Channel Operating Margin

Comparison - ER (6/6)



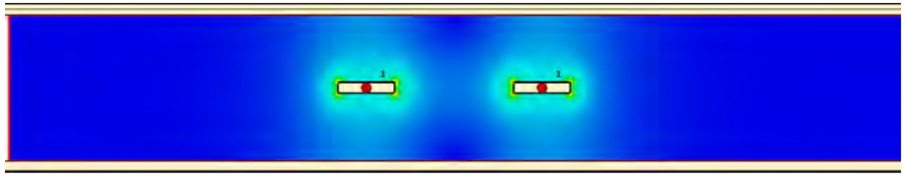
- Epoxy Resin between the diff. pair has also impact on COM.
- Epoxy Resin effect is more significant for designs with strong coupling (in the sense 1.5 > 0.85 + 0.11 dB)



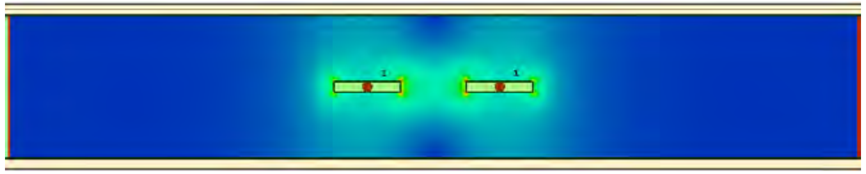


COM: Channel Operating Margin
PR: Pulse Response
SR: Surface Roughness
SC: Strong Coupling
ER: Epoxy Resin

Summary



Ref.



SC

- COM gives qualitative evaluation on passive channel designs in system level.
- COM PR can be validated by circuit simulations.
- SR effect is significant and should be considered according to COM analysis.
- If the diff. pair is strong coupled, effects of SR and ER can be more significant, which could be related to the field distribution.
- Etching and ER have also impact on the overall performance.

References

[1] IEEE Std. 802.3bj-2014.

[2] G. Zhang, M. Huang and H. Zhang, “COM for PAM4 Link Analysis – what you need to know”, *EDI CON USA, 2018*.

[3] Dassault Systèmes, https://www.3ds.com/

[4] J. D. Hunter, “Matplotlib: A 2D Graphics Environment”, Computing in Science & Engineering, vol. 9, no. 3, pp. 90-95, 2007

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