212 Gb/s PAM4 per Lane C2M Channels
A Via Length Performance Study

Rick Rabinovich
September 21, 2022

KEYSIGHT TECHNOLOGIES

200G PAM4 C2M Via Length Effect Study

Contributors and Supporters

Contributors:

Ali Hammoodi	- Amphenol
Richard Mellitz	- SAMTEC

Supporters:

Sam Kocsis	- Amphenol
Richard Mellitz	- SAMTEC
Liav Ben-Artsi	- Marvell

200G PAM4 C2M Via Length Effect Study

Objectives

- Study the effect of via length in channel performance
  - ✓ Via lengths = 19/67/93 mil
- Investigate the effect of Raised Cosine vs. Butterworth filter performance
- Illustrate the paradox when cascading s-parameters of vias and connector models

The intention of this presentation is <u>NOT</u> to:

- ✓ Discuss specific materials
- ✓ Discuss specific implementations
- ✓ Discuss specific ASIC footprints
- ✓ Recommend specific receive filters

The intention of this presentation is to:

- ✓ Contribute six "optimized" channels based on "actual" channel implementations which includes the ASIC breakout, routing, via transitions, and the latest OSFP model available
  - ➢ Via antipads in PCB inner layers were optimized using HFSS Optimetrix
- ✓ Provide channels with **<u>impairments</u>** that seasoned design engineers will encounter when implementing channels operating at 224 Gb/s per lane.
- ✓ Analyze receiver equalization solutions to pass COM

KEYSIGHT TECHNOLOGIES

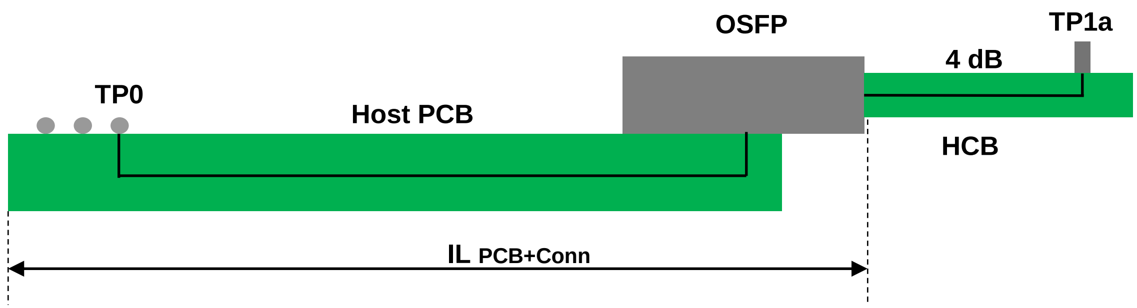
200G PAM4 C2M Via Length Effect Study

C2M Channel Highlights

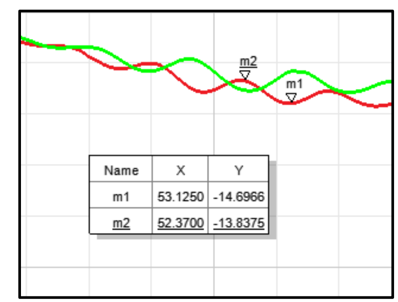
- Traditional Topology, i.e., medium PCB material between ASIC and Connector
  - ❖ Short Channel - Ex. NIC card
- Short Host Channel
  - ❖ Well engineered challenging channel
  - ❖ Includes Huray model for copper roughness
- Channel with IMPAIRMENTS
  - ❖ ASIC/Connector vias and module finger transition
  - ❖ Layout trace turns
  - ❖ Skew compensation
  - ❖ Full channel crosstalk
- MDI is an OSFP connector model
- Crosstalk source mostly at the connector and footprint
- HCB – Ideal transmission line with IL=4.0 dB @ Nyquist
- COM rev. 3.8 BetaL – Includes raise cosine option
  - Spreadsheets taken from Mellitz_3df_elec_01_220621.pdf - Slides 17 and 18

200G PAM4 C2M Via Length Effect Study

Structure View & Insertion Losses



- **Full Structure:**
  - **Two adjacent channels**
    - ➢ **Matching segmentation meshing (i.e., common minimum element size)**
  - **Connector integrated with PCB**
  - **HCB is ideal transmission line with IL = 4 dB @ Nyquist**
  - **NEXT is evaluated at the ASIC model for more realistic results**
- **Vias = 19/67/93 mil long**
- **Blind Vias**
- **Frequency Sweep Range = 10 MHz to 120 GHz**



Reflections Effect

IL @ Nyquist (53.125 GHz)

Parallel Breakout

- $IL_{PCB+Conn}$ = 8.24/9.32/10.31 dB
- IL_{HCB} = 4 dB
- $IL_{TP0\text{-}to\text{-}TP1a}$ = 12.27/13.32/13.44 dB

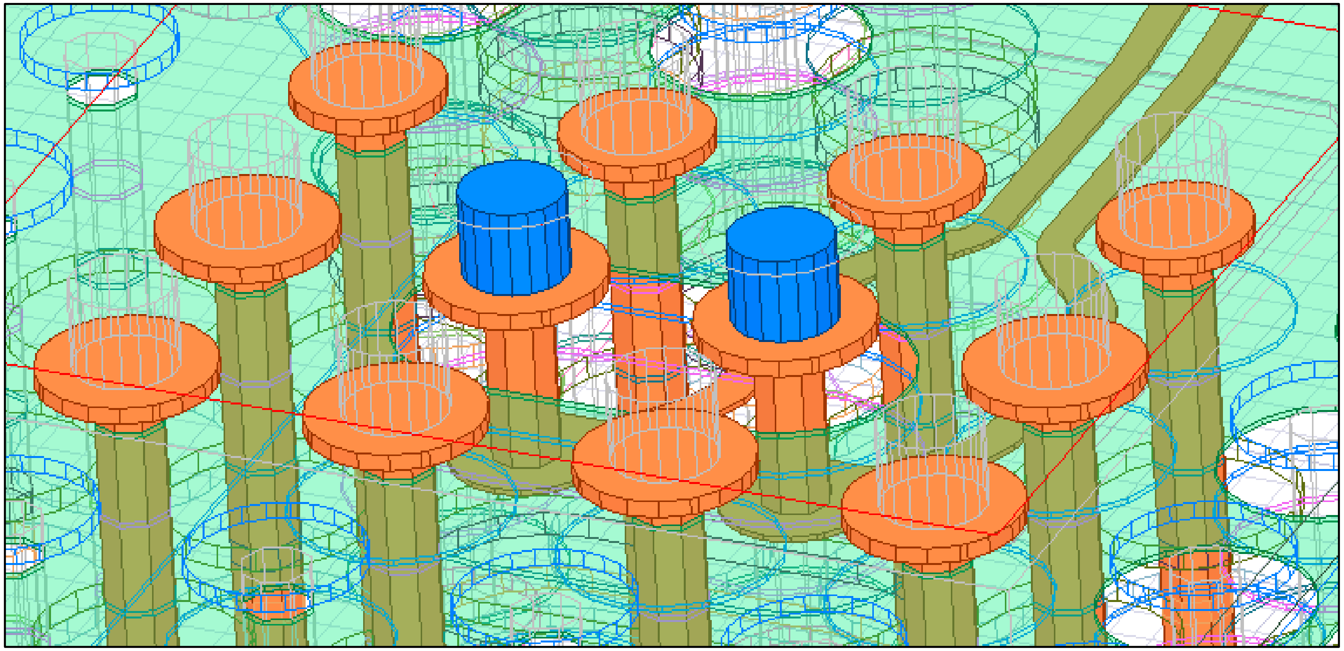
Orthogonal Breakout

- $IL_{PCB+Conn}$ = 8.34/10.69/10.14 dB
- IL_{HCB} = 4 dB
- $IL_{TP0\text{-}to\text{-}TP1a}$ = 12.38/14.69/14.17 dB

KEYSIGHT TECHNOLOGIES

200G PAM4 C2M Via Length Effect Study

ASIC Ball Model Example

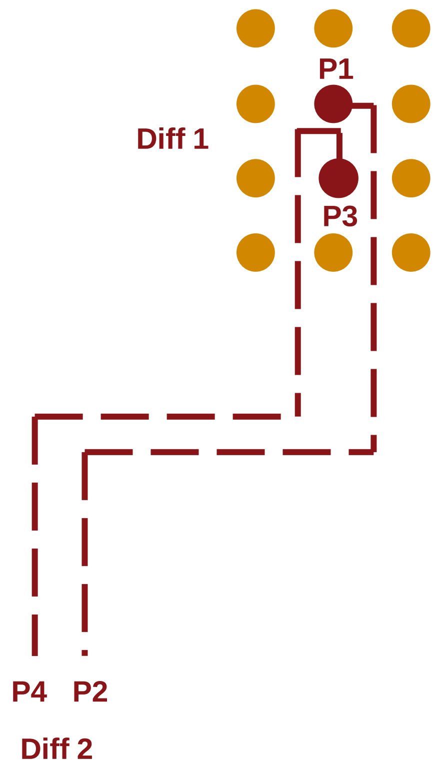


Cp already included in model => Cp=0

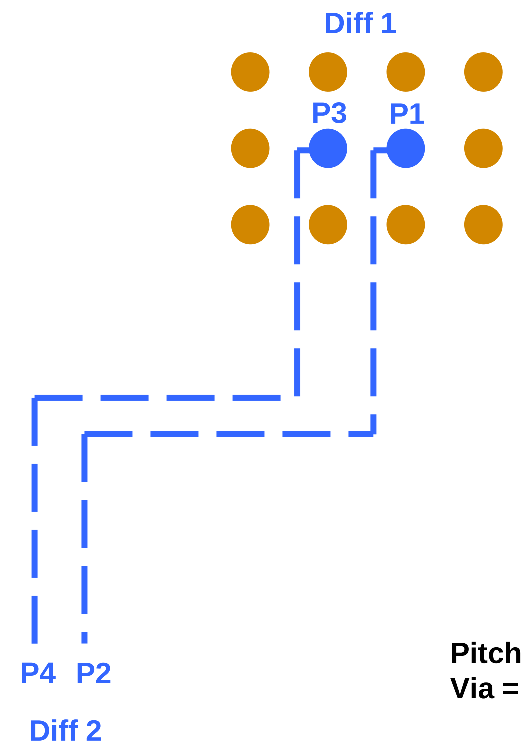
200G PAM4 C2M Via Length Effect Study

Two ASIC breakouts: Orthogonal vs. Parallel

Orthogonal Breakout



Parallel Breakout

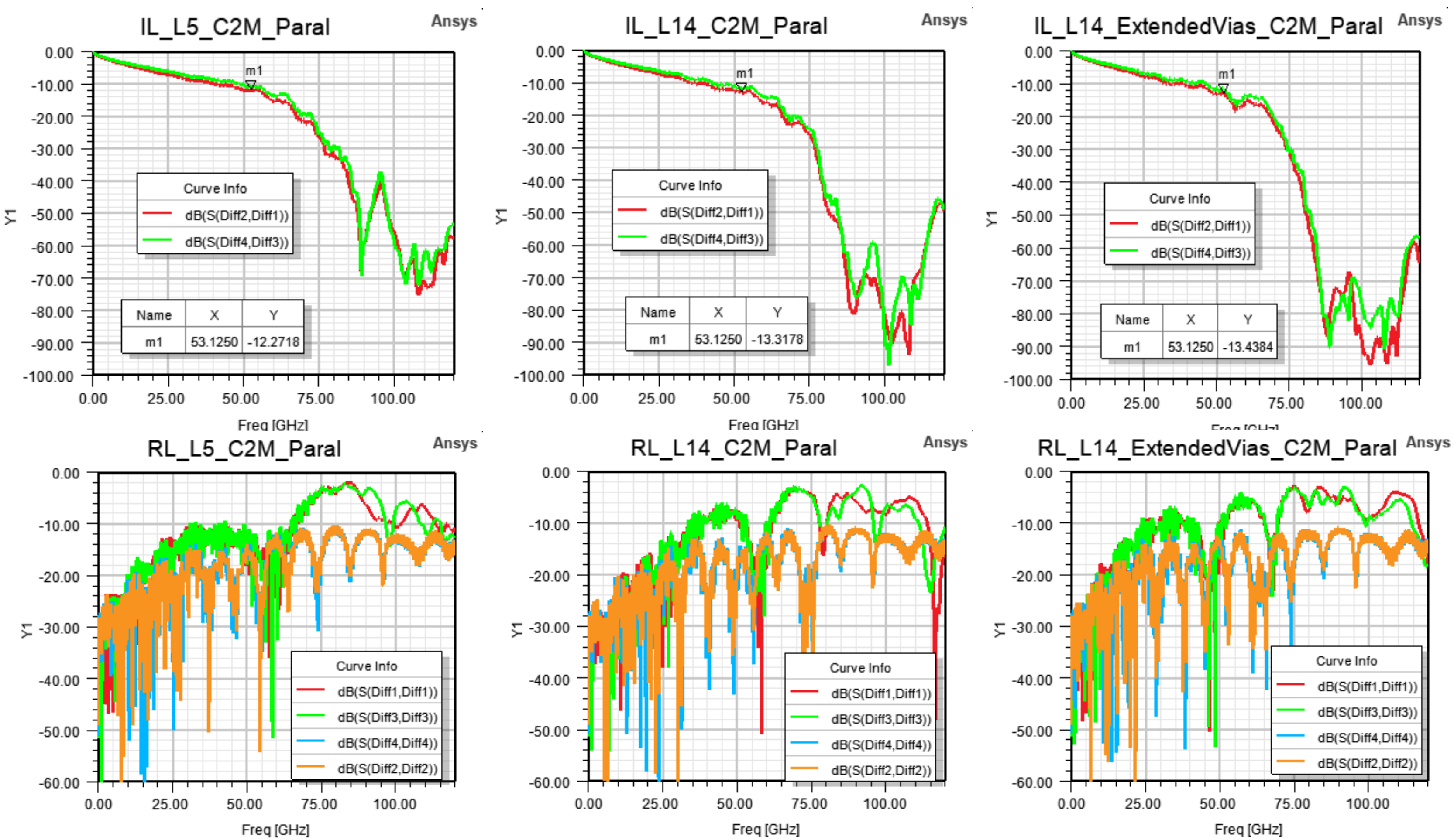


Pitch = 0.8 mm
Via = 1 mm

200G PAM4 C2M Via Length Effect Study

Parallel Breakout - IL/RL Performance

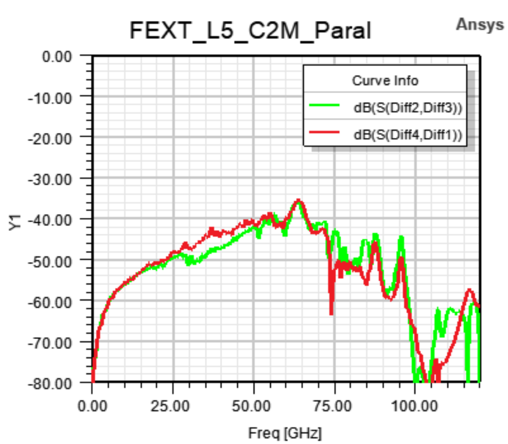
19 mil | 67mil | 93 mil

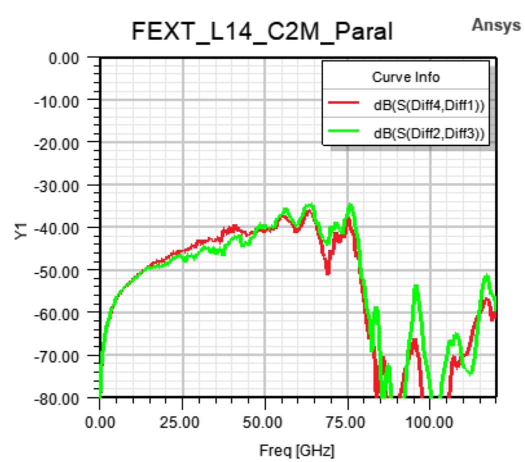


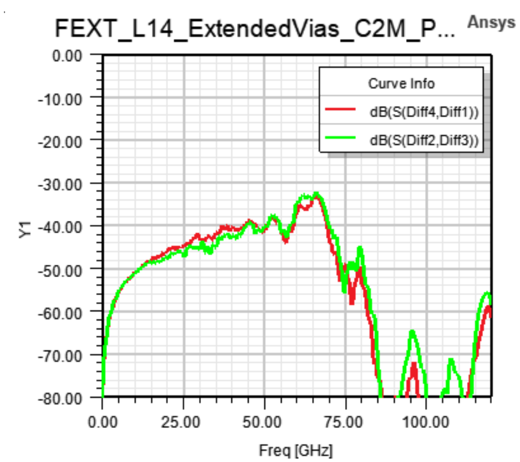
200G PAM4 C2M Via Length Effect Study

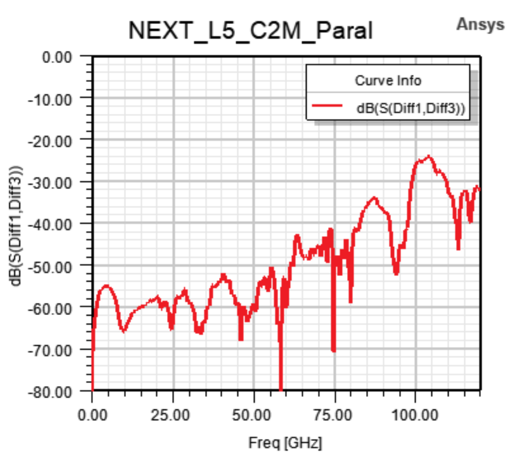
Parallel Breakout - FEXT/NEXT(ASIC) Performance

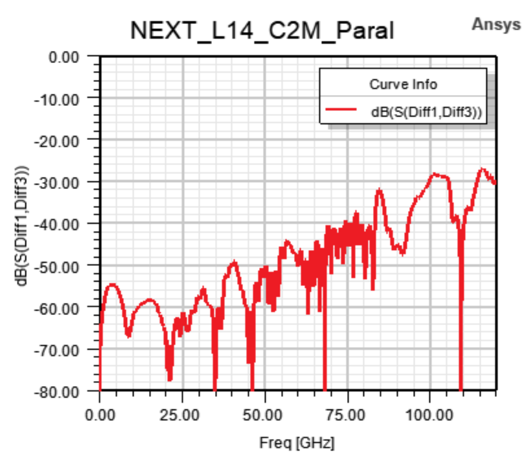
19 mil | 67mil | 93 mil

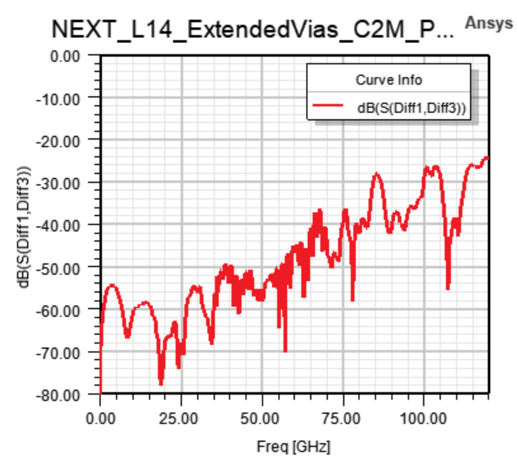








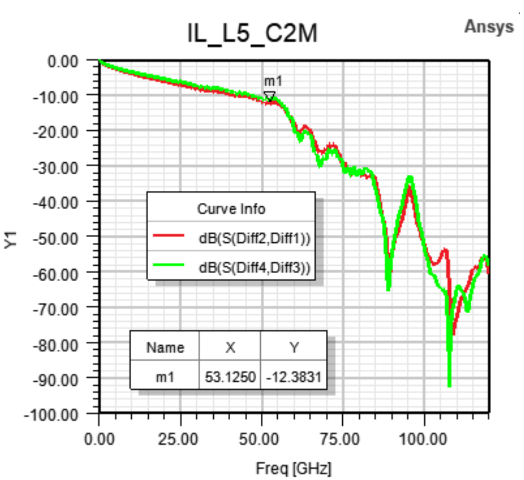


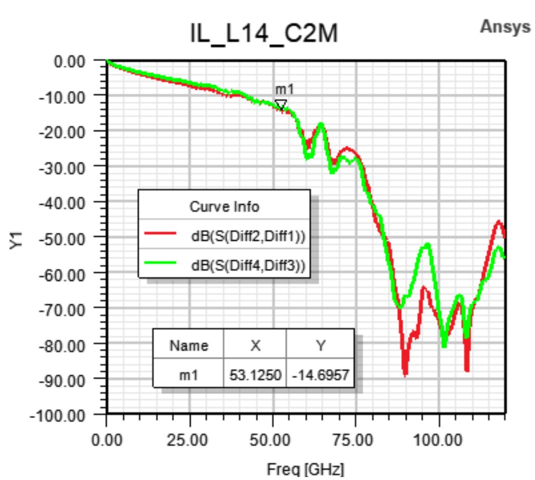


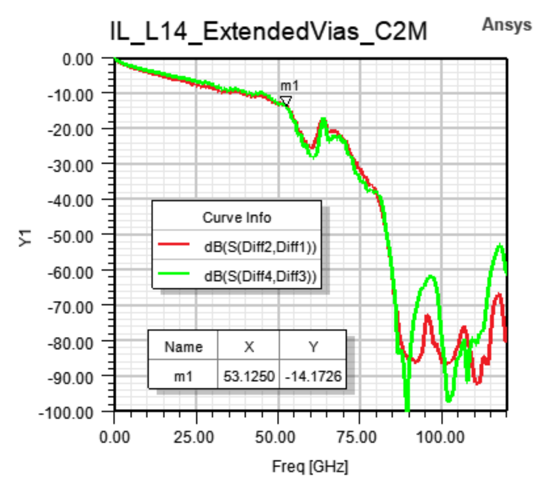
200G PAM4 C2M Via Length Effect Study

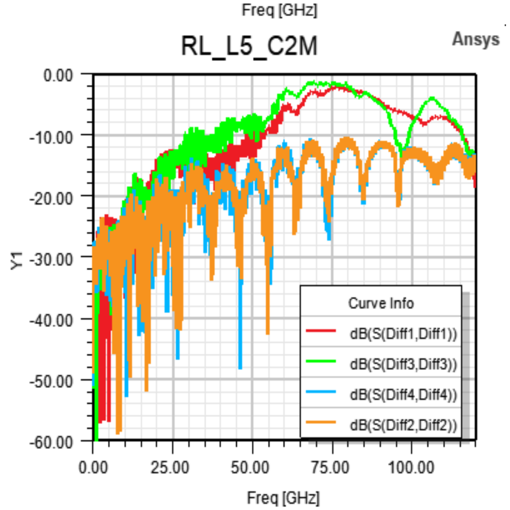
Orthogonal Breakout - IL/RL Performance

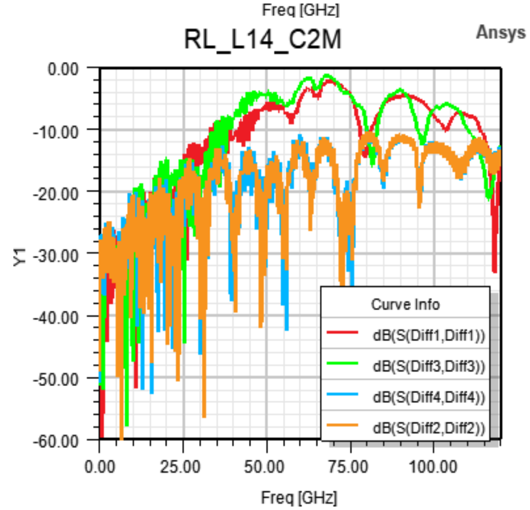
19 mil | 67mil | 93 mil

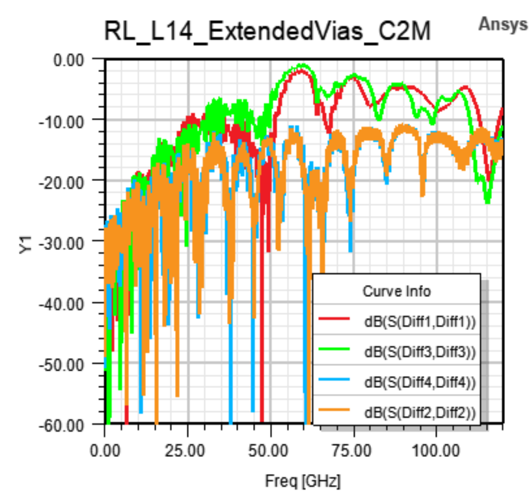








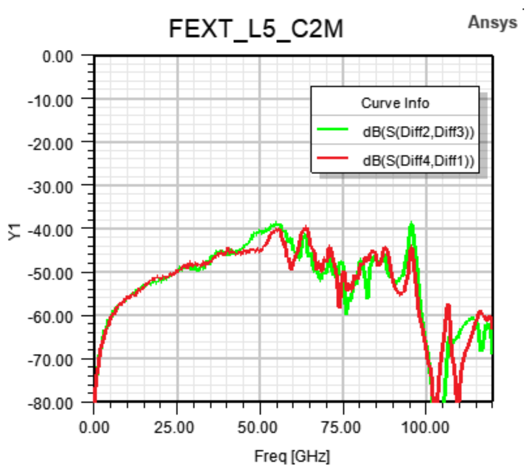


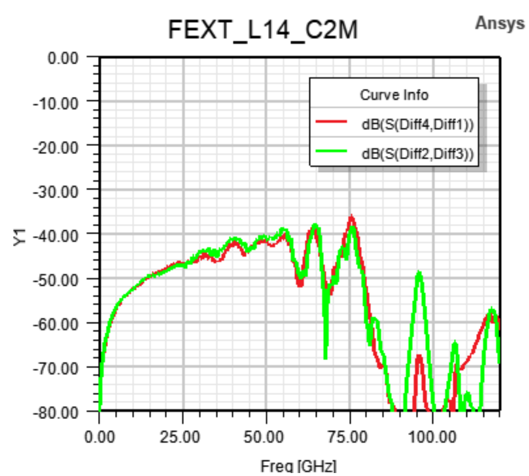


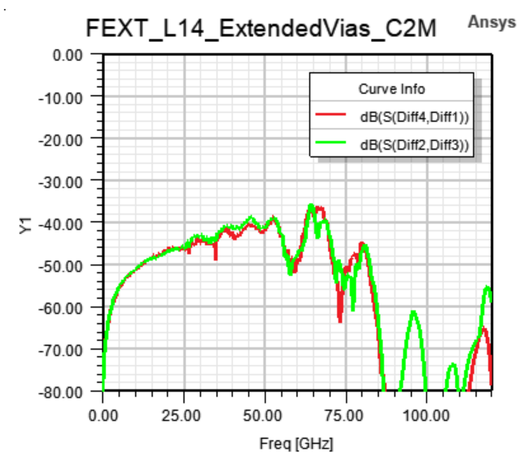
200G PAM4 C2M Via Length Effect Study

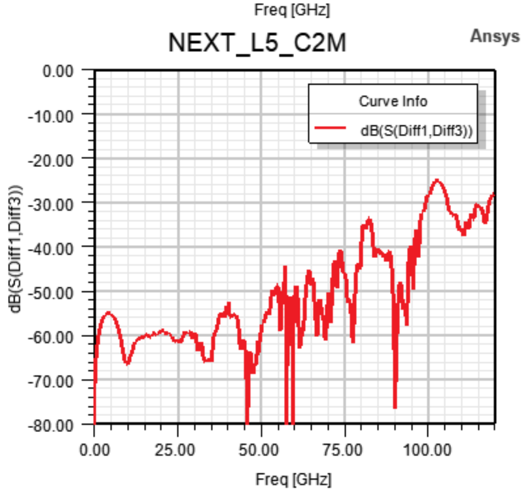
Orthogonal Breakout – FEXT/NEXT(ASIC) Performance

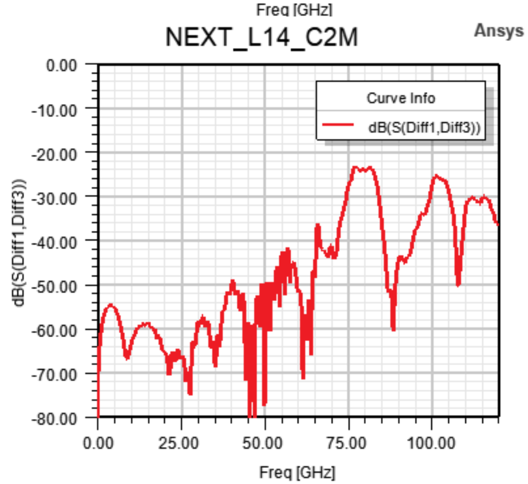
19 mil | 67mil | 93 mil

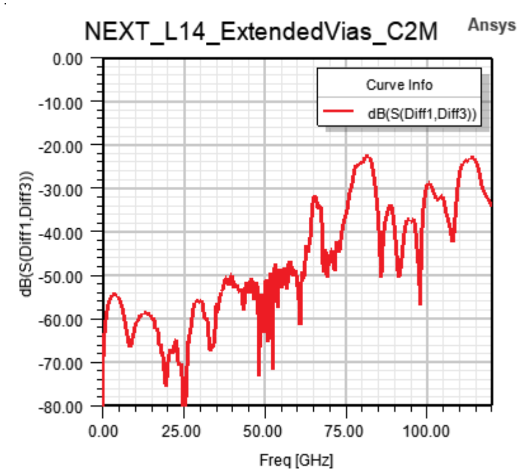












200G PAM4 C2M Via Length Effect Study

Structures and COM Configurations

- Three Via Lengths
  - ✓ 19 mil – 67 mil – 93 mil

- Two Breakouts
  - ✓ Parallel
  - ✓ Orthogonal
-
- Two Filters
  - ✓ Butterworth
  - ✓ Raised Cosine (starts @ 42.5 GHz, ends @ 80 GHz)

- Two Equalization Strengths *:

Equalization	DER_0	SNR_TX	eta_0	Float. Taps
Less Aggressive	1.00E-05	32.5	2.05E-08	NO
More Aggressive	5.00E-05	34	2.05E-09	YES

* **Slides 17 and 18 - Mellitz_3df_elec_01_220621.pdf**

KEYSIGHT TECHNOLOGIES

200G PAM4 C2M Via Length Effect Study

COM Results

2 FEXTs - 1 NEXT - Small Package

Orthogonal Breakout

Case #	Via Length	C2M Configuration	Filter	DER_0	SNR_TX	eta_0	Float. Taps	EH (mV)	VEC (dB)	COM (dB)	ICN	ERL (dB)	DER
1	19 mil	Less Aggressive	Butterworth	1.00E-05	32.5	2.05E-08	NO	18.7	9.06	3.77	1.47	18.1	1.05E-12
2	19 mil	More Aggressive	Butterworth	5.00E-05	34	2.05E-09	YES	25.7	5.59	6.47	1.47	18.6	6.70E-26
3	19 mil	Less Aggressive	Raised Cosine	1.00E-05	32.5	2.05E-08	NO	19.3	8.19	4.29	1.47	18.1	6.75E-15
4	19 mil	More Aggressive	Raised Cosine	5.00E-05	34	2.05E-09	YES	30.3	5.16	6.98	1.47	18.6	7.10E-34
5	67 mil	Less Aggressive	Butterworth	1.00E-05	32.5	2.05E-08	NO	9.2	12.79	2.26	2.04	17.5	8.27E-09
6	67 mil	More Aggressive	Butterworth	5.00E-05	34	2.05E-09	YES	19.9	7.30	4.91	2.04	18.1	3.01E-14
7	67 mil	Less Aggressive	Raised Cosine	1.00E-05	32.5	2.05E-08	NO	15.8	9.78	3.40	2.04	17.5	2.11E-11
8	67 mil	More Aggressive	Raised Cosine	5.00E-05	34	2.05E-09	YES	24.1	5.99	6.05	2.04	18.1	5.35E-21
9	93 mil	Less Aggressive	Butterworth	1.00E-05	32.5	2.05E-08	NO	5.6	18.36	1.12	2.27	15.4	5.09E-07
10	93 mil	More Aggressive	Butterworth	5.00E-05	34	2.05E-09	YES	17.0	8.23	4.26	2.27	15.9	6.62E-12
11	93 mil	Less Aggressive	Raised Cosine	1.00E-05	32.5	2.05E-08	NO	11.5	12.19	2.45	2.27	15.4	3.57E-09
12	93 mil	More Aggressive	Raised Cosine	5.00E-05	34	2.05E-09	YES	19.9	6.65	5.43	2.27	15.9	1.15E-16

Parallel Breakout

Case #	Via Length	C2M Configuration	Filter	DER_0	SNR_TX	eta_0	Float. Taps	EH (mV)	VEC (dB)	COM (dB)	ICN	ERL (dB)	DER
1	19 mil	Less Aggressive	Butterworth	1.00E-05	32.5	2.05E-08	NO	15.2	10.18	3.22	1.79	18.3	5.66E-11
2	19 mil	More Aggressive	Butterworth	5.00E-05	34	2.05E-09	YES	25.8	6.23	5.82	1.79	18.8	3.06E-19
3	19 mil	Less Aggressive	Raised Cosine	1.00E-05	32.5	2.05E-08	NO	19.8	8.66	4.00	1.79	18.3	1.99E-13
4	19 mil	More Aggressive	Raised Cosine	5.00E-05	34	2.05E-09	YES	26.0	5.53	6.54	1.79	18.8	4.97E-26
5	67 mil	Less Aggressive	Butterworth	1.00E-05	32.5	2.05E-08	NO	10.1	13.27	2.12	2.36	17.9	1.39E-08
6	67 mil	More Aggressive	Butterworth	5.00E-05	34	2.05E-09	YES	20.6	8.19	4.29	2.36	18.5	2.75E-12
7	67 mil	Less Aggressive	Raised Cosine	1.00E-05	32.5	2.05E-08	NO	16.2	10.36	3.14	2.36	17.9	1.12E-10
8	67 mil	More Aggressive	Raised Cosine	5.00E-05	34	2.05E-09	YES	23.4	6.49	5.58	2.36	18.5	7.34E-18
9	93 mil	Less Aggressive	Butterworth	1.00E-05	32.5	2.05E-08	NO	7.9	16.38	1.43	2.62	15.0	1.81E-07
10	93 mil	More Aggressive	Butterworth	5.00E-05	34	2.05E-09	YES	17.8	9.19	3.70	2.62	15.5	1.73E-10
11	93 mil	Less Aggressive	Raised Cosine	1.00E-05	32.5	2.05E-08	NO	13.6	12.20	2.45	2.62	15.0	3.48E-09
12	93 mil	More Aggressive	Raised Cosine	5.00E-05	34	2.05E-09	YES	24.1	7.09	5.07	2.62	15.5	3.29E-15

*** Pass: EHmin = 10 mV; VECmax = 12.5; ERLmin = 10**

200G PAM4 C2M Via Length Effect Study

COM Results Highlights

Longer vias require additional equalization features regardless of the ASIC breakout style:

- Stronger filter than Butterworth
  - Raised Cosine or equivalent
- Reduce receiver intrinsic noise
- Higher SNR
- Stronger FEC (segmented?) to account for higher DER
- Floating DFE taps

KEYSIGHT TECHNOLOGIES

200G PAM4 C2M Via Length Effect Study

Modeling Paradox – Via + Connector ≠ Via and Connector

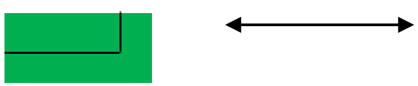
Cascading s-parameters from different sources has risks:

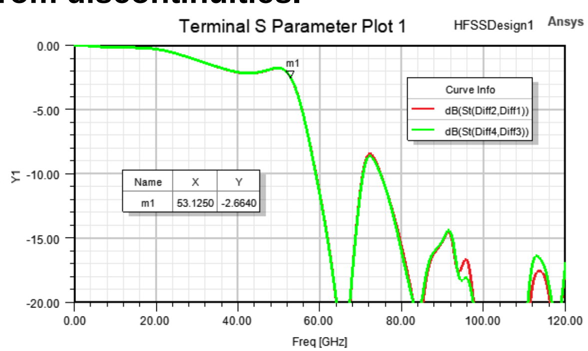
- **Actual x-talk is lost by interconnecting non-TEM boundaries.**
- **Cascading s-parameters from different sources**
  - ✓ **Missing interconnect structure pieces and phase information**
  - ✓ **Double counting of transitions and creating phase distortion**
- **Unaccounted meshing mismatch**

➢ **Build channel model with a "holistic" approach**

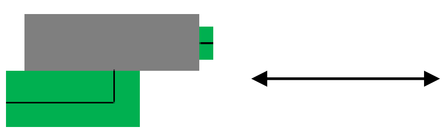
- ❖ **Channel model should <u>NOT</u> be just an aggregate of s-parameter structures**
- ❖ **Channel should be segmented with wave ports along uniform transmission lines several wavelengths away from discontinuities.**

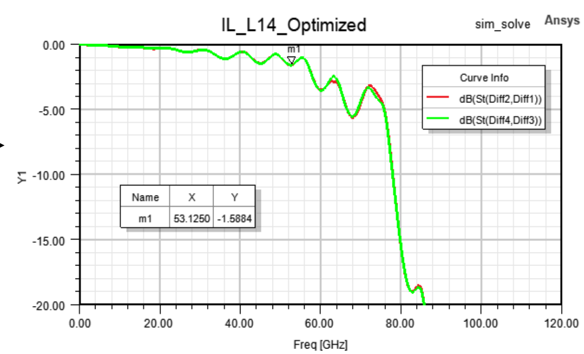
Example:





OSFP





200G PAM4 C2M Via Length Effect Study

Summary

"Equal Distribution of *PAIN*" to make C2M a viable interface

Longer PCB via solutions are feasible but:

1. **Need to optimize via transitions**
   - **Cancel via capacitive and inductive effects**
   - **Optimize connector to module PCB transition**

2. **Stronger FEC to support higher DER**
   - **Segmented FEC (?)**

3. **Enhanced Receiver Equalization (compared to P802.3ck):**
   - **Stronger filter**
   - **Higher SNR**
   - **Include floating taps option**
   - **Reduce intrinsic chip noise**

➢ **Channel Modeling: Take a holistic approach**

Q & A

Additional Data

200G PAM4 C2M Via Length Effect Study

Working Spreadsheet – Less Aggressive

Table 93A-1 parameters			
Parameter	**Setting**	**Units**	**Information**
f_b	106.25	GBd	
f_min	0.05	GHz	
Delta_f	0.01	GHz	
C_d	[0.4e-4 0.9e-4 1.1e-4 ; 0 0 0]	nF	[TX RX]
L_s	[.12 .15 .14; 0 0 0]	nH	[TX RX]
C_b	[.3e-4 0]	nF	[TX RX]
z_p select	[1 2]		[test cases to run]
z_p (TX)	[12 30; 1.8 1.8]	mm	[test cases]
z_p (NEXT)	[0 0; 0 0]	mm	[test cases]
z_p (FEXT)	[12 31; 1.8 1.8]	mm	[test cases]
z_p (RX)	[0 0; 0 0]	mm	[test cases]
C_p	0.00E+00	nF	[TX RX]
R_0	50	Ohm	
R_d	[50 50]	Ohm	[TX RX]
A_v	0.413	V	vp/vf=
A_fe	0.413	V	vp/vf=
A_ne	0.608	V	
L	4		
M	32		
filter and Eq			
f_r	0.75	*fb	
c(0)	0.65		min
c(-1)	[-0.2:0.02:0]		[min:step:max]
c(-2)	[0:.02:0.1]		[min:step:max]
c(-3)	[-0.1:.02:0]		[min:step:max]
c(1)	[-0.2:0.02:0]		[min:step:max]
N_b	9	UI	
b_max(1)	0.85		As/dffe1
b_max(2..N_b)	0.15		As/dfe2..N_b
b_min(1)	0		As/dffe1
b_min(2..N_b)	-0.15		As/dfe2..N_b
g_DC	[-13:1:0]	dB	[min:step:max]
f_z	42.5	GHz	
f_p1	42.5	GHz	
f_p2	106.25	GHz	
g_DC_HP	[-6:1:0]		[min:step:max]
f_HP_PZ	1.0625	GHz	

Receiver testing			
RX_CALIBRATION	0	logical	
Sigma BBN step	5.00E-03	V	
Raised_Cosine	1	logical	1 is an enable
Butterworth	0	logical	1 is an enable
RC_end	7.97E+10	Hz	End of Tukey range
RC_start	4.25E+10	Hz	Begin Tukey range

I/O control		
DIAGNOSTICS	1	logical
DISPLAY_WINDOW	1	logical
CSV_REPORT	1	logical
RESULT_DIR	.\results\c2m106_{date}\	
SAVE_FIGURES	0	logical
Port Order	[1 2 3 4]	
RUNTAG	C2M TP1a	
COM_CONTRIBUTION	0	logical
Operational		
ERL Pass threshold	10	dB
VEC Pass threshold	12.5	db
DER_0	1.00E-05	
T_r	2.35E-03	ns
FORCE_TR	1	logical
Min_VEO_Test	1	mV
PHY_type	C2M	
EH_min	10	Value
EH_max	1000	Value
T_O	50	mUI
samples_for_C2M	100	amples/UI
Dynamic TXFFE	1	
FloatingDFE_Development	1	
EW	1	
TDR and ERL options		
TDR	1	logical
ERL	1	logical
ERL_ONLY	0	logical
TR_TDR	0.01	ns
N	6000	
TDR_Butterworth	1	logical
beta_x	0	
rho_x	0.618	
TDR_W_TXPKG	0	
N_bx	8	UI
fixture delay time	[0 0.2e-9]	
Tukey_Window	1	
Noise, jitter		
sigma_RJ	0.01	UI
A_DD	0.02	UI
eta_0	2.05E-08	V^2/GHz
SNR_TX	32.5	dB
R_LM	0.95	

** not implemented in 3.7

Table 93A–3 parameters		
Parameter	**Setting**	**Units**
package_tl_gamma0_a1_a2	[0 8.4e-4 1.1e-4]	2.75 dB /in at 56G
package_tl_tau	6.14E-03	ns/mm
package_Z_c	[87.5 87.5 ; 92.5 92.5]	Ohm
Parameter	**Setting**	
board_tl_gamma0_a1_a2	[0 6.44084e-4 3.6036e-05]	1.5 db/in @ 56G
board_tl_tau	5.790E-03	ns/mm
board_Z_c	100	Ohm
z_bp (TX)	50	mm
z_bp (NEXT)	0	mm
z_bp (FEXT)	50	mm
z_bp (RX)	0	mm
C_0	[0.2e-4 0]	nF
C_1	[0.2e-4 0]	nF
Include PCB	**0**	**logical**
Selections (rectangle, gaussian,dual_rayleigh,triangle		
Histogram_Window_Weight	gaussian	
QL	2.5	
ICN parameters		
f_v	0.278	Fb
f_f	0.278	Fb
f_n	0.278	Fb
f_2	79.688	GHz
A_ft	0.450	V
A_nt	0.450	V
Floating Tap Control		
N_bg	0	0 1 2 or 3 groups
N_bf	3	taps per group
N_f	40	span for floating taps
bmaxg	0.05	FE value for floating taps
B_float_RSS_MAX	0.02	rss tail tap limit
N_tail_start	9	) start of tail taps limit

KEYSIGHT TECHNOLOGIES

200G PAM4 C2M Via Length Effect Study

Working Spreadsheet – More Aggressive

Table 93A-1 parameters			
Parameter	**Setting**	**Units**	**Information**
f_b	106.25	GBd	
f_min	0.05	GHz	
Delta_f	0.01	GHz	
C_d	[0.4e-4 0.9e-4 1.1e-4 ; 0 0 0]	nF	[TX RX]
L_s	[.12 .15 .14; 0 0 0]	nH	[TX RX]
C_b	[.3e-4 0]	nF	[TX RX]
z_p select	[1 2 3 4]		[test cases to run]
z_p (TX)	[12 16 25 30; 1.0 1.0 1.0 1.0]	mm	[test cases]
z_p (NEXT)	[0 0 0 0 ; 0 0 0 0]	mm	[test cases]
z_p (FEXT)	[12 16 25 30; 1.0 1.0 1.0 1.0]	mm	[test cases]
z_p (RX)	[0 0 0 0 ; 0 0 0 0]	mm	[test cases]
C_p	0.00E+00	nF	[TX RX]
R_0	50	Ohm	
R_d	[50 50]	Ohm	[TX RX]
A_v	0.408	V	vp/vf=
A_fe	0.408	V	vp/vf=
A_ne	0.608	V	
L	4		
M	32		
filter and Eq			
f_r	0.75	*fb	
c(0)	0.65		min
c(-1)	[-0.2:0.02:0]		[min:step:max]
c(-2)	[0:.02:0.1]		[min:step:max]
c(-3)	[-0.1:.02:0]		[min:step:max]
c(1)	[-0.2:0.02:0]		[min:step:max]
N_b	8	UI	
b_max(1)	**0.85**		**As/dffe1**
b_max(2..N_b)	**0.15**		**As/dfe2..N_b**
b_min(1)	**0**		**As/dffe1**
b_min(2..N_b)	**-0.15**		**As/dfe2..N_b**
g_DC	[-13:1:0]	dB	[min:step:max]
f_z	42.5	GHz	
f_p1	42.5	GHz	
f_p2	106.25	GHz	
g_DC_HP	[-6:1:0]		[min:step:max]
f_HP_PZ	1.0625	GHz	

Receiver testing			
RX_CALIBRATION	0	logical	
Sigma BBN step	5.00E-03	V	
Raised_Cosine	**1**	**logical**	**1 is an enable**
Butterworth	**0**	**logical**	**1 is an enable**
RC_end	**7.97E+10**	**Hz**	**End of Tukey range**
RC_start	**4.25E+10**	**Hz**	**Begin Tukey range**

I/O control		
DIAGNOSTICS	1	logical
DISPLAY_WINDOW	1	logical
CSV_REPORT	1	logical
RESULT_DIR	.\results\c2m106_{date}\	
SAVE_FIGURES	0	logical
Port Order	[1 2 3 4]	
RUNTAG	C2M TP1a	
COM_CONTRIBUTION	0	logical
Operational		
ERL Pass threshold	10	dB
VEC Pass threshold	12.5	db
DER_0	5.00E-05	
T_r	2.35E-03	ns
FORCE_TR	1	logical
Min_VEO_Test	1	mV
PHY_type	C2M	
EH_min	10	Value
EH_max	1000	Value
T_O	50	mUI
samples_for_C2M	100	samples/UI
Dynamic TXFFE	1	
FloatingDFE_Development	1	
EW	1	
TDR and ERL options		
TDR	1	logical
ERL	1	logical
ERL_ONLY	0	logical
TR_TDR	0.01	ns
N	6000	
TDR_Butterworth	1	logical
beta_x	0	
rho_x	0.618	
TDR_W_TXPKG	0	
N_bx	8	UI
fixture delay time	[0 0.2e-9]	
Tukey_Window	1	
Noise, jitter		
sigma_RJ	0.01	UI
A_DD	0.02	UI
eta_0	2.05E-09	V^2/GHz
SNR_TX	34	dB
R_LM	0.95	

** not implemented in 3.7	

Table 93A–3 parameters		
Parameter	**Setting**	**Units**
package_tl_gamma0_a1_a2	[0 8.4e-4 1.1e-4]	2.75 dB /in at 56G
package_tl_tau	6.14E-03	ns/mm
package_Z_c	[87.5 87.5 ; 92.5 92.5]	Ohm

Parameter	**Setting**	
board_tl_gamma0_a1_a2	*[0 6.44084e-4 3.6036e-05]*	1.5 db/in @ 56G
board_tl_tau	*5.790E-03*	ns/mm
board_Z_c	100	Ohm
z_bp (TX)	*125*	mm
z_bp (NEXT)	*0*	mm
z_bp (FEXT)	*125*	mm
z_bp (RX)	*0*	mm
C_0	[0.2e-4 0]	nF
C_1	[0.2e-4 0]	nF
Include PCB	**0**	**logical**

Seletions (rectangle, gaussian,dual_rayleigh,triangle		
Histogram_Window_Weight	gaussian	
QL	*2.5*	

ICN parameters		
f_v	0.278	Fb
f_f	0.278	Fb
f_n	0.278	Fb
f_2	79.688	GHz
A_ft	0.450	V
A_nt	0.450	V

Floating Tap Control		
N_bg	6	0 1 2 or 3 groups
N_bf	3	taps per group
N_f	64	UI span for floating taps
bmaxg	0.2	max DFE value for floating taps
B_float_RSS_MAX	0.1	rss tail tap limit
N_tail_start	9	(UI) start of tail taps limit

KEYSIGHT TECHNOLOGIES

200G PAM4 C2M Via Length Effect Study

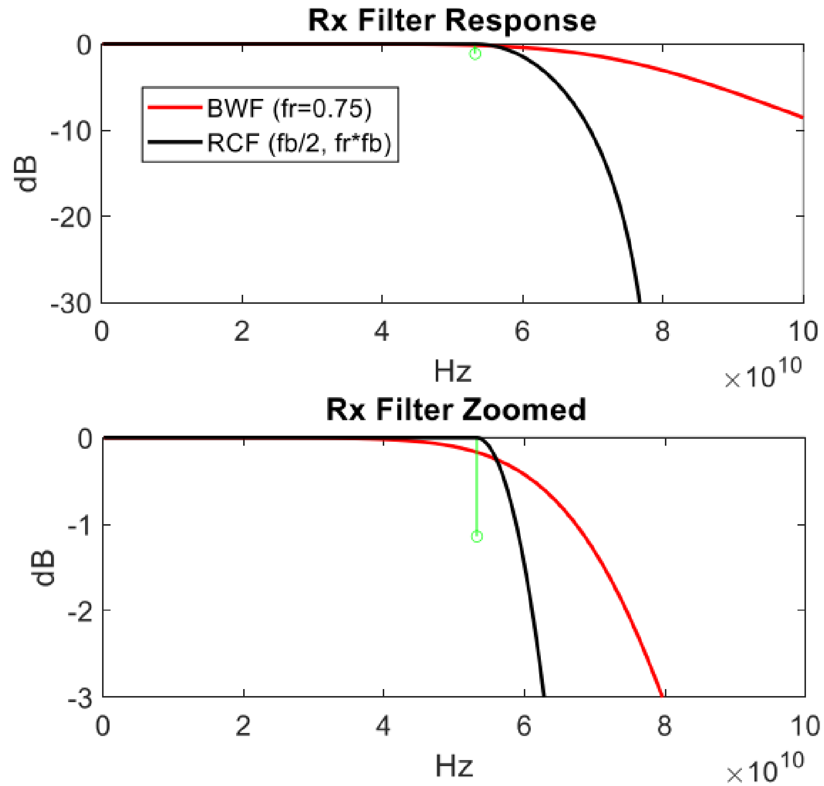
Channel Contributions

- Rabinovich_C2M_200G_Paral_19mil_092122_FEXT.s4p
- Rabinovich_C2M_200G_Paral_19mil_092122_NEXT.s4p
- Rabinovich_C2M_200G_Paral_19mil_092122_Thru.s4p
- Rabinovich_C2M_200G_Paral_67mil_092122_FEXT.s4p
- Rabinovich_C2M_200G_Paral_67mil_092122_NEXT.s4p
- Rabinovich_C2M_200G_Paral_67mil_092122_Thru.s4p
- Rabinovich_C2M_200G_Paral_93mil_092122_FEXT.s4p
- Rabinovich_C2M_200G_Paral_93mil_092122_NEXT.s4p
- Rabinovich_C2M_200G_Paral_93mil_092122_Thru.s4p
- Rabinovich_C2M_200G_Ortho_19mil_092122_FEXT.s4p
- Rabinovich_C2M_200G_Ortho_19mil_092122_NEXT.s4p
- Rabinovich_C2M_200G_Ortho_19mil_092122_Thru.s4p
- Rabinovich_C2M_200G_Ortho_67mil_092122_FEXT.s4p
- Rabinovich_C2M_200G_Ortho_67mil_092122_NEXT.s4p
- Rabinovich_C2M_200G_Ortho_67mil_092122_Thru.s4p
- Rabinovich_C2M_200G_Ortho_93mil_092122_FEXT.s4p
- Rabinovich_C2M_200G_Ortho_93mil_092122_NEXT.s4p
- Rabinovich_C2M_200G_Ortho_93mil_092122_Thru.s4p

*Note: Use Port Order = [1 2 3 4]

200G PAM4 C2M Via Length Effect Study

IL Comparison Between Butterworth and Raise Cosine Filters



*** Source: Mellitz_3df_elec_01_220621.pdf**