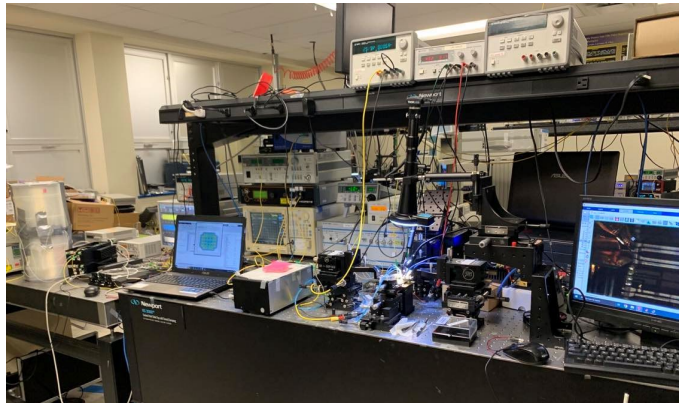
Recent Advances in High Baud Rate IM/DD and Coherent Transmission

The Team

Department of Electrical and Computer Engineering,

McGill University



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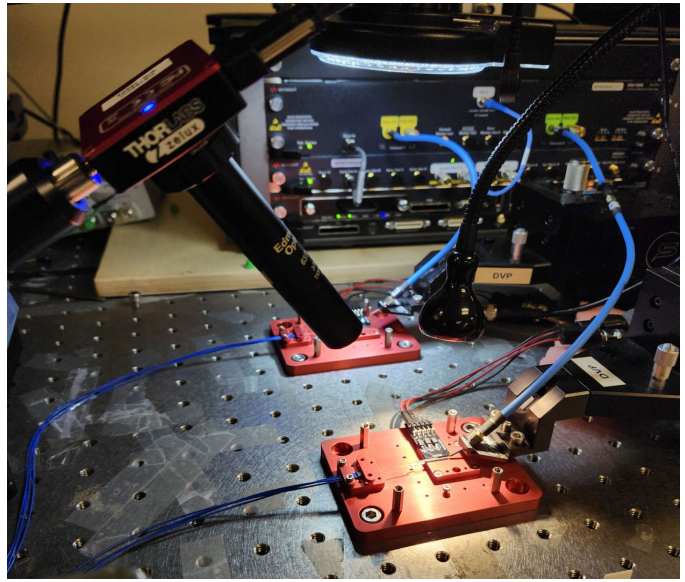
MOPA
September 22, 2024



Optical Fiber Transmission Systems – A Context

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Applications	Reach; Band (nm)	Transmission Systems, Enabling Transceiver Technologies
Data Center Interconnects, Metro, Regional, and Long-Haul Networks	10 – 1000 km	Coherent transmission, w/w_{out} Erbium Doped Fiber Amplifiers, point-to-point/multipoint
5/6G Xhaul, Intra-Data Center Interconnects, Hyperscale Data Center Interconnects	0.5 – 80 km	Direct detection and coherent detection based transmission, no amplification, point-to-point
Enabling Transceiver Technologies	All reaches	Transceiver elements (e.g., electro-optic modulators, photodiodes)

Optical Fiber Transmission Systems – A Thought Experiment

C-Band	O-Band
IM/DD	IM/DD
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Summary of 2022/2023/2024 Experimental Results

McGill

Link Architecture	Modulator Technology	Modulation Format	Reach (km)	FEC OH (%)	Net Bit Rate
IM/DD	EML	120 Gbaud PAM-4	80	20% SD	200 Gbps
IM/DD	TFLN (O-band)	172 Gbaud PS PAM-8	10	20% SD	400 Gbps
IM/DD (DWDM4)	TFLN (O-band)	160 Gbaud PAM8	10	20% SD	1.6 Tbps
Coherent	SiP (C-Band)	105 Gbaud DP-64 QAM	80	25% SD	1.0 Tbps
Coherent	TFLN (O-band)	167 Gbaud DP-64 QAM	10	25% SD	1.6 Tbps
IM/DD (DWDM; 26 λs)	TFLN (O-band with QD MLL comb source)	56 Gbaud PAM4	10	6.7% HD	2.73 Tbps
Coherent (DWDM; 26 λs)	TFLN (O-band with QD MLL comb source)	56 Gbaud DP-32 QAM	10	20% SD	12.14 Tbps

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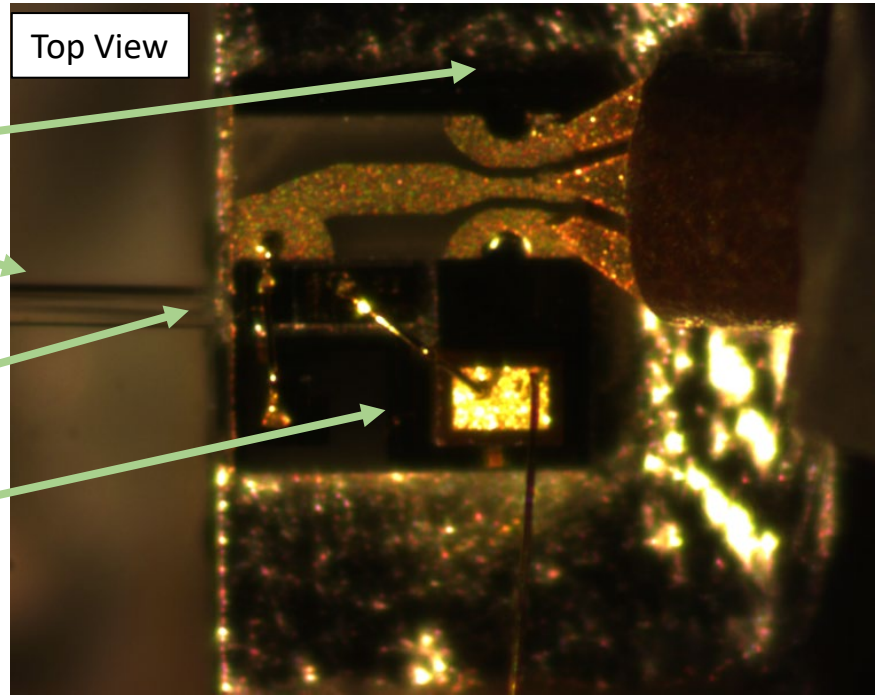
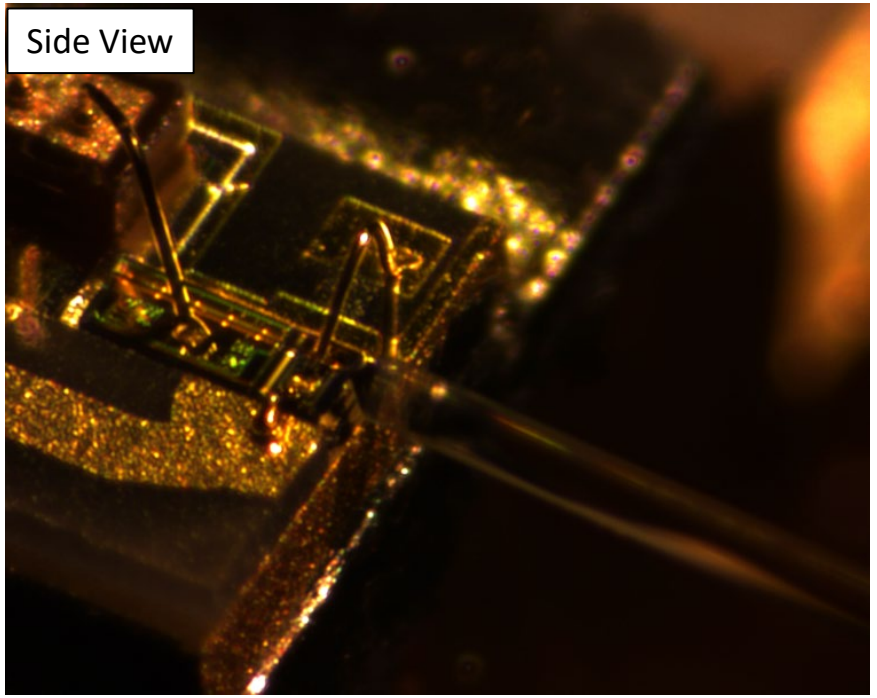
Net 200 Gbps O-band IM/DD transmission over 80 km SMF using InP EML with sub 1-Vpp driving signal and QD-SOA

200G InP EML





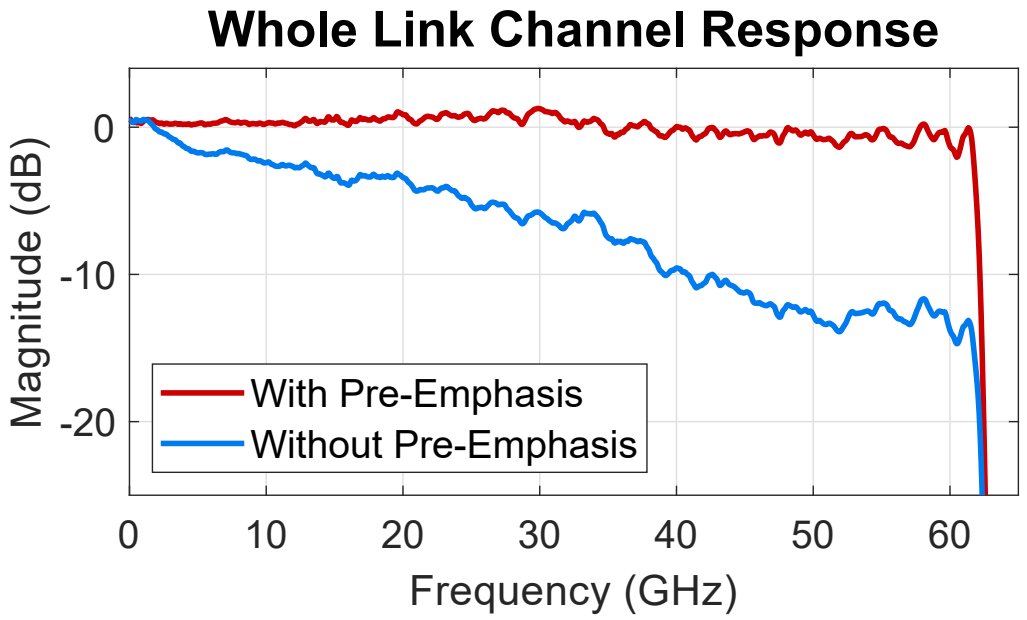
200G InP EML:

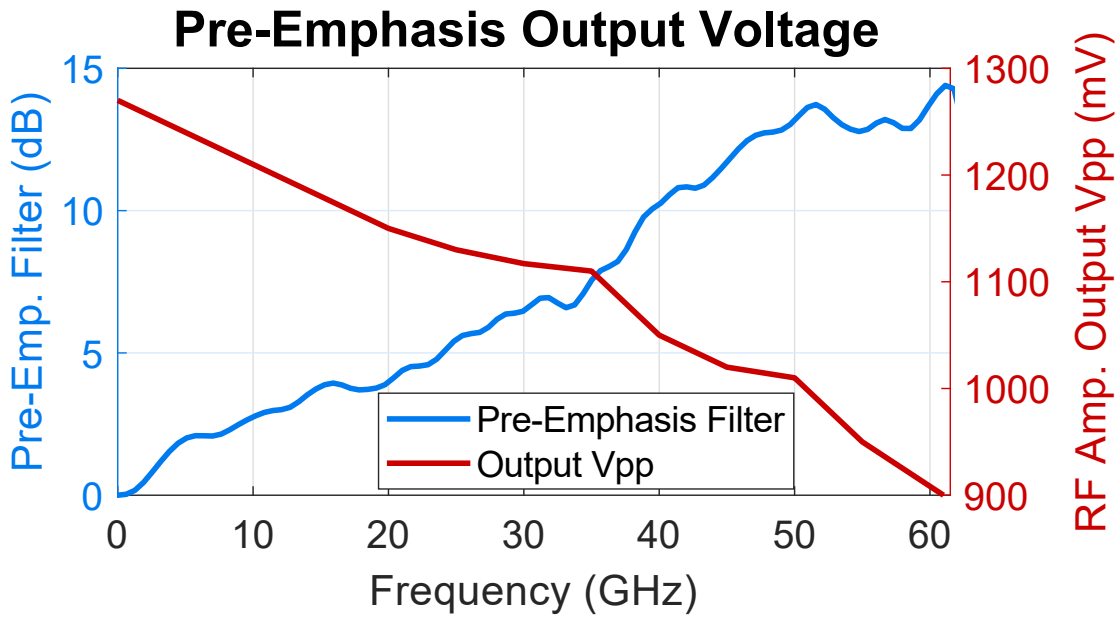
- Distributed feedback (DFB) laser
- Lumped-electrode electro-absorption modulator (EAM)

Low Power Consumption (0.2W):

- Low driving signal: sub 1 Vpp
- Low operating temperature: 55°

Full Link Pre-emphasis





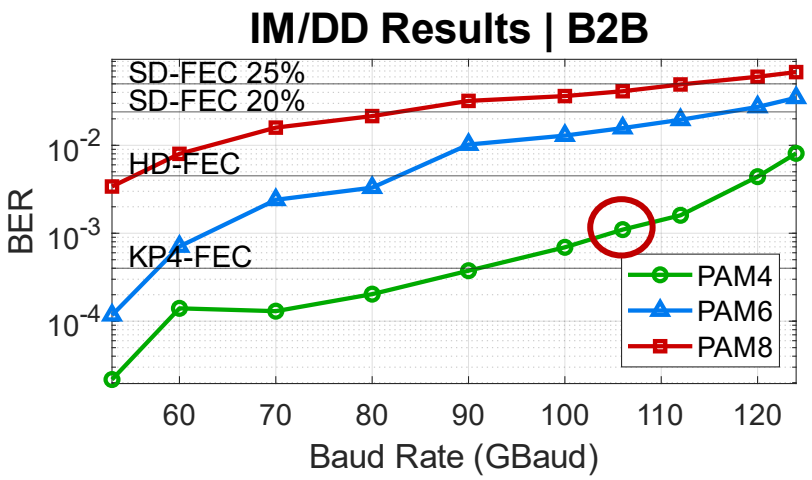
Without Pre-emphasis:

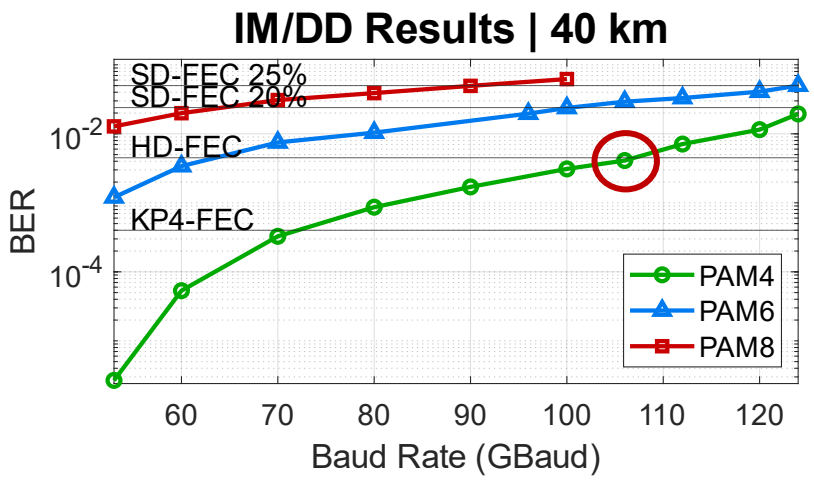
- Relative RF loss: 13. 84 dB
- Output RF swing: 1250 mVpp

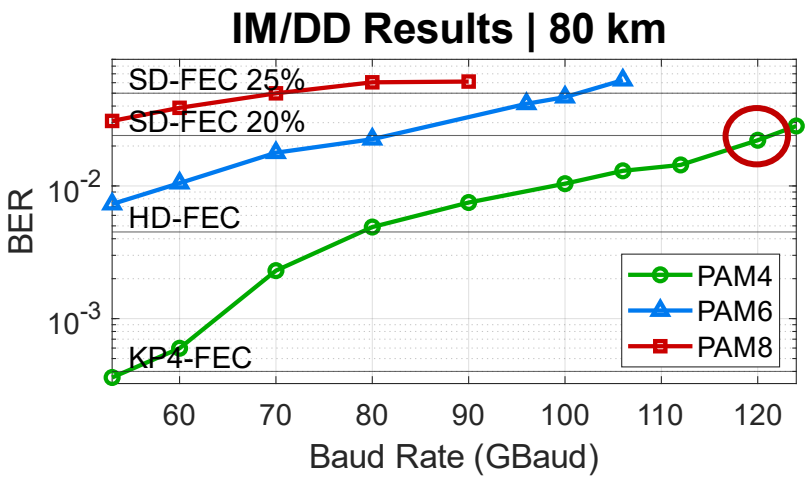
With Pre-emphasis:

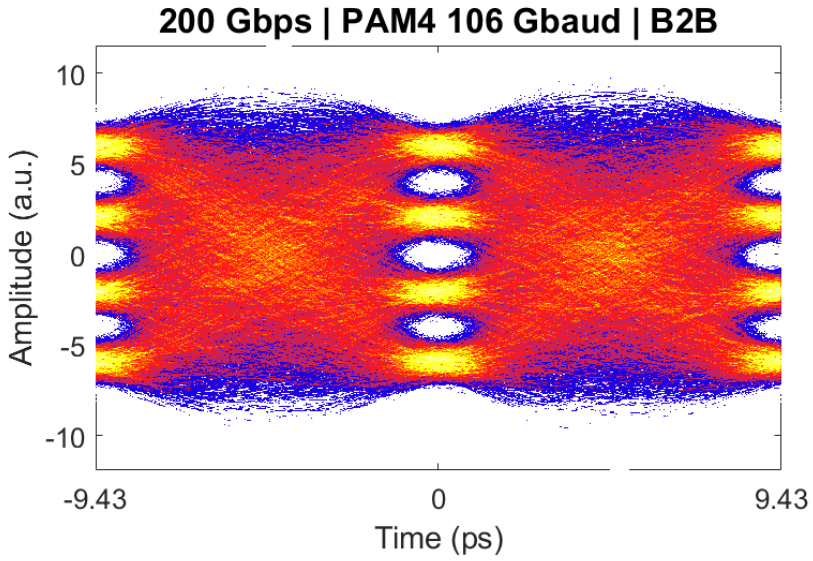
- Relative RF loss: **1 dB**, a flat gain spectrum for the whole bandwidth
- Output RF swing: **950 mVpp**, meeting the low driving swing requirement of the EML

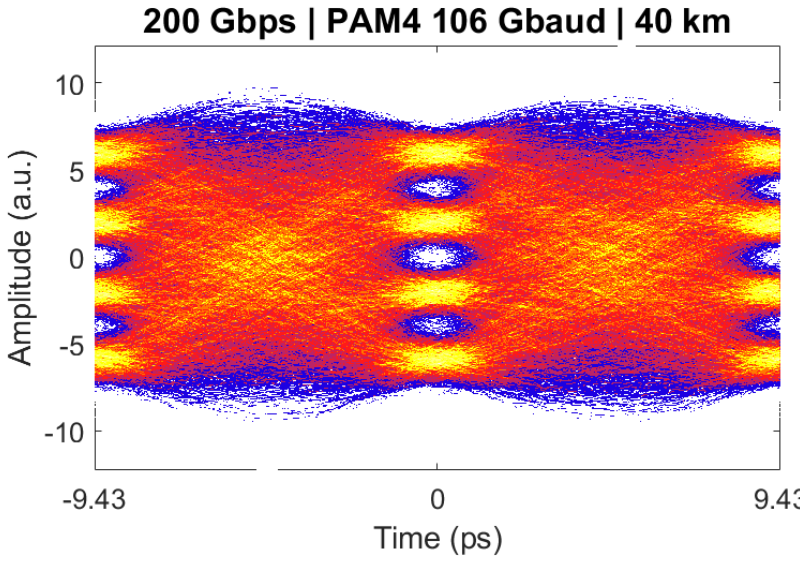
Transmission Results and Eye Diagrams

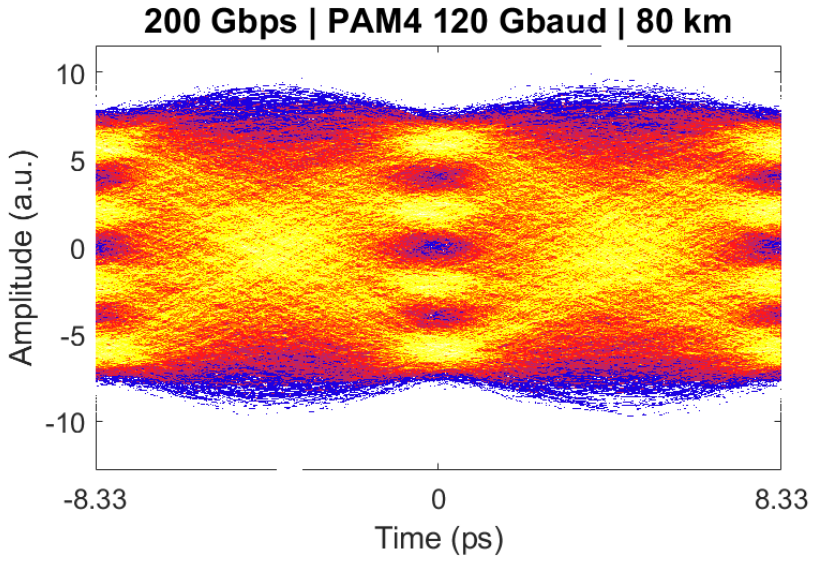








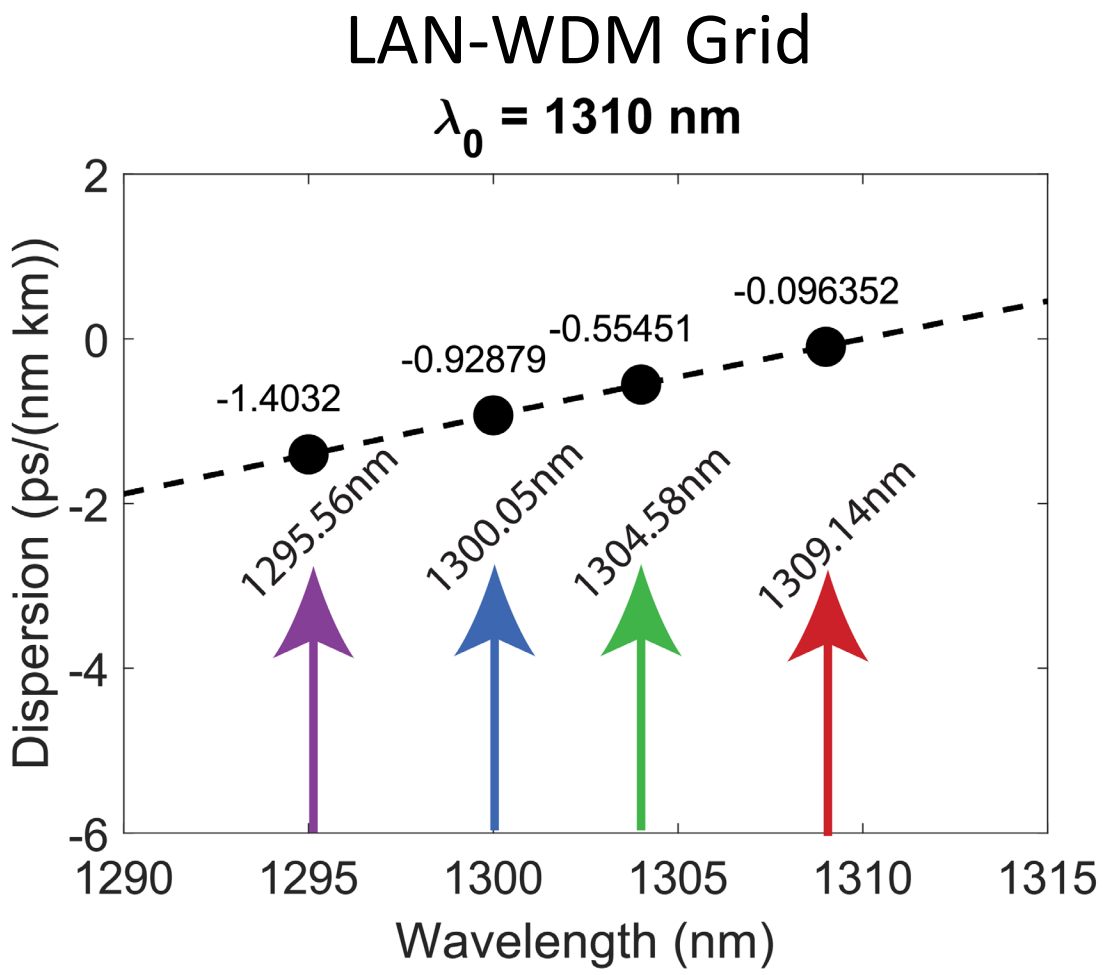




Net 1.6 Tbps (4×400Gbps/λ) O-Band IM/DD Transmission Over 2 km Using Uncooled DFB Lasers on the LAN-WDM grid and Sub-1V Drive TFLN Modulators

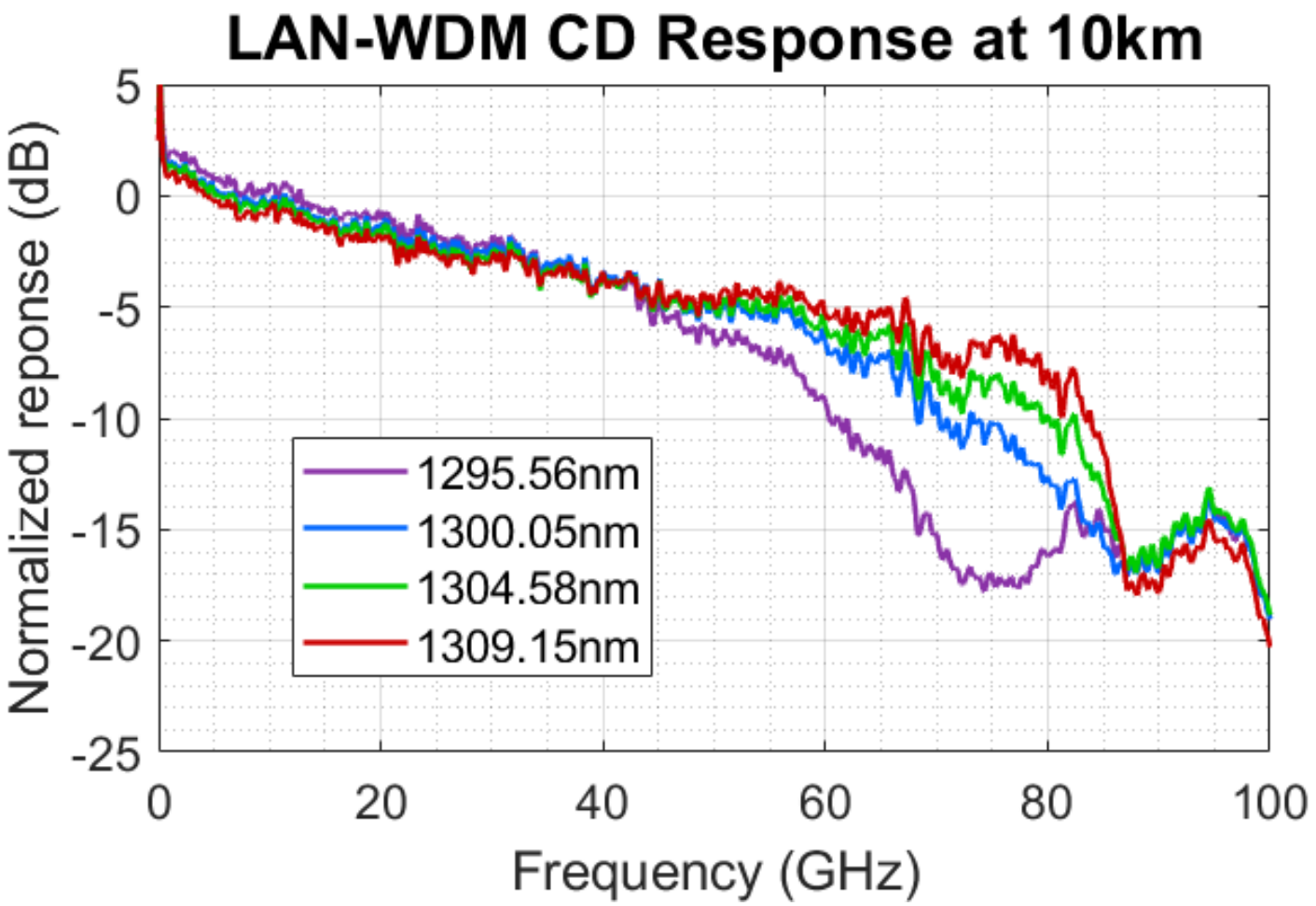
Background and Motivation

- 800GBASE-LR4 Ethernet
  - LAN-WDM grid : 4.5 nm spacing in the O-band
  - 4 x 200 Gbps : 112 Gbaud PAM4
- How to scale this Ethernet Node to 1.6 T
  - Can this grid support the bandwidth increase needed for 1.6 T?
  - Will Chromatic Dispersion limit the reach to 2 km?
  - PAM4 or PAM8?



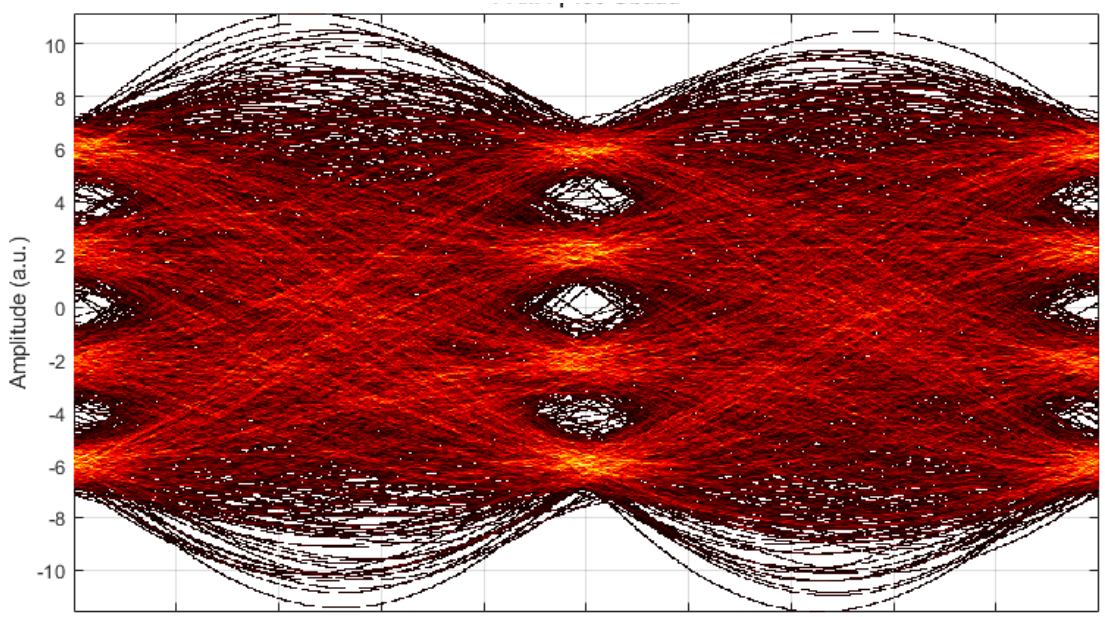
Measured Chromatic Dispersion

- λ_0 = 1310 nm for these experiments
- For 3 wavelengths, PNLE can be used to mitigate some CD
- At 1295.56 nm CD induced power fading is severe, and limits modulation bandwidths to ~ 65 GHz

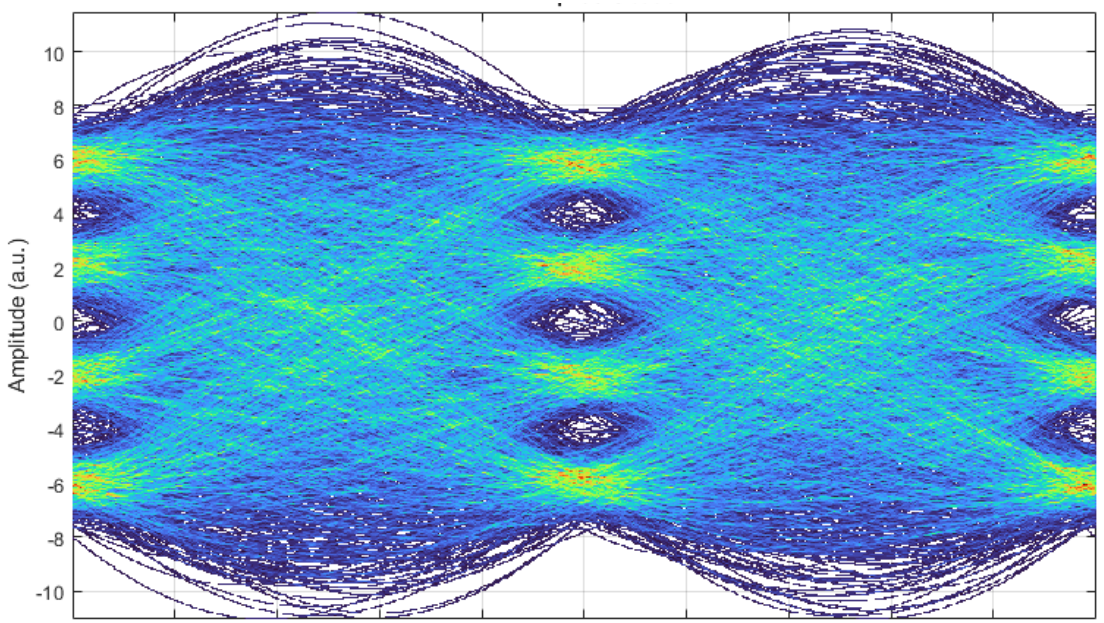


Eye Diagrams

Electrical Eye (from AWG) 190Gbaud PAM4



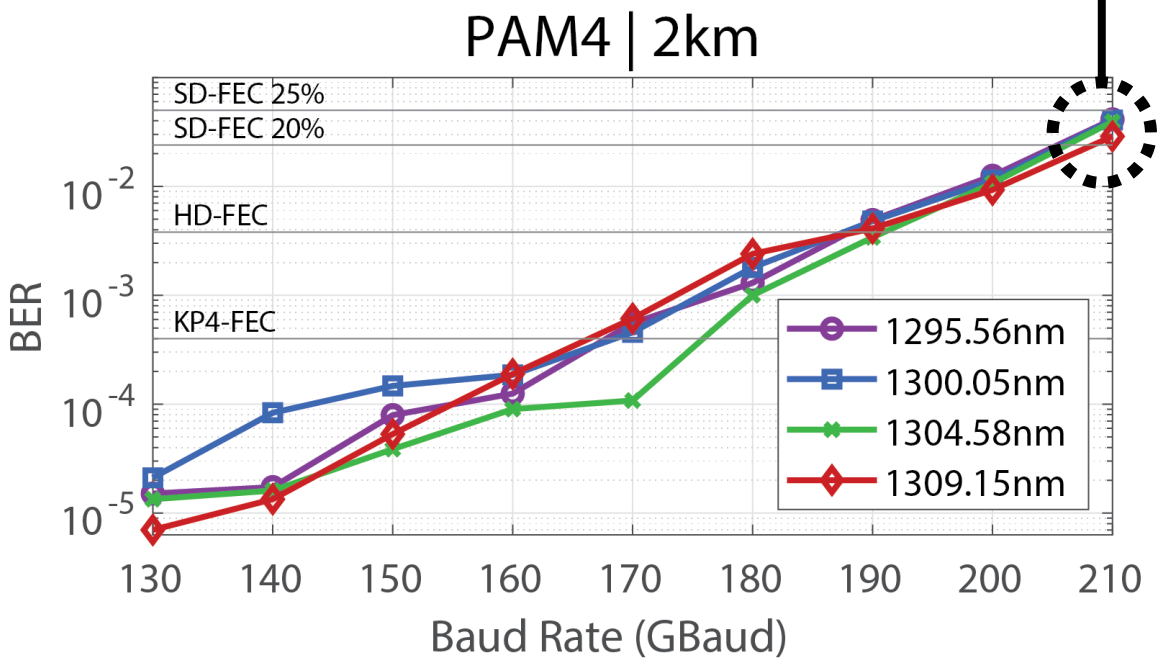
Optical B2B Eye 190Gbaud PAM4

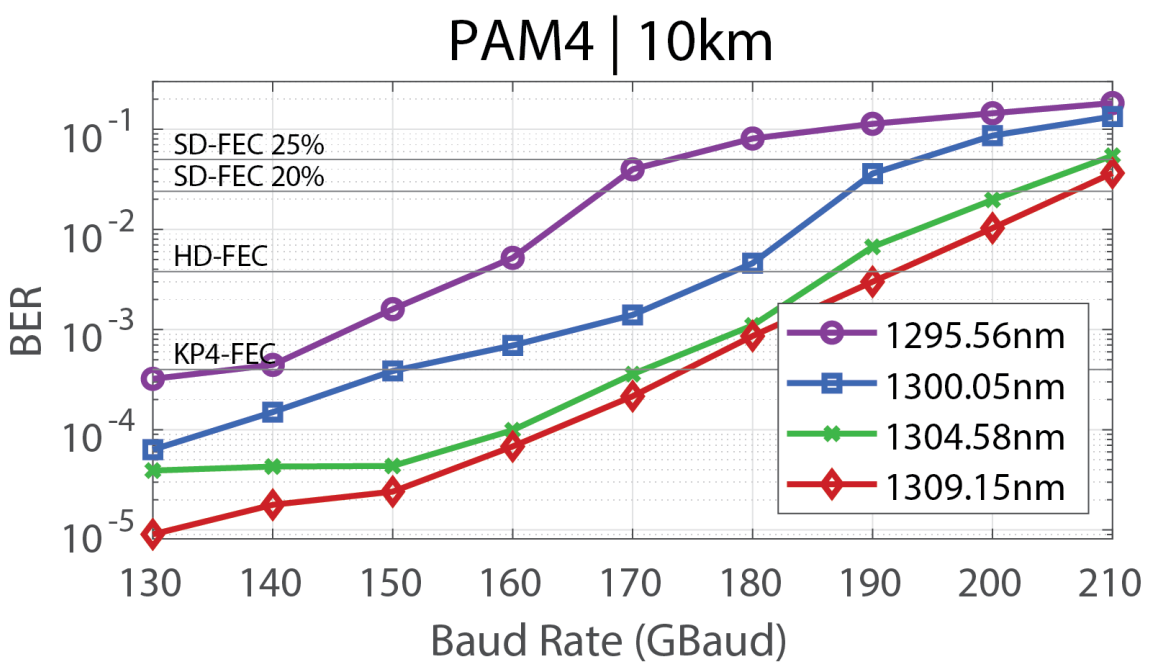


PAM Results

Net 1.33 Tbps
(4 x 336 Gbps/λ)
210 Gbaud PAM4

At 1295.56 nm CD severely limits the baud rate at 10km





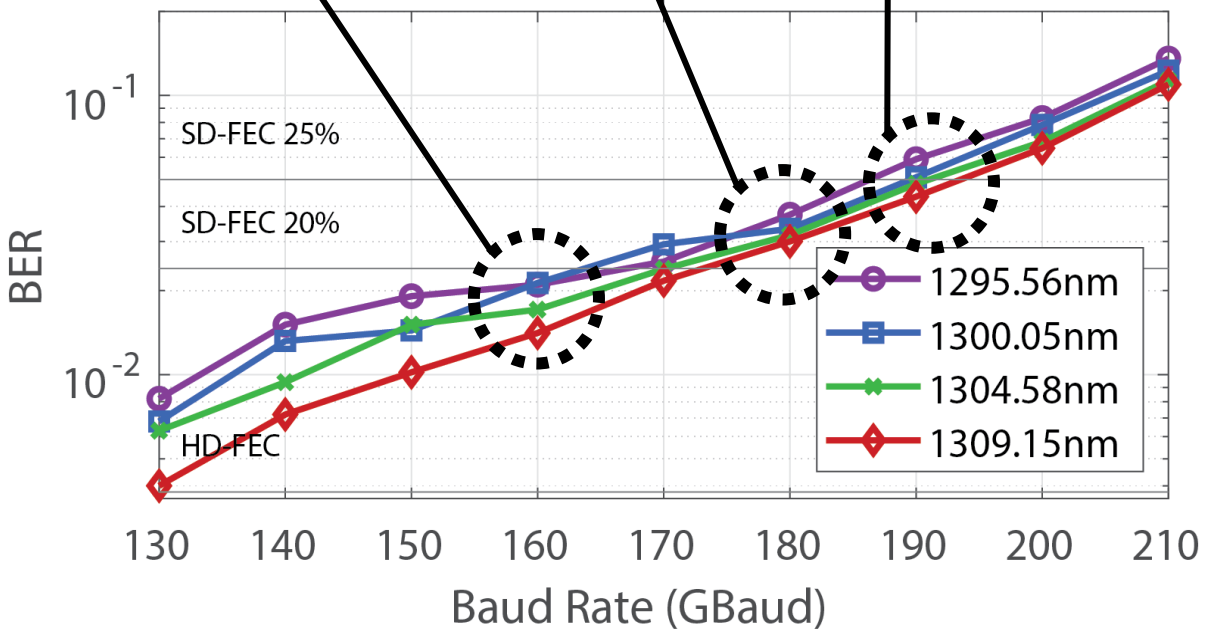
PAM8 Results

Net 1.72T (4 x 432G)
180 Gbaud PAM8

456Gbps @ 1304
and 1309 nm

Net 1.6T (4 x 400G)
160 Gbaud PAM8

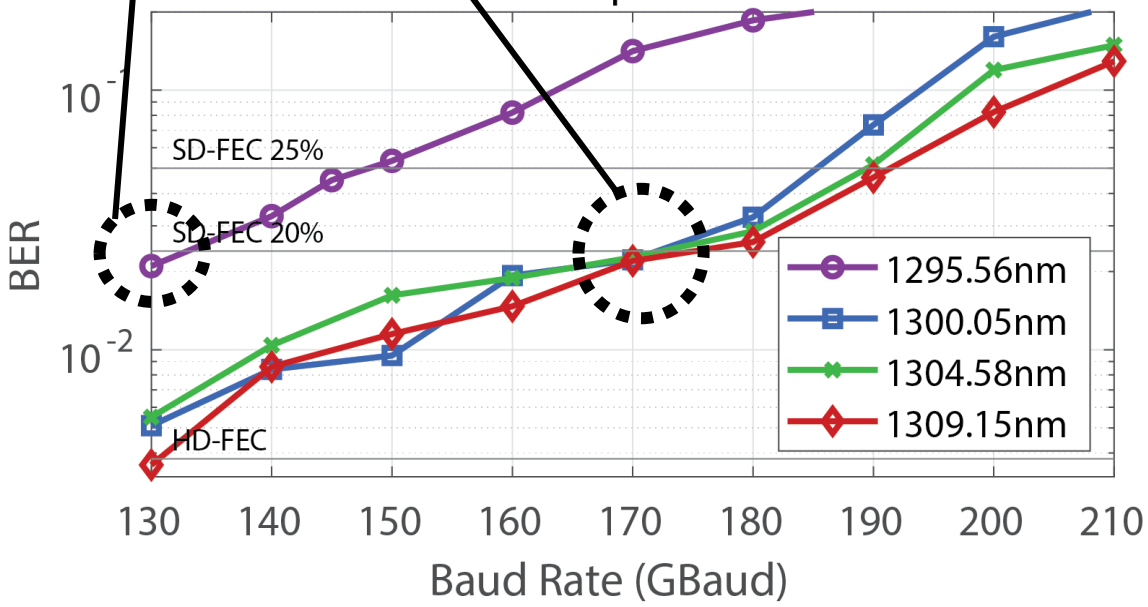
PAM8 | 2km



325 Gbps @ 1295 nm
425 Gbps @ remaining

} Net 1.6 Tbps

PAM8 | 10km



Net 12.4 Tbps O-band Coherent Transmission over 10 km Using a TFLN IQMs and Comb Lasers for Carrier and LO

Data Center Interconnects Using Comb Lasers: 2 – 10 KM

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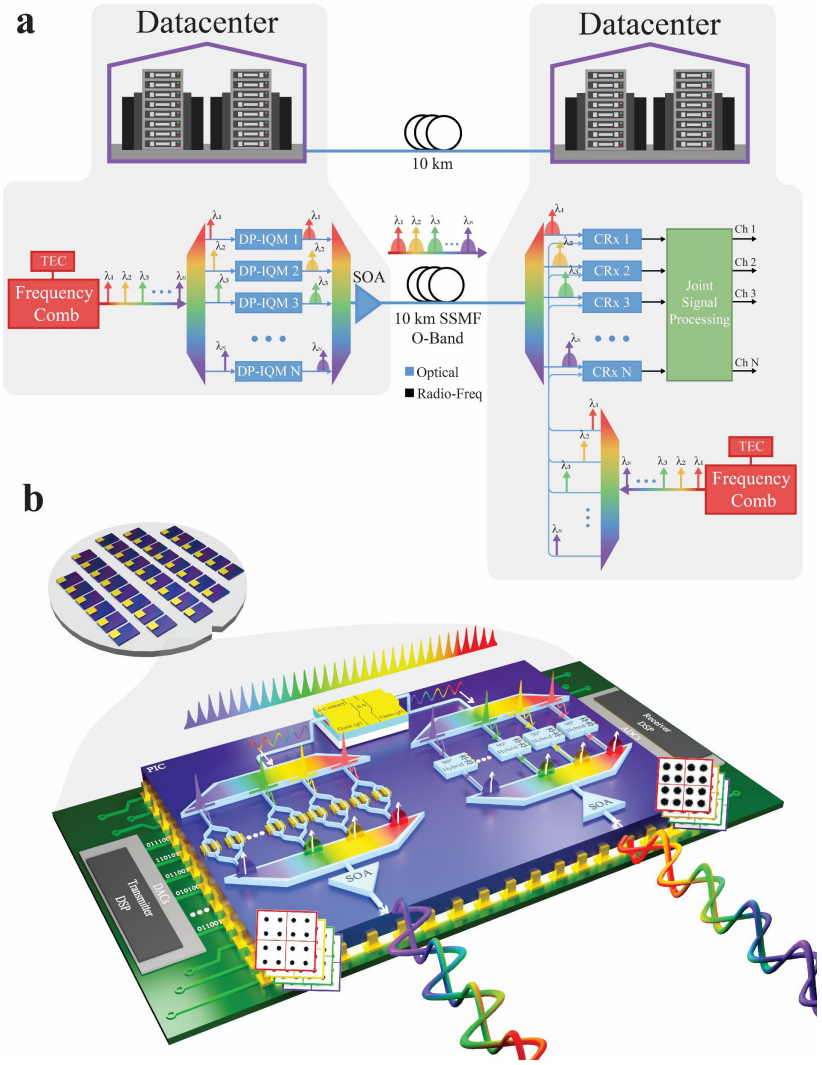
IMDD: *Dense* wavelength division multiplexing *using comb sources*

- This solution relaxes the requirements on laser tuning to just one TEC controller and laser driver
- Optical amplification needed due to comb power
- Requires very precise and stable optical Mux/demux process
- More prone to fiber non-linearities (FWM)

Coherent: *Dense* wavelength division multiplexing *using comb sources*

- This solution relaxes the requirements on laser tuning to just one TEC controller and laser driver
- Coherent detection relaxes requirements on optical Mux/Demux process
- DSP can tolerate ±1 GHz of frequency offset
- More tolerant to four-wave mixing (FWM)
- Optical amplification needed due to comb power splitting over channels
- More complexity



Quantim-Dot-Mode Locked Lasers (QD-MLL)

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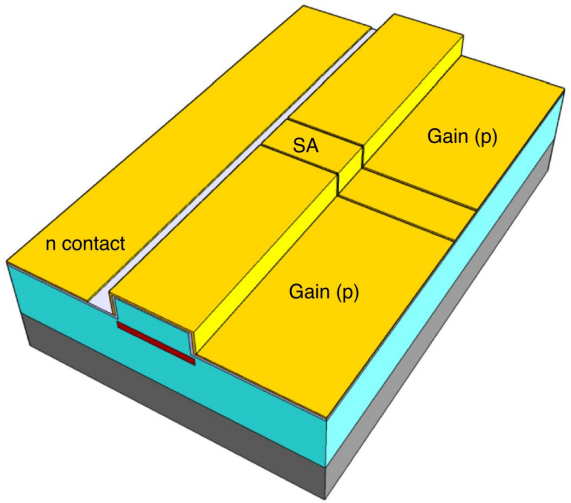
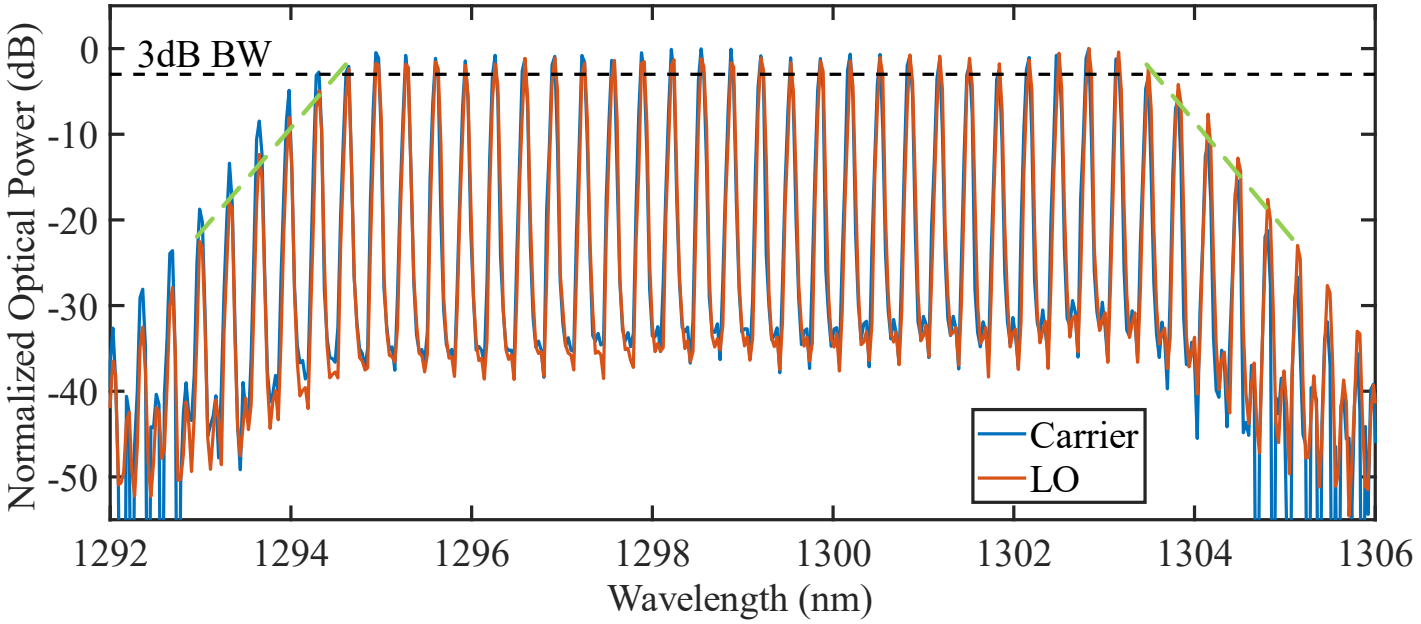
- ❑ InAs/GaAs QD lasers with 60 GHz spacing in the O-band → - No chromatic dispersion compensation - Relaxes laser linewidth requirements
- ❑ Single saturation absorber (SA) with cavity length: 1.35 mm
  - Comb spacing: 58.311 GHz
  - Number of lines within 3dB: 19
  - Max power/line: -3 dBm
  - Linewidth: ~10 KHz
  - Central wavelength: 1300 nm
  - Rate of side mode suppression: 12.5 dB/nm



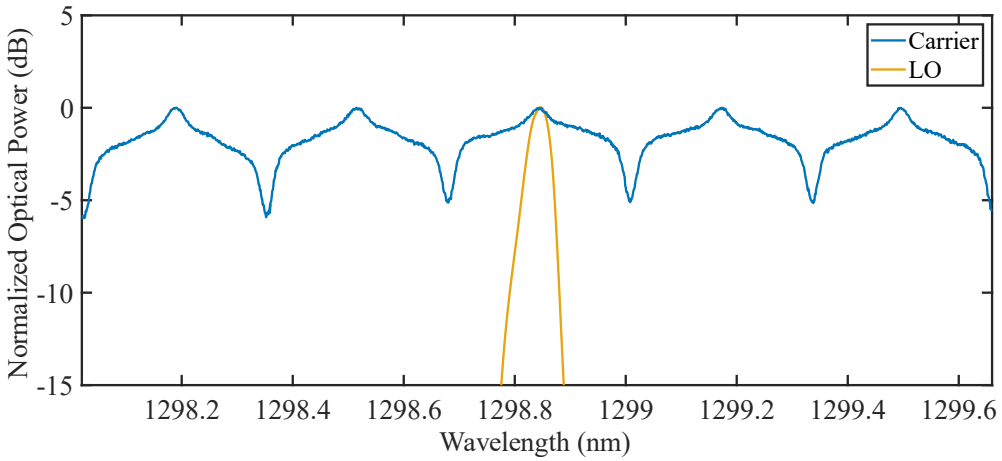


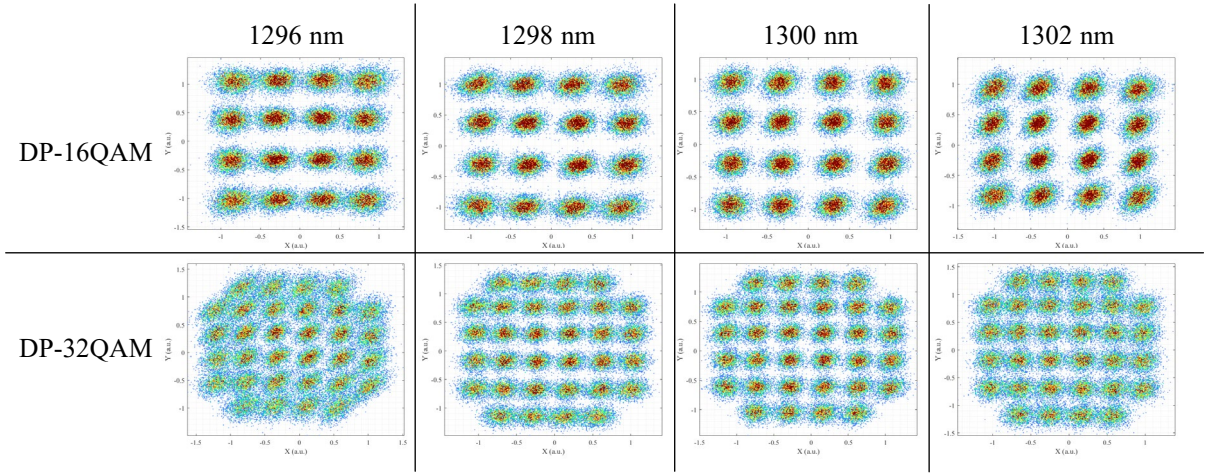
Transmission with 2 QD-MLL - Carrier and LO

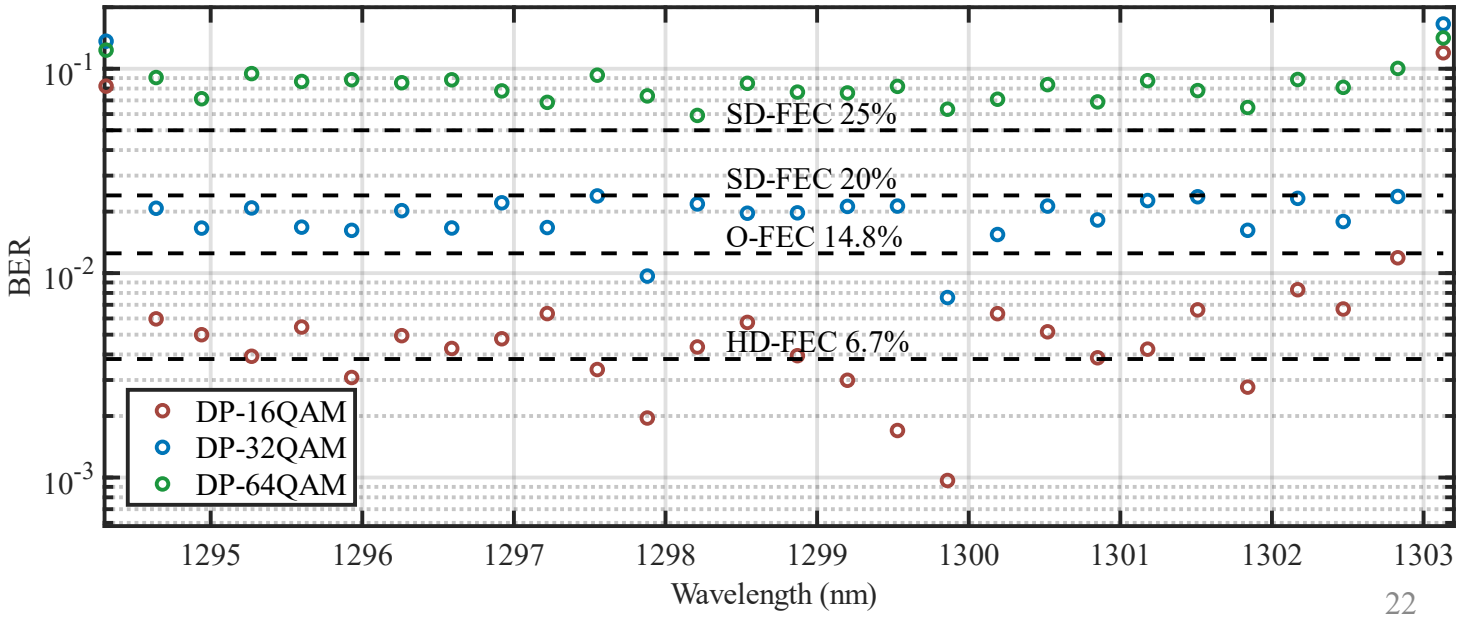
- O-band, 56 Gbaud, 10 km
- 26 λs using a sliding window of 5

❑Total net transmitted after FEC:

- DP-16QAM: 10.18 Tbps under 14.8% SD-FEC
- DP-32QAM: 12.14 Tbps under 20% SD-FEC







Conclusions and Where to Next

- What are the benefits of higher rates per lane vs. wavelength multiplexing vs. spatial multiplexing?
  - Higher rates are appropriate
  - Comb lasers may play a significant role in the deployment of IM/DD and coherent systems.
- What are the DSP challenges, and the electrical/optical component requirements?
  - DSP power consumption to be reduced, modulator drive voltages should become CMOS compatible, and modulator bandwidths need to increase.
- Direct-detection vs. coherent: when will the price levels meet?
  - Do believe that coherent will become a cost effective and power consumption effective solution for optical interconnect applications. Operating wavelength will be a topic of significant debate.