Evolution of Optical Interfaces for Data Centers

SPRC 2013 Annual Symposium

Stanford Photonics Research Center

Stanford, California

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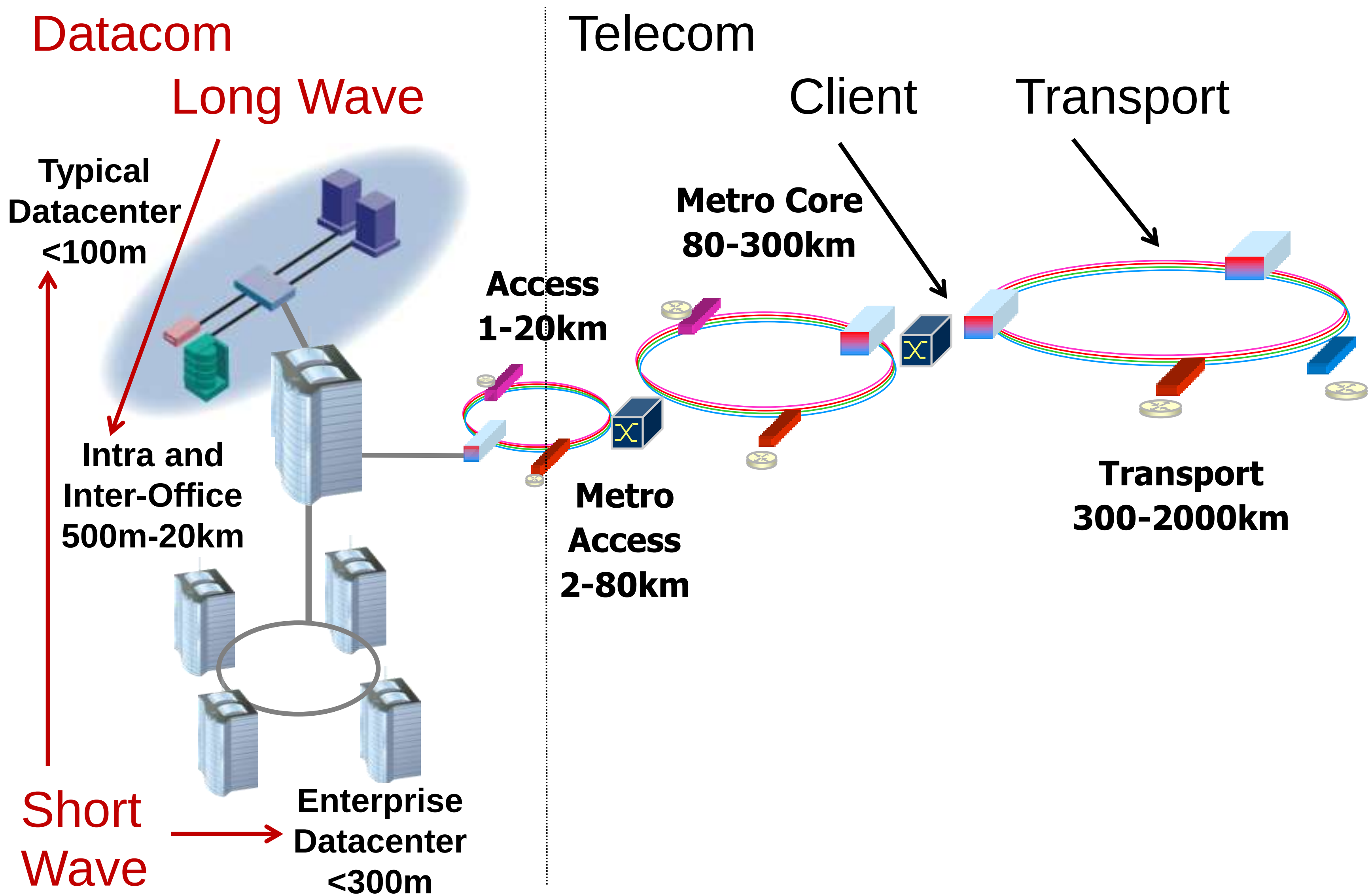
Outline

- Optics Categories
- Non-optics Communication: Voiceband & Wireline
- 1Gb/s Datacom Optics
- 10Gb/s Datacom Optics
- Optics Limits
- 40Gb/s Datacom Optics
- 100Gb/s Datacom Optics
- Advanced Optics Technologies
- 400Gb/s & Beyond Datacom Optics

Fiber Optic Communication (Optics) Types



Long Wave (LW) Datacom Optics

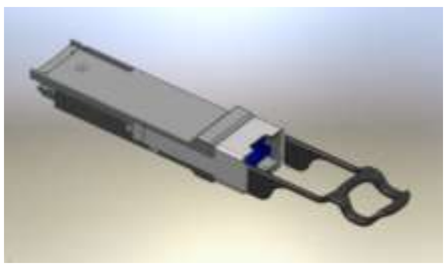
- Single Mode Fiber (SMF) point to point interconnect
- 1310nm Distributed Feedback (DFB) Laser (dominant)
- 1310nm InP and Silicon (SiP) Modulator (emerging)
- 500m, 2km, 10km, 20km inter-rack, data-center, campus, short metro links
- Ethernet (IEEE) primary standards
- FibreChannel (storage) other standards
- High volume (100ks to 1Ms / year)
- Client Telecom Optics similar except ITU-T primary standards

Short Wave (SW) Datacom Optics

- Multi Mode Fiber (MMF) point to point interconnect
- 850nm Vertical Cavity Surface Emitting Laser (VCSEL)
- 10m, 30m, 100m, 300m, intra-rack, inter-rack, data-center links
- Ethernet (IEEE) primary standards
- FibreChannel (storage) other standards
- High volume (100ks to 1Ms / year)

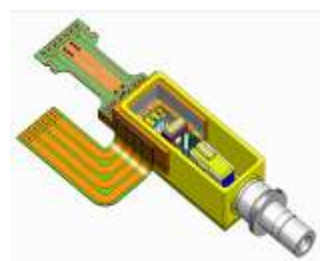
Optics Hierarchy


Systems:
routers / switch
chassis and boxes

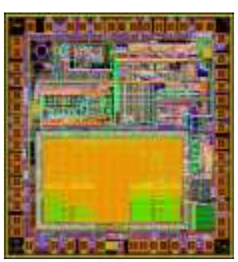


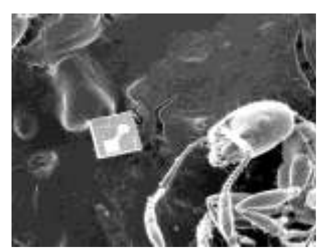

Sub-systems:
pluggable transceiver
modules





Components:
optical
sub-assemblies





Devices:
ICs, lasers,
photo-detectors

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Voiceband (Wire) Datacom Example

ITU standard	V.22 (1980)	V.32 (1984)
bits/sec	1200	9600
Baud	600	2400
bits/symbol	2 (4 state QPSK)	4 (16 state QAM)
channels	1 (duplex wire pair)	1 (duplex wire pair)
DSP	none	Echo cancellation, adaptive equalization, forward error correction (FEC)

Wireline Datacom Example

IEEE standard	100BASE-TX (1995)	1000BASE-T (1999)
Mbits/sec	100	1000
MBaud	125	125
bits/symbol	1 (3 state PAM)	~2 (5 state PAM)
channels	1 (2 simplex wire pairs)	4 (bi-directional wire pairs)
DSP	4B/5B encoding	Echo cancellation, trellis coding across all channels

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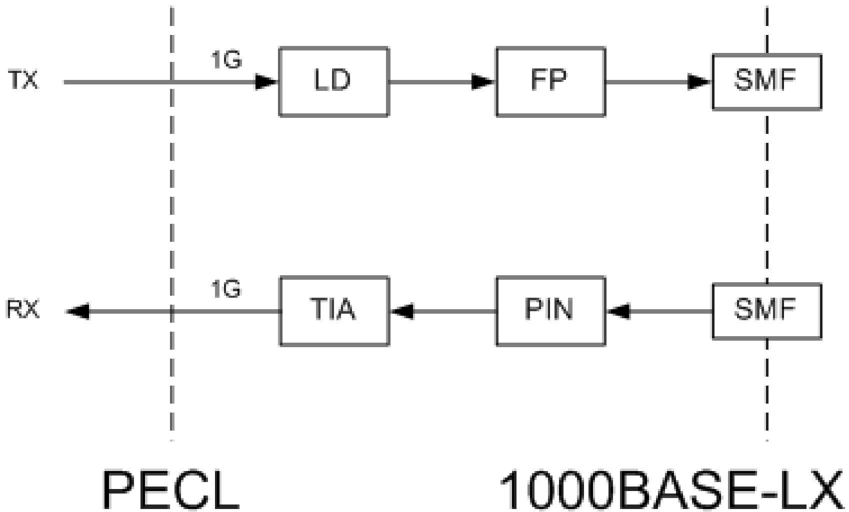
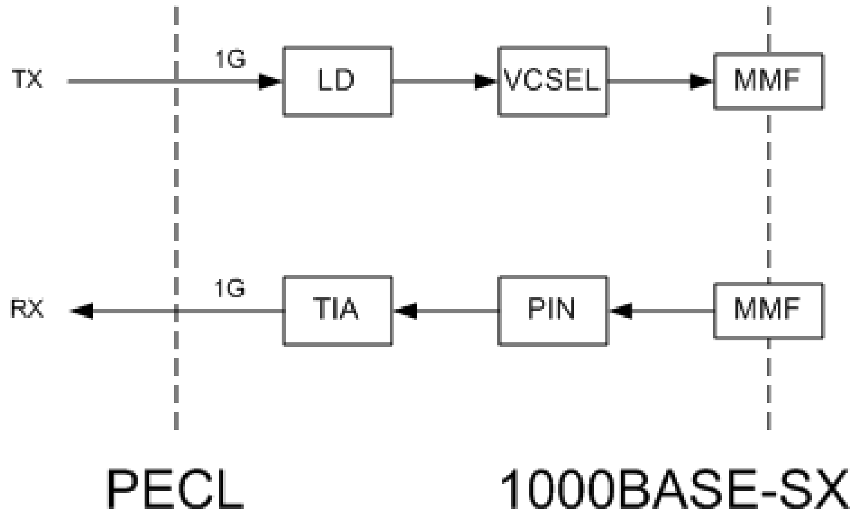
1Gb/s LX SMF 1310nm NRZ GBIC



Electric I/O		Optical I/O		
pin pair	Gb/s	fiber pair	λ	Gb/s
1	1	1	1	1
1		1		

IEEE standard: 1998

1Gb/s SX MMF 850nm NRZ GBIC

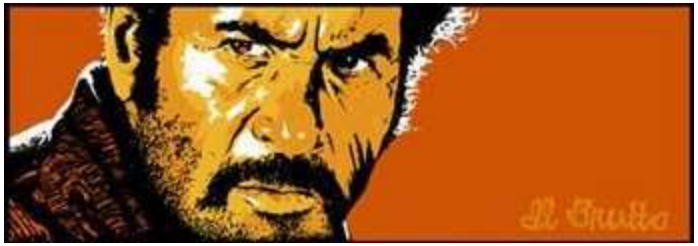


Electric I/O		Optical I/O		
pin pair	Gb/s	fiber pair	λ	Gb/s
1	1	1	1	1
1		1		

IEEE standard: 1998

Why Pluggable Optics Modules?

- The good (il buono)
  - multiple applications supported
  - pay as you go
  - confined, replaceable failures
  - common market
  - specialized R&D & production
- The bad (il cattivo)
  - increased component count
  - SI complicated by I/O connector
  - power increased by I/O ICs
  - placement limited to the front
- The ugly (il brutto)
  - poor thermal interface
  - heat localized at host front



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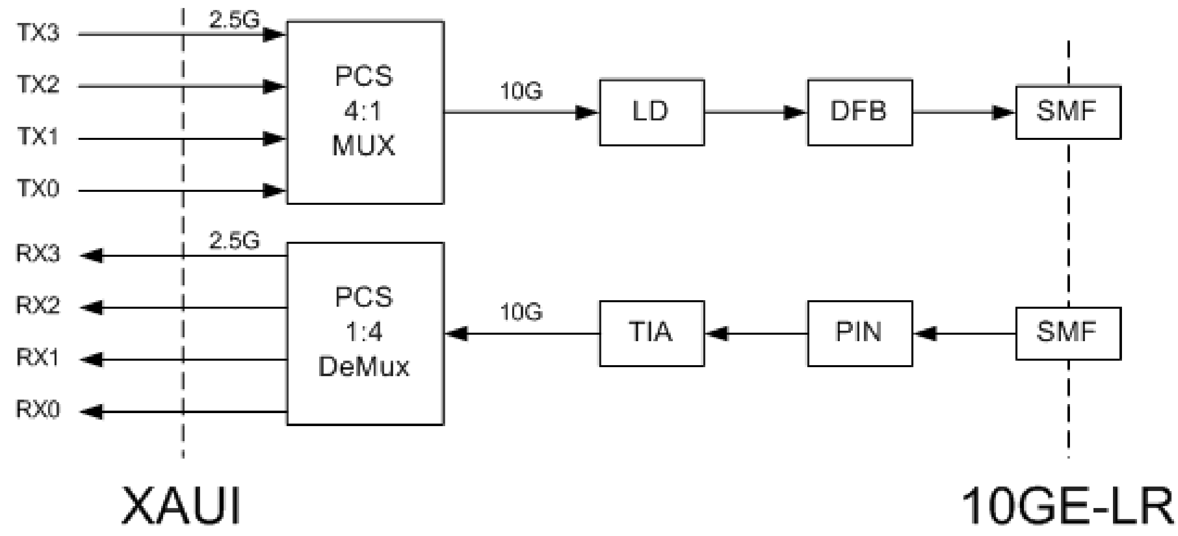
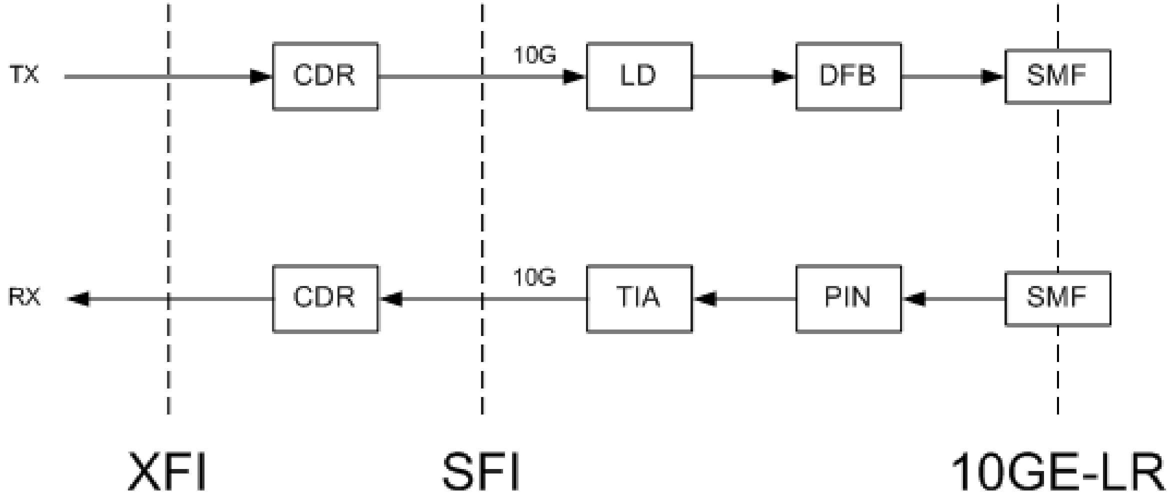
First 10Gb/s LR SMF 1310nm NRZ XENPAK



Electric I/O		Optical I/O		
pin pair	Gb/s	fiber pair	λ	Gb/s
	2.5	1	1	
4				10
10		10		

IEEE standard: 2002

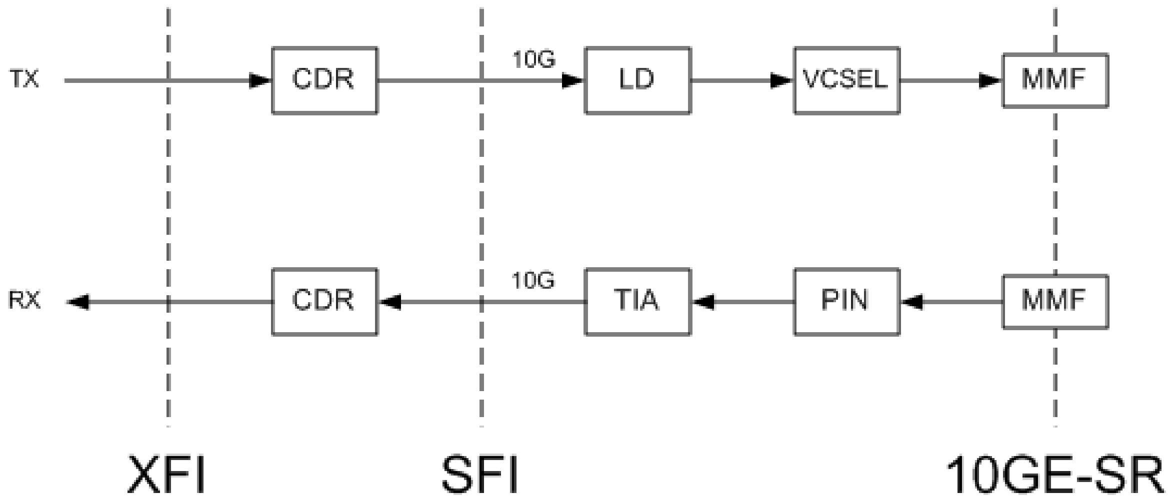
10Gb/s LR SMF 1310nm NRZ SFP+



Electric I/O		Optical I/O		
pin pair	Gb/s	fiber pair	λ	Gb/s
1		1	1	
	10			10
10		10		

IEEE standard: 2002

10Gb/s SR MMF 850nm NRZ SFP+



Electric I/O		Optical I/O		
pin pair	Gb/s	fiber pair	λ	Gb/s
1		1	1	
	10			10
10		10		

IEEE standard: 2002

Why are Optics so Simple vs. Wire Interfaces?

- Possible reasons:
  - Optics engineers are lazy and/or stupid
  - Fiber channel is far below Nyquist and Shannon limits
- Voice band channel: BW = ~4kHz
- Shielded twisted wire pair channel: BW = ~100MHz/50m
- SMF channel:
  - 1310nm window ~100nm wide → BW = ~15THz:
    Nyquist limit = ~ 30TBaud
  - 1310nm window Mitra & Stark capacity limit:
    Shannon limit = ~100Tbps
- IC and Laser devices limit Datacom Optical Com.

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Baud Limit of Bipolar (SiGe) Circuits

Max Baud ≈ fT/10

- Bipolar IC process figure of merit:
  fT = unity magnitude short circuit current gain
- Reference: Paul Gray & Robert Meyer, "Analysis and Design of Analog Integrated Circuits", ©1977
- Why fT/10?
- All optics IC communication building blocks require gain
- 10x gain at baud gives efficient, low power circuits
- 3x gain is difficult; requires cascading gain stages
- 1x gain is not usable

Baud Limit Examples of Bipolar (SiGe) Circuits

2002 – 2004 (Gen1 10G in design)

- fT ≈ 110GHz (mainstream 250nm production process)
- 10GHz ≈ fT/10
- 10Gbaud SiGe ICs feasible

2008 – 2010 (Gen1 100G in design)

- fT ≈ 220GHz (mainstream 130nm production process)
- 25GHz ≈ fT/10
- 25Gbaud SiGe ICs feasible

Baud Limit of CMOS Circuits

<u>Max Baud ≈ fT/10</u>

- CMOS IC process figure of merit:

  fT = unity magnitude short circuit current gain

  [fMax (unity magnitude power gain) is better but not general]
- Reference: Thomas Lee, “The Design of CMOS Radio-Frequency Integrated Circuits”, ©1998
- Why fT/10?
- Same as for SiGe Circuits
- All optics IC communication building blocks require gain
- 10x gain at baud gives efficient, low power circuits
- 3x gain is not usable; low CMOS g_m makes cascading gain stages impractical

Baud Limit Examples of CMOS Circuits

2004 – 2006 (Gen2 10G in design)

- fT ≈ 120GHz (mainstream 90nm production process)
- 10GHz < fT/10
- 10Gbaud CMOS ICs feasible

2010 – today (Gen2 100G in design)

- fT ≈ 240GHz (mainstream 40nm production process)
- 25GHz < fT/10
- 25Gbaud CMOS ICs feasible

Baud Limit of Direct Mod. Lasers

Max Baud ≈ fR * 1.5

- Laser process figure of merit:

  fR = relaxation resonant frequency

  $= fR_{slope} * \sqrt{(I_{operation} - I_{threshold})}$ (temperature dependant)

- Reference: Larry Coldren & Scott Corzine (UCSB), “Diode Lasers and Photonic Integrated Circuits”, ©1995
- Why fR * 1.5?
- Max baud should be no higher than f3dB (Laser 3dB BW)

  f3dB = fR * 1.55 (when fR = fPeak)

  (fPeak = Laser peak response frequency)

Baud Limit Examples of Direct Mod. Lasers

2002 – 2004 (Gen1 10G in design)

- fR ≈ 9GHz (mainstream Laser production process)
- 10GHz < fR * 1.5
- 10GBaud DFB Lasers feasible

2010 – today (Gen2 100G in design)

- fR ≈ 17GHz (mainstream Laser production process)
- 25GHz ≈ fR * 1.5
- 25GBaud DFB Lasers feasible

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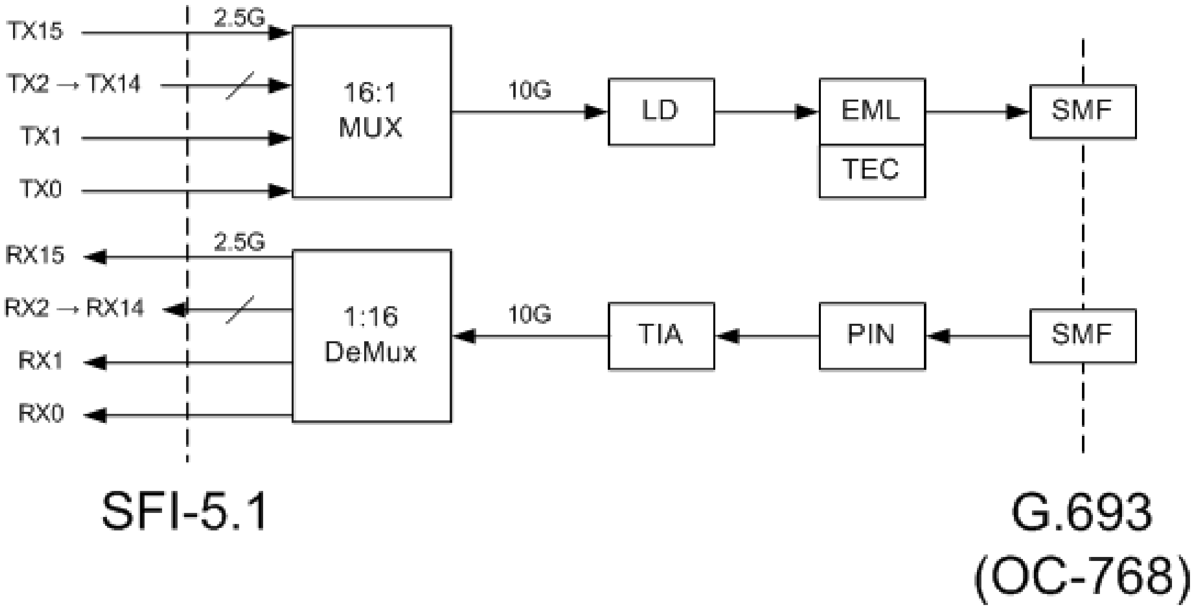
1st 40Gb/s G.693 SMF 1550nm NRZ 300-pin



Electric I/O		Optical I/O		
pin pair	Gb /s	fiber pair	λ	Gb /s
	2.5	1	1	
16				40
40		40		

ITU-T standard: 2000

40Gb/s LR4 WDM SMF 1310nm NRZ

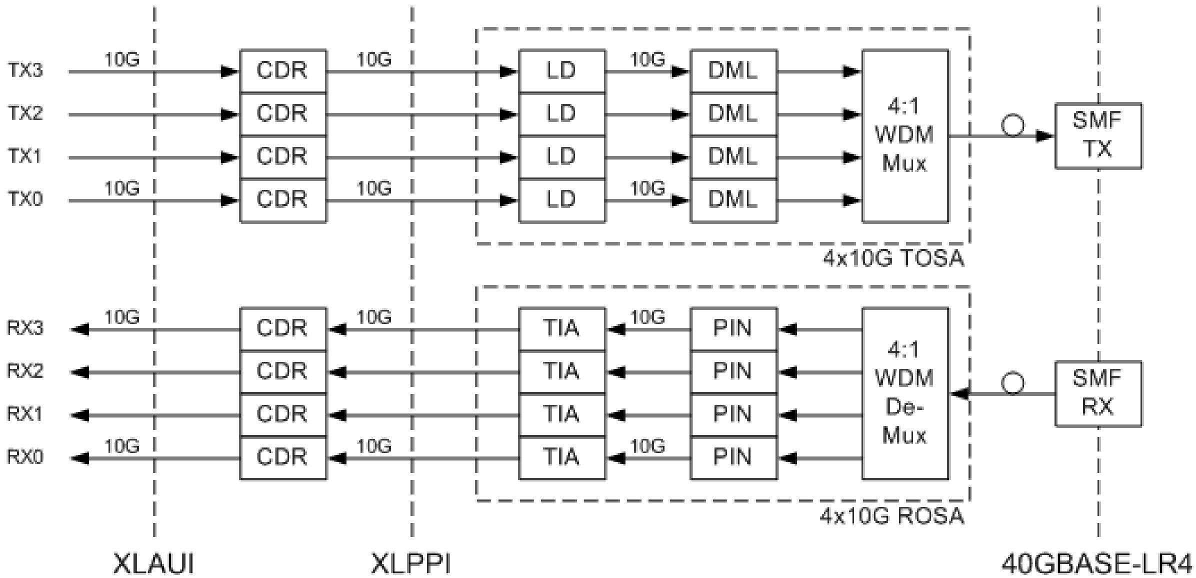


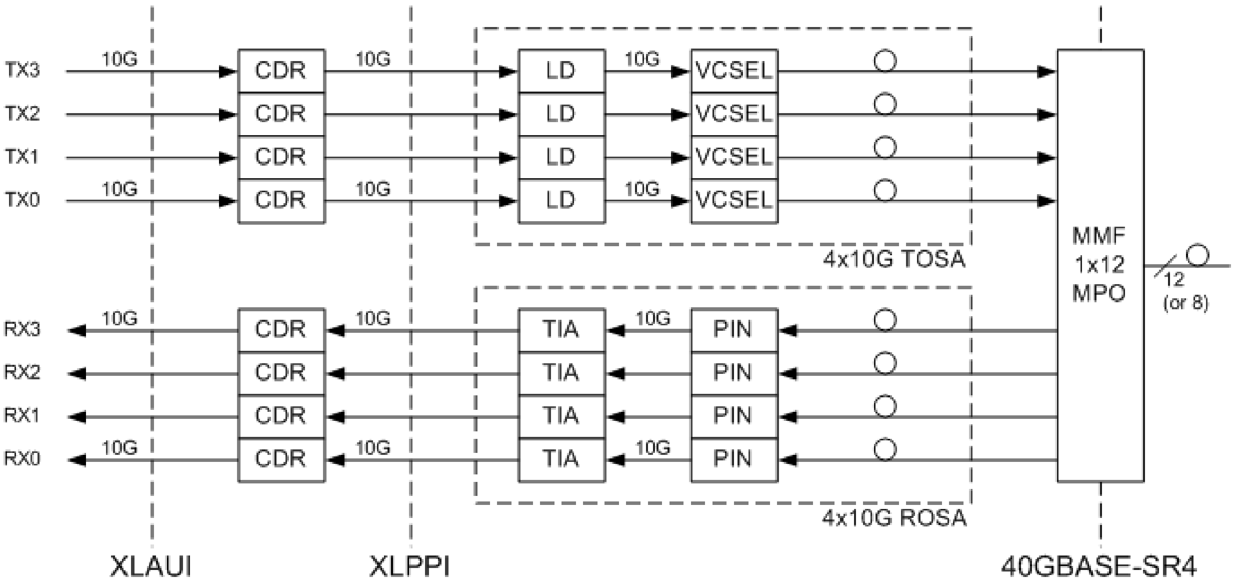
Table 87–5—Wavelength-division-multiplexed lane assignments

Lane	Center wavelength	Wavelength range
L_0	1271 nm	1264.5 to 1277.5 nm
L_1	1291 nm	1284.5 to 1297.5 nm
L_2	1311 nm	1304.5 to 1317.5 nm
L_3	1331 nm	1324.5 to 1337.5 nm

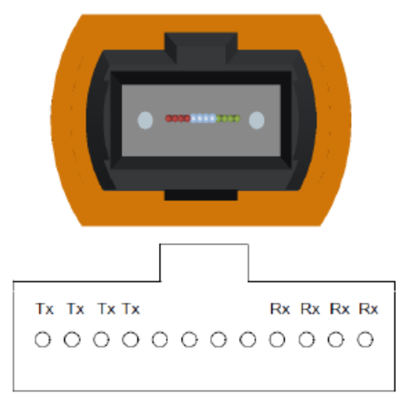
Electric I/O		Optical I/O		
pin pair	Gb/s	fiber pair	λ	Gb/s
		1		
4	10		4	10
40		40		

IEEE standard: 2010

40Gb/s SR4 Parallel MMF 850nm NRZ



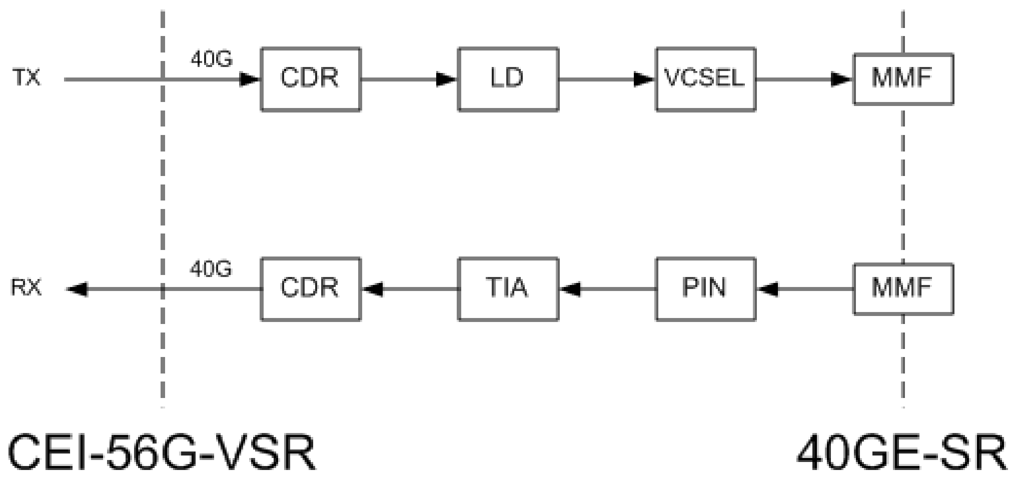
Electric I/O		Optical I/O		
pin pair	Gb/s	fiber pair	λ	Gb/s
			1	
4	10	4		10
40		40		



MPO connector & MMF differs from 10GE-SR

IEEE standard: 2010

Future 40Gb/s SR MMF 850nm NRZ



Electric I/O		Optical I/O		
pin pair	Gb/s	fiber pair	λ	Gb/s
1		1	1	
	40			40
40		40		

duplex LC connector & MMF cable is same as 10GE-SR

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1st 100Gb/s LR4 WDM SMF 1310nm NRZ

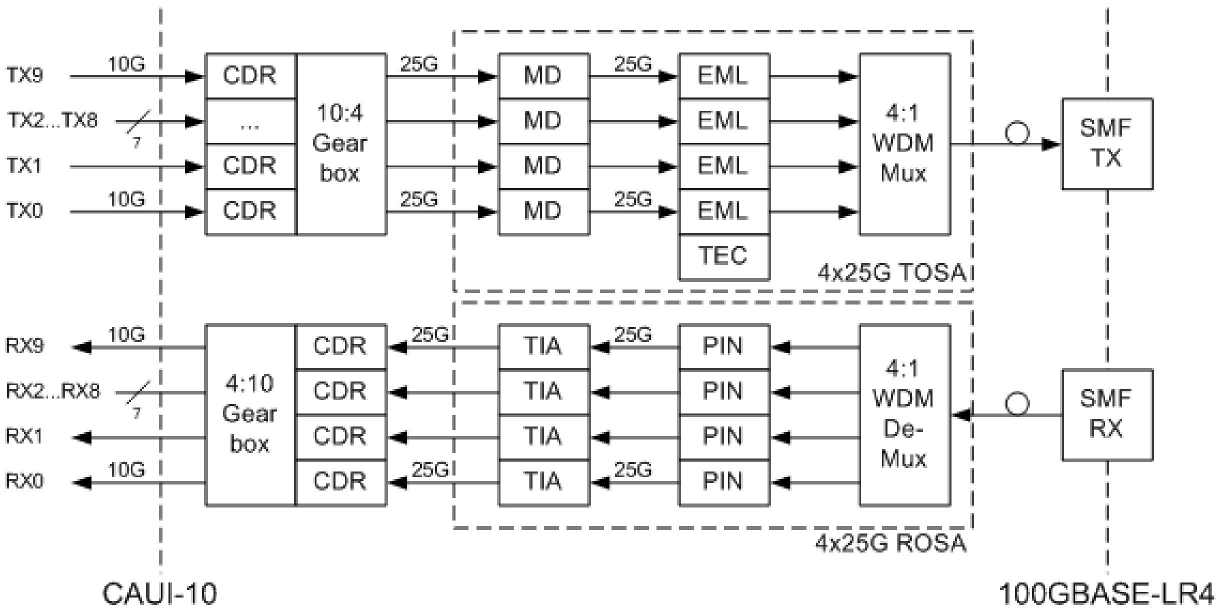


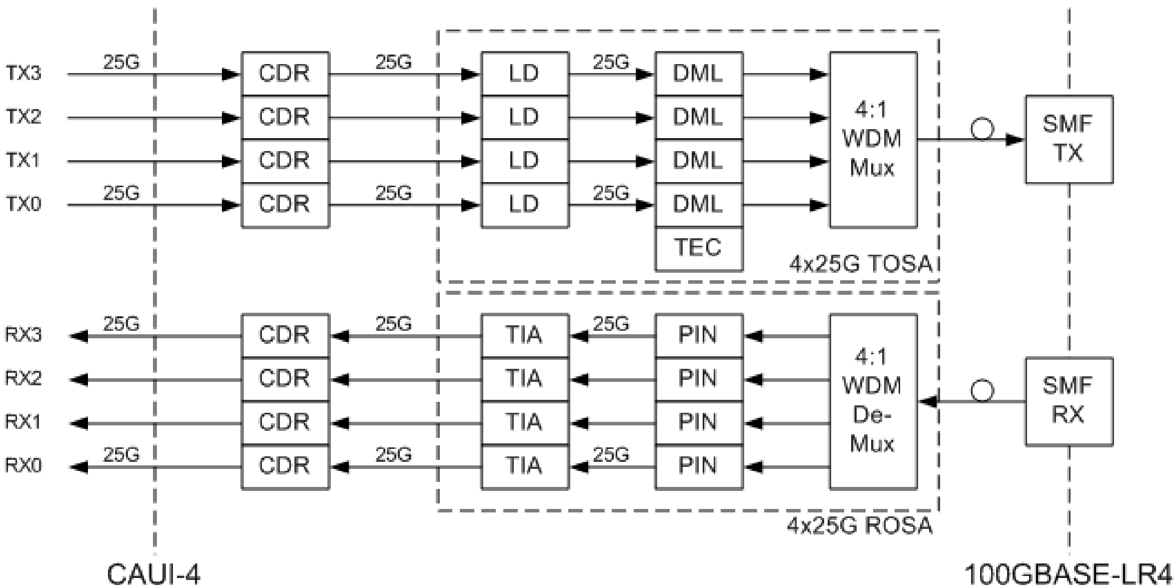
Table 88–5—Wavelength-division-multiplexed lane assignments

Lane	Center frequency	Center wavelength	Wavelength range
L_0	231.4 THz	1295.56 nm	1294.53 to 1296.59 nm
L_1	230.6 THz	1300.05 nm	1299.02 to 1301.09 nm
L_2	229.8 THz	1304.58 nm	1303.54 to 1305.63 nm
L_3	229 THz	1309.14 nm	1308.09 to 1310.19 nm

Electric I/O		Optical I/O		
pin pair	Gb/s	fiber pair	λ	Gb/s
		1		
	10		4	
10				25
100		100		

IEEE standard: 2010

100Gb/s LR4 WDM SMF 1310nm NRZ

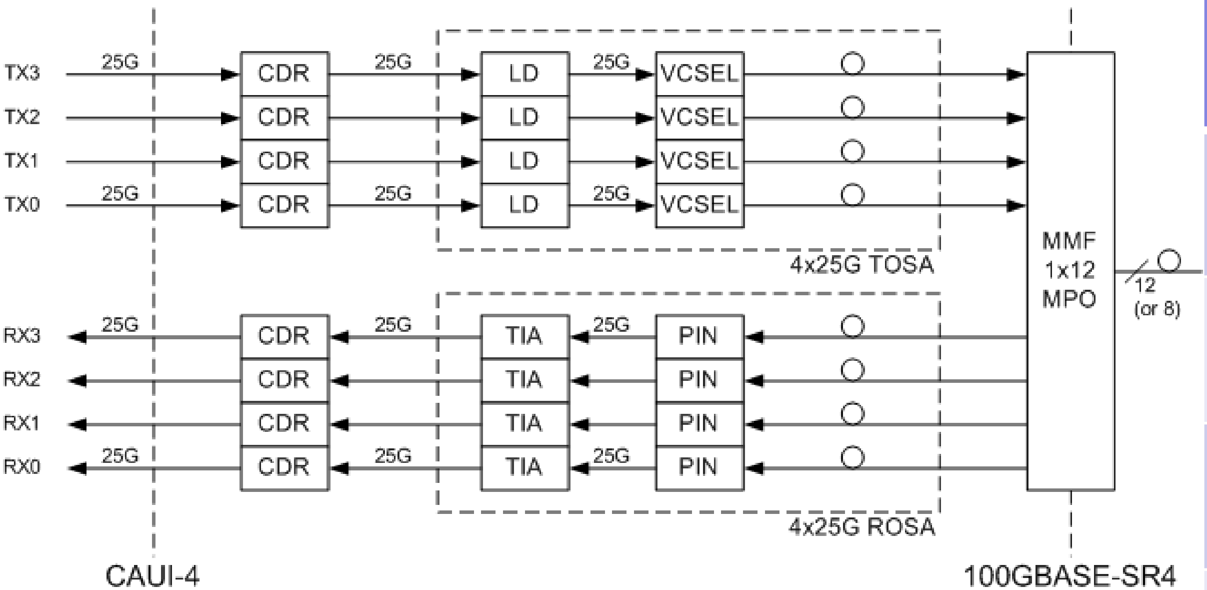


Electric I/O		Optical I/O		
pin pair	Gb /s	fiber pair	λ	Gb /s
		1		
4			4	
	25			25
100		100		

Alternative λs are could be on CWDM grid used for 40GBASE-LR4 (no TEC)

IEEE standards: 2010 & 2014

100Gb/s SR4 Parallel MMF 850nm NRZ



Electric I/O		Optical I/O		
pin pair	Gb/s	fiber pair	λ	Gb/s
			1	
4		4		
	25			25
100		100		

IEEE standard: 2014

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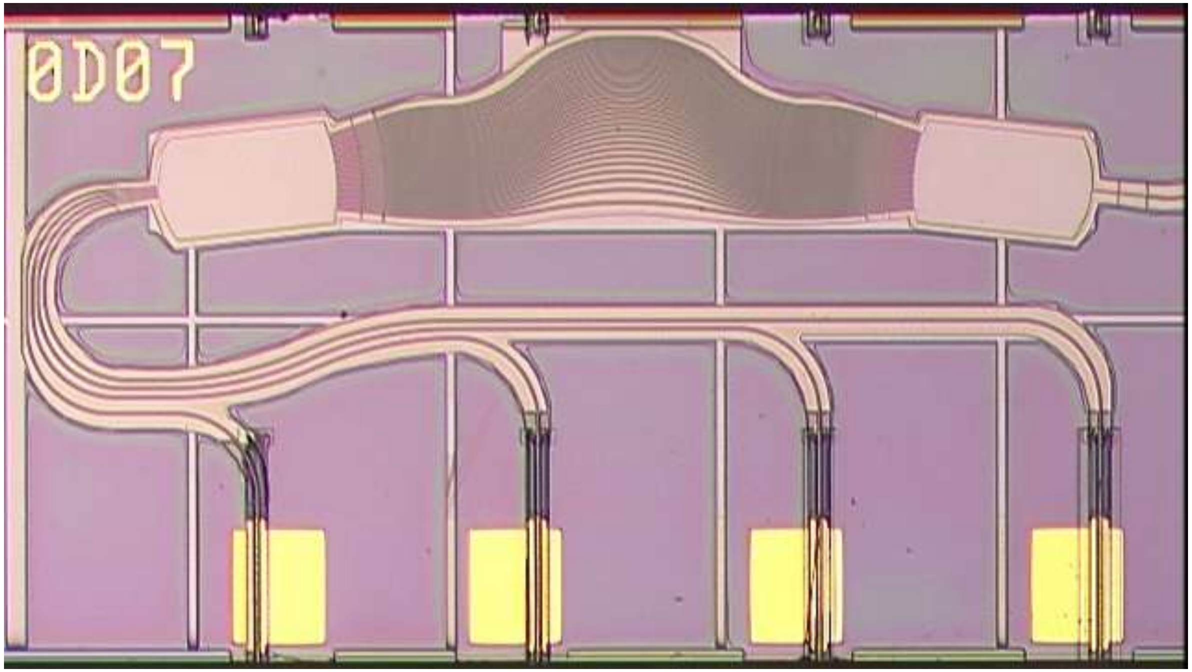
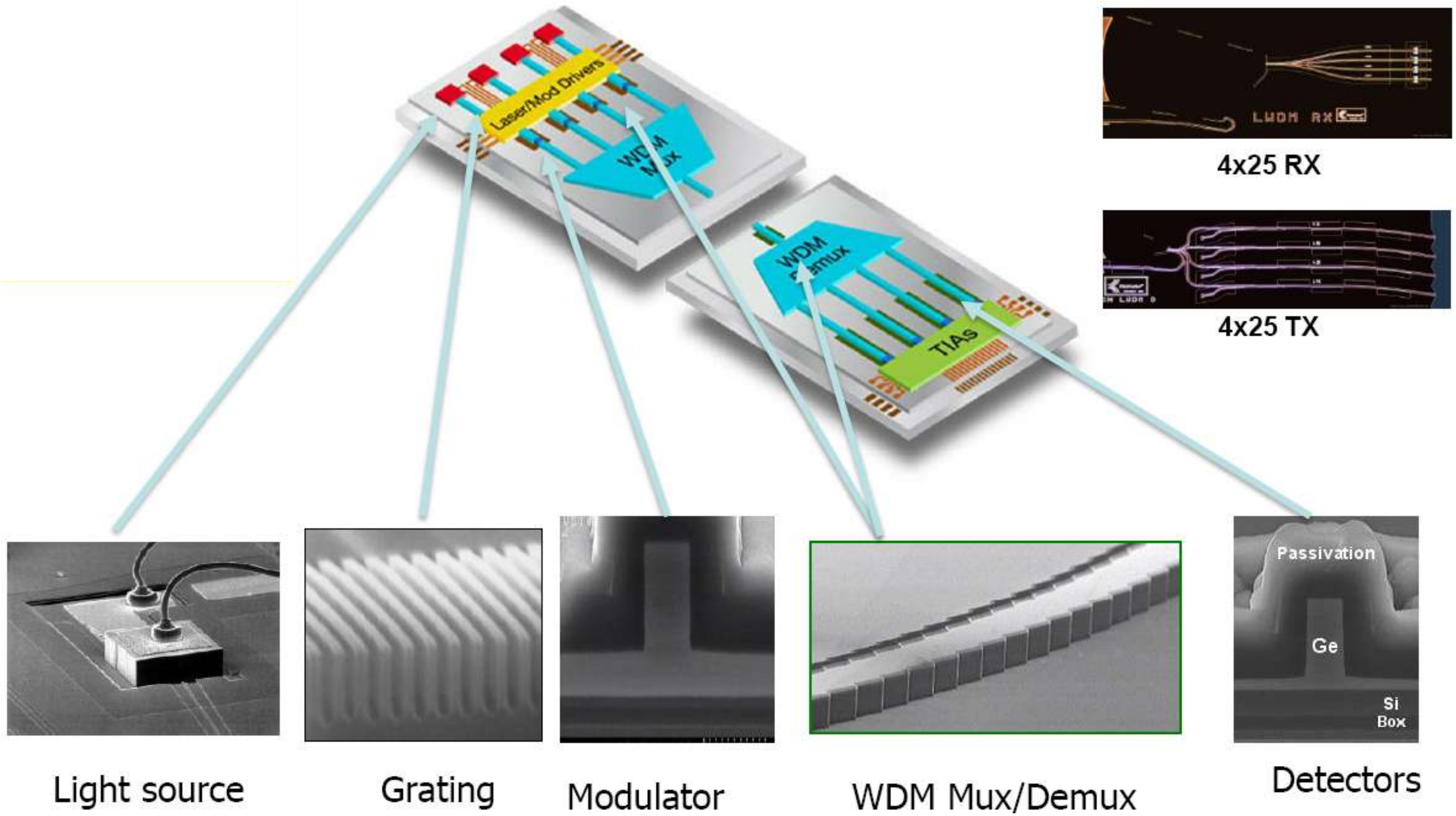
InP LW Technology

- Photonic Integrated Circuit (PIC) WDM quad DFB array
- Ex. monolithic InP quad 1310nm band DFB laser array with AWG, 1.1mm x 2.4mm PIC, CyOptics Inc.



SiP LW Technology

- Photonic Integrated Circuit (PIC) Transceiver Chips
- Ex. Hybrid Si Photonics quad 1550nm band PICs, Kotura



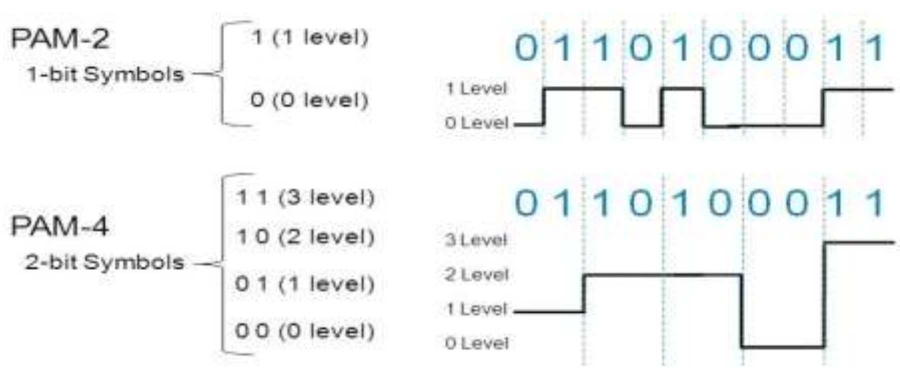
GaAs SW Technology

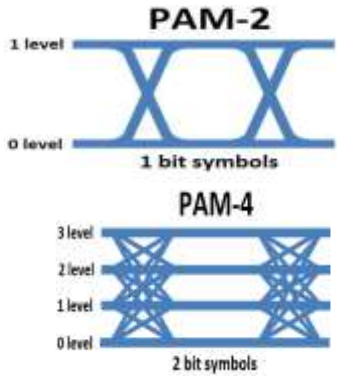
- Photonic Integrated Circuit (PIC*) parallel quad VCSEL array
- Ex. monolithic GaAs quad 850nm VCSEL array, 0.25mm x 1.0mm PIC, Finisar Corp.

* The "C" in PIC is a stretch since there are no optical connections

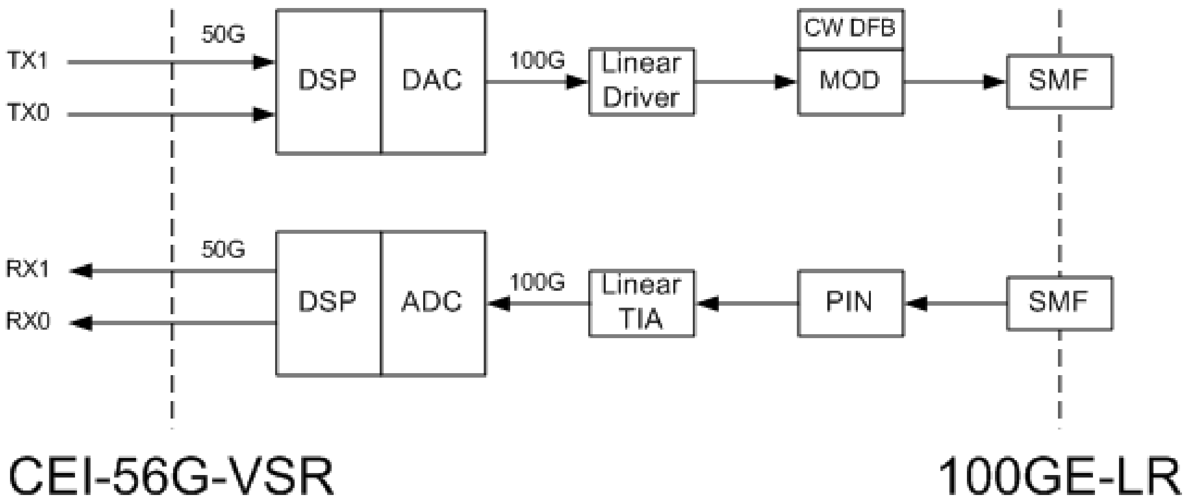
Higher Order Modulation Technology

- Three basic parameters determine link rate:
  - Symbol rate (Baud)
  - Number of channels (fibers or wavelengths)
  - Number of bits/symbol (modulation order)
- Higher Order Modulation (>1bit/symbol) example
  - PAM-4 vs. NRZ (PAM-2) reduces by 2x the Baud, or number of fibers, or number of wavelengths





Future 100Gb/s LR SMF 1310nm PAM-4



2x 50Gb/s NRZ λs WDM is an alternative

Electric I/O		Optical I/O		
pin pair	Gb /s	fiber pair	λ	Gb /s
		1	1	
2				
	50			100
100		100		

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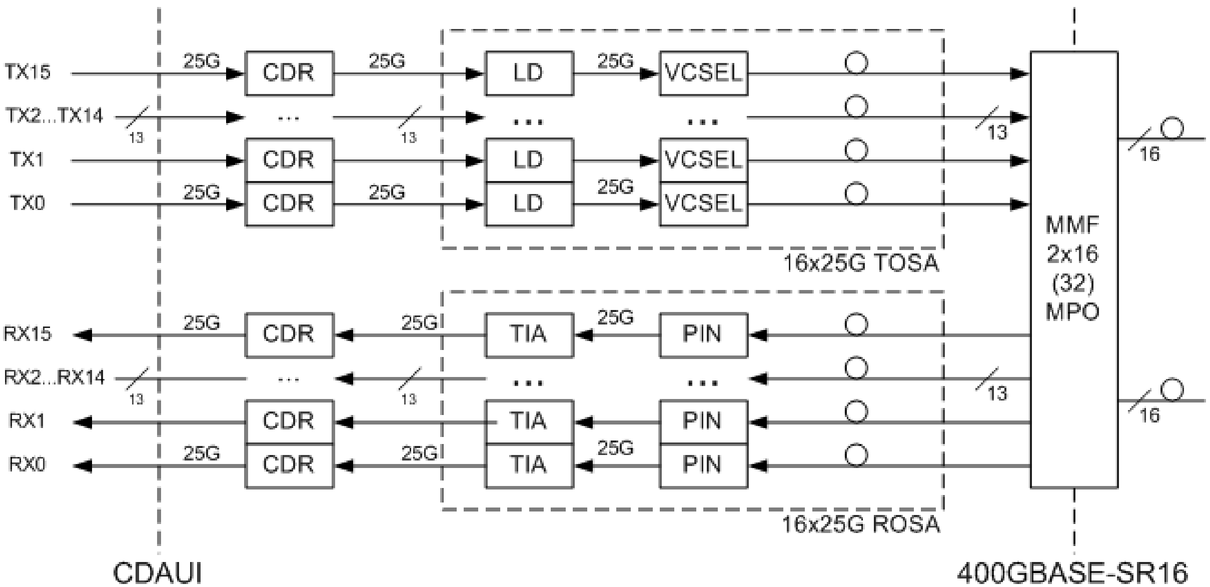
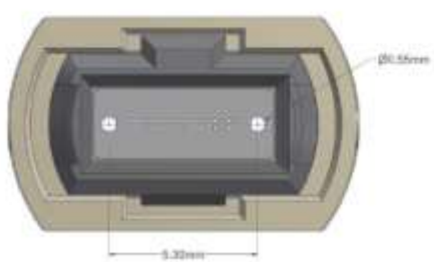
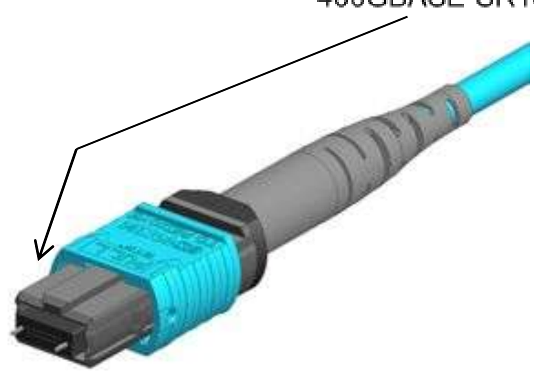
400Gb/s SR16 Parallel MMF 850nm NRZ



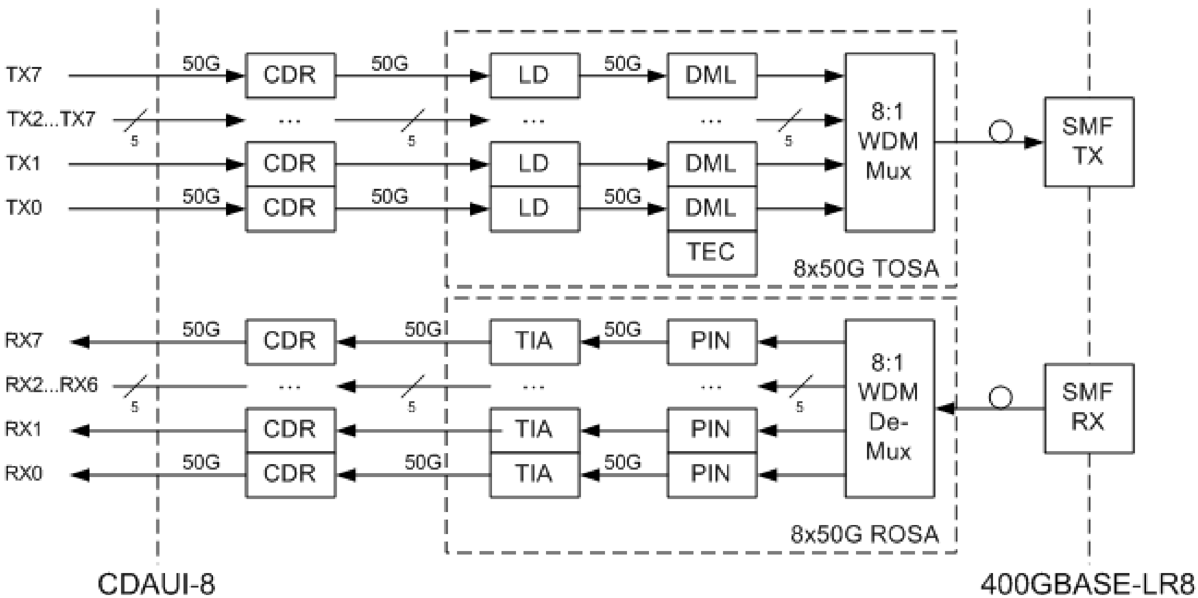
2 x 16 MMF MT ferrule





Electric I/O		Optical I/O		
pin pair	Gb/s	fiber pair	λ	Gb/s
			1	
	25			25
16		16		
400		400		

400G LR8 WDM SMF 1310nm NRZ



Electric I/O		Optical I/O		
pin pair	Gb/s	fiber pair	λ	Gb/s
		1		
8			8	
	50			50
400		400		

4x 100Gb/s PAM-4 λs HOM alternative

What's After 400Gb/s?

- 1Tb/s Ethernet
  - Has been extensively discussed
  - Vestige of 10x historical Ethernet speed jumps
  - Will require huge R&D investment
  - 2.5x speed increase from 400Gb/s is not compelling
- 1.6Tb/s Ethernet
  - 4x speed increase reasonable return on huge R&D $
  - 4x is more likely for future speed increases
  - Similar to historical 4x Transport speed jumps
  - 1.6Tb/s will require all advanced technologies:
    - Parallel
    - WDM
    - Higher Order Modulation
    - Photonic Integration

Thank you