ECEN720: High-Speed Links Circuits and Systems
Spring 2025

Lecture 16: Optical Transceivers

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Announcements

- Project Final Report due Apr 29

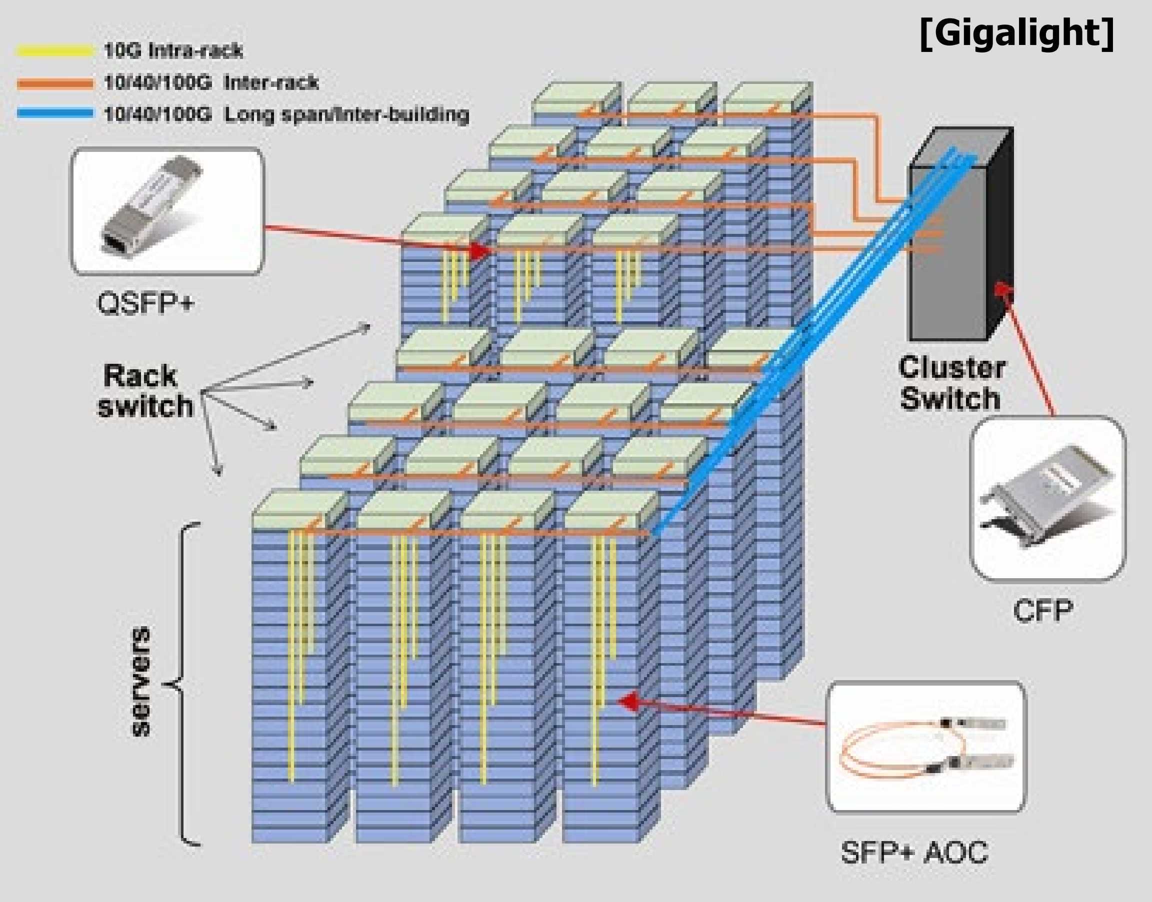
- Exam 2 May 2
  - 1PM-3PM for in-person sections
  - Focuses on material from Lectures 7-15
  - Previous years' Exam 2s are posted on the website for reference

Outline

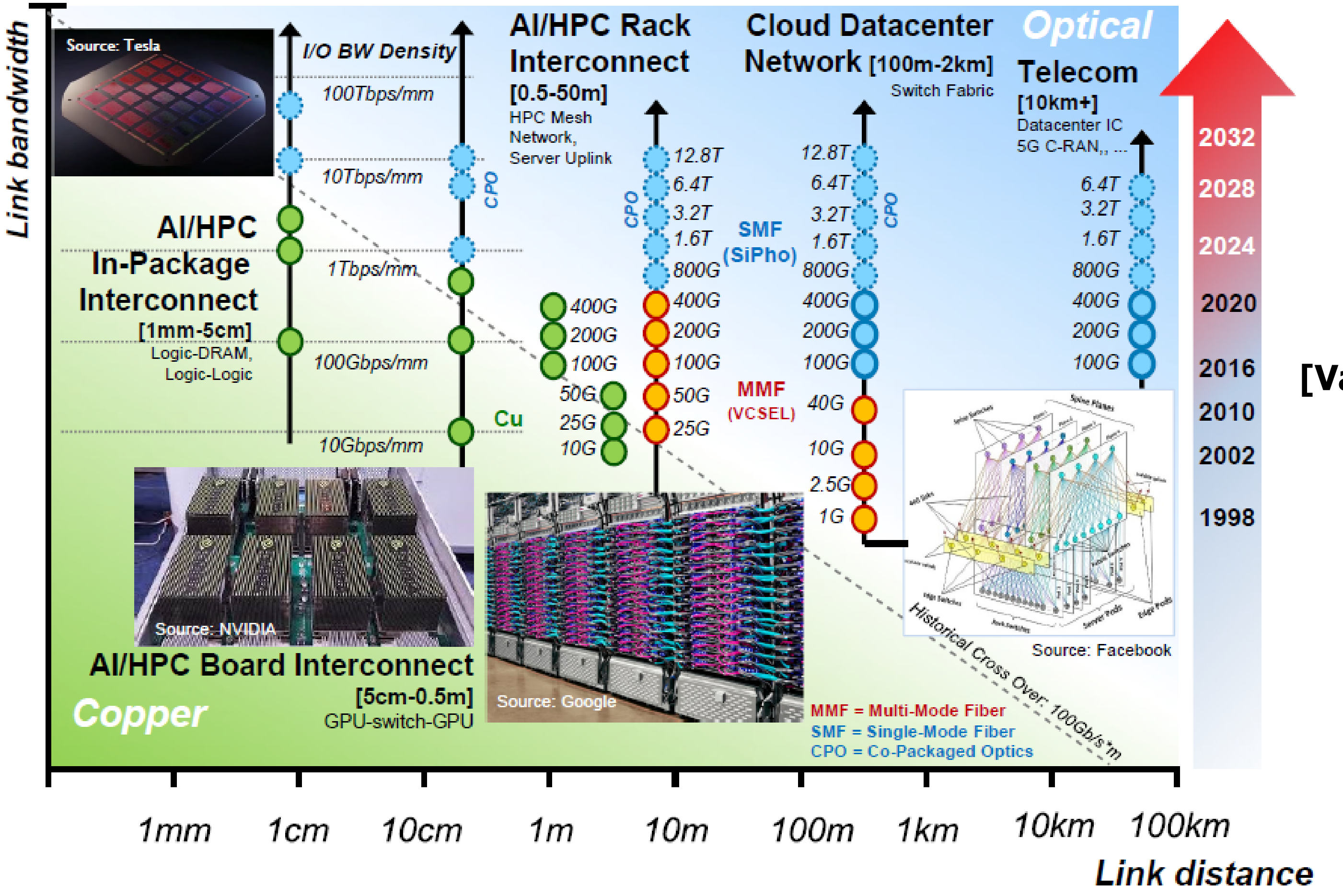
- Optical Interconnect Motivation
- Optical Channel Properties
- IMDD and Coherent Transceivers
- Transmitter Properties and Devices
- Receiver Architecture and Devices
- Conclusion

Data Center Links

- Different interconnect technologies are used to span various distances
- Electrical I/O
  - Chip-to-module
  - Intra-rack (DAC cables)
- Optical I/O
  - Intra-rack (AO cables)
  - TOR switch to edge switch



Data Center Link Length



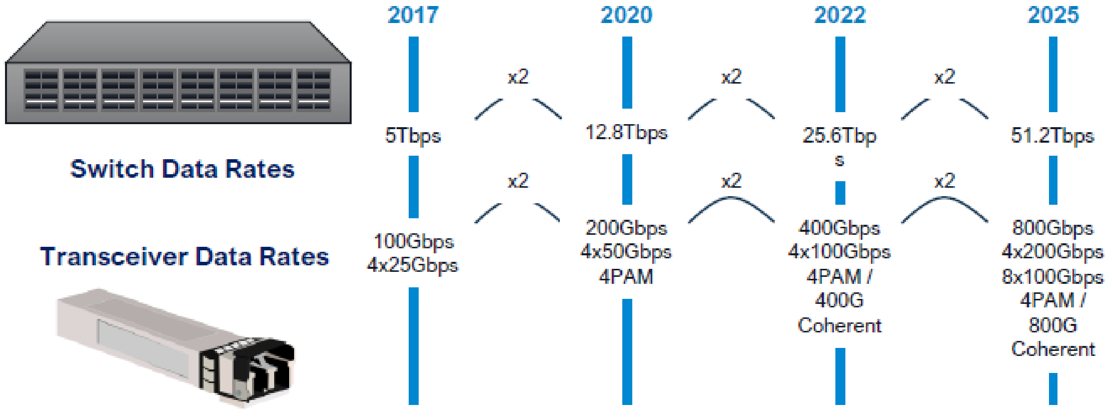
[Van Campenhout ISSCC 2022]

- Maximum reach scales inversely with data rate

AI Datacenter Connectivity Demands

- Scaling up with more xPUs in compute clusters
- Scaling out to larger clusters
- Higher per-lane data rates
- Flatter network topologies with higher radix switches to reduce latency
- Pushing optical connectivity to within the rack

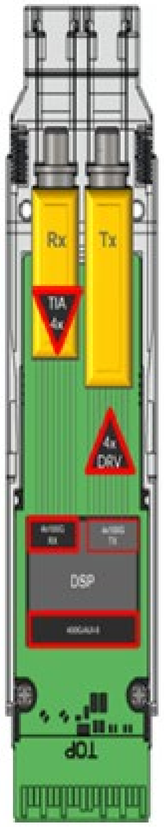
[Wang ISSCC 2024]



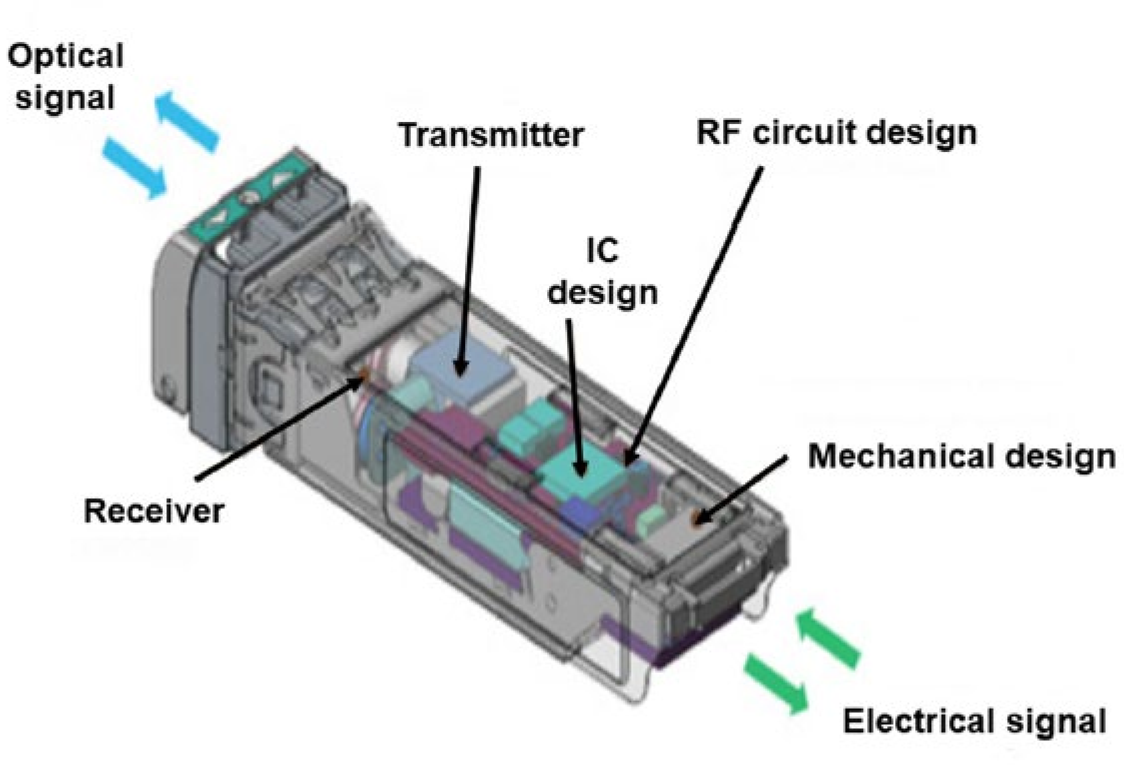
[Chan Carusone ISSCC 2024]

Optical Modules

- Retimed pluggable modules
  - TX/RX DSP in advanced node CMOS
  - Separate driver and TIA chips, which can be SiGe, InP, CMOS
- Linear optics
  - Remove DSP to save power
  - Need to be very linear and have high bandwidth



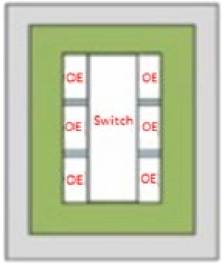
[Lau JEP 2025]

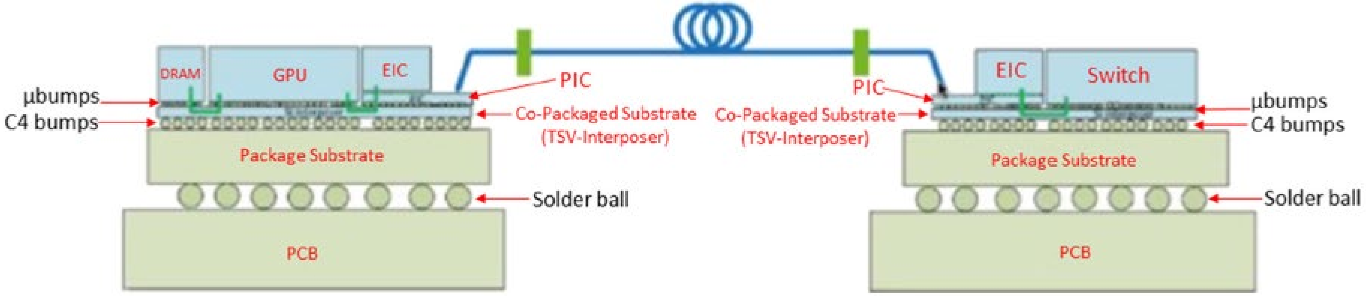


NVIDIA CPO Example

[NVIDIA GTC 2025]

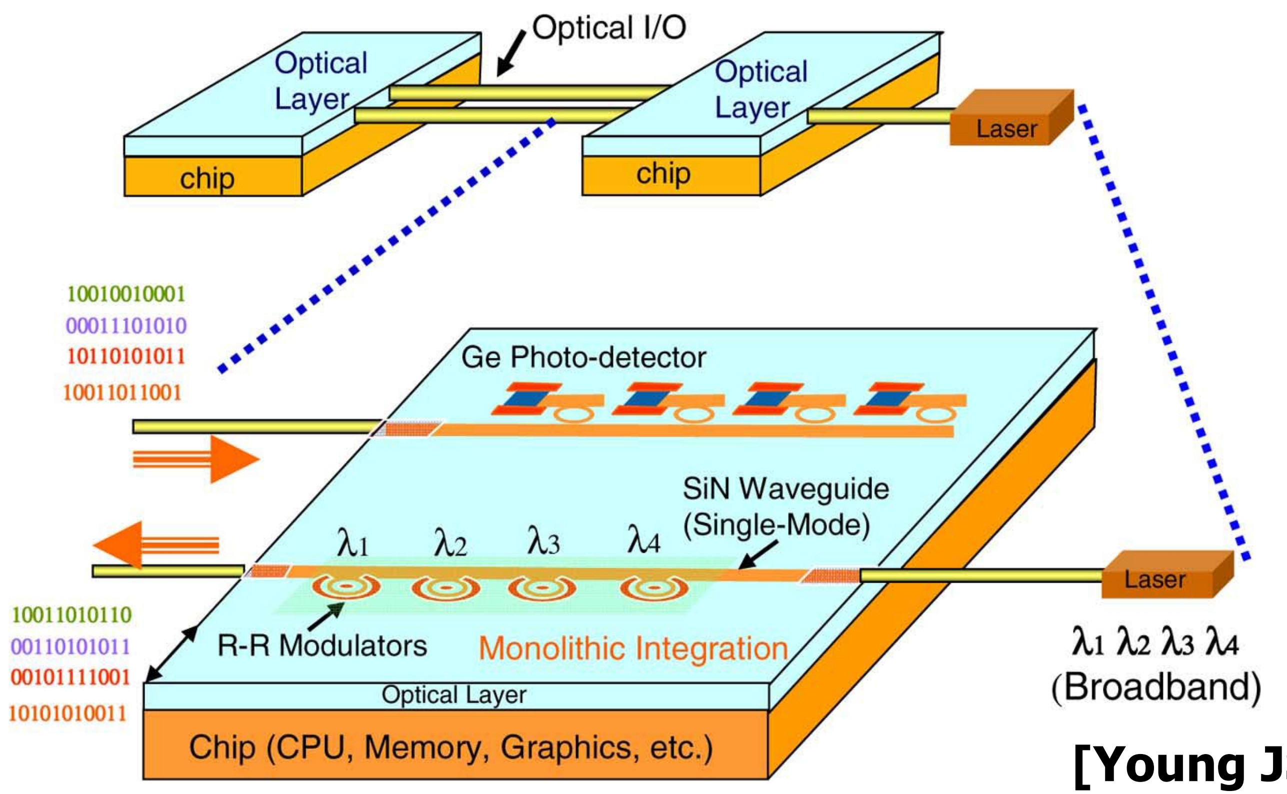
[Lau JEP 2025]





- 4x28.8Tb/s Switch
  - Based on microring resonator modulators driven by 200Gb/s PAM4 SERDES
  - 3D hybrid bonding for EIC-PIC interface
  - External laser source
  - 6 optical assemblies X 3 photonic engines
  - 288 data link fibers per 28.8Tb/s plus 36 laser fibers

Wavelength-Division Multiplexing (WDM)



[Young JSSC 2010]

- WDM allows for multiple high-bandwidth (10 - 200Gb/s) signals to be packed onto one optical channel

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Optical Channels

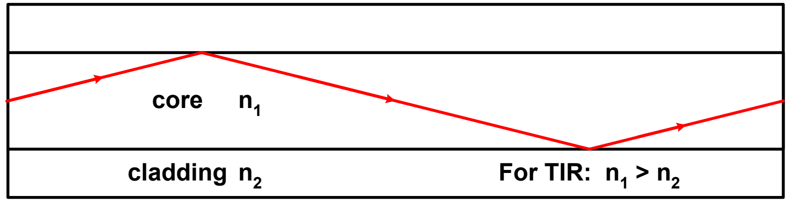
- Short distance optical I/O channels are typically waveguide (fiber)-based

- Optical channel advantages
  - Much lower loss
  - Lower cross-talk
  - Smaller waveguides relative to electrical traces
  - Potential for multiple data channels on single fiber via WDM

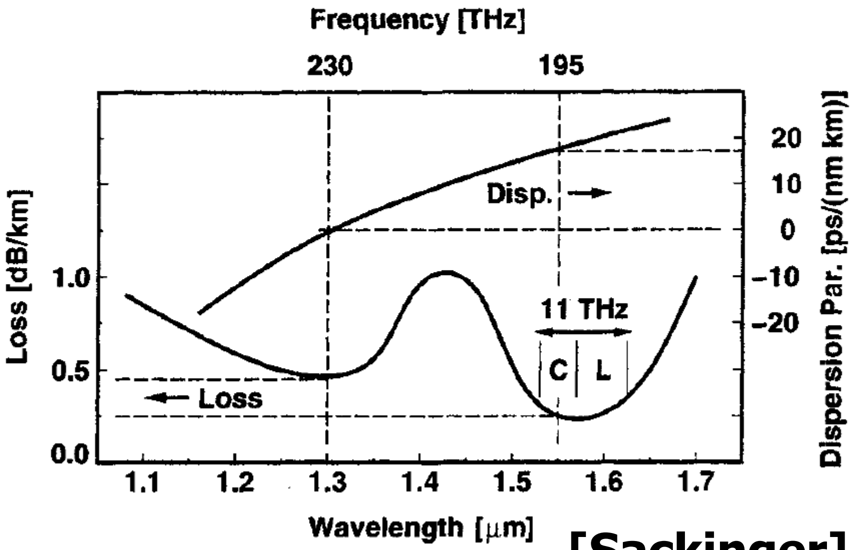
Waveguide (Fiber)-Based Optical Links

- Optical fiber loss is specified in dB/km
  - Single-Mode Fiber loss ~0.25dB/km at 1550nm
  - RF coaxial cable loss ~100dB/km at 10GHz
- Frequency dependent loss is very small
  - <0.5dB/km over a bandwidth >10THz
- Bandwidth may be limited by dispersion (pulse-spreading)
  - Important to limit laser linewidth for long distances (>1km)

Optical Fiber Cross-Section



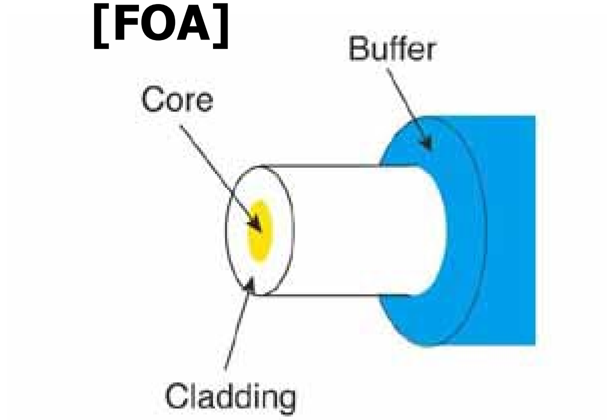
Single-Mode Fiber Loss & Dispersion

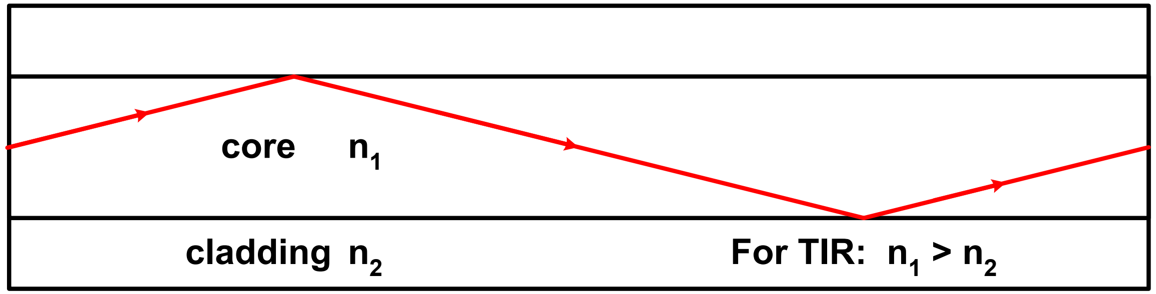


[Sackinger]

Optical Fiber Cross-Section

[FOA]



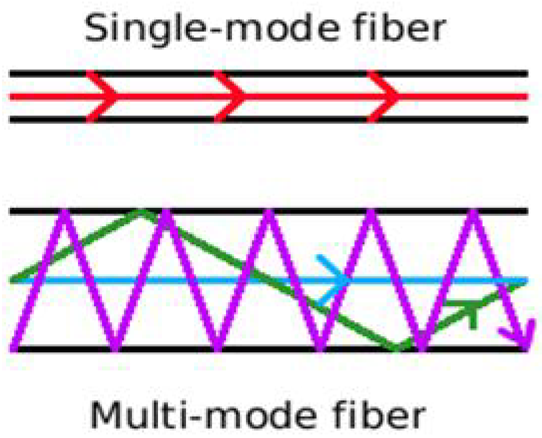


- Optical fibers confine light between a higher index core and a lower index cladding via total internal reflection

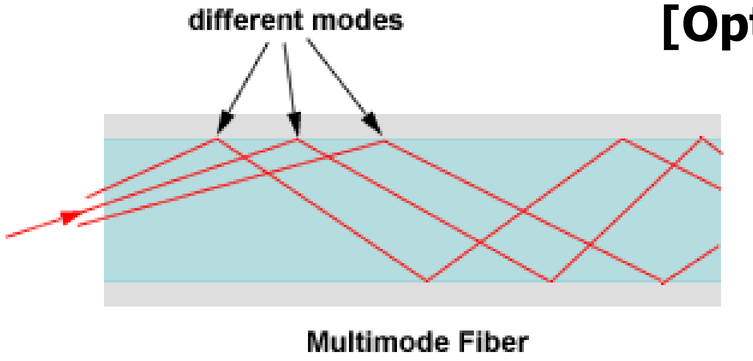
Optical Fiber Modes

- For light to propagate down the fiber, the interference pattern or **mode** generated from reflecting off the fiber's boundaries must satisfy resonance conditions
- Fibers are classified based on their ability to support multiple or single modes

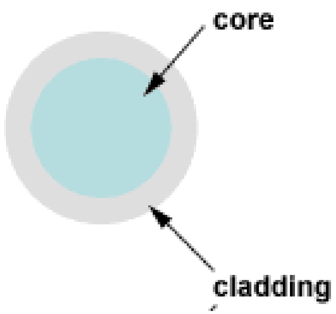
[Fibertronics]



Multi-Mode Fibers



[Optical Fiber Tutorial]

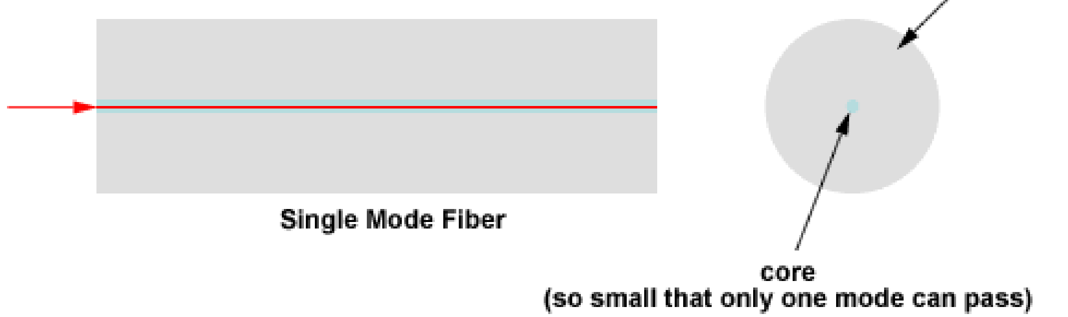


[FOA]

- Multi-mode fibers have large core diameters
  - Typically 50 or 62.5μm
  - Relatively easy to couple light into
- The large diameter allows for multiple propagating modes
- Major performance limitation is modal dispersion caused by the different modes propagating at different velocities
- Typically specified with a bandwidth-distance product
  - Legacy MMF 200MHz-km
  - Optimized MMF >4GHz-km

Single-Mode Fibers

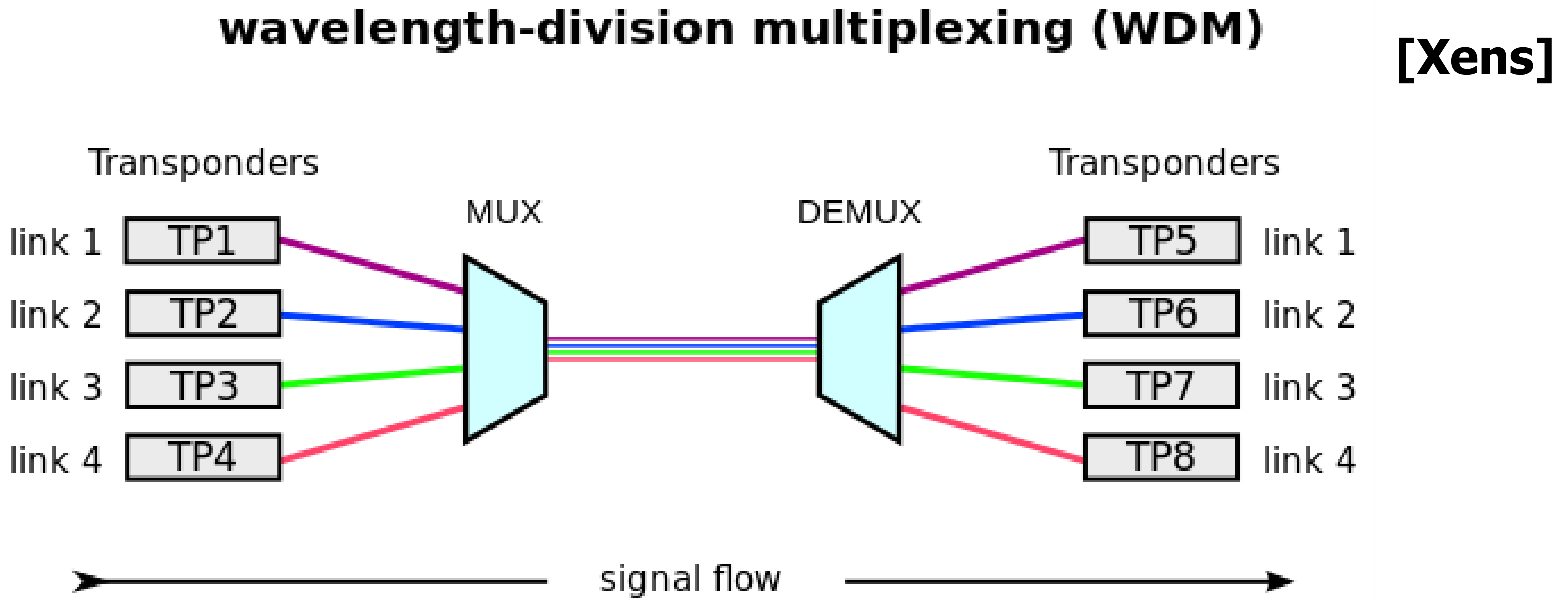
[Optical Fiber Tutorial]



[FOA]

- Multi-mode fibers have much smaller core diameters
  - Typically 8-10μm
  - Requires careful alignment (cost)
- The small diameter allows for only one propagating mode (with two orthogonal polarizations)
- Allows for much longer transmission distances (>100km)
- At long distance, major performance limitation is fiber loss
- Chromatic- and polarization-mode dispersion can also limit performance, but generally negligible <10km

Wavelength-Division Multiplexing (WDM)



- While single-mode fibers only support one mode, one way to increase the bandwidth density is to use multiple wavelengths to transmit independent information
- This is called wavelength-division multiplexing (WDM)
- Allows efficient use of the several THz bandwidth of the optical fiber with many wavelengths independently modulated at 10s of Gb/s

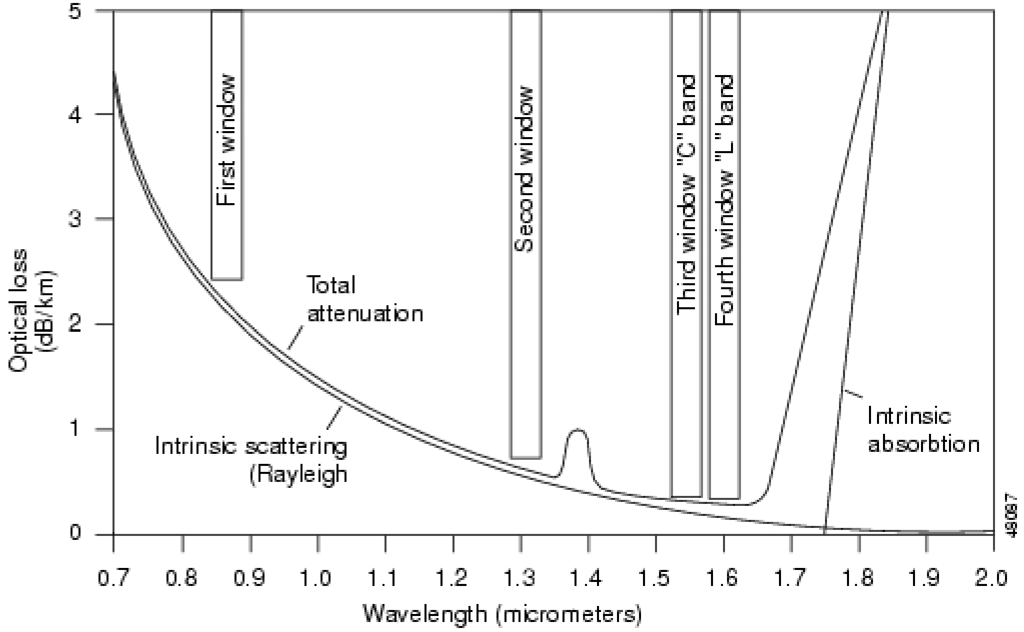
Silica Glass Fiber Standard Transmission Windows

- Standard silica glass fiber has a loss minimum near 1550nm
  - This region occupies a bandwidth of 95nm or 11THz!
  - Divided into 2 bands or transmission windows
    - Conventional or C-band (1530 – 1565nm)
    - Long-wavelength or L-band (1565 – 1625nm)

- Another window popular for long distance is near 1310nm, where the fiber chromatic dispersion is near zero
  - Original or O-band (1260 – 1360nm)

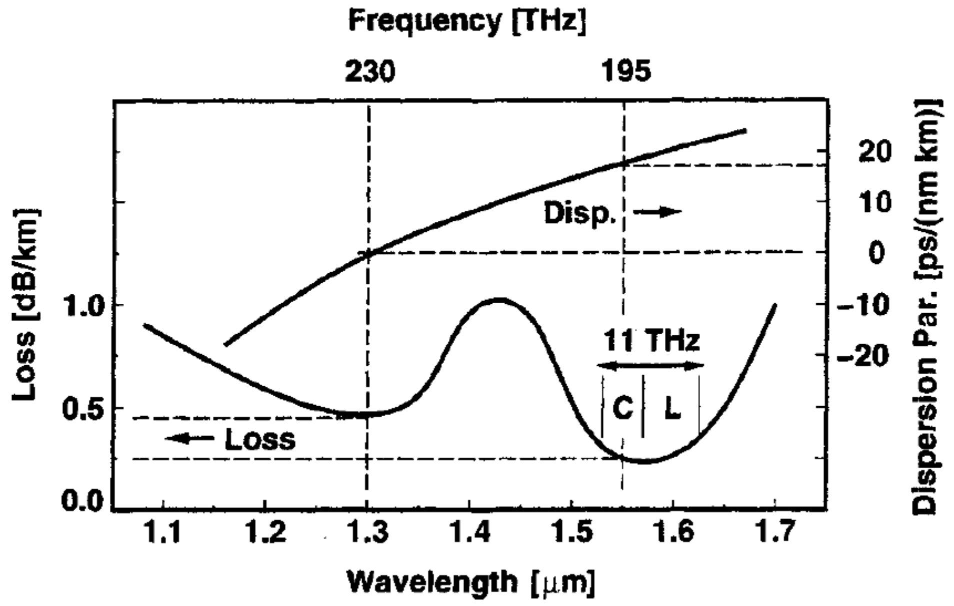
- A window near 850nm (800 – 900nm) is also commonly used for short distance communication due to low-cost optical sources and detectors

[Cisco]



Fiber Bandwidth and Dispersion

- While optical fiber has very wide bandwidth over which there is very low loss, there are still limits to high-speed communication
- Optical fiber can disperse a broadband signal, as different spectral components travel at different speeds
- This is Chromatic Dispersion



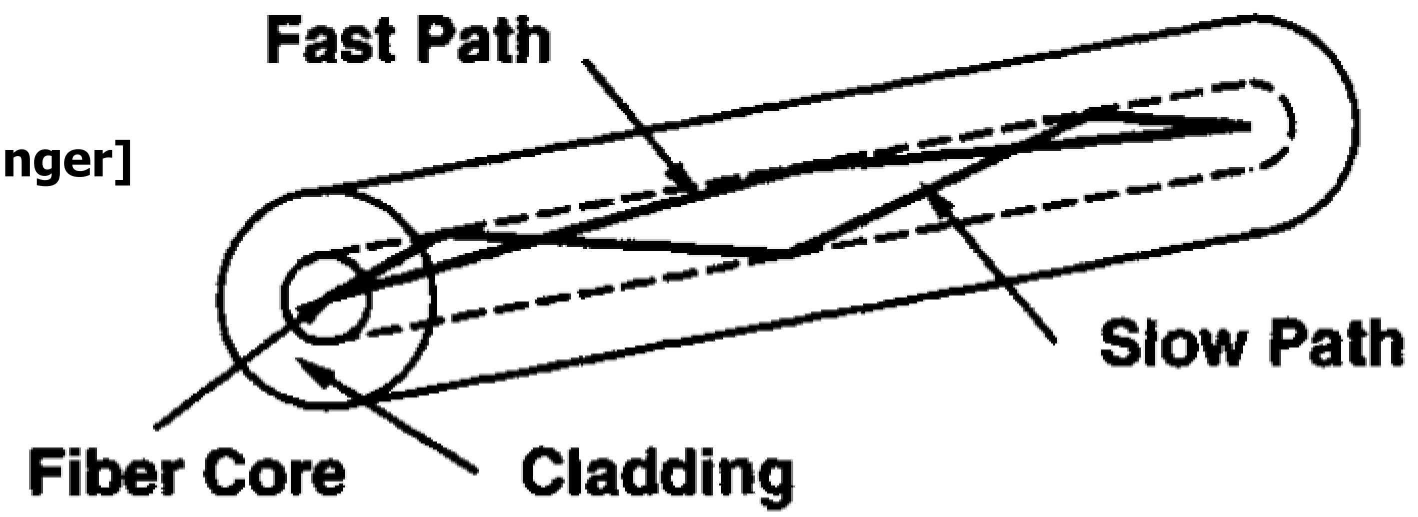
[Sackinger]

Dispersion

- Dispersion is the temporal spreading of high-speed pulses (bits)
  - Can cause intersymbol interference (ISI) and degrade BER
- Modal Dispersion
  - In a MMF, different modes of light travel at different speeds
- Chromatic Dispersion
  - In a SMF, different frequency content of a modulated optical carrier travels at different speeds
- Polarization-Mode Dispersion
  - In a SMF, different polarizations travel at different speeds

Modal Dispersion

[Sackinger]



- The multiple propagating modes in a MMF have different propagation delays
- This results in pulse spreading at the receiver end or **modal dispersion**

Modal Dispersion Example

- The pulse spreading is the time difference between the longest and shortest paths, ΔT

For a graded - index multimode fiber (GRIN - MMF)

$$\Delta T = \frac{(n_{cor} - n_{clad})^2}{8cn_{cor}} L$$

where L is the fiber length, c is the speed of light, and n_{cor} and n_{clad} are the core and cladding refracitve indexes, respectively.

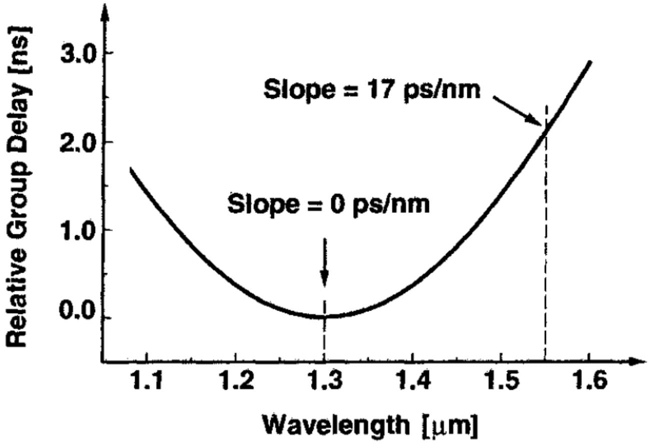
With $n_{cor} = 1.48$, $n_{cor} - n_{clad} = 0.02$, $\mathrm{L} = 1\mathrm{km}$

$$\Delta T = \frac{(0.02)^2}{8\left(3 \times 10^8 \frac{m}{s}\right)1.48}(1km) = 113\,ps$$

- For this example, if we want this to be ~10% of the bit period, then this limits the maximum data rate to less than 1Gb/s at 1km
- Optimized multi-mode fibers have >4GHz-km

Chromatic Dispersion

Relative Group Delay for 1km SMF



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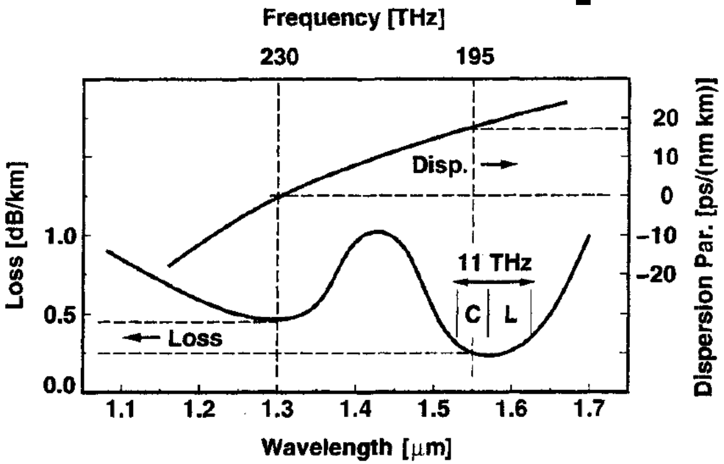


- Different wavelengths travel at different speeds down a fiber, resulting in group-velocity or **chromatic dispersion**
- Specified by the change in group delay (τ) per nm wavelength and km distance

$$\text{Dispersion Parameter:} \quad D = \frac{1}{L} \cdot \frac{\partial \tau}{\partial \lambda}$$

- Standard SMF has D=17ps/(nm*km) at 1550nm

Chromatic Dispersion Pulse Spreading

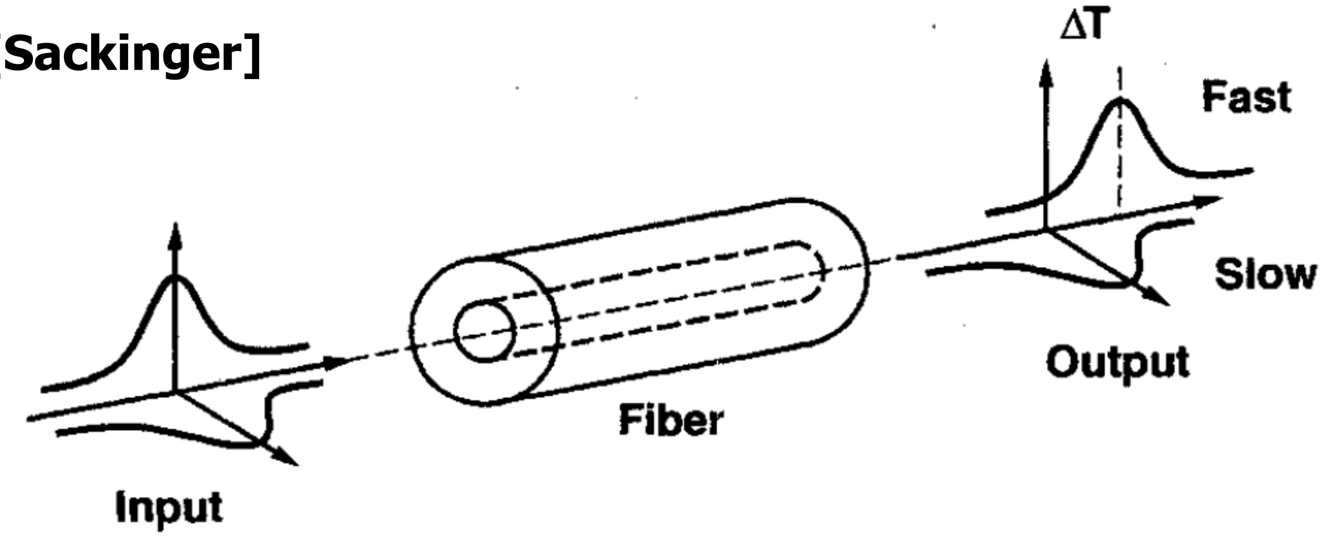
- Chromatic dispersion is a function of the transmitter spectral linewidth (ΔL) (the nm in the denominator)
- The transmitter linewidth is a function of
  - Source laser phase noise
  - Modulation scheme
  - Modulation technique (direct vs external)
- Chromatic dispersion pulse spreading

$$\Delta T = \left| D \right| \cdot \Delta\lambda \cdot L$$

- For a 1nm spectral linewidth source, the signal will spread by 17ps over 1km of standard SMF with D=17ps/(nm*km) at 1550nm

Polarization-Mode Dispersion

[Sackinger]



- While a SMF can only support one pathway or transverse mode, the transmitter typically has both horizontal and vertical polarization modes which both propagate down the fiber
- If a fiber has a slightly elliptical core or experiences asymmetrical mechanical stress, then the two polarization modes travel at different speeds and **polarization-mode dispersion** (PMD) results

Polarization-Mode Dispersion Pulse Spreading

- The fiber's effect on the polarization changes randomly along it's length, making PMD have statistical uncertainty

- The pulse spreading, averaged over multiple fibers, is

$$\overline{\Delta T} = D_{PMD}\sqrt{L}$$

$$\text{where } D_{PMD} \text{ is the polarization - mode dispersion parameter}$$

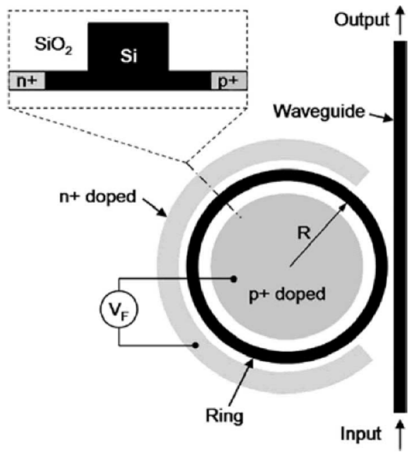
- PMD is also a time-varying parameter, which can complicate compensation

Polarization-Mode Dispersion Mitigation

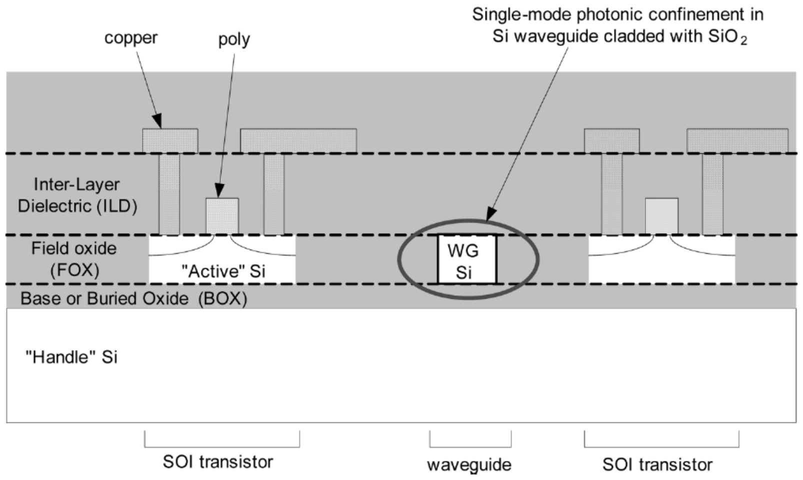
- Luckily, PMD is not too bad
  - Legacy fiber D_{PMD}=2ps/sqrt(km)
  - New fiber D_{PMD}=0.1ps/sqrt(km)
- For data center scale interconnects (<10km), PMD can generally be neglected
- Long-haul mitigation techniques
  - Short polarization maintaining fiber with adaptively-controlled polarization controlled
  - Adaptive electronic equalizer

Silicon Photonic Waveguides

Ridge waveguide used in a ring resonator modulator



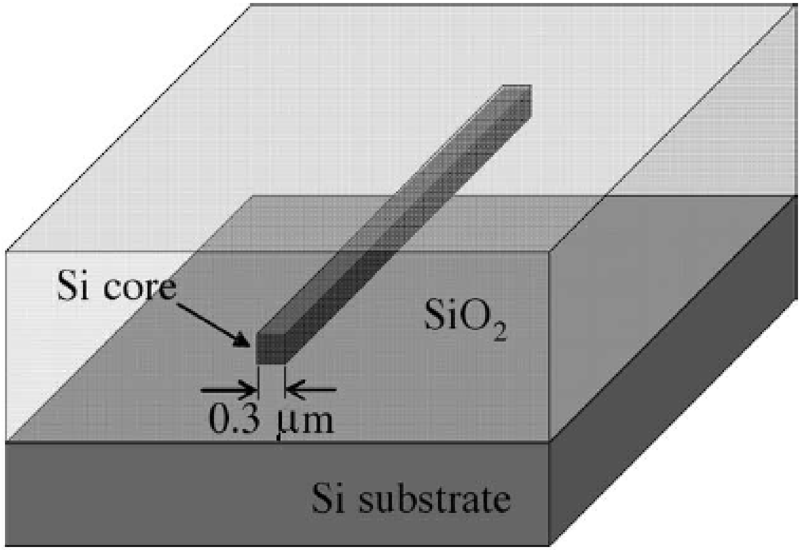
Wire/rectangular waveguide



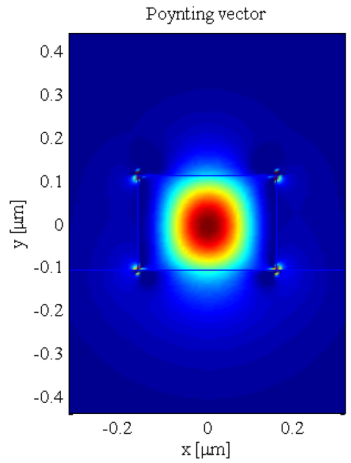
- Waveguides can be made in CMOS processes with a silicon core surrounded by an SiO_2 (or similar) cladding
- Common structures are the "ridge" and "wire/rectangular" waveguides

Silicon Photonic Waveguides

Wire/rectangular waveguide



Width = 320nm
Height = 220nm



- The high index contrast between Si (~3.5) and SiO_2 (~1.5) allow for submicron cross-section dimensions
- The evanescent field outside the core typically decays within 300nm, allowing for tight pitches of parallel waveguides
- Tight bending radius (<5µm) is possible, allowing for compact photonic integrated circuits

TE & TM Polarization Modes

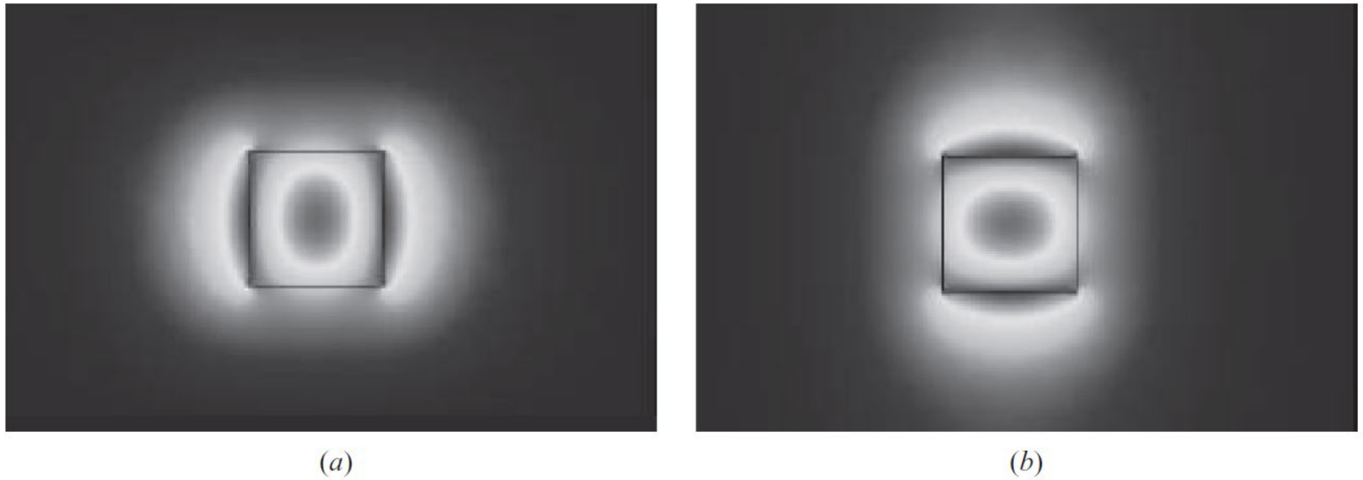
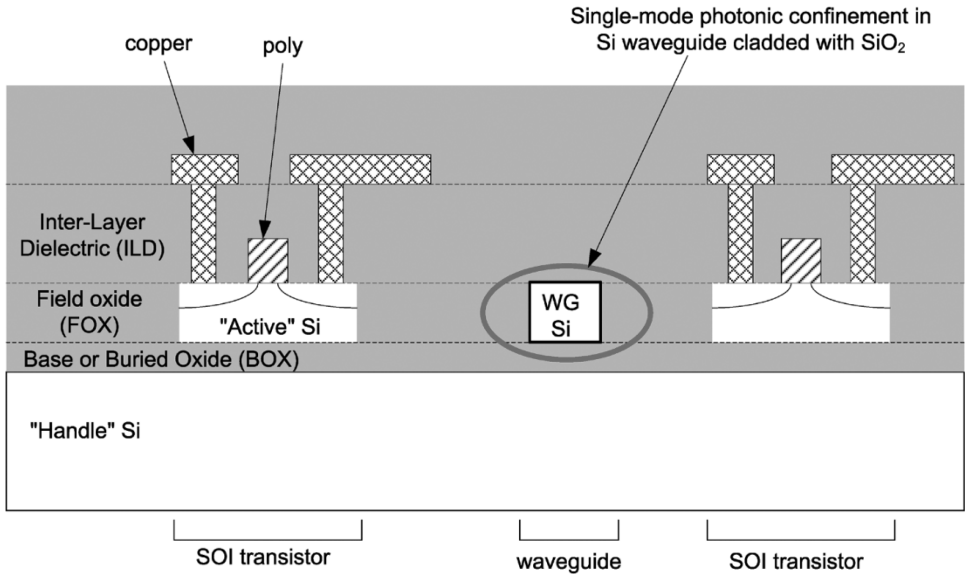


Figure 2.14 Field profiles for: (*a*) TE; (*b*) TM polarisation in a small strip silicon waveguide

- While on-chip silicon waveguides are most commonly single transversal mode, they generally support both TE and TM polarization modes
- Depending on the waveguide cross-section, these polarization modes can have different propagation constants. Although, PMD should be negligible for on-chip distances.
- TE modes have higher field intensity at the sidewalls, which are harder to keep smooth in the fabrication process
- This sidewall roughness results in typically higher loss for the TE mode

CMOS Waveguides – SOI

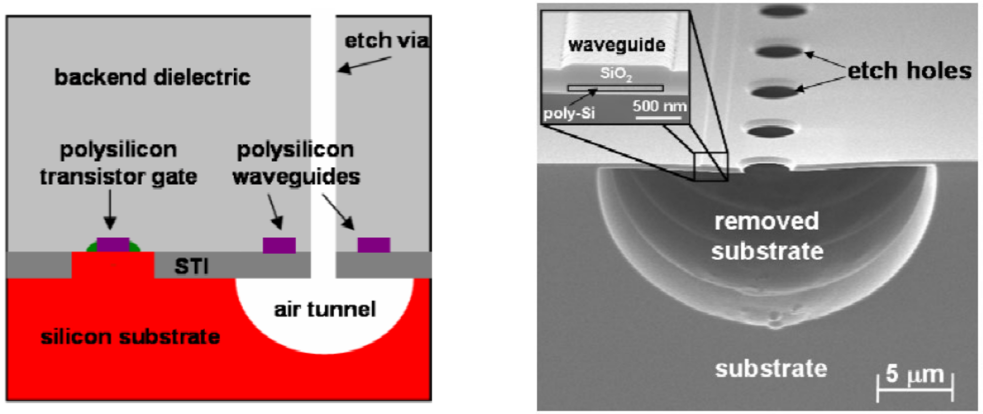
[Narasimha JSSC 2007]



- SOI processes have thicker buried oxide layers to sufficiently confine the optical mode
- Allows for relatively low-loss waveguides, with typical reported values of ~1dB/cm

CMOS Waveguides – Bulk CMOS

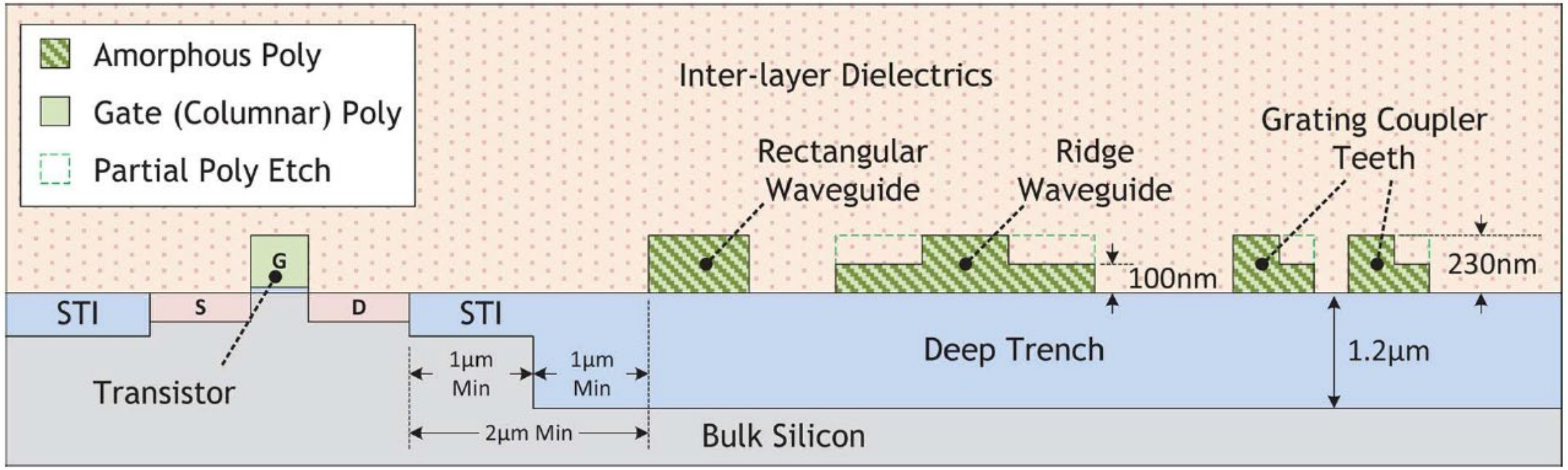
[Holzwarth CLEO 2008]



- Waveguides can be made in a bulk process with a polysilicon core surrounded by an SiO_2 cladding
- However, thin STI layer means a significant portion of the optical mode will leak into the Si substrate, causing significant loss (1000dB/cm)
- Significant post-processing is required for reasonable loss (10dB/cm) waveguides in a bulk process

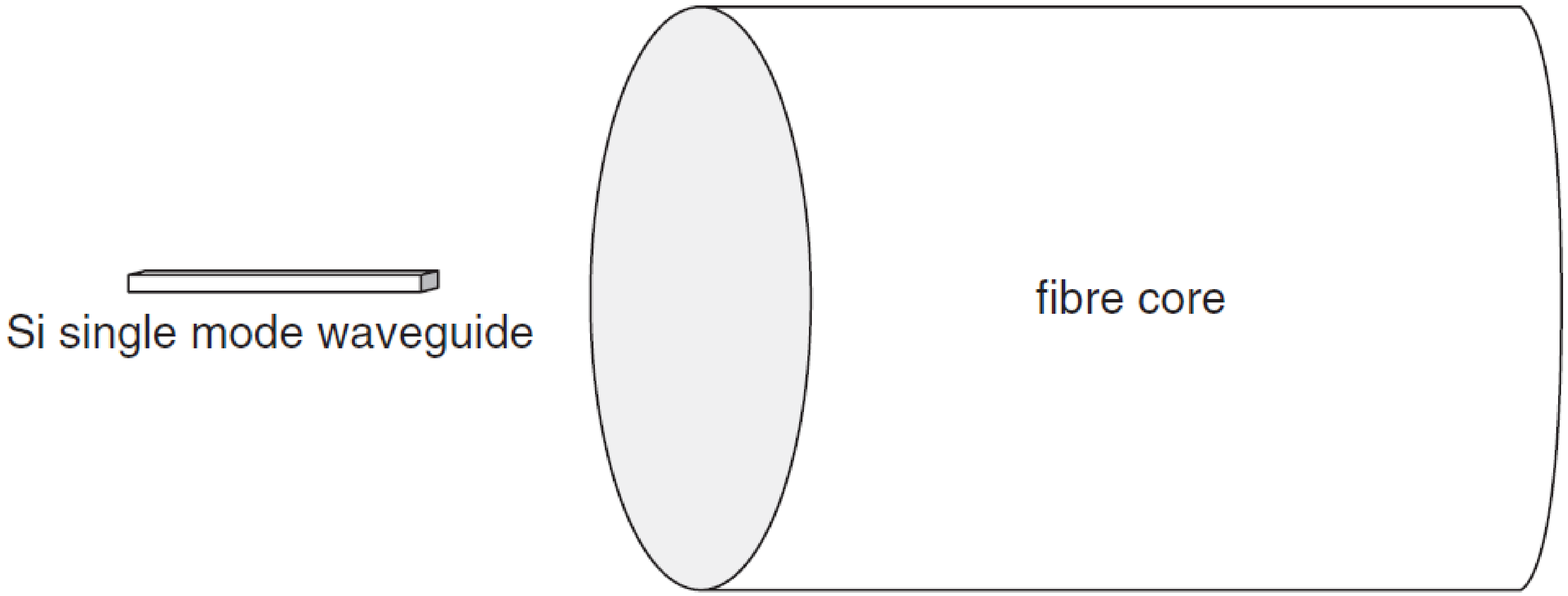
CMOS Waveguides – Bulk CMOS

[Sun JSSC 2015]



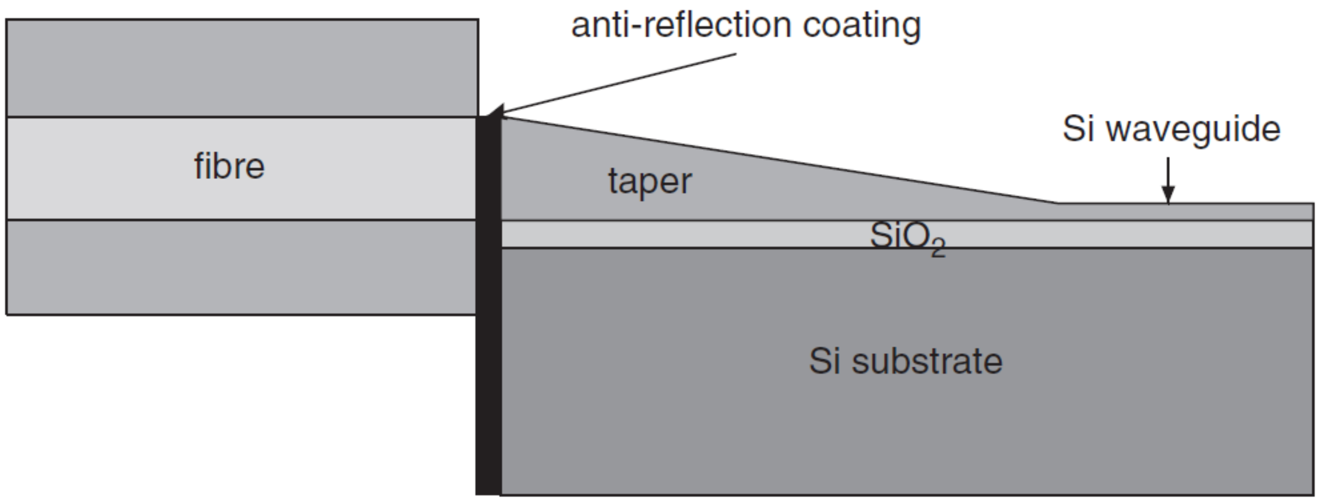
- Introducing additional processing steps can also allow photonics in bulk CMOS
- Key step is the introduction of a deep-trench isolation oxide layer between the waveguides and the substrate
- Another partial polysilicon etch step allows for ridge waveguides and improved coupler design
- Reported loss is still close to 10dB/cm

Coupling In & Out of the Chip



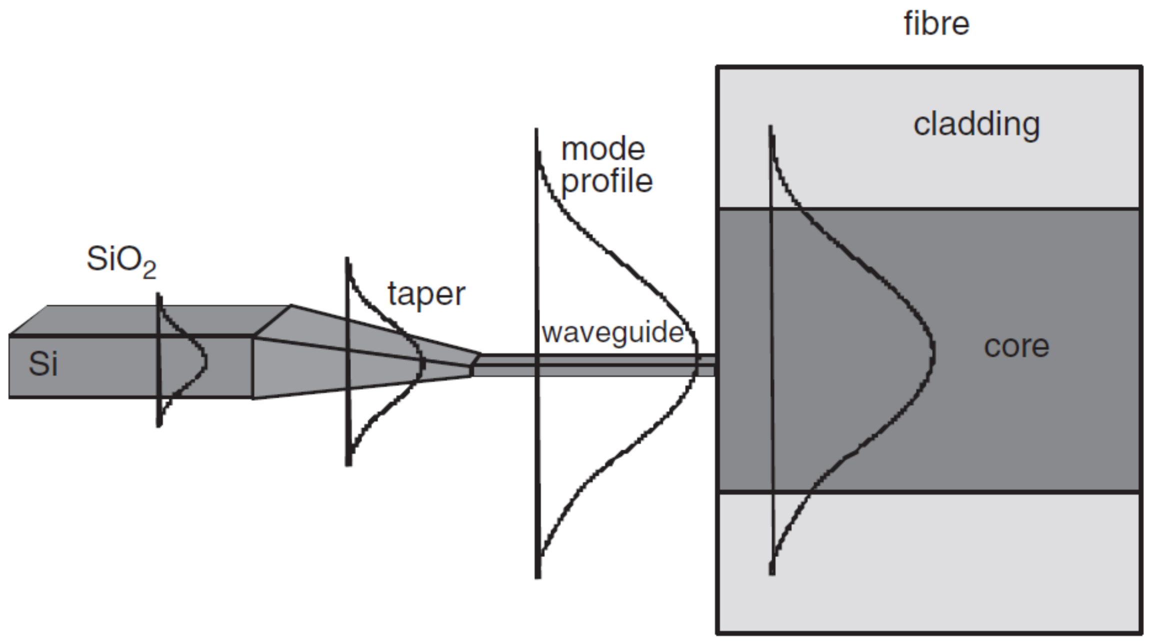
- Butt or edge coupling of small silicon waveguides is inefficient, with ~20dB of loss common
- Thus, efficient mode converters or couplers are necessary

Vertically-Tapered Waveguide



- Waveguide height is increased near the edge of the chip to create an adiabatic taper
- Ideally, this transforms the fiber mode to the waveguide mode
- Reported losses are near 3dB

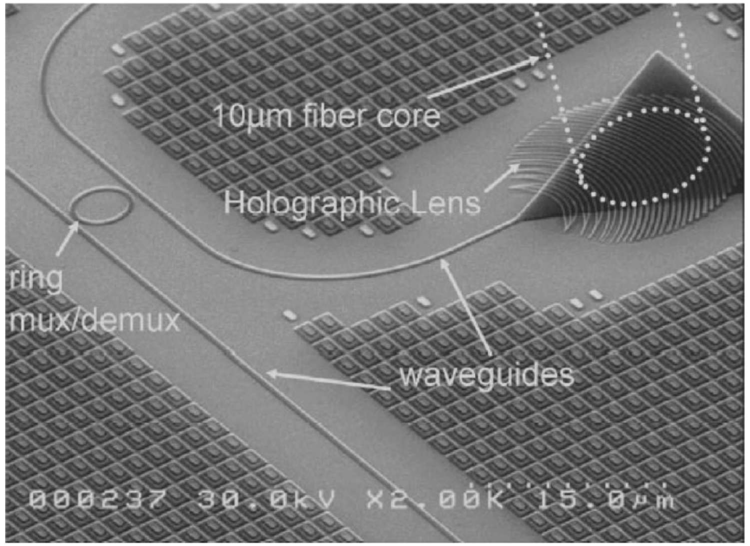
Inverted-Tapered Waveguide



- Tapering the waveguide height down can cause the mode to become delocalized from the waveguide core and better match the fiber core
- Can actually achieve better coupling, with better than 1dB loss reported

Surface Grating Couplers

- Surface grating couplers are often more convenient for systems
- Here the fiber is brought in at a specific angle and the vertical light is coupled into the horizontal waveguide
- Loss of 1-1.5dB has been reported for over a 20nm (1537-1557nm) range



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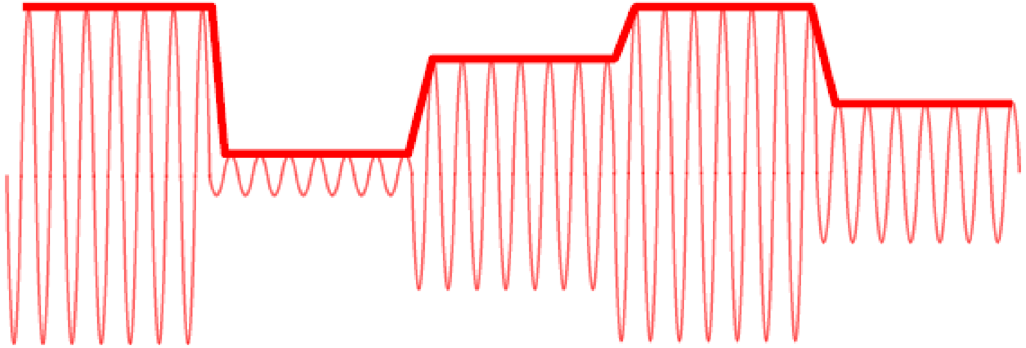
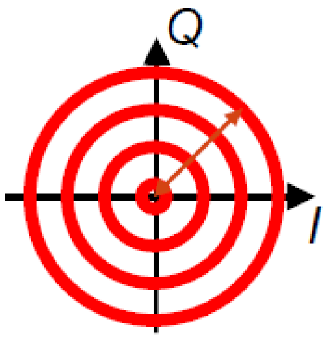
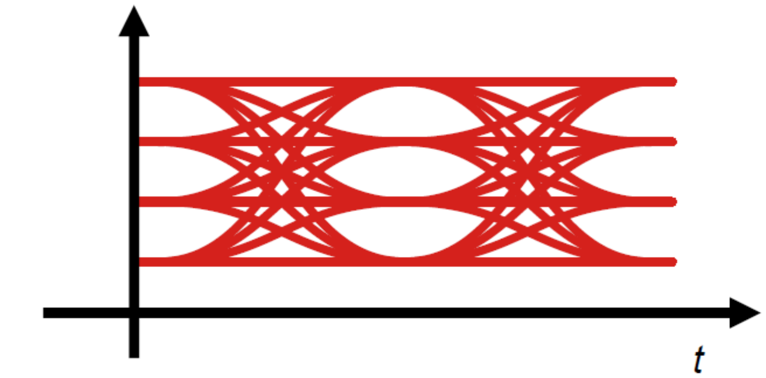
Intensity Modulation Direct Detection (IMDD)

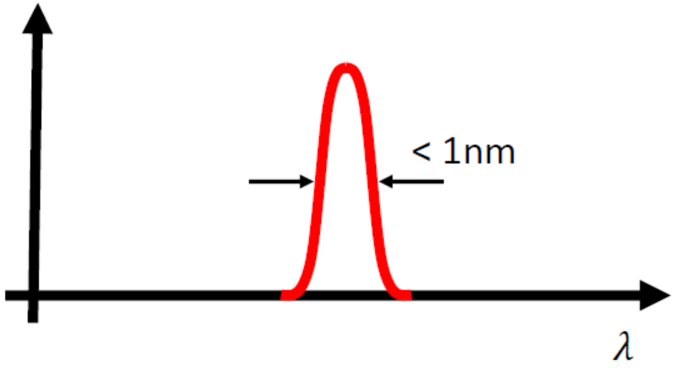
[Chan Carusone VLSI 2023]



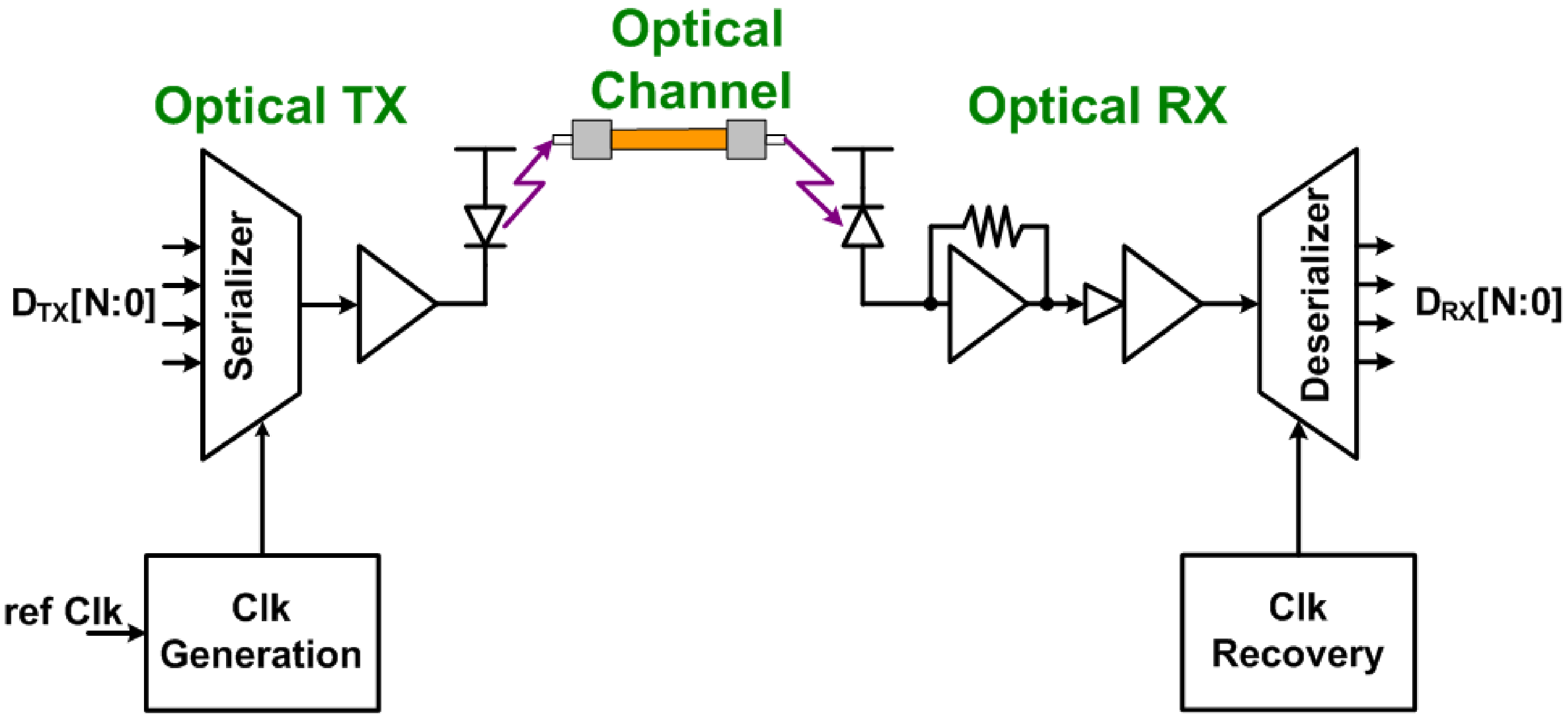




- Symbols modulated in optical "intensity", $|E|^2$, and the receiver "directly detects" this intensity/power level
- Effectively doing amplitude modulation on the optical carrier (1550nm = 194THz)
- Optical bandwidth is proportional to the baud rate
  - 100GBd modulation would induce approximately 100GHz bandwidth around the optical carrier, or 0.8nm in the wavelength domain



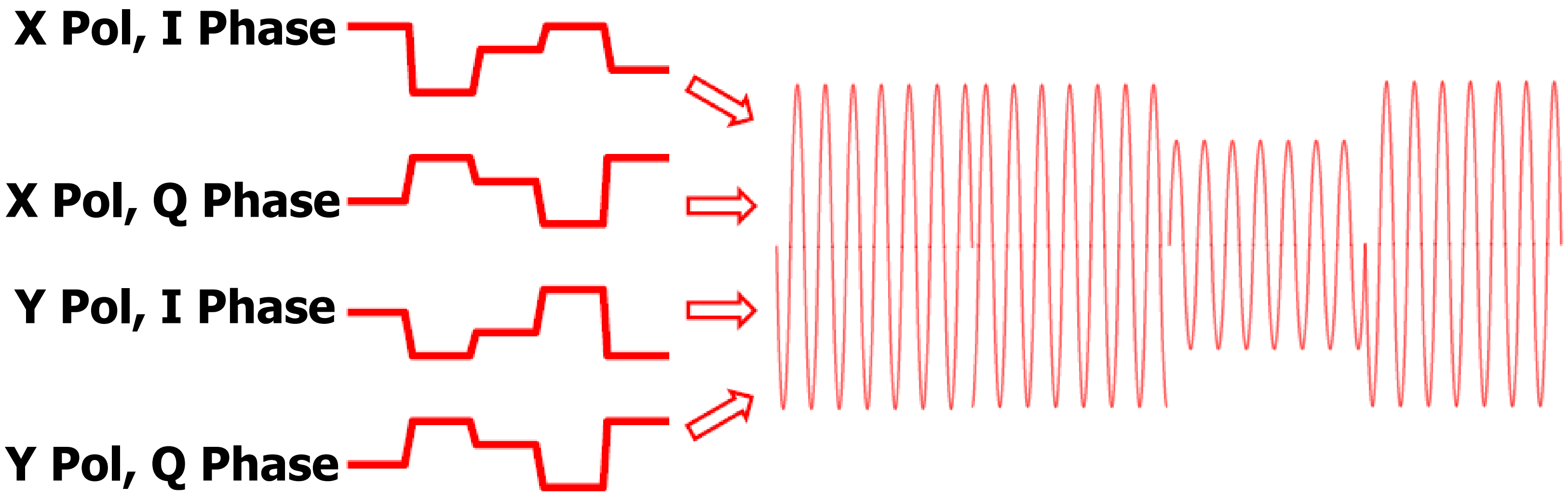
Simple IMDD Transceiver

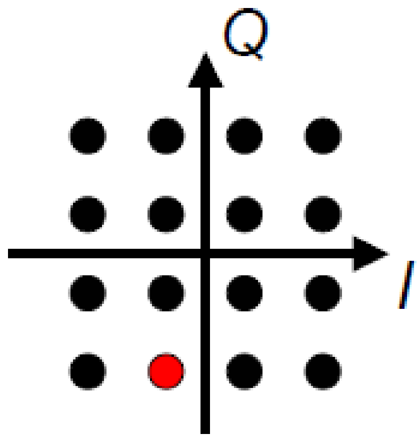


- The signal is transmitted with the optical carrier power either directly modulated with a single laser or externally modulated with a single optical modulator
- At the receiver, a single photodiode acts as a "square-law" detector and detects the incoming signal intensity/power and converts this to a photocurrent
  - Power of the photocurrent is proportional to the square of the optical power

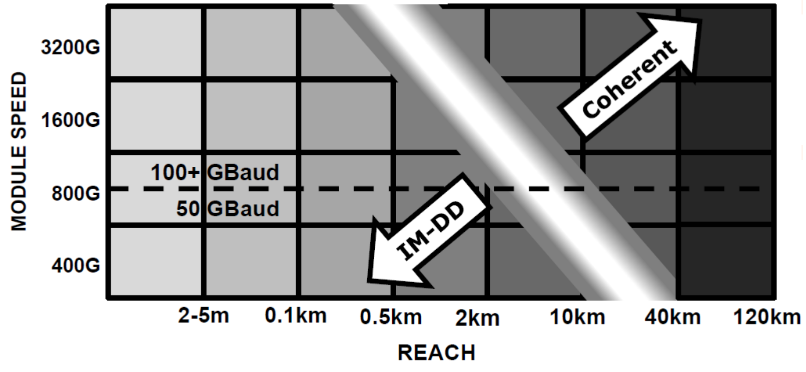
Coherent Optical Communication

[Chan Carusone VLSI 2023]

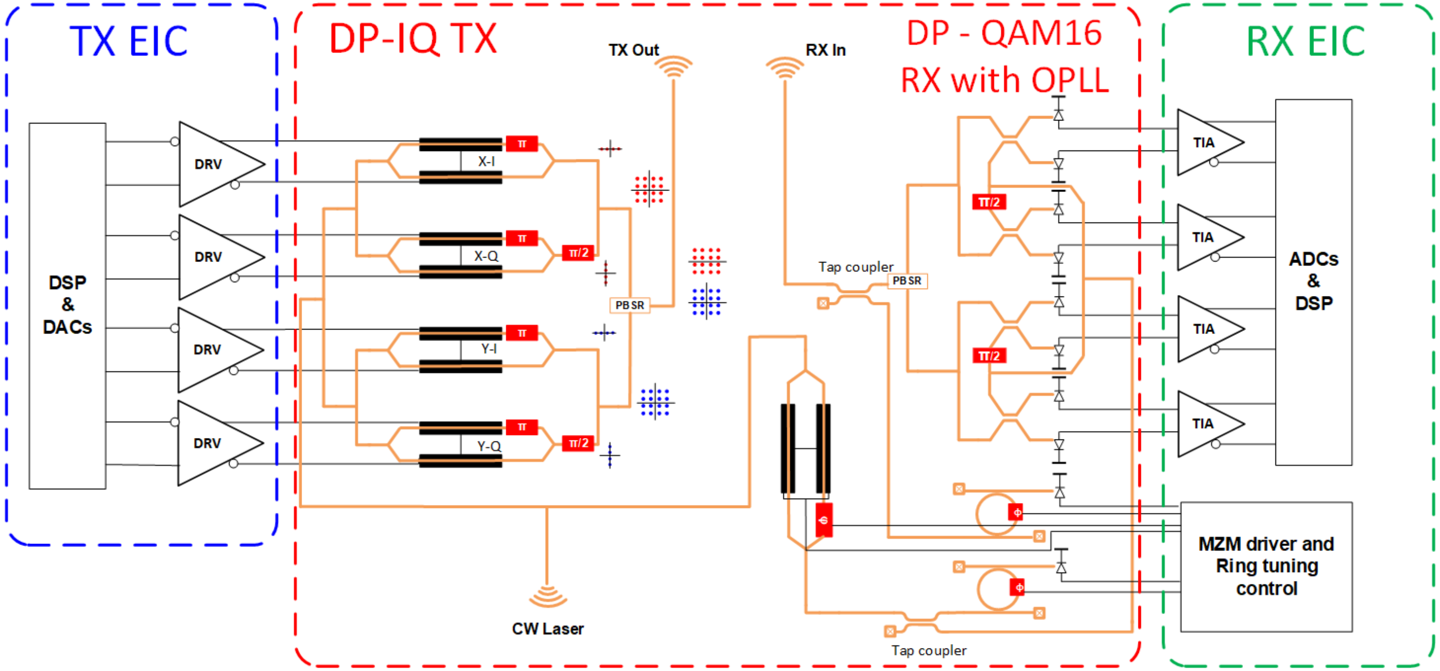




- Symbol encoded in optical carrier power and phase
- Allows for 4 independent data streams on a single wavelength
  - I & Q phase
  - Dual polarization (X & Y)



Dual-Polarization Coherent Transceiver

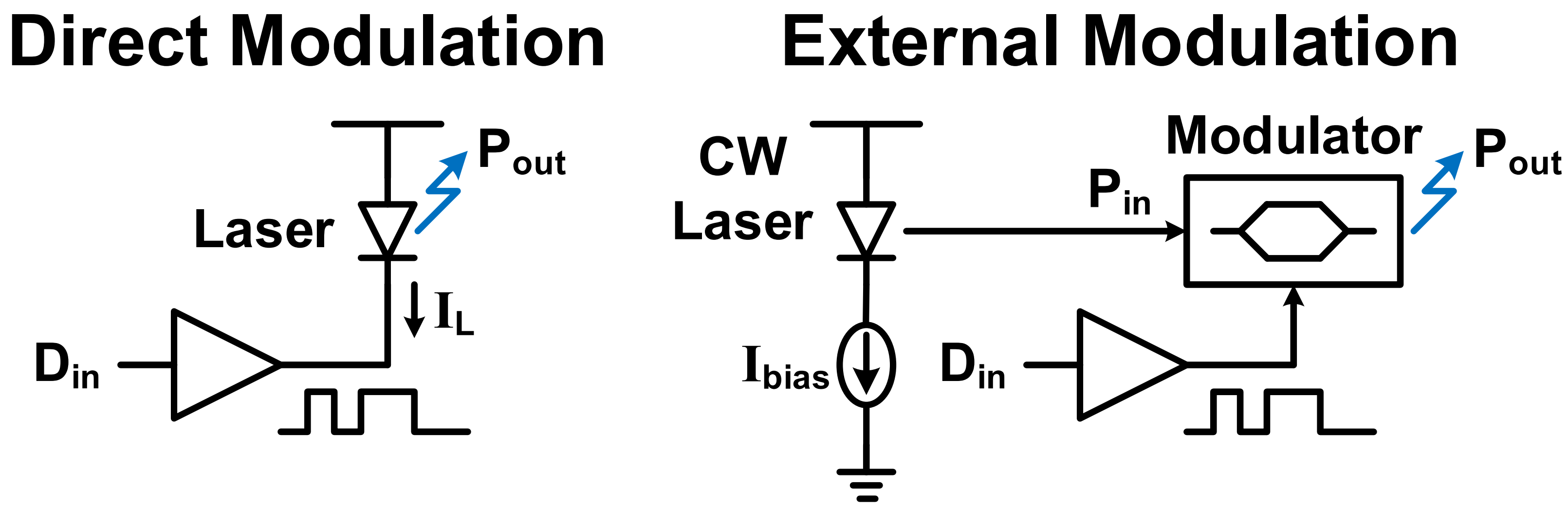


- At the transmitter, 2 modulators perform I/Q signal up-conversion to the optical carrier for the 2 polarizations
  - 4 total modulators
- At the receiver, the signal is down-converted with an optical hybrid and balanced photodetectors
- Phase must be tracked
  - Commonly done in the electrical DSP
  - Optical PLL offers the potential for lower-complexity “analog” coherent transceivers

Outline

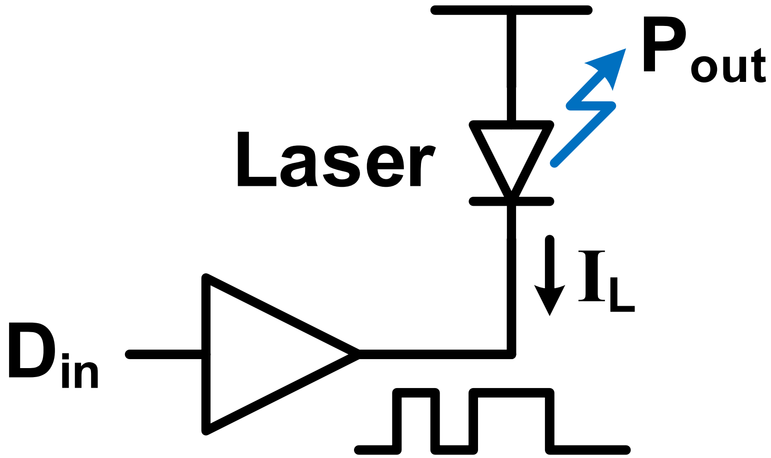
- Optical Interconnect Motivation
- Optical Channel Properties
- IMDD and Coherent Transceivers
- Transmitter Properties and Devices
- Receiver Architecture and Devices
- Conclusion

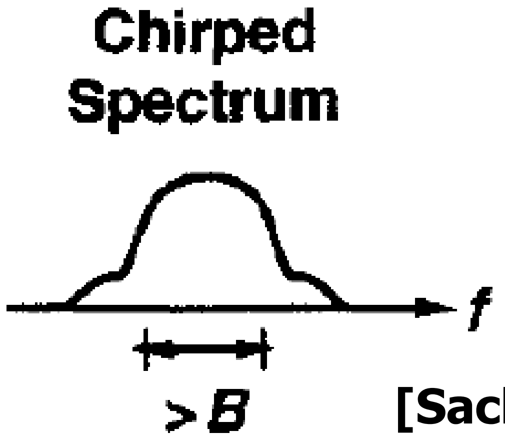
Optical Modulation Techniques



- Two modulation techniques
  - Direct modulation of laser
  - External modulation of continuous-wave (CW) "DC" laser with absorptive or refractive modulators

Directly Modulated Laser

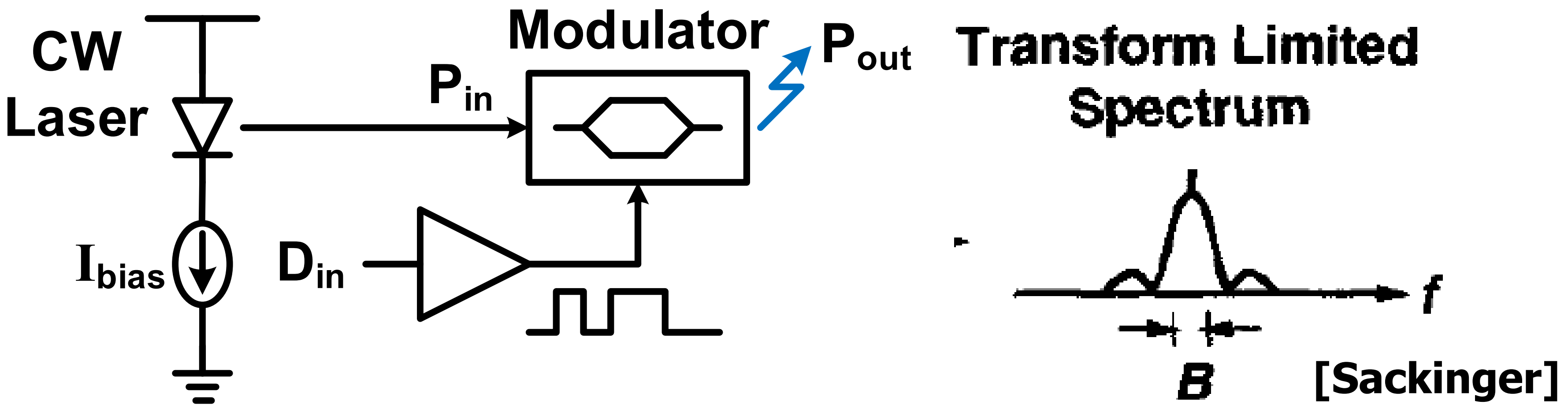




[Sackinger]

- Directly modulating laser output power
- Simplest approach
- Introduces laser “chirp”, which is unwanted frequency (wavelength) modulation
- This chirp causes unwanted pulse dispersion when passed through a long fiber

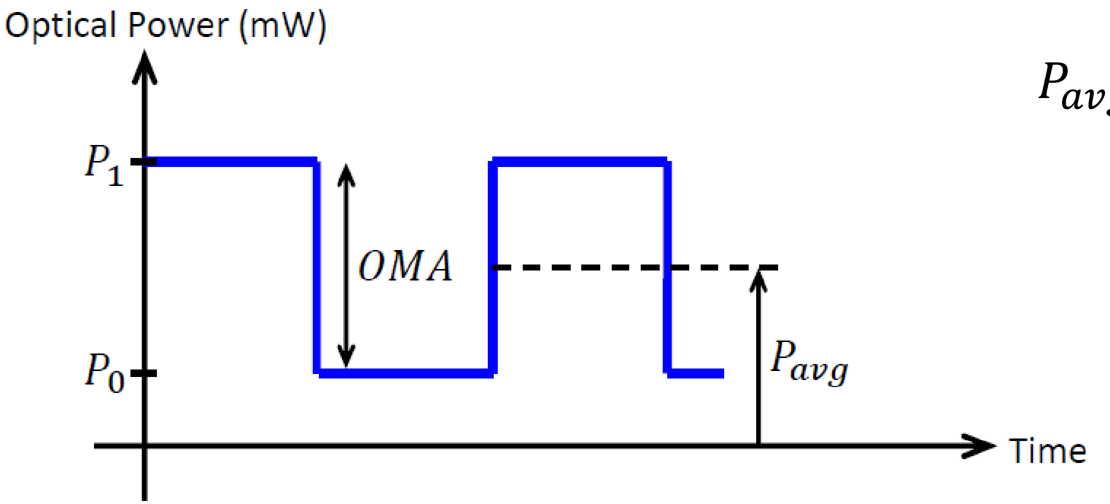
Externally Modulated Laser



- External modulation of continuous-wave (CW) "DC" laser with absorptive or refractive modulators
  - Adds an extra component
  - Doesn't add chirp, and allows for a transform limited spectrum

Basic Definitions

[Webster CSICS 2015]



Average Optical Power

$$P_{avg} = \left(\frac{P_1 + P_0}{2}\right)$$

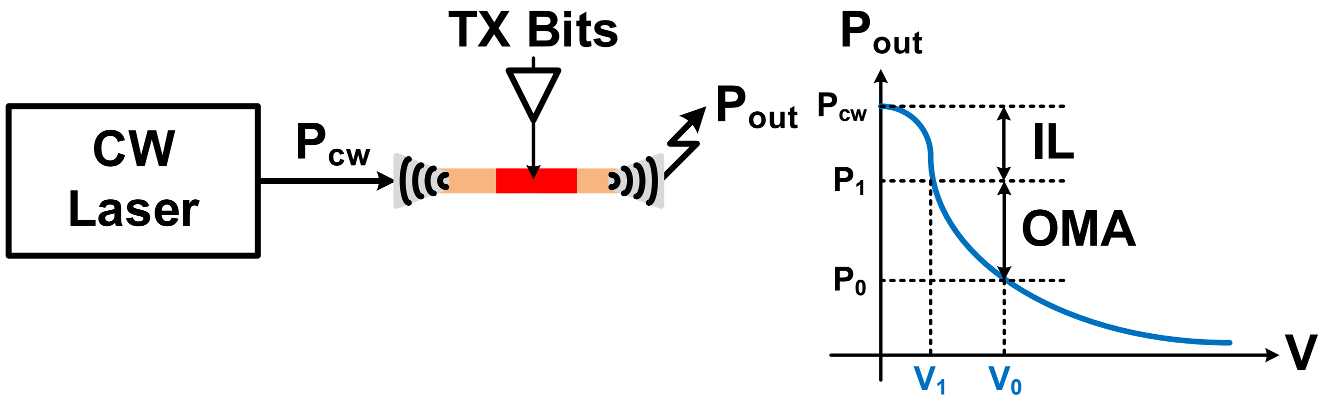
Optical Modulation Amplitude

$$OMA = P_1 - P_0$$

Extinction Ratio

$$ER = \frac{P_1}{P_0}$$

$$OMA = 2P_{avg}\left(\frac{ER - 1}{ER + 1}\right) \qquad P_{avg} = \frac{1}{2} OMA \left(\frac{ER + 1}{ER - 1}\right)$$



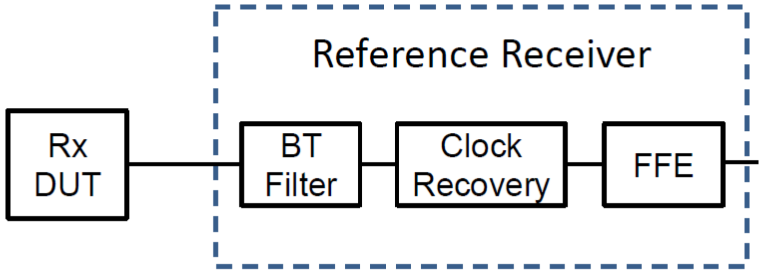
Modulator OMA Penalty

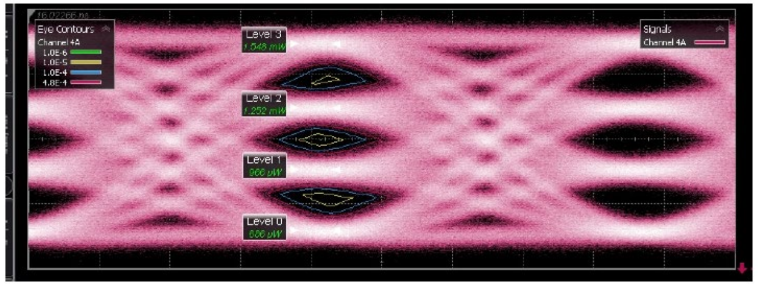
$$TP_{OMA} = \frac{P_{CW}}{P_1 - P_0} = \frac{P_{CW}}{OMA} = \frac{ER}{IL(ER - 1)}$$

Transmitter and Dispersion Eye Closure Quaternary (TDECQ)

- Optical transmitter specification that captures the impact of TX nonidealities on RX OMA sensitivity
  - TX with 3dB TDECQ will require the RX OMA sensitivity to be 3dB better for the same SER
- Measured with a reference receiver consisting of a 4th-order Bessell-Thomson lowpass filter and 5-tap FFE
- Ideal PAM4 tolerable noise: $\sigma_{ideal} = \frac{OMA}{2Q^{-1}(\frac{2}{3}SER_{target})}$
- Measurement calculates the actual noise that can be added to the TX to achieve the target SER, which will be less than σ_{ideal} due to nonidealities

[Chan Carusone]





$$TDECQ = 10 \cdot \log_{10}(\frac{\sigma_{ideal}}{\sigma_R})$$

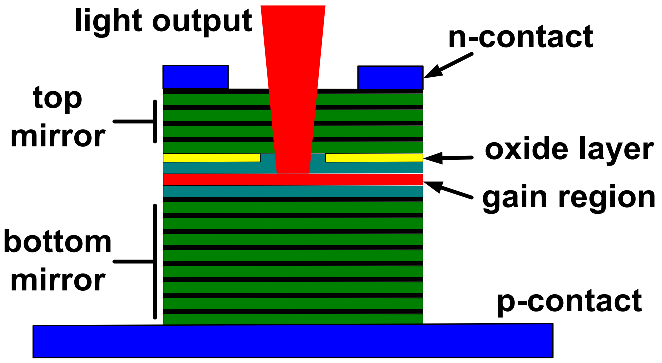
- Typical spec: TDECQ < 2.4dB

Optical Transmitter Devices

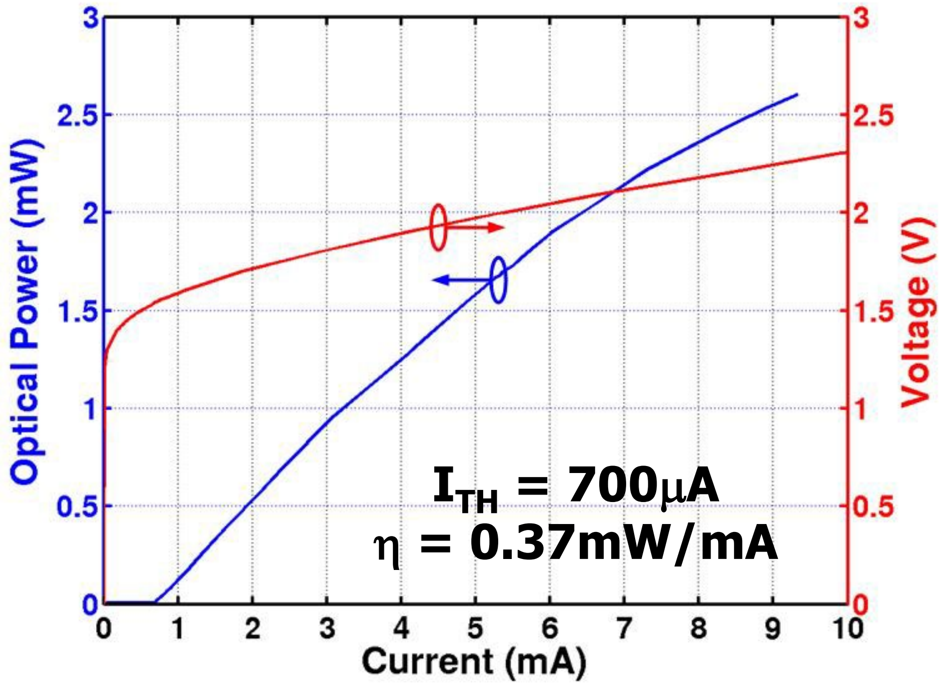
- Vertical-Cavity Surface-Emitting Laser (VCSEL)
- Electro-Absorption Modulator (EAM)
- Ring-Resonator Modulator (RRM)
- Mach-Zehnder Modulator (MZM)

Vertical-Cavity Surface-Emitting Laser (VCSEL)

VCSEL Cross-Section



VCSEL L-I-V Curves



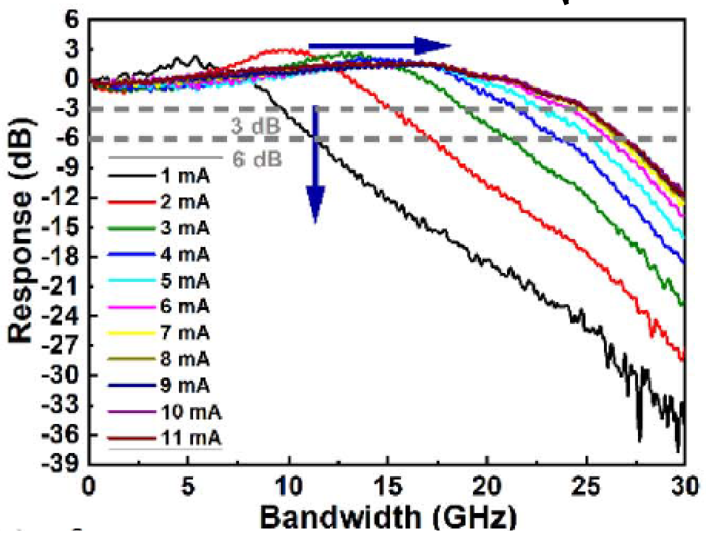
- VCSEL emits light perpendicular from top (or bottom) surface
- Important to always operate VCSEL above threshold current, I_{TH}, to prevent "turn-on delay" which results in ISI
- Operate at finite extinction ratio (P_1/P_0)

$$P_o = \eta\left(I - I_{TH}\right)$$

$$\textbf{Slope Efficiency} \quad \eta = \frac{\Delta P}{\Delta I}\left(\frac{\mathbf{W}}{\mathbf{A}}\right)$$

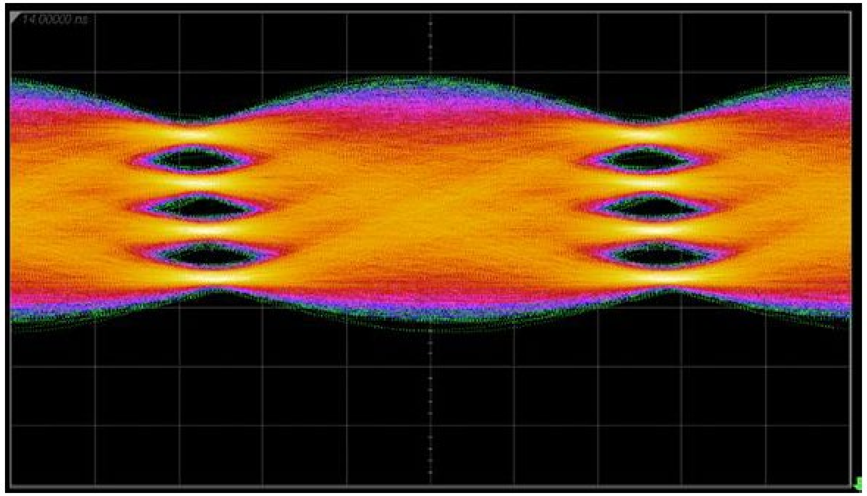
VCSEL Bias-Dependent Bandwidth

[Wu PhRes 2024] $BW \propto \sqrt{I_{avg} - I_{TH}}$



200Gb/s 850nm MM-VCSEL **[Wang PhWest 2025]**

(c) 9mA, 50m (EMB 7500 MHz.km)

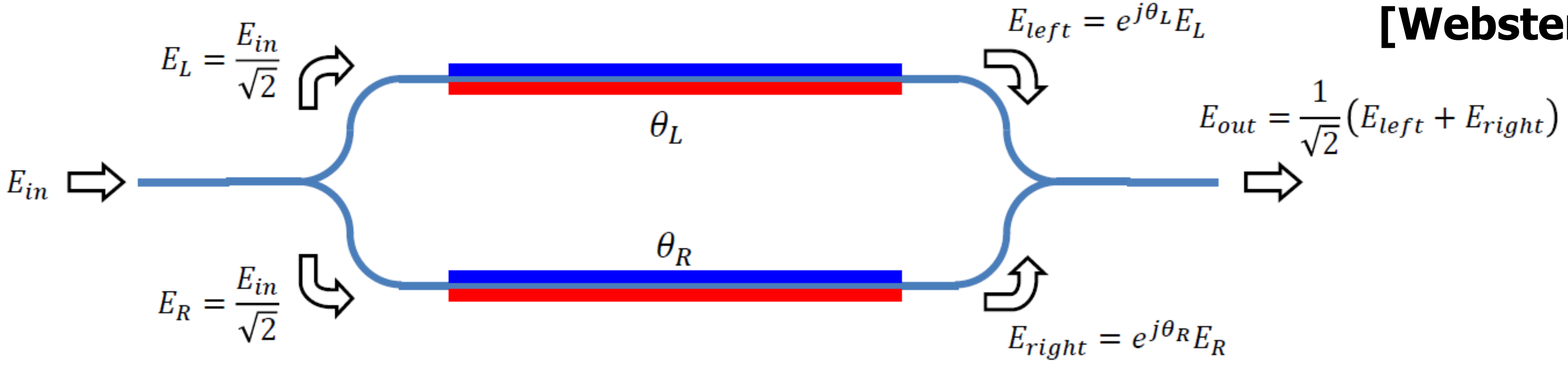


- 9mA bias
- 7-tap TX FIR
- 2.2dB ER
- 50m enhanced MMF
- 25-tap FFE at scope (RX)

- VCSEL electrical impedance and rate equations cause bias-dependent bandwidth
  - State of the art is 39GHz at 9mA bias [Wang PhWest 2025]
- Lower bias results in an underdamped low-bandwidth response
- Driving the VCSELs significantly above threshold reduces ER and results in a speed/power tradeoff
- 200Gb/s PAM4 demonstrated

Mach-Zehnder Modulator (MZM)

[Webster CSICS 2015]



- An optical interferometer is formed with the incoming light split, experiencing phase shifts through the two paths, and then recombined
- Assuming no loss and a perfect 50/50 splitter/combiner

$$\Delta\phi = \frac{(\theta_R - \theta_L)}{2} \qquad \phi = \frac{(\theta_R + \theta_L)}{2}$$

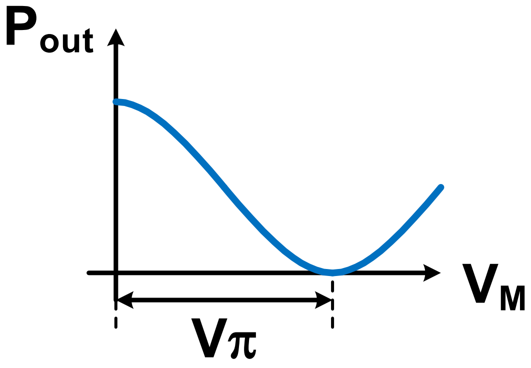
Field Response

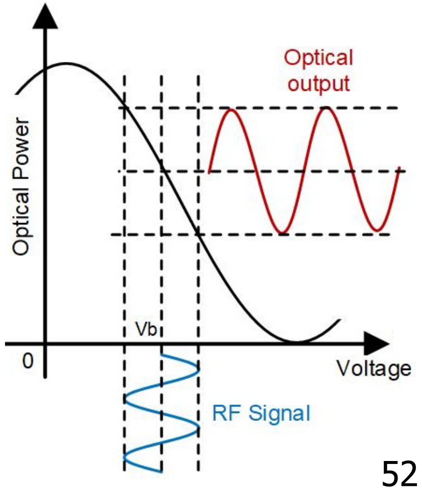
$$E_{out} = E_{in}\cos(\Delta\phi)e^{j\phi}$$

Intensity Response

$$P_{out} = |E_{out}|^2 = \frac{1}{2}|E_{in}|^2[1 + \cos(\theta_R - \theta_L)]$$

$$\frac{P_{out}}{P_{in}} = \frac{1}{2}[1 + \cos(\theta_R - \theta_L)] = \frac{1}{2}\left[1 + \cos\left(\pi \cdot \frac{V_M}{V\pi}\right)\right]$$

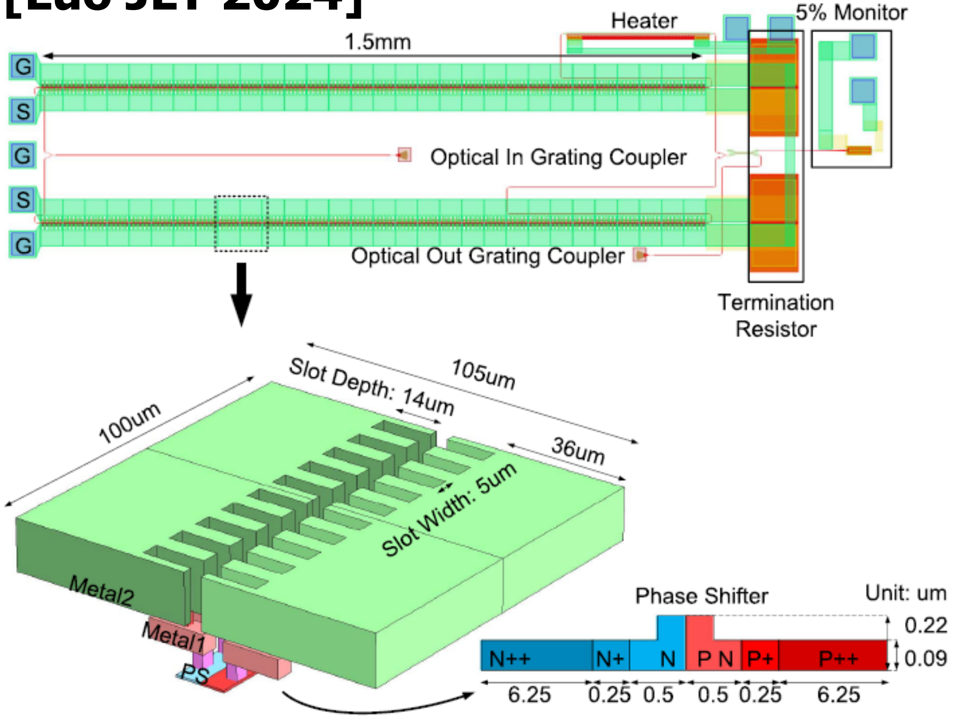


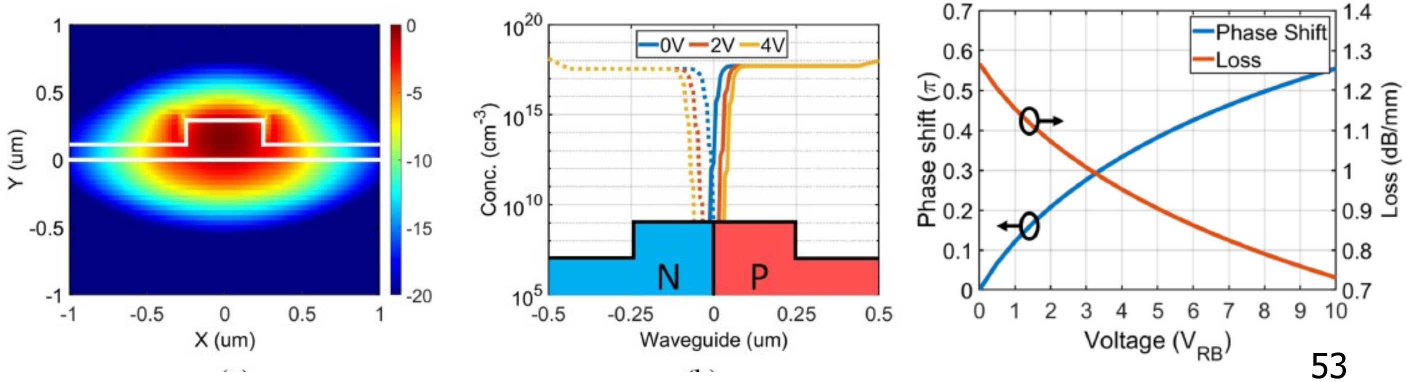


Silicon Photonic MZMs

- Silicon waveguide is doped as a PN junction with the depletion region modulated as a function of the applied reverse bias voltage
- The resultant change in carrier density within the depletion region causes the refractive index to change through the plasma dispersion effect
- Tradeoffs in V_{Π}, bandwidth, and loss
- Typical values
  - $V_{\Pi}L$ = 1.5-2V*cm
  - V_{Π} = 6-7V
  - BW = 30-35GHz
- Results in mm-scale devices typically driven in a traveling-wave manner

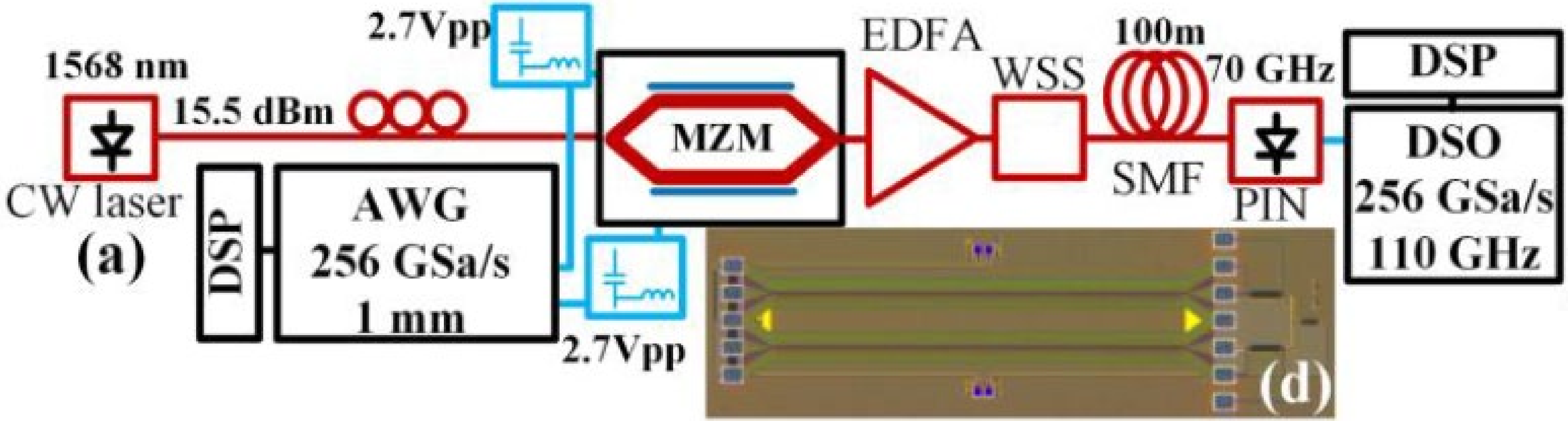
[Luo JLT 2024]

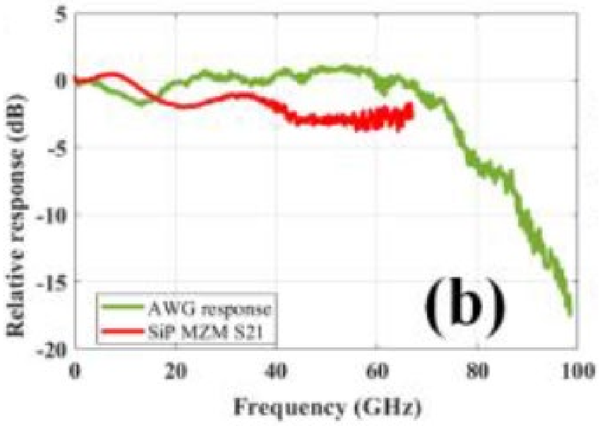




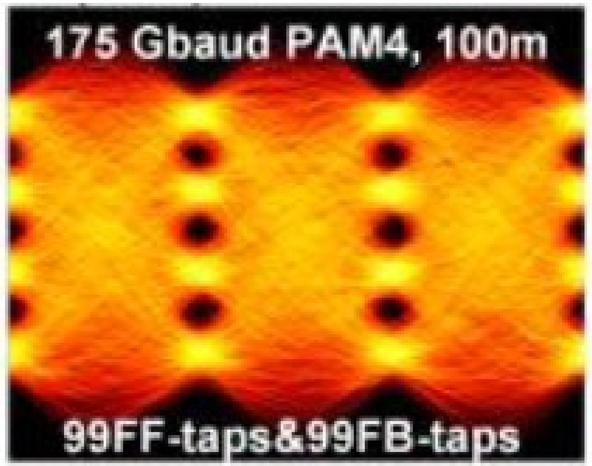
42GHz Silicon Photonic MZM

[Ostrovskis OFC 2025]





350Gb/s PAM4

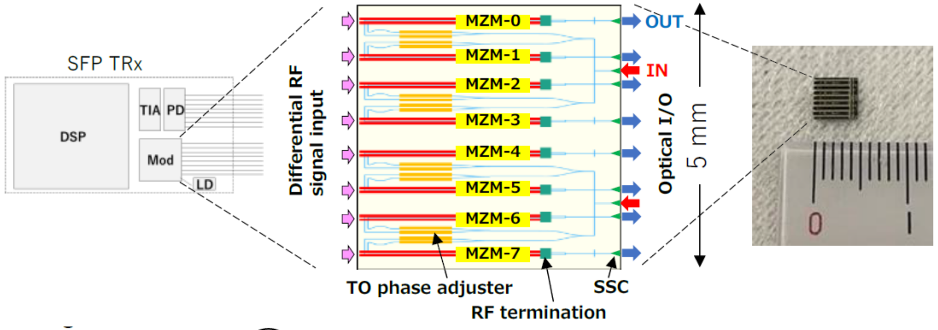


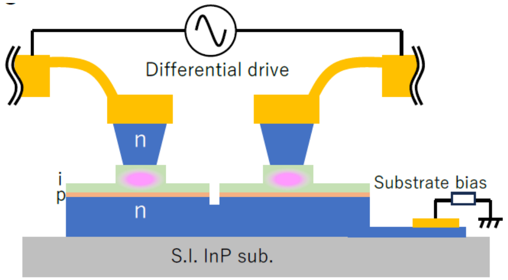
- 42GHz bandwidth with 2.5V bias
- $V_{\Pi}L$ = 1.7V*cm
- L=1.5mm
- 3.6dB insertion loss plus 2.5dB per grating coupler
- 350Gb/s PAM4 operation achieved with scope (RX) equalization of 99-tap FFE and 99-tap DFE

InP MZMs

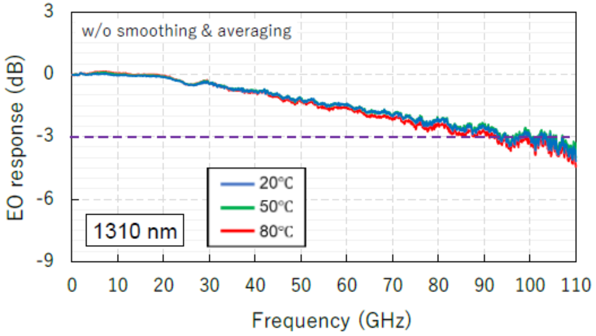
- InP MZMs are commonly used for long-reach transmission due to small V_{Π}, high bandwidth, and low chirp
- Comparable with differential drive
- InP is generally an expensive material
- State of the art is 100GHz bandwidth that achieved 430Gb/s PAM6
  - 65Ω differential impedance
  - Mismatch with 100Ω AWG required a 4001 tap T/2-spaced FFE
  - RX DSP used 61-tap T/2-spaced FFE

[Ogiso OFC 2025]
8-Channel Module

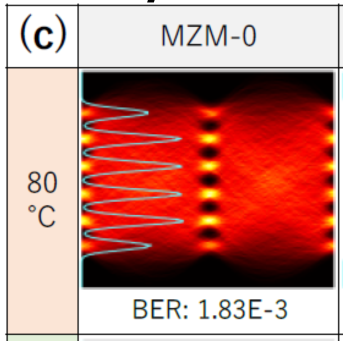




100GHz Bandwidth

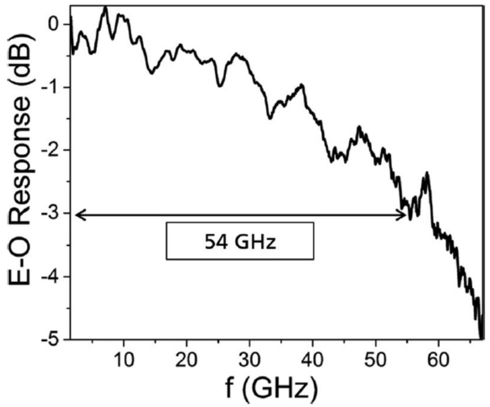


430Gb/s PAM6

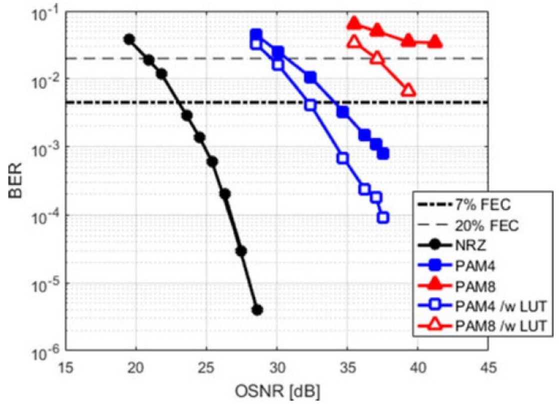


InP Monolithic DFB Laser + MZM

[Lange JLT 2018]

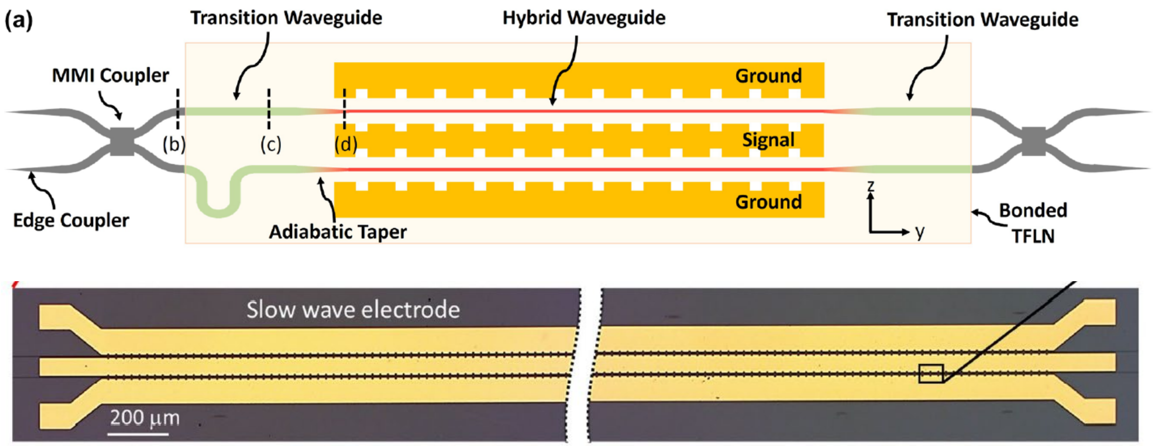


100GBd BER

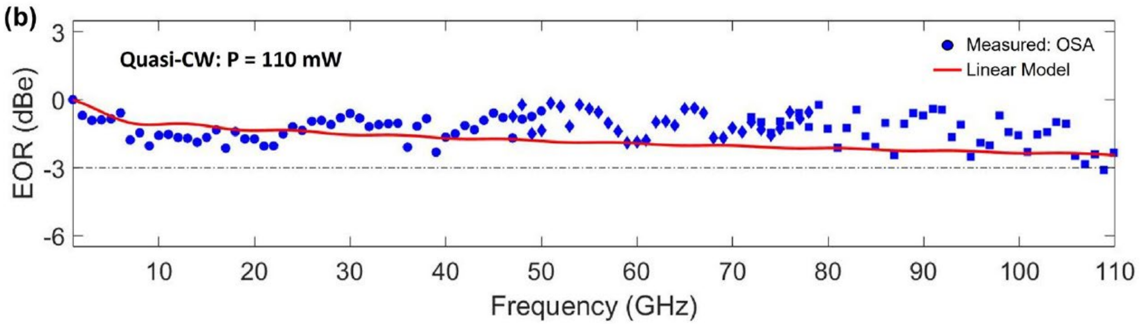


- InP platform allows for monolithic DFB laser and MZM integration
- MZM parameters
  - 54GHz bandwidth
  - $V_{\Pi} = 2V$
  - $V_{\Pi}L = 0.55V*cm$
- 200Gb/s PAM4 operation achieved with 7% FEC
- 300Gb/s PAM8 possible with 20% FEC and LUT-based equalizer

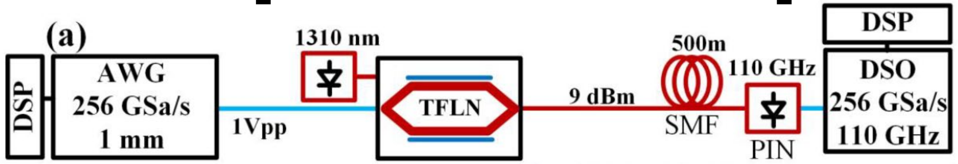
Thin-Film Lithium Niobate (TFLN) MZM



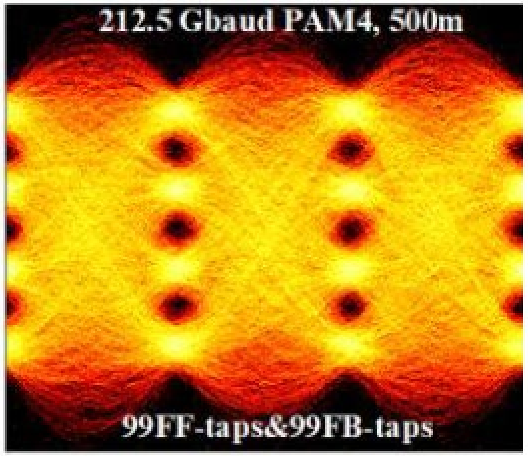
[Valdez SciRep 2022]



[Ostrovskis OFC 2025]



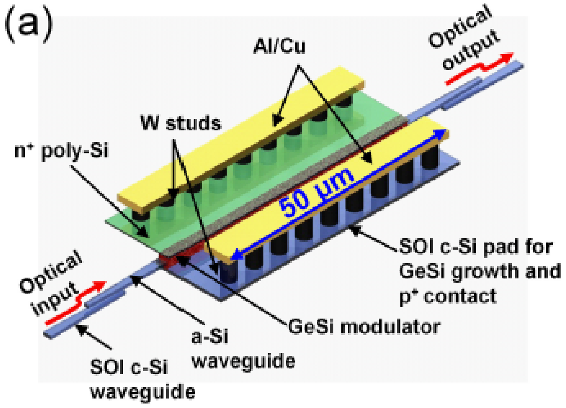
425Gb/s PAM4



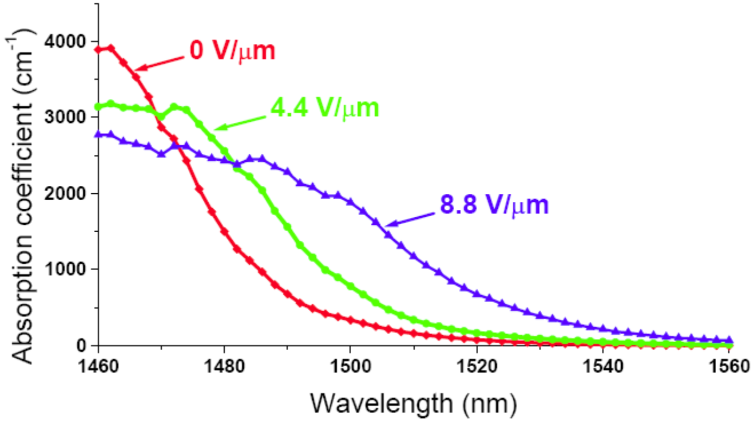
- Low loss and high bandwidth allow for longer modulators with low V_Π values
- 110GHz MZM realized by bonding LN on Si waveguides
  - Potential to leverage existing SiP platforms
  - $V_\Pi L$ = 3.1V*cm
  - L=5mm
  - 1.8dB insertion loss
- 425Gb/s PAM4 demonstrated with similar device

Electro-Absorption Modulator (EAM)

Waveguide EAM [Liu 2008]



[Helman JSTQE 2005]

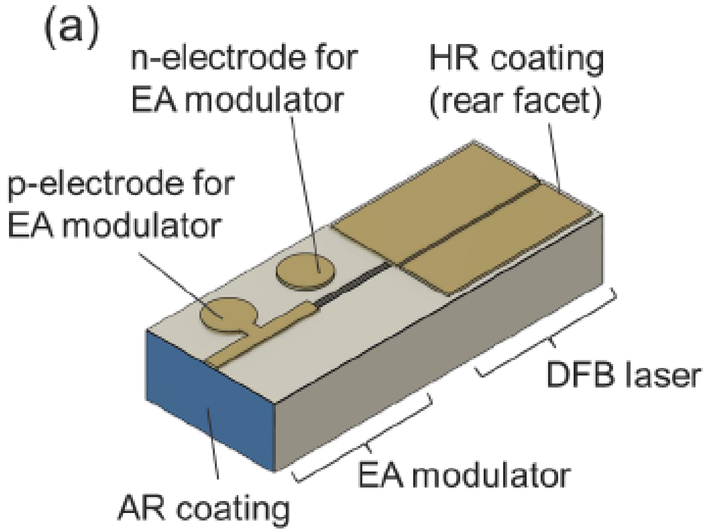


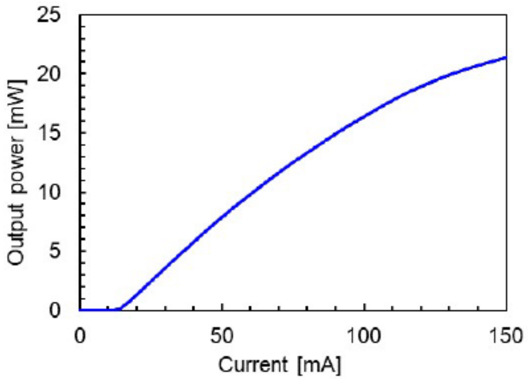
- Electro-absorption modulators operate with voltage-dependent absorption of light passing through the device
- The device structure is a reverse-biased p-i-n diode
- The Franz-Keldysh effect describes how the effective bandgap of the semiconductor decreases with increasing electric field, shifting the absorption edge
- While this effect is weak, it can be enhanced with device structures with multiple quantum wells (MQW) through the quantum-confined Stark effect

Monolithic DFB Laser + EAM (EA-DFB)

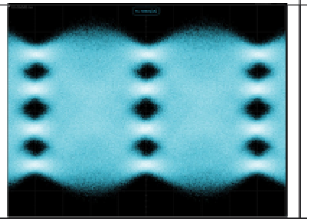
- InP platform allows for monolithic DFB laser and EAM integration
- DFB laser operates in forward bias and the EAM is in reverse bias
- 226Gb/s PAM4 operation achieved with 15-tap TX FFE
  - Semi-insulating substrate allows for 4 independent electrodes, 2 for DFB and 2 for EAM
  - Allows for differential drive of EAM
  - 5.1dB extinction ratio with $2V_{ppd}$ swing

[Ohno OFC 2025]

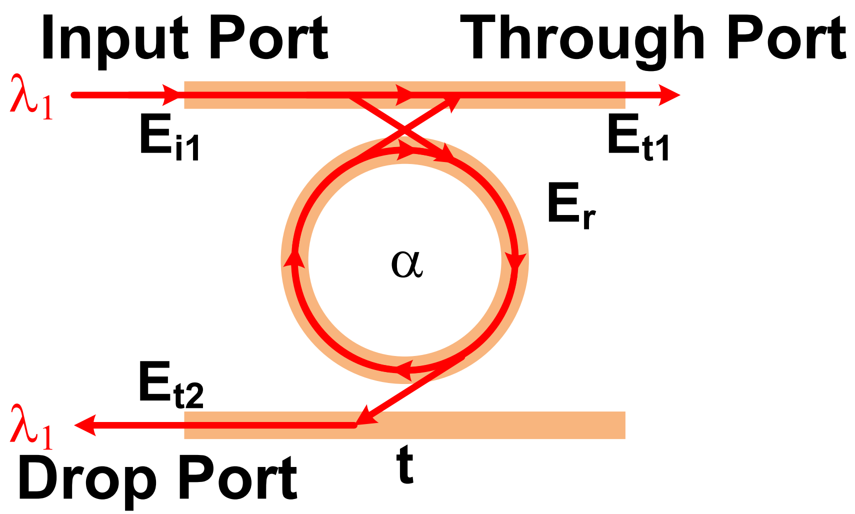


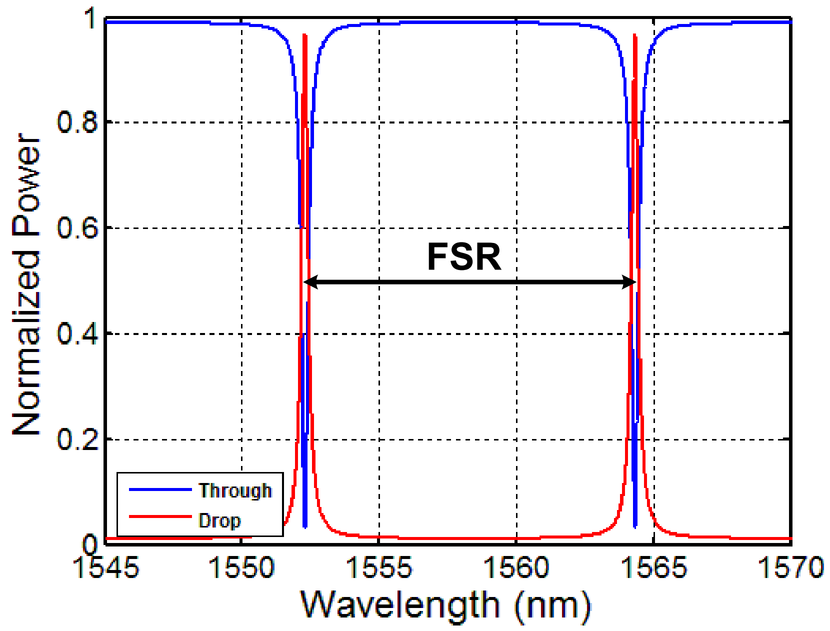


226Gb/s PAM4

Fiber length	BTB
OuterER [dB]	4.8
TDECQ [dB]	2.13
Waveform with 15-tap FFE	

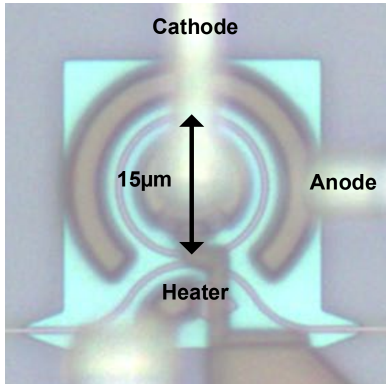
Ring Resonator Filter

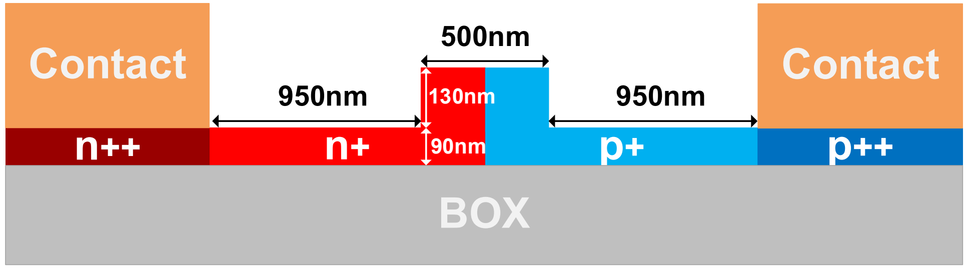


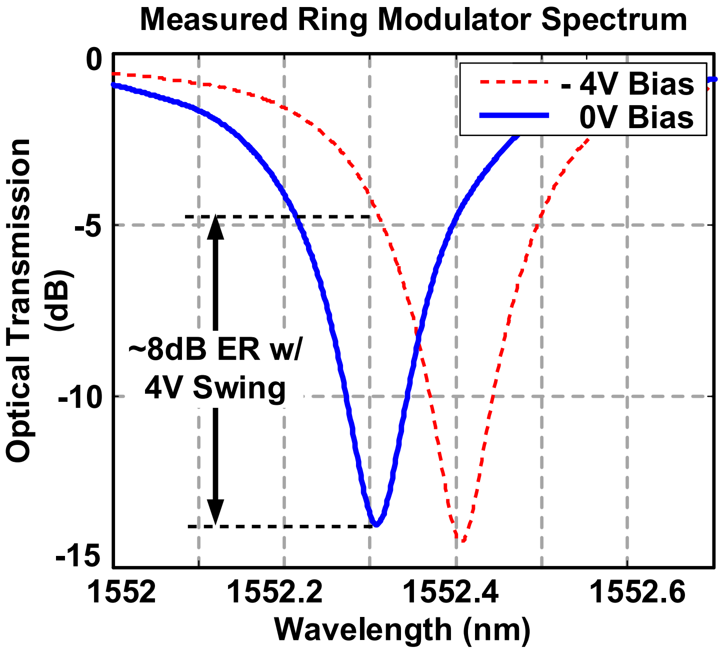


- Ring resonators display a high-*Q* notch filter response at the through port and a band-pass response at the drop port
- This response repeats over a free spectral range (FSR)

Carrier-Depletion Ring Modulator

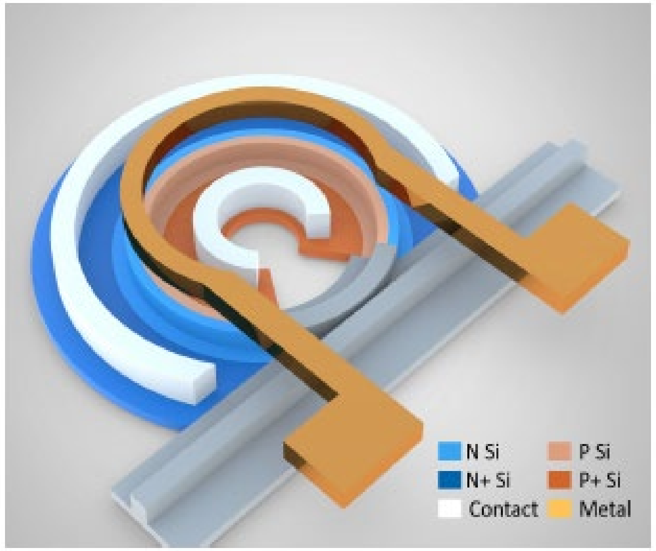




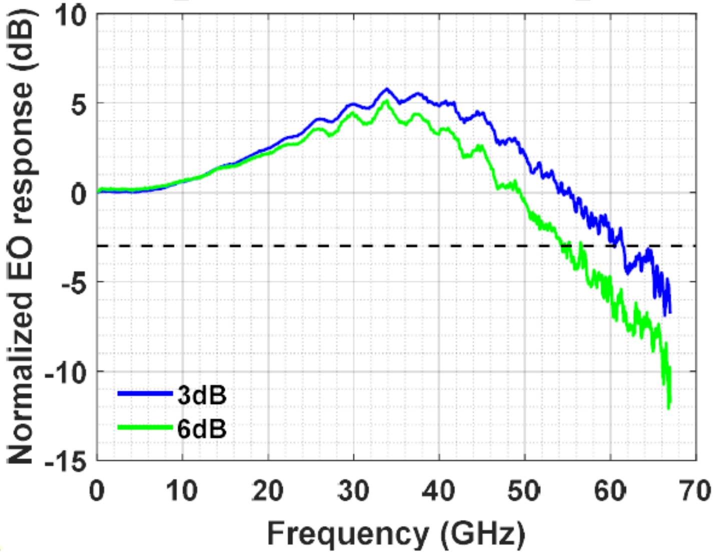


	ISSCC 2013	ISSCC 2015
Ring Type	Injection	Depletion
Doping Profile	PIN	Lateral PN
Q	8000	5000
Tunability (pm/V)	350	25
Data Rate	9Gb/s	25Gb/s
Swing for >7dB ER	$< 2V_{pp}$	$> 4V_{pp}$

240Gb/s PAM4 RRM

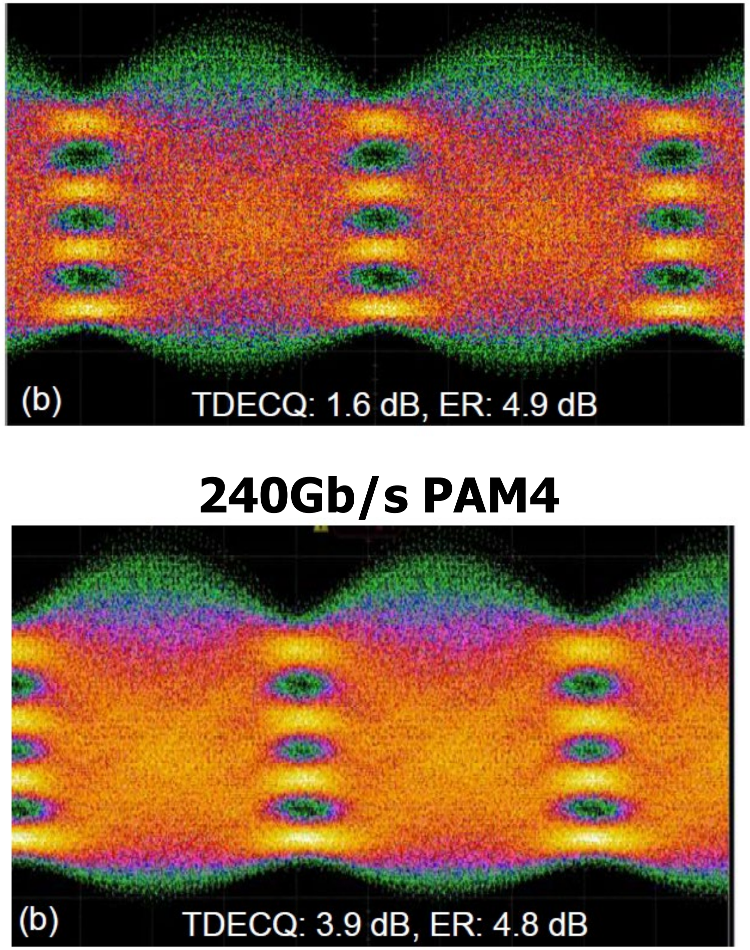


[Sakib OFC 2022]



224Gb/s PAM4

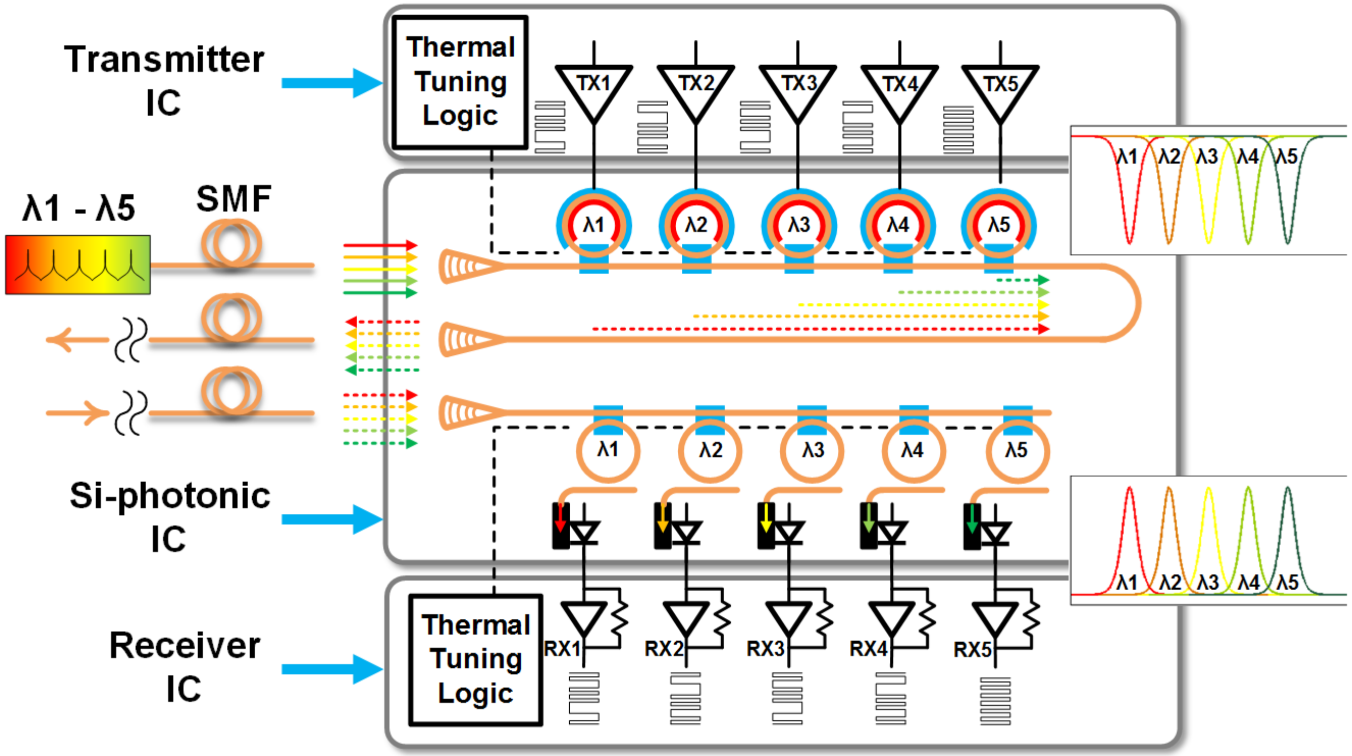
240Gb/s PAM4



- 4mm radius ring for reduced capacitance and 16.3nm FSR
  - Capable of supporting 12 DWDM channels with 200GHz spacing
- Q=4000
- Intrinsic RC bandwidth of 100GHz

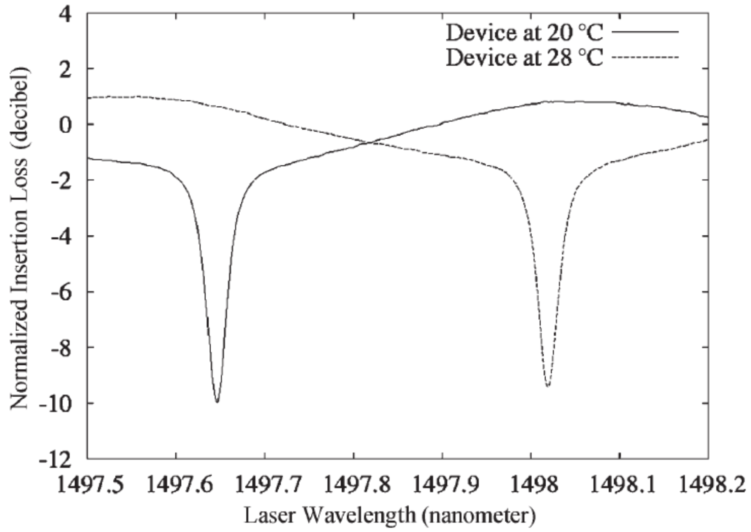
Wavelength Division Multiplexing w/ Ring Resonators

- Ring resonators can act as both modulators and add/drop filters to steer light to receivers or switch light to different waveguides
- Potential to pack >30 waveguides, each modulated at more than 10Gb/s on a single on-chip waveguide

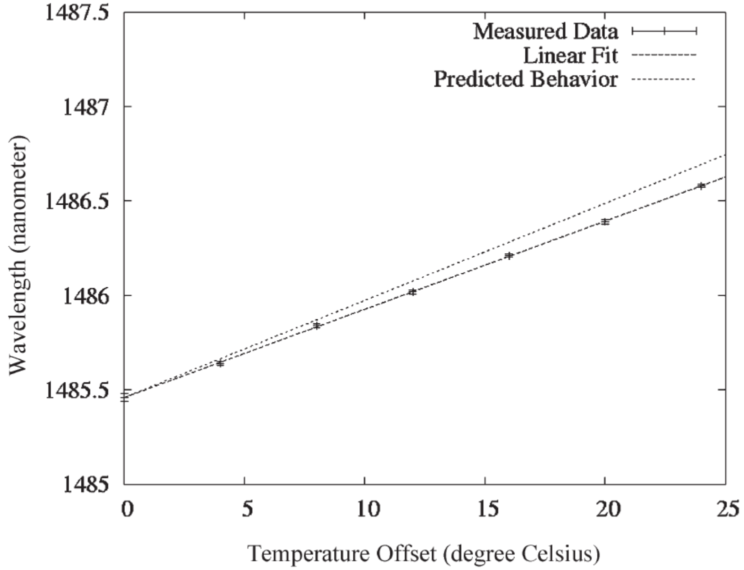


RRM Thermal Sensitivity

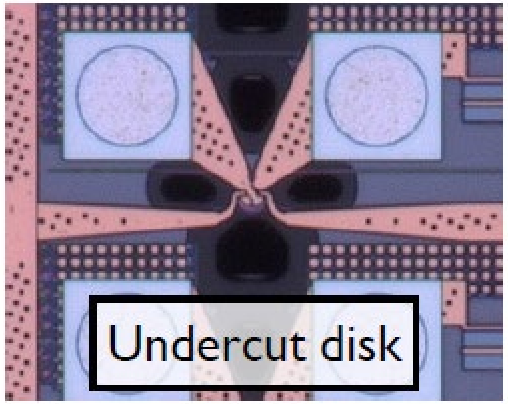
$$\mathrm{d}n_{\mathrm{eff}} = \left(\frac{\partial n_{\mathrm{eff}}}{\partial \varepsilon_{\mathrm{c}}}\right)\left(\frac{\partial \varepsilon_{\mathrm{c}}}{\partial T}\right)\mathrm{d}T + \left(\frac{\partial n_{\mathrm{eff}}}{\partial \lambda}\right)\mathrm{d}\lambda.$$

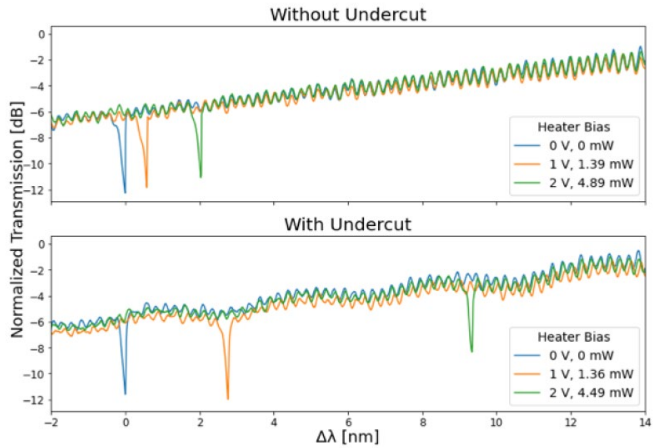


[Baehr-Jones JLT 2005]



Microdisk Modulator w/ Thermal Undercut





- RRM resonance wavelength shifts with temperature due to the thermo-optic effect (dn/dT)
- Requires closed-loop control with local heaters
- Heater efficiency can be improved with undercut processing

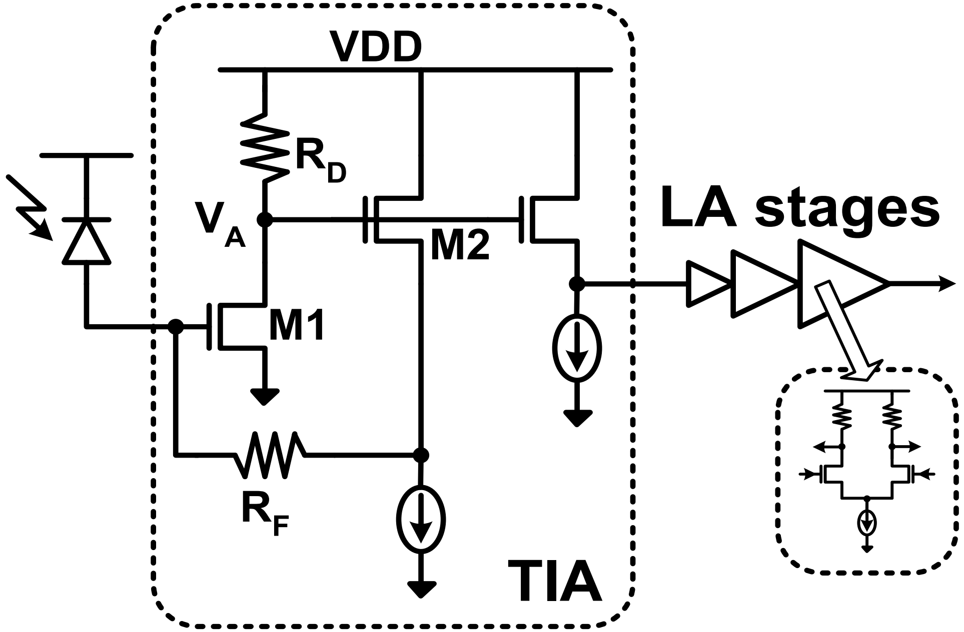
[Rizzo CLEO 2002]

Outline

- Optical Interconnect Motivation
- Optical Channel Properties
- IMDD and Coherent Transceivers
- Transmitter Properties and Devices
- Receiver Architecture and Devices
- Conclusion

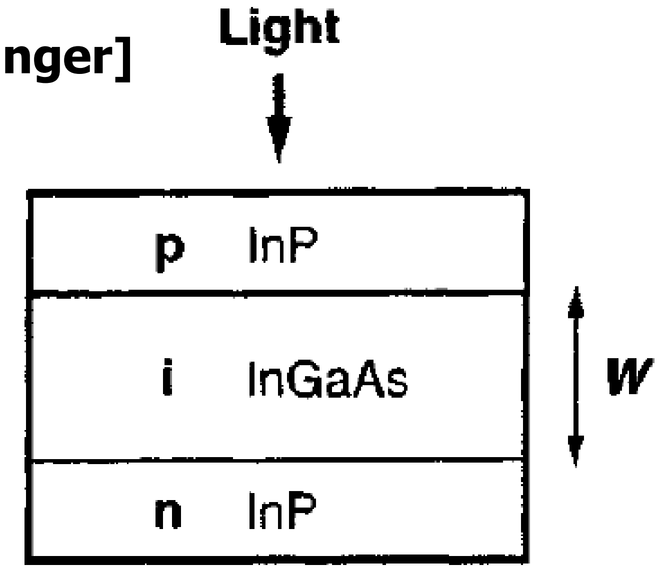
Optical Receiver Technology

- Photodetectors convert optical power into current
  - Surface-normal p-i-n photodiodes
  - Integrated waveguide photodetectors
- Electrical amplifiers then convert the photocurrent into a voltage signal
  - Transimpedance amplifiers
  - Limiting amplifiers



p-i-n Photodiode

[Sackinger]



Responsivity:

$$\rho = \frac{I}{P_{opt}} = \frac{\eta_{pd}\lambda q}{hc} = 8\times10^{5}\left(\eta_{pd}\lambda\right) \quad (\text{mA/mW})$$

Quantum Efficiency:

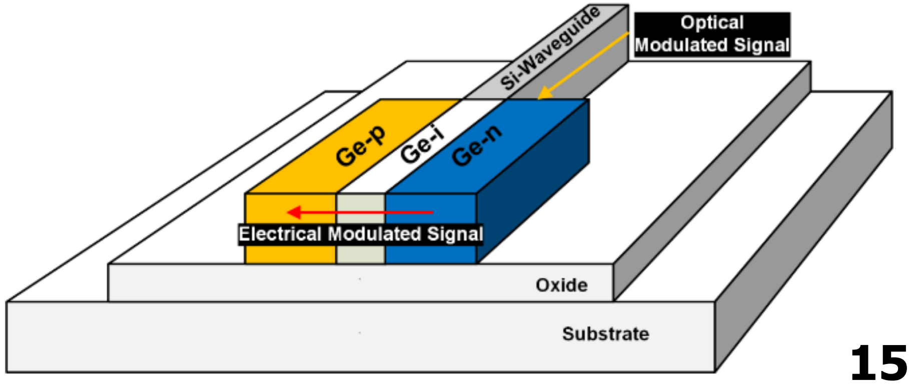
Transit-Time Limited Bandwidth:

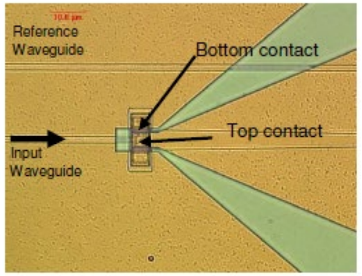
$$f_{3dBPD} = \frac{2.4}{2\pi\tau_{tr}} = \frac{0.45 v_{sat}}{W}$$

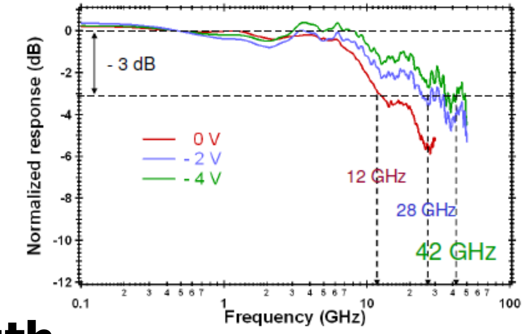
- Normally incident light absorbed in intrinsic region and generates carriers
- Trade-off between capacitance and transit-time
- Typical capacitance ~100fF for 28Gb/s p-i-n PDs

Waveguide p-i-n Photodetector

[Vivien OptExp 2009]







15µm detector length

- A waveguide p-i-n photodetector structure allows this efficiency-speed trade-off to be broken
- The light travels horizontally down the intrinsic region and the electric field is formed orthogonal
- Allows for both a thin i-region for short transit times and a sufficiently long i-region for high quantum efficiency

Conclusion

- Optical fiber channels can support the required distances for large datacenters
- Directly-modulated laser-based transmitters are simple, but have chirp penalties and laser bandwidth limitations
- External-modulated transmitters generally have minimal chirp and higher bandwidth
- High-speed optical receivers need photodiodes with high responsivity and low capacitance