



TRANSMITTER OPTIMIZATION, TDECQ AND INTER-OP

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Overview

- TDECQ and what it measures
- Simulations
 - Impact of TDECQ on BER Sensitivity and BER Floor
- Measurements
 - Single mode measurements
 - Multimode measurement with FEC bins
- Interpretation of results – SNR and Distortion
- Recommendations for managing transmitter performance
- Proposed Specification Changes

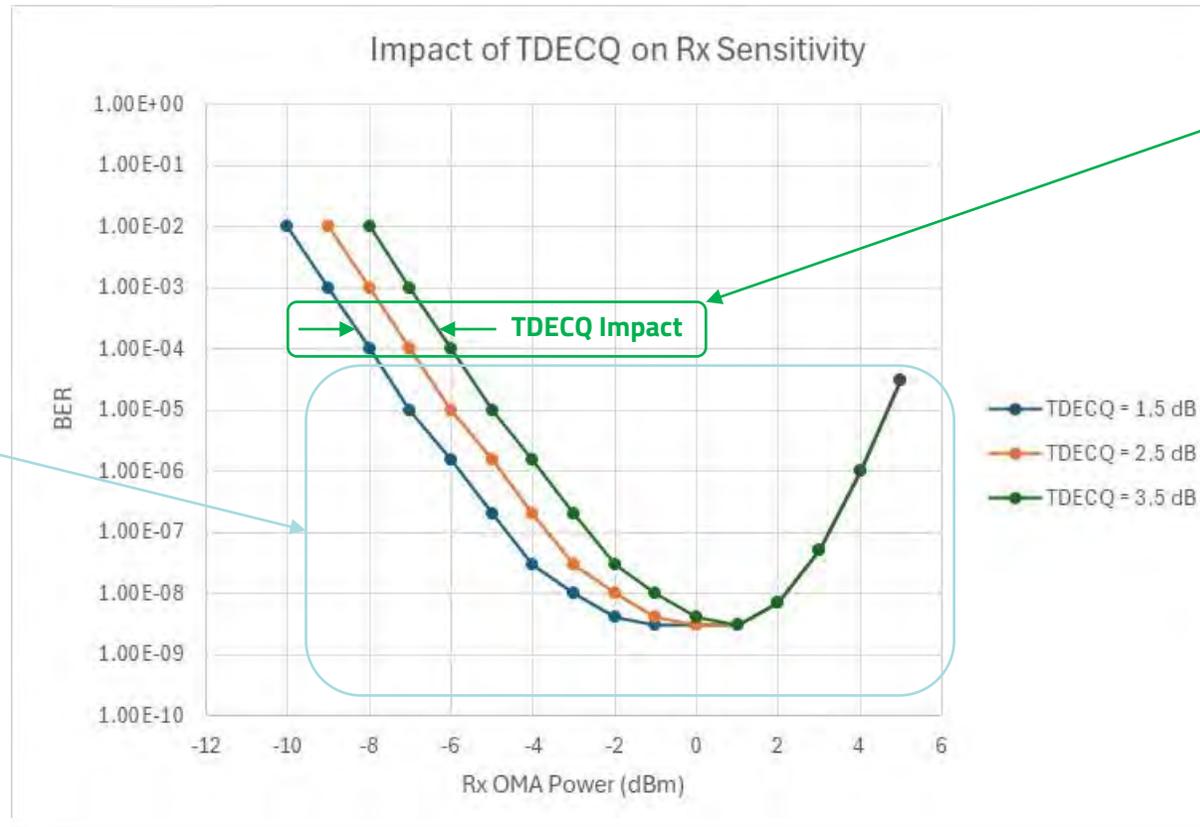
Note: This presentation deals with equalization and distortion at the transmitter. A mixture of TDECQ (simulation – 500 m NDSF) and TECQ (measured data) are used but the focus is on equalization and distortion and not on dispersion.

TDECQ and what it measures

- TDECQ is a measure of eye closure
- TDECQ measures the impact of the transmitter on receiver sensitivity **at the SER level**
- The transmitter impact on receiver sensitivity is due to:
 - Unequalizable frequency response and distortion components
 - Receiver noise amplification cause by the receiver having to equalize the transmitter
- It is NOT a direct measure of the BER floor and not intended to give any indication of performance at any other BER other than the specified SER
- Can we use TDECQ to infer a better indication of transmitter performance?

TDECQ and what it measures

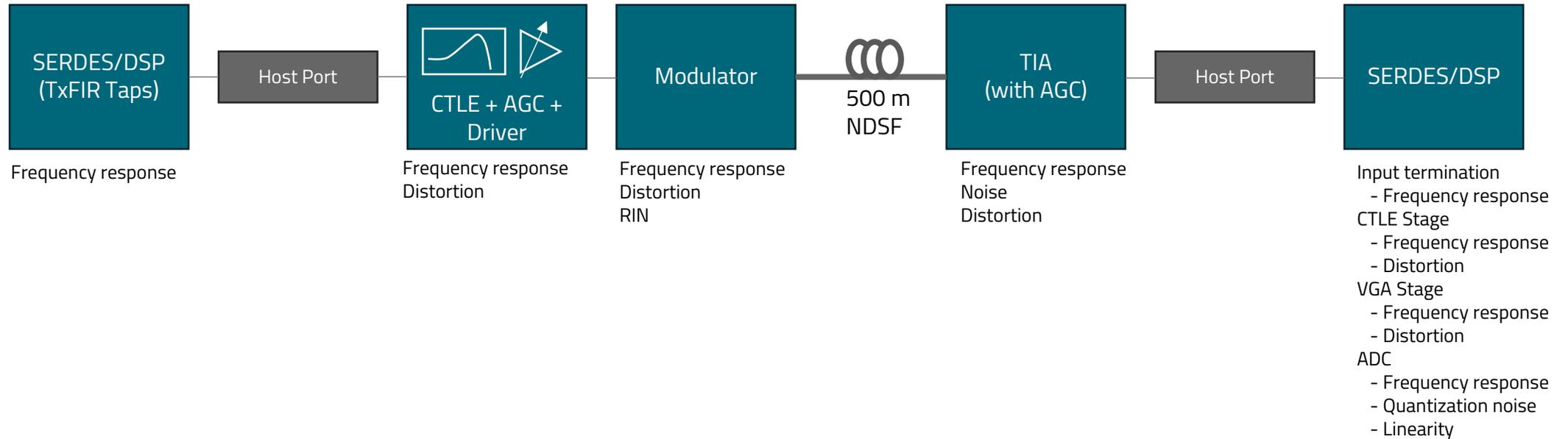
Can TDECQ tell us anything about this area?



This is what TDECQ is defined to fundamentally measure

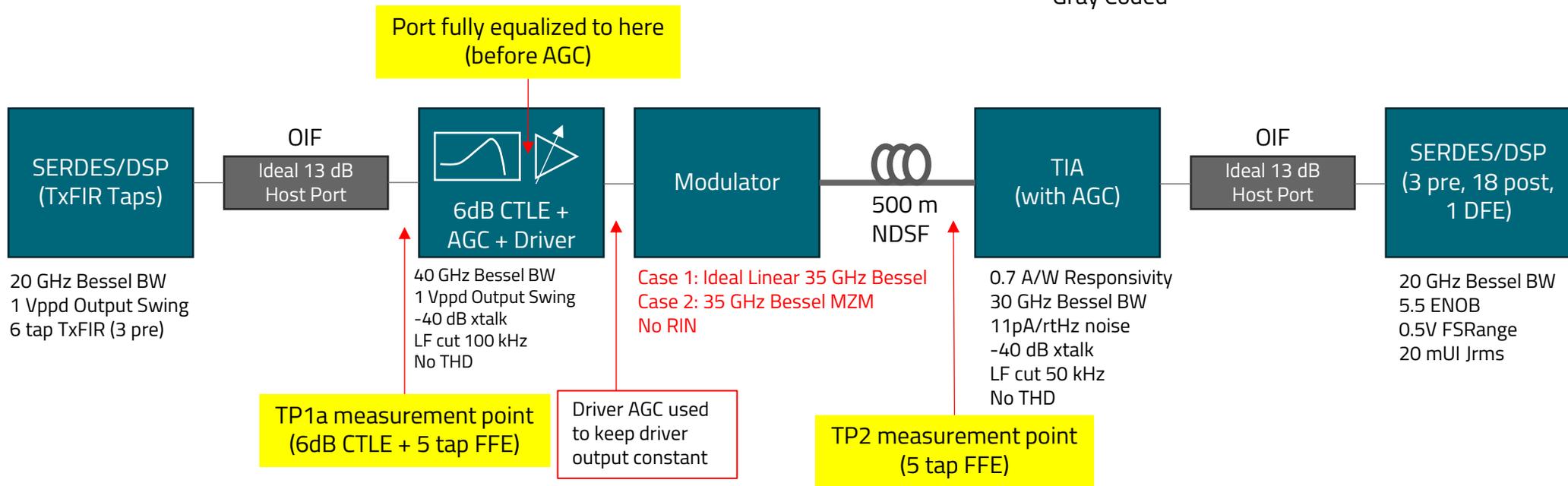
Assumption : TDECQ only shifts the Rx sensitivity curve and the slope is unchanged – IDEAL SCENARIO

Typical LPO System



Simulation Setup

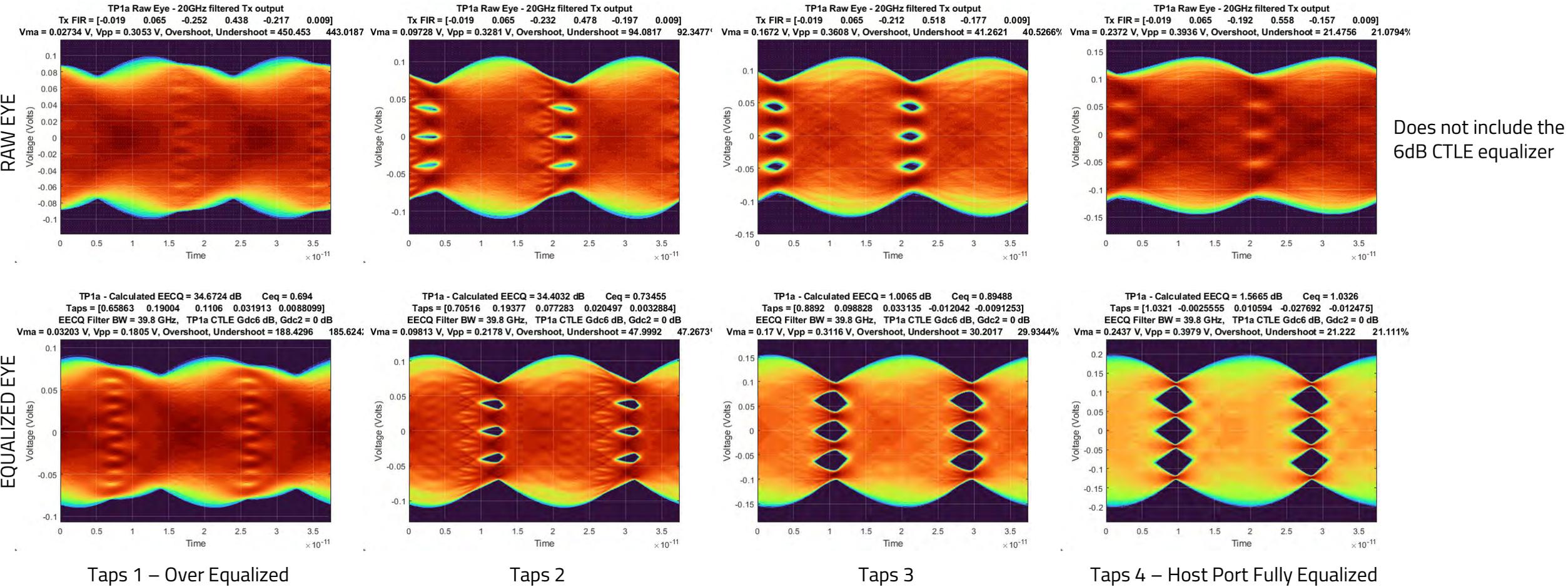
PRBS15Q
60 frames
1,966,020 symbols
Gray Coded



Taps{1} = [-0.019 0.065 -0.252 0.438 -0.217 0.009]; % Over equalized
 Taps{2} = [-0.019 0.065 -0.232 0.478 -0.197 0.009]; %
 Taps{3} = [-0.019 0.065 -0.212 0.518 -0.177 0.009]; %
 Taps{4} = [-0.019 0.065 -0.192 0.558 -0.157 0.009]; % Fully equalized
 Taps{5} = [-0.019 0.065 -0.172 0.598 -0.137 0.009]; %
 Taps{6} = [-0.019 0.065 -0.152 0.638 -0.117 0.009]; %
 Taps{7} = [-0.019 0.065 -0.132 0.678 -0.097 0.009]; % Under equalized

Case 1: Fully linear system
 Case 2: Non-linearity introduced by MZM
 (only non-linearity in link)

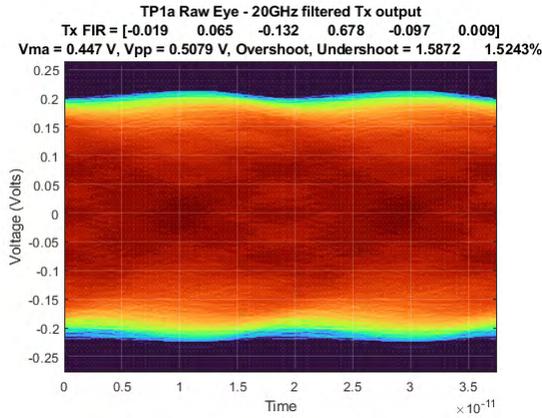
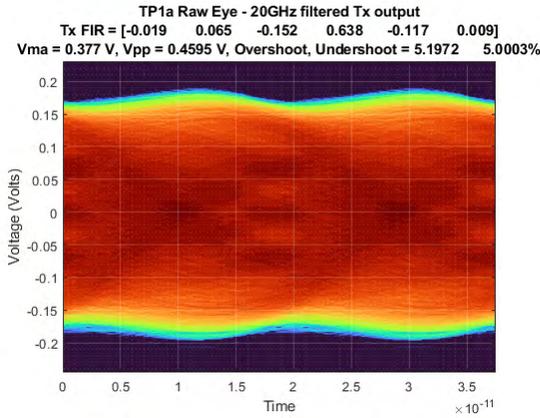
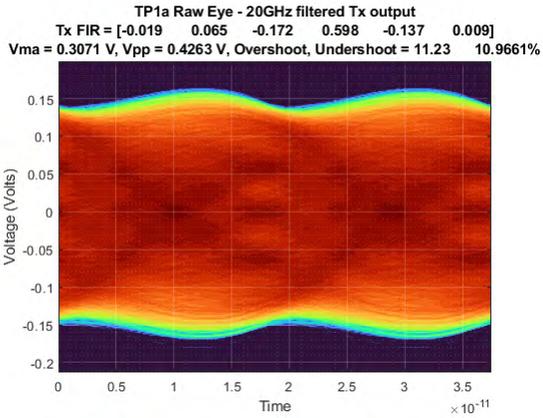
TP1a Eye Diagrams



Measured at TP1a before AGC

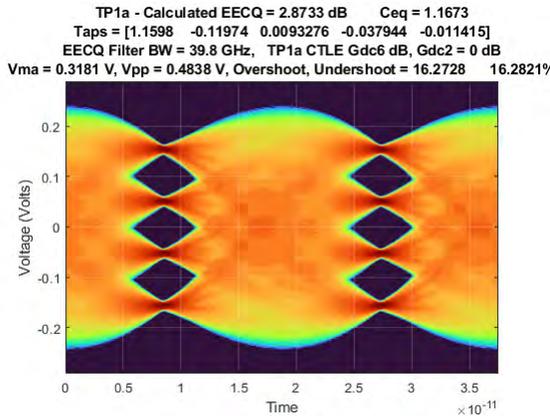
TP1a Eye Diagrams (2)

RAW EYE

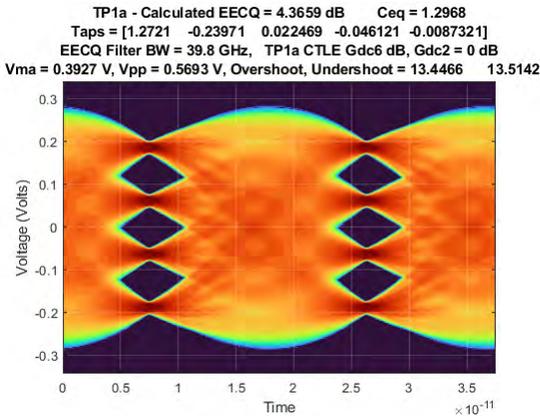


Does not include the 6dB CTLE equalizer

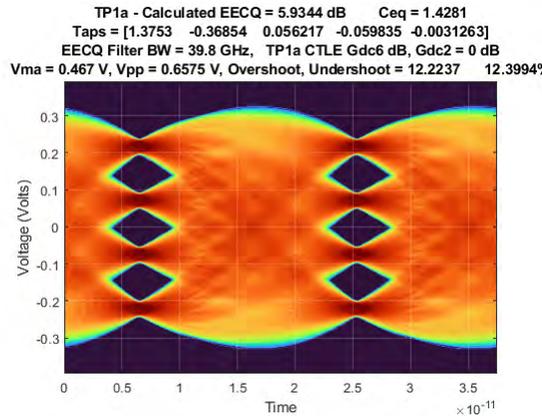
EQUALIZED EYE



Taps 5



Taps 6



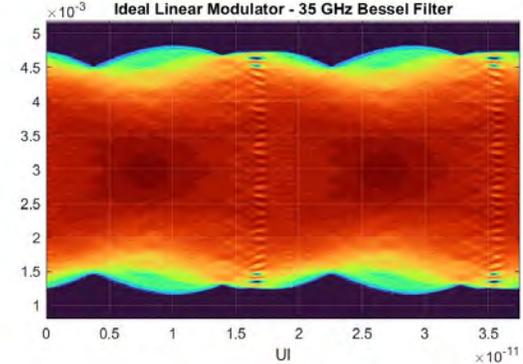
Taps 7 – Under Equalized

Measured at TP1a before AGC

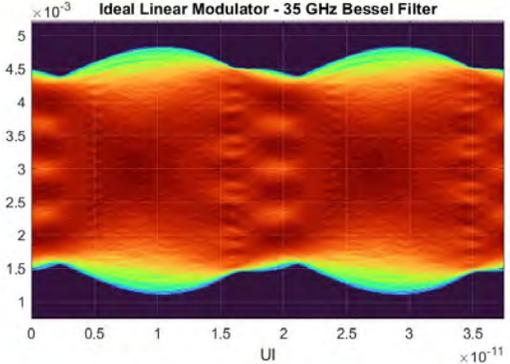
TP2 Eye Diagrams – Ideal Linear Modulator (1)

RAW EYE

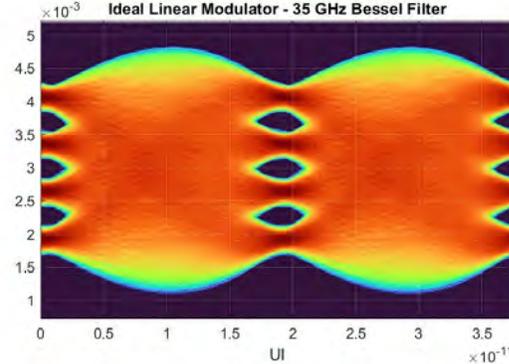
Tx Waveform + Tx EQ + Driver + Modulator
 Tx - Simulated with 20GHz Bessel Response
 FIR EQ[1:5] - [-0.019 0.065 -0.25 0.44 -0.22]
 Driver with 40GHz Bessel Response
 Ideal Linear Modulator - 35 GHz Bessel Filter



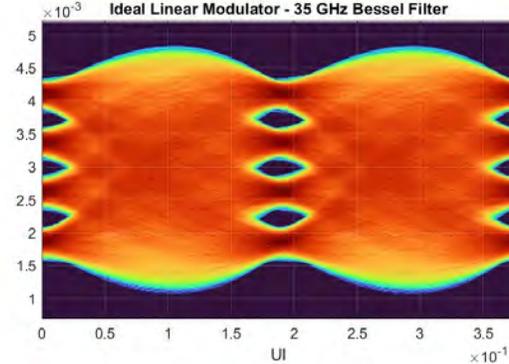
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 Driver with 40GHz Bessel Response
 Ideal Linear Modulator - 35 GHz Bessel Filter

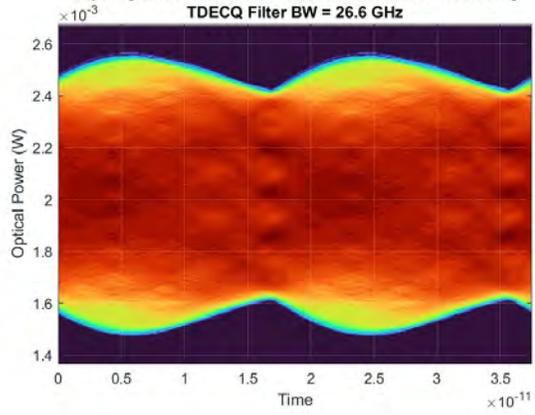


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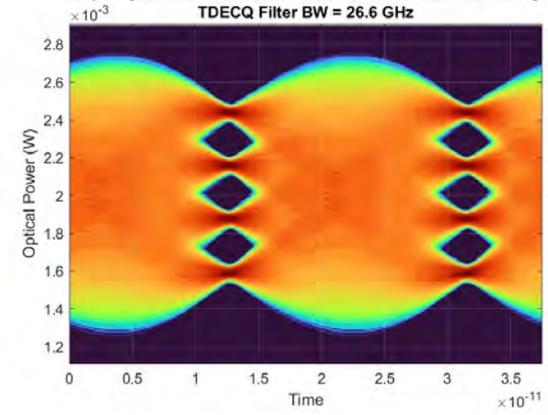
EQUALIZED EYE

TP2 - Calculated TDECQ = 21.5107 dB Ceq = 0.63607
 Taps = [0.5778 0.20691 0.13131 0.059999 0.023982]
 TDECQ Filter BW = 26.6 GHz



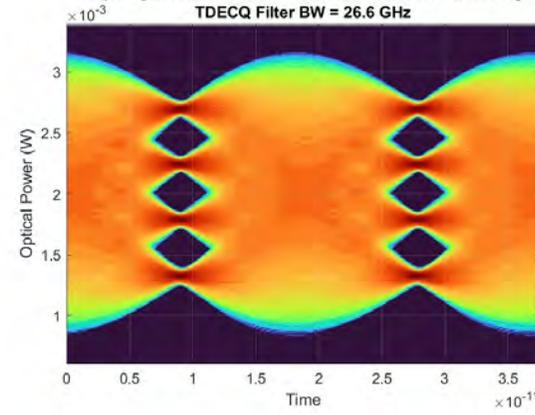
Taps 1 – Over Equalized

TP2 - Calculated TDECQ = -0.2443 dB Ceq = 0.74578
 Taps = [0.069167 0.071084 0.73039 0.056454 0.072908]
 TDECQ Filter BW = 26.6 GHz



Taps 2

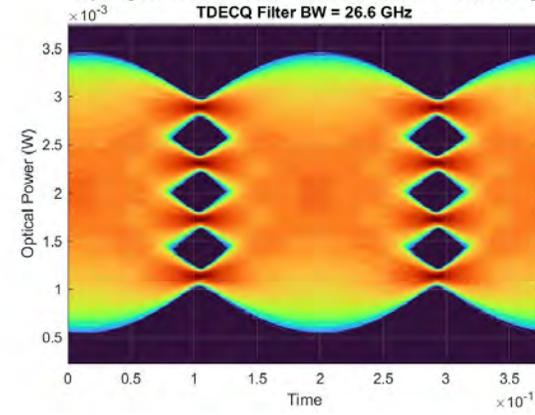
TP2 - Calculated TDECQ = 1.0725 dB Ceq = 1.0718
 Taps = [0.14172 1.036 -0.2012 0.10665 -0.083133]
 TDECQ Filter BW = 26.6 GHz



Taps 3

Best visually optimized Tx

TP2 - Calculated TDECQ = 2.0493 dB Ceq = 1.3417
 Taps = [-0.018569 1.3124 -0.28251 0.078384 -0.089717]
 TDECQ Filter BW = 26.6 GHz

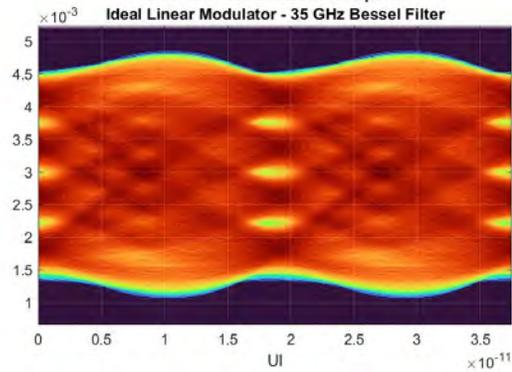


Taps 4 – Host Port Fully Equalized

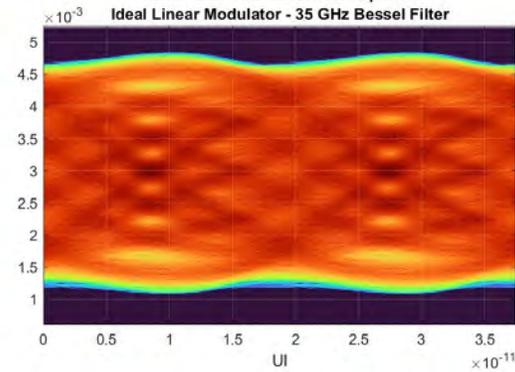
TP2 Eye Diagrams – Ideal Linear Modulator (2)

RAW EYE

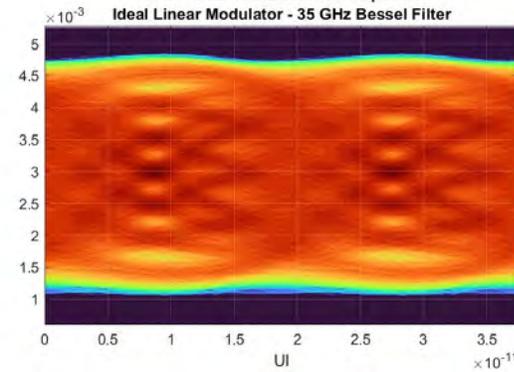
Tx Waveform + Tx EQ + Driver + Modulator
Tx - Simulated with 20GHz Bessel Response
FIR EQ[1:5] - [-0.019 0.065 -0.17 0.6 -0.14]
Driver with 40GHz Bessel Response
Ideal Linear Modulator - 35 GHz Bessel Filter



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Ideal Linear Modulator - 35 GHz Bessel Filter

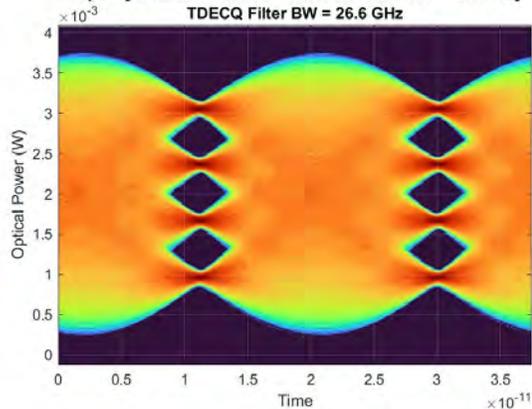


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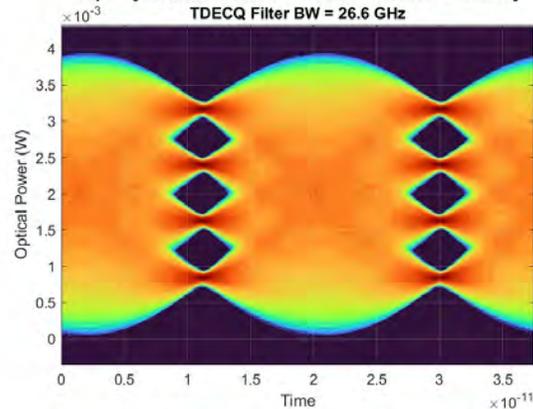
EQUALIZED EYE

TP2 - Calculated TDECQ = 2.9155 dB Ceq = 1.6371
Taps = [-0.15262 1.5834 -0.41033 0.084307 -0.10473]
TDECQ Filter BW = 26.6 GHz



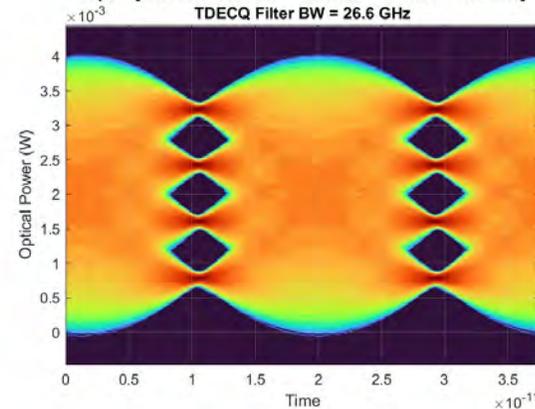
Taps 5

TP2 - Calculated TDECQ = 3.603 dB Ceq = 1.9287
Taps = [-0.26308 1.8356 -0.56294 0.1111 -0.12067]
TDECQ Filter BW = 26.6 GHz



Taps 6

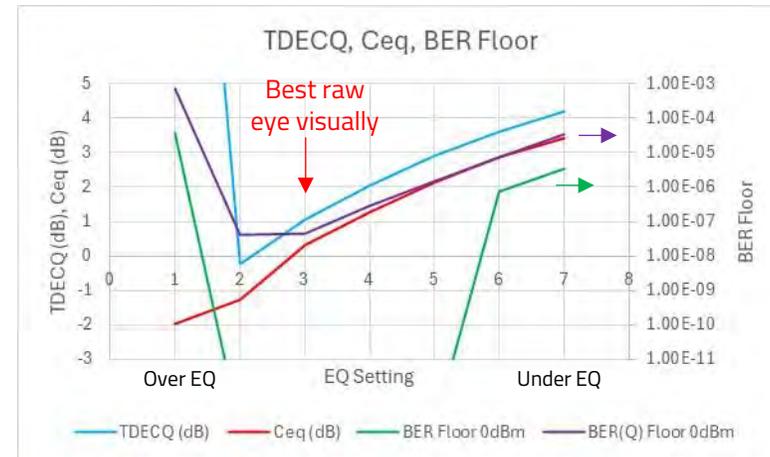
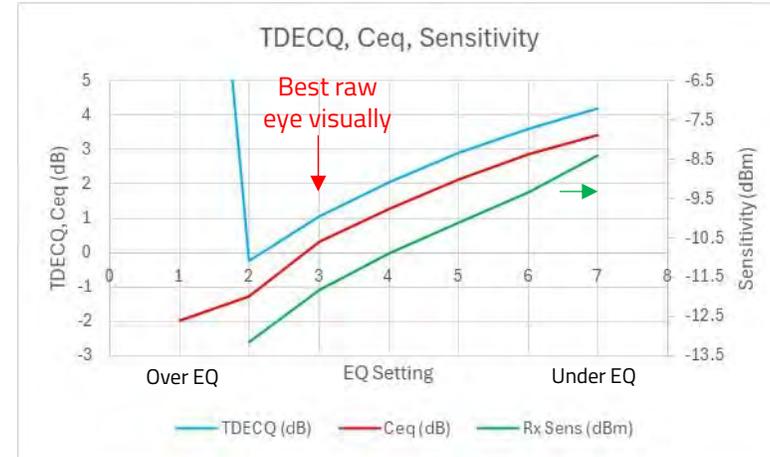
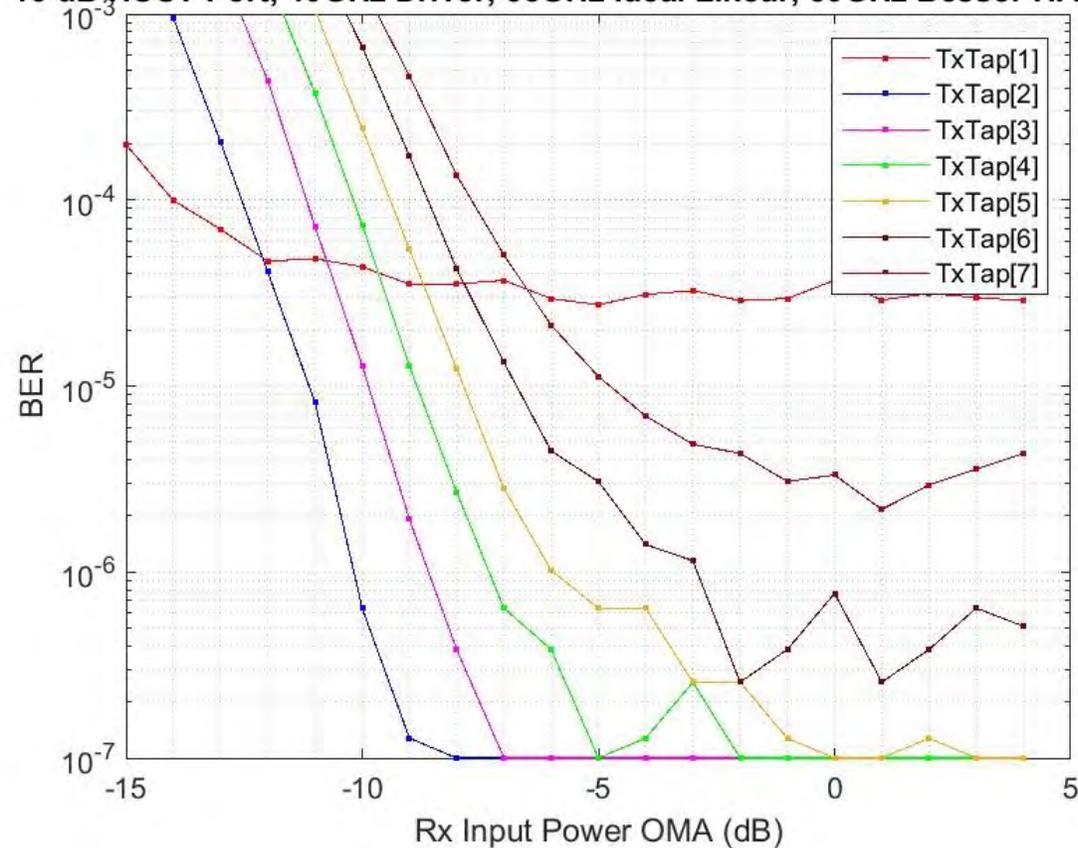
TP2 - Calculated TDECQ = 4.1908 dB Ceq = 2.2034
Taps = [-0.31987 2.0521 -0.76289 0.17685 -0.14623]
TDECQ Filter BW = 26.6 GHz



Taps 7 – Under Equalized

Simulation Results – Ideal Linear Modulator

13 dB HOST Port, 40GHz Driver, 35GHz Ideal Linear, 30GHz Bessel TIA, Noise

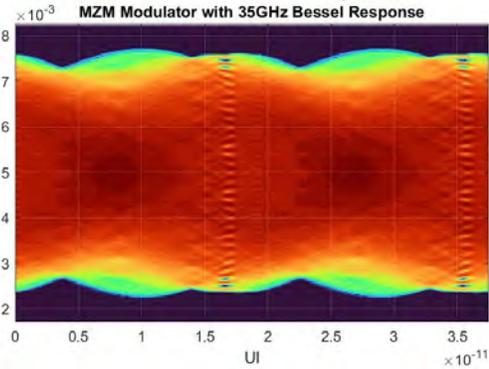


BER(Q) is estimated BER from Q

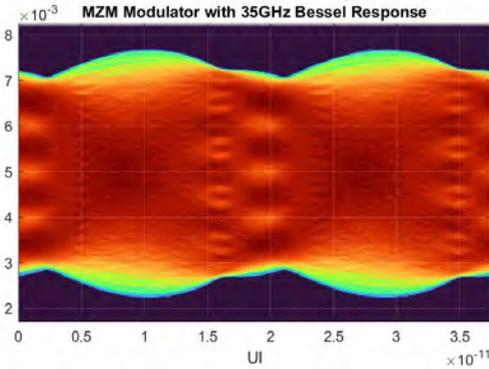
TP2 Eye Diagrams – MZM Modulator 3dB ER (1)

RAW EYE

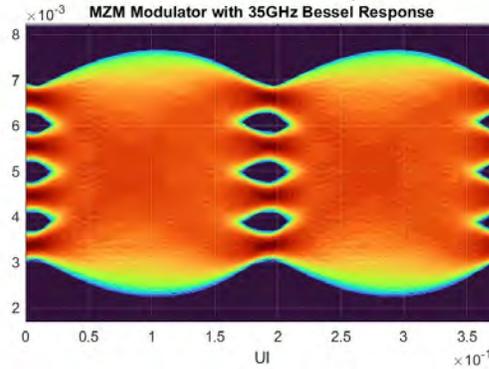
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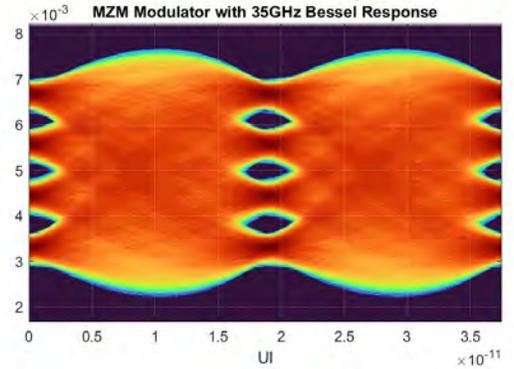
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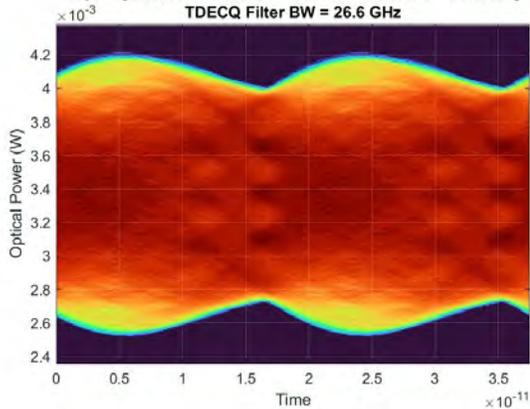


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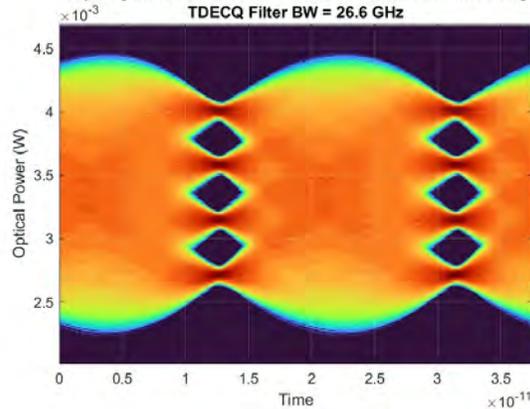
EQUALIZED EYE

TP2 - Calculated TDECQ = 21.5365 dB Ceq = 0.64642
 Taps = [0.59359 0.19567 0.13148 0.055674 0.023581]
 TDECQ Filter BW = 26.6 GHz



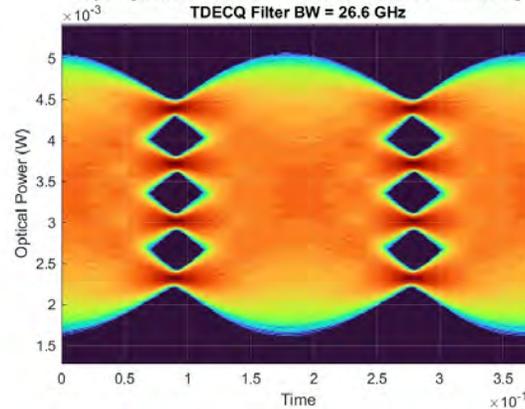
Taps 1 – Over Equalized

TP2 - Calculated TDECQ = -0.13338 dB Ceq = 0.74872
 Taps = [0.071353 0.06341 0.73382 0.059932 0.071485]
 TDECQ Filter BW = 26.6 GHz



Taps 2

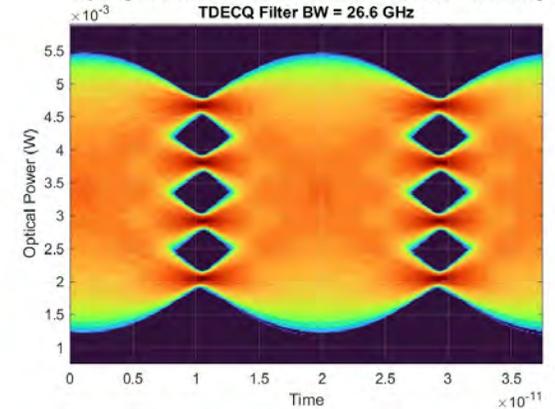
TP2 - Calculated TDECQ = 1.1258 dB Ceq = 1.0727
 Taps = [0.14255 1.0364 -0.20324 0.10734 -0.083091]
 TDECQ Filter BW = 26.6 GHz



Taps 3

Best visually optimized Tx

TP2 - Calculated TDECQ = 2.0541 dB Ceq = 1.3361
 Taps = [-0.0053961 1.3045 -0.29096 0.082866 -0.091008]
 TDECQ Filter BW = 26.6 GHz

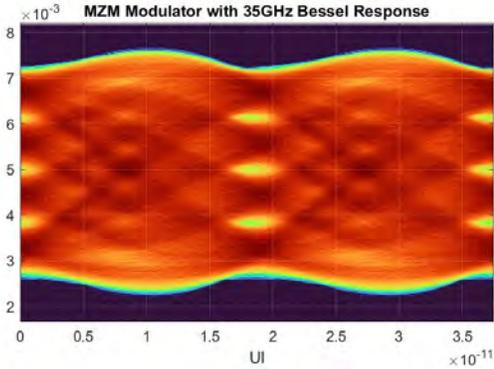


Taps 4 – Host Port Fully Equalized

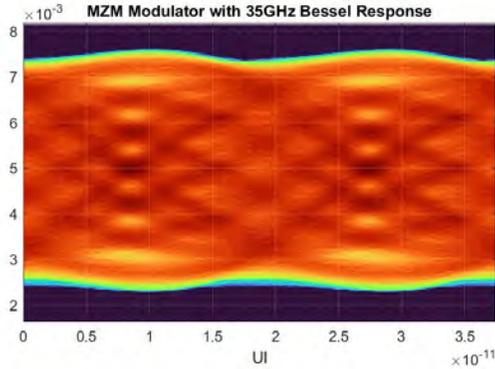
TP2 Eye Diagrams – MZM Modulator 3dB ER (2)

RAW EYE

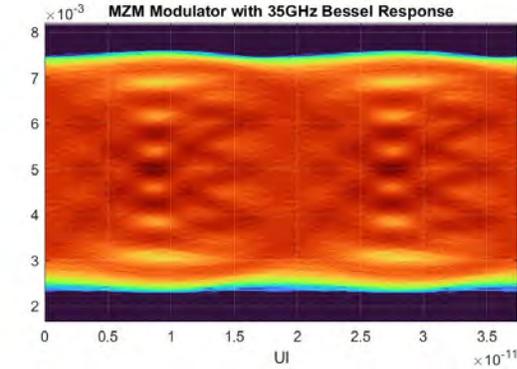
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 MZM Modulator with 35GHz Bessel Response



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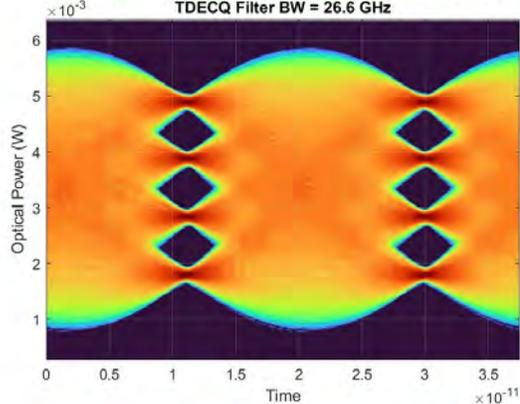


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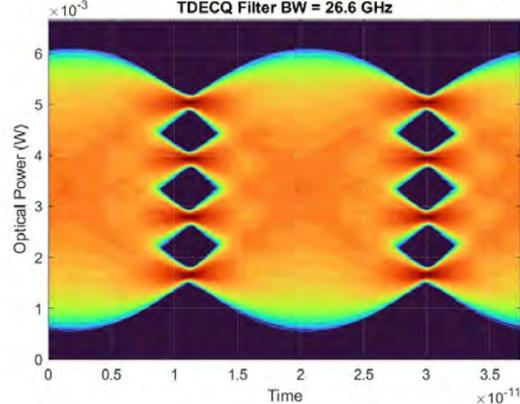
EQUALIZED EYE

TP2 - Calculated TDECQ = 2.8843 dB Ceq = 1.6339
 Taps = [-0.15045 1.5798 -0.41117 0.087743 -0.1059]
 TDECQ Filter BW = 26.6 GHz



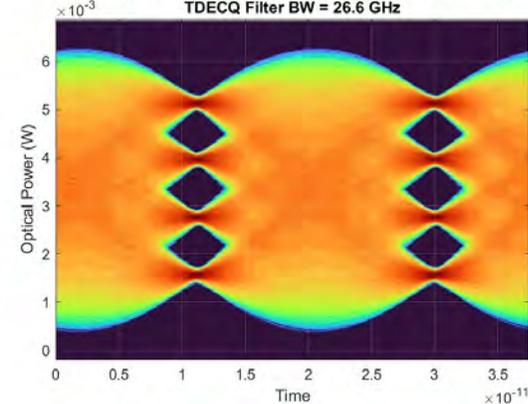
Taps 5

TP2 - Calculated TDECQ = 3.534 dB Ceq = 1.9166
 Taps = [-0.26492 1.8269 -0.54971 0.10504 -0.11729]
 TDECQ Filter BW = 26.6 GHz



Taps 6

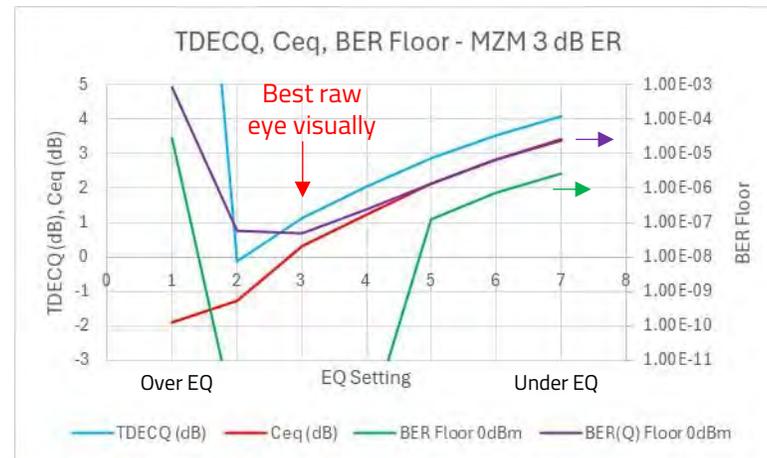
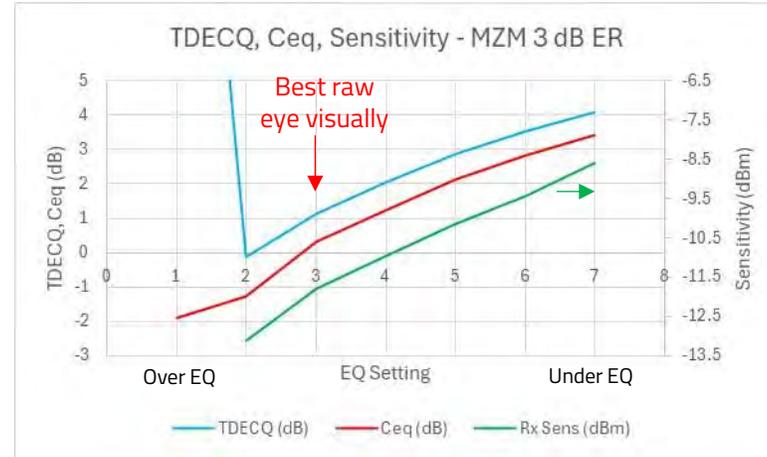
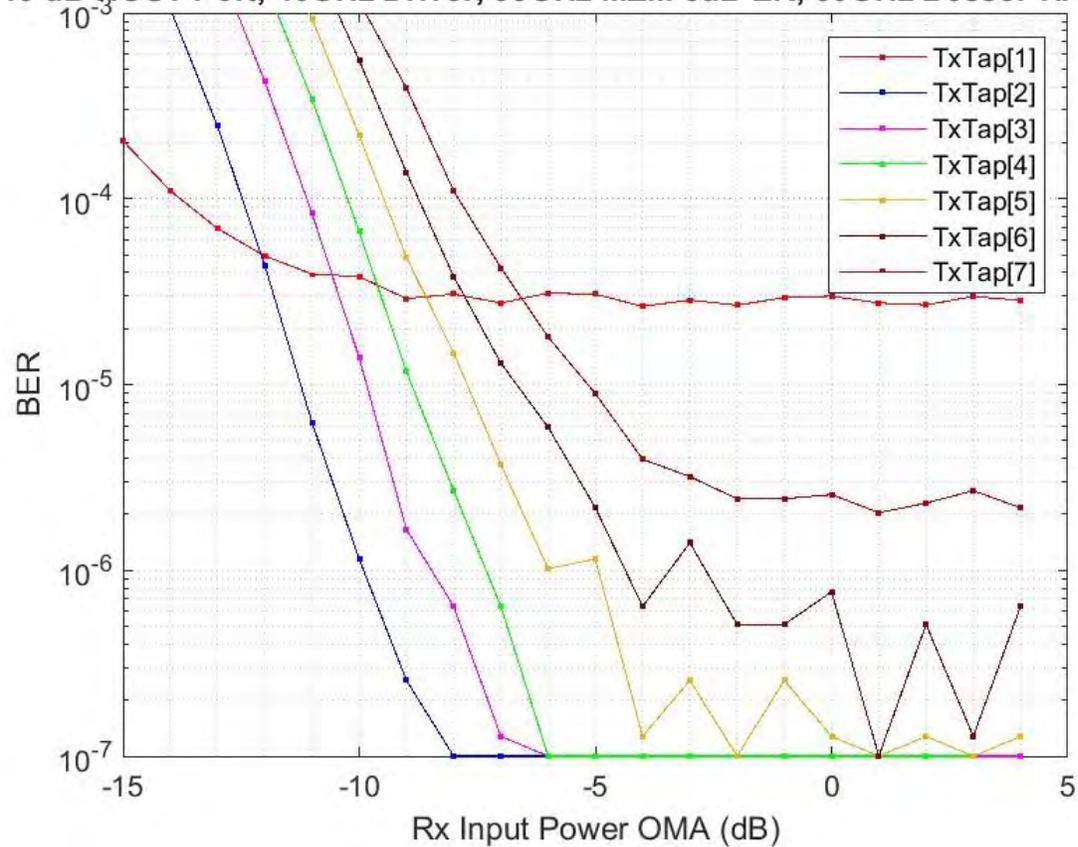
TP2 - Calculated TDECQ = 4.1001 dB Ceq = 2.2021
 Taps = [-0.36955 2.0663 -0.70568 0.14085 -0.13189]
 TDECQ Filter BW = 26.6 GHz



Taps 7 – Under Equalized

Simulation Results – MZM Modulator 3dB ER

13 dB HOST Port, 40GHz Driver, 35GHz MZM 3dB ER, 30GHz Bessel TIA, Noise

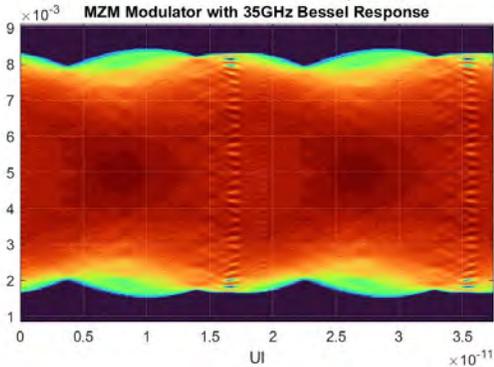


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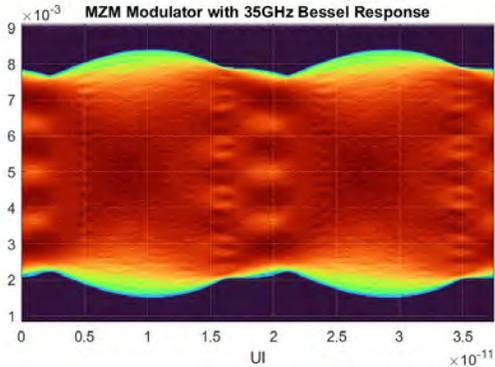
TP2 Eye Diagrams – MZM Modulator 4dB ER (1)

RAW EYE

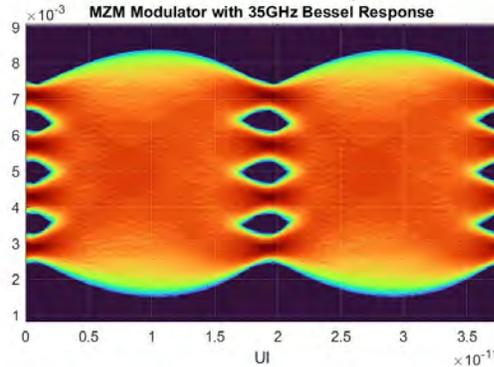
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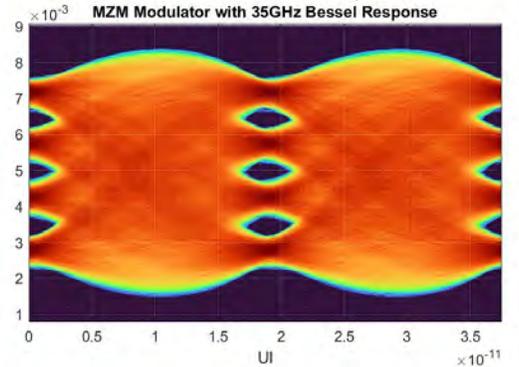
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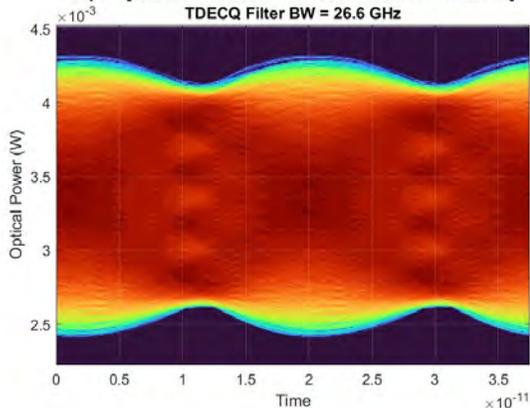


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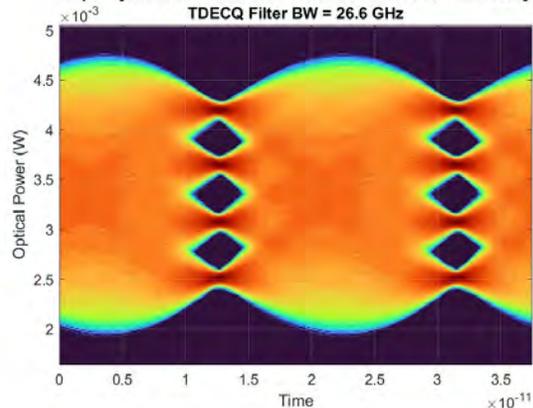
EQUALIZED EYE

TP2 - Calculated TDECQ = 18.3012 dB Ceq = 0.61151
Taps = [0.15384 0.5548 0.13561 0.12496 0.030792]
TDECQ Filter BW = 26.6 GHz



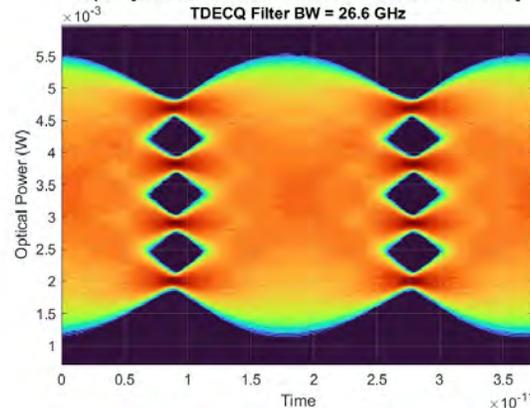
Taps 1 – Over Equalized

TP2 - Calculated TDECQ = -0.077746 dB Ceq = 0.75006
Taps = [0.070069 0.065418 0.73531 0.057714 0.071486]
TDECQ Filter BW = 26.6 GHz



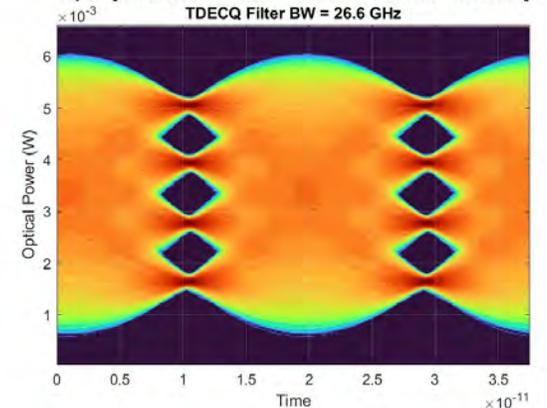
Taps 2

TP2 - Calculated TDECQ = 1.1498 dB Ceq = 1.0708
Taps = [0.13249 1.0384 -0.19359 0.10186 -0.079182]
TDECQ Filter BW = 26.6 GHz



Taps 3

TP2 - Calculated TDECQ = 2.0734 dB Ceq = 1.3336
Taps = [-0.0063477 1.3027 -0.28815 0.081528 -0.089737]
TDECQ Filter BW = 26.6 GHz



Taps 4 – Host Port Fully Equalized

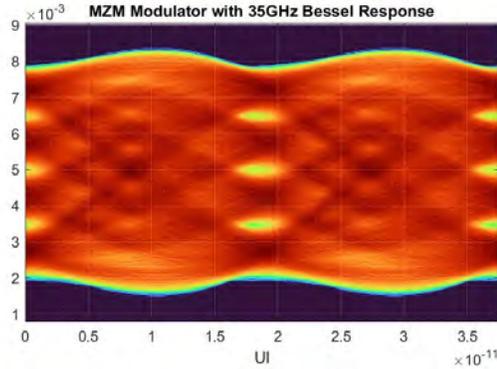
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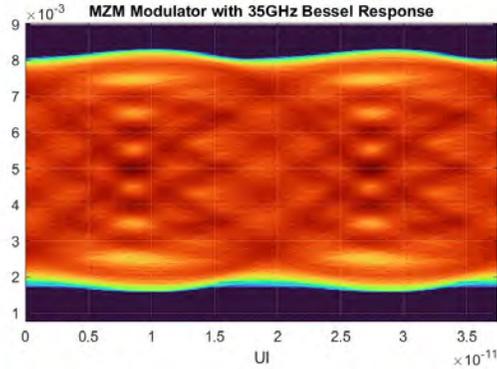
RAW EYE

EQUALIZED EYE

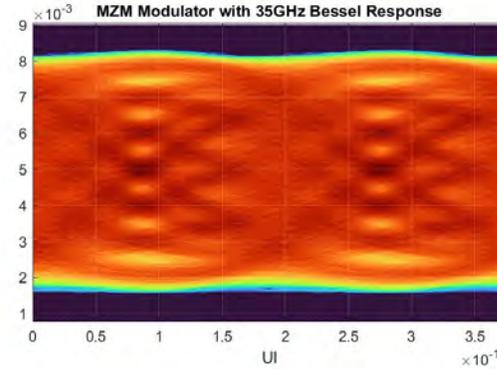
Tx Waveform + Tx EQ + Driver + Modulator
 Tx - Simulated with 20GHz Bessel Response
 FIR EQ[1:5] - [-0.019 0.065 -0.17 0.6 -0.14]
 Driver with 40GHz Bessel Response
 MZM Modulator with 35GHz Bessel Response



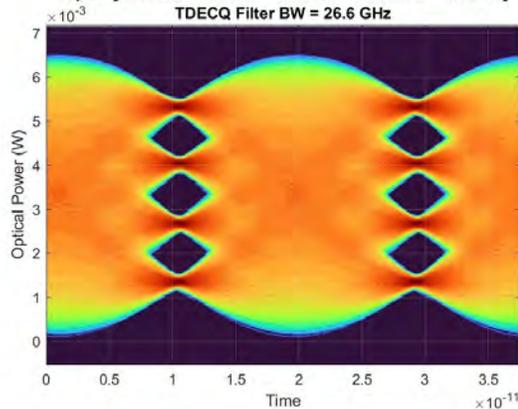
Tx Waveform + Tx EQ + Driver + Modulator
 Tx - Simulated with 20GHz Bessel Response
 FIR EQ[1:5] - [-0.019 0.065 -0.15 0.64 -0.12]
 Driver with 40GHz Bessel Response
 MZM Modulator with 35GHz Bessel Response



Tx Waveform + Tx EQ + Driver + Modulator
 Tx - Simulated with 20GHz Bessel Response
 FIR EQ[1:5] - [-0.019 0.065 -0.13 0.68 -0.097]
 Driver with 40GHz Bessel Response
 MZM Modulator with 35GHz Bessel Response

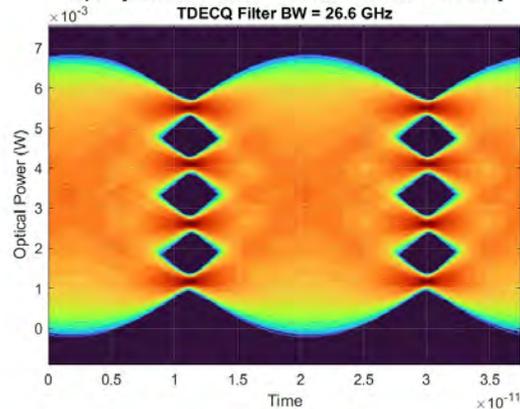


TP2 - Calculated TDECQ = 2.8578 dB Ceq = 1.6113
 Taps = [-0.11066 1.5528 -0.43191 0.098206 -0.10846]
 TDECQ Filter BW = 26.6 GHz



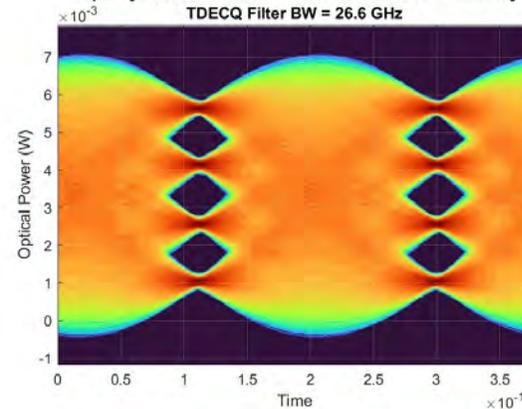
Taps 5

TP2 - Calculated TDECQ = 3.4948 dB Ceq = 1.8999
 Taps = [-0.24356 1.809 -0.5582 0.11167 -0.11886]
 TDECQ Filter BW = 26.6 GHz



Taps 6

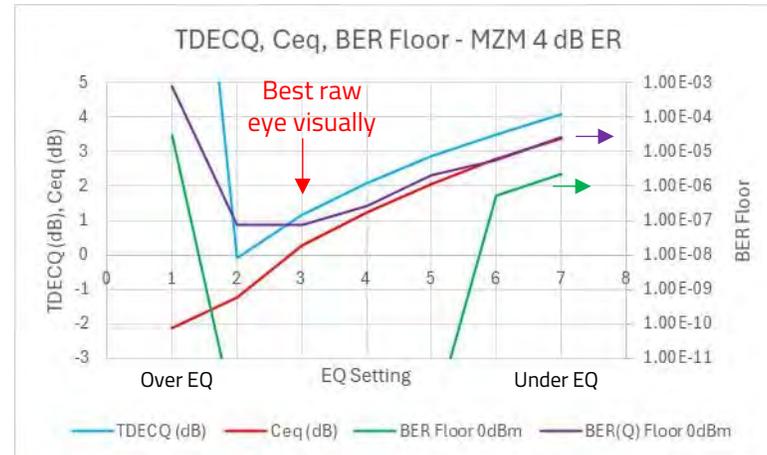
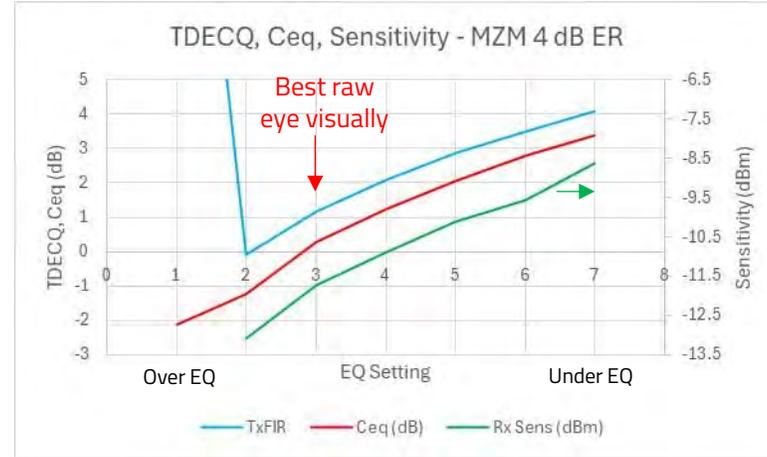
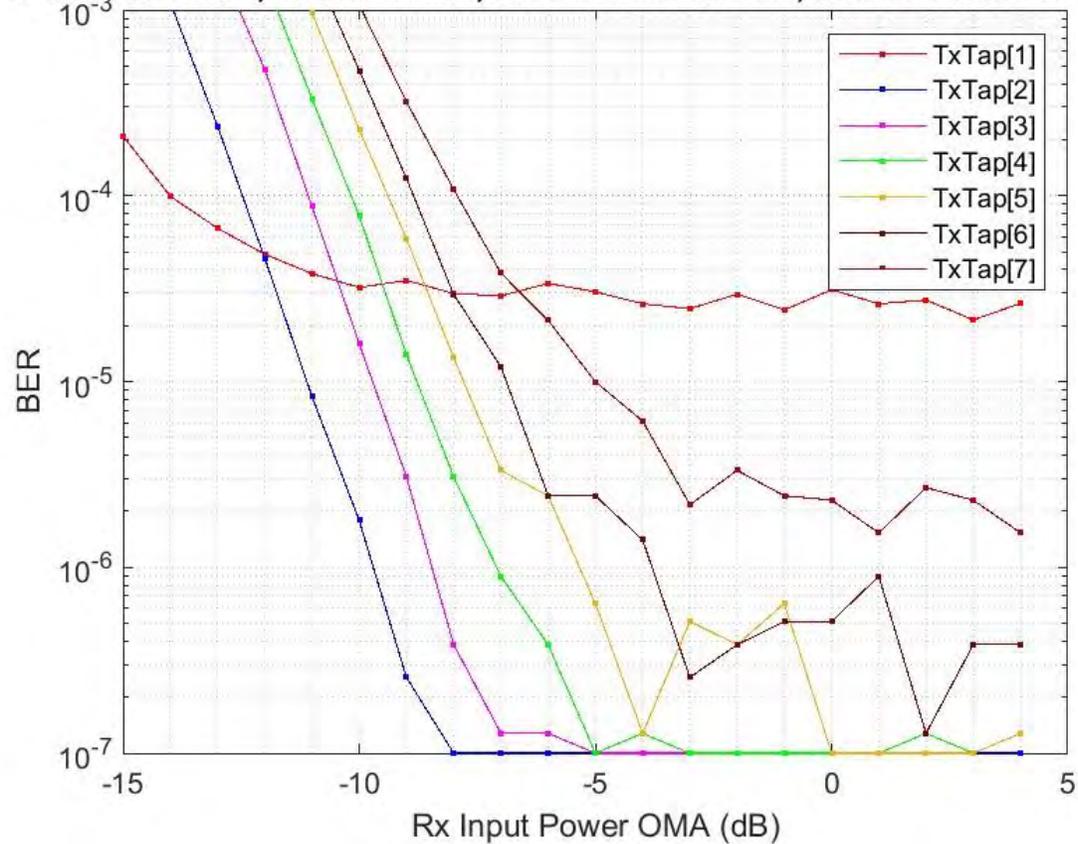
TP2 - Calculated TDECQ = 4.1012 dB Ceq = 2.187
 Taps = [-0.36488 2.054 -0.69663 0.13734 -0.12982]
 TDECQ Filter BW = 26.6 GHz



Taps 7 – Under Equalized

Simulation Results – MZM Modulator 4dB ER

13 dB HOST Port, 40GHz Driver, 35GHz MZM 4dB ER, 30GHz Bessel TIA, Noise

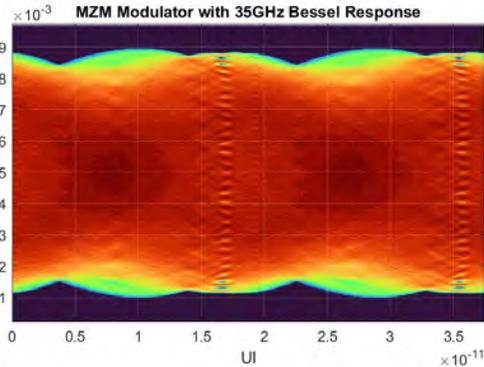


BER(Q) is estimated BER from Q

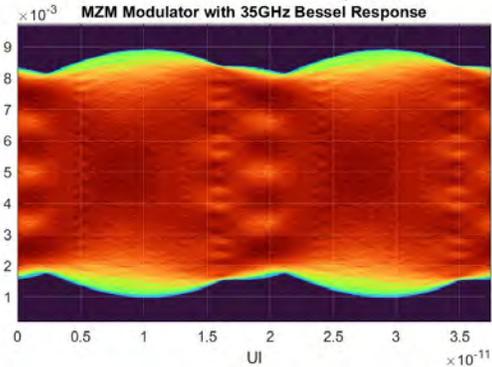
TP2 Eye Diagrams – MZM Modulator 5dB ER (1)

RAW EYE

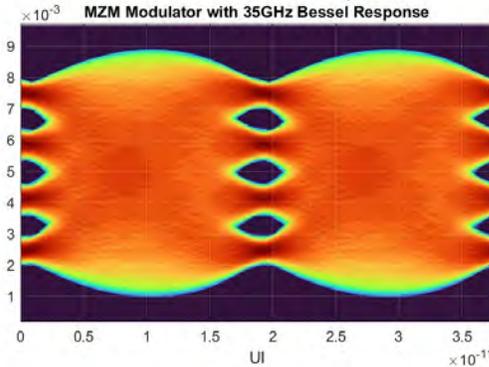
Tx Waveform + Tx EQ + Driver + Modulator
Tx - Simulated with 20GHz Bessel Response
FIR EQ[1:5] - [-0.019 0.065 -0.25 0.44 -0.22]
Driver with 40GHz Bessel Response
MZM Modulator with 35GHz Bessel Response



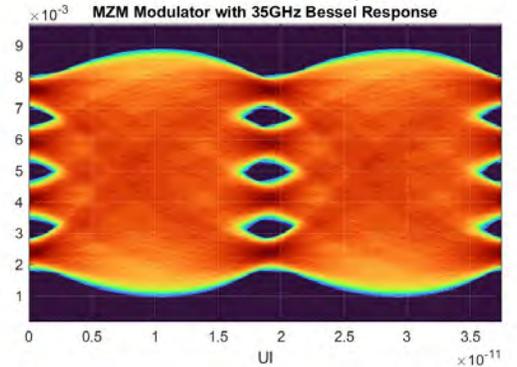
Tx Waveform + Tx EQ + Driver + Modulator
Tx - Simulated with 20GHz Bessel Response
FIR EQ[1:5] - [-0.019 0.065 -0.23 0.48 -0.2]
Driver with 40GHz Bessel Response
MZM Modulator with 35GHz Bessel Response



Tx Waveform + Tx EQ + Driver + Modulator
Tx - Simulated with 20GHz Bessel Response
FIR EQ[1:5] - [-0.019 0.065 -0.21 0.52 -0.18]
Driver with 40GHz Bessel Response
MZM Modulator with 35GHz Bessel Response

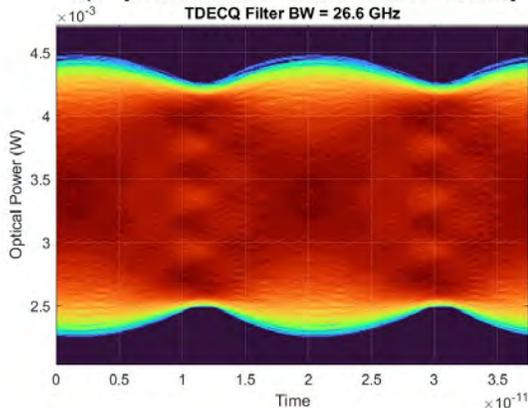


Tx Waveform + Tx EQ + Driver + Modulator
Tx - Simulated with 20GHz Bessel Response
FIR EQ[1:5] - [-0.019 0.065 -0.19 0.56 -0.16]
Driver with 40GHz Bessel Response
MZM Modulator with 35GHz Bessel Response



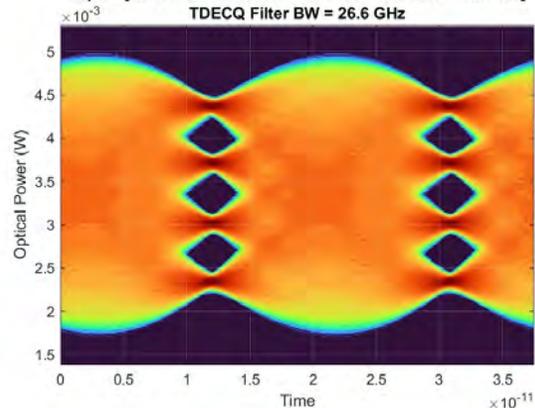
EQUALIZED EYE

TP2 - Calculated TDECQ = 19.1096 dB $C_{eq} = 0.61179$
Taps = [0.14875 0.55576 0.13962 0.12336 0.032512]
TDECQ Filter BW = 26.6 GHz



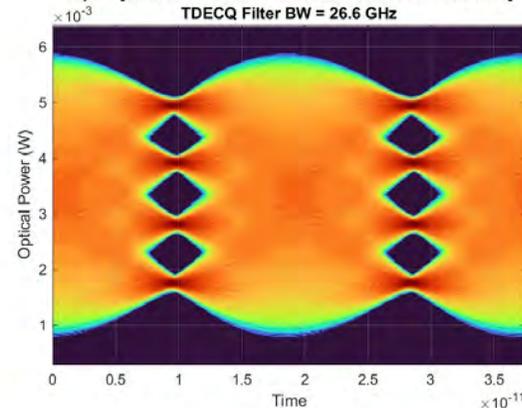
Taps 1 – Over Equalized

TP2 - Calculated TDECQ = -0.084333 dB $C_{eq} = 0.75045$
Taps = [0.061588 0.085056 0.73506 0.04532 0.07298]
TDECQ Filter BW = 26.6 GHz



Taps 2

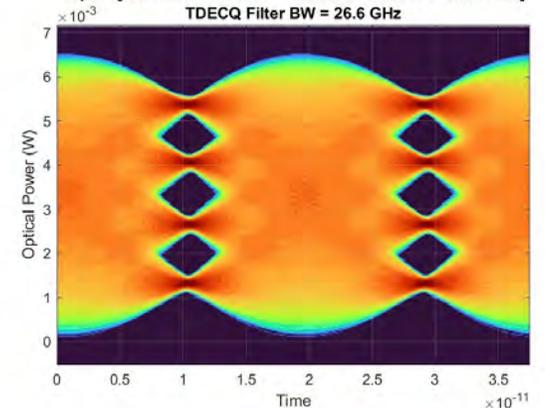
TP2 - Calculated TDECQ = 1.1779 dB $C_{eq} = 1.0653$
Taps = [0.11555 1.0397 -0.17423 0.090183 -0.071214]
TDECQ Filter BW = 26.6 GHz



Taps 3

Best visually optimized Tx

TP2 - Calculated TDECQ = 2.1002 dB $C_{eq} = 1.3375$
Taps = [-0.017135 1.3081 -0.28231 0.080471 -0.089118]
TDECQ Filter BW = 26.6 GHz



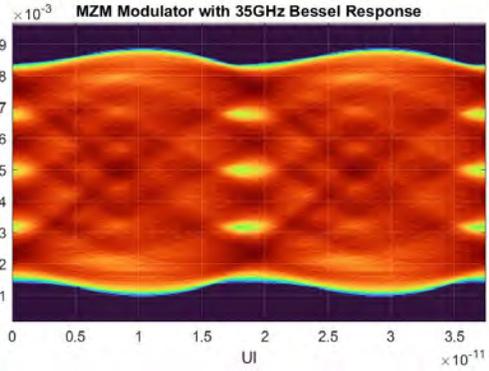
Taps 4 – Host Port Fully Equalized

TP2 Eye Diagrams – MZM Modulator 5dB ER (2)

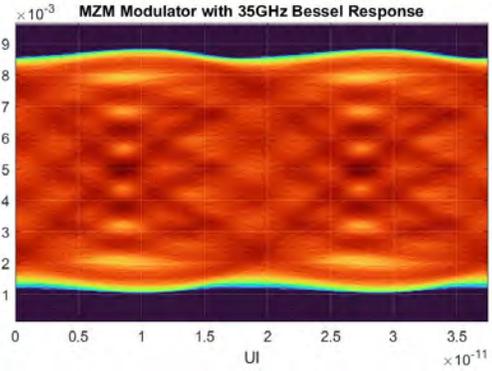
RAW EYE

EQUALIZED EYE

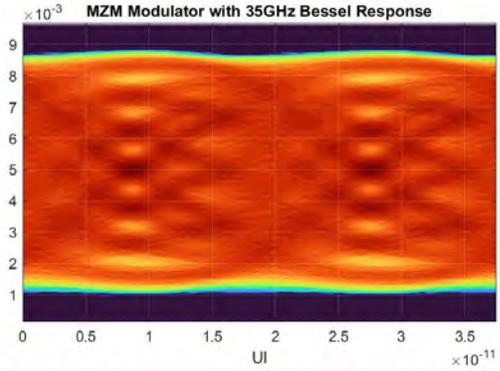
Tx Waveform + Tx EQ + Driver + Modulator
 Tx - Simulated with 20GHz Bessel Response
 FIR EQ[1:5] - [-0.019 0.065 -0.17 0.6 -0.14]
 Driver with 40GHz Bessel Response
 MZM Modulator with 35GHz Bessel Response



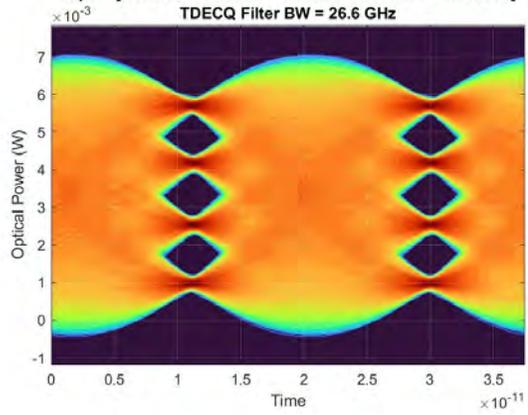
Tx Waveform + Tx EQ + Driver + Modulator
 Tx - Simulated with 20GHz Bessel Response
 FIR EQ[1:5] - [-0.019 0.065 -0.15 0.64 -0.12]
 Driver with 40GHz Bessel Response
 MZM Modulator with 35GHz Bessel Response



Tx Waveform + Tx EQ + Driver + Modulator
 Tx - Simulated with 20GHz Bessel Response
 FIR EQ[1:5] - [-0.019 0.065 -0.13 0.68 -0.097]
 Driver with 40GHz Bessel Response
 MZM Modulator with 35GHz Bessel Response

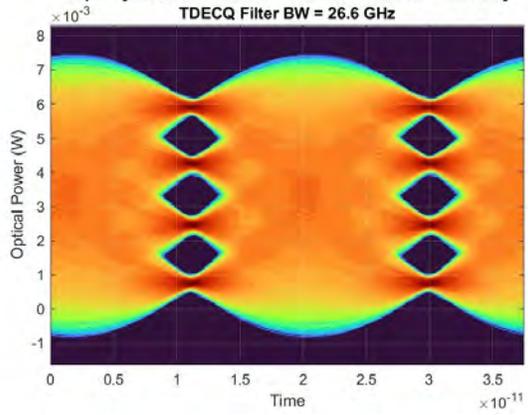


TP2 - Calculated TDECQ = 2.8789 dB Ceq = 1.6158
 Taps = [-0.15167 1.5662 -0.39256 0.077091 -0.099093]
 TDECQ Filter BW = 26.6 GHz



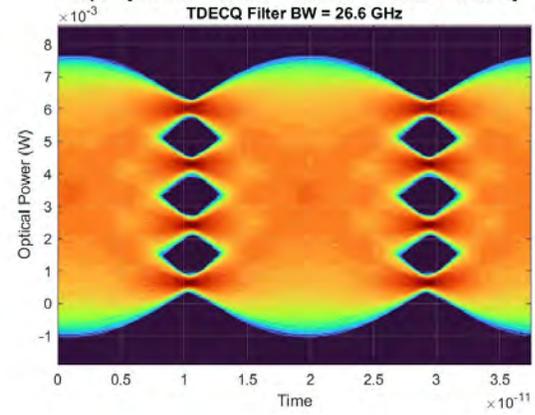
Taps 5

TP2 - Calculated TDECQ = 3.5693 dB Ceq = 1.8953
 Taps = [-0.26043 1.8096 -0.53504 0.0993 -0.11342]
 TDECQ Filter BW = 26.6 GHz



Taps 6

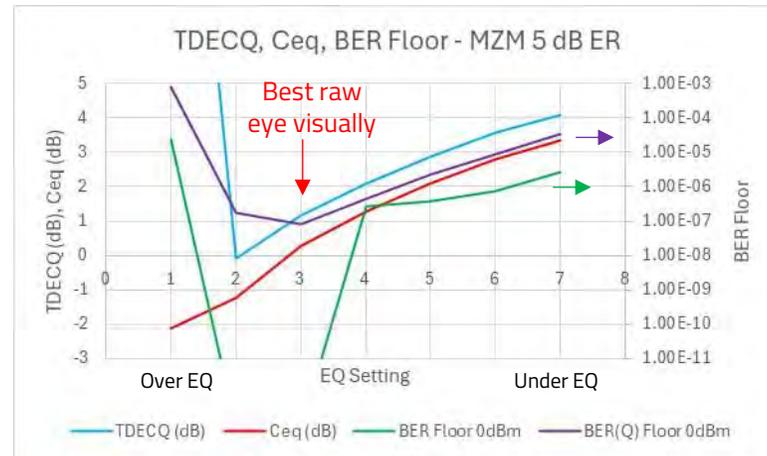
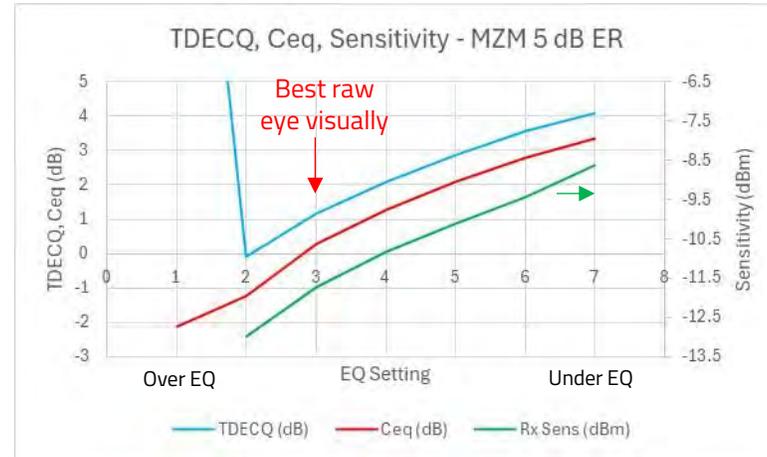
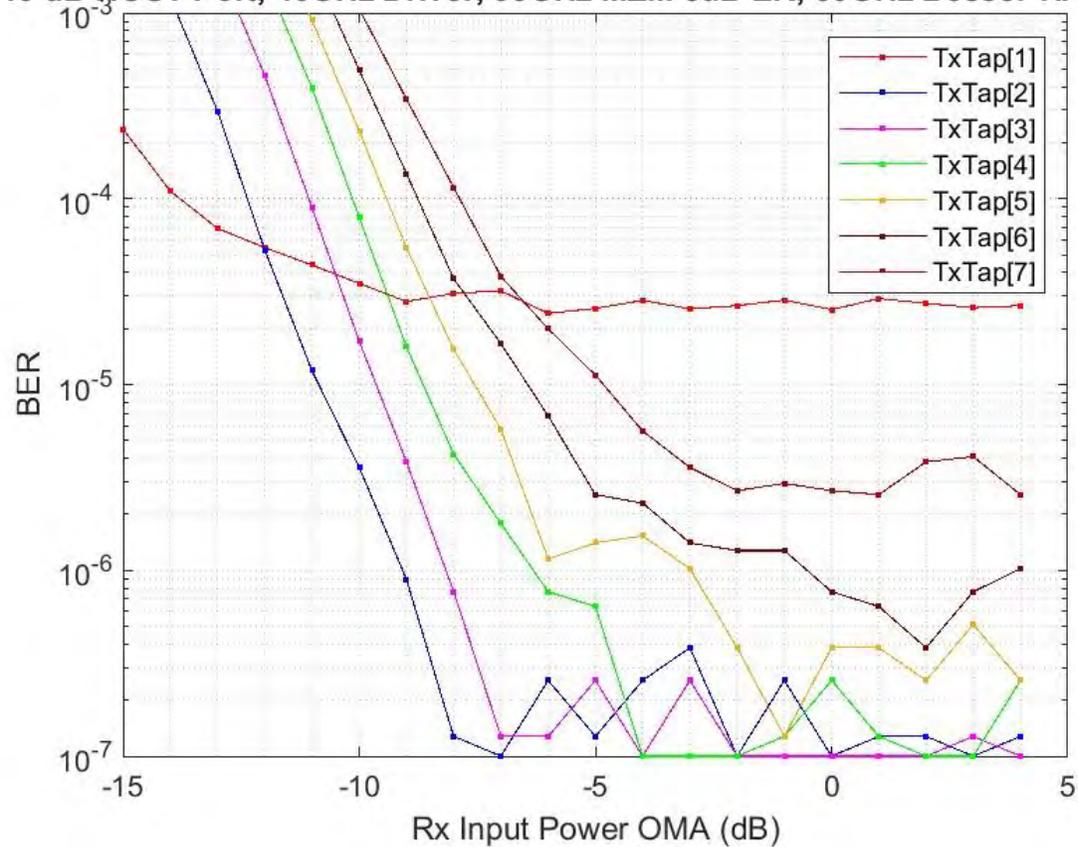
TP2 - Calculated TDECQ = 4.0848 dB Ceq = 2.1573
 Taps = [-0.31075 2.0166 -0.73011 0.16228 -0.13803]
 TDECQ Filter BW = 26.6 GHz



Taps 7 – Under Equalized

Simulation Results – MZM Modulator 5dB ER

13 dB HOST Port, 40GHz Driver, 35GHz MZM 5dB ER, 30GHz Bessel TIA, Noise

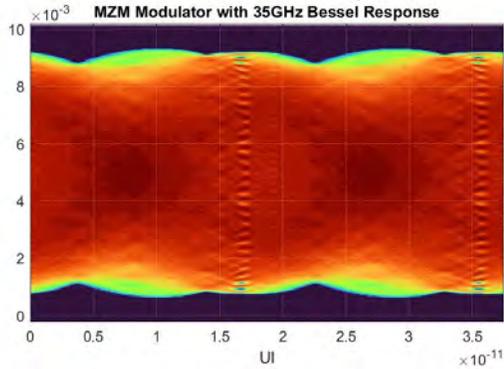


BER(Q) is estimated BER from Q

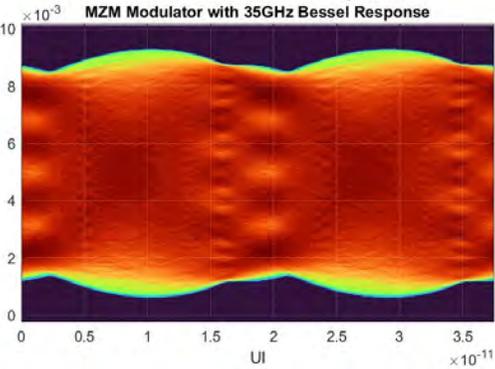
TP2 Eye Diagrams – MZM Modulator 6dB ER (1)

RAW EYE

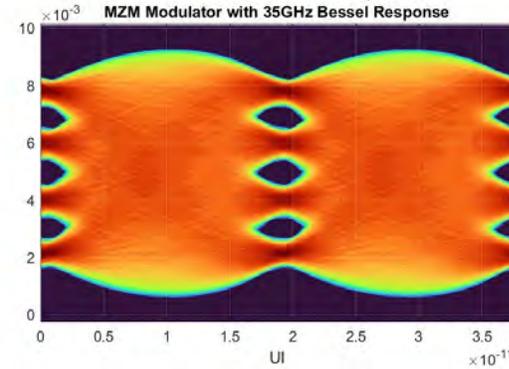
Tx Waveform + Tx EQ + Driver + Modulator
Tx - Simulated with 20GHz Bessel Response
FIR EQ[1:5] - [-0.019 0.065 -0.25 0.44 -0.22]
Driver with 40GHz Bessel Response
MZM Modulator with 35GHz Bessel Response



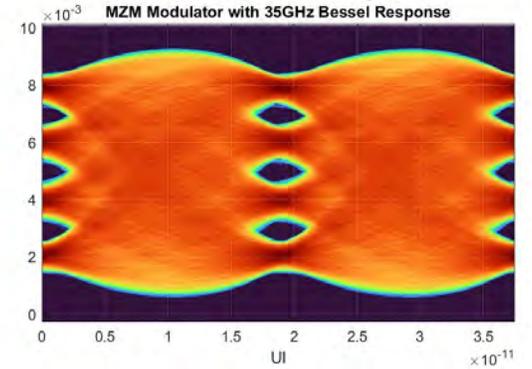
Tx Waveform + Tx EQ + Driver + Modulator
Tx - Simulated with 20GHz Bessel Response
FIR EQ[1:5] - [-0.019 0.065 -0.23 0.48 -0.2]
Driver with 40GHz Bessel Response
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Tx Waveform + Tx EQ + Driver + Modulator
Tx - Simulated with 20GHz Bessel Response
FIR EQ[1:5] - [-0.019 0.065 -0.21 0.52 -0.18]
Driver with 40GHz Bessel Response
MZM Modulator with 35GHz Bessel Response

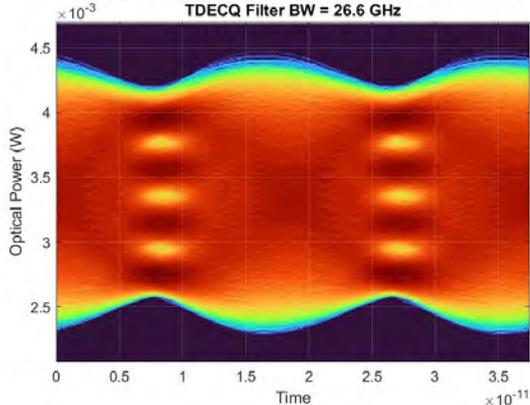


Tx Waveform + Tx EQ + Driver + Modulator
Tx - Simulated with 20GHz Bessel Response
FIR EQ[1:5] - [-0.019 0.065 -0.19 0.56 -0.16]
Driver with 40GHz Bessel Response
MZM Modulator with 35GHz Bessel Response



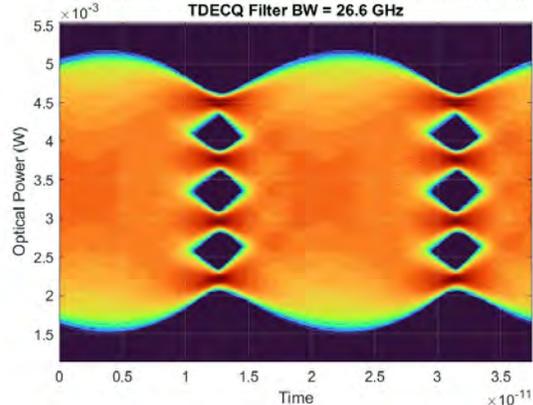
EQUALIZED EYE

TP2 - Calculated TDECQ = 22.0764 dB Ceq = 0.5739
Taps = [0.080358 0.21642 0.49669 0.086174 0.12036]
TDECQ Filter BW = 26.6 GHz



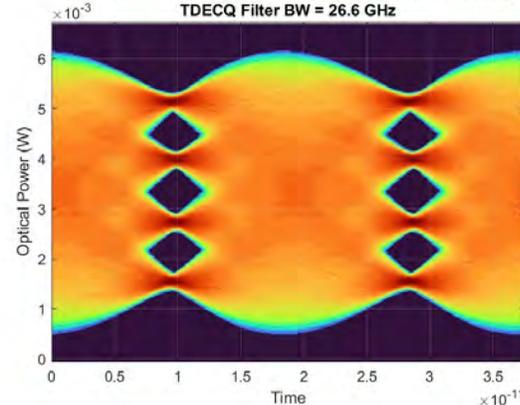
Taps 1 – Over Equalized

TP2 - Calculated TDECQ = 0.11341 dB Ceq = 0.75383
Taps = [0.070107 0.06232 0.7396 0.057505 0.070467]
TDECQ Filter BW = 26.6 GHz



Taps 2

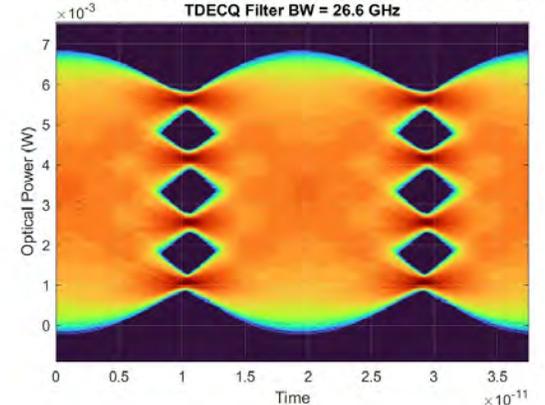
TP2 - Calculated TDECQ = 1.2766 dB Ceq = 1.0662
Taps = [0.12173 1.0386 -0.18069 0.093095 -0.072692]
TDECQ Filter BW = 26.6 GHz



Taps 3

Best visually optimized Tx

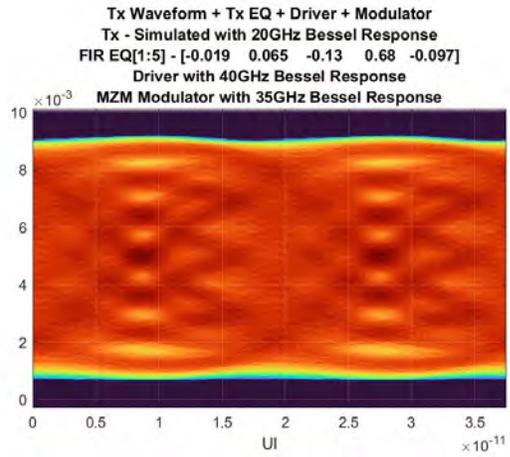
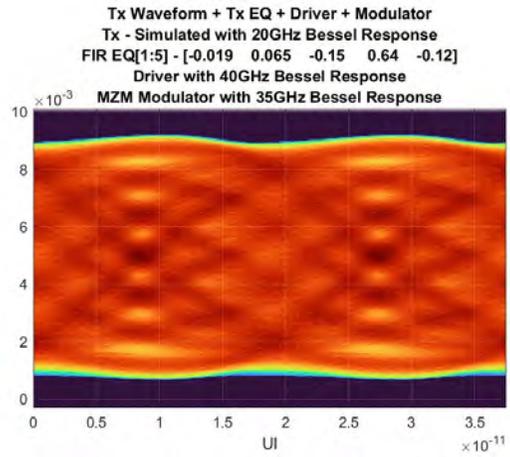
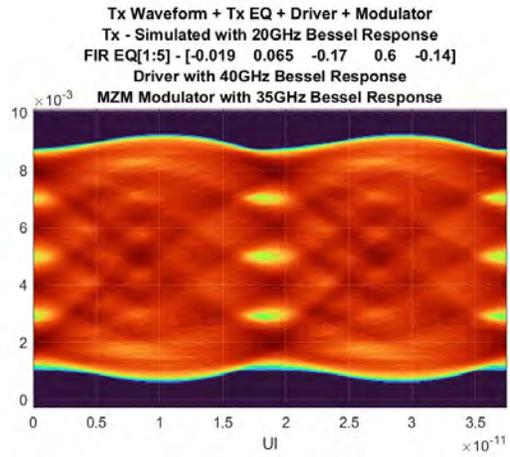
TP2 - Calculated TDECQ = 2.1332 dB Ceq = 1.3284
Taps = [-0.0062307 1.2983 -0.28433 0.079794 -0.087549]
TDECQ Filter BW = 26.6 GHz



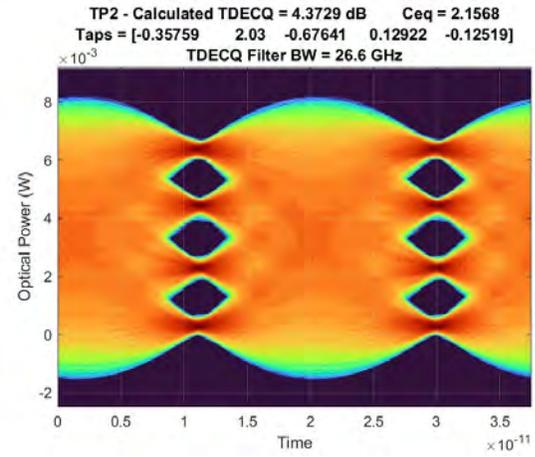
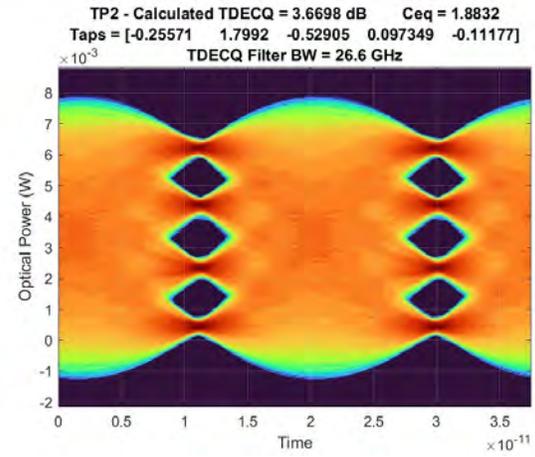
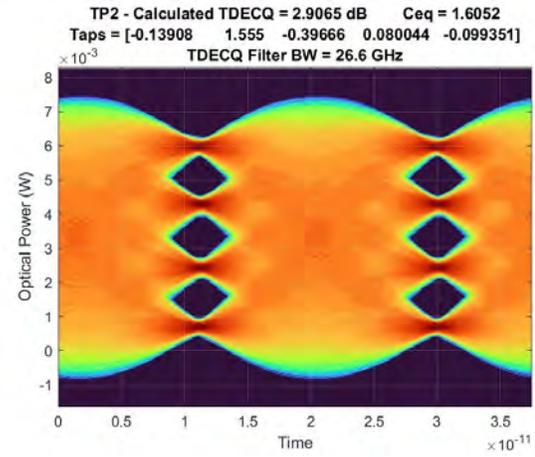
Taps 4 – Host Port Fully Equalized

TP2 Eye Diagrams – MZM Modulator 6dB ER (2)

RAW EYE



EQUALIZED EYE



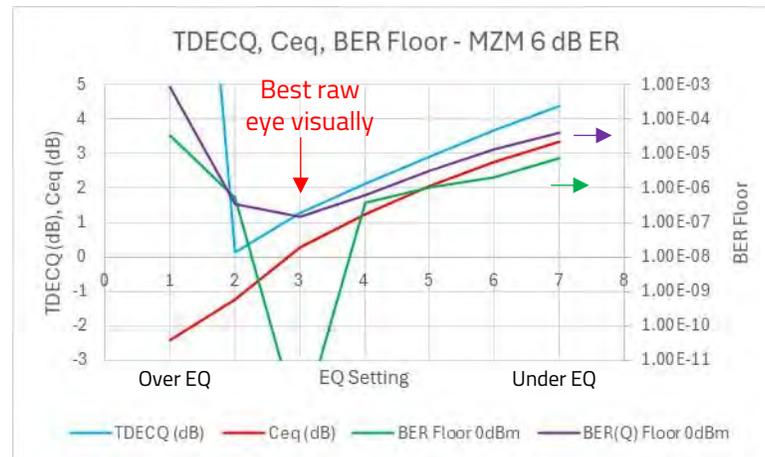
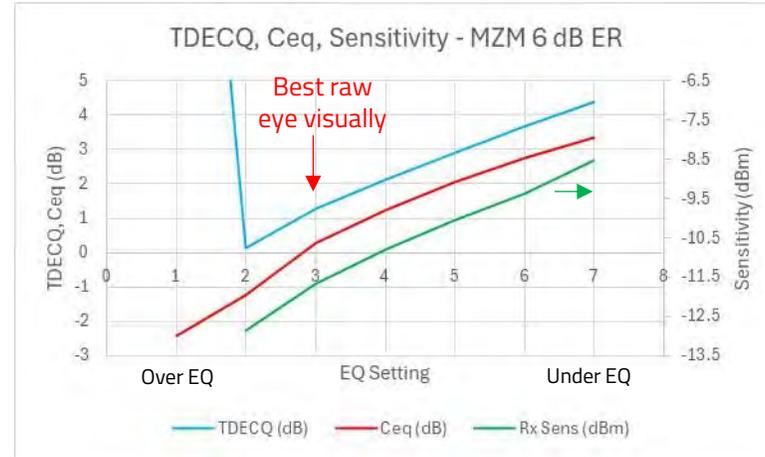
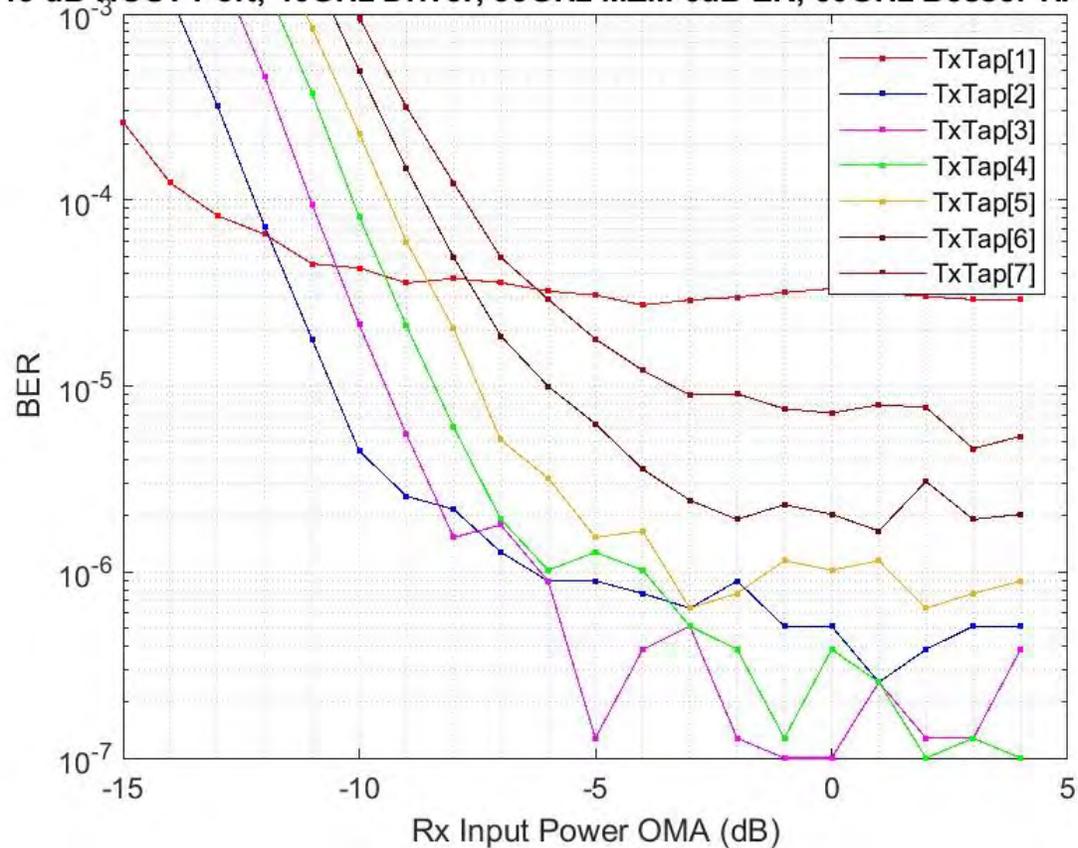
Taps 5

Taps 6

Taps 7 – Under Equalized

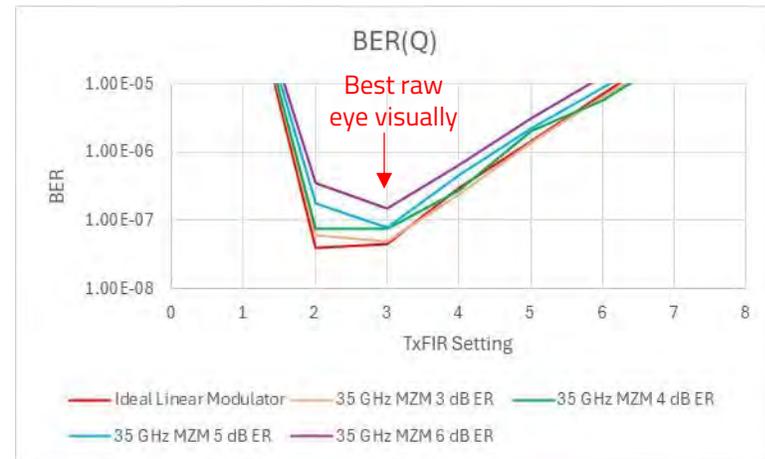
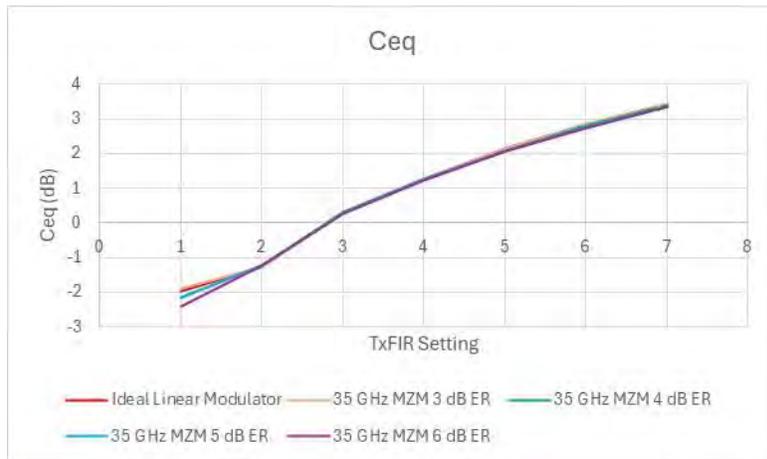
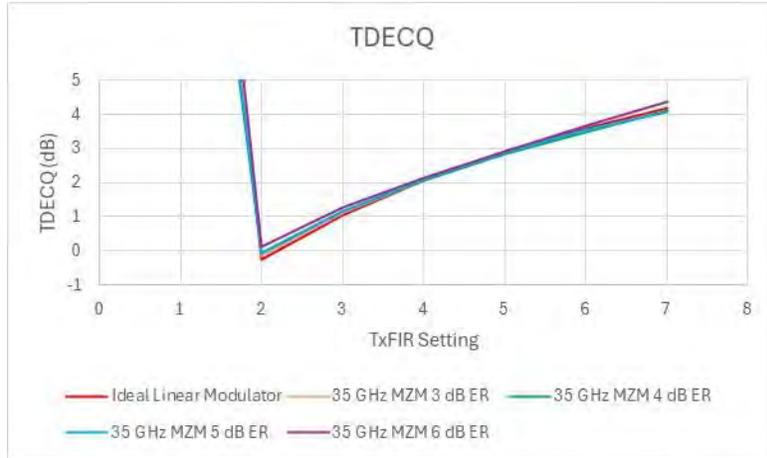
Simulation Results – MZM Modulator 6dB ER

13 dB HOST Port, 40GHz Driver, 35GHz MZM 6dB ER, 30GHz Bessel TIA, Noise



BER(Q) is estimated BER from Q

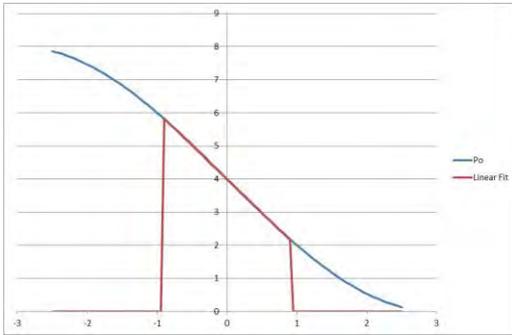
Simulation Summary



- BER floor is more sensitive to distortion when Ceq < 0dB
- Distortion needs to be limited

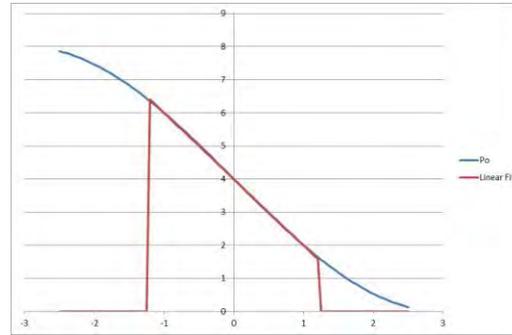
MZM Distortion

3 dB ER



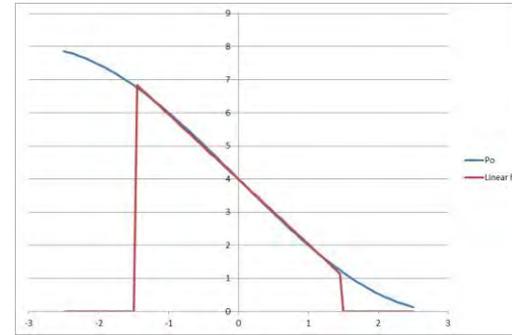
	1.01138117 %
Largest Non-linearity	-0.7511887 %

4 dB ER



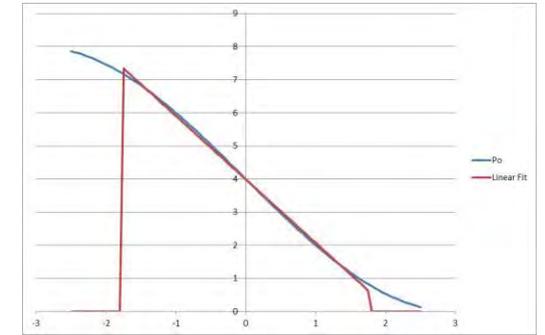
	1.88538071 %
Largest Non-linearity	-2.5820818 %

5 dB ER



	3.4349621 %
Largest Non-linearity	-4.2132656 %

6 dB ER



	5.2479737 %
Largest Non-linearity	-8.4590574 %

Rule of thumb – Distortion < 3% is usually acceptable for performance
 Indicates that ER should be kept < 4.5 dB

Other Tx Metrics

Measured using TDECQ derived parameters

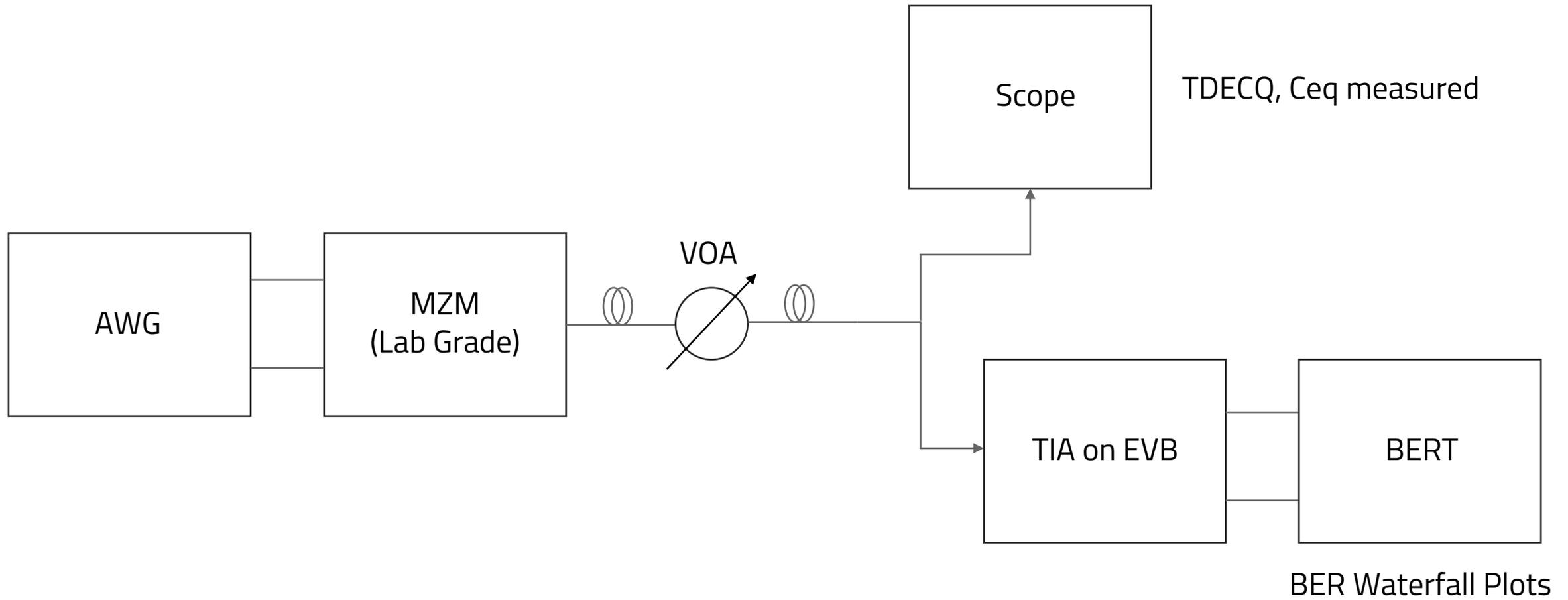
$$\text{SNR} = 10 \cdot \log_{10}(\text{Signal power} / \sigma_G)^2$$

$$\text{SNDR} = 10 \cdot \log_{10}((\text{Signal power} / \sigma_G)^2 + \text{aver}(\text{Level variance}))$$

SNR		Ideal Linear	3dB MZM	4dB MZM	5 dB MZM	6dB MZM
Taps	TP1a	TP2				
1	62.5	68.7	68.7	61.7	63.1	68.4
2	56	19.8	19.9	19.9	20	20.2
3	20.1	19.4	19.5	19.6	19.6	19.8
4	18.9	19.3	19.3	19.4	19.5	19.6
5	18.9	19.3	19.3	19.4	19.5	19.7
6	19.1	19.3	19.3	19.3	19.7	20
7	19.9	19.2	19.3	19.4	19.6	20.4
SNDR		Ideal Linear	3dB MZM	4dB MZM	5 dB MZM	6dB MZM
Taps	TP1a	TP2				
1	7.1	8.4	8.5	9.8	9.8	10.4
2	15.5	17.6	17.6	17.7	17.8	17.8
3	17.4	17.6	17.6	17.7	17.8	17.8
4	17.6	17.6	17.7	17.7	17.8	17.8
5	17.6	17.6	17.6	17.7	17.8	17.8
6	17.6	17.6	17.6	17.7	17.8	18
7	17.7	17.6	17.6	17.7	17.8	18.1

- Under equalization slightly degrades Tx SNR
 - Only noise included in Tx side is -40dB crosstalk so degradation should be small
- Increasing ER slightly increases Tx SNR
- No clear correlation with BER floor performance (expected as σ_G calculated for $2.4e-4$)

Measurement setup

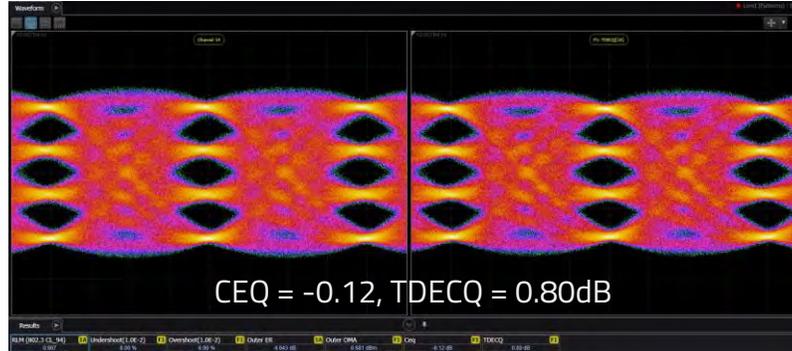


TX ER = 4dB

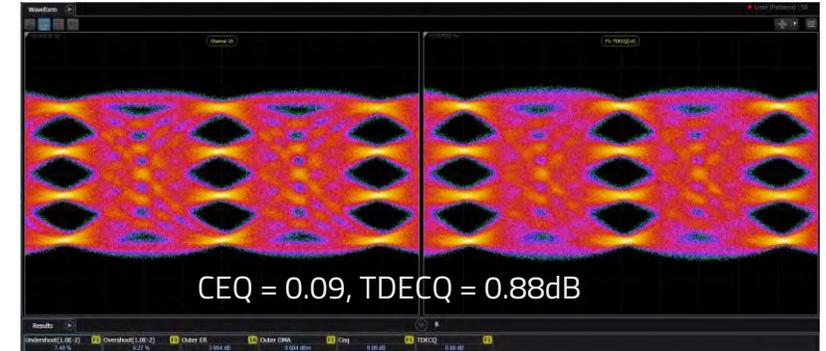
TDECQ IEEE 802.3cd
Bessel 4th 26.6GHz
TX ER = 4dB

Note
AWG output swing
adjusted for different tap
settings to keep optical
ER at 4 dB as measured
on the scope for all FIR
settings.

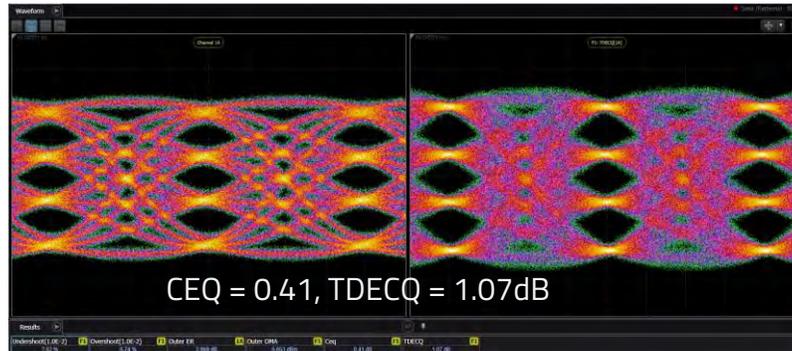
FIR: -0.15/1.3/-0.15 AWG=750



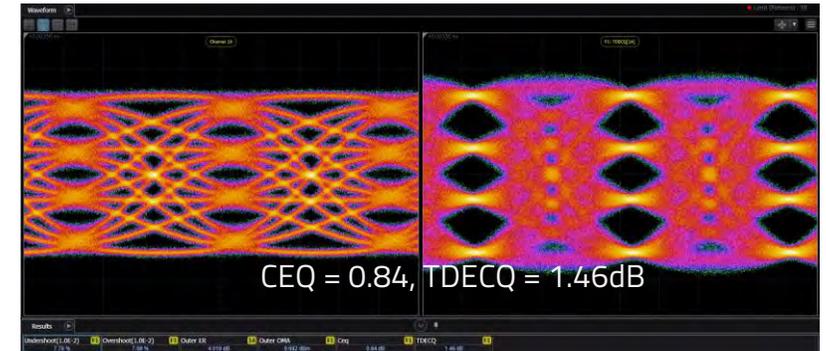
FIR: -0.1/1.2/-0.1 AWG=690



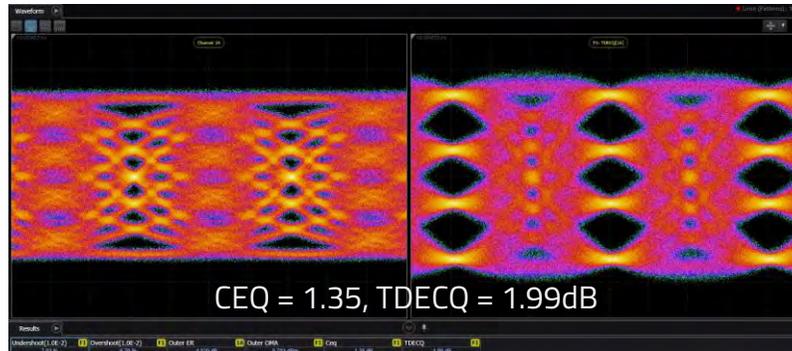
FIR: -0.05/1.1/-0.05 AWG=630



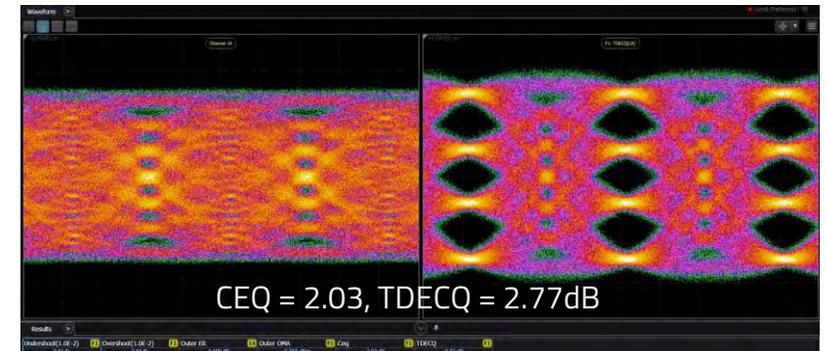
FIR: 0/1/0 AWG=580



FIR: 0.05/0.9/0.05 AWG=520



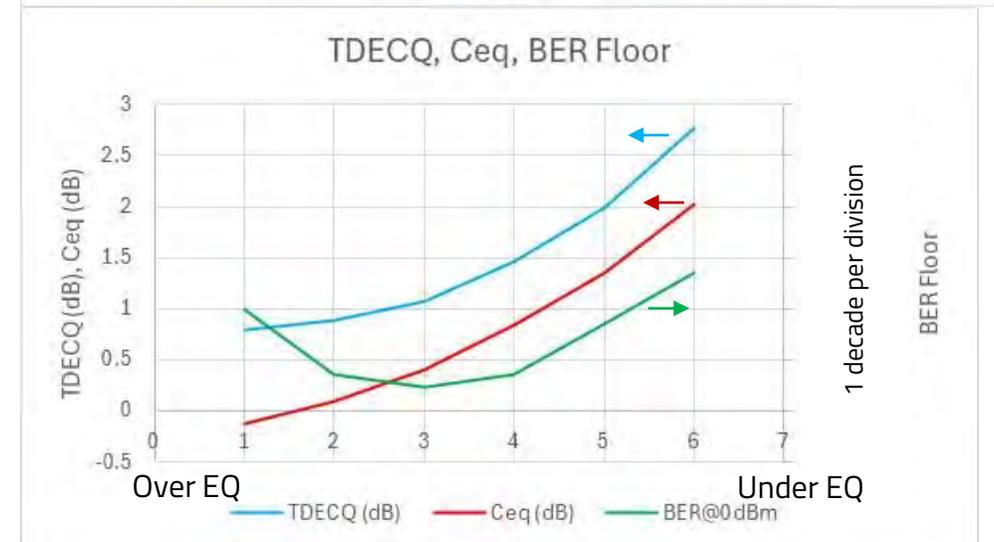
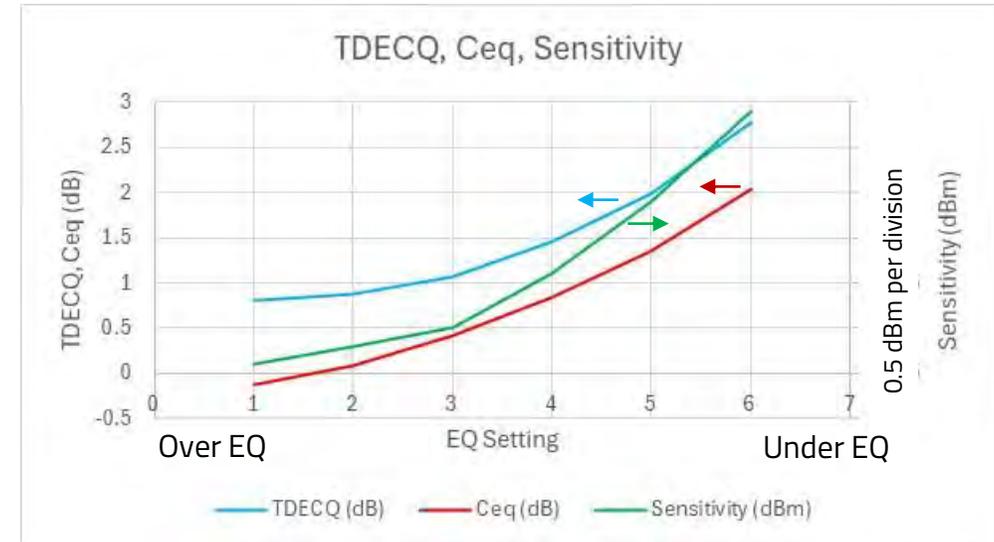
FIR: 0.1/0.8/0.1 AWG=470



SM Measured Performance - 1

- TDECQ and Rx Sensitivity track each other as expected
- Ceq and TDECQ track each other
- BER floor
 - Tracks TDECQ for $C_{eq} > 0.75$ dB
 - Fairly flat for 0.2 dB $< C_{eq} < 0.75$ dB
 - Goes in opposite direction for $C_{eq} < 0.25$ dB
- BEST TDECQ = BEST Rx SENSITIVITY
- BEST TDECQ \neq BEST BER FLOOR
- As TDECQ increases (for $C_{eq} > 0$ dB)
 - Tx SNR is decreasing
 - Rx equalization of the Tx results in noise amplification (C_{eq} increases)
 - Caveat: Reasonable and smooth frequency response implied
- For $C_{eq} < 0.5$ dB, Tx SNR might be improving but signal phase is being distorted

ER_outer = 4 dB

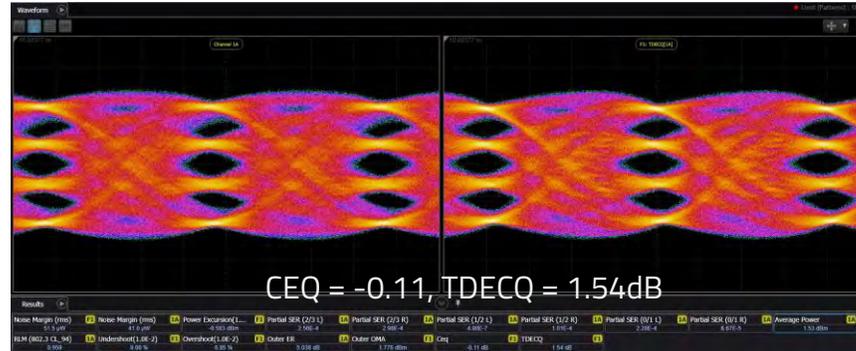


TX ER = 5dB

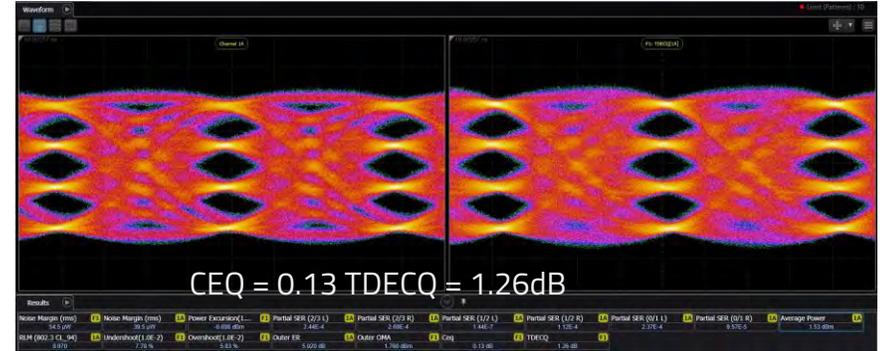
TDECQ IEEE 802.3cd
Bessel 4th 26.6GHz
TX ER = 5 dB

Note
AWG output swing
adjusted for different tap
settings to keep optical
ER at 5 dB as measured
on the scope for all FIR
settings.

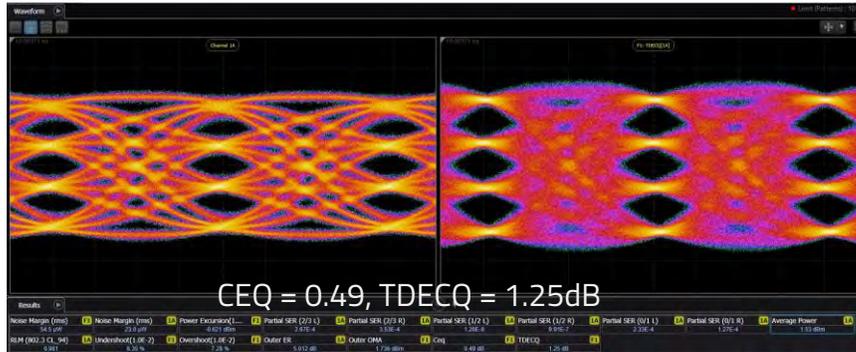
FIR: -0.15/1.3/-0.15 AWG=940



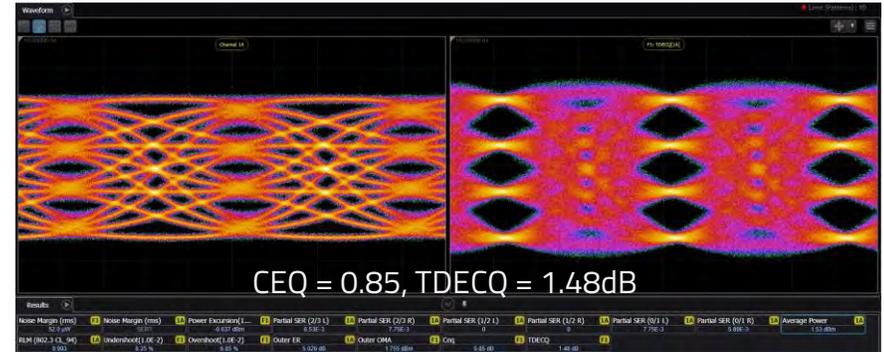
FIR: -0.1/1.2/-0.1 AWG=870



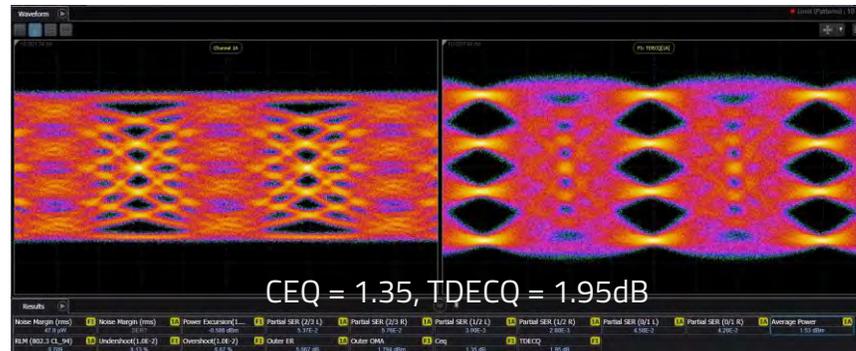
FIR: -0.05/1.1/-0.05 AWG=810



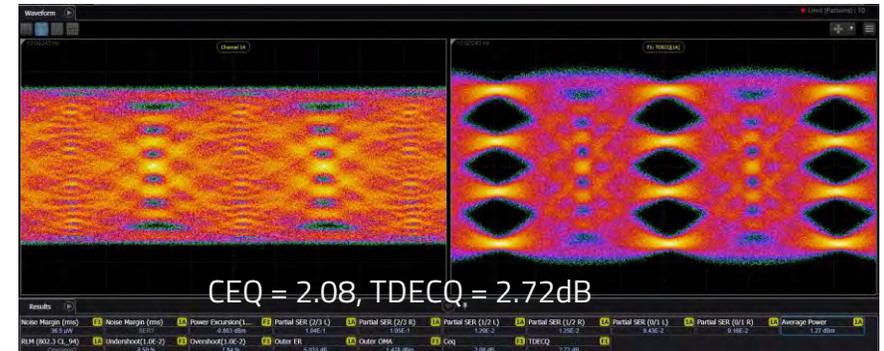
FIR: 0/1/0 AWG=750



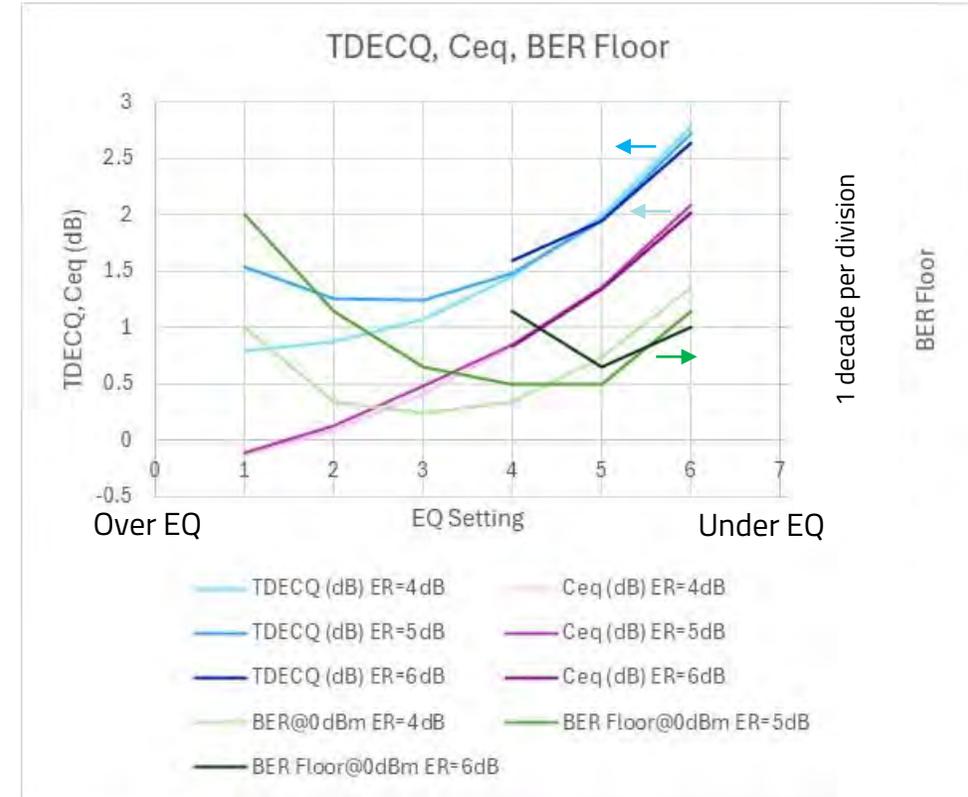
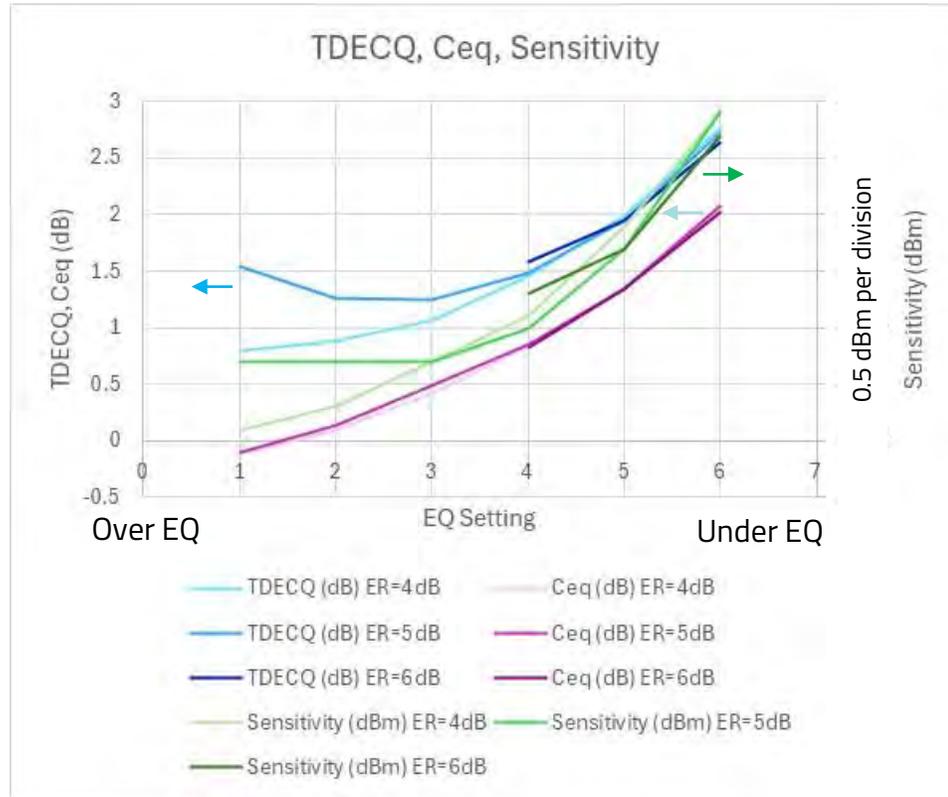
FIR: 0.05/0.9/0.05 AWG=680



FIR: 0.1/0.8/0.1 AWG=470

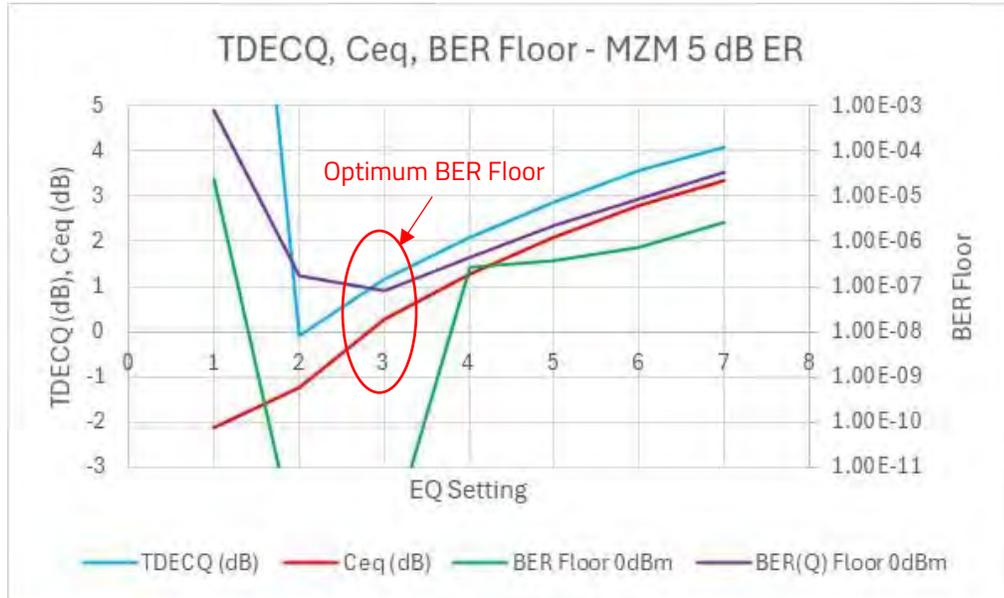


SM Measured Performance - 2

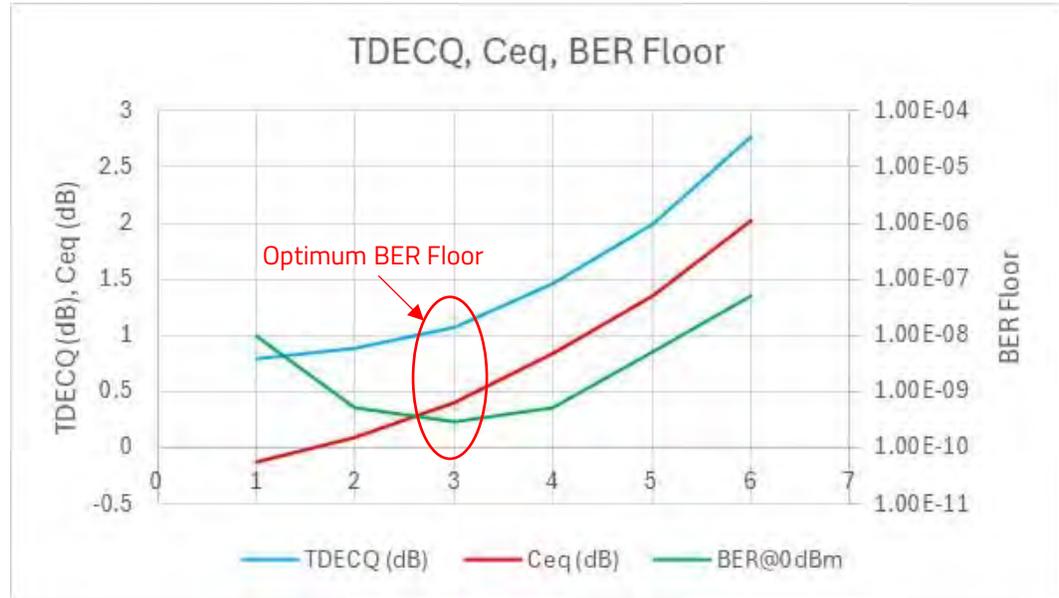


- Ceq doesn't change with ER indicating that the frequency is not changing
- BER Floor is very sensitivity to ER and low Ceq indicating that the high ER has distortion
 - Combination of driver + MZM distortion

Simulation vs Measurement (Single Mode)



Simulated – only MZM THD

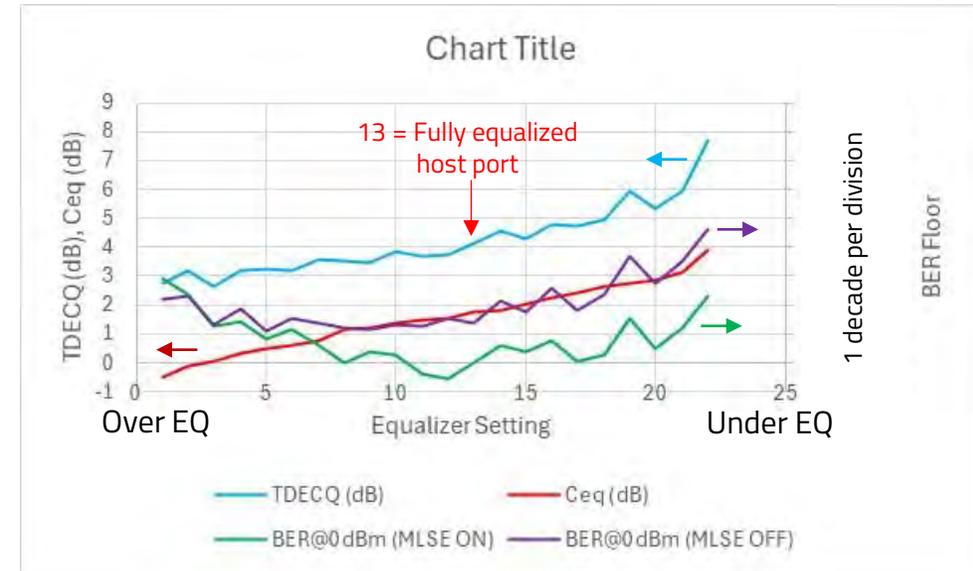


Measured (4dB case) – MZM and driver THD

- Good agreement with trends between simulation and measurement
- Both simulation and measurement indicate that Ceq ~0.3-0.5dB for best BER floor with moderate THD levels
- Lowest TDECQ does not align with best BER floor
- Transmitter should be tuned for TDECQ and Ceq limits

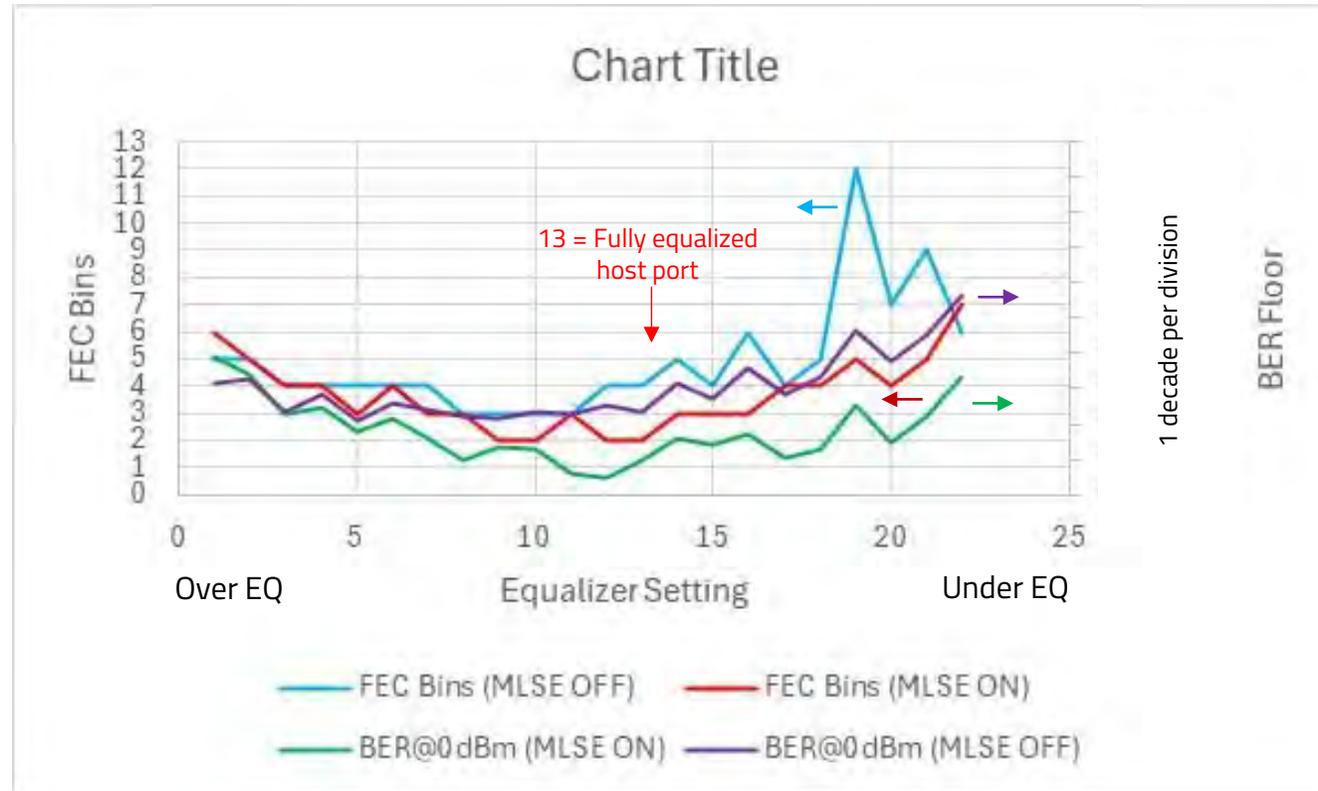
Multimode Module Measurements - 1

Switch used to generate Tx signal and measure BER



Same trend using MM optics and switch environment

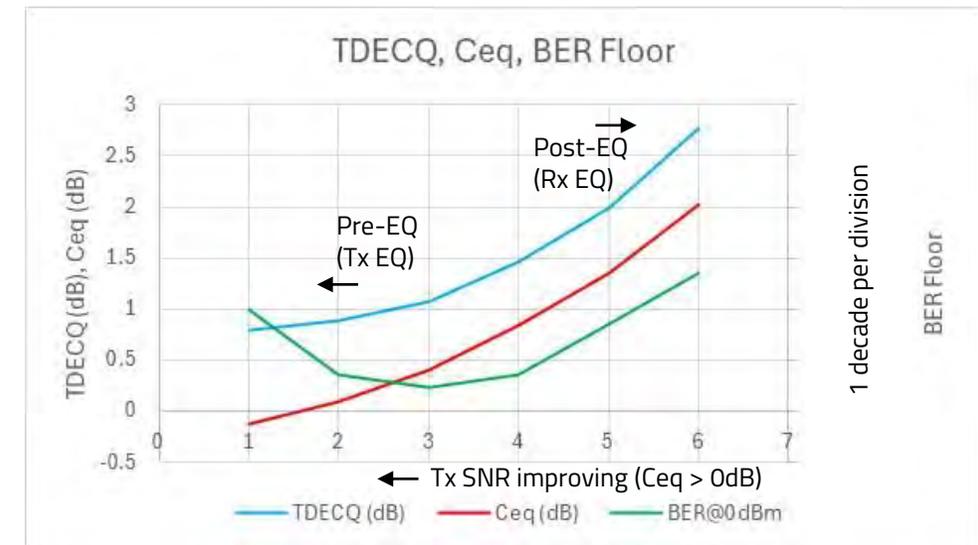
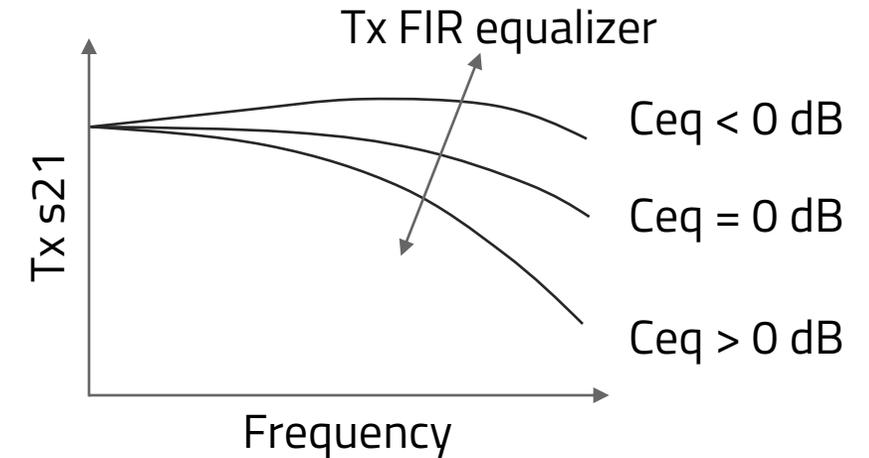
Multimode Module Measurements - 2



- FEC Bins follow BER Floor trend
- Best FEC Bin for $C_{eq} > 0$ dB

Some thoughts...

- For a smooth Tx (driver + modulator) frequency response:
 - C_{eq} is indicating how much equalization is required to equalize (or flatten) the Tx frequency response
 - TDECQ (for $C_{eq} > 0$ dB) is giving an indication of link SNR penalty
 - Lower TDECQ = More open Tx eye
 - Better Tx SNR
 - Lower Rx noise amplification due to equalizer
- Simulations and measurements are telling us that Tx peaking is bad
- C_{eq} is showing when the Tx is starting to be over peaked
- $C_{eq} < 0$ dB results in degraded performance
 - $0.5 \text{ dB} < C_{eq} < 1 \text{ dB}$ tends to be close to optimum for SM optics
- Equalization at the Tx improves
 - Tx SNR (by a small amount)
 - Link SNR (significantly) by reducing noise amplification of Rx EQ
- Equalization of the Tx by the Rx does not improve Tx SNR
 - Degrades link SNR by introducing noise amplification
- These measurements appear to be quite fundamental (i.e. not linked to implementation) and apply widely

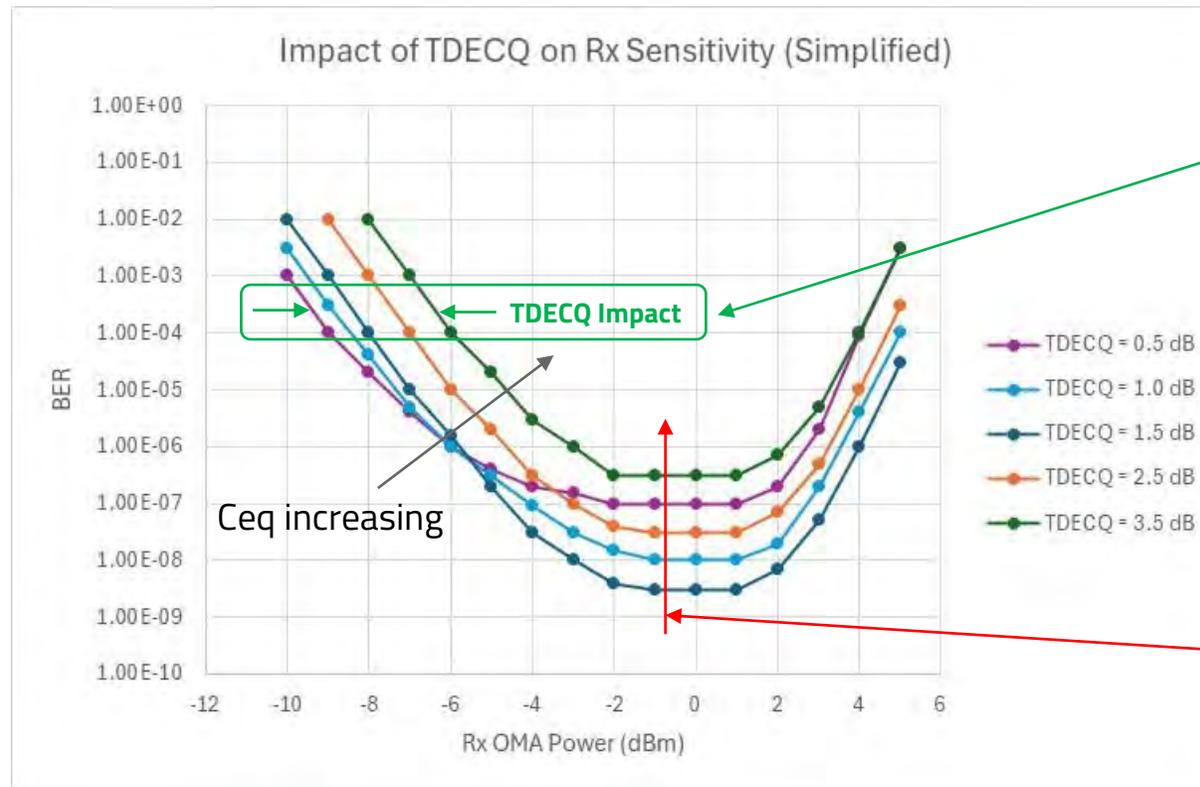


What about TDECQ – 10 log Ceq?

TDECQ (dB)	Ceq (dB)	TDECQ-10log(Ceq)
0.8	-0.12	0.92
0.88	0.09	0.79
1.07	0.41	0.66
1.46	0.84	0.62
1.99	1.35	0.64
2.77	2.03	0.74

- TDECQ – 10 log Ceq was used as a metric to try and avoid over peaked transmitters
- Limit was set at 3.4 dB
- This data indicates that:
 - TDECQ – 10 log Ceq does show correlation with best performance
 - The limit was set too high as TDECQ – 10 log Ceq is the unequalizable ISI
 - TDECQ and Ceq are more correlated than previously considered
 - Most transmitters appear to be bandwidth limited
 - The delta between good and worse performance is too small to accurately detect

TDECQ and Ceq - what it measures



This is what TDECQ is defined to fundamentally measure

Ceq < 0 dB

Ceq > 0 dB

Tx SNR decreasing, BER Floor increasing with increasing TDECQ for Ceq > 0 dB

Cartoon to show impact of TDECQ and Ceq on BER Curve

Conclusions

- TDECQ by itself is not adequate to determine transmitter performance
 - TDECQ gives a measure of transmitter SNR impairment for $C_{eq} > 0$ dB
- The combination of TDECQ and C_{eq} can be used to better infer transmitter performance
- For a smooth frequency response transmitter C_{eq} can be used to determine transmitter peaking
 - Keeping $C_{eq} > 0$ dB avoids transmitter peaking
 - Practically, $0.5 \text{ dB} < C_{eq} < 1 \text{ dB}$ appears to be optimum in these measurements
- Pre-equalization (Tx EQ) improves transmitter SNR
 - Post equalization (Rx EQ) does not improve SNR
 - Majority of transmitter equalization should be done at the transmitter
 - i.e. Do not rely on the Rx equalizer to equalize the transmitter
- ER should not be pushed to a high value ($> \sim 4$ dB) to avoid modulator non-linearity (MZM)
- Minimum FEC bin count appears to align with minimum BER Floor

Possible Changes to Specifications

- Introduce C_{eq} lower limit of 0 dB
 - Limit over peaking of transmitter
- Introduce upper limit on Tx ER
 - Suggest 4.5 dB upper limit on ER
 - Limit distortion introduced by MZM modulator
- Will help maximize inter-op performance in volume link deployment

THANK YOU