Chromatic Dispersion Constraints on 400G/lane PAM4 PMDs

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July 11, 2026

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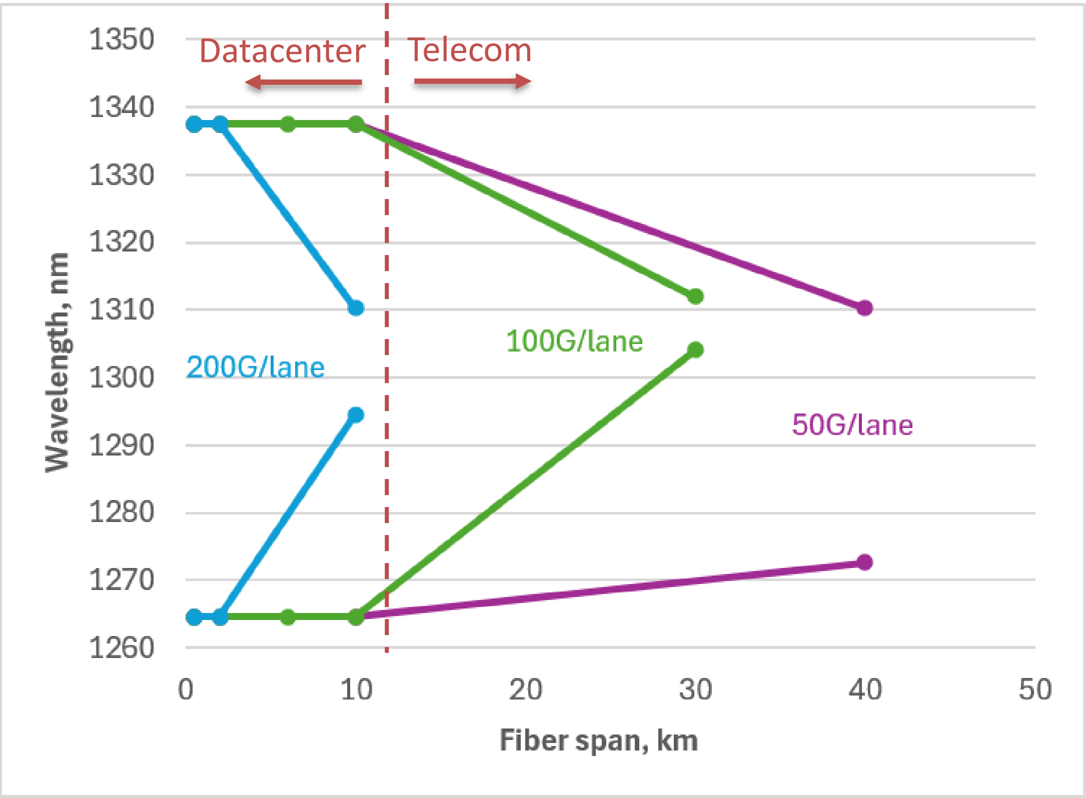
Shrinking O-band

- Single mode fiber (SMF) was *designed* and optimized for long-haul telecom, but O-band around the zero-dispersion wavelength has long been *exploited* for datacom applications using low-cost, uncooled IM-DD optics at massive scale.
- SMF operation in O-band has been highly successful for many datacenter generations but has begun to feel the pinch with 200G/lane optics.
- Statistical analysis of chromatic dispersion (CD) was added to ITU-T G.652 (08/2024) to avoid building in excessive margin for CD penalty into 200G/lane optical PMDs being developed by IEEE 802.3dj.
- Starting with the 400G/lane generation, the CD limitations of standard SMF start to impose severe restrictions for intra-datacenter reaches using uncooled optics.
- This presentation will document the dwindling CD-limited wavelength range in O-band and discuss opportunities for the fiber industry to help further the success of uncooled 400G per lane optics in the datacenter.

Evolution of Ethernet PAM4 PMDs

- For hyperscale datacenters, fiber reaches up to 10km are needed.
- For 50G/lane and 100G/lane, uncooled CWDM has been specified up to 10km reach.
  - 200GBASE-LR4 used conservative LAN-WDM but could have used CWDM based on 400G-LR4-10.
  - 400GBASE-LR4-6 limited CWDM to 6km, but 400G-LR4-10 extended the reach to 10km.
- For 200G/lane, uncooled CWDM has only been specified up to 2km reach.
  - 800GBASE-FR4 uses uncooled CWDM with inner FEC over 2 km, but some feel RS FEC is sufficient.
  - 800GBASE-LR4 must use LAN-WDM wavelengths and inner FEC to manage the chromatic dispersion.
  - Many concerns about four-wave mixing (FWM) had to be addressed to use LAN-WDM wavelengths around the zero-dispersion wavelength.

Wavelength range for PAM4 PMDs



Transmission simulation setup

Host RS FEC is assumed for both 200G and 400G
- Symbol rate = 106.25 and 212.5 GBaud
- “Pre-FEC” BER = 2.4e-4

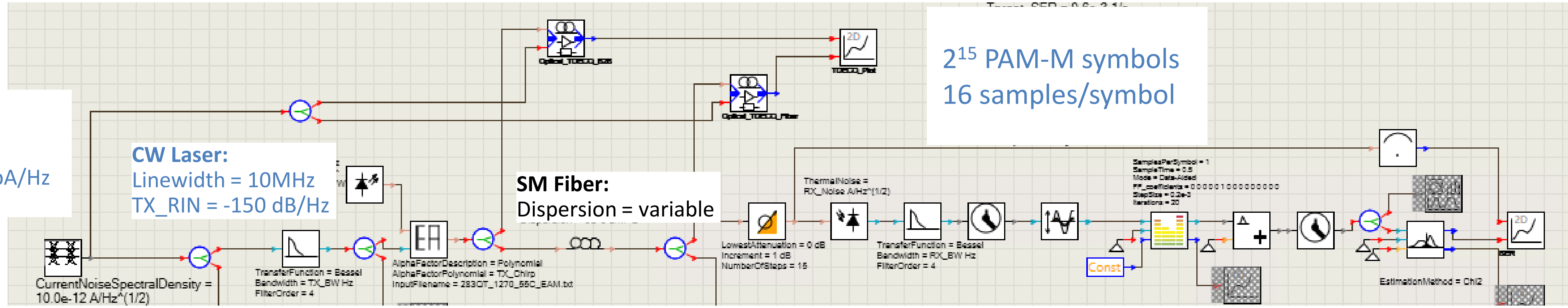
TECQ/TDECQ
B/2 BT4 with 15 tap FFE
Target SER = 4.8e-4

2^{15} PAM-M symbols
16 samples/symbol

PAM-M coder:
PRBS23
Rise time = 0.1 UI
Current noise = 10pA/Hz
TX_Jrms = 0.035 UI

CW Laser:
Linewidth = 10MHz
TX_RIN = -150 dB/Hz

SM Fiber:
Dispersion = variable



TX Lowpass Filter:
4^{th} order Bessel
TX_BW = 65 or 110GHz

EA Modulator:
Chirp = 0 or 0.5

PIN Receiver:
Thermal noise = 25pA/Hz
BT4 lowpass filter
RX_BW = 65 or 110GHz
Ideal clock recovery

FFE:
Taps = 15 (5 pre)

Linear RX:
Chi^2 estimation

For each condition, the minimum and maximum CD for 1dB BER penalty is calculated.
See johnson_E4AI_01a_250227 for discussion of 400G PAM4 vs PAM6.

Simulation results – CD limits

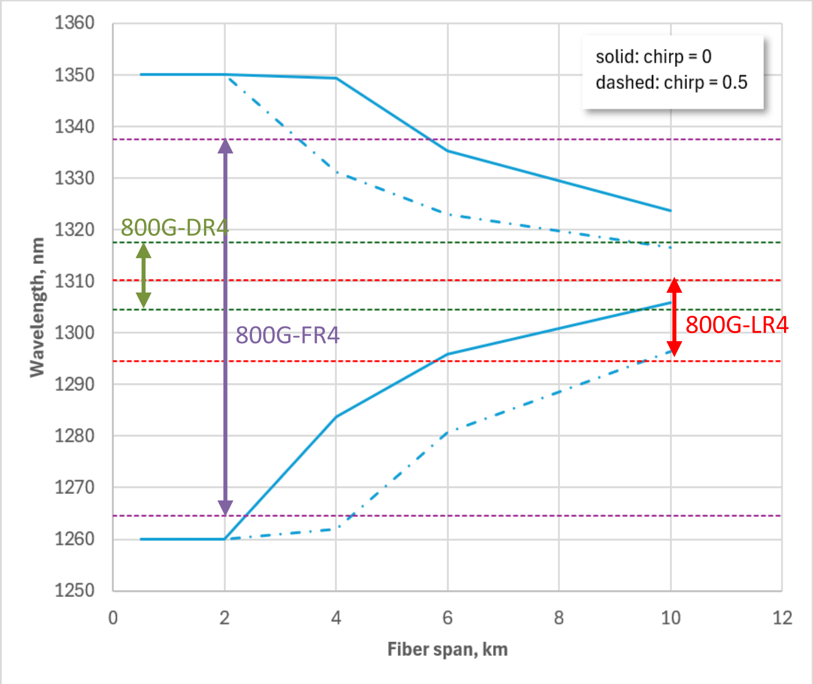
- The usable CD range shrinks by 4x between 200G and 400G/lane PAM4.
- The ranges for chirp=0 (MZM) and chirp=0.5 (EAM) are offset.
- If both technologies are to be supported, the usable range is the intersection of the two.

PAM4 Symbol Rate (GBd)	TX Chirp	Min CD (ps/nm)	Max CD (ps/nm)
106.25	0.5	-22.8	8.1
	0	-14.0	14.2
	0~0.5	-14.0	8.1
212.5	0.5	-6.1	2.0
	0	-3.5	3.5
	0~0.5	-3.5	2.0

- ITU-T G.652 Appendix-I statistical analysis of CD is used to estimate the wavelengths limits associated with the CD limits for a given fiber span.
- The confidence limit Q = 10^{-3} is assumed, representing fiber widely available from multiple vendors.
- Fiber spans up to 2 km are assumed to be a single cable segment (M=1).
- Spans from 4 km to 10 km are assumed to be four cable segments (M=4).

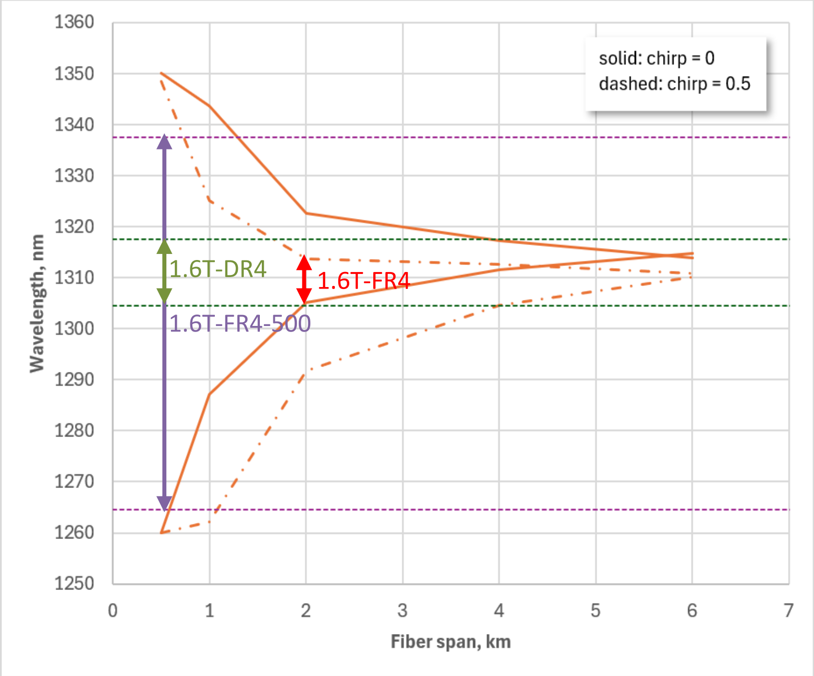
Usable wavelength range

106.25 GBd PAM4



- 800G-FR4 can use uncooled CWDM lasers over 2km.
- 800G-LR4 uses LAN-WDM wavelengths optimized for EML transmitters.

212.5 GBd PAM4



- Uncooled CWDM lasers are supported up to 500m.
- Usable wavelength range at 2km is very narrow
  - Usable range = 17.5/21.9/8.6 nm for MZM/EML/Both
  - Single channel uncooled operation is marginal
  - Lasers for FR4 and BiDi must be cooled.
- Longer links require coherent transmission.

Improving standard SMF for 400G PAM4

- Low-cost uncooled lasers for 2 km intra-datacenter links are key for economic feasibility.
  - Uncooled CW lasers are a critical element of low-cost silicon photonics transmitters.
  - A 13 nm window is needed for uncooled 1.6T-DR4-2 to be supported (1311 ± 6.5 nm)
- Tighter specifications on SMF could help to achieve a 13 nm usable window.
  - Increasing Q from 10^{-3} to 10^{-2} increases the usable range from 8.6 nm to 12.1 nm.
  - Additional fiber specs, receiver design and/or FEC will enable a usable 13 nm window.
- Uncooled CWDM is not possible over 2 km, but additional usable wavelength range helps to maximize the channel spacing for 1.6T-FR4 optics.
  - Narrow channel spacing increases cost and mux/demux loss and enhances FWM.
  - Four channels with 800 GHz spacing require a wavelength range of at least 18.3 nm.
  - A combination of fiber specs with $Q > 10^{-2}$, along with receiver and FEC improvements, will be needed to increase the usable wavelength range from 13 nm to >18.3 nm for 1.6T-FR4.

Other fiber and cable limitations

- Polarization mode dispersion (PMD)
  - Differential group delay (DGD) relative to the bit period doubles going from 200G to 400G.
  - Trends to higher fiber density in datacenters could further increase PMD: higher array counts, smaller diameters, smaller bend radius, multi-core fiber, etc.
  - 800G-FR4 allocates 0.2dB for DGD penalty. For same fiber PMD, 1.6T-FR4 penalty will be ~0.5dB higher.
  - SMF DGD specs must be cut in half to keep the 400G power budget from growing.*
- Four wave mixing (FWM)
  - Tight WDM channels in the narrow window around zero dispersion increase the magnitude of FWM.
  - Increasing the CD-limited wavelength range would allow wider channel spacing and grid placement away from the zero-dispersion wavelength.
- Multipath interference (MPI)
  - MPI does not depend on bit rate but does depend on extinction ratio (ER).
  - 400G drivers and modulators may give lower ER than 200G, which would increase MPI penalty.
  - Simulations show ER(min) of 3 dB increases MPI penalty by > 0.1dB over ER(min) of 3.5 dB.

* ferretti_3dj_optx_01b_240829

Hollow-core fiber (HCF) for 400G PAM4

- HCF has more design degrees of freedom than SMF, potentially creating fibers specifically tailored for 400G PAM4 datacenter applications.
  - Ultra-low CD (< ±1 ps/nm·km) over a wide wavelength range is the key enabler for uncooled CWDM links over 2km.
  - Insertion loss is not a major concern for short-reach datacenter links.
  - Low nonlinearity and low latency are useful and come naturally with HCF.
- This can only be achieved if HCF is designed specifically for datacenters.
  - Current HCF research is focused on long-haul telecom applications (Again!).
  - Unlike long-haul optimized SMF, HCF optimized for long-haul may not serve datacenter needs.
- Broad industry buy-in will be needed to make HFC designed for IM-DD a reality for future 400G+ datacenters.

Summary

- The reach of uncooled CWDM transmission in O-band has been shrinking with each datacenter generation.
- At 400G/lane, long-established low-cost uncooled optical interfaces will no longer work over 2 km of standard SMF.
  - Tighter CD specs ($Q > 10^{-2}$) are needed to enable uncooled single wavelength PMDs.
  - Further CD spec tightening and advanced receiver designs would be needed to enable 1.6T-FR4 on an 800 GHz grid.
  - Tighter PMD specs are needed to prevent increasing DGD penalties at 400G.
- HCF has promise to break out of the shrinking CD box, but it will require broad industry consensus and investment to develop a fiber specifically for IM-DD hyperscale datacenter applications at 400G and beyond.

IEEE 802

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