On the technical feasibility of optical 200 Gb/s PAM4

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Introduction

- This presentation is following up on a previous presentation, *kuschnerov_b400g_01_210503*, provided during the SG phase in May 2021.
- PAM4 is a candidate modulation format to satisfy the following df SMF objectives at 200G/lane:
  - Define a physical layer specification that supports 800 Gb/s operation:
    - over 4 pairs of SMF with lengths up to at least 500 m
    - over 4 pairs of SMF with lengths up to at least 2 km
    - over 4 wavelengths over a single SMF in each direction with lengths up to at least 2 km
  - Define a physical layer specification that supports 1.6 Tb/s operation:
    - over 8 pairs of SMF with lengths up to at least 500 m
    - over 8 pairs of SMF with lengths up to at least 2 km
- This presentation provides updated results on the technical feasibility of 200G/lane PAM4 using integrated TOSA/ROSA components

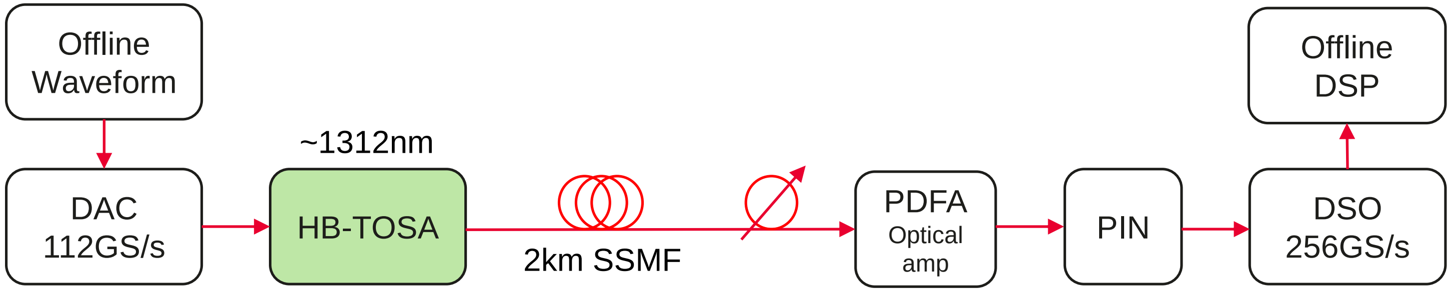
Previous results

Our previous presentation, *kuschnerov_b400g_01_210503*, provided during the SG phase in May 2021, has shown an initial analysis of 200 Gb/s optical feasibility comparing PAM4 and PAM6 modulation schemes:

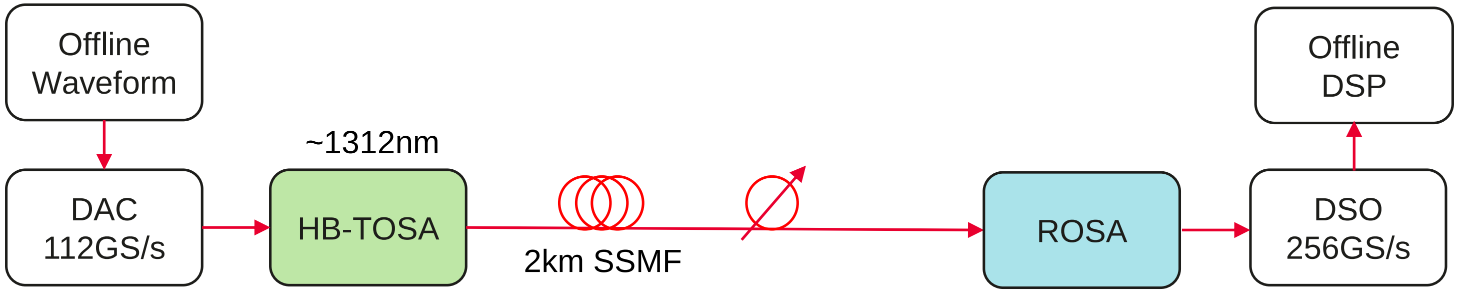
- Using discrete components & despite the limited Tx bandwidth, PAM4 was shown to offer superior performance compared to PAM6 for an EML transmitter
- PAM6 was demonstrated to not fulfill triple link connectivity due to high MPI penalty and thus would have severe limitations in the 2km FR4 use case
- Measurements used optical amplification at the Rx for lack of an integrated ROSA and the comparison to electrical amplification using a TIA was not fully understood yet
- An analysis of CD penalty for 4x200G CWDM4 PAM4 showed the need for a stronger reference receiver (longer FFE + optional MLSE)

Measurements series

1) Measurement of a TOSA (driver + EML) and optical amplification at the Rx side to analyze pure TOSA characteristics

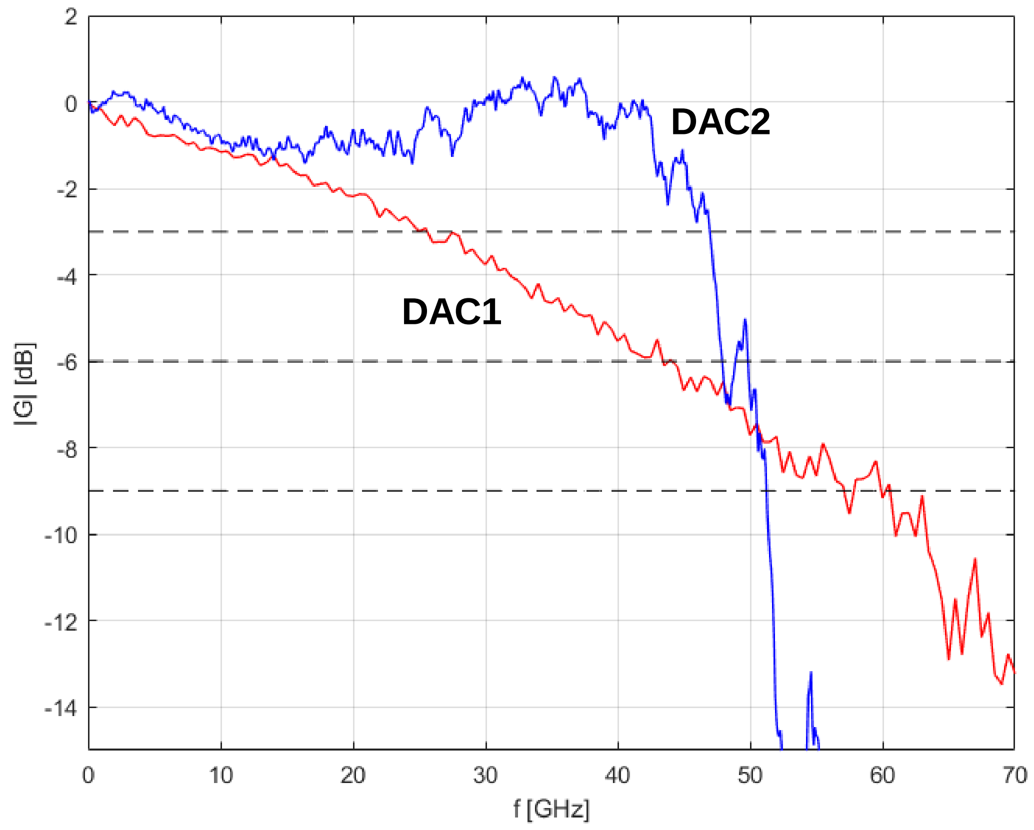


2) Combined measurement of a TOSA & ROSA (TIA+PIN) for an end-to-end unamplified link



DAC characteristics

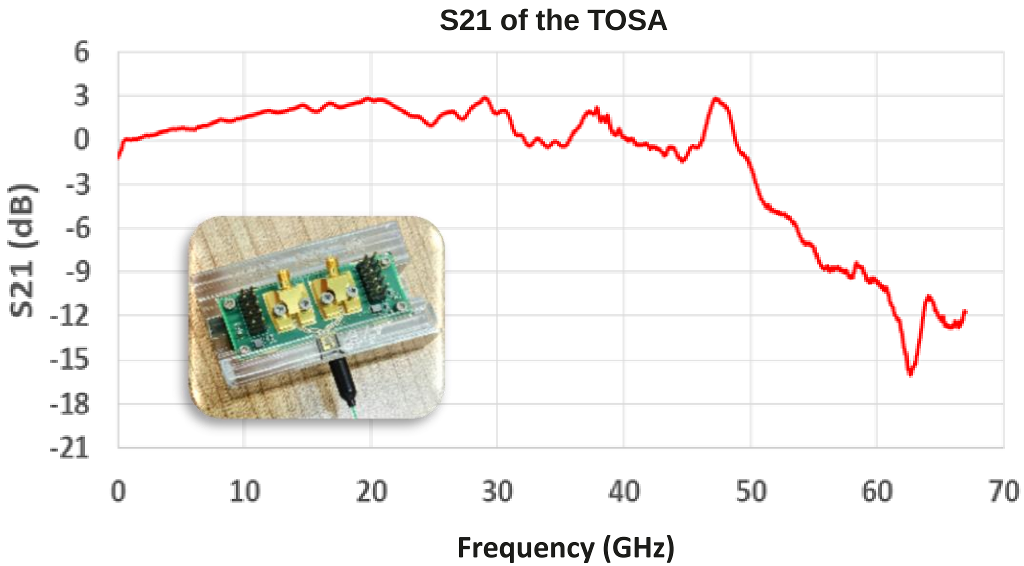
- Two different SiGe arbitrary waveform generators used in the assessment (test & measurement equipment for the lab)
- Target product would use integrated CMOS DAC with higher bandwidth
- Performance is optimal for 600mVppd swing into the TOSA
- 3dB bandwidth of DAC1 is lower with more moderate roll-off vs. DAC2

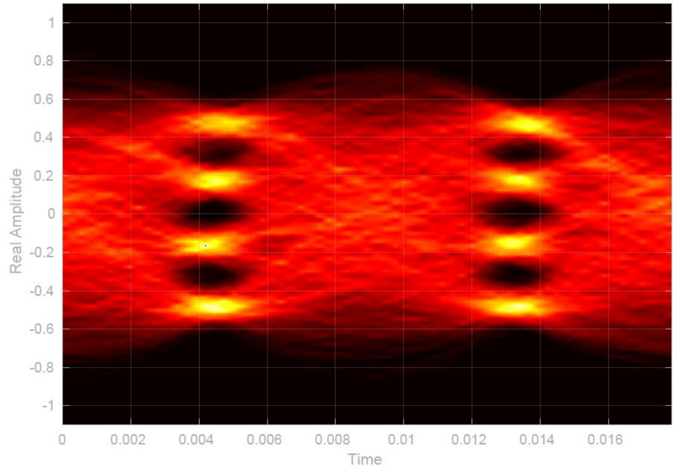


TOSA

Transmitter Optical Subassembly (TOSA):

- The TOSA module uses SiGe driver technology with >56 GHz 3 dB bandwidth
- It is flip-chipped on a carrier to achieve higher bandwidth and lower group delay
- Relative intensity noise (RIN) <-149 dB/Hz
- Modulated output power of >3 dBm @ bias voltage of -3V
- The S21 of the transmitter optical subassembly achieves 50 GHz 3 dB E/O bandwidth for the packaged module
- ~1312nm wavelength



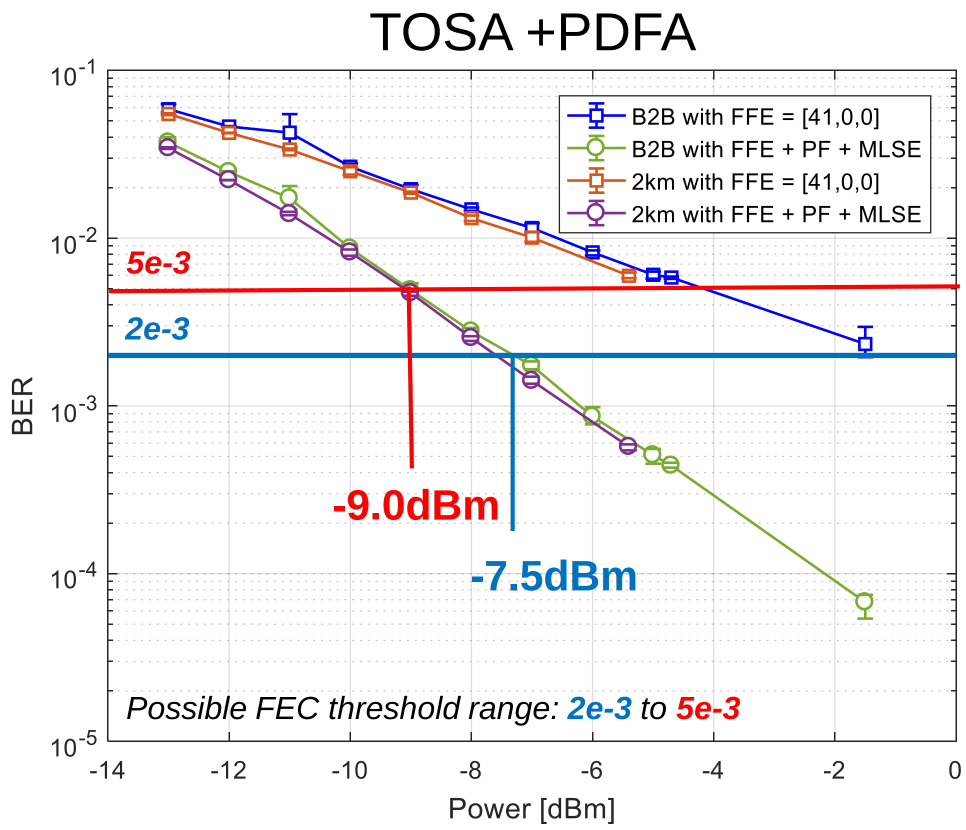


224Gb/s PAM4 optical eye diagram using a 41 linear FFE taps in the receiver.

Note: the reference receiver is yet to be defined and will be subject of future discussions

TOSA transmission results (DAC1)

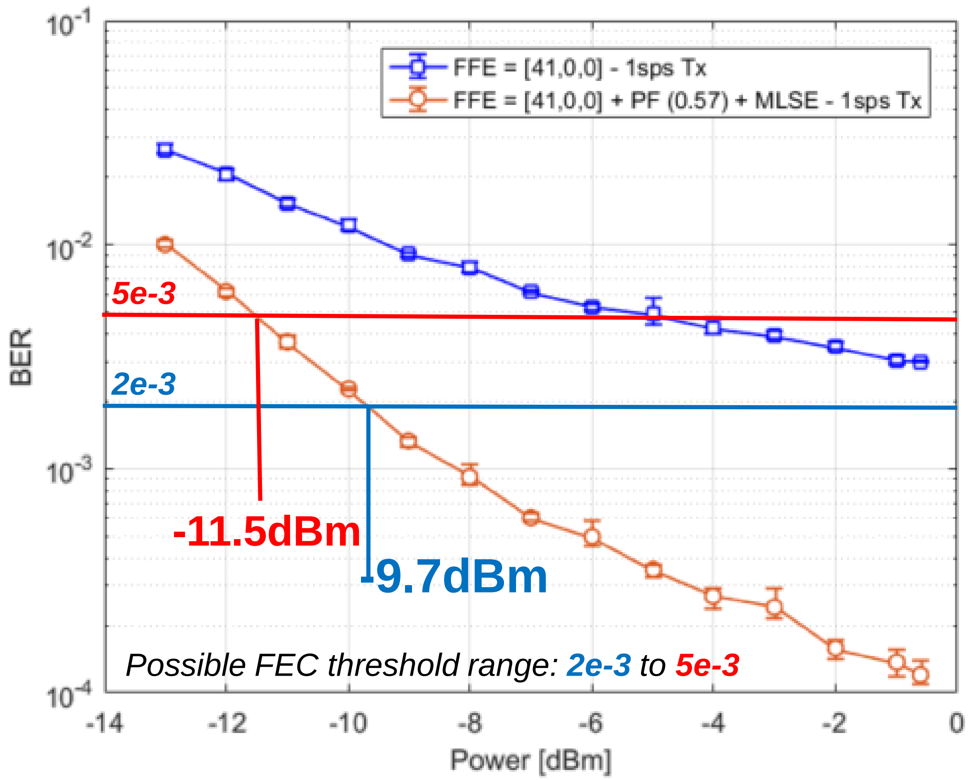
- 41 linear FFE taps
- Partial response filtering (PF) + MLSE is needed to improve performance due to the bandwidth limitations and RF cabling (DAC⇔TOSA)
- **Note**: Integrated product to have shorter equalizers
- FEC is tbd and assumed to be in the range of 2e-3 to 5e-3 for assessment purposes
- Rx sensitivity:
  - -7.5dBm @ 2e-3
  - -9.0dBm @ 5e-3



TOSA transmission results (DAC2)

- DAC2 features a larger 3dB bandwidth, however leads to a higher error floor for the overall system
- Partial response filtering (PF) + MLSE are still key for achieving acceptable performance
- Low complexity MLSE implementation options, e.g. reduced-state sequence estimation (RSSE), are known to address this use case
- Rx sensitivity:
  - -9.7dBm @ 2e-3 (Δ-2.2dB vs. DAC1)
  - -11.5dBm @ 5e-3 (Δ-2.5dB vs. DAC1)

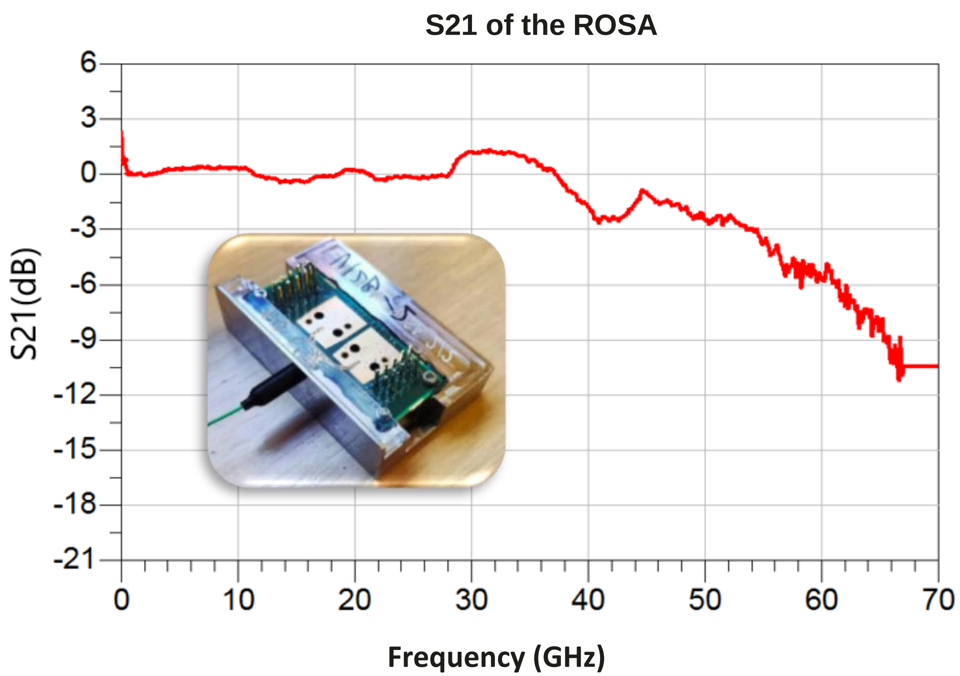
DAC2



ROSA

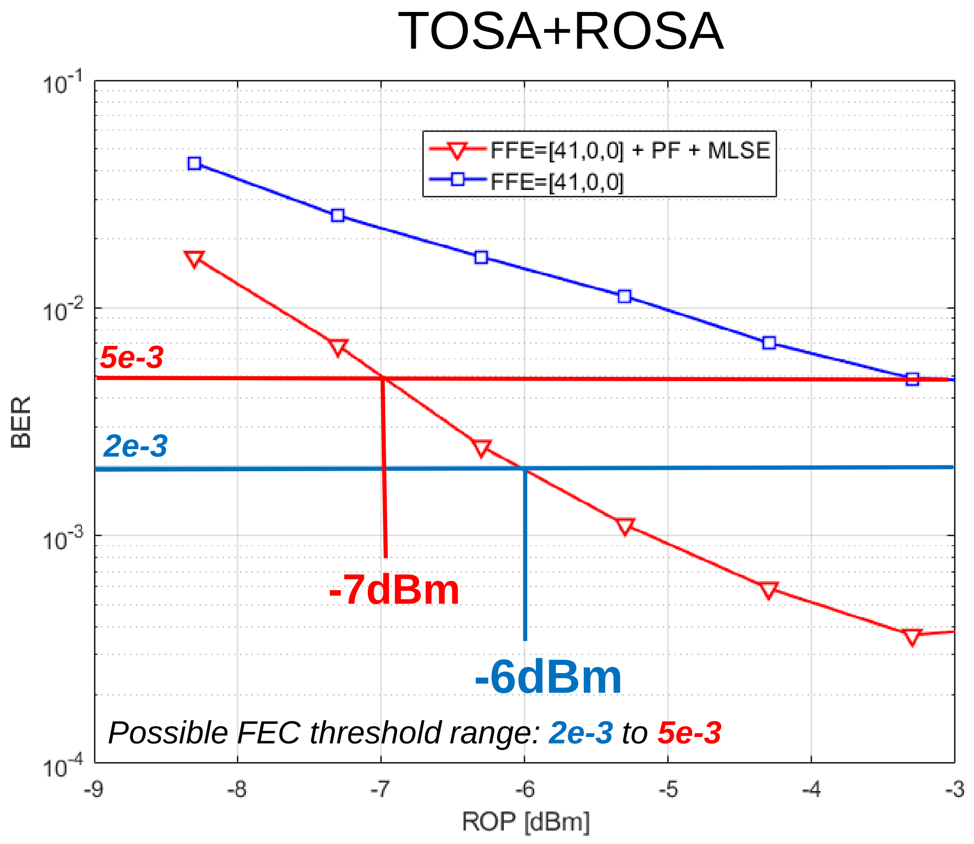
Receiver optical subassembly (ROSA)

- Photodiode with >56 GHz 3 dB bandwidth
- SiGe transimpedance amplifier (TIA) with >50 GHz 3 dB bandwidth
- Responsivity > 0.7 A/W
- Noise <17 pA/√Hz
- TIA and PD are co-packaged in 2.5D assembly to achieve a higher overall bandwidth
- 3 dB bandwidth is at 50 GHz



TOSA + ROSA transmission results (DAC1)

- These tests only used DAC1 as a reference
- Rx sensitivity:
  - -6dBm @ 2e-3   (Δ-1.5dB vs. PDFA)
  - -7.0dBm @ 5e-3 (Δ-2dB vs. PDFA)
- Using a DAC similar to DAC2, an improvement could be expected (>2dB) for an estimated Rx sensitivity of about -8dBm to -9dBm depending on the FEC



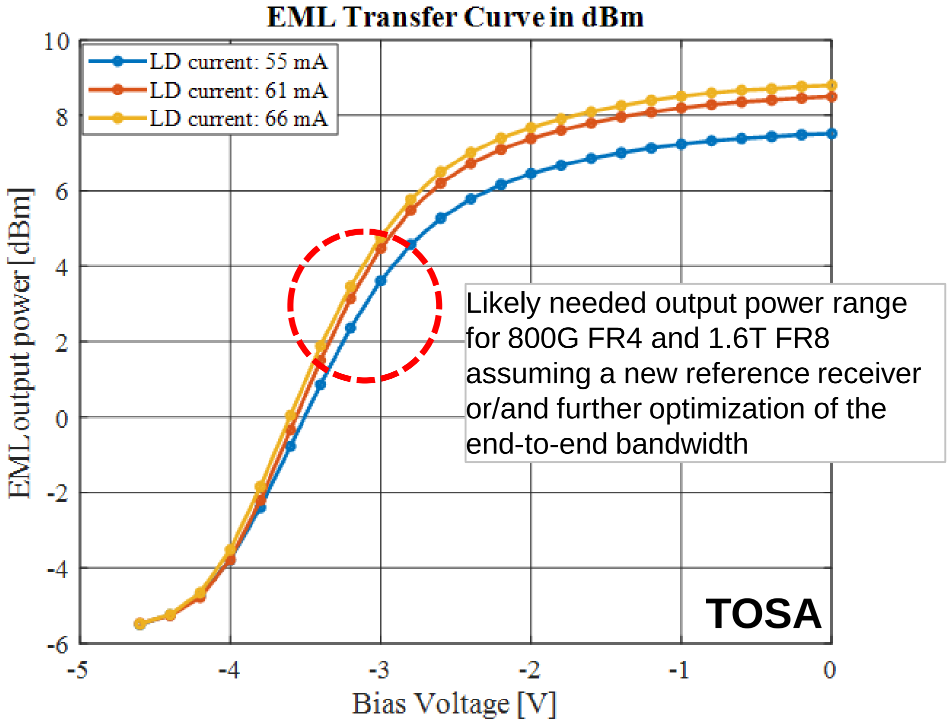
FR 2km link budget

4 / 8 wavelengths over single fiber

- **Note**: 1.6T FR8 over single fiber is not part of the current task force objectives and is shown for reference purposes
- For a FR4/8 2km transmission we estimate a required TOSA to ROSA (not module to module) link budget of ~12.5dB for 800G and 14.5dB for 1.6T
- Our measurements indicate that a BOL Rx sensitivity in the range of ~ **-8dBm:-9dBm** could be feasible using components with around 50GHz 3dB bandwidth and MLSE
- Part of the transmitter penalty is already included in the measurements
- Exact TDECQ value would need a reference receiver definition
- Achieved TOSA output power seems sufficient for 800G and 1.6T over single fiber (and thus also for PSM objectives)

xWDM possible link budget (tbd)

Components	4x200G	8x200G
Channel loss	4dB	4dB
MUX/DEMUX	2×2dB	2×3dB
MPI	0.4dB	0.4dB
DGD	0.4dB	0.4dB
TDECQ	3.7dB	3.7dB
Total	**12.5dB**	**14.5dB**



Conclusions

- The demonstration of 224Gb/s PAM4 transmission without optical amplification using integrated TOSA and ROSA subcomponents is creating confidence in the feasibility of 200G/lane objectives based on PAM4
- The results indicate that 4x200G and 8x200G transmission over 500m & 2km could be realized in the future using PAM4 pending further optimization on the subcomponents and/or an adjusted reference receiver
- The FFE tap number will likely be lower for the reference receiver in the range of ~15-21taps (800G Pluggable MSA suggests 21 taps)
- Assessment of longer reaches for 200G/lane (e.g. 800G 10km LR4) would require further analysis of CD penalty, FWM penalty and Rx sensitivity

Thank you.