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.

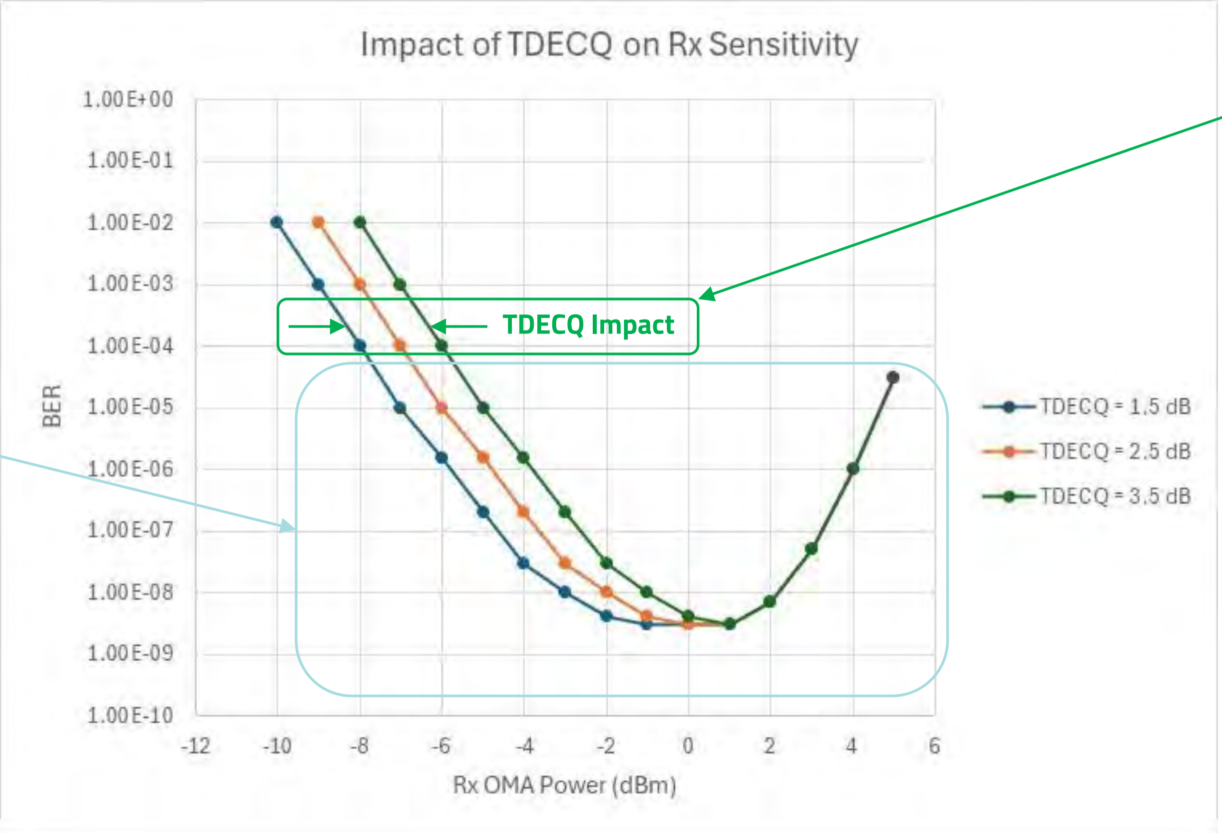
TDECQ and what it measures

- 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

This is what TDECQ is defined to fundamentally measure

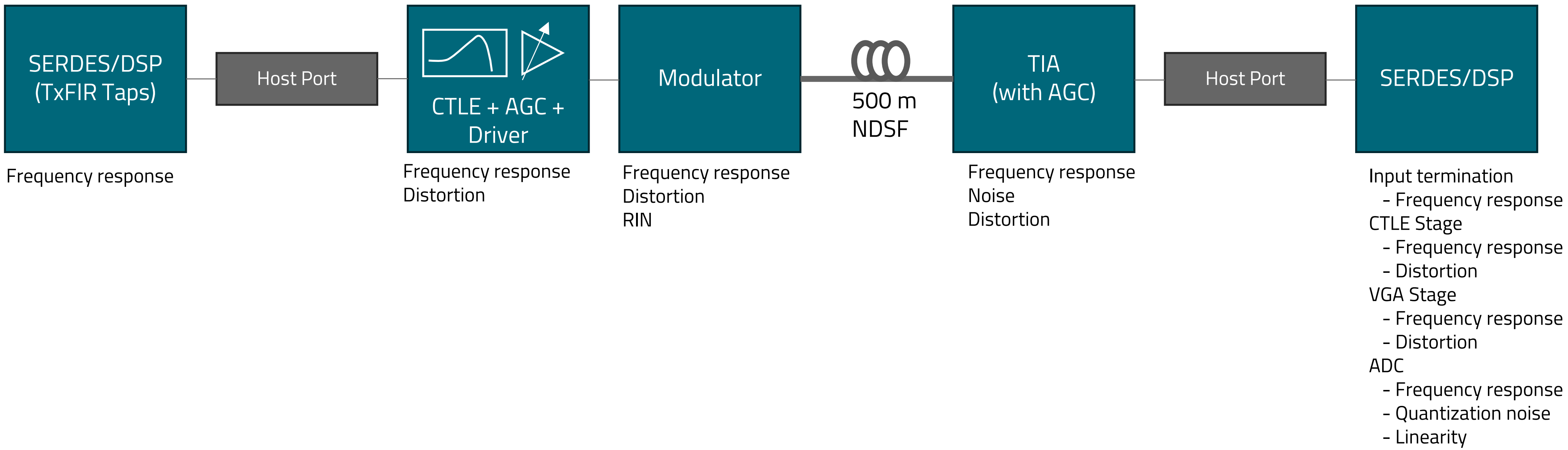
Can TDECQ tell us anything about this area?



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

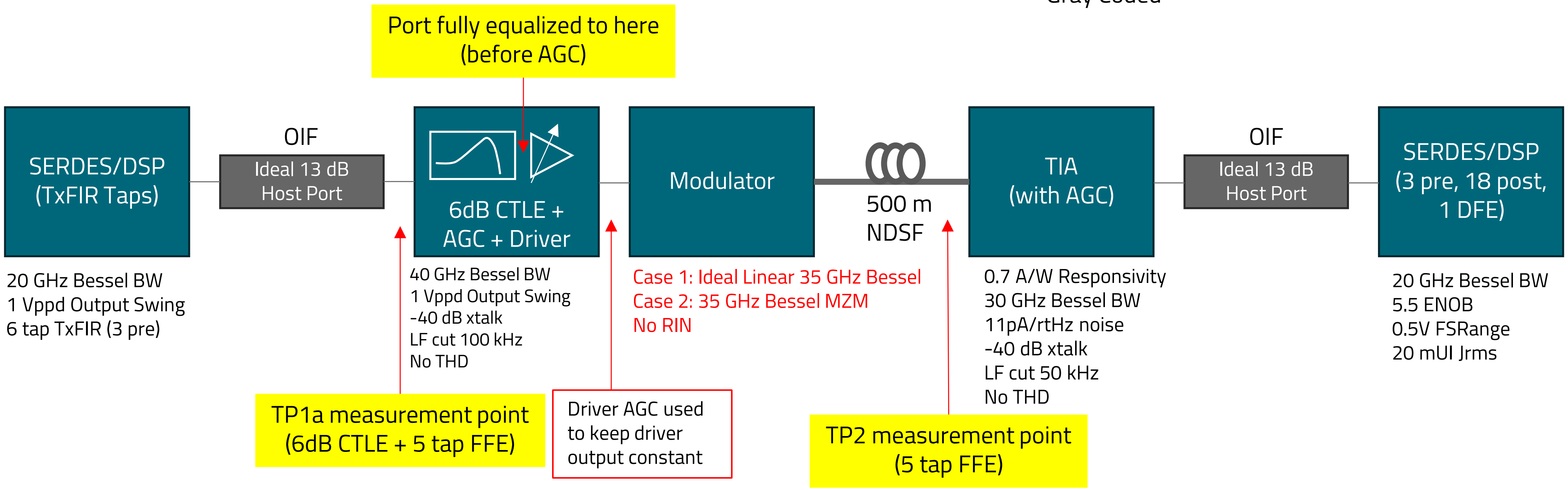
SEMTECH

Typical LPO System



Simulation Setup

PRBS15Q
60 frames
1,966,020 symbols
Gray Coded



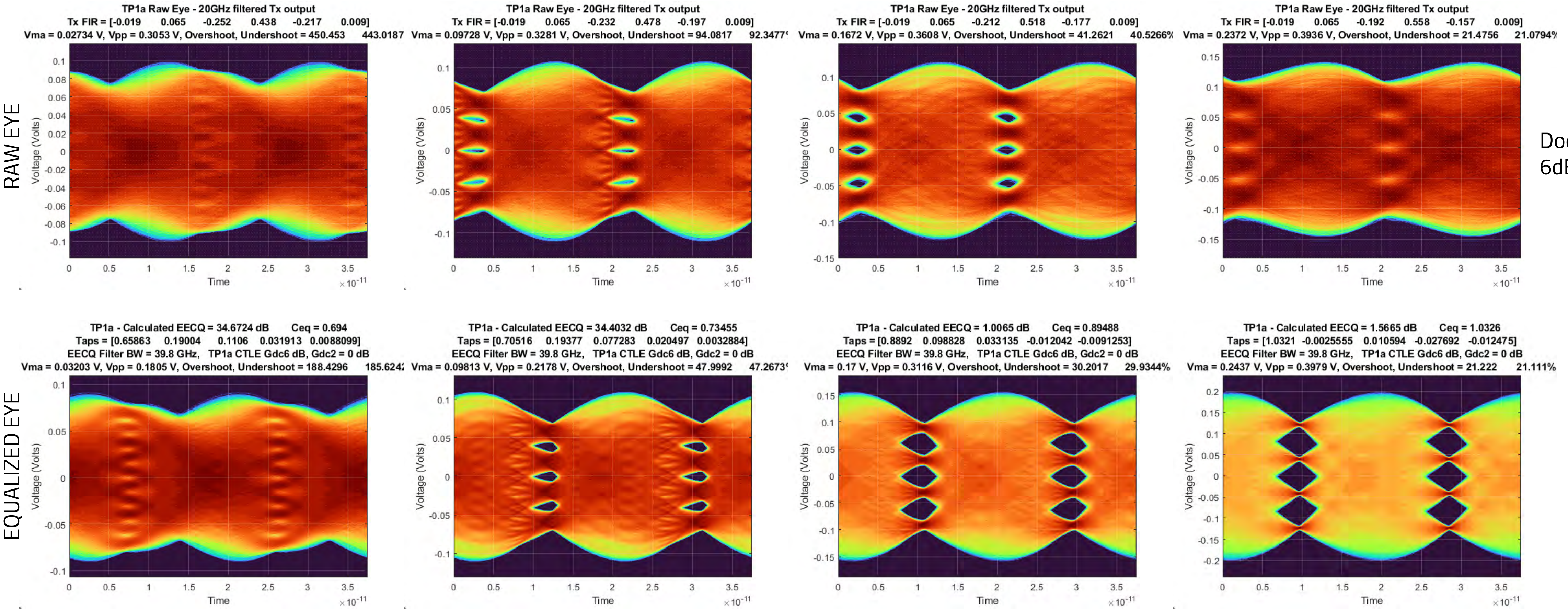

```
Taps{1} = [-0.019 0.065 -0.252 0.438 -0.217 0.009]; % Over equalized
Taps{2} = [-0.019 0.065 -0.232 0.478 -0.197 0.009]; %
Taps{3} = [-0.019 0.065 -0.212 0.518 -0.177 0.009]; %
Taps{4} = [-0.019 0.065 -0.192 0.558 -0.157 0.009]; % Fully equalized
Taps{5} = [-0.019 0.065 -0.172 0.598 -0.137 0.009]; %
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

RAW EYE

EQUALIZED EYE

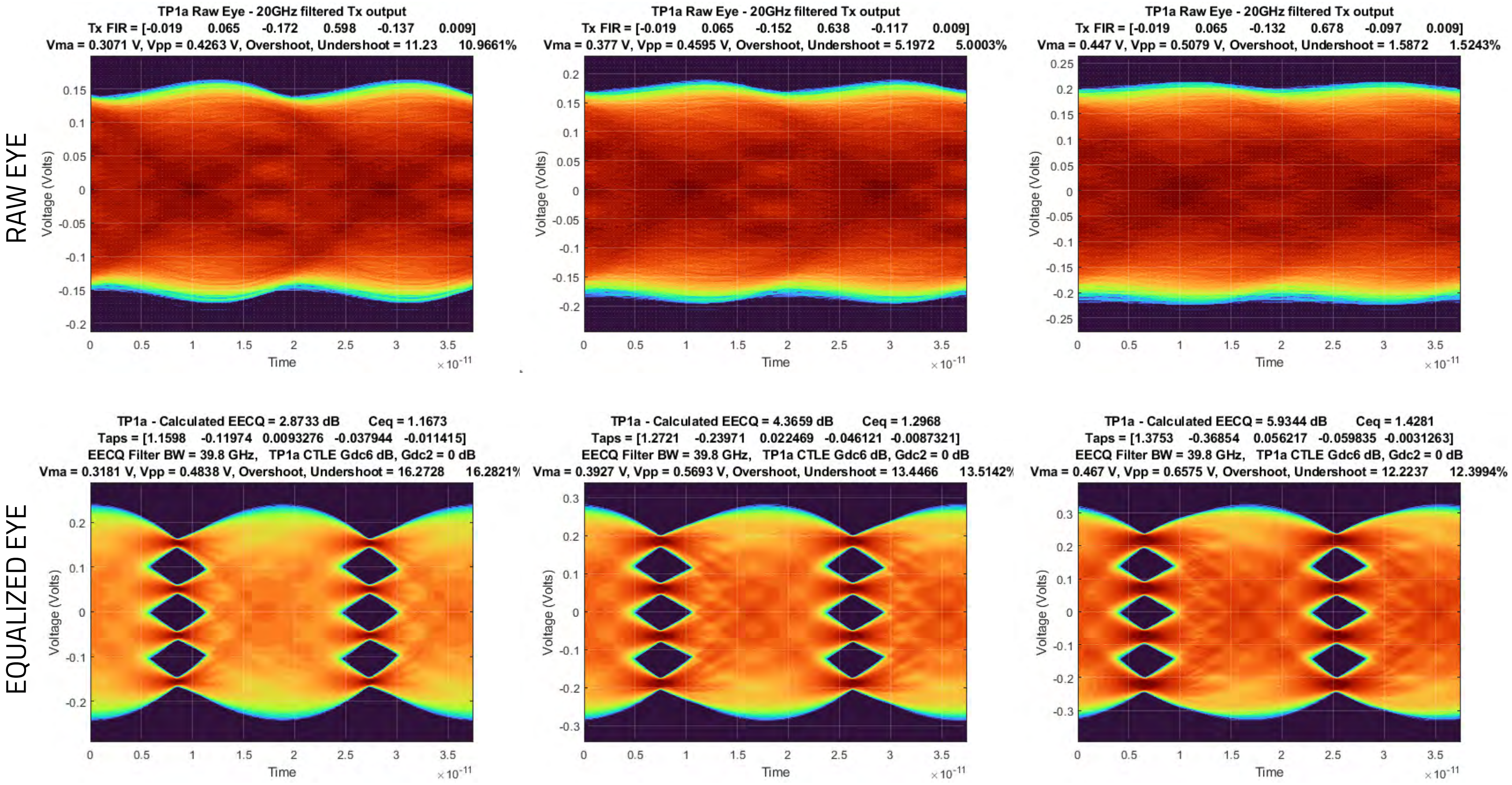


Taps 1 – Over Equalized | Taps 2 | Taps 3 | Taps 4 – Host Port Fully Equalized

Does not include the 6dB CTLE equalizer

Measured at TP1a before AGC

TP1a Eye Diagrams (2)



Taps 5

Taps 6

Taps 7 – Under Equalized

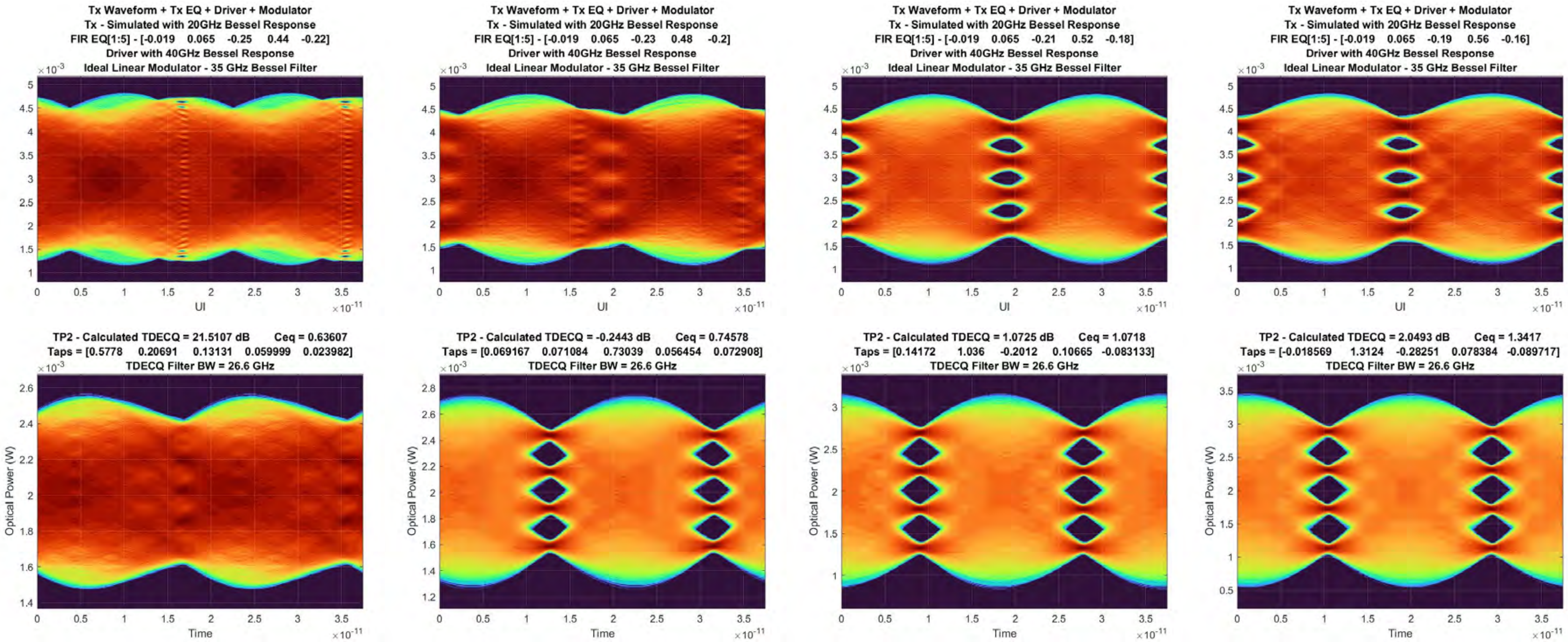
Does not include the 6dB CTLE equalizer

Measured at TP1a before AGC

TP2 Eye Diagrams – Ideal Linear Modulator (1)

RAW EYE

EQUALIZED EYE



Taps 1 – Over Equalized

Taps 2

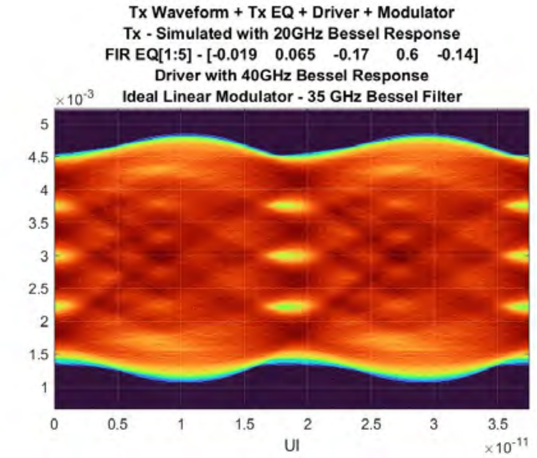
Taps 3

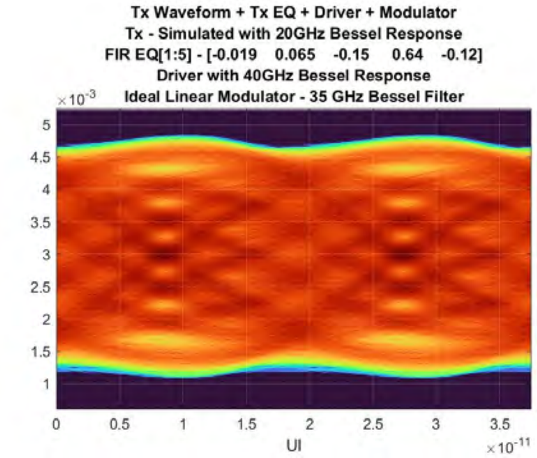
Best visually optimized Tx

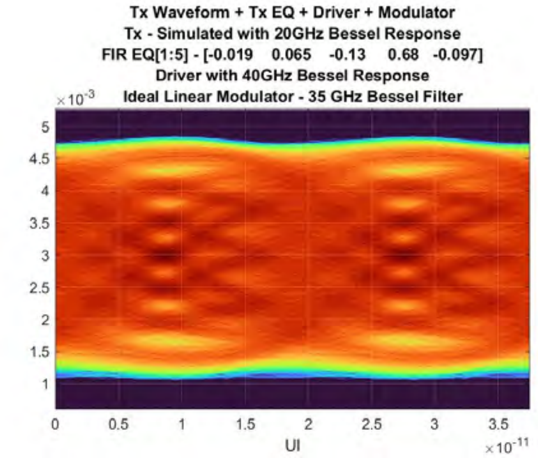
Taps 4 – Host Port Fully Equalized

TP2 Eye Diagrams – Ideal Linear Modulator (2)

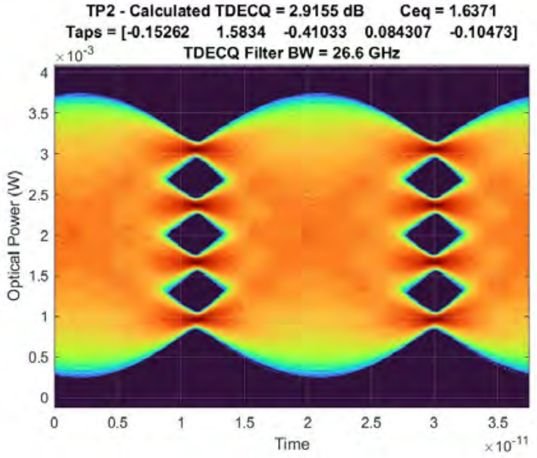
RAW EYE



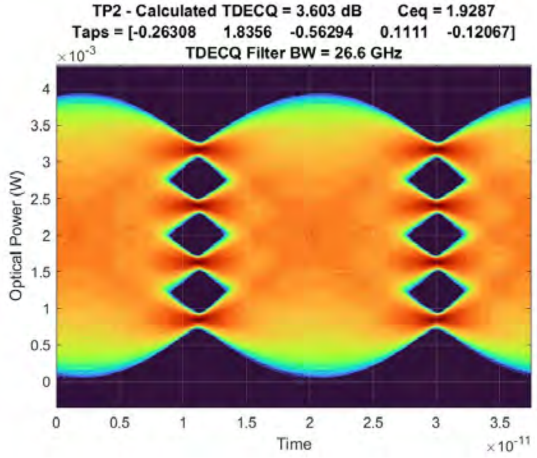




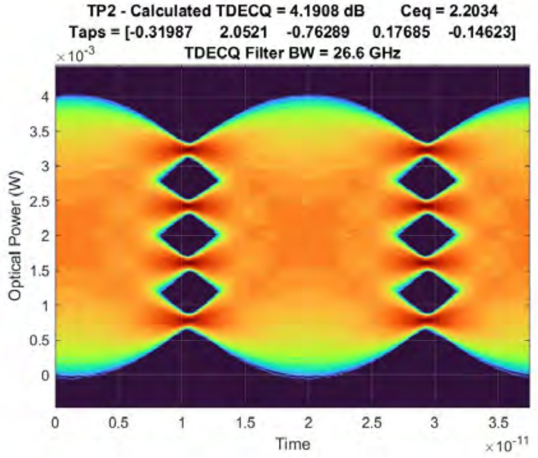
EQUALIZED EYE



Taps 5

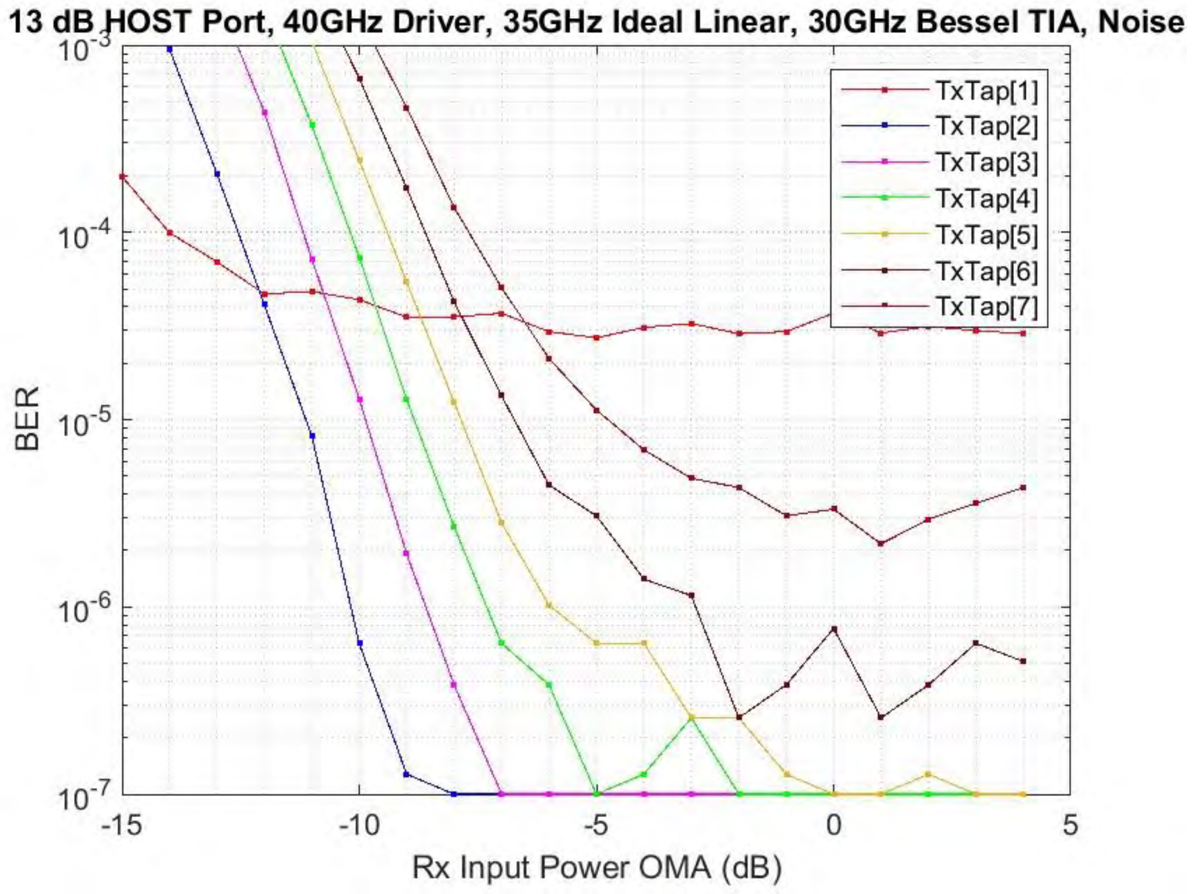


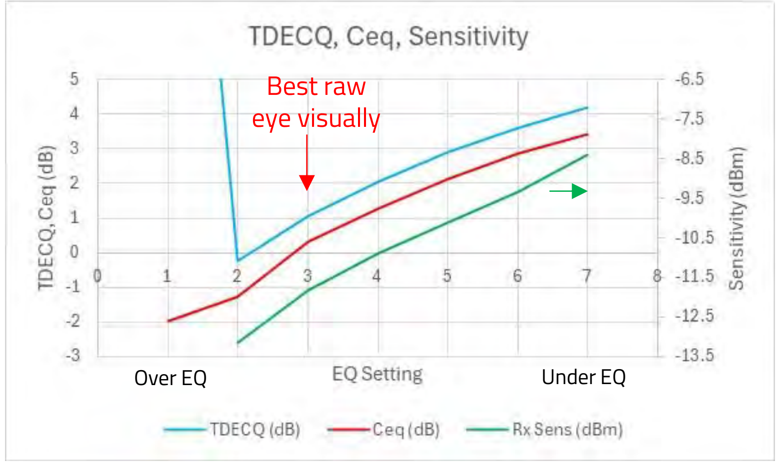
Taps 6

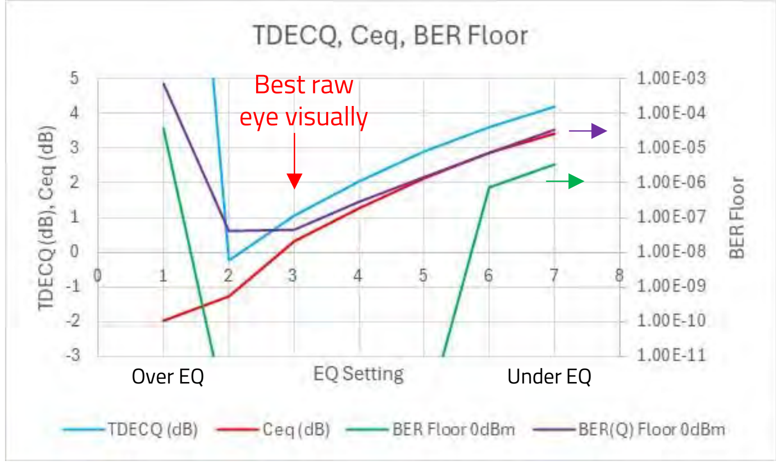


Taps 7 – Under Equalized

Simulation Results – Ideal Linear Modulator





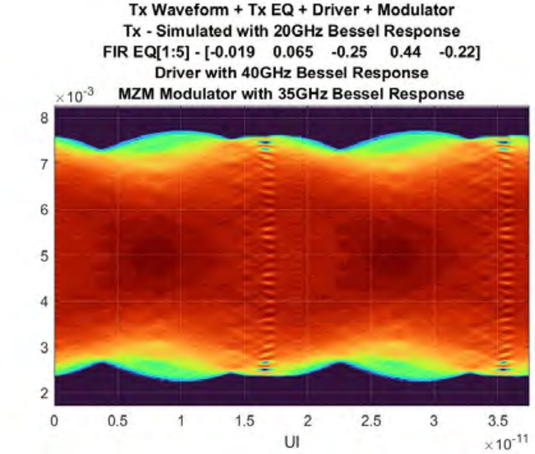


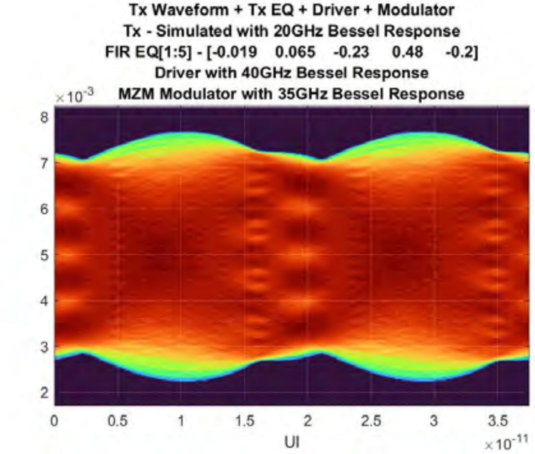
BER(Q) is estimated BER from Q

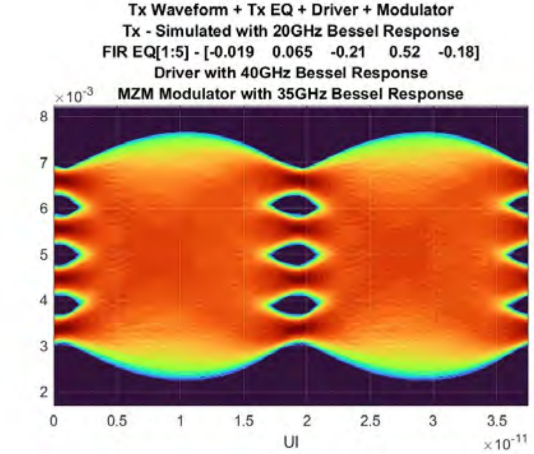
SEMTECH

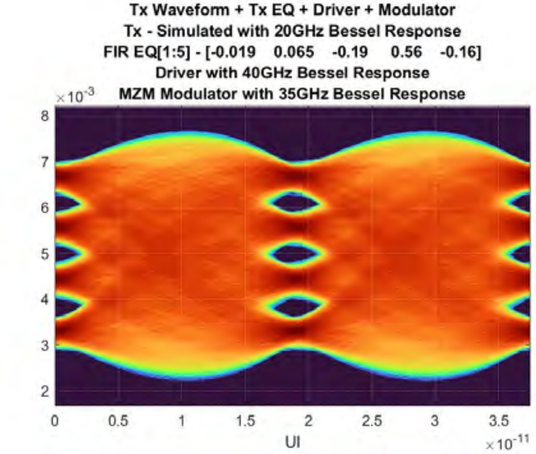
TP2 Eye Diagrams – MZM Modulator 3dB ER (1)

RAW EYE

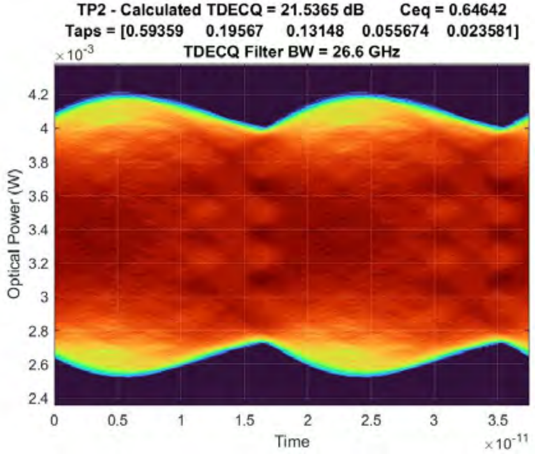




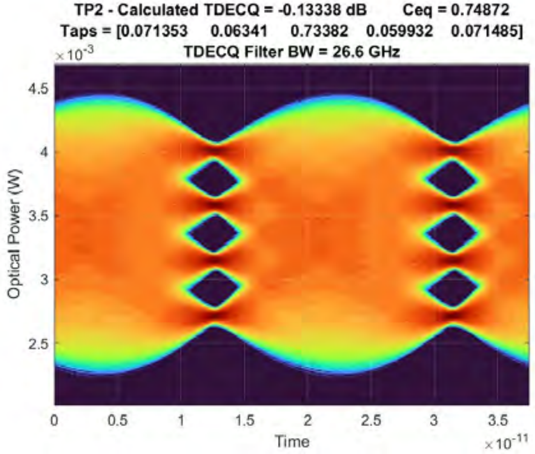




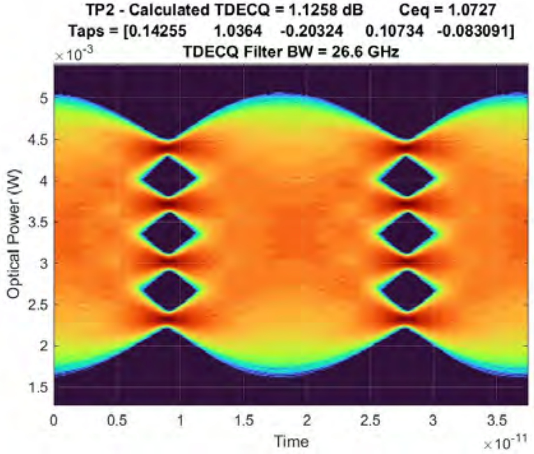
EQUALIZED EYE



Taps 1 – Over Equalized

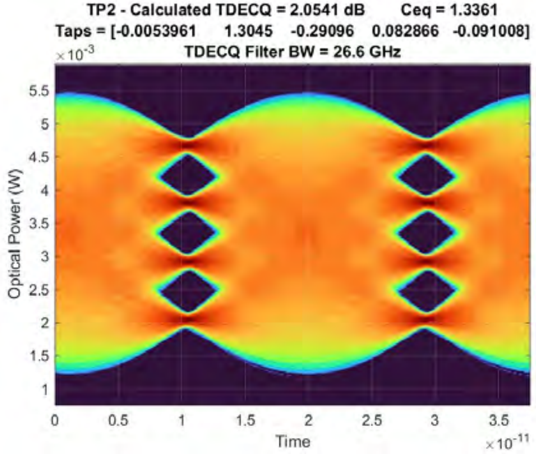


Taps 2



Taps 3

Best visually optimized Tx

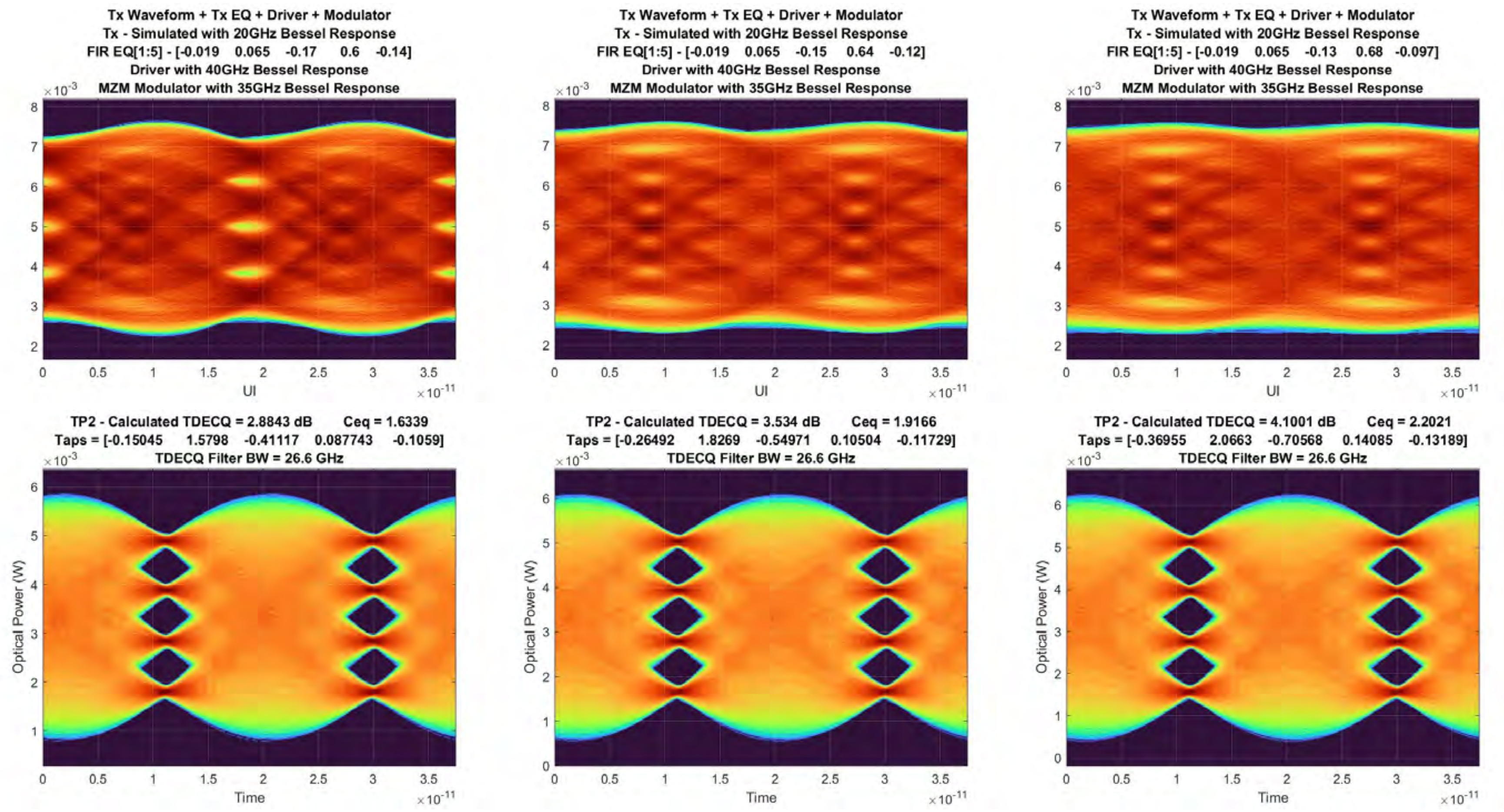


Taps 4 – Host Port Fully Equalized

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

RAW EYE

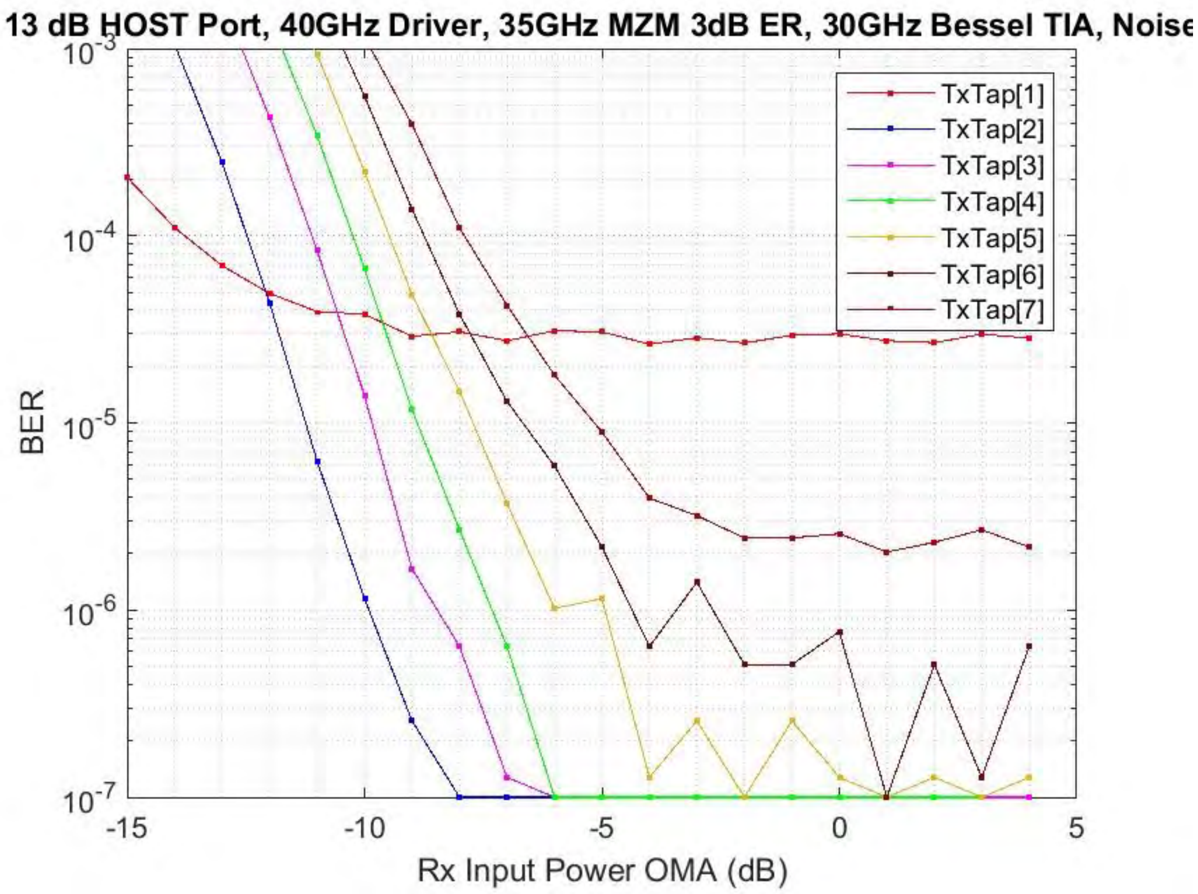
EQUALIZED EYE

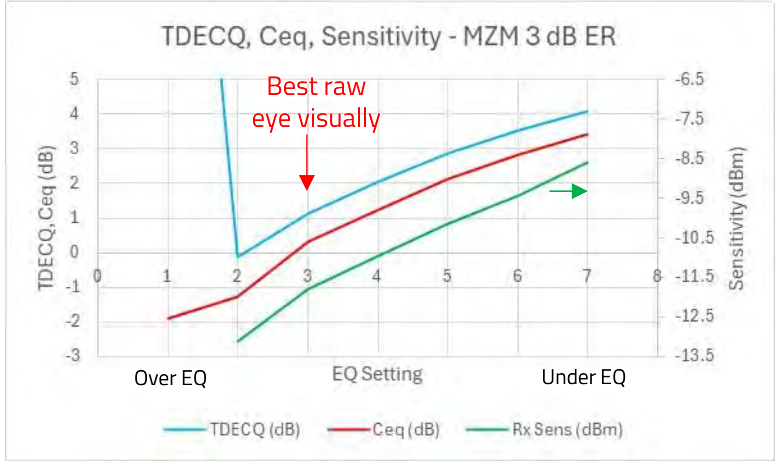


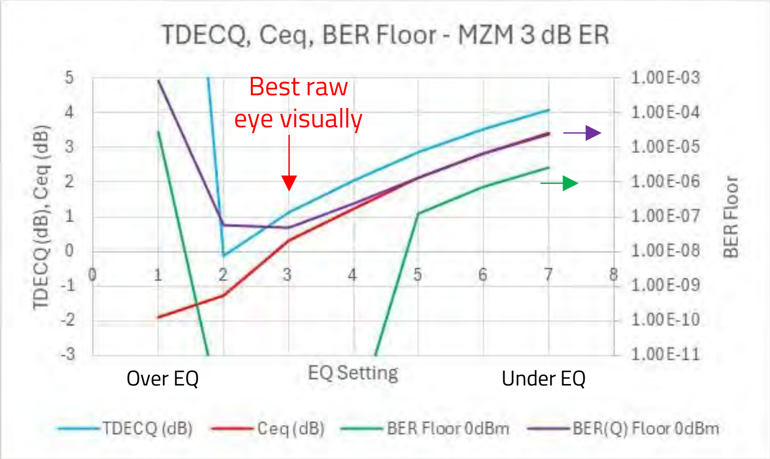
Taps 5 Taps 6 Taps 7 – Under Equalized

SEMTECH

Simulation Results – MZM Modulator 3dB ER





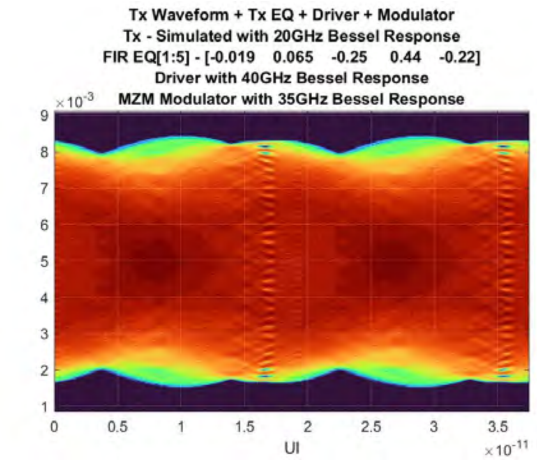


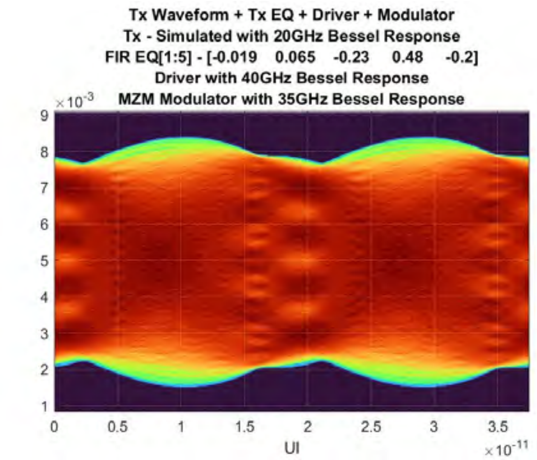
BER(Q) is estimated BER from Q

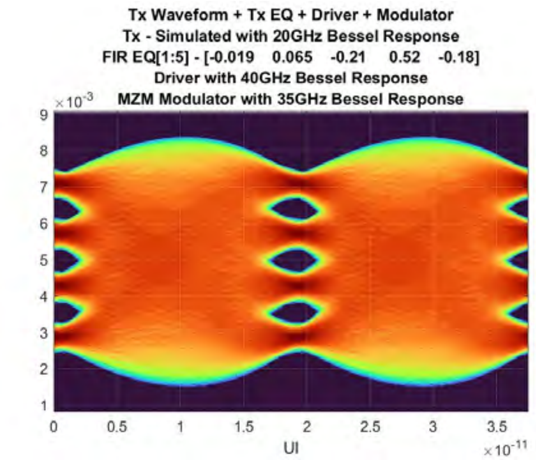
SEMTECH

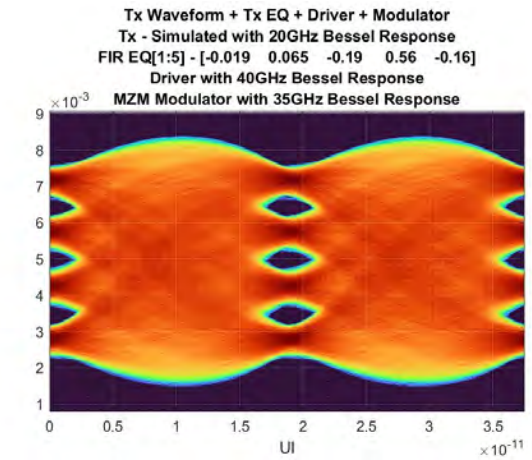
TP2 Eye Diagrams – MZM Modulator 4dB ER (1)

RAW EYE

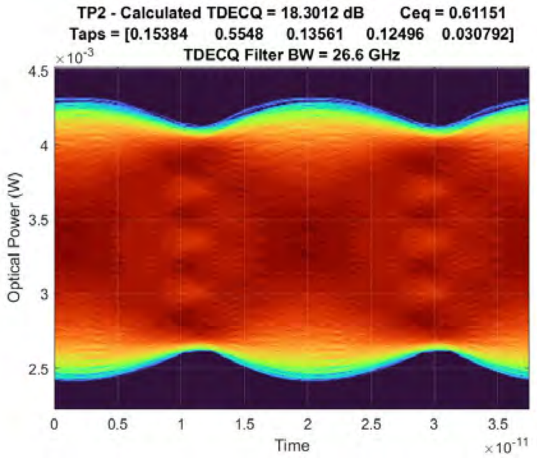




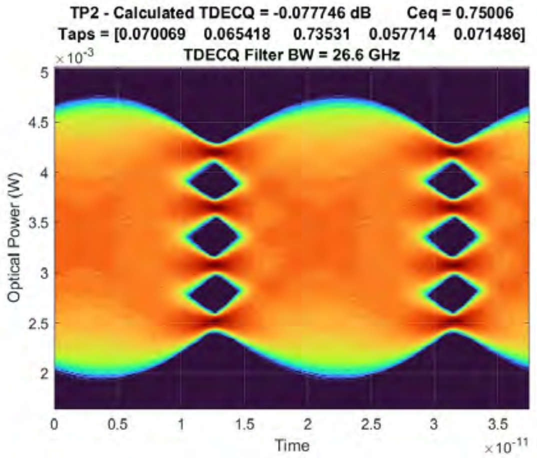




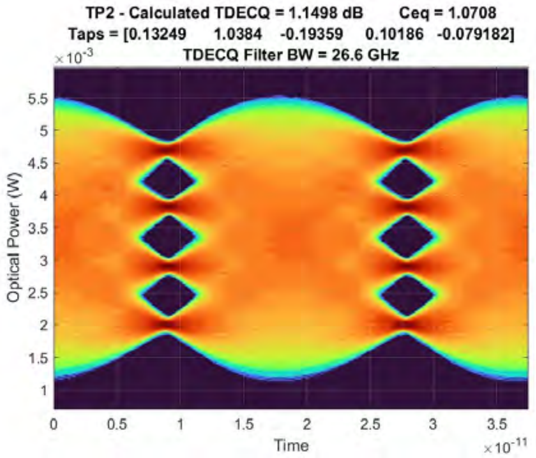
EQUALIZED EYE



Taps 1 – Over Equalized

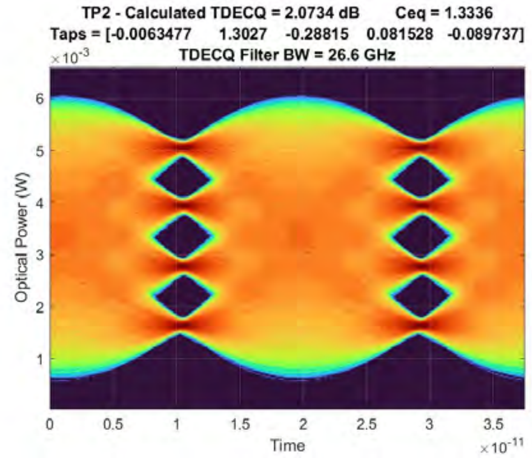


Taps 2



Taps 3

Best visually optimized Tx

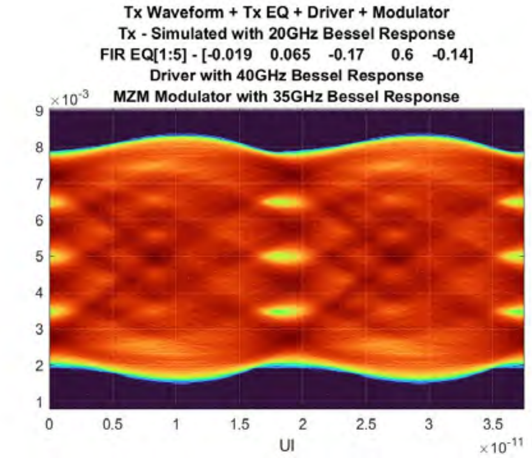


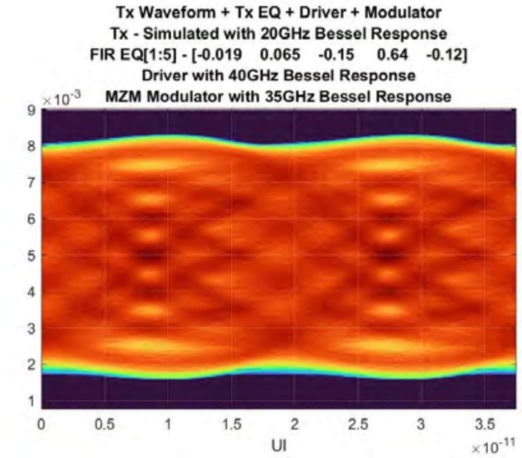
Taps 4 – Host Port Fully Equalized

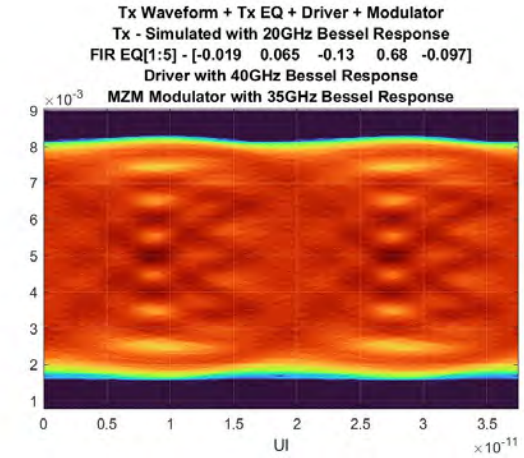
SEMTECH

TP2 Eye Diagrams – MZM Modulator 4dB ER (2)

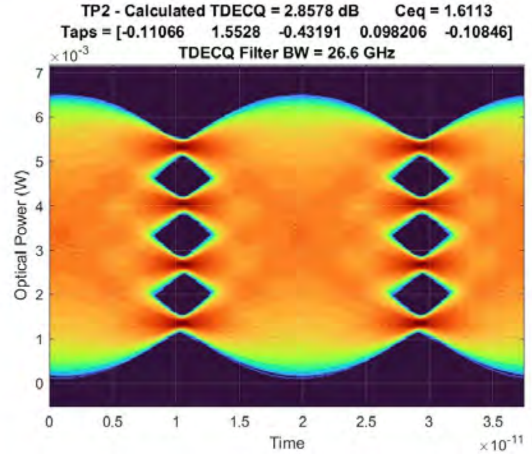
RAW EYE



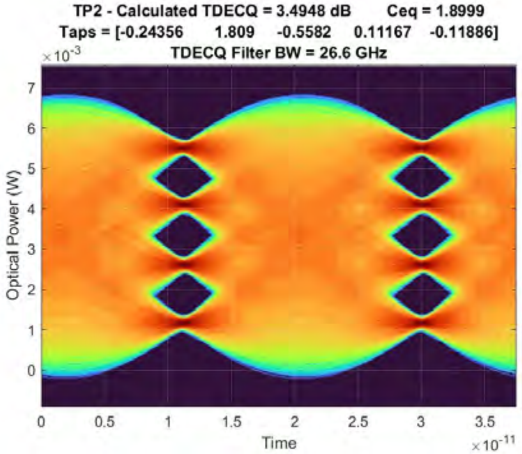




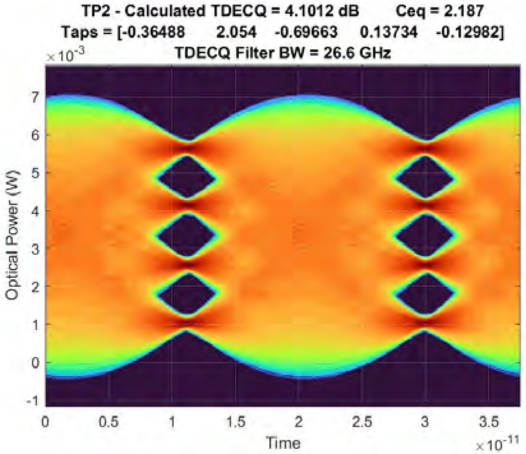
EQUALIZED EYE



Taps 5

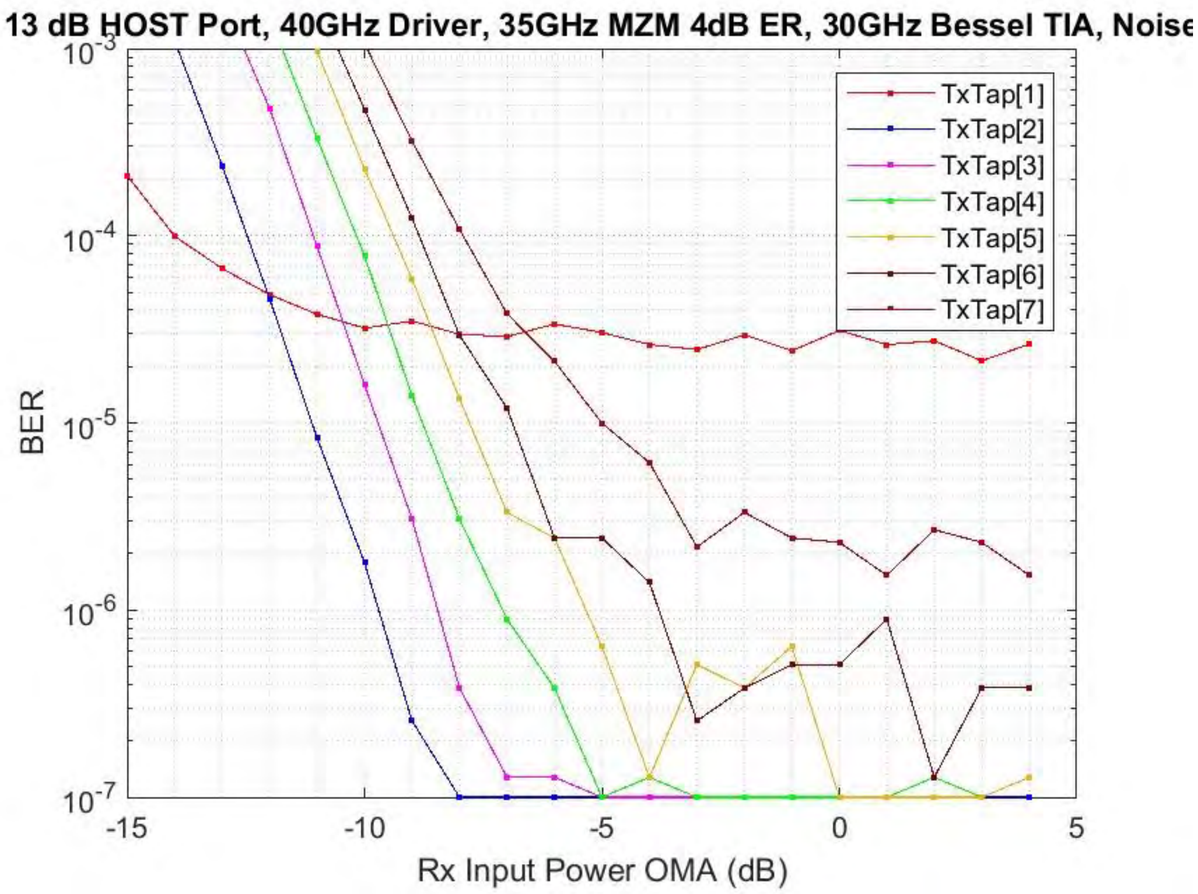


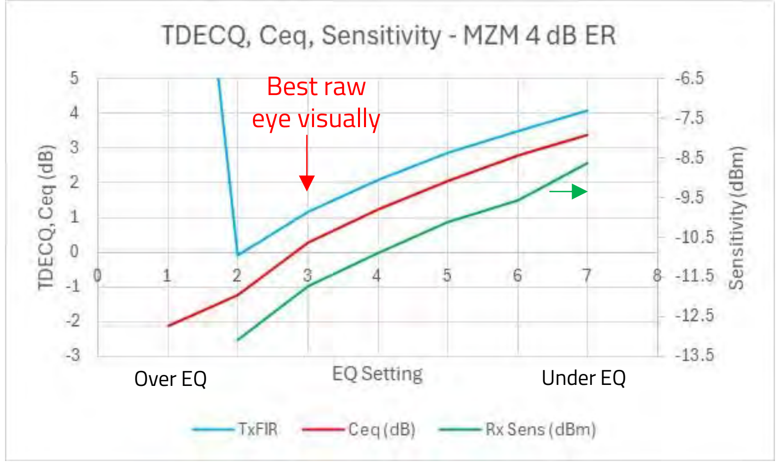
Taps 6

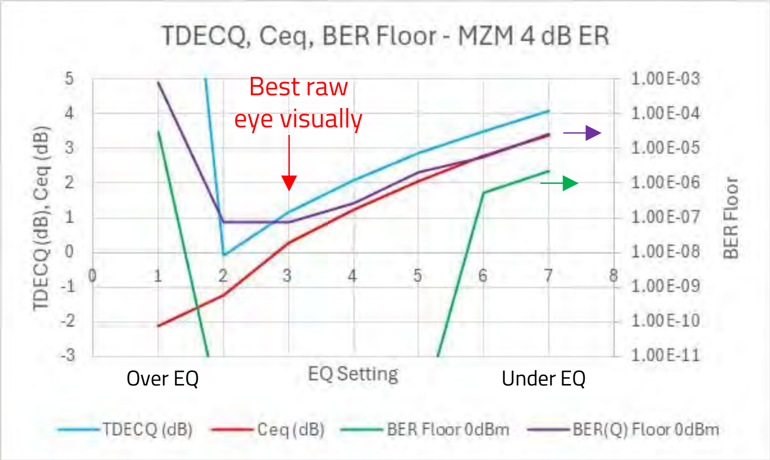


Taps 7 – Under Equalized

Simulation Results – MZM Modulator 4dB ER

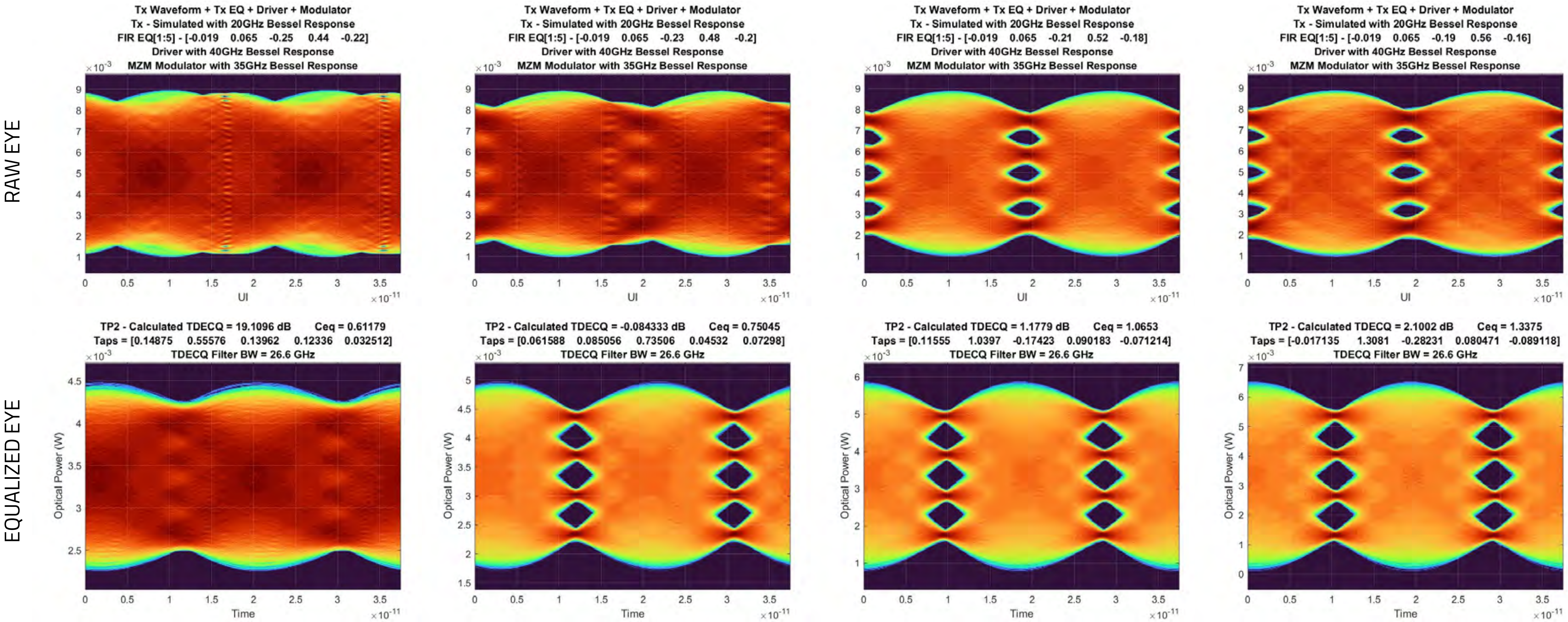






BER(Q) is estimated BER from Q

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



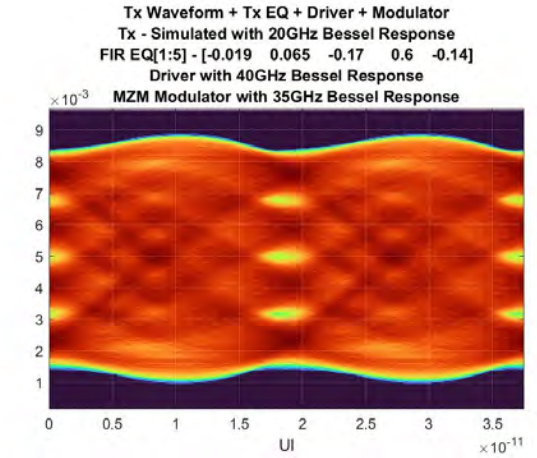
Taps 1 – Over Equalized | Taps 2 | Taps 3 | Taps 4 – Host Port Fully Equalized

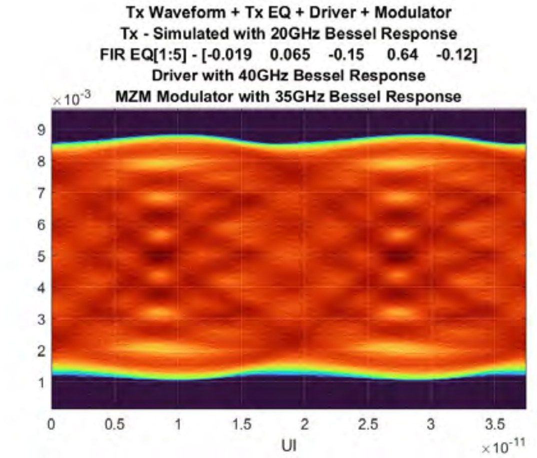
Best visually optimized Tx

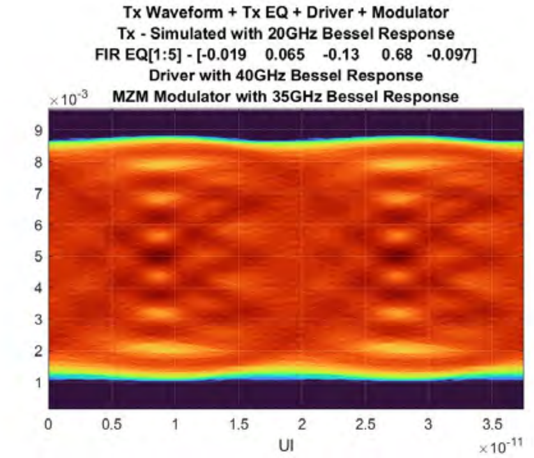
SEMTECH

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

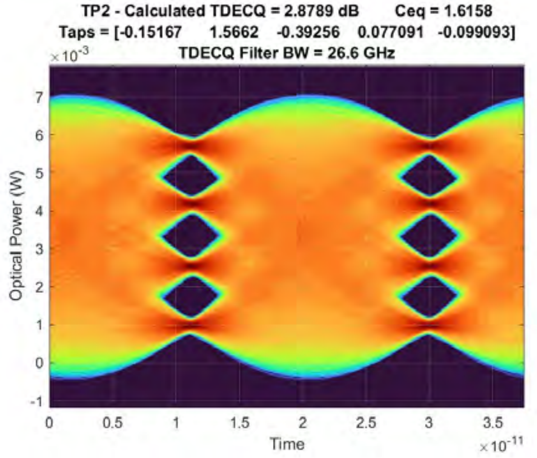
RAW EYE



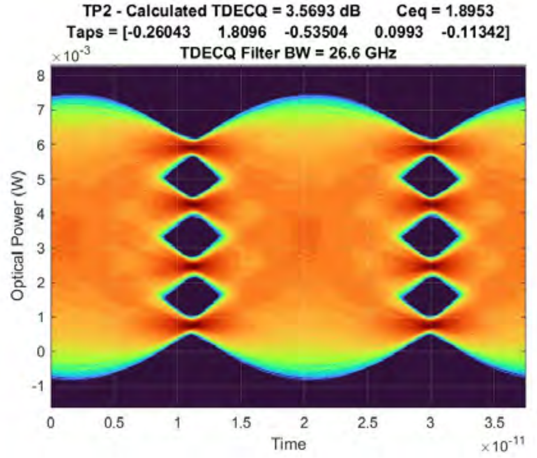




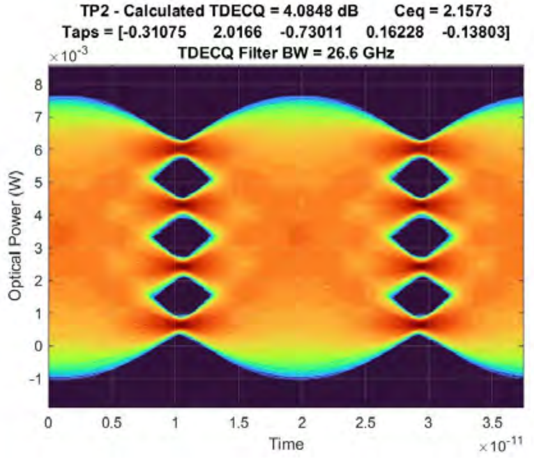
EQUALIZED EYE



Taps 5



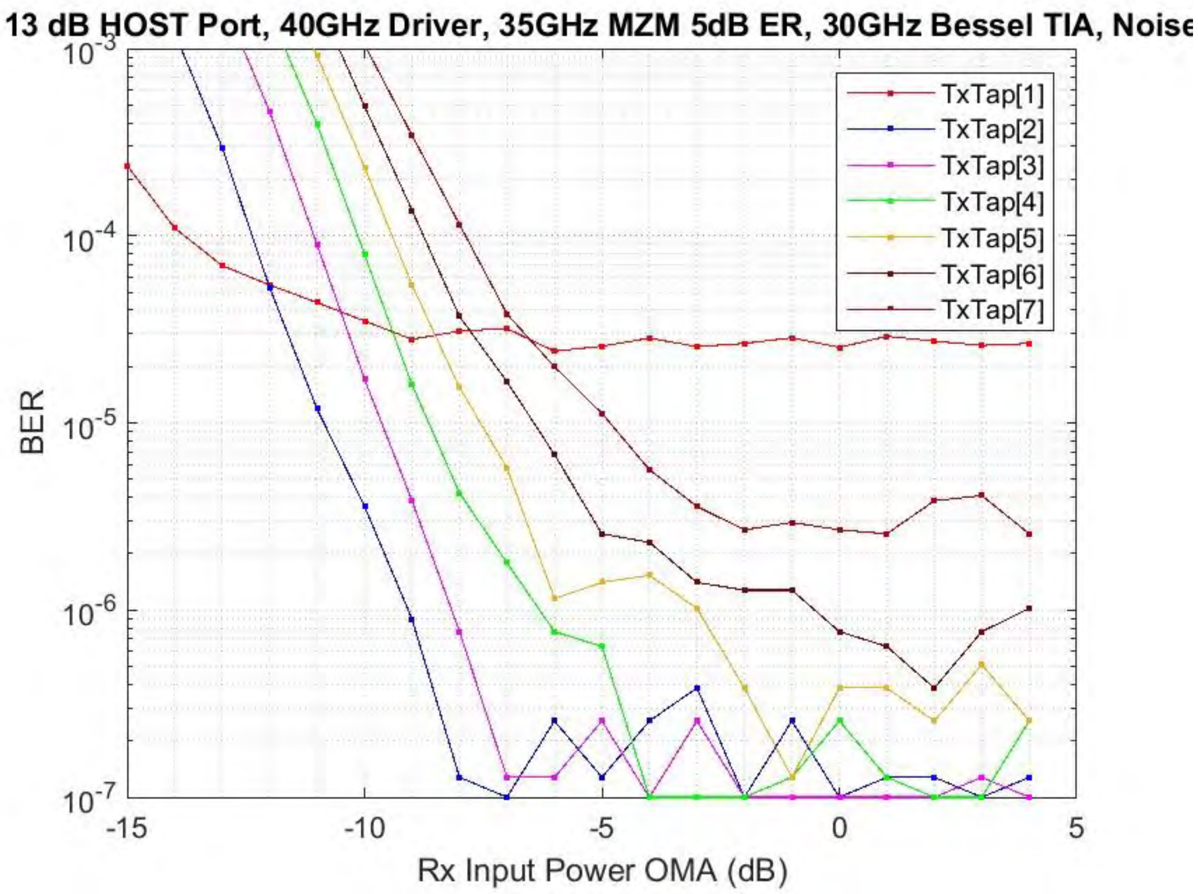
Taps 6

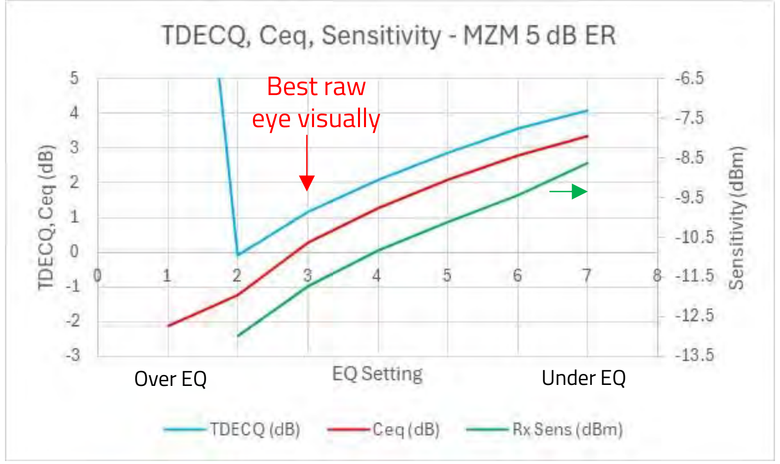


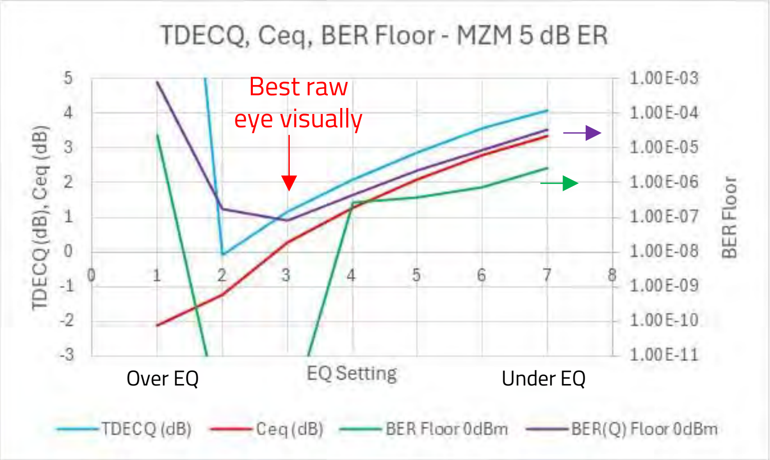
Taps 7 – Under Equalized

SEMTECH

Simulation Results – MZM Modulator 5dB ER

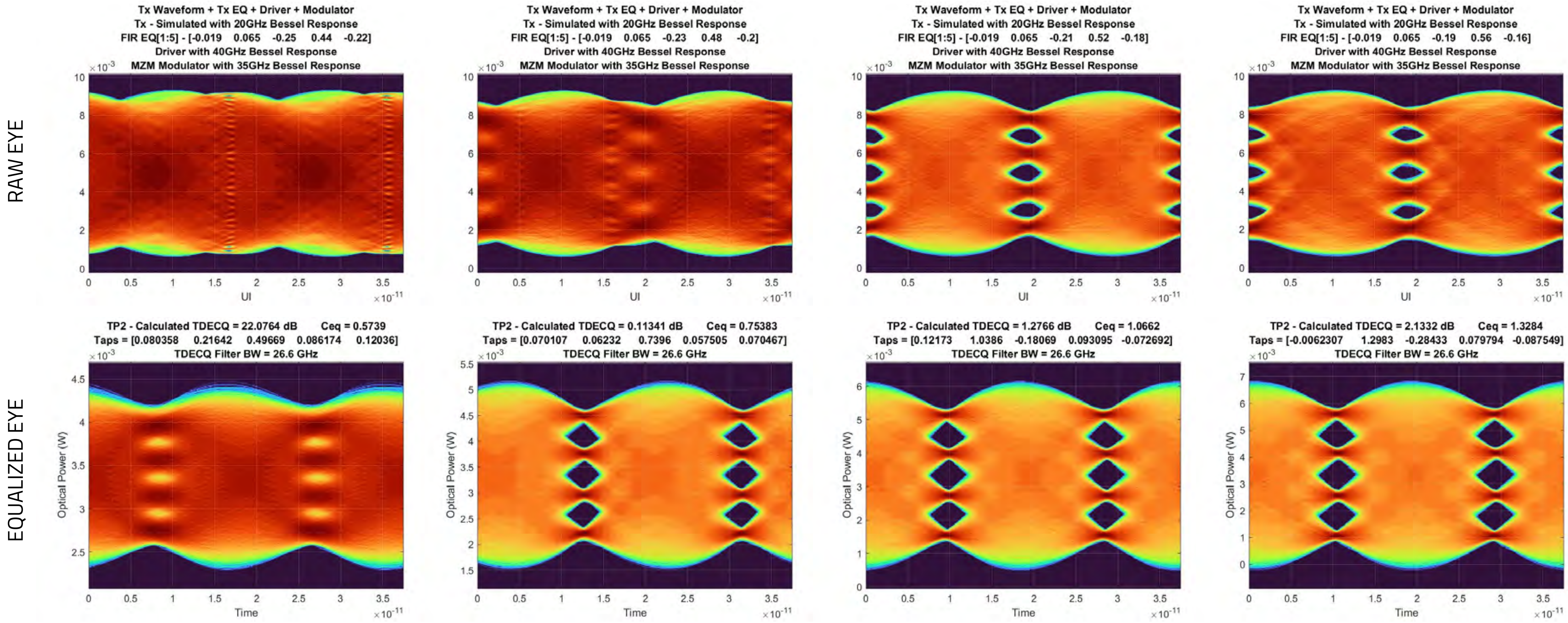






BER(Q) is estimated BER from Q

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



Taps 1 – Over Equalized

Taps 2

Taps 3

Best visually optimized Tx

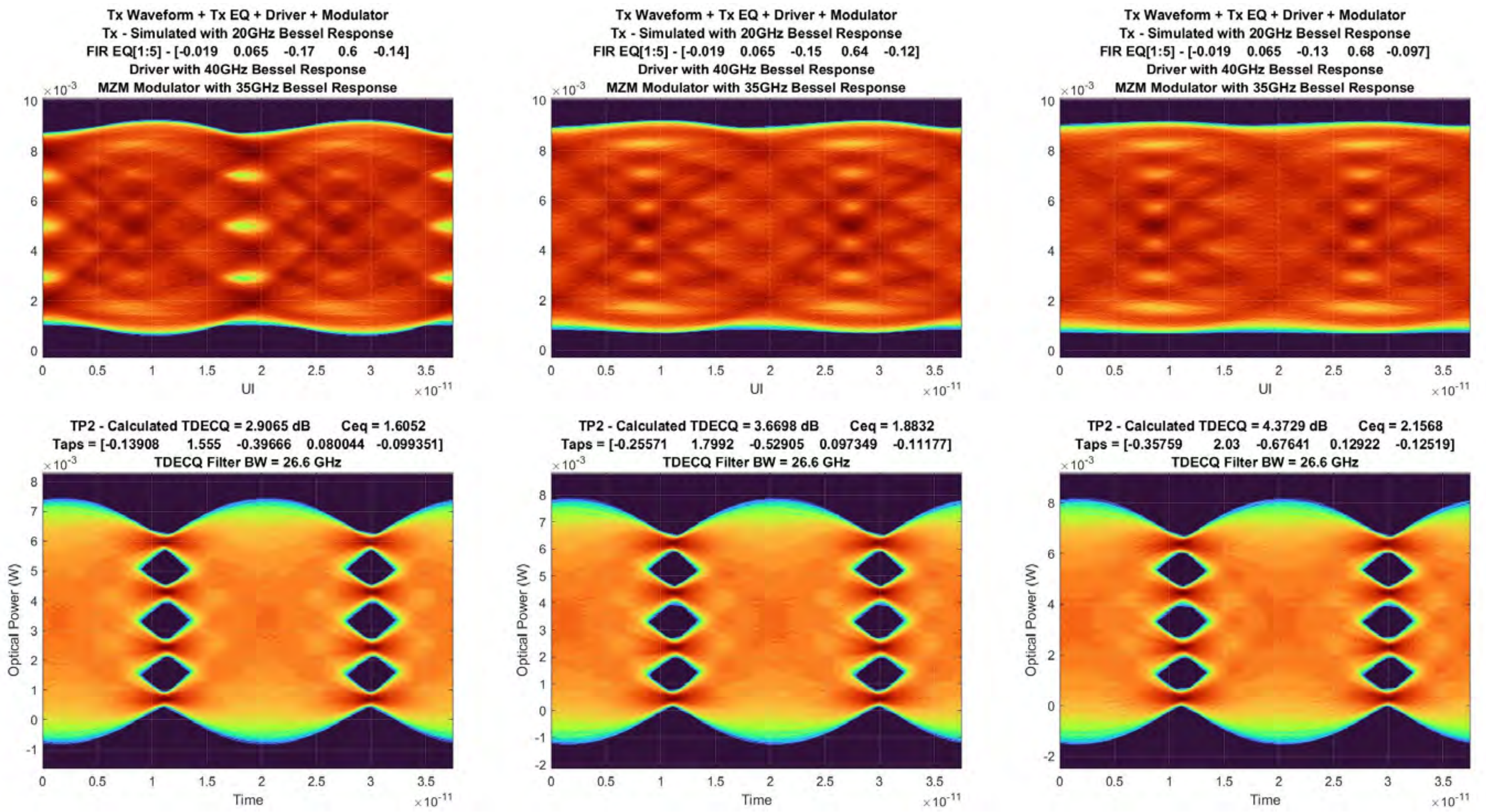
Taps 4 – Host Port Fully Equalized

SEMTECH

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

RAW EYE

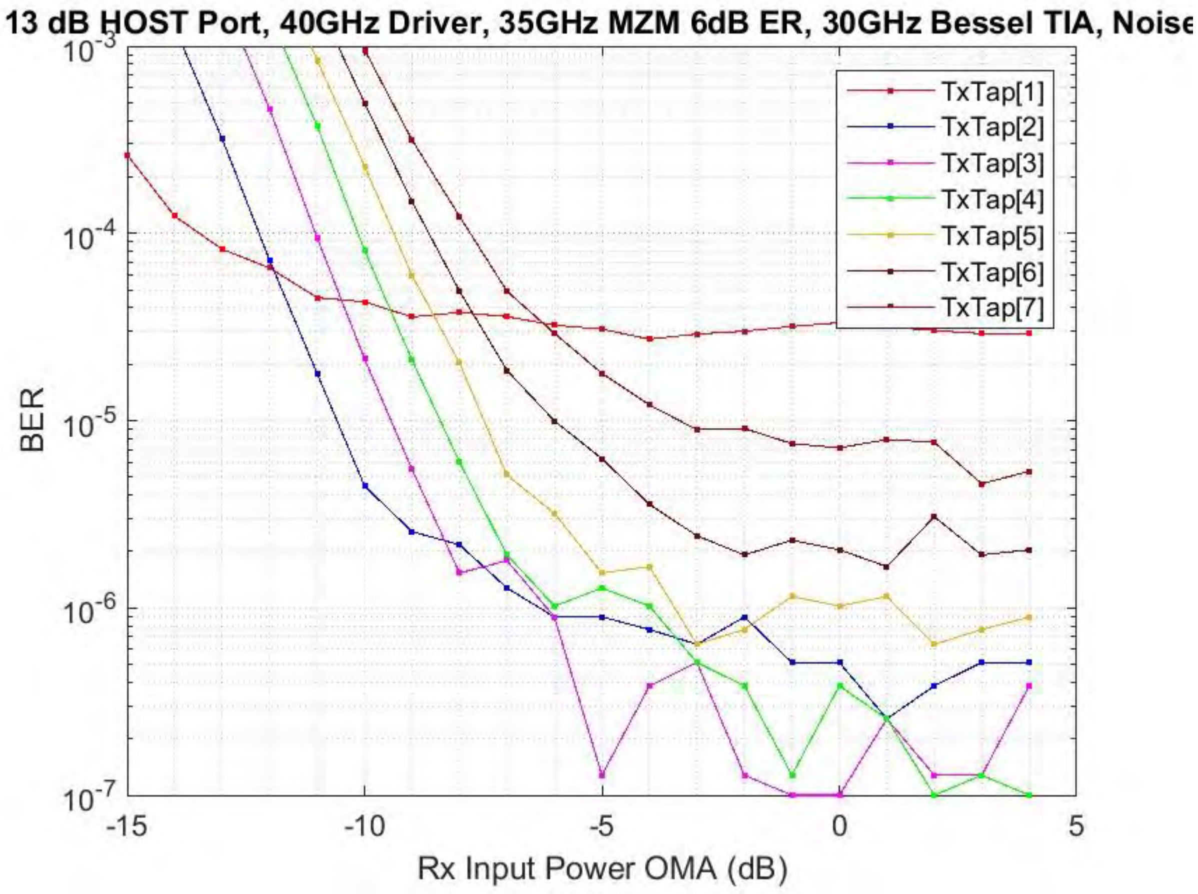
EQUALIZED EYE

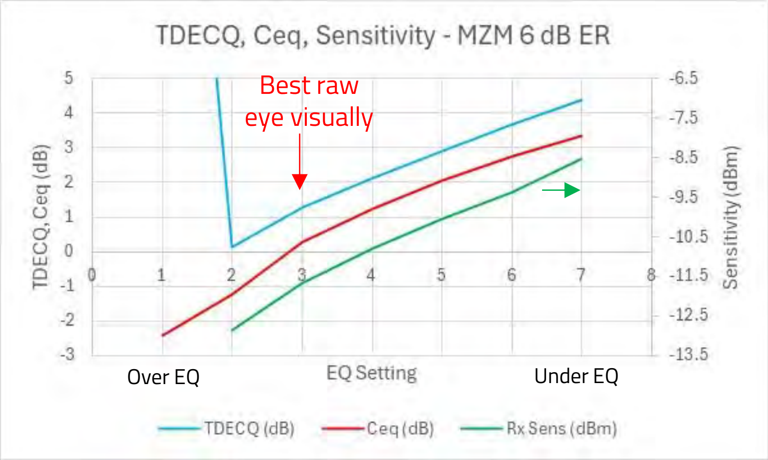


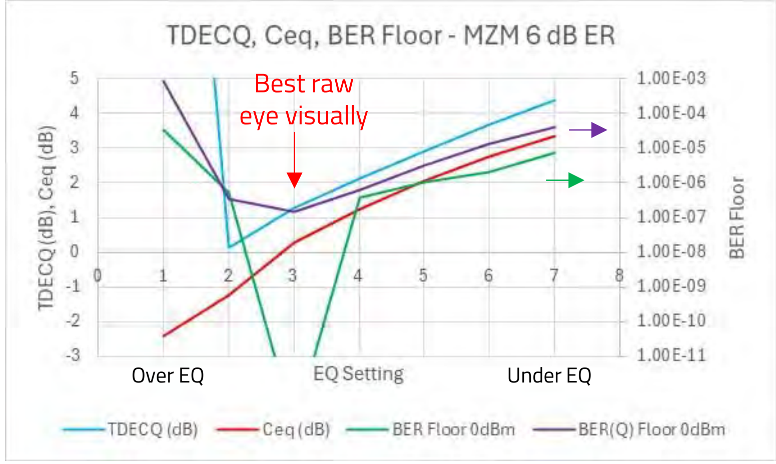
Taps 5 | Taps 6 | Taps 7 – Under Equalized

SEMTECH

Simulation Results – MZM Modulator 6dB ER

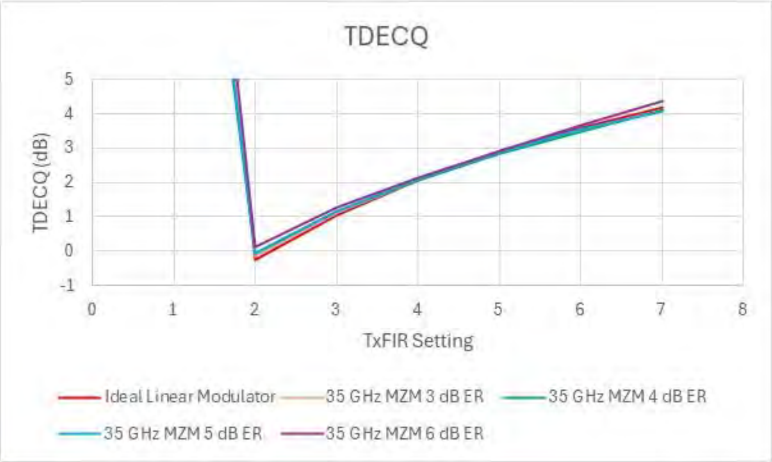


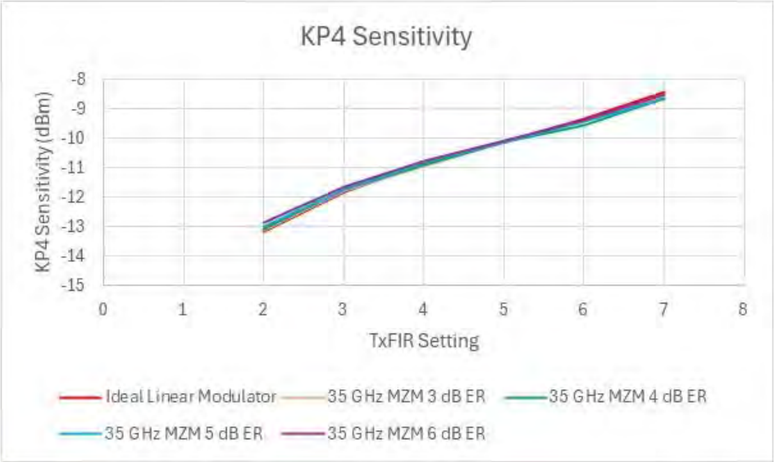


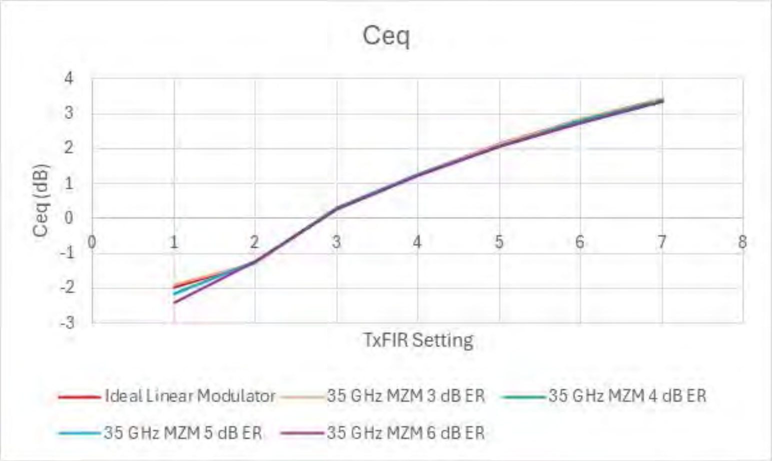


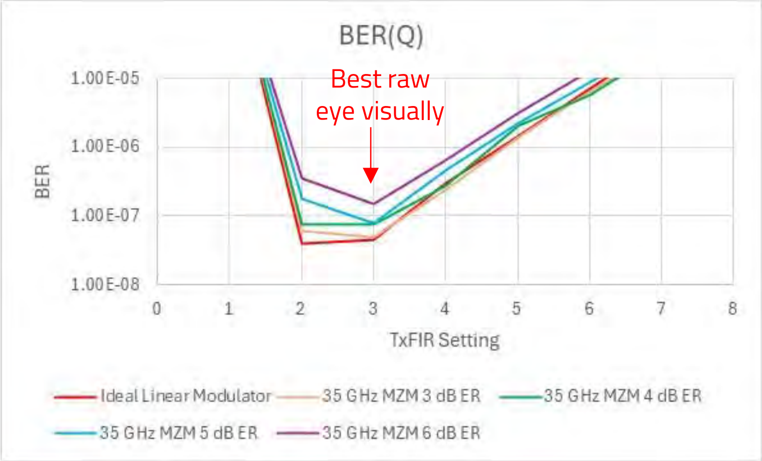
BER(Q) is estimated BER from Q

Simulation Summary





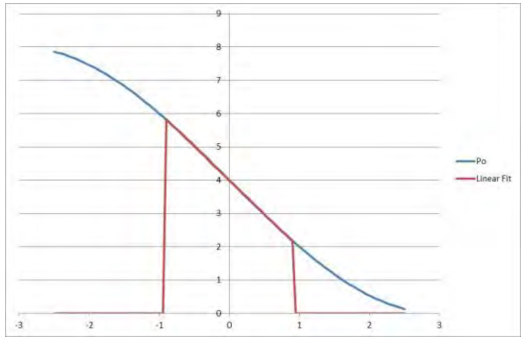




- BER floor is more sensitive to distortion when Ceq < 0dB
- Distortion needs to be limited

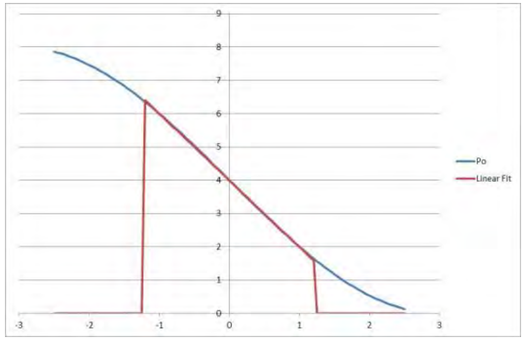
MZM Distortion

3 dB ER



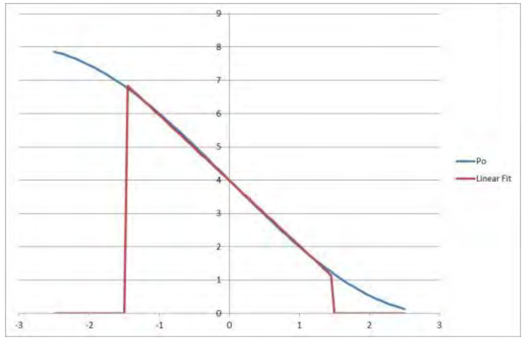
	1.01138117	%
Largest Non-linearity	-0.7511887	%

4 dB ER



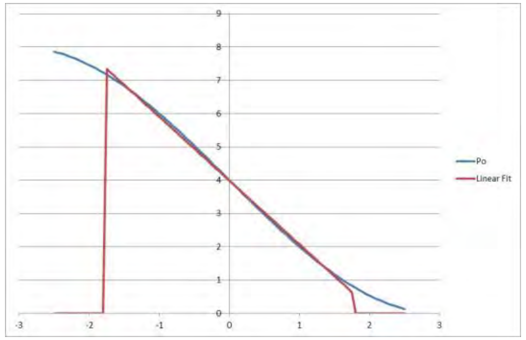
	1.88538071	%
Largest Non-linearity	-2.5820818	%

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

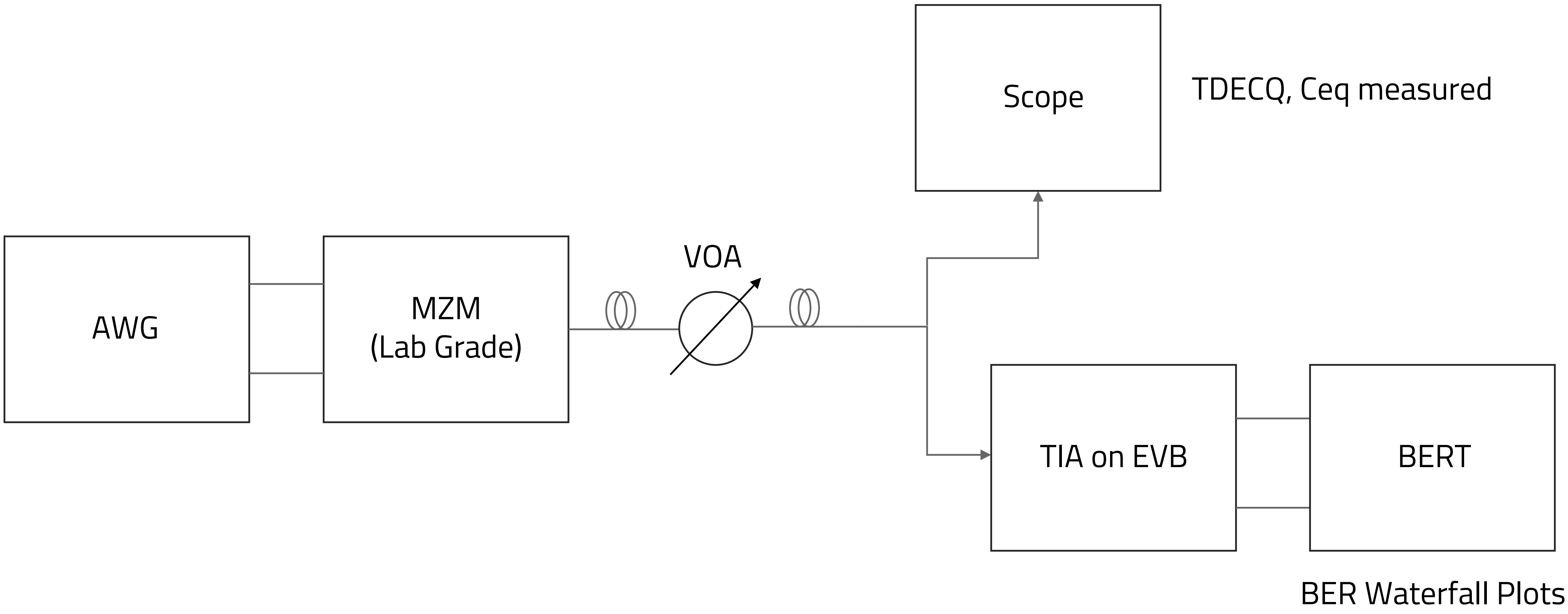
Measured using TDECQ derived parameters
SNR = 10*log10(Signal power/σ_G)^2
SNDR = 10*log10((Signal power/σ_G)^2 + aver (Level variance))

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)

SEMTECH

Measurement setup



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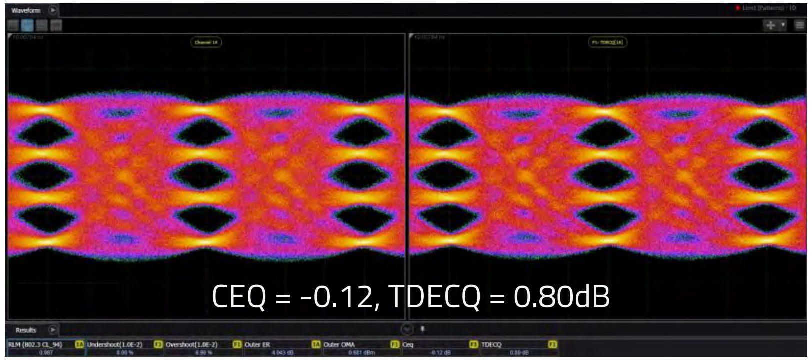
TX ER = 4dB

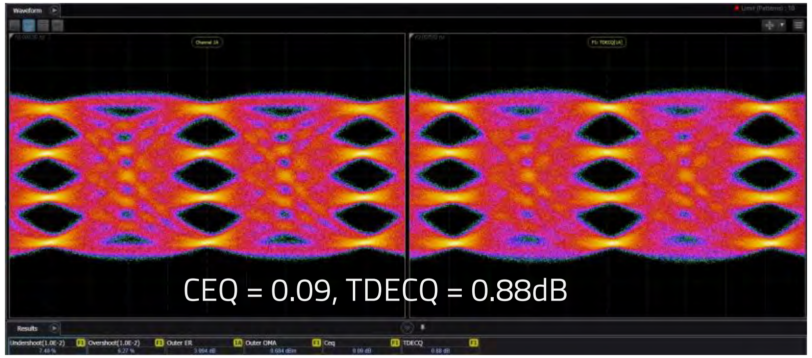
TDECQ IEEE 802.3cd
Bessel 4^{th} 26.6GHz
TX ER = 4dB

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.

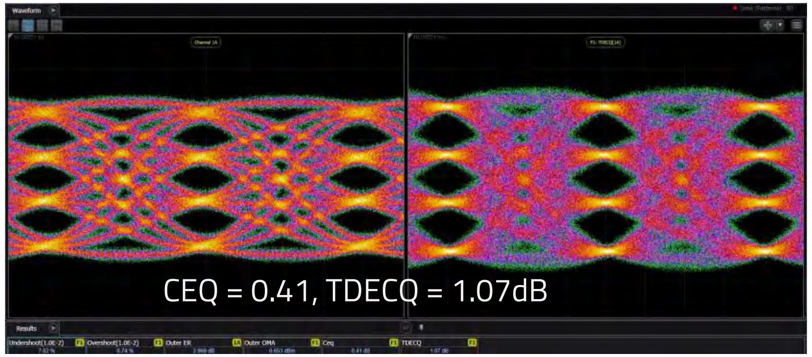
FIR: -0.15/1.3/-0.15 AWG=750



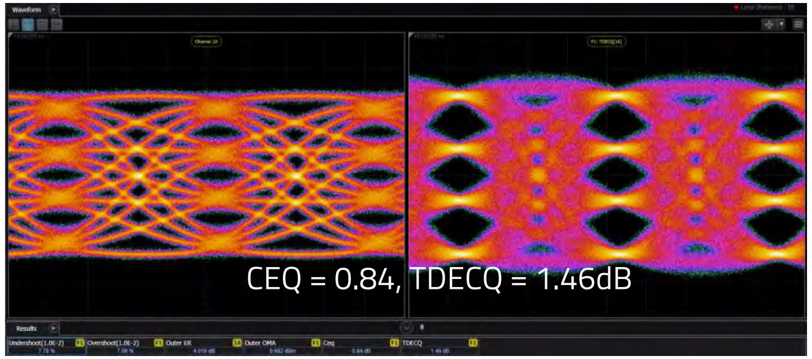
FIR: -0.1/1.2/-0.1 AWG=690



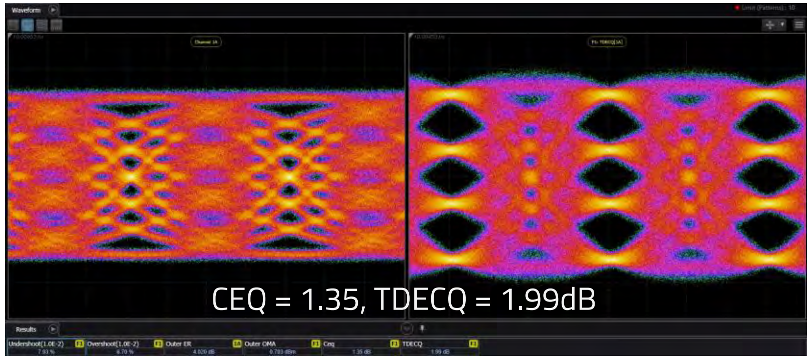
FIR: -0.05/1.1/-0.05 AWG=630



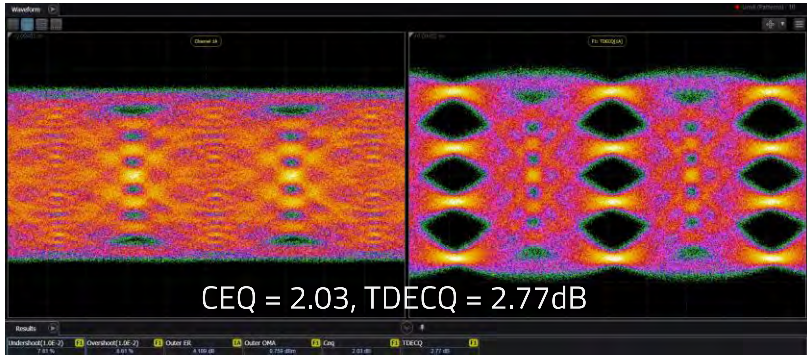
FIR: 0/1/0 AWG=580



FIR: 0.05/0.9/0.05 AWG=520



FIR: 0.1/0.8/0.1 AWG=470



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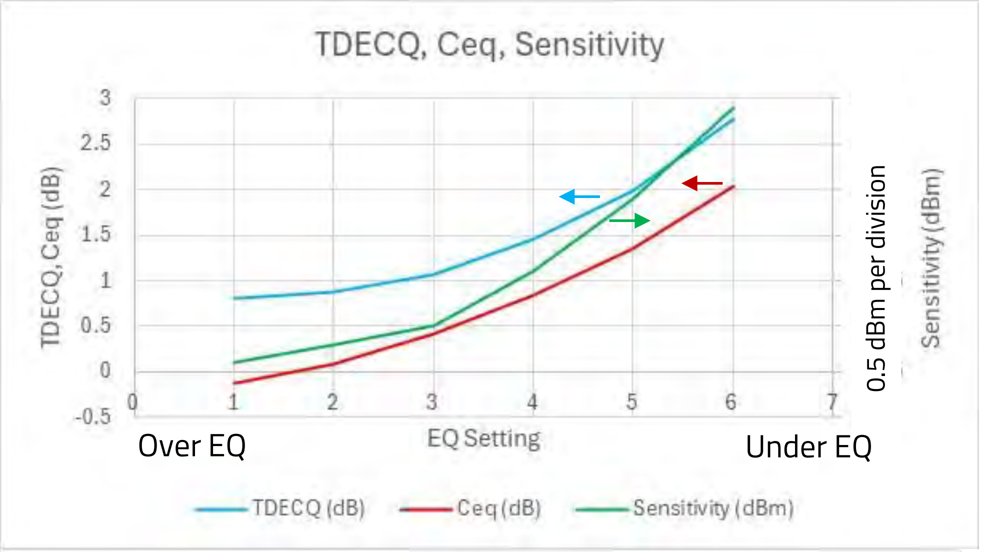
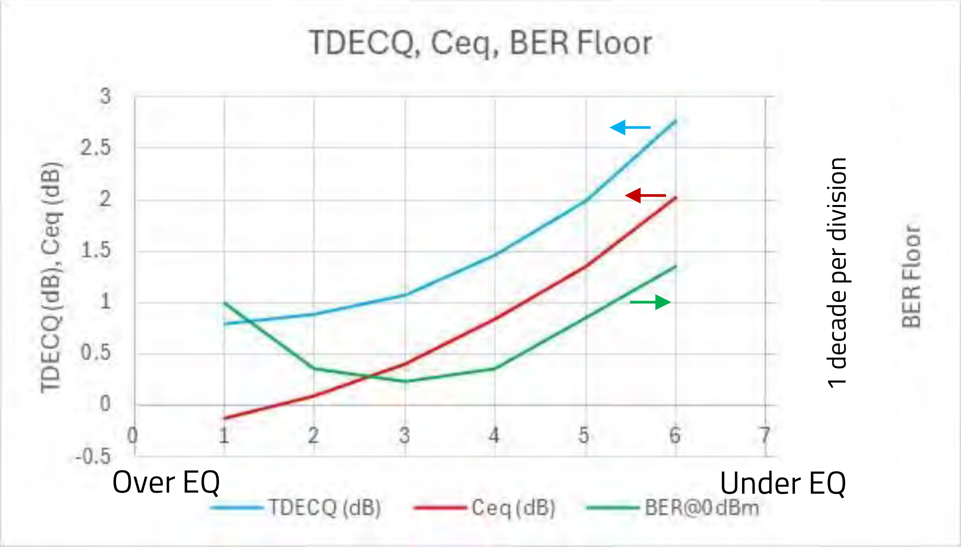
SM Measured Performance - 1

- TDECQ and Rx Sensitivity track each other as expected
- Ceq and TDECQ track each other
- BER floor
  - Tracks TDECQ for Ceq > 0.75 dB
  - Fairly flat for 0.2 dB < Ceq < 0.75 dB
  - Goes in opposite direction for Ceq < 0.25 dB
- BEST TDECQ = BEST Rx SENSITIVITY
- BEST TDECQ ≠ BEST BER FLOOR

- As TDECQ increases (for Ceq > 0 dB)
  - Tx SNR is decreasing
  - Rx equalization of the Tx results in noise amplification (Ceq increases)
  - Caveat: Reasonable and smooth frequency response implied
- For Ceq < 0.5 dB, Tx SNR might be improving but signal phase is being distorted

ER_outer = 4 dB





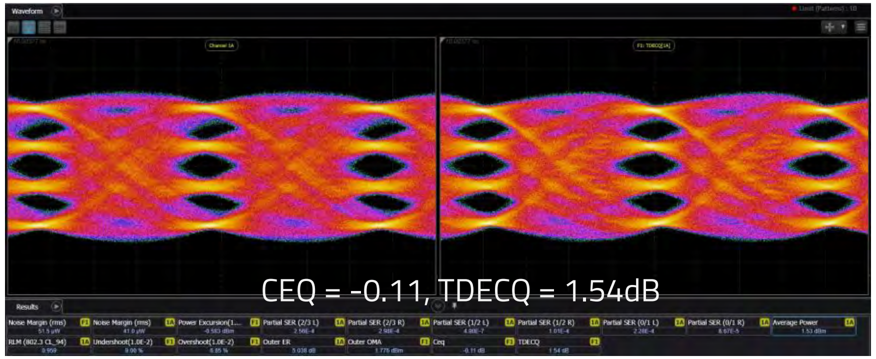
SEMTECH

TX ER = 5dB

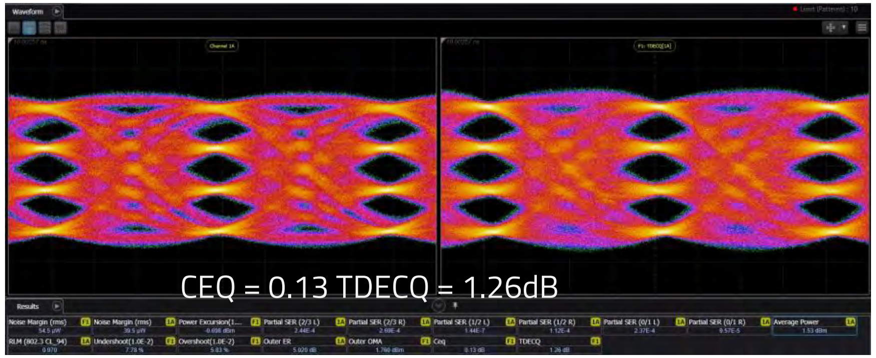
TDECQ IEEE 802.3cd
Bessel 4th 26.6GHz
TX ER = 5 dB

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.

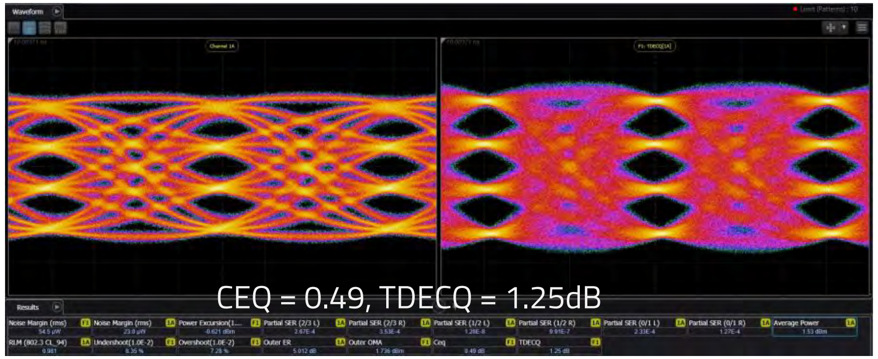
FIR: -0.15/1.3/-0.15 AWG=940



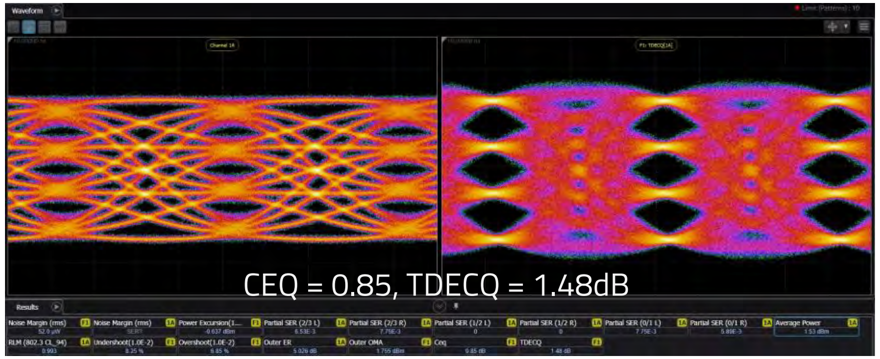
FIR: -0.1/1.2/-0.1 AWG=870



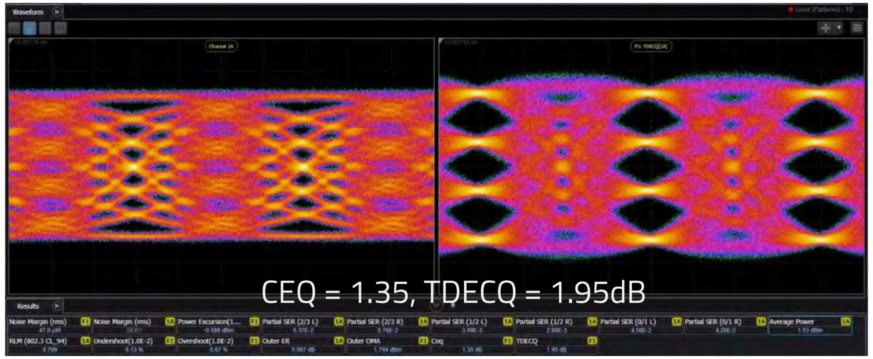
FIR: -0.05/1.1/-0.05 AWG=810



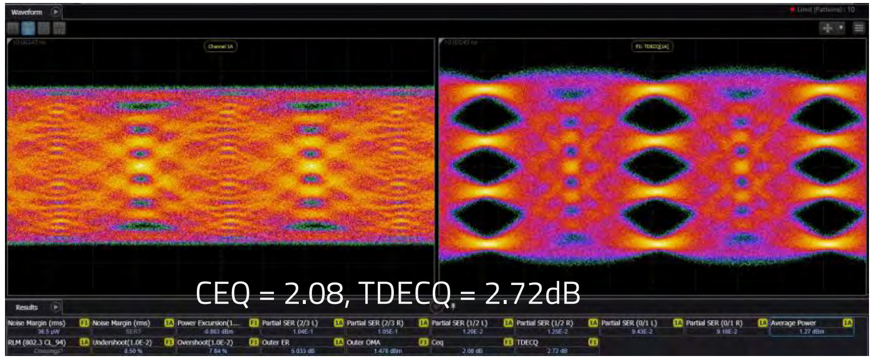
FIR: 0/1/0 AWG=750



FIR: 0.05/0.9/0.05 AWG=680



FIR: 0.1/0.8/0.1 AWG=470



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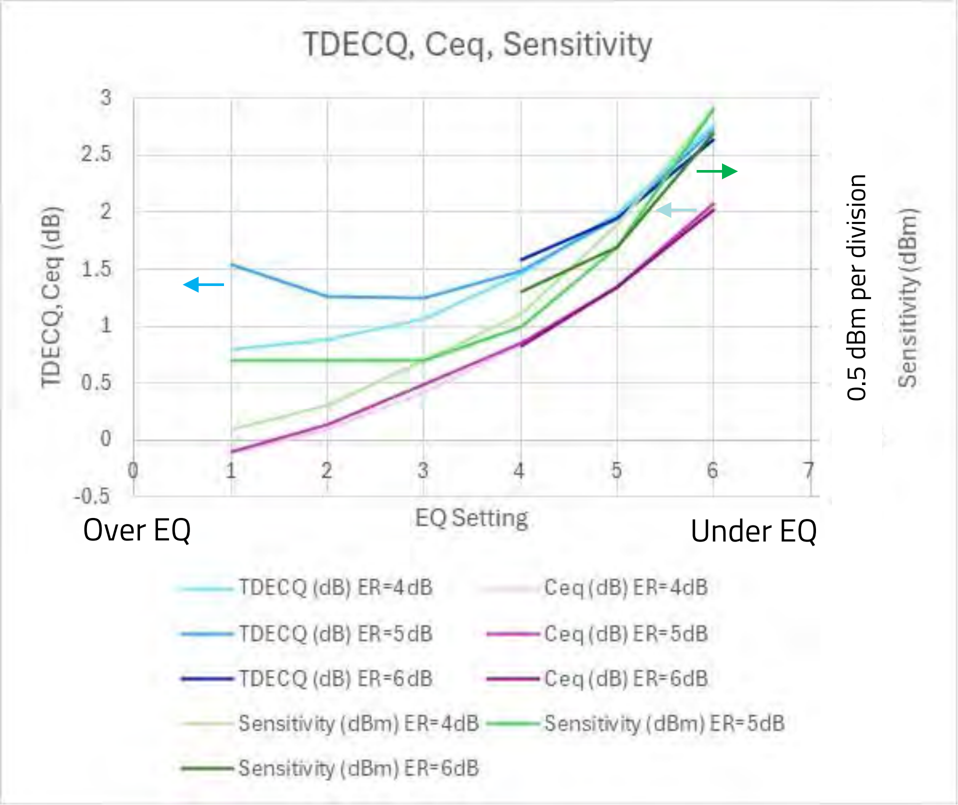
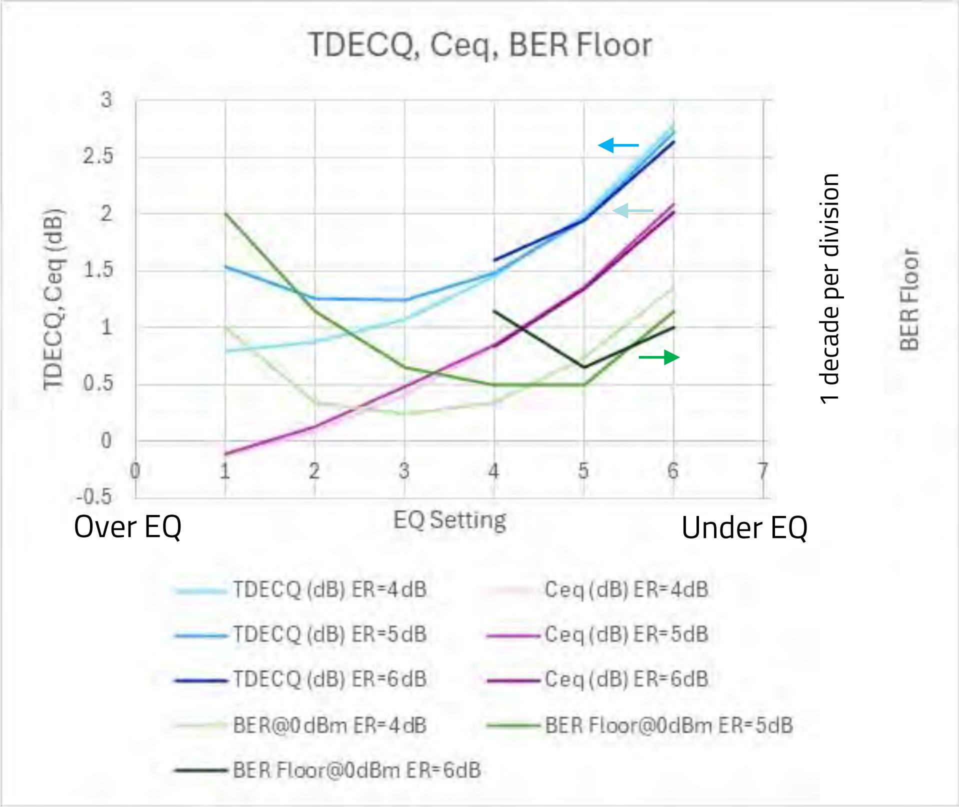
SM Measured Performance - 2





- 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

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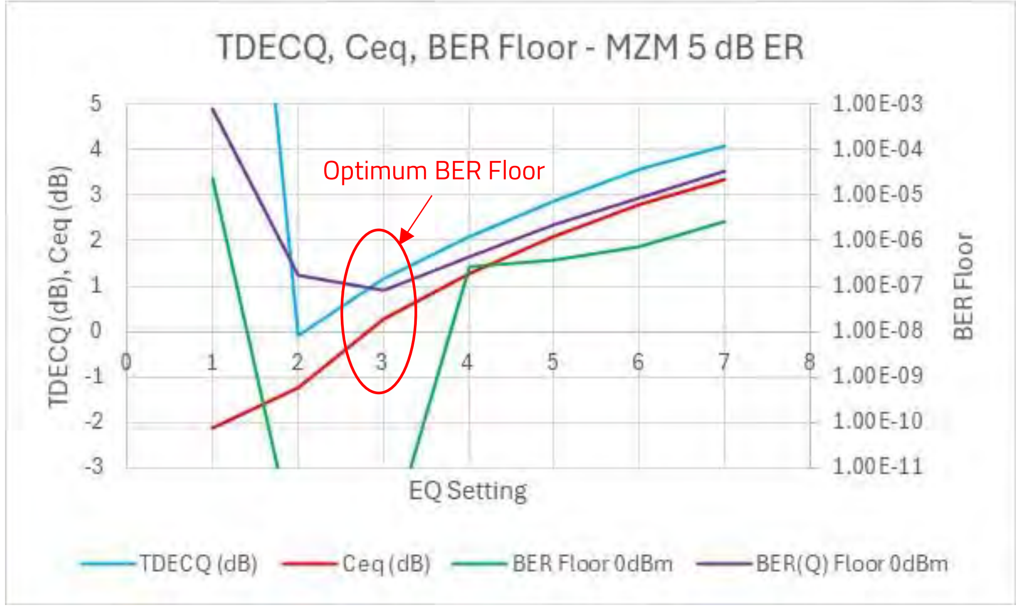
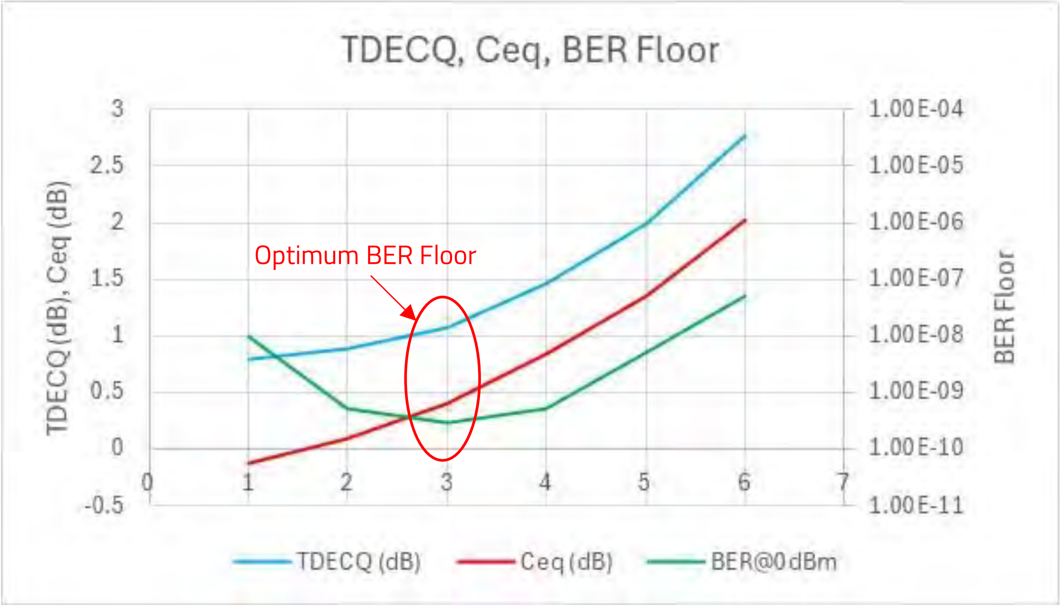
Simulation vs Measurement (Single Mode)



Simulated – only MZM THD

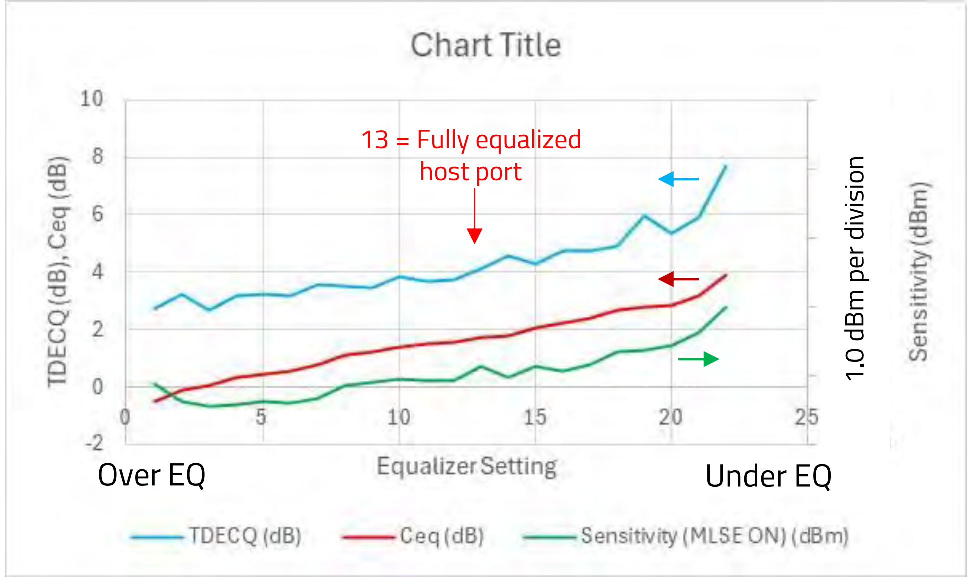


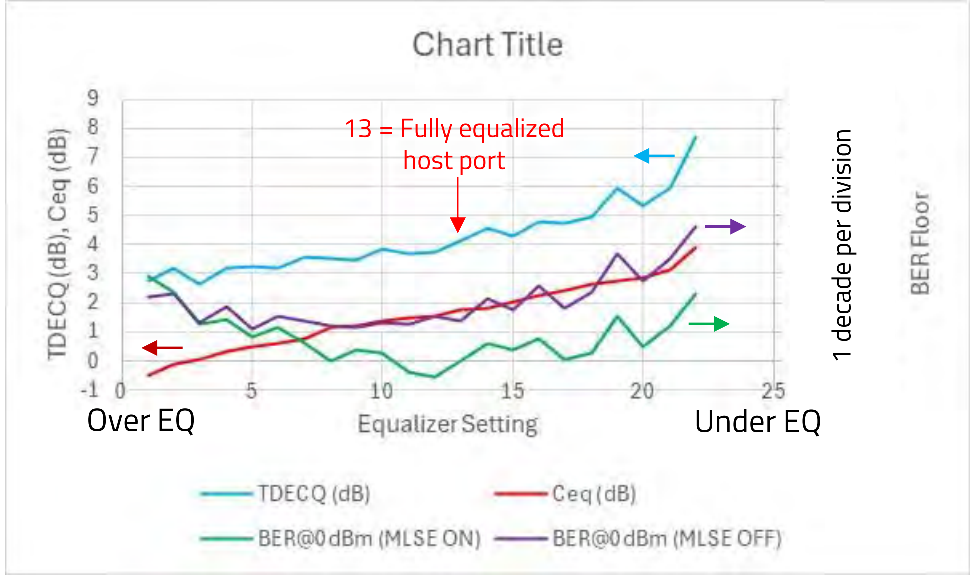
Measured (4dB case) – MZM and driver THD

- 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

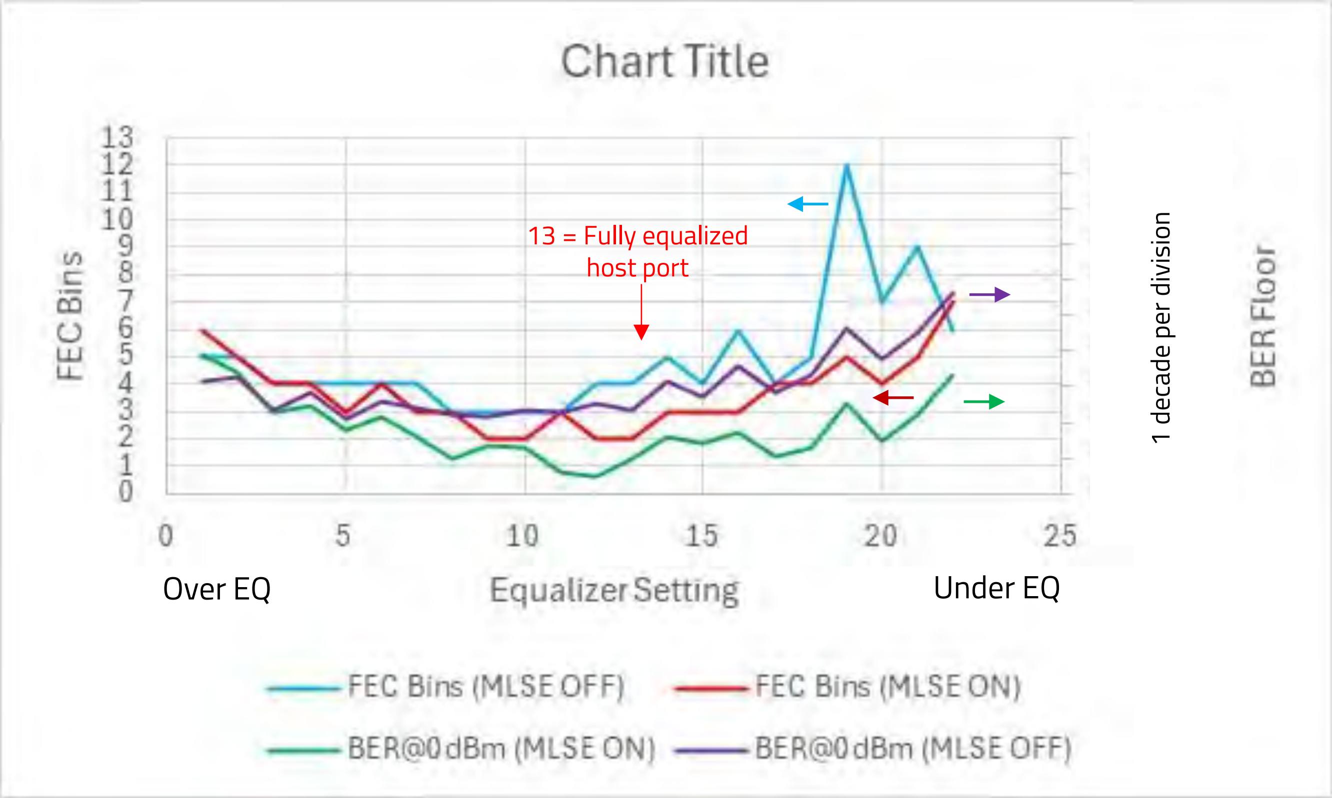
Switch used to generate Tx signal and measure BER





Same trend using MM optics and switch environment

Multimode Module Measurements - 2



- FEC Bins follow BER Floor trend
- Best FEC Bin for Ceq > 0 dB

Some thoughts…

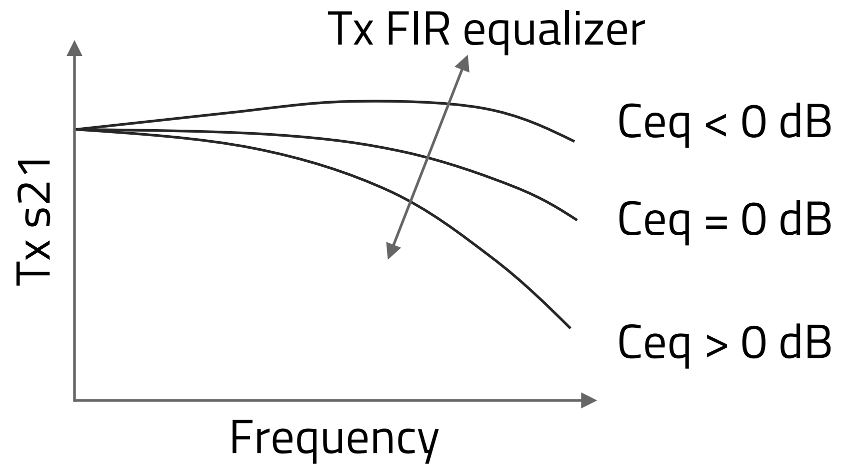
- For a smooth Tx (driver + modulator) frequency response:
  - Ceq is indicating how much equalization is required to equalize (or flatten) the Tx frequency response
  - TDECQ (for Ceq > 0 dB) is giving an indication of link SNR penalty
    - Lower TDECQ = More open Tx eye
      - Better Tx SNR
      - Lower Rx noise amplification due to equalizer

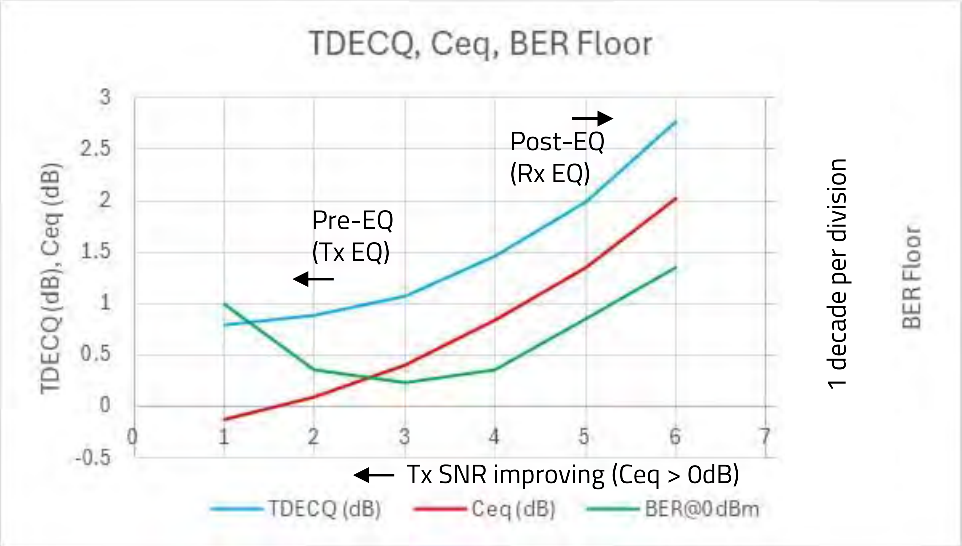
- Simulations and measurements are telling us that Tx peaking is bad
- Ceq is showing when the Tx is starting to be over peaked

- Ceq < 0 dB results in degraded performance
  - 0.5 dB < Ceq < 1 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





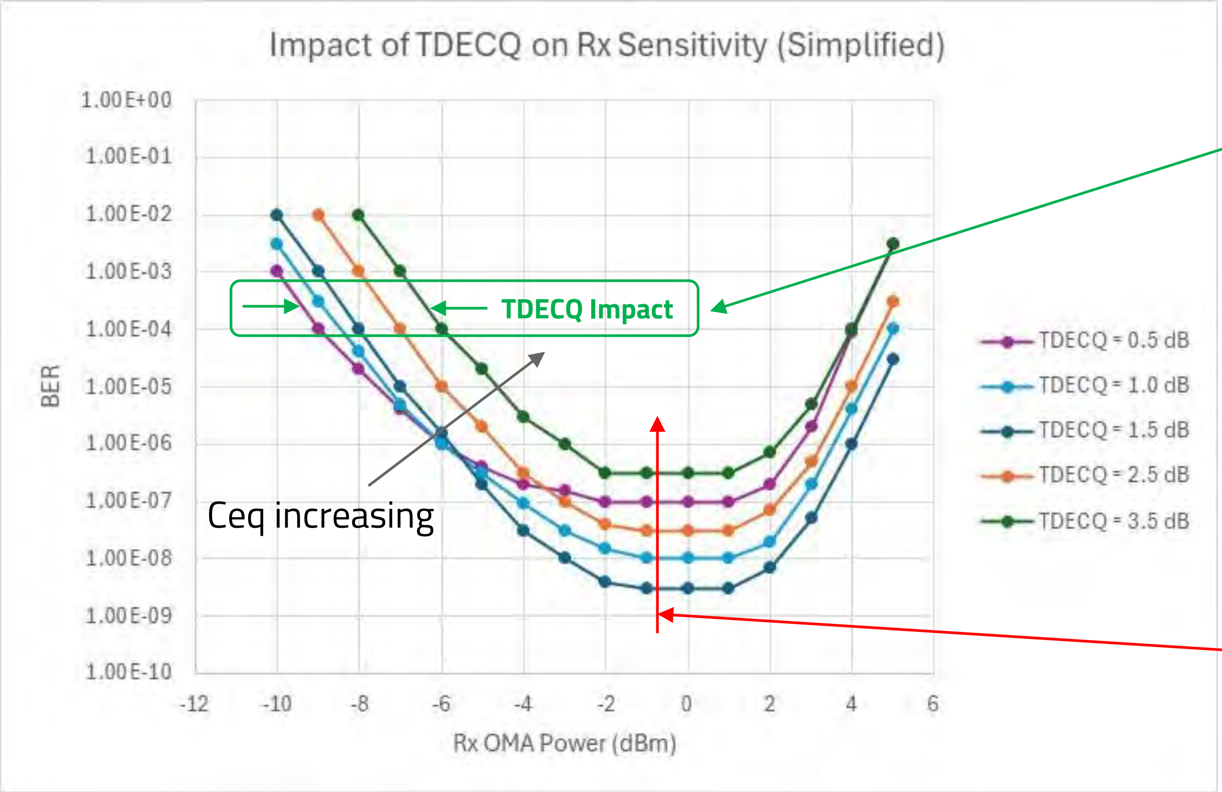
What about TDECQ – 10 log Ceq?

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 Ceq > 0 dB
- The combination of TDECQ and Ceq can be used to better infer transmitter performance
- For a smooth frequency response transmitter Ceq can be used to determine transmitter peaking
  - Keeping Ceq > 0 dB avoids transmitter peaking
  - Practically, 0.5 dB < Ceq <1 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 (>~4dB) to avoid modulator non-linearity (MZM)
- Minimum FEC bin count appears to align with minimum BER Floor

Possible Changes ro Specifications

- Introduce Ceq 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