Photonics for AI Infrastructure – Scale Across

The Photonics Systems Group

Department of Electrical and Computer Engineering

McGill University

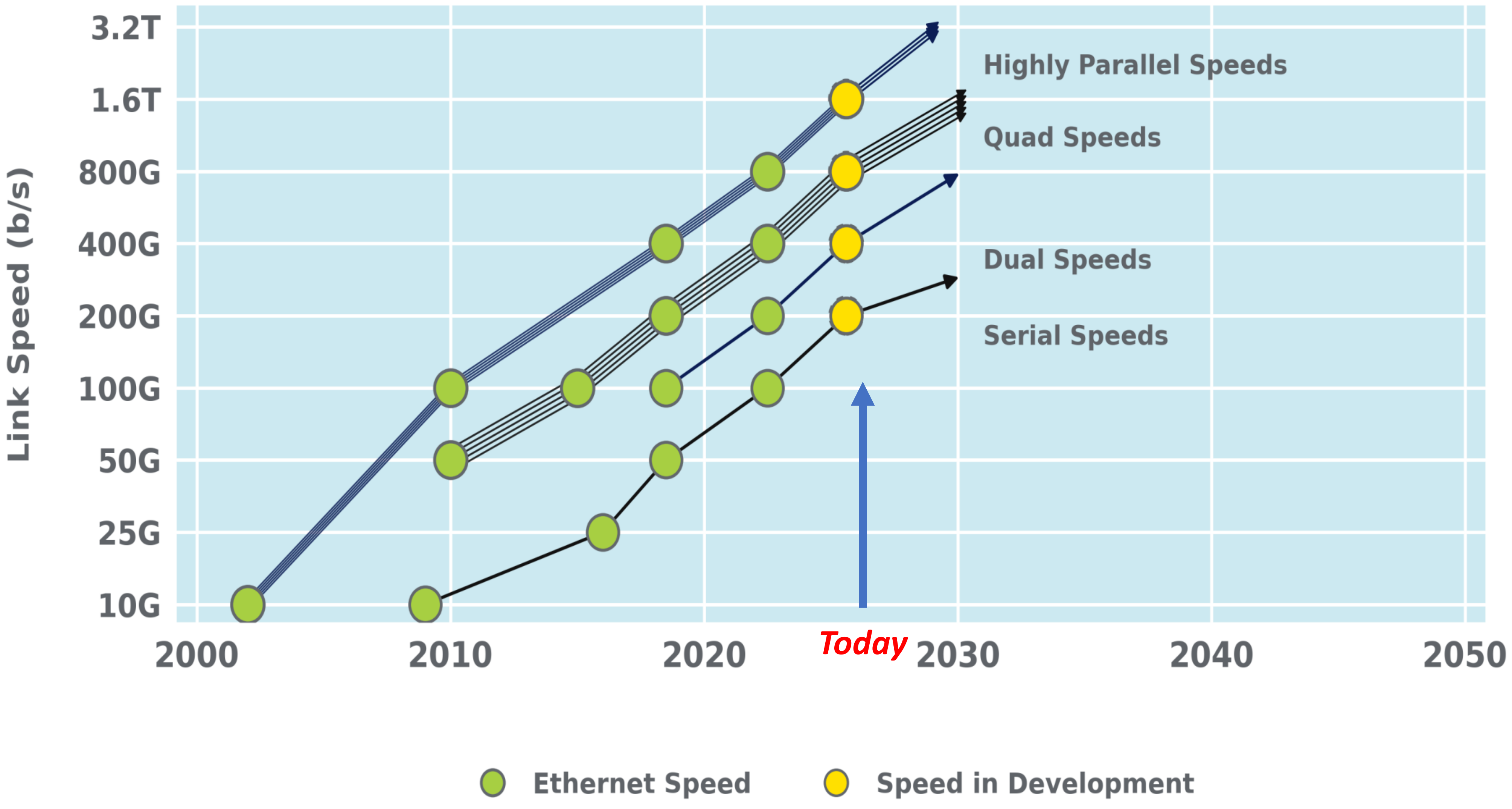
www.photonics.ece.mcgill.ca/Plant/Plant.html

OFC
July 5, 2026

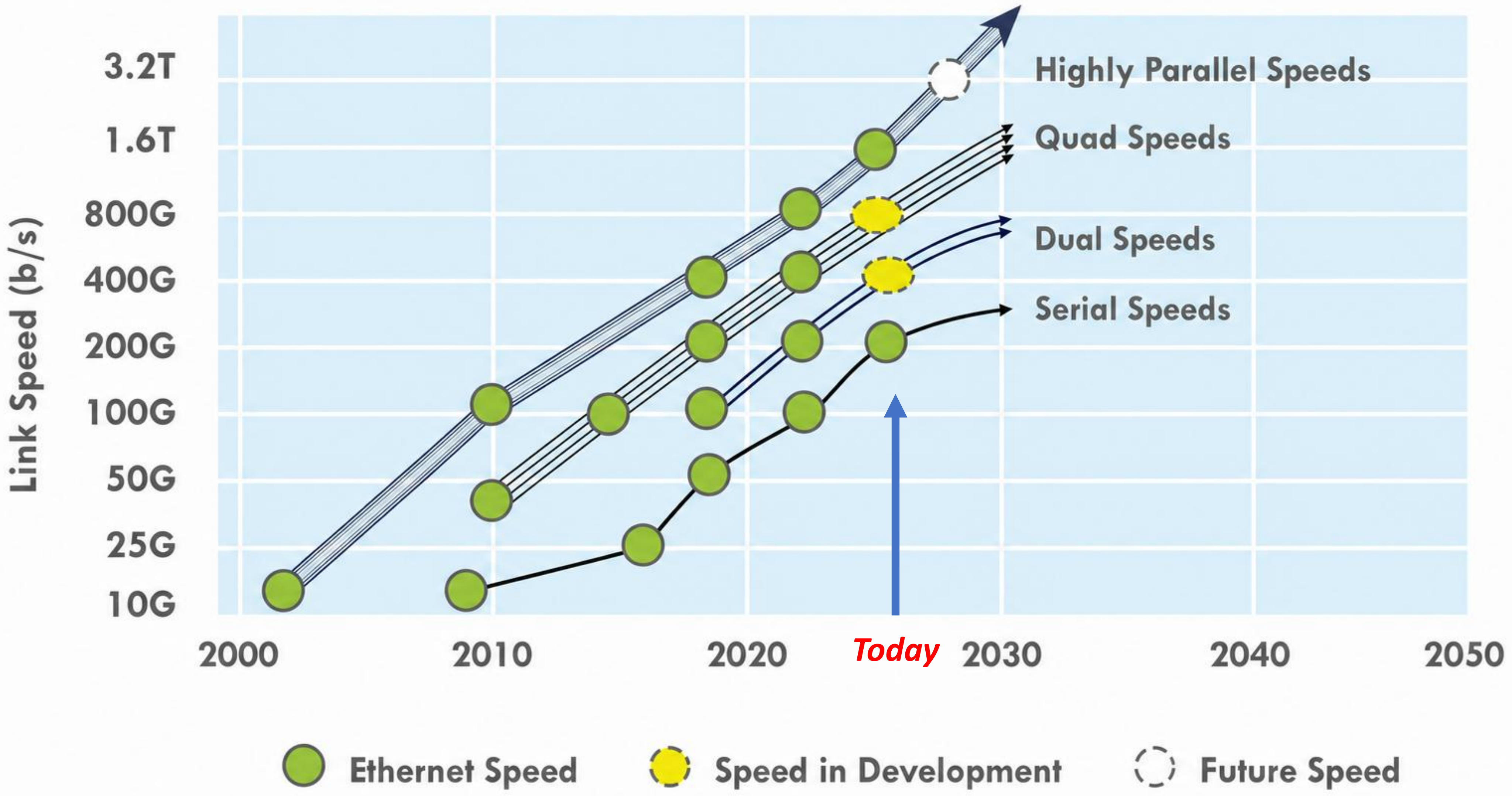
Outline

- Ethernet Roadmap
  - 2025
  - 2026
- Recent IM/DD Transmission Systems
- System Performance Analysis
- Conclusions

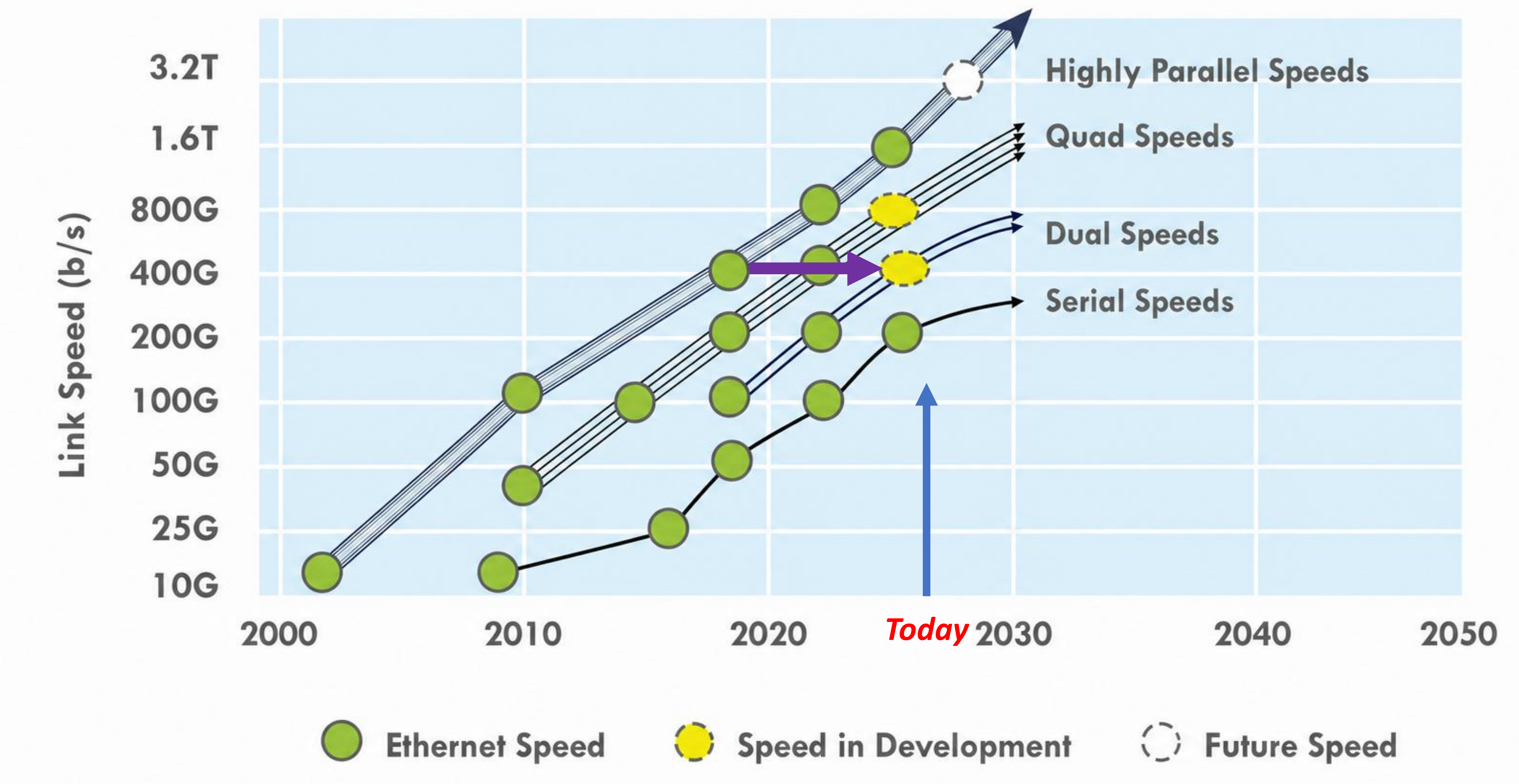
Ethernet Roadmap: Path to Single Lane (2025)



Ethernet Roadmap: Path to Single Lane (2026)



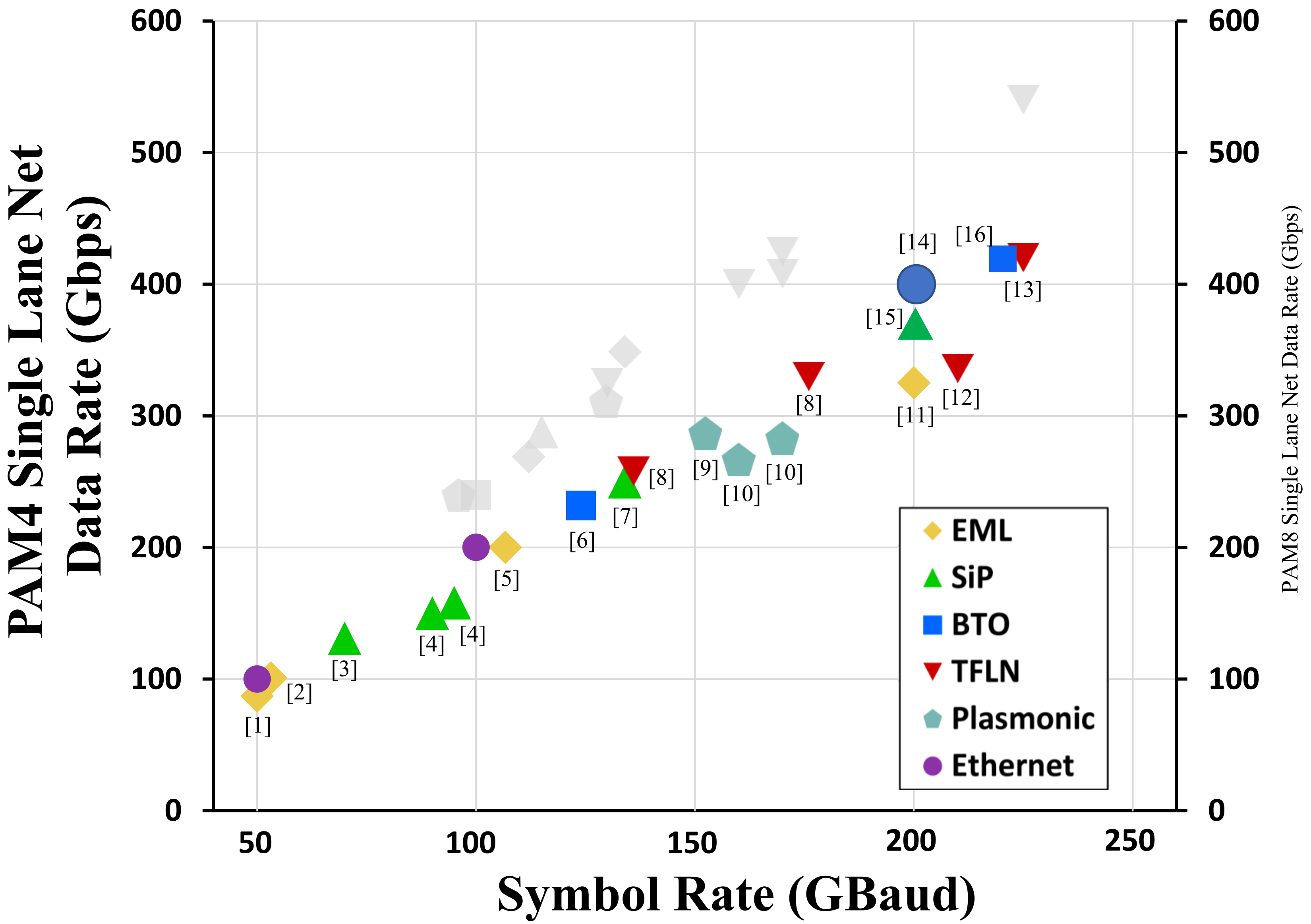
Ethernet Roadmap: Path to Single Lane (2026)



Observations: 2025 - 2026

- Ethernet Alliance roadmap:
  - 200G Serial Speeds moved from Speed in Development to Ethernet Speed
  - 1.6T Highly Parallel Speeds point moved from Speed in Development to Ethernet Speed.
- CMOS ASIC scaling:
  - 3 nm-class FinFET → 2 nm-class nanosheet/GAA;
  - transistor density increased by ~15% for mixed designs and up to ~20% for logic-only blocks.
- Ethernet bandwidth scaling is being driven not only by CMOS scaling, but also by higher order modulation formats, DSP, SerDes, optical/electrical device advances, and lane parallelism.

Recent Reports: PAM4 with Six Platforms



[1] J. Potet, PTL, 2022

[2] J. Y. Huh, OE, 2022

[3] E. Berikaa, PTL, 2022

[4] Z. Zhang, LPR, 2025

[5] W. Li, ECOC, 2024

[6] W. Li, JTL, 2024

[7] E. Berikaa, OFC, 2022

[8] E. Berikaa, PTL, 2023

[9] Q. Hu, JLT, 2022

[10] M. Kohli, OFC, 2024

[11] H. Asakura, ECOC, 2024

[12] C. St-Arnault, OFC, 2024

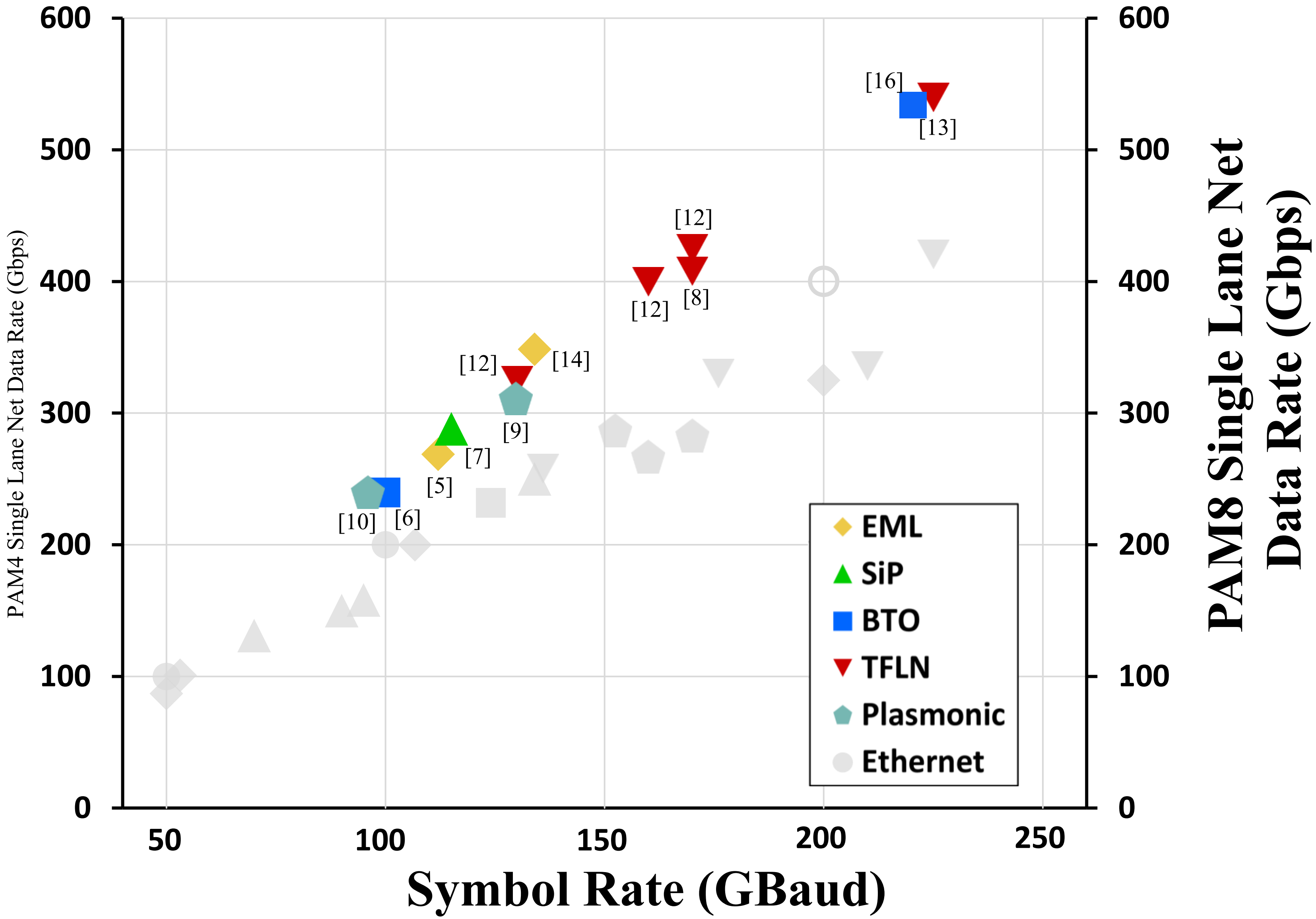
[13] C. St-Arnault, OFC, 2025

[14] OFC Exhibit Floor, 2025

[15] Po Dong, OFC 2026

[16] B. Qiu, C St-Arnault, OFC 2026

Recent Reports: PAM8 with Six Platforms



[5] W. Li, ECOC, 2024

[6] W. Li, JTL, 2024

[7] E. Berikaa, OFT, 2022

[8] E. Berikaa, PTL, 2023

[9] Q. Hu, JLT, 2022

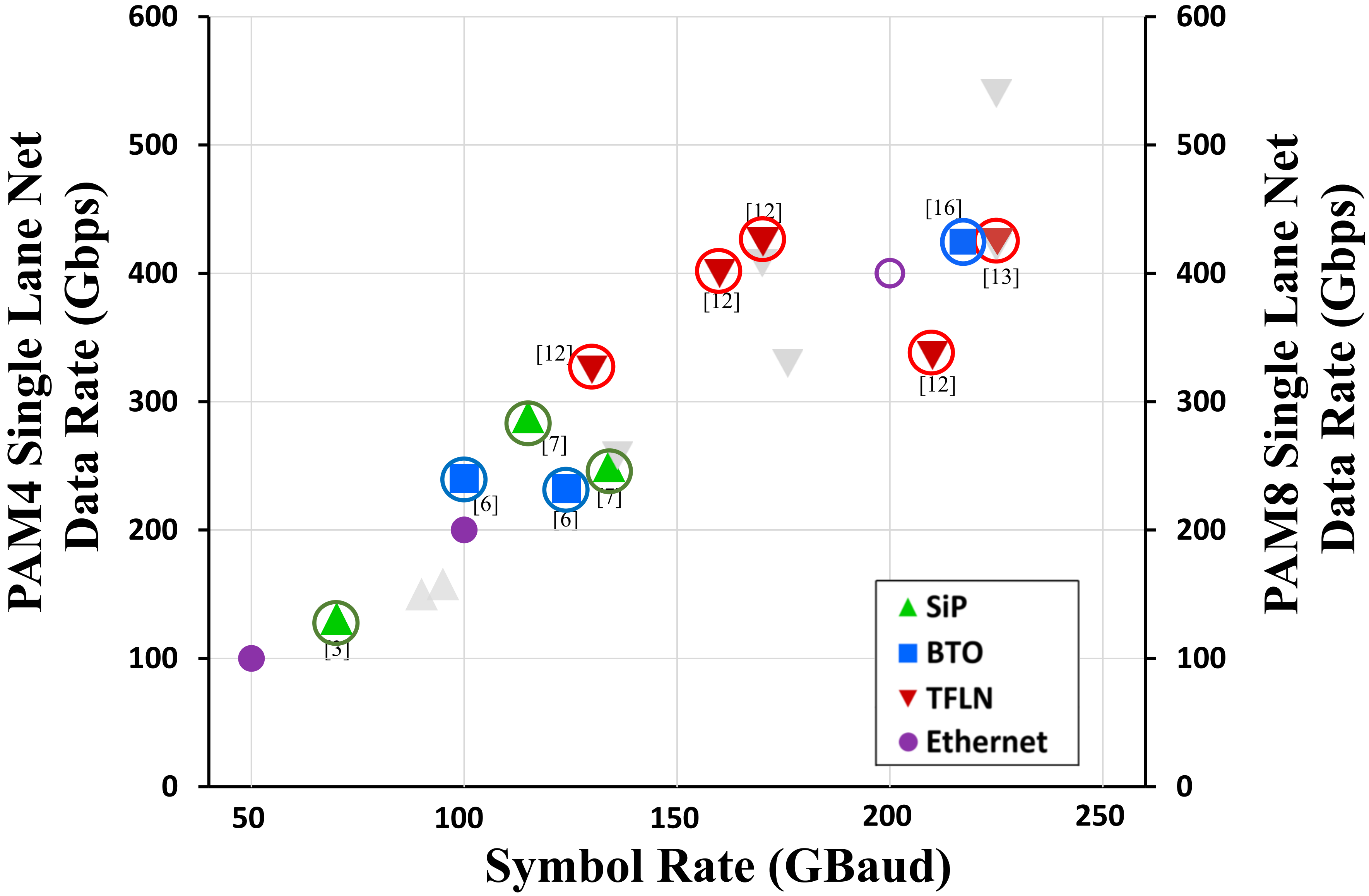
[10] M. Kohli, OFC, 2024

[12] C. St-Arnault, OFC, 2024

[13] C. St-Arnault, OFC, 2025

[16] B. Qiu, C. St-Arnault OFC 2026

Recent Reports: Detailed Results



[3] E. Berikaa, PTL, 2022

[6] W. Li, JTL, 2024

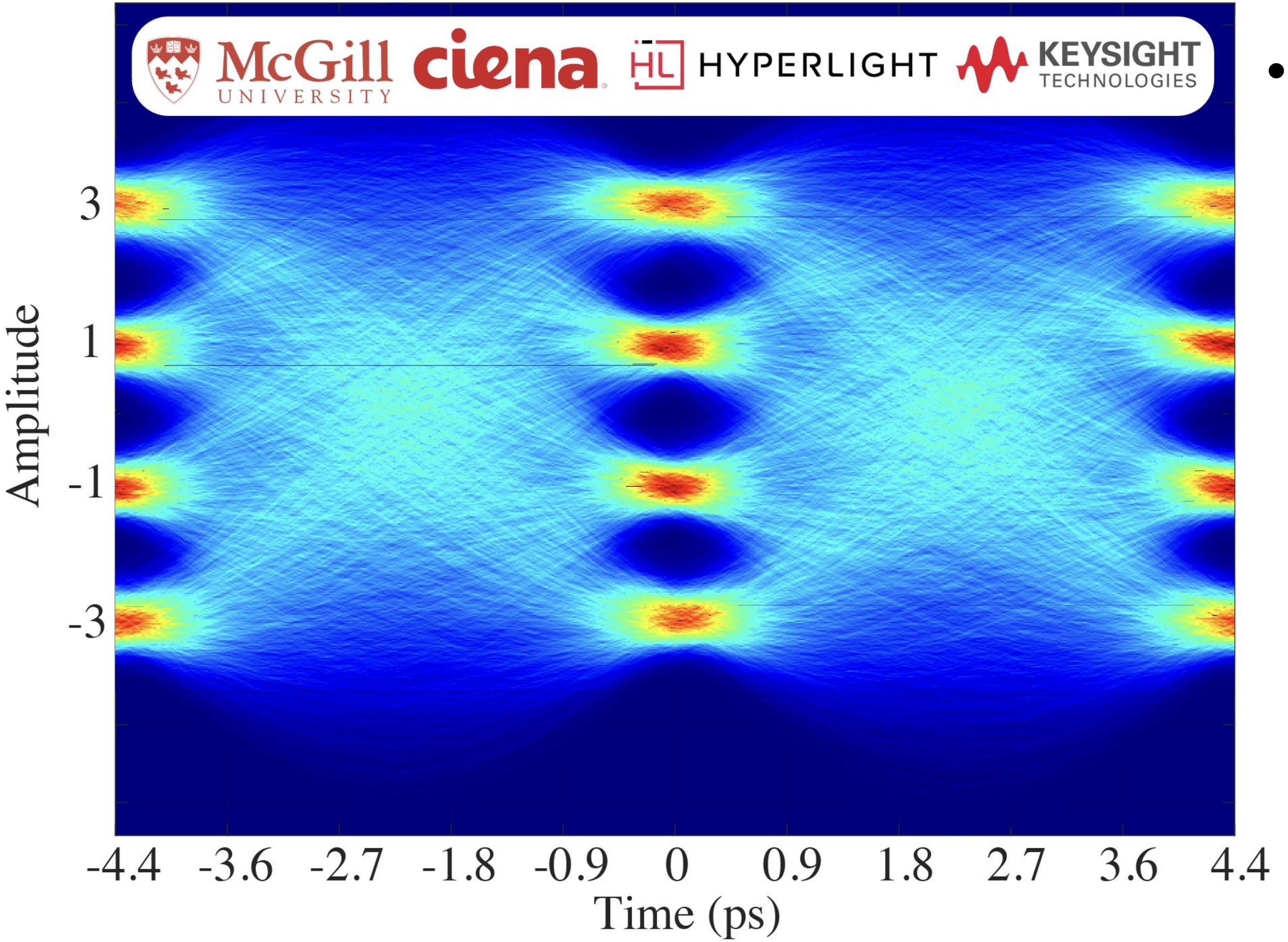
[7] E. Berikaa, OFT, 2022

[12] C. St-Arnault, OFC, 2024

[13] C. St-Arnault, OFC, 2025

[16] B. Qiu, C. St-Arnault OFC 2026

225 GBaud, 450 Gbps Transmission in O-Band

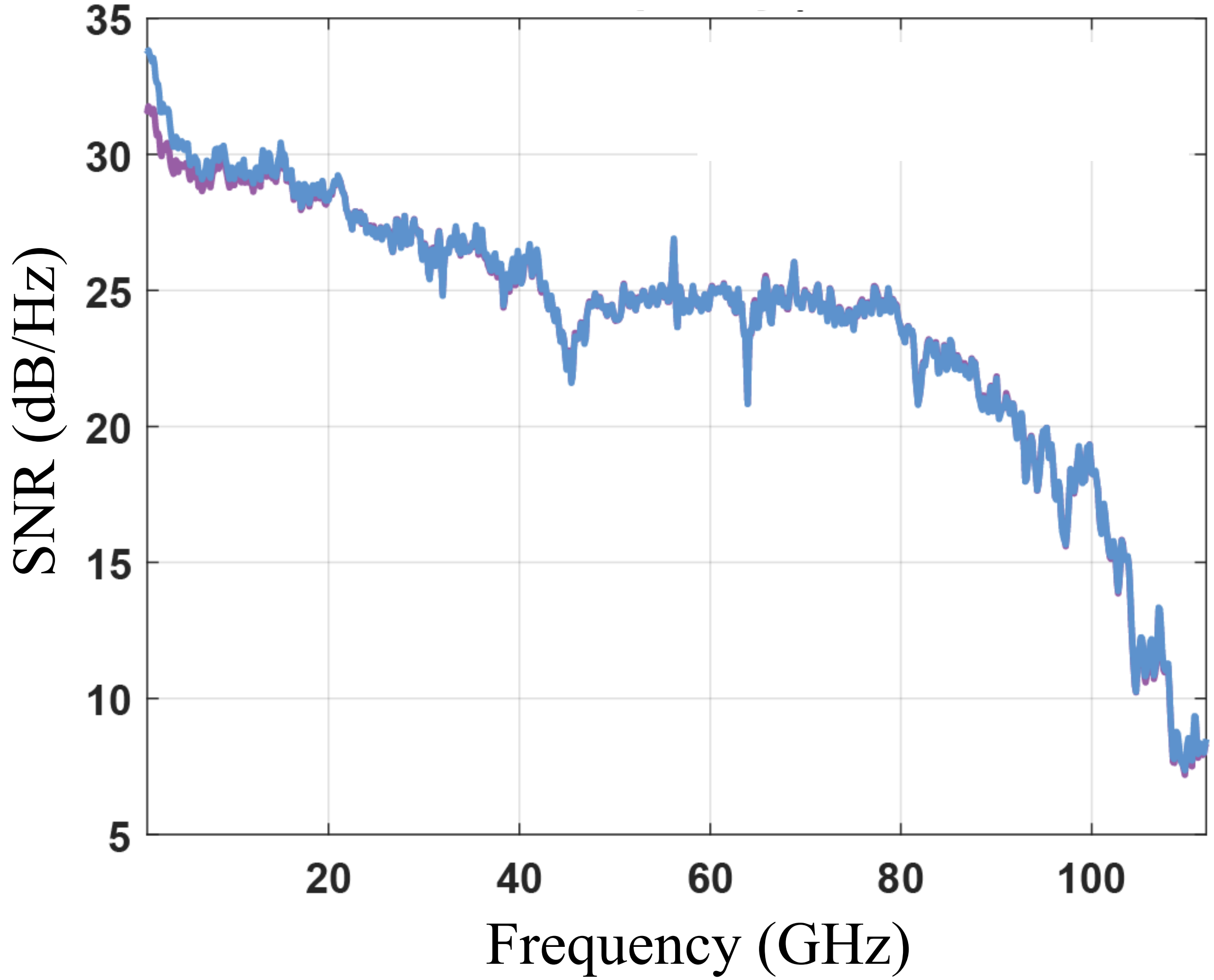


- Net 3.2 Tbps with the following two architectures:
  - 8-WDM at 2 km
  - DR8 at 500 m and 2 km

C. St-Arnault, PDP, OFC, 2025

Measured Received SNR vs. Frequency @ 225 GBaud/448 Gbps PAM4

McGill

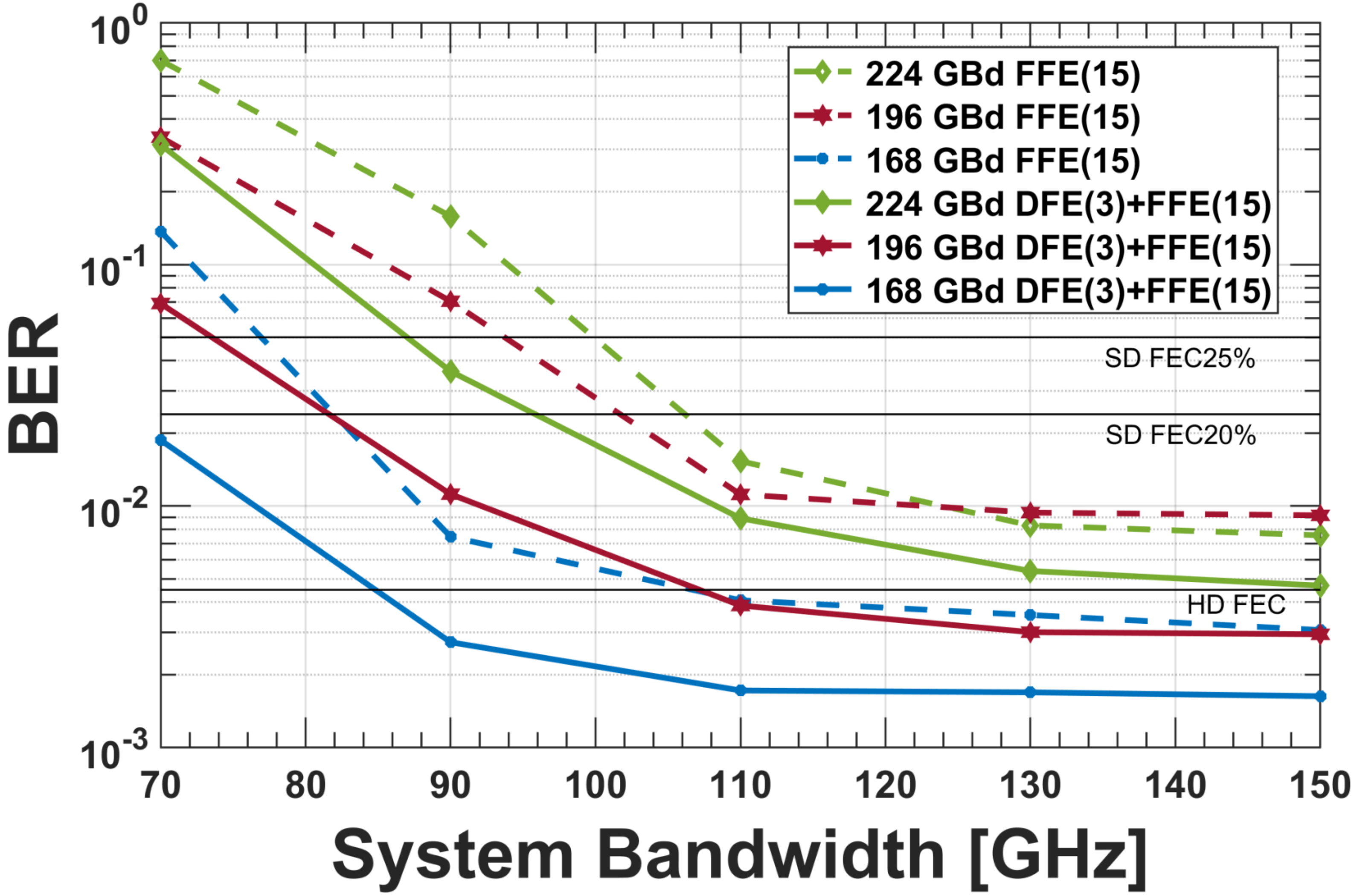


Conclusions

- SiP, BTO, and TFLN modulators offer unique bandwidth, drive voltage, and insertion-loss advantages
- PAM8, probabilistic shaping, and nonlinear equalizers enable high capacities under standard FEC thresholds
- Multi-wavelength channel plans achieve multi-terabit throughput
- System analysis underscores bandwidth and noise impact on performance

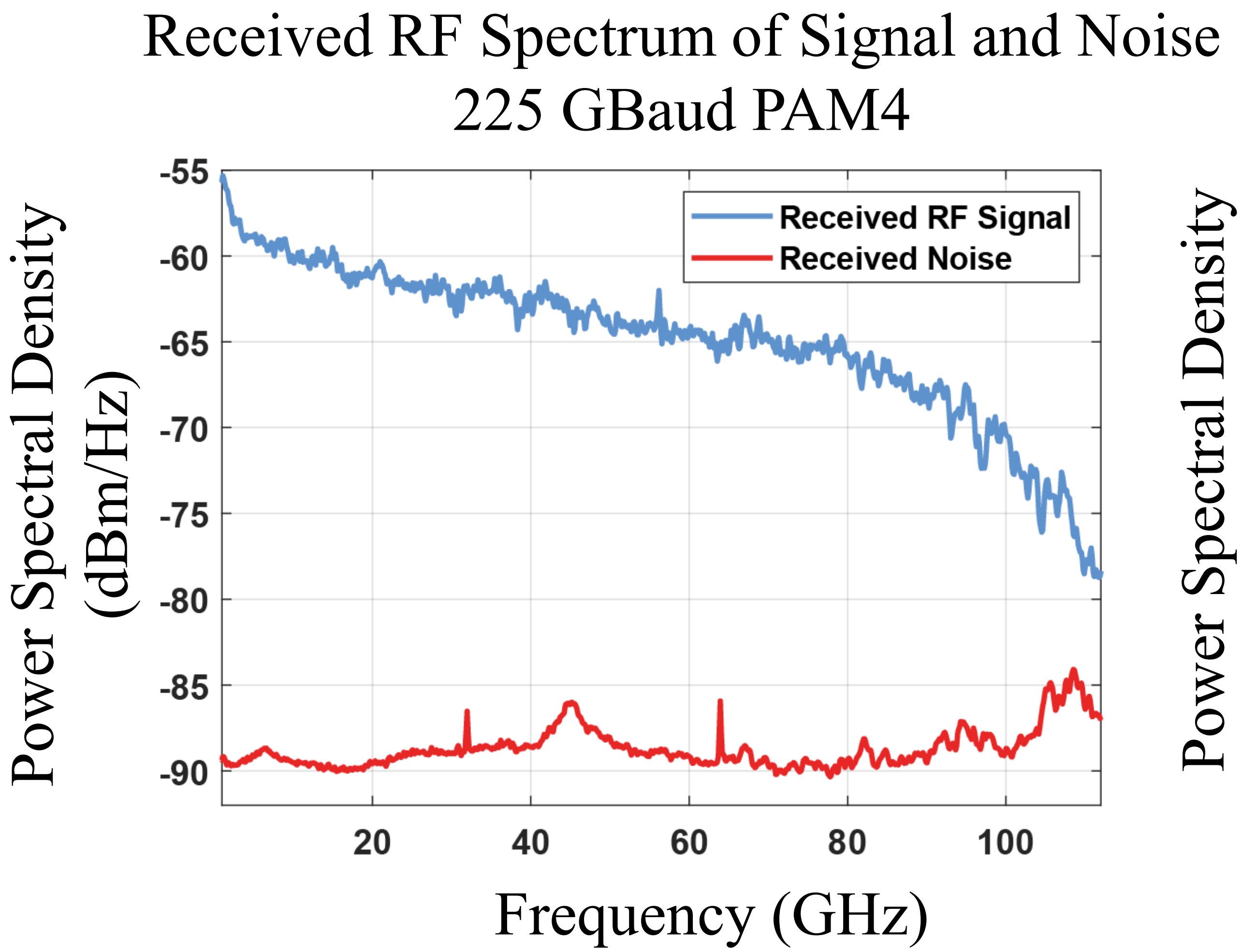
System Performance
Bandwidth, Noise

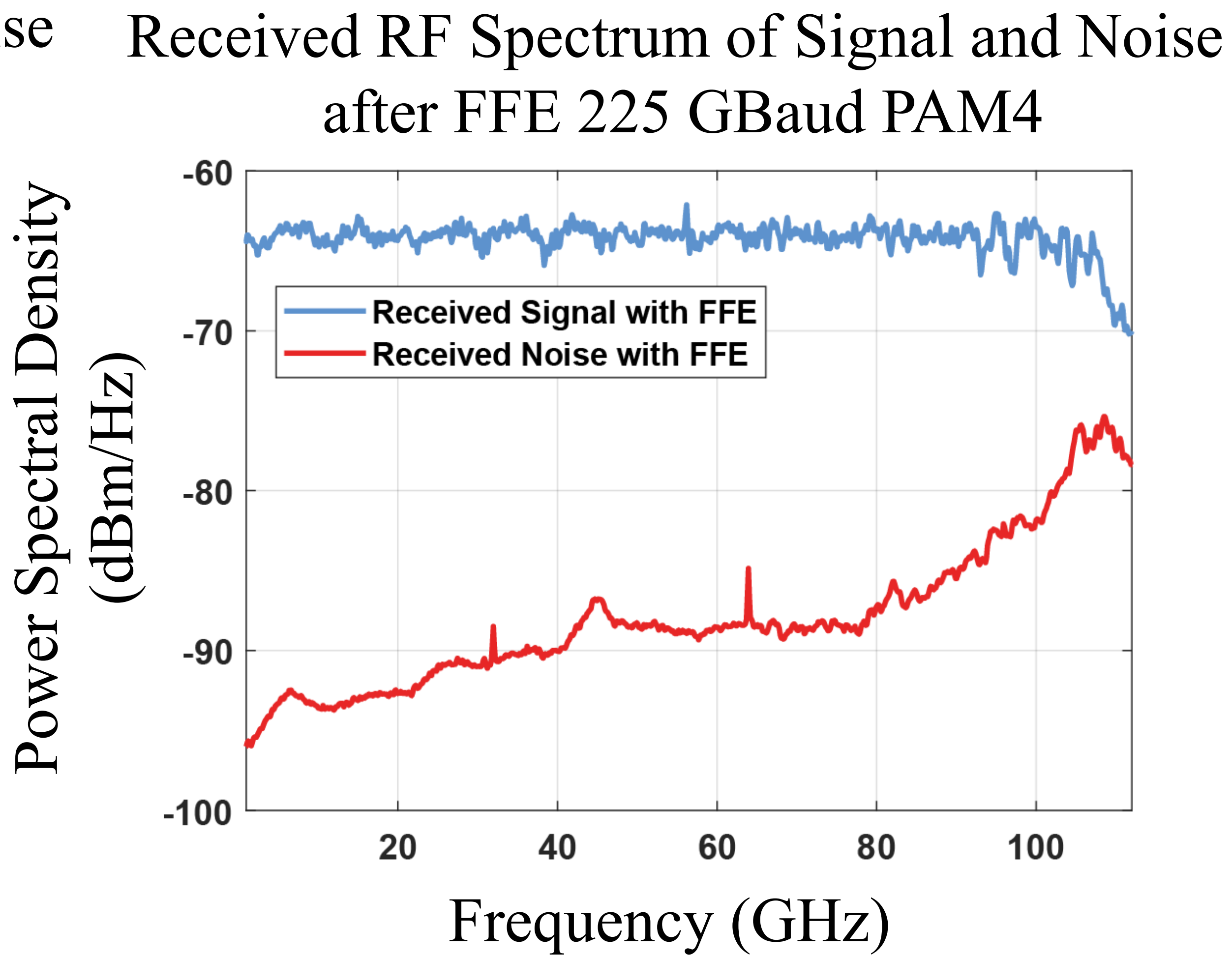
BER vs. System Bandwidth: FFE vs. DFE Comparison



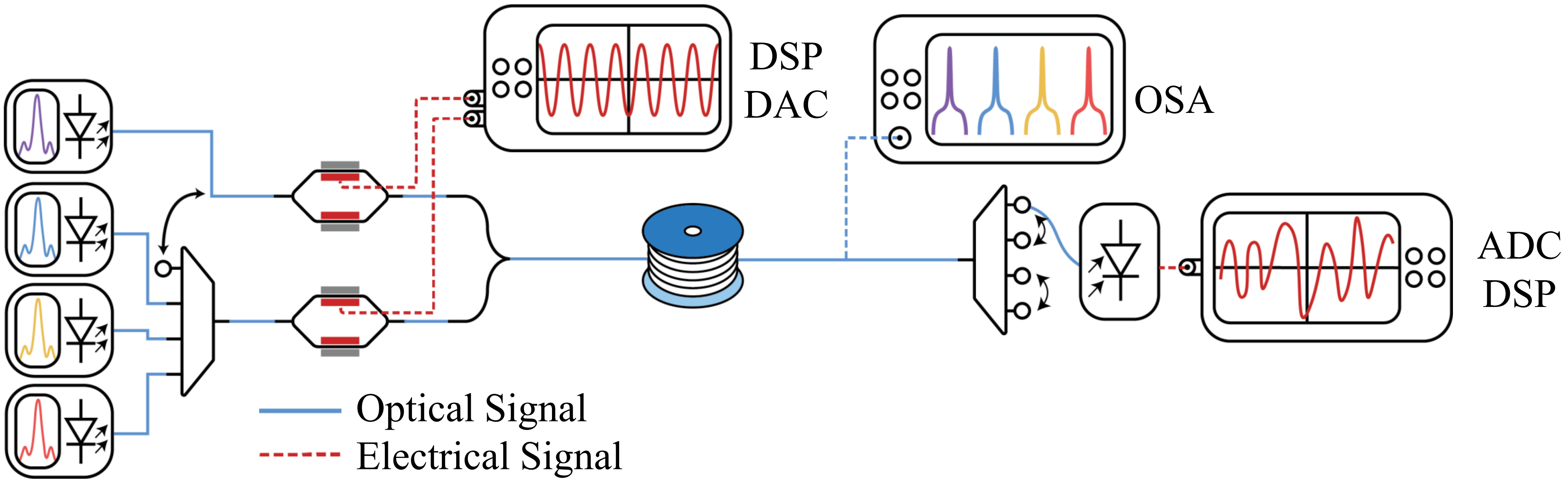
- Bandwidth simulated with a low pass root raised cosine electrical filter and a roll off factor of 0.05; cut-off frequency is 70 to 150 GHz
- Lower baud rates achieve better BER performance at a given system bandwidth
- A lower BER is obtained with increasing bandwidth; eventually saturates due to SNR

Measured Power Spectral Density vs. Frequency





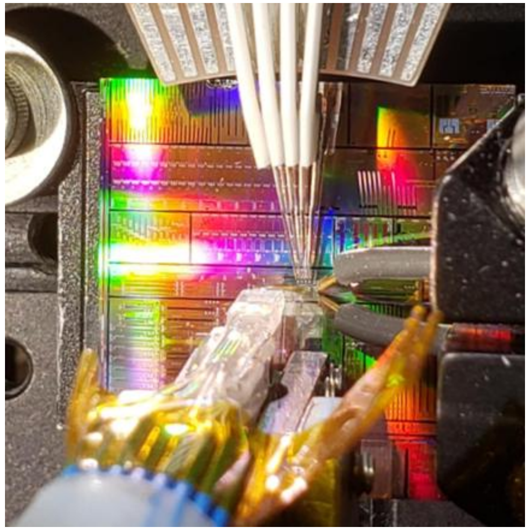
Canonical IM/DD System Setup

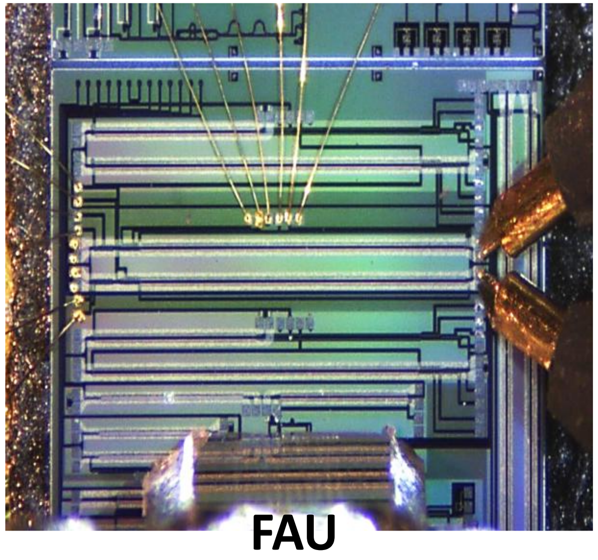


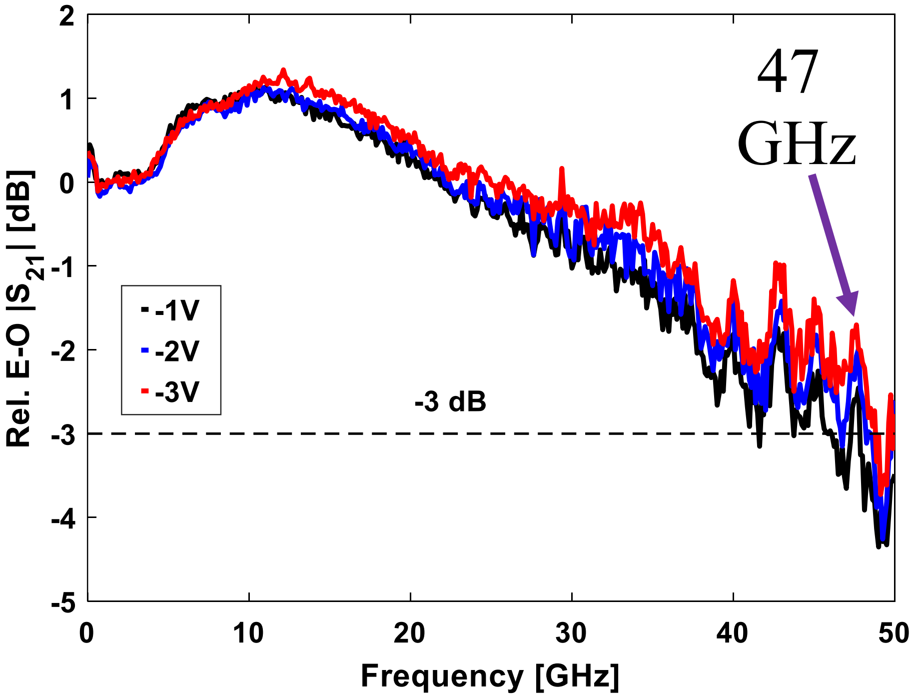
- CWDM grid: 1270 – 1330 nm ($\Delta\lambda$ = 20 nm)
- LAN-WDM grid: 1295.56 – 1309.14 nm ($\Delta\lambda$ = 4.4 nm)
- Launched powers ≤ 4 dBm (avoid fiber nonlinearities)
- Conventional Mach-Zehnder Modulator structures
- PAM4/PAM8 signaling
- Transmission distances ≤ 10 km (unamplified)
- Linear and Nonlinear Digital Signal Processing (DSP)
- HD-FEC (7%), SD-FEC (20%), SD-FEC (25%)

SiP – Sampling Rate, DSP Variants
Dr. Samiul Alam, Dr. Essam Berikaa
(OFT 2022, PTL 2022)

Advanced Micro Foundry (AMF) SiP MZM

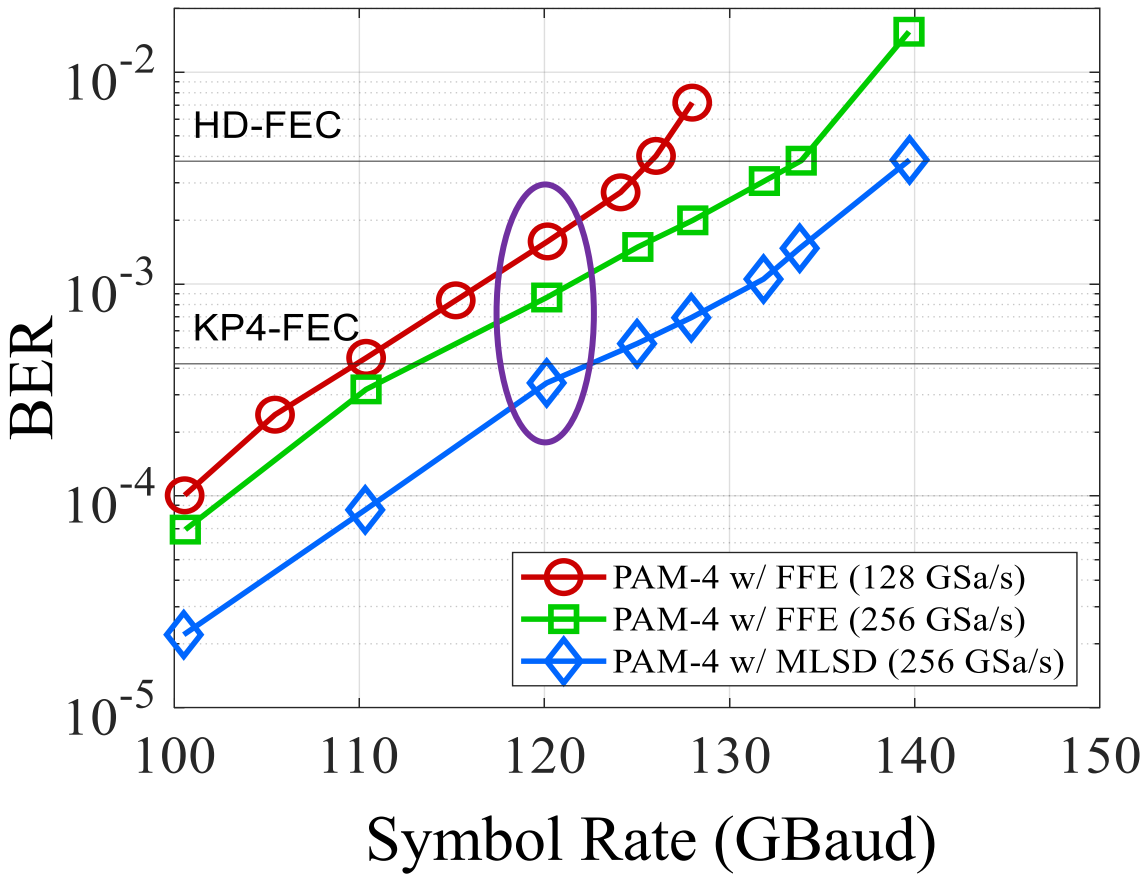






- Electrode Length: 2.5 mm
- Modulator insertion loss: 5.4 dB
- EO S21 @ 3 dB = 47 GHz
- DC Vπ = 5.6 Volts
- Drive voltage: 3 Vpp

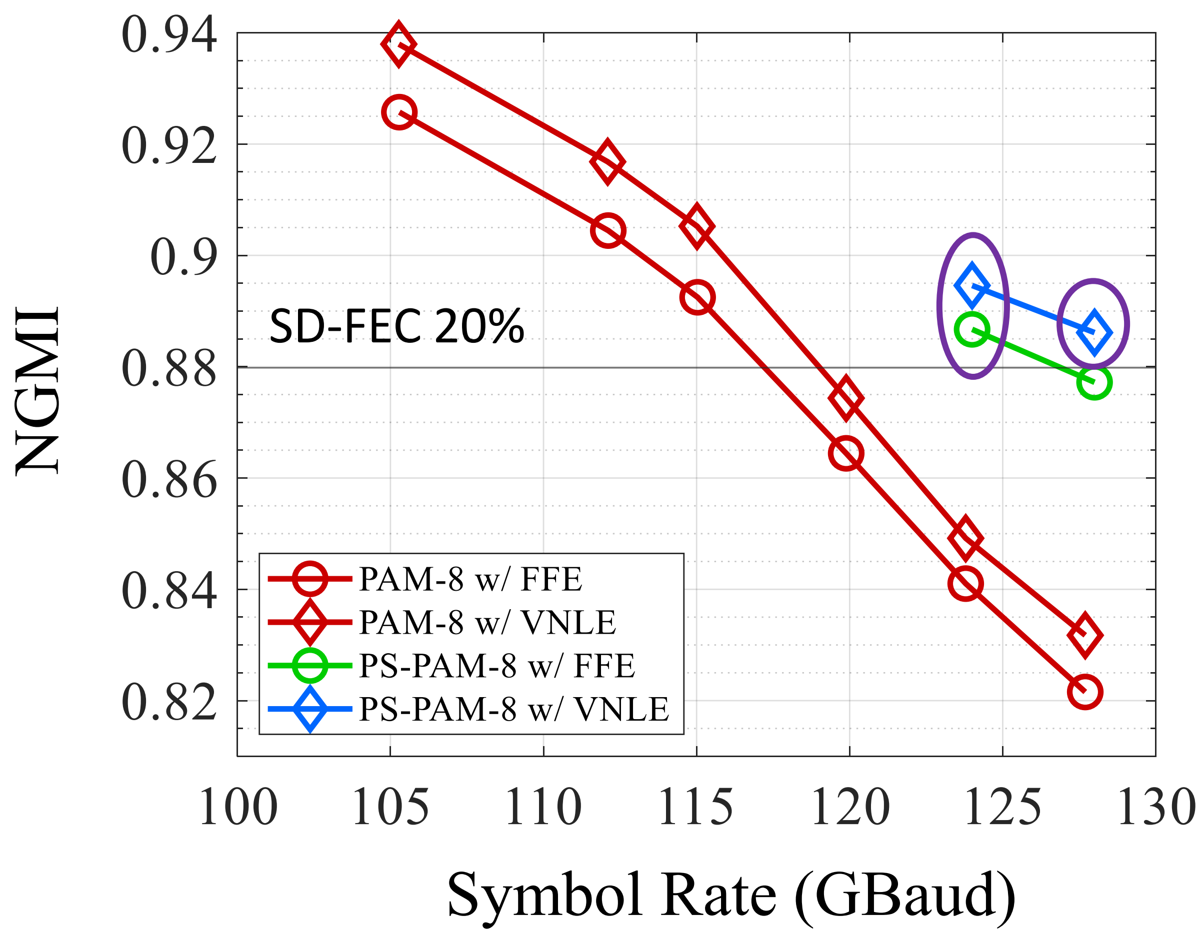
BER vs. Symbol Rate PAM4 @ 1310 nm over 2 km



- Net rates @ 120 GBaud:
  - 225 (R)
  - 225 (G)
  - 228 (B)

- At 256 GSa/s (vs. 128 GSa/s) pulse shaping flexibility increases in order to reduce PAPR
- Feed Forward Equalizer (FFE) compensates for channel induced bandwidth loss and ISI
- Maximum Likelihood Sequence Detection (MLSD) mitigates impairments most effectively to achieve best BER performance

BER vs. Symbol Rate PAM8 @ 1310 nm over 2 km



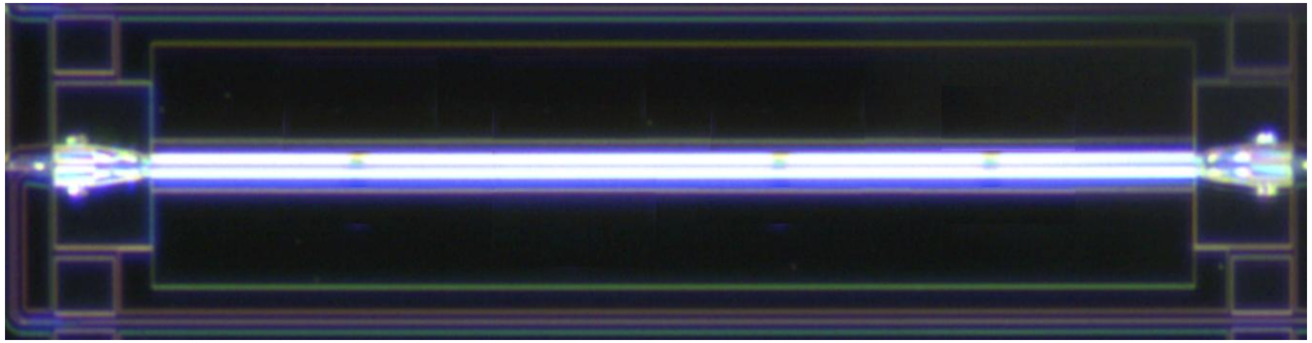
- At 124 GBaud with Probabilistic Shaping (PS) + FFE or Volterra Nonlinear Equalizer (VNLE):
  - 300 Gbps (B)
  - 300 Gbps (G)
- At 128 GBaud with PS and VNLE:
  - 310 Gbps (B)
- Several configurations possible to achieve net 300 Gbps below 20% SD-FEC

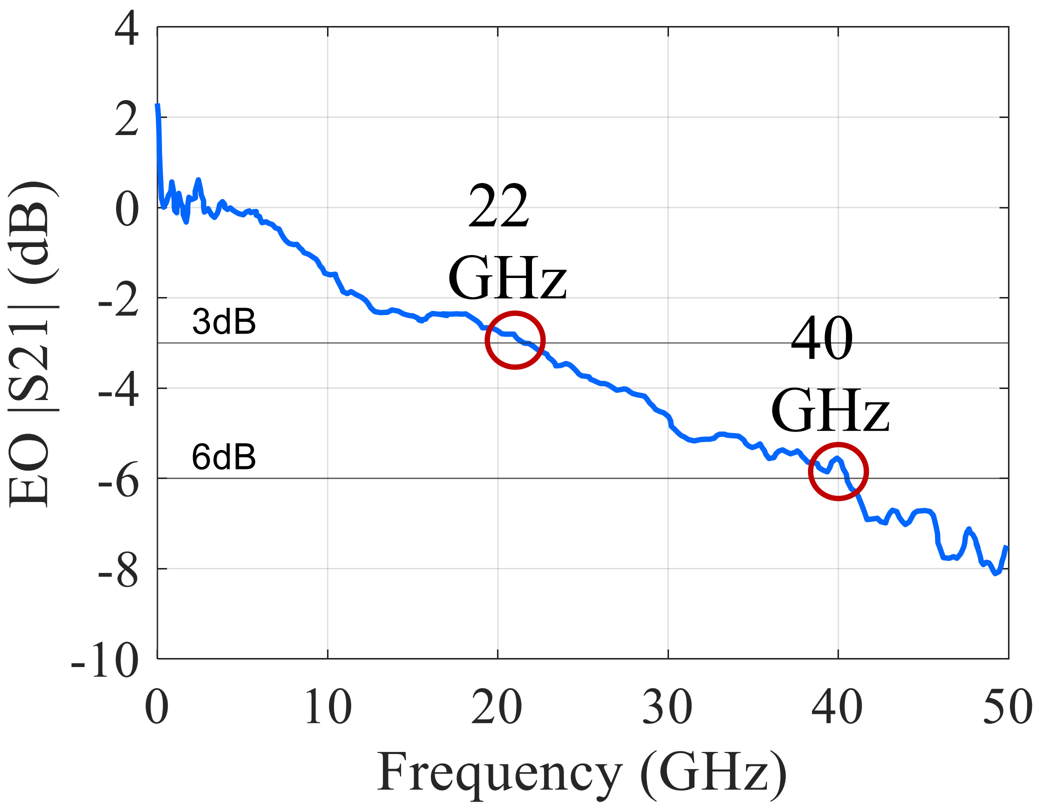
BTO – DSP Variants, λ Performance

Dr. Weijia Li

(ECOC 2023, JLT 2024)

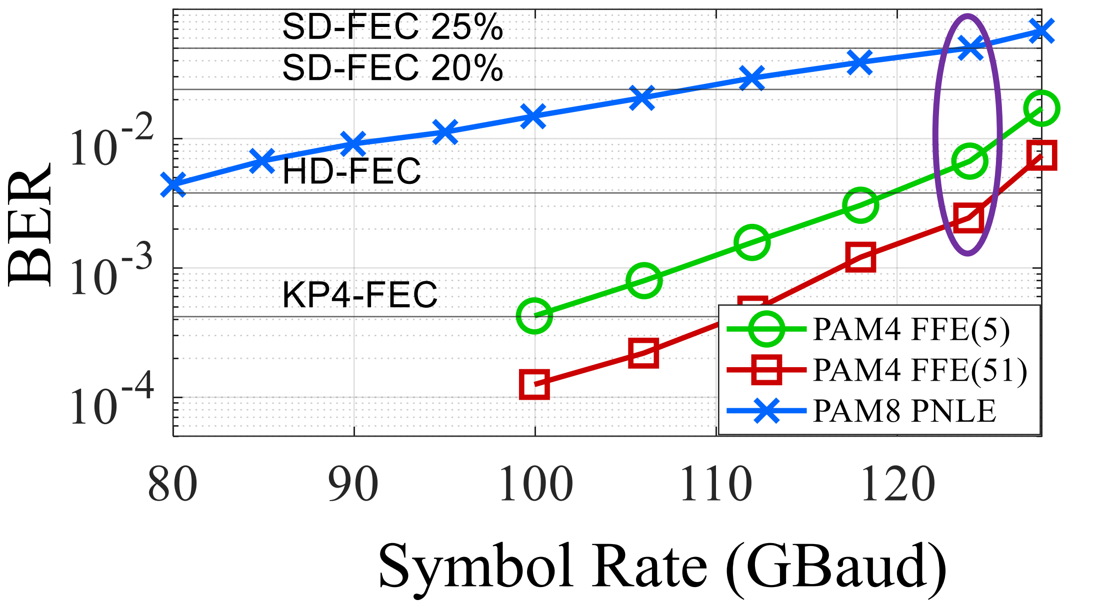
Lumiphase Barium Titanate Oxide (BTO) MZM



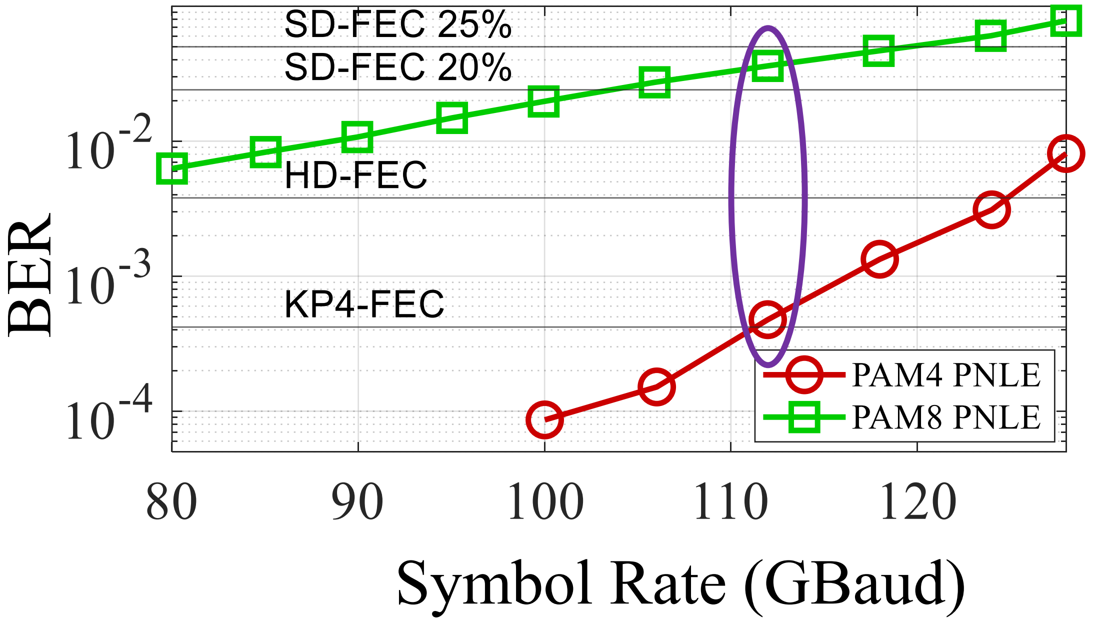


- Electrode Length: 1.5 mm
- On-chip insertion loss: ~ 2 dB
- EO S21 = 22/40 GHz @ 3/6 dB
- RF Vπ @ 10 MHz = 3.6 V
- Drive voltages: 2 – 4 Vpp

BER vs. Symbol Rate @ 1310 nm

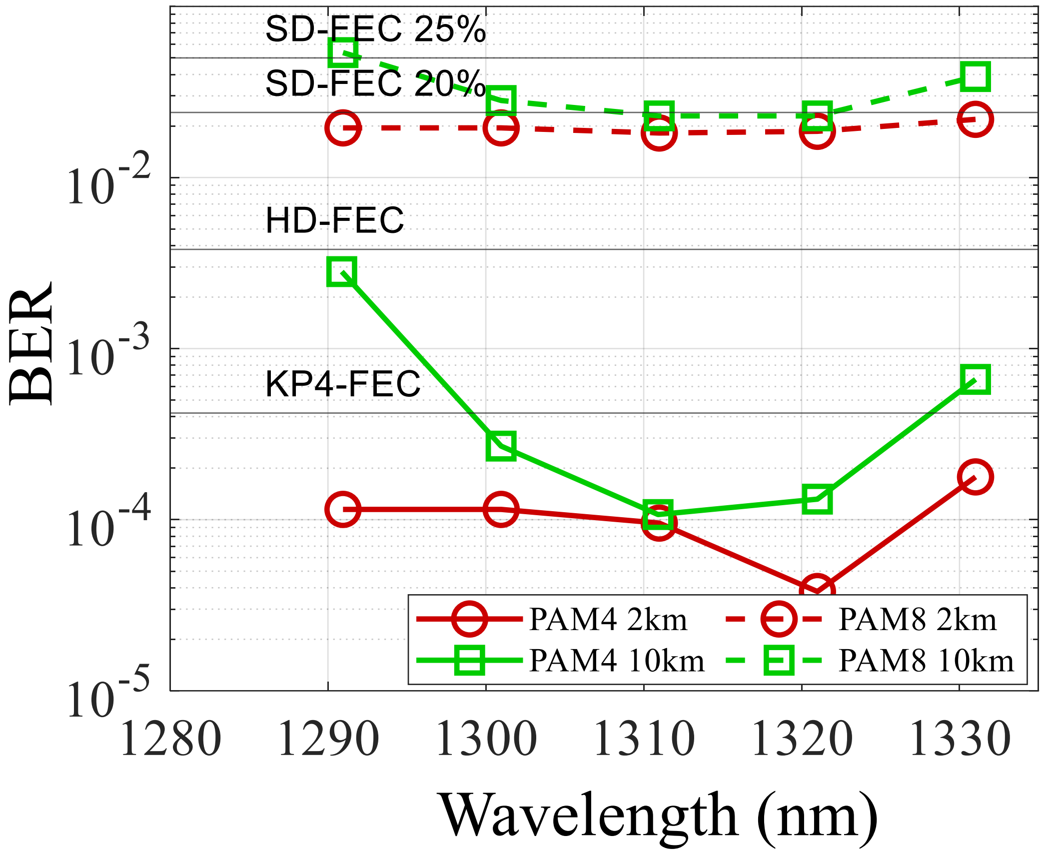


- Net rates @ 124 GBaud over 2 km:
  - 232 (R)
  - 207 (G)
  - 298 (B)
- FFE with more taps reduces BER
- Polynomial Nonlinear Equalizer (PNLE) with PAM8 increases capacity but requires stronger FEC



- Net rates @ 112 GBaud over 10 km:
  - 210 (R)
  - 269 (G)
- Here for 10 km, capacity governed by PAM order

BER vs. Multi λ Transmission @ 106 Gbaud over 2/10 km



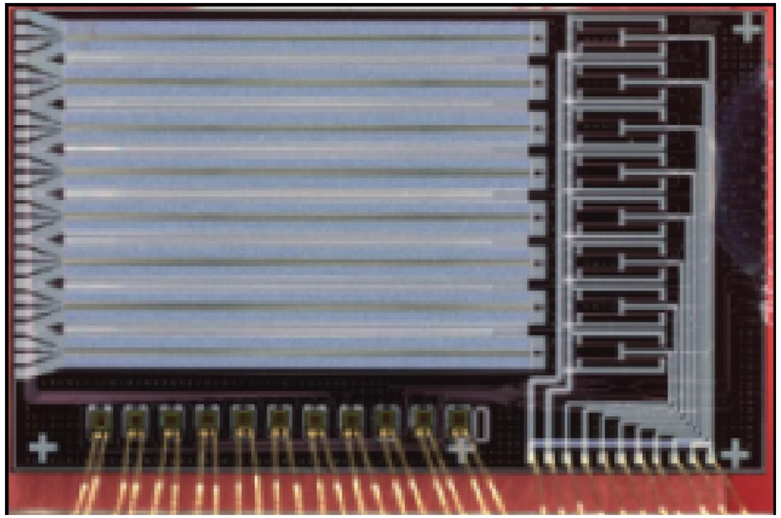
- Solid Red: PAM4 Below KP4-FEC over 2 km:
  - 201 Gbps per λ;
- Solid Green: PAM4 Below HD-FEC over 10 km:
  - 199 Gbps per λ
- Dotted Red PAM8 Below SD-FEC 20% over 2 km:
  - 265 Gbps per λ
- Solid Green: The band edge λ's experience increased dispersion penalties

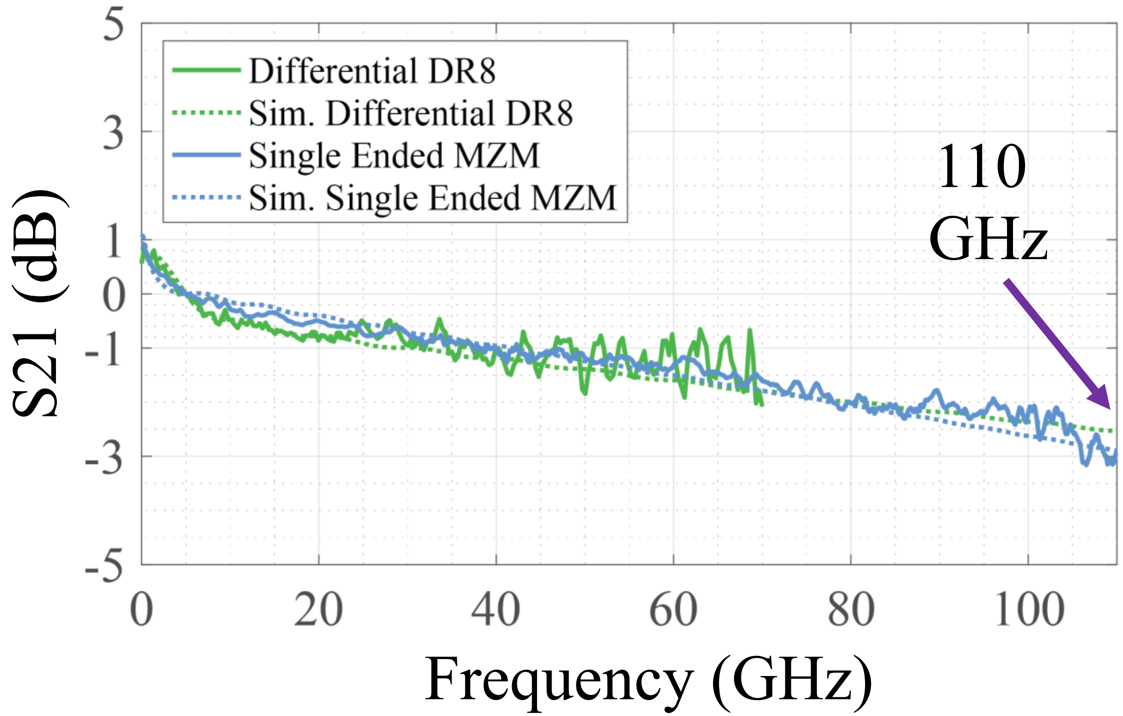
TFLN – λ Performance, High Bauds

Mr. Charles St. Arnault

(OFC 2024 PDP, JLT 2025)

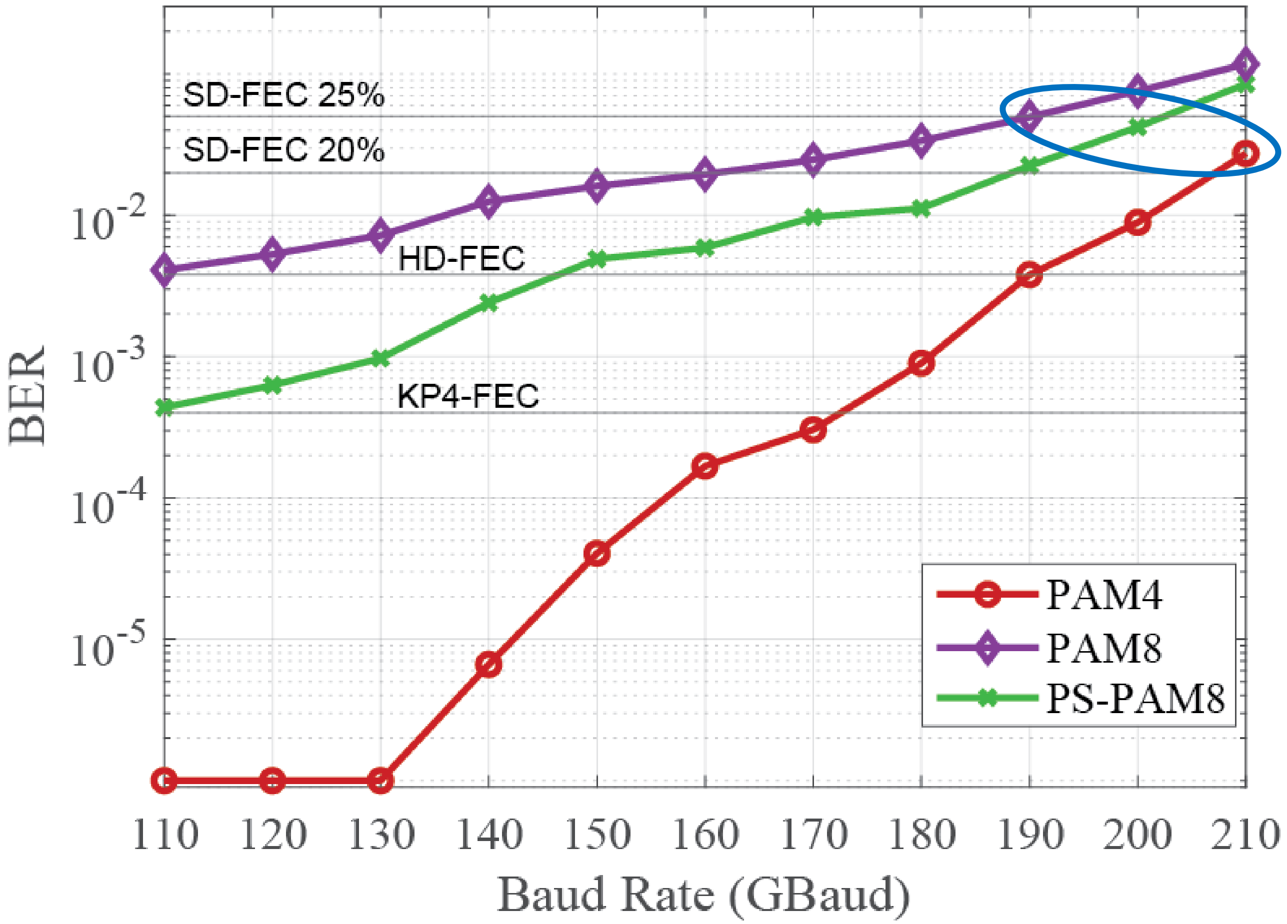
Hyperlight Thin Film Lithium Niobate (TFLN) MZM





- Electrode Length: 10 mm
- On-chip insertion loss: < 0.1 dB/cm (almost lossless)
- EO S21 3 dB > 110 GHz
- RF Vπ = 1.5 V low MHz
- Drive voltages: < 1 Vpp @ 2 km; 2 Vpp @ 10 km

BER vs. Symbol Rate @ 1310 nm over 10 km



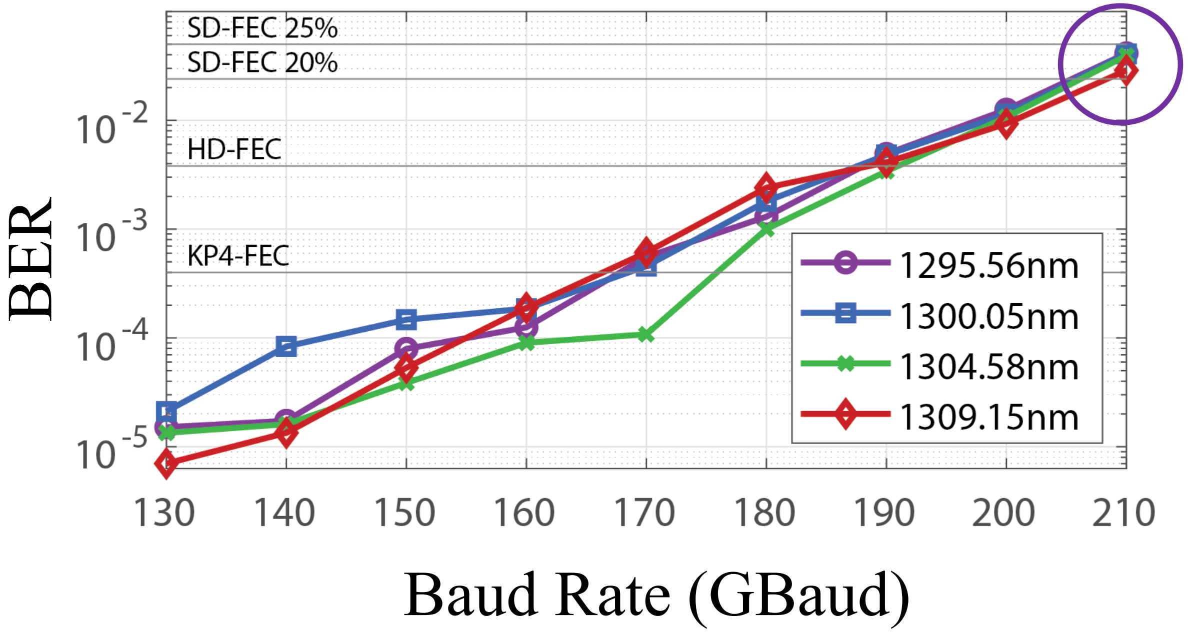
- Net rates:
  - 336 Gbps @ 210 GBaud PAM4 (R)
  - 443 Gbps @ 200 GBaud Probalistically Shaped-PAM8 (G)
  - 456 Gbps @ 190 GBaud PAM8 (P)
- Increases capacity by with increasing PAM order and employing polynomial nonlinear equalizers to mitigate linear and nonlinear impairments

BER vs. Symbol Rate vs. λ @ PAM4

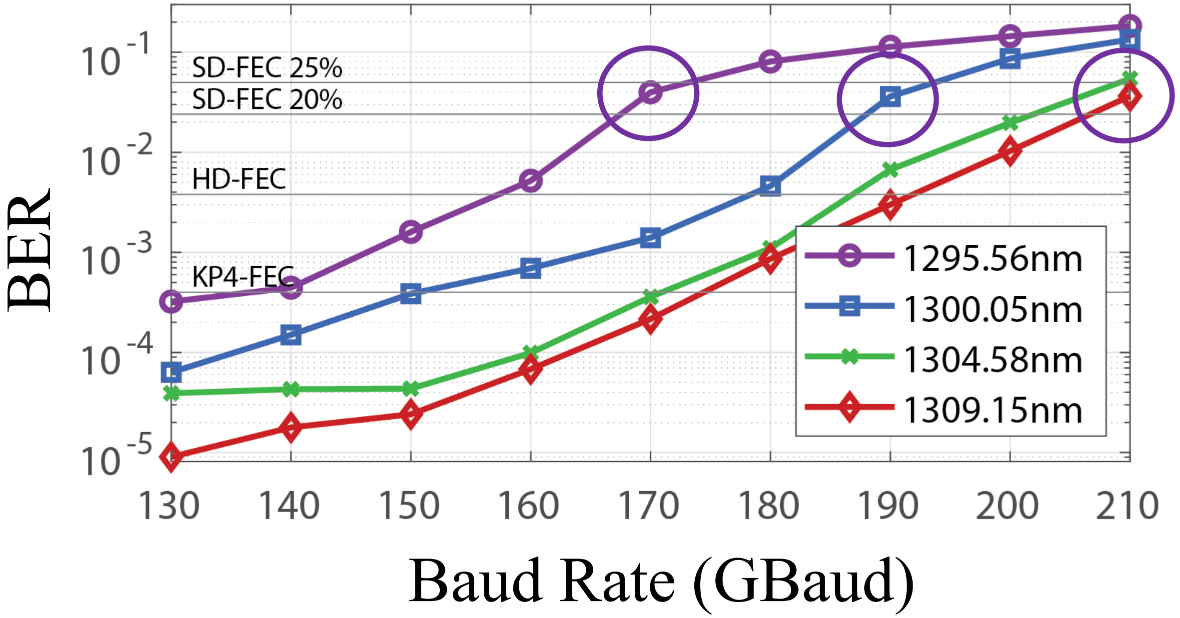
Net 1.33 Tbps:
4 x 336 Gbps/λ
210 GBaud

Net 1.25 Tbps:
272 Gbps @ 1295 nm @ 170 GBaud
304 Gbps @ 1300 nm @ 190 GBaud
336 Gbps/λ for 2 λs @ 210 GBaud

PAM4 | 2 km



PAM4 | 10 km



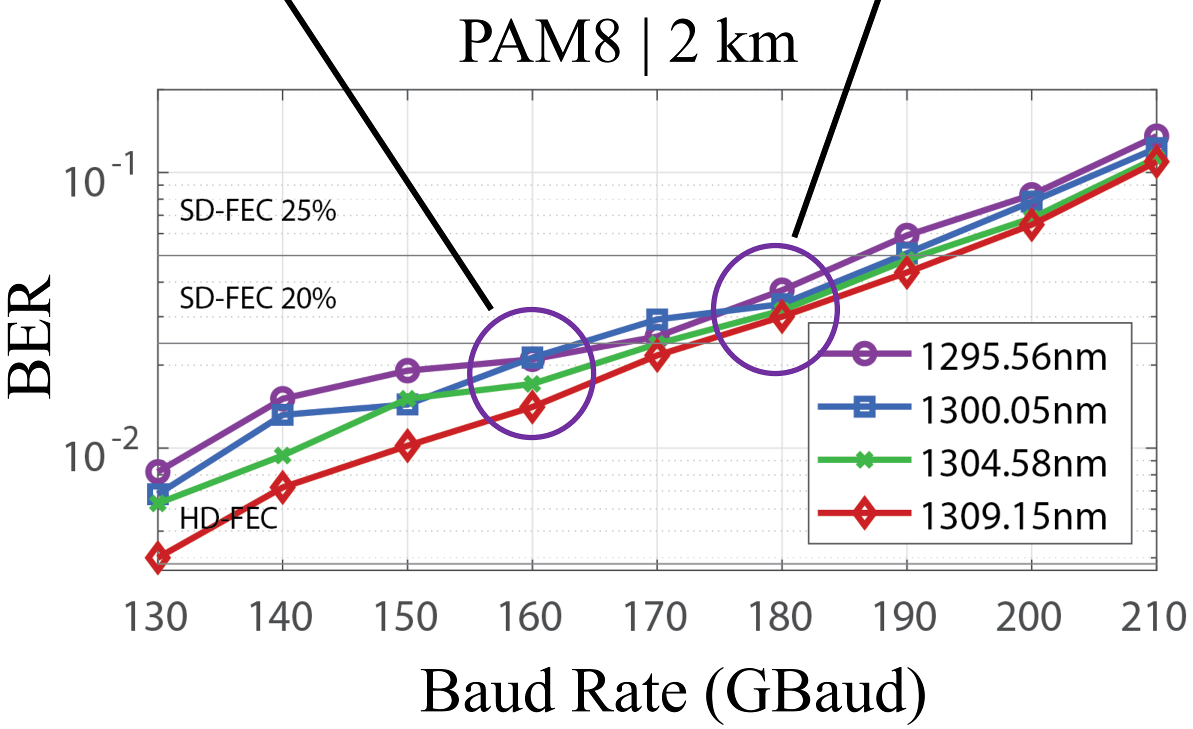
BER vs. Symbol Rate vs. λ @ PAM8

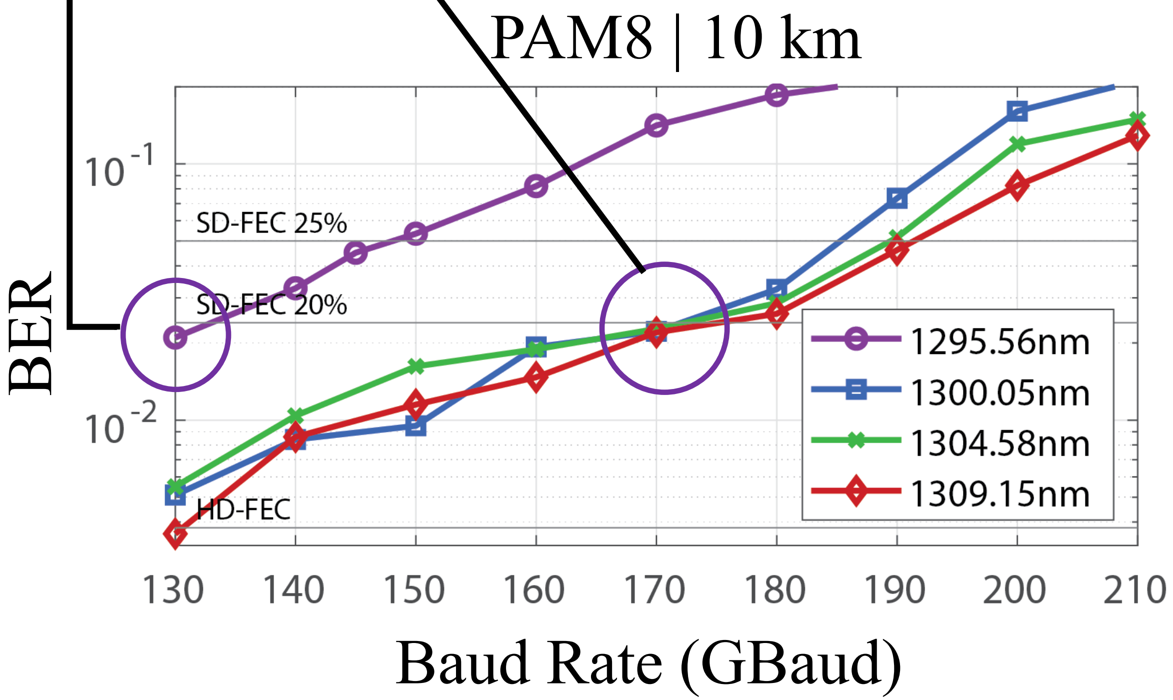
Net 1.6T: 4 x 400G
160 GBaud

Net 1.72T: 4 x 432G
180 GBaud

325 Gbps @ 1295 nm
425 Gbps @ remaining

Net 1.6 Tbps





References

[1] J. Potet et al., "Real-Time DSP-Free 100 Gbit/s/λ PAM-4 Fiber Access Link Using EML and Direct Detection," in IEEE Photonics Technology Letters, vol. 34, no. 17, pp. 895-898, 1 Sept.1, 2022, doi: 10.1109/LPT.2022.3191460.

[2] J. Y. Huh, S.-K. Kang, S.-R. Moon, and J. K. Lee, '106.25-Gbps PAM-4 bidirectional optical sub-assembly module with in-line arrangement of optical and electrical interfaces', Optics Express, vol. 30, no. 2, pp. 1534–1545, 2022.

[3] E. Berikaa et al., "Net 67 Gbps Transmission Over 2 km at Sub 1 Vpp Using Packaged Silicon Photonic MZM," in IEEE Photonics Technology Letters, vol. 34, no. 21, pp. 1139-1142, 1 Nov.1, 2022, doi: 10.1109/LPT.2022.3204186.

[4] Z. Zhang et al., 'Grating-Based Eight-Channel Lan-WDM Silicon Photonic Transceiver for Tb/s Applications', Laser & Photonics Reviews, vol. 19, no. 4, p. 2401249, 2025.

[5] W. Li et al., 'Net 200 Gbps O-band IM/DD transmission over 80 km SMF using InP EML with sub 1-Vpp driving signal and QD-SOA', in ECOC 2024, pp. 55–58.

[6] W. Li et al., "Thin-Film BTO-Based MZMs for Next-Generation IMDD Transceivers Beyond 200 Gbps/λ," in Journal of Lightwave Technology, vol. 42, no. 3, pp. 1143-1150, 1 Feb.1, 2024, doi: 10.1109/JLT.2023.3339472.

[7] E. Berikaa, M. Samiul Alam, and D. V. Plant, 'Silicon photonic modulators for net 300 Gbps/λ IM/DD and Net 1 Tbps/λ coherent transmission using All-Electronic equalization', Optical Fiber Technology, vol. 74, p. 103056, 2022.

[8] E. Berikaa et al., "TFLN MZMs and Next-Gen DACs: Enabling Beyond 400 Gbps IMDD O-Band and C-Band Transmission," in IEEE Photonics Technology Letters, vol. 35, no. 15, pp. 850-853, 1 Aug.1, 2023, doi: 10.1109/LPT.2023.3285881.

[9] Q. Hu et al., "Ultrahigh-Net-Bitrate 363 Gbit/s PAM-8 and 279 Gbit/s Polybinary Optical Transmission Using Plasmonic Mach-Zehnder Modulator," in Journal of Lightwave Technology, vol. 40, no. 10, pp. 3338-3346, 15 May15, 2022, doi: 10.1109/JLT.2022.3172246.

[10] M. Kohli et al., "256 GBd Barium-Titanate-on-SiN Mach-Zehnder Modulator," OFC 2024, San Diego, CA, USA, 2024, pp. 1-3.

[11] H. Asakura et al., "400 Gbps Semi-Cooled Lumped-Electrode EA-DFB Laser Operating At 200 GBaud PAM4 Modulation With 0.6 Vpp," in ECOC 2024, PDP, Th3A.1.

[12] C. St-Arnault et al., "Net 1.6 Tbps (4×400Gbps/λ) O-Band IM/DD Transmission Over 2 km Using Uncooled DFB Lasers on the LAN-WDM grid and Sub-1V Drive TFLN Modulators," OFC 2024, PDP, pp. 1-3.

[13] C. St-Arnault et al., "Net 3.2 Tbps 225 GBaud PAM4 O-Band IM/DD 2 km Transmission Using FR8 and DR8 with a CMOS 3 nm SerDes and TFLN Modulators," OFC 2025, PDP, pp. 1-3.