ECEN721: Optical Interconnects Circuits and Systems
Spring 2024

Lecture 1: Introduction

Sam Palermo

Analog & Mixed-Signal Center

Texas A&M University

Announcements

- Homework 1 is posted on website and due Jan 25

Class Topics

- System and design issues relevant to high-speed optical interconnects
- Channel properties
  - Modeling, measurements, communication techniques
- Optical interconnect circuits
  - Drivers, receivers, equalizers, timing systems
- Optical interconnect system design
  - Modeling and performance metrics
- Optical interconnect system examples

Administrative

- Instructor:
  - Sam Palermo
  - 315E WERC Bldg., 979-458-4114, spalermo@tamu.edu
  - Office hours: M 2:30PM-4:00PM & W 2:00PM-3:30PM
    - In-person and via Zoom
- Lectures: TR 5:30PM-6:46PM, ETB 1003
- Class web page
  - https://people.engr.tamu.edu/spalermo/ecen721.html

Class Material

- Textbook: Class Notes and Technical Papers
- Key References
  - *Broadband Circuits for Optical Fiber Communication*, E. Sackinger, Wiley, 2005.
    - http://onlinelibrary.wiley.com/book/10.1002/0471726400
  - *Design of Integrated Circuits for Optical Communications*, B. Razavi, McGraw-Hill, 2003.
  - *Advanced Signal Integrity for High-Speed Digital Designs,* S. H. Hall and H. L. Heck, John Wiley & Sons, 2009.
  - *High-Speed Digital Design: A Handbook of Black Magic*, H. Johnson & M. Graham, Prentice Hall, 1993.
- Class notes will be posted on the web

Grading

- Exams (50%)
  - Two midterm exams (25% each)
- Homework (25%)
  - Collaboration is allowed, but independent simulations and write-ups
  - Need to setup CADENCE simulation environment
  - Turn in via Canvas
  - No late homework will be graded
- Final Project (25%)
  - Groups of 1-3 students
  - Report and PowerPoint presentation required
  - Turn in report and presentation files via Canvas

Prerequisites

- This is a circuits & systems & photonics class
- Circuits
  - ECEN474/704 or approval of instructor
  - Basic knowledge of CMOS gates, flops, etc…
  - Circuit simulation experience (HSPICE, Spectre)
- Systems
  - Basic knowledge of s- and z-transforms
  - Basic digital communication knowledge
  - MATLAB experience
- If you are strong in photonics, but weak in the above areas, then the assignments can be adjusted for more of a photonics emphasis

Simulation Tools

- Matlab
- ADS (Statistical BER link analysis)
- Cadence
- 90nm CMOS device models
  - Can use other technology models if they are a 90nm or more advanced CMOS node
- Other tools, schematic, layout, etc… are optional

Preliminary Schedule

Topic		Week
I.	Optical Channel Properties	Week 1-8
II.	Optical Devices	
III.	Receiver Analysis	
IV.	Receiver Circuits	
	1st MIDTERM	**Mar. 7**
V.	Transmitter Analysis	Week 9-14
VI.	Transmitter Circuits	
VII.	Laser Sources	
VIII.	RF Photonics & Photonic NoCs	
	2nd MIDTERM	**Apr. 23**
	Project Report Due	**Apr. 30**
	Project Presentations	**May 7 (3:30PM-5:30PM)**

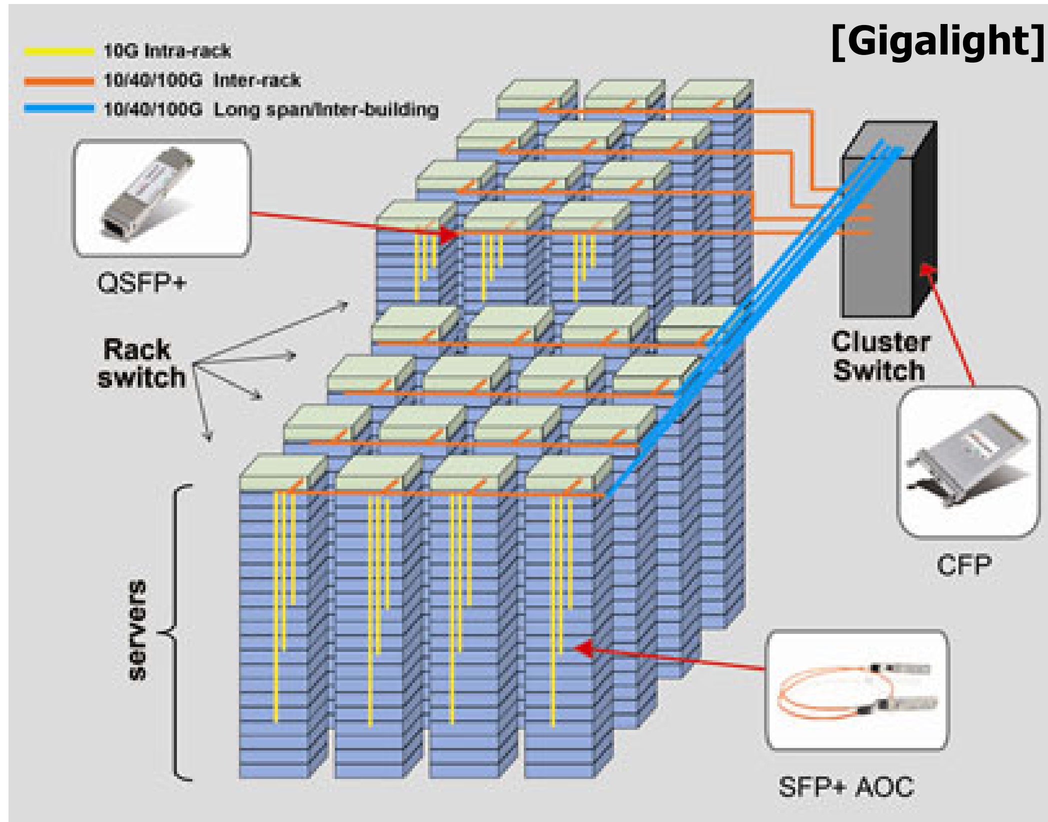
- Dates may change with reasonable notice

Optical Interconnects

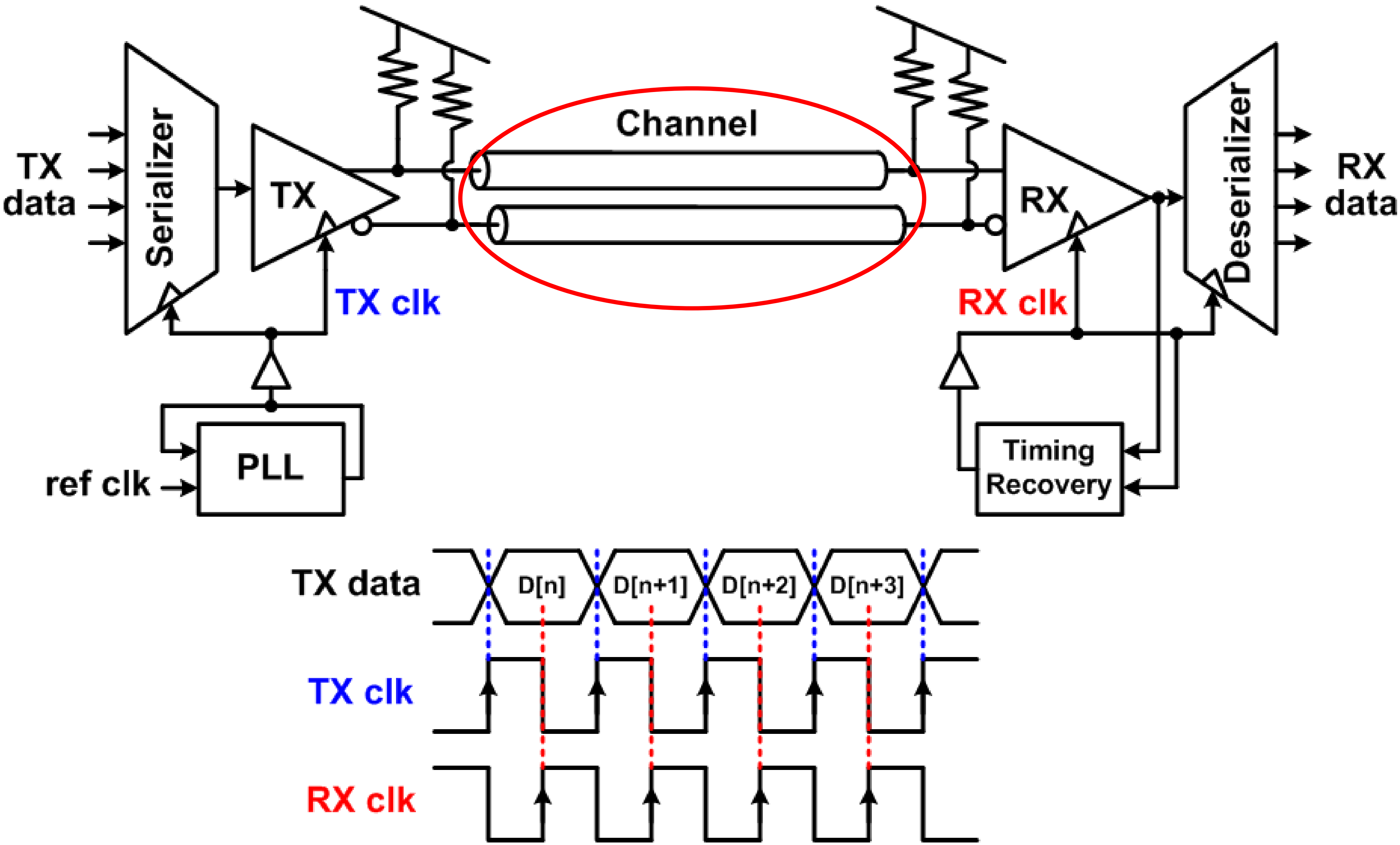
- Electrical Channel Issues
- Optical Channel
- Optical Transmitter Technology
- Optical Receiver Technology
- Optical Integration Approaches

Data Center Links

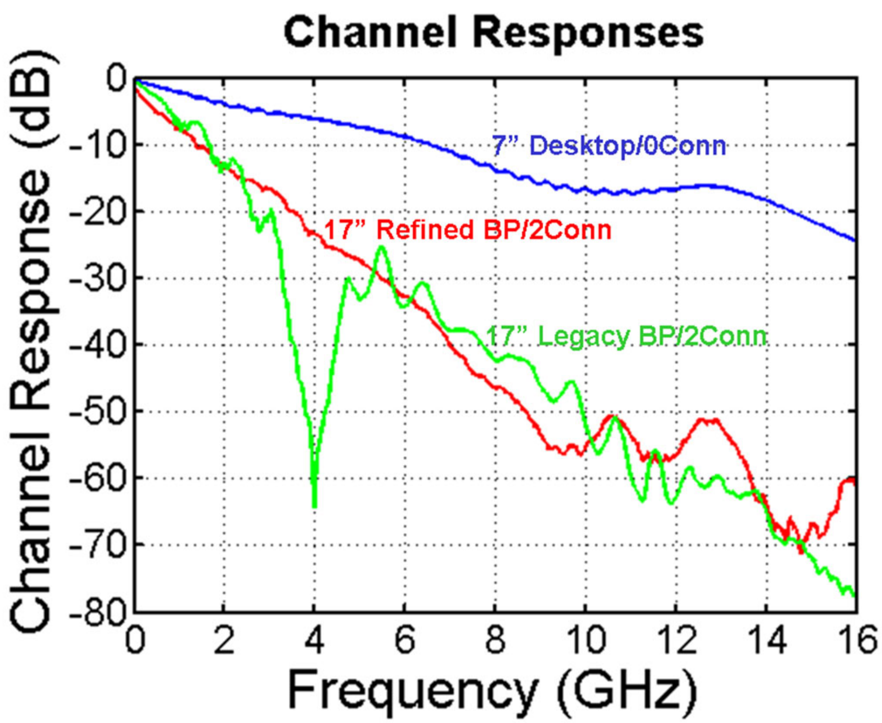
- Different interconnect technologies are used to span various distances
- Electrical I/O
  - Chip-to-module
  - Intra-rack (DAC cables)
- Optical I/O
  - Intra-rack (AO cables)
  - TOR switch to edge switch

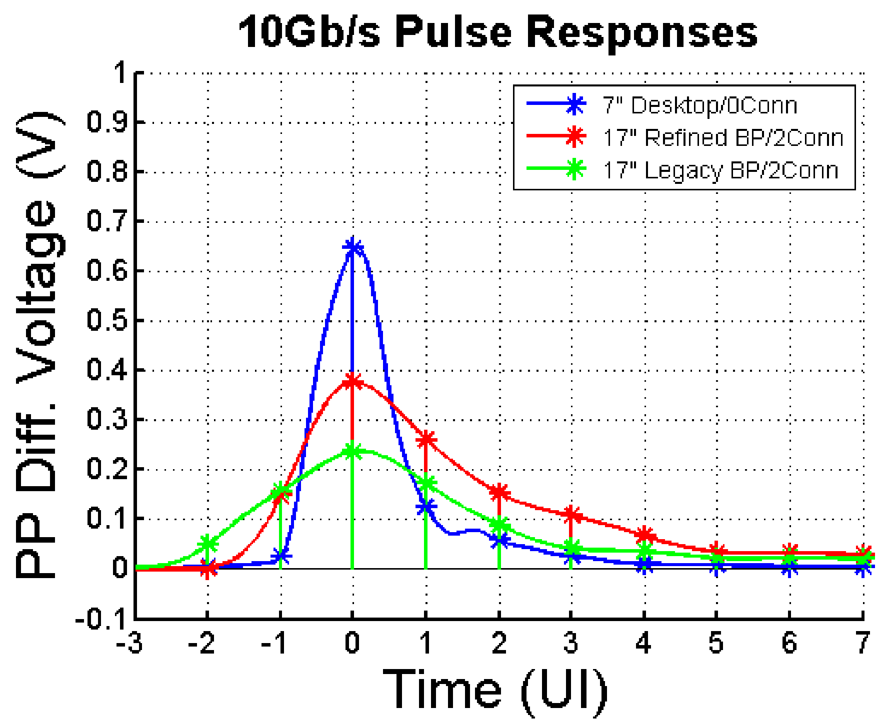


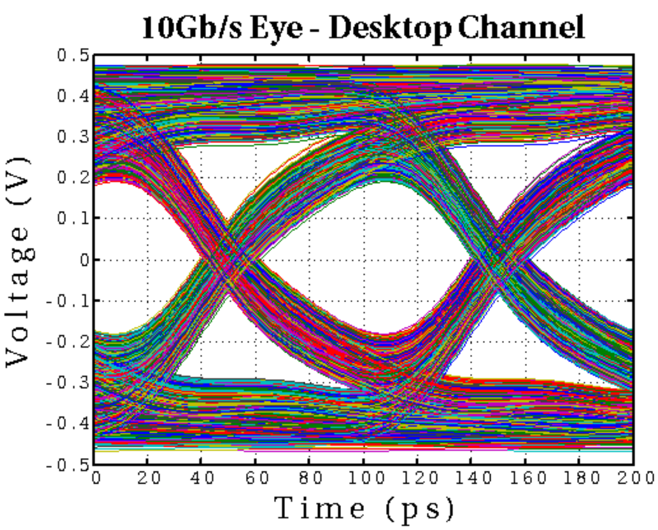
High-Speed Electrical Link System

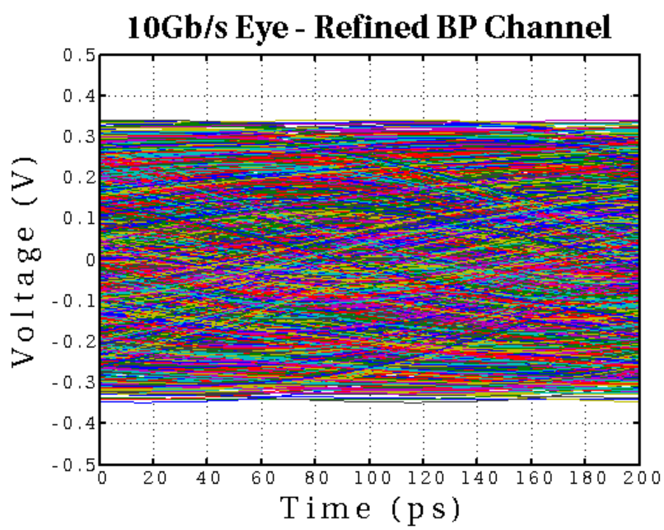


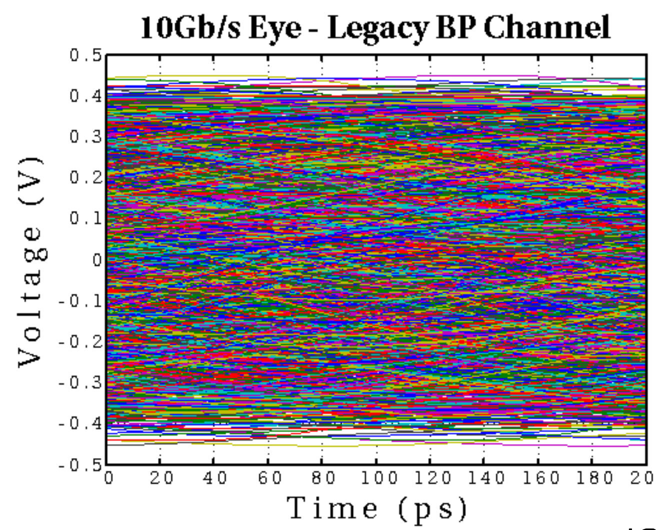
Channel Performance Impact



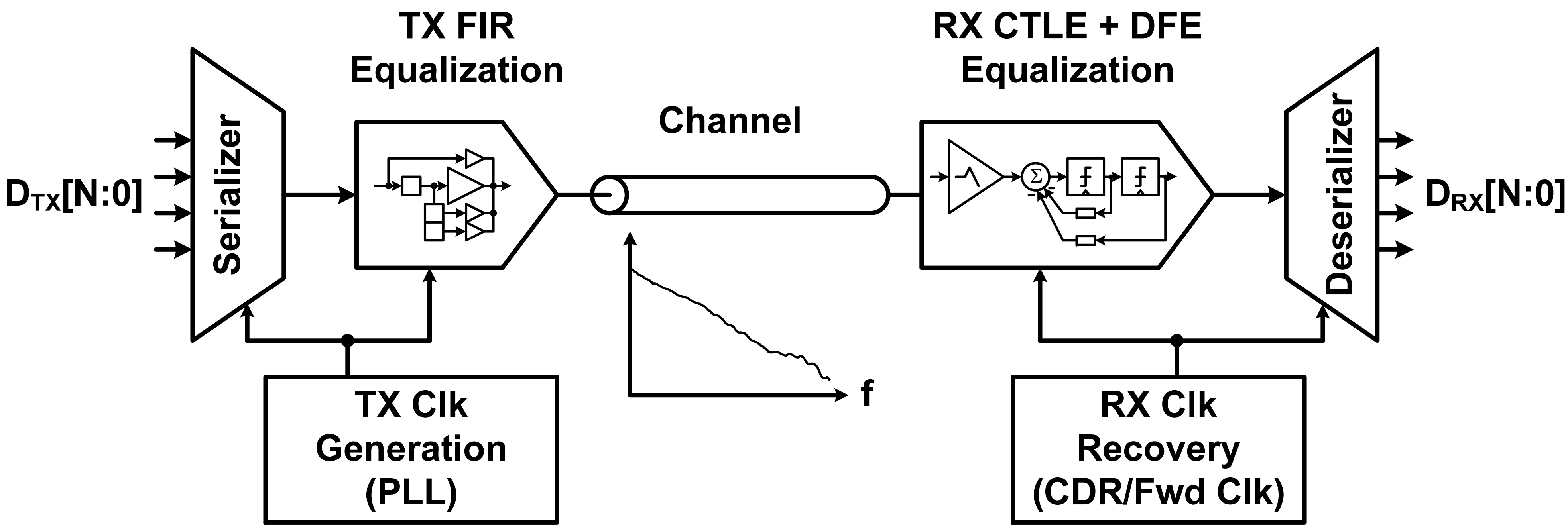




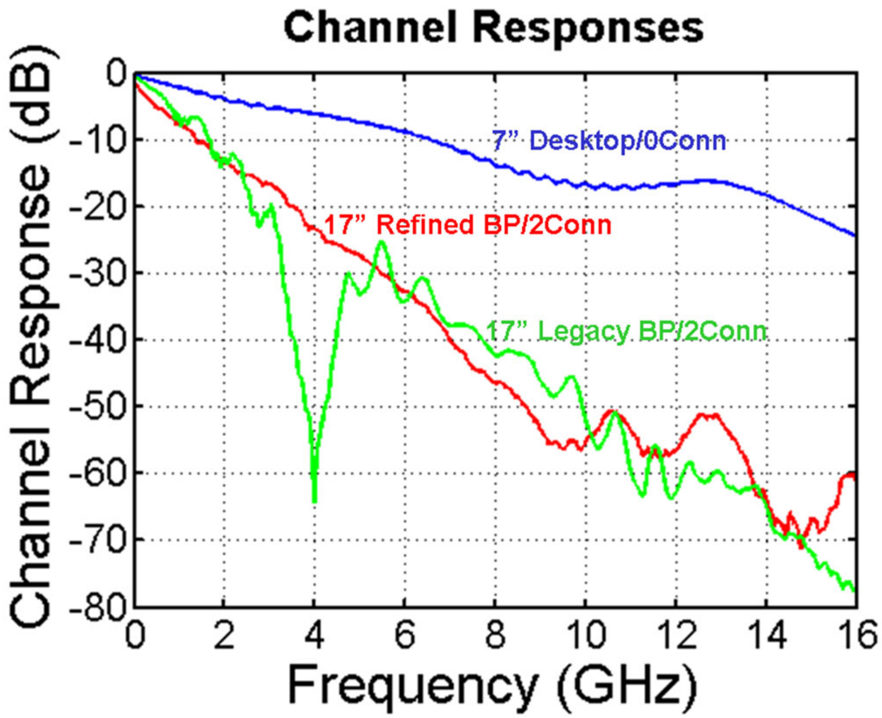


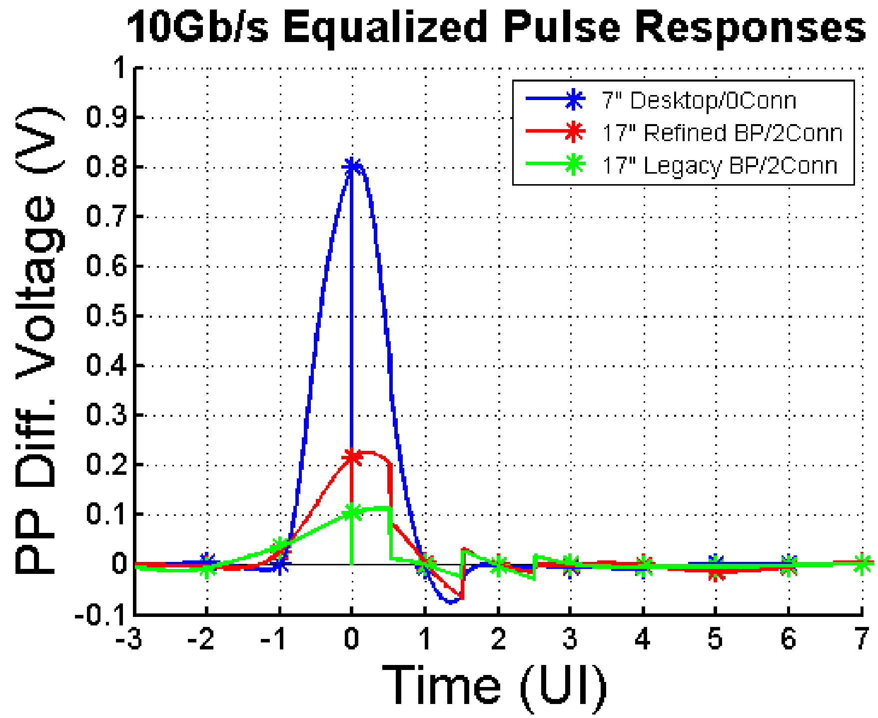


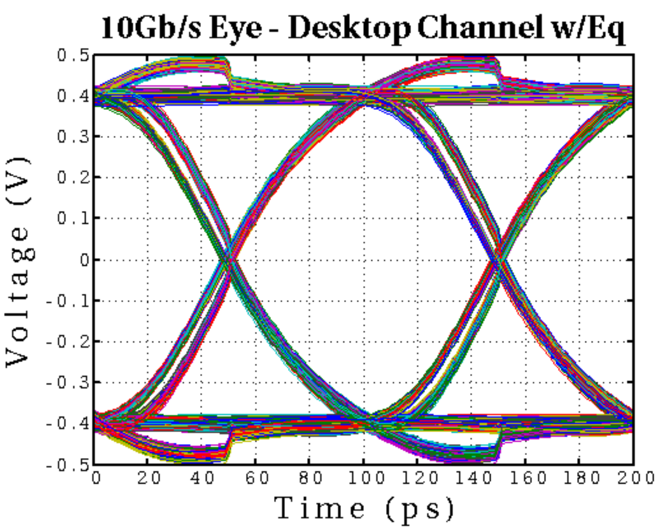
Link with Equalization

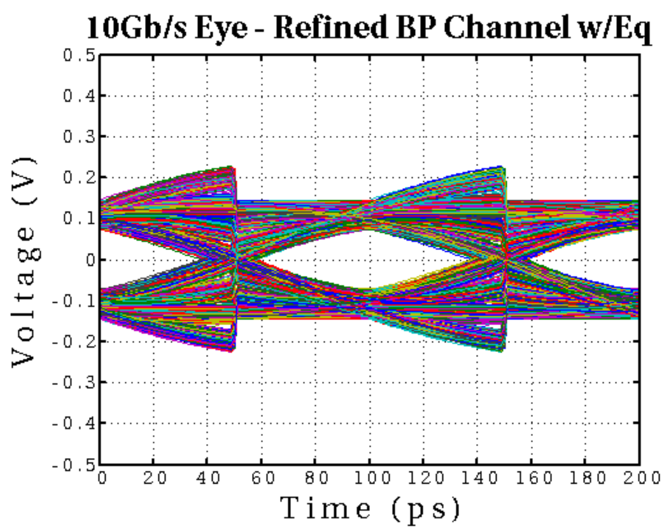


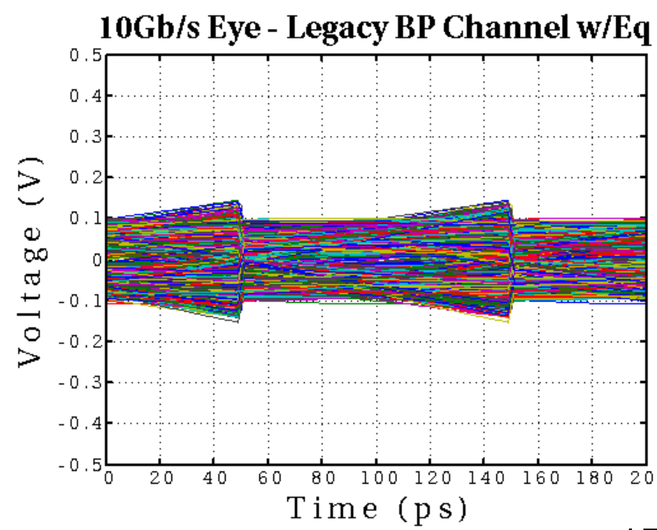
Channel Performance Impact



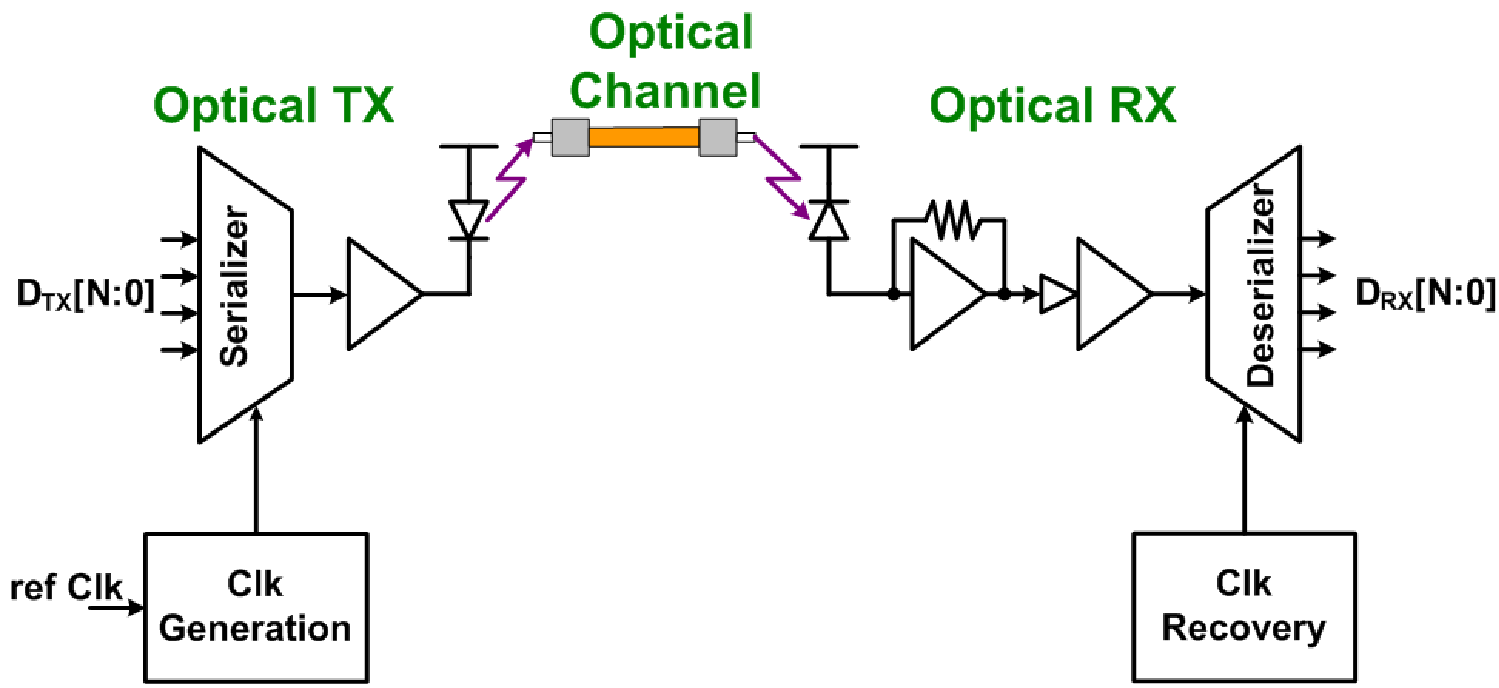




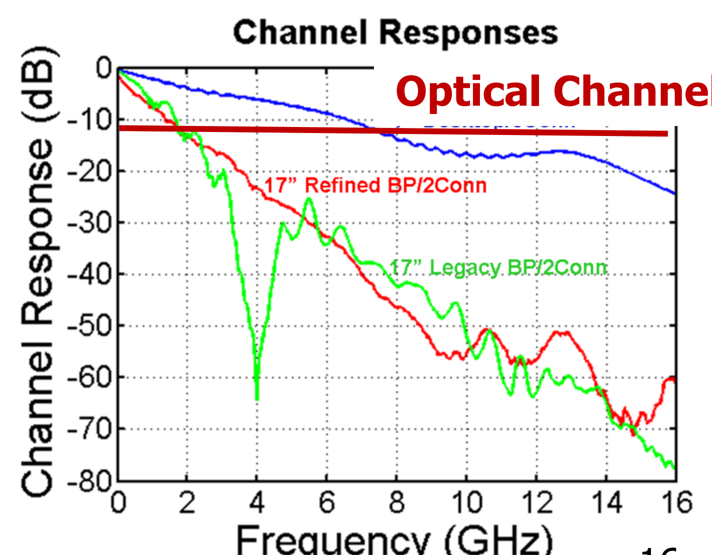




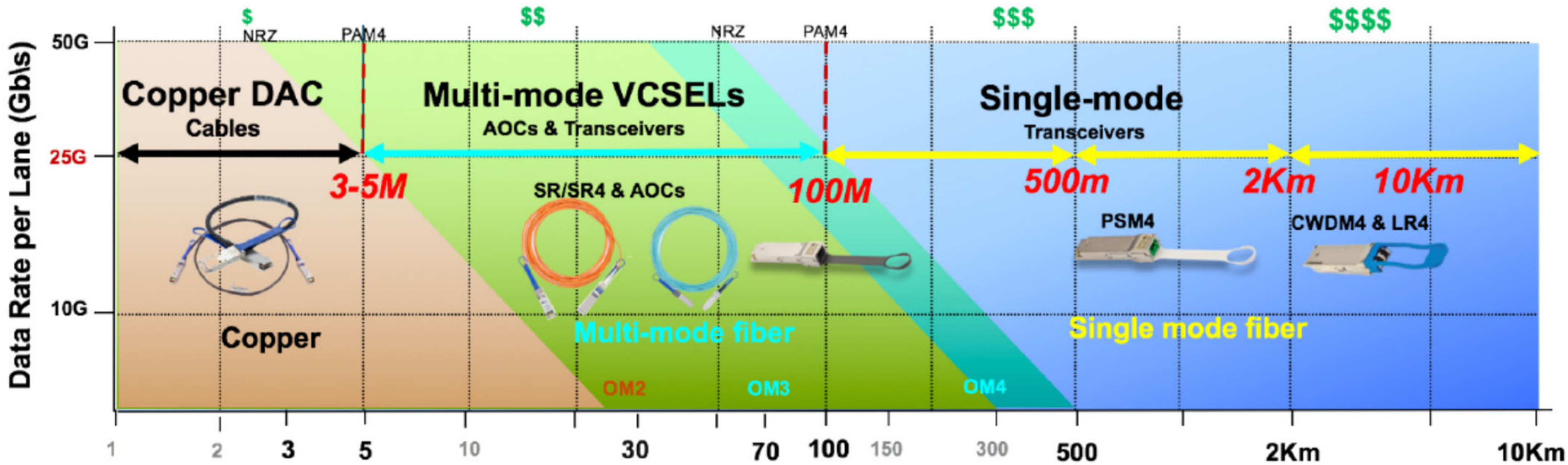
High-Speed Optical Link System



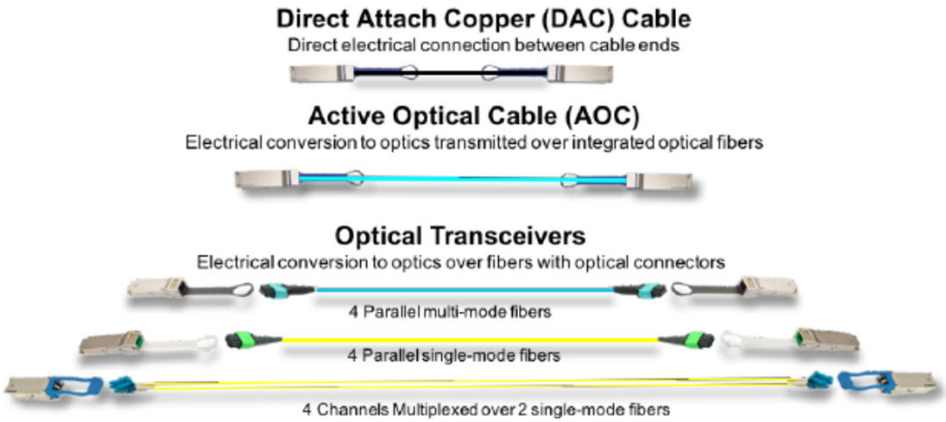
- Optical interconnects remove many channel limitations
  - Reduced complexity and power consumption
  - Potential for high information density with wavelength-division multiplexing (WDM)



Data Center Link Length

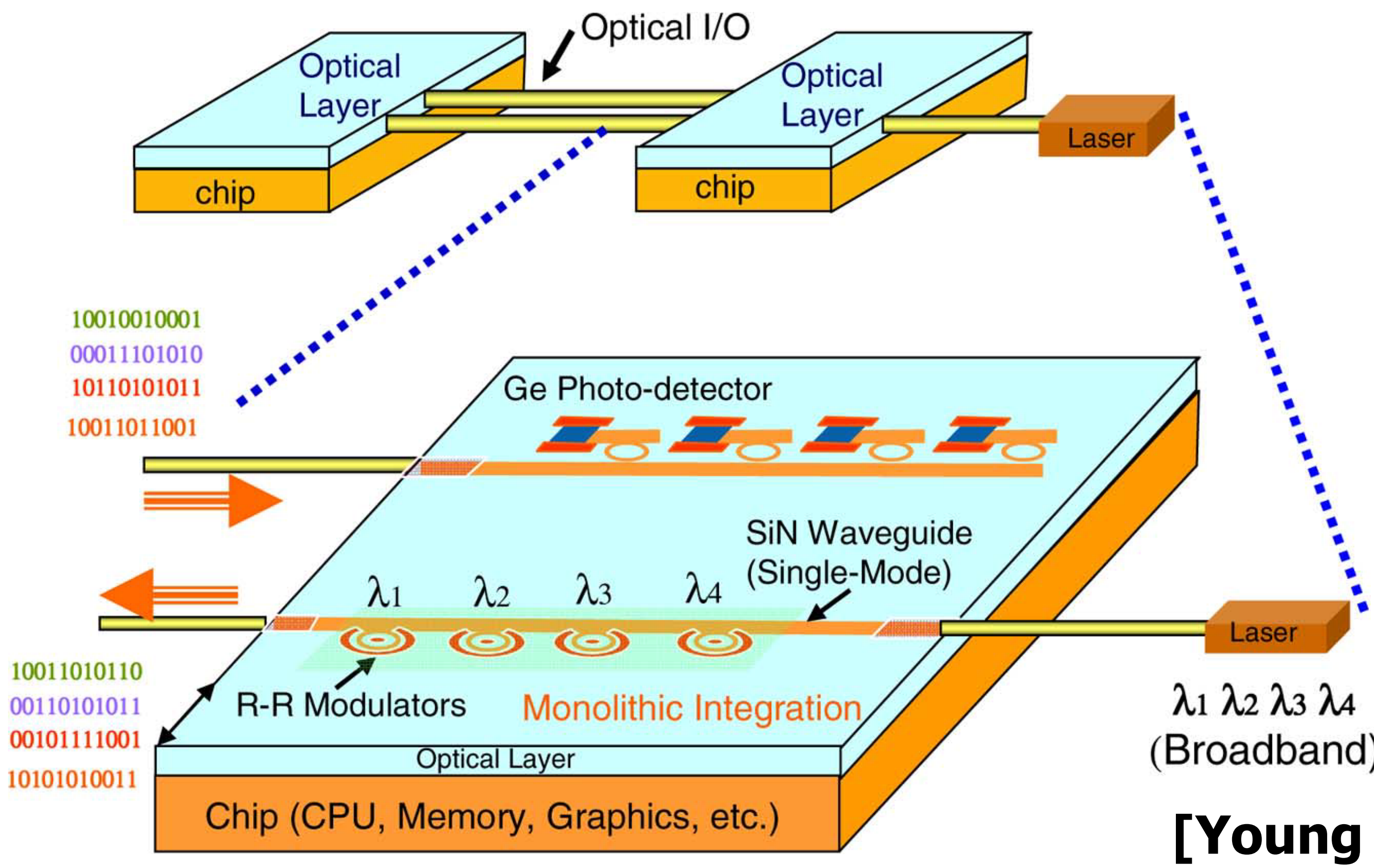


[Mellanox]



- Maximum reach scales inversely with data rate

Wavelength-Division Multiplexing



[Young JSSC 2010]

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

Optical Interconnects

- Electrical Channel Issues
- Optical Channel
- Optical Transmitter Technology
- Optical Receiver Technology
- Optical Integration Approaches

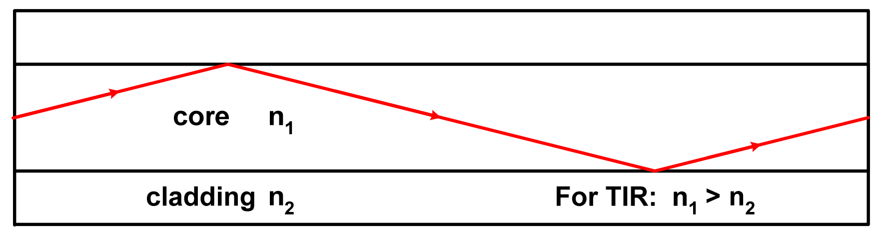
Optical Channels

- Short distance optical I/O channels are typically either waveguide (fiber)-based or free-space
- 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

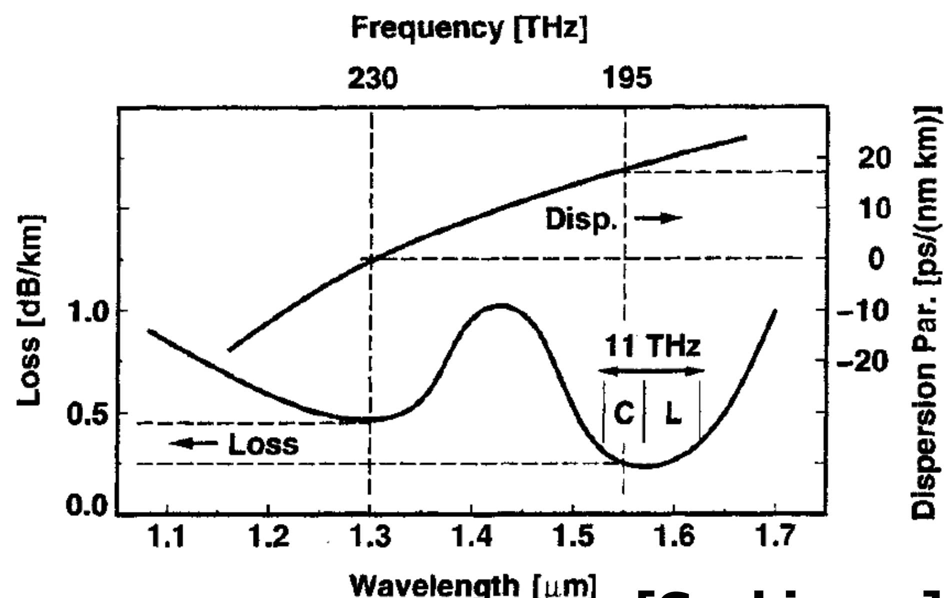
Waveguide (Fiber)-Based Optical Links

- 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



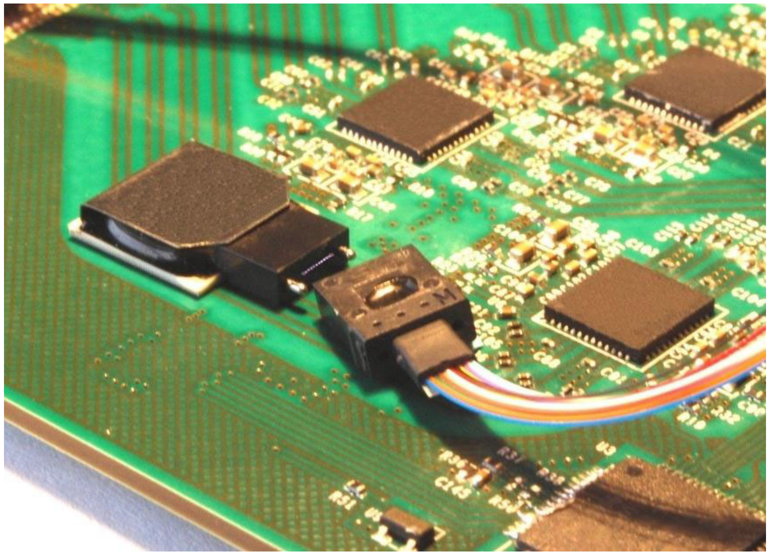
Single-Mode Fiber Loss & Dispersion



[Sackinger]

Inter-Chip Waveguide Examples

12-Channel Ribbon Fiber

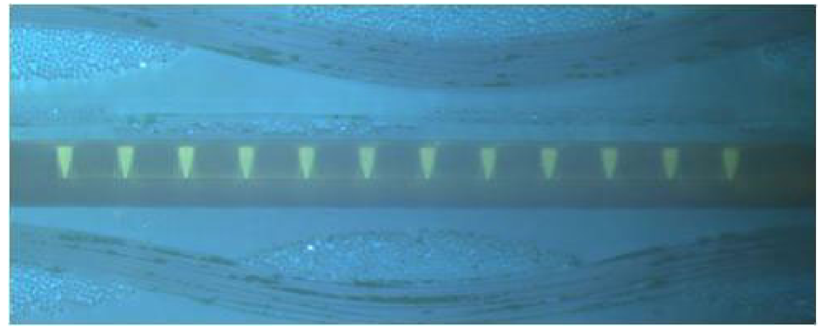


[Reflex Photonics]

12 channels at a 250μm pitch

10Gb/s mod. → 40Gb/s/mm

Optical Polymer Waveguide in PCB



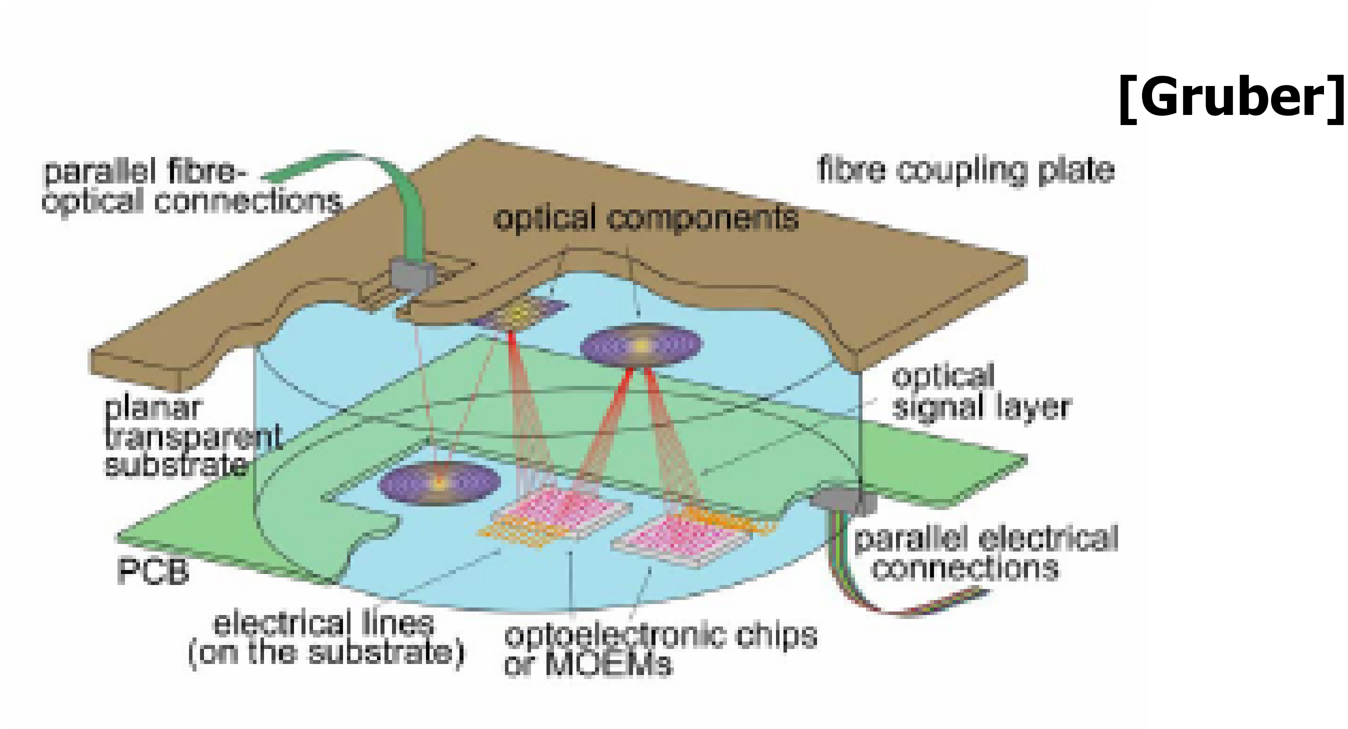
[Immonen 2009]

<100μm channel pitch possible

10Gb/s mod. → 100+Gb/s/mm

- Typical differential electrical strip lines are at ~500μm pitch

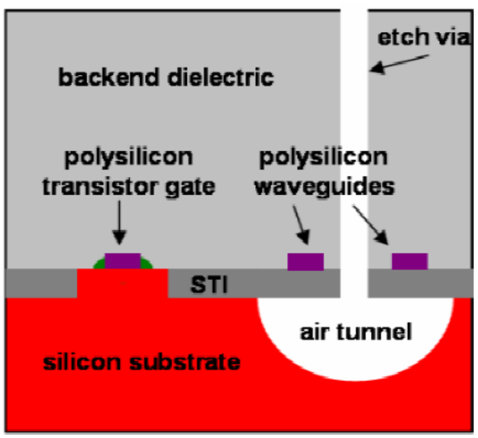
Free-Space Optical Links

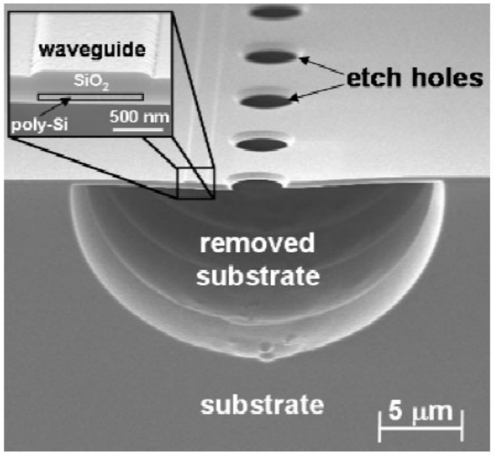


- Free-space (air or glass) interconnect systems have also been proposed
- Optical imaging system routes light chip-to-chip

CMOS Waveguides – Bulk CMOS

- Waveguides can be made in a bulk process with a polysilicon core surrounded by an SiO2 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

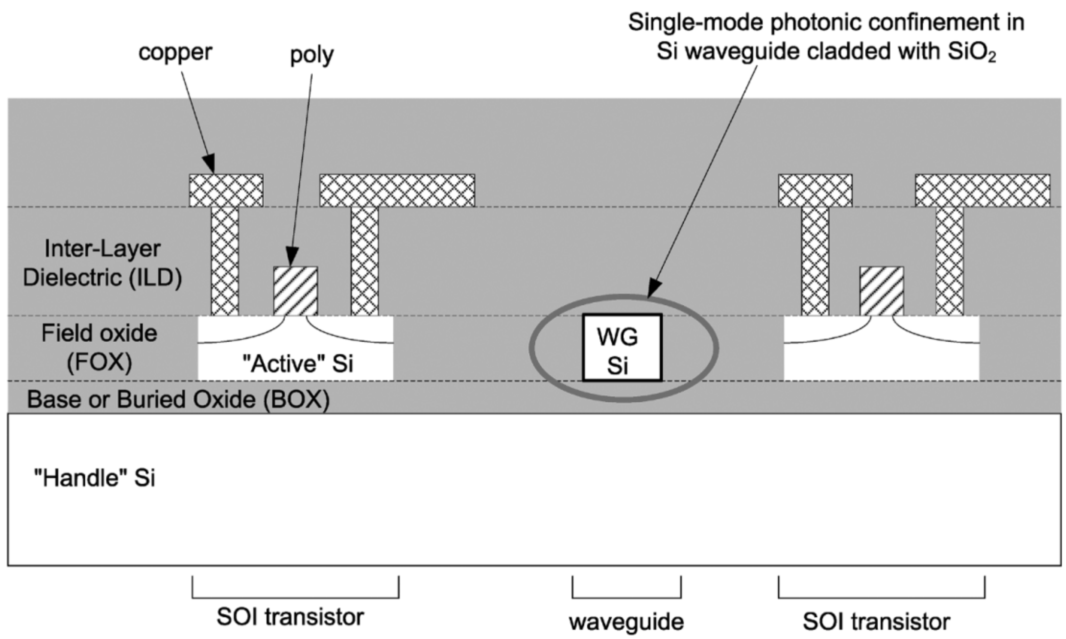




[Holzwarth CLEO 2008]

CMOS Waveguides – SOI

- SOI processes have thicker buried oxide layers to sufficiently confine the optical mode
- Allows for low-loss waveguides

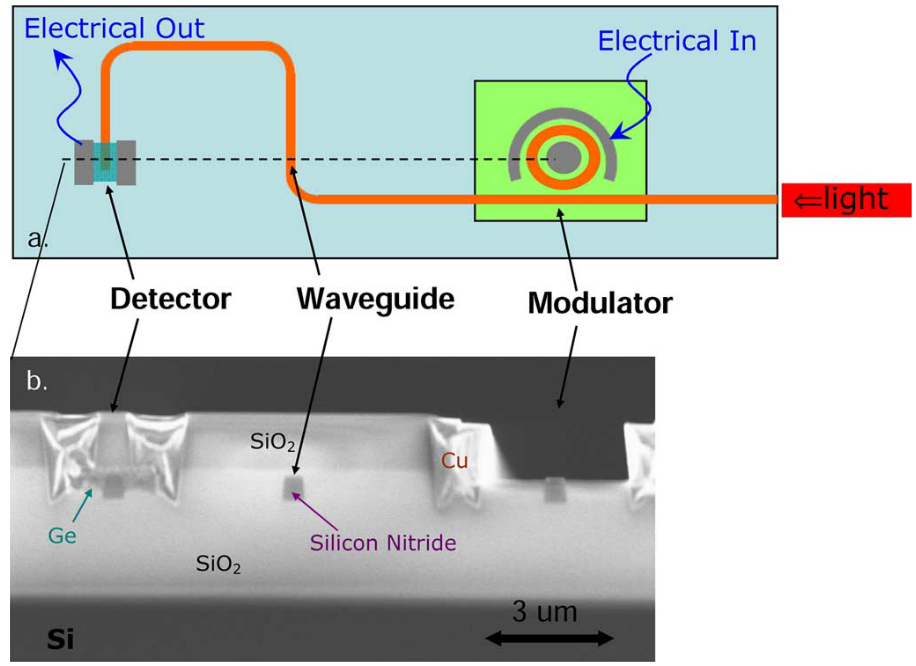


[Narasimha JSSC 2007]

CMOS Waveguides – Back-End Processing

- Waveguides & optical devices can be fabricated above metallization
- Reduces active area consumption
- Allows for independent optimization of transistor and optical device processes

[Young JSSC 2010]

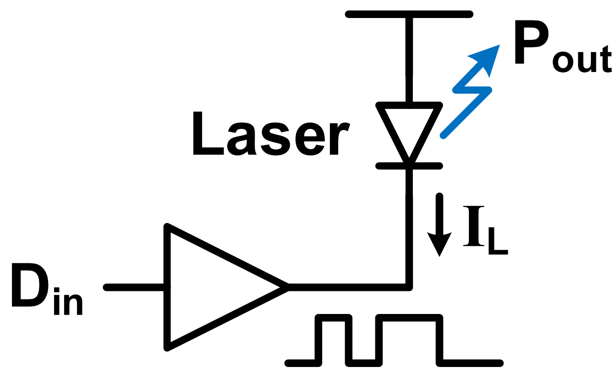


Optical Interconnects

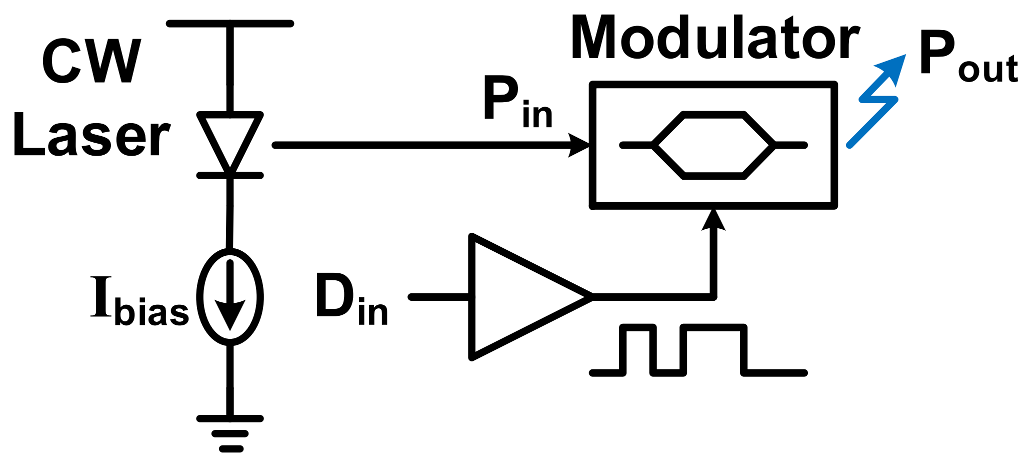
- Electrical Channel Issues
- Optical Channel
- Optical Transmitter Technology
- Optical Receiver Technology
- Optical Integration Approaches

Optical Modulation Techniques

Direct Modulation

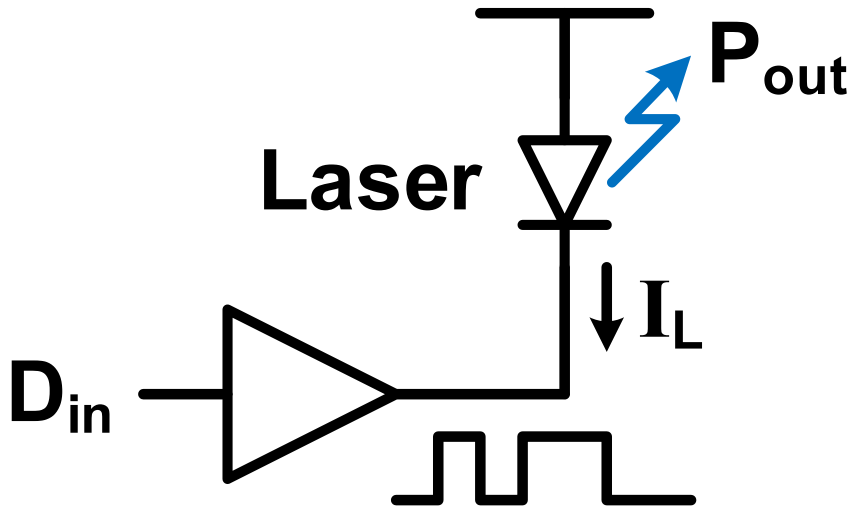


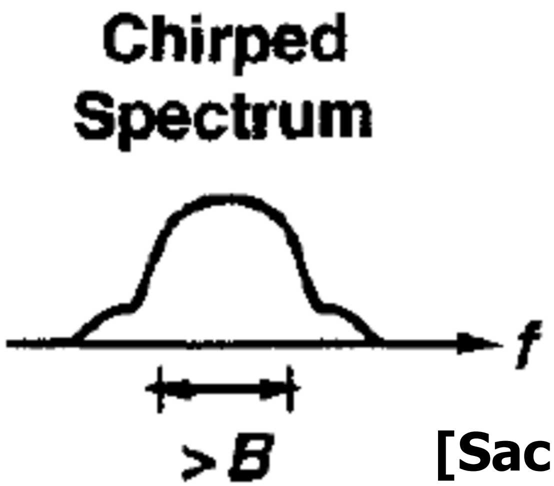
External Modulation



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

Directly Modulated Laser

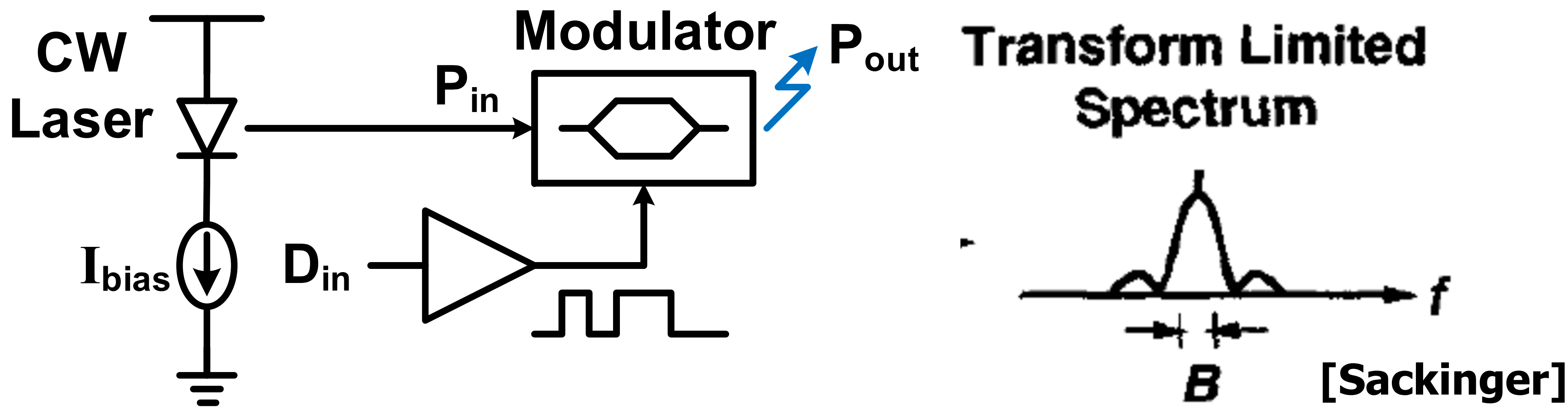




[Sackinger]

- 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



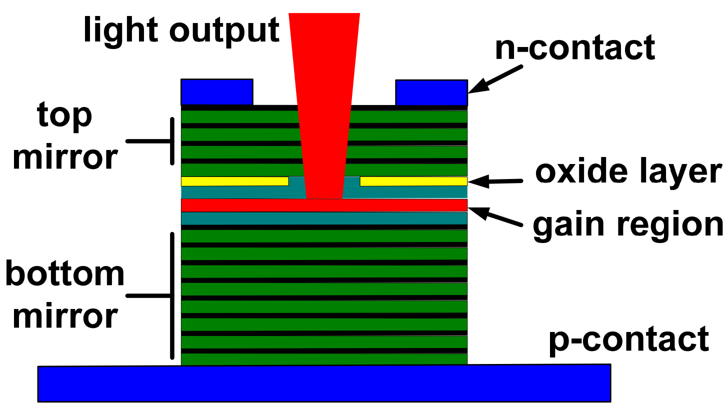
- External modulation of continuous-wave (CW) "DC" laser with absorptive or refractive modulators
  - Adds an extra component
  - Doesn't add chirp, and allows for a transform limited spectrum

Optical Sources for Chip-to-Chip Links

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

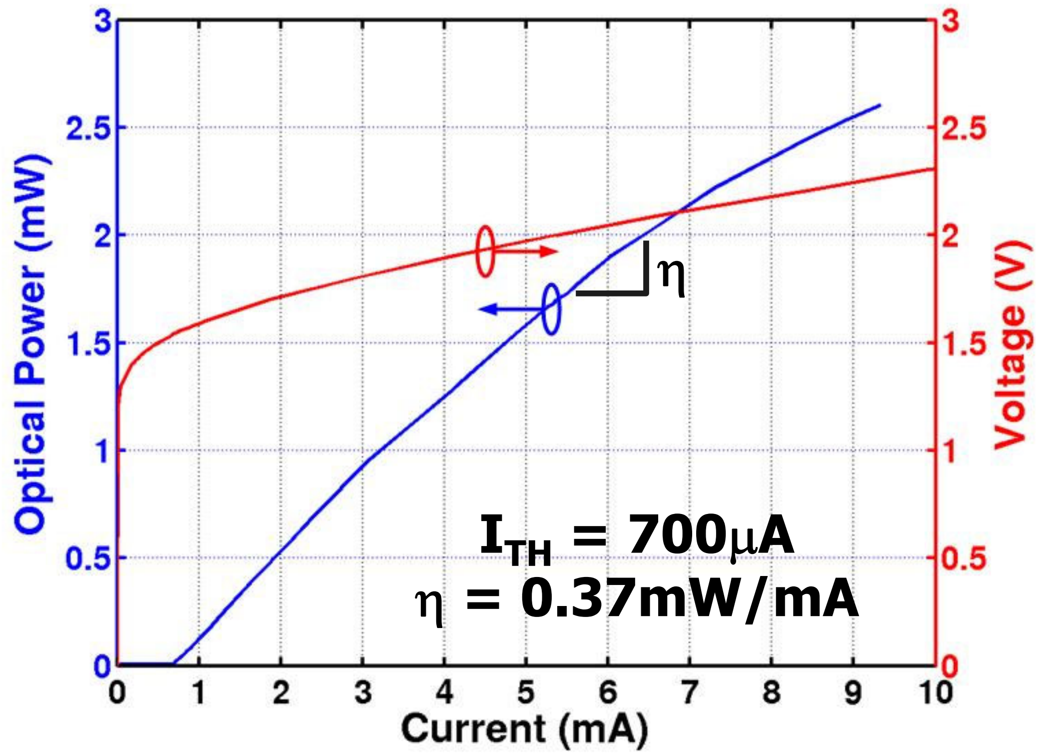
Vertical-Cavity Surface-Emitting Laser (VCSEL)

VCSEL Cross-Section



- VCSEL 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)

VCSEL L-I-V Curves

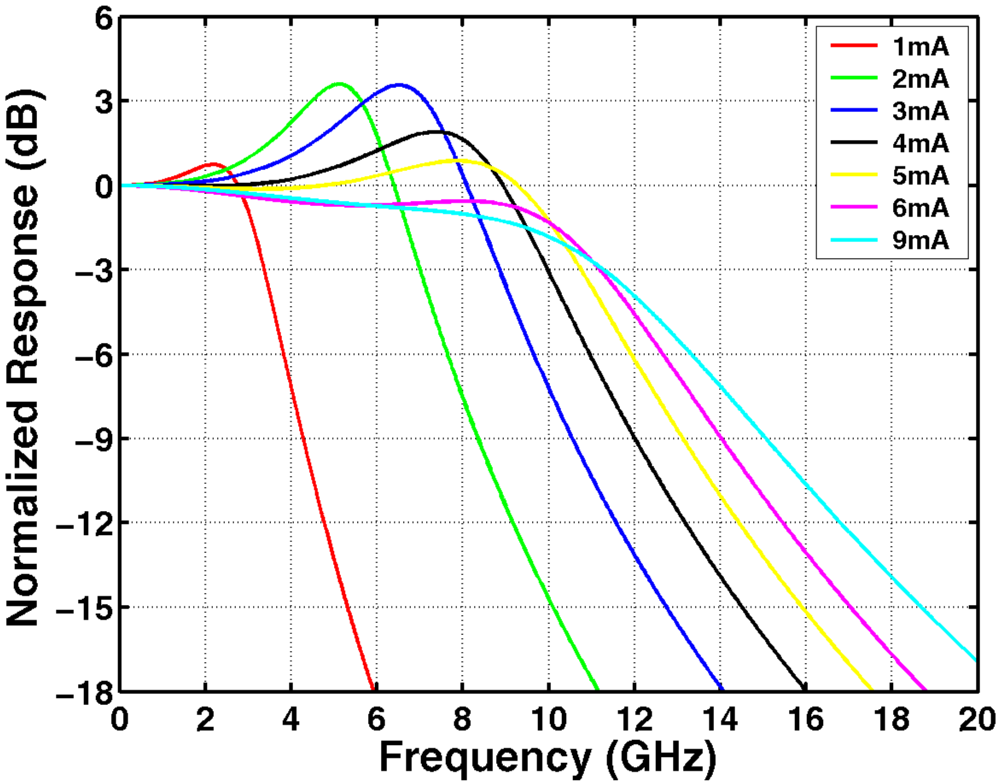


$$P_o = \eta\left(I - I_{TH}\right)$$

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

VCSEL Bandwidth vs Reliability

10Gb/s VCSEL Frequency Response [1]



$$BW \propto \sqrt{I_{avg} - I_{TH}}$$

- Mean Time to Failure (MTTF) is inversely proportional to current density squared

$$MTTF = \frac{A}{j^2} e^{\left(\frac{E_A}{k}\right)\left(\frac{1}{T_j} - \frac{1}{373}\right)}$$ [2]

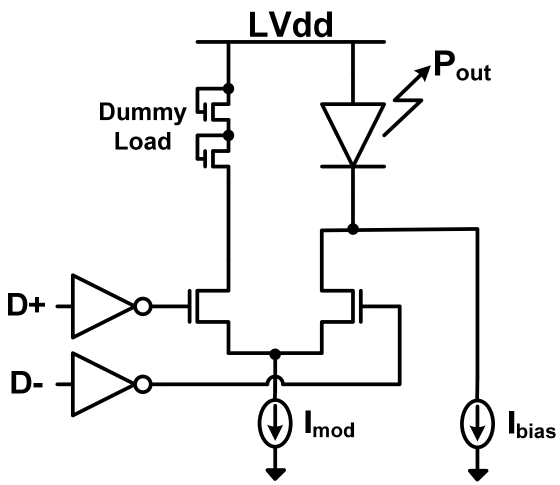
- Steep trade-off between bandwidth and reliability

$$MTTF \propto \frac{1}{BW^4}$$

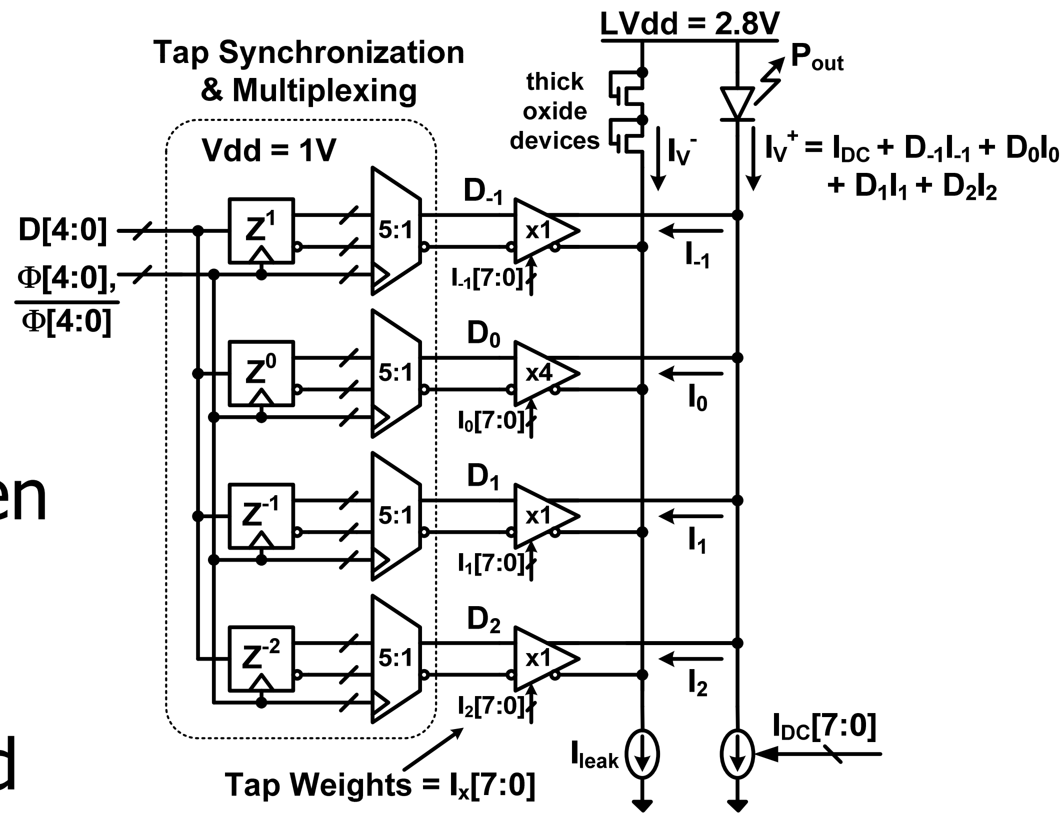
1. D. Bossert *et al*, "Production of high-speed oxide confined VCSEL arrays for datacom applications," *Proceedings of SPIE*, 2002.
2. M. Teitelbaum and K. Goossen, "Reliability of Direct Mesa Flip-Chip Bonded VCSEL's," *LEOS*, 2004.

VCSEL Drivers

Current-Mode VCSEL Driver



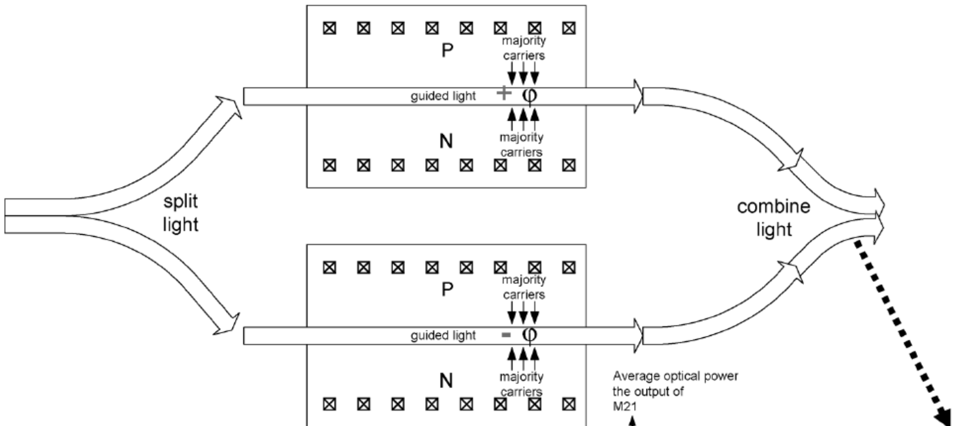
VCSEL Driver w/ 4-tap FIR Equalization



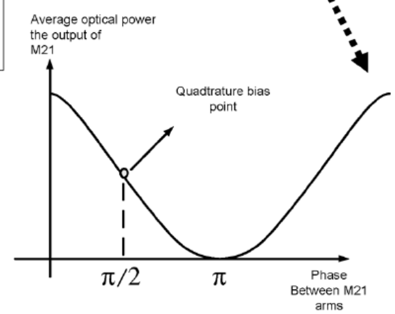
S. Palermo and M. Horowitz, "High-Speed Transmitters in 90nm CMOS for High-Density Optical Interconnects," *ESSCIRC*, 2006.

- Current-mode drivers often used due to linear L-I relationship
- Equalization can be added to extend VCSEL bandwidth for a given current density

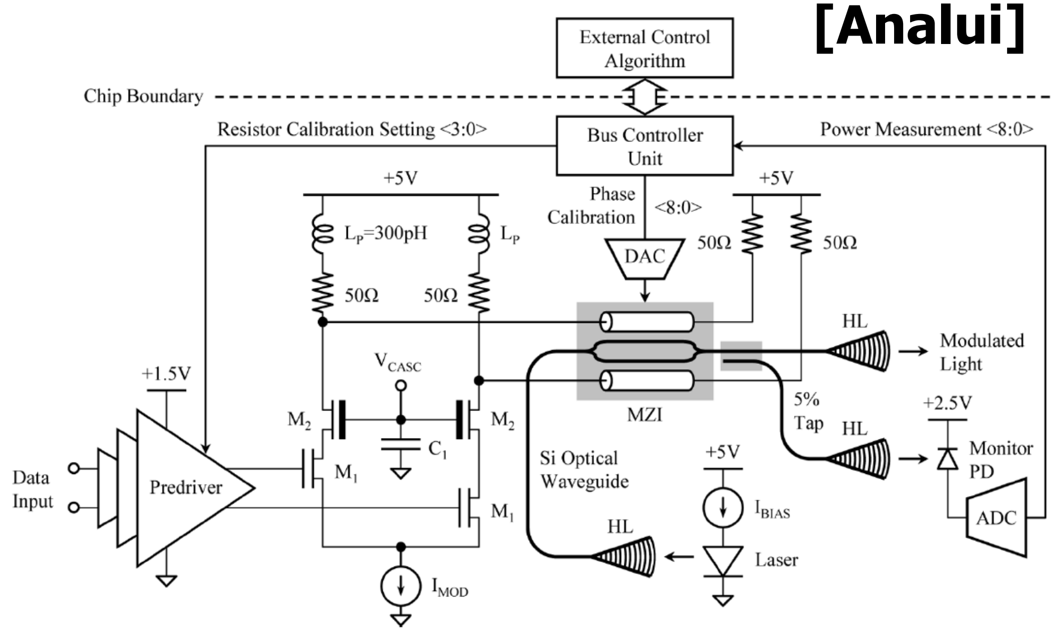
Mach-Zehnder Modulator (MZM)



$$\frac{P_{out}}{P_{in}} = \frac{1+\cos\Delta\varnothing}{2}$$

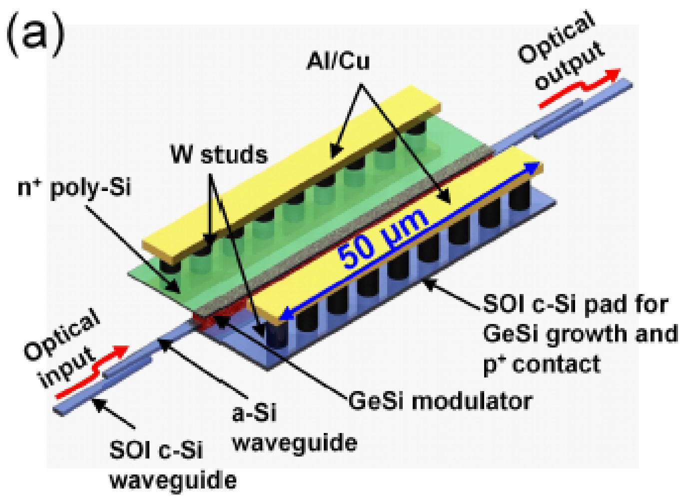


[Analui]

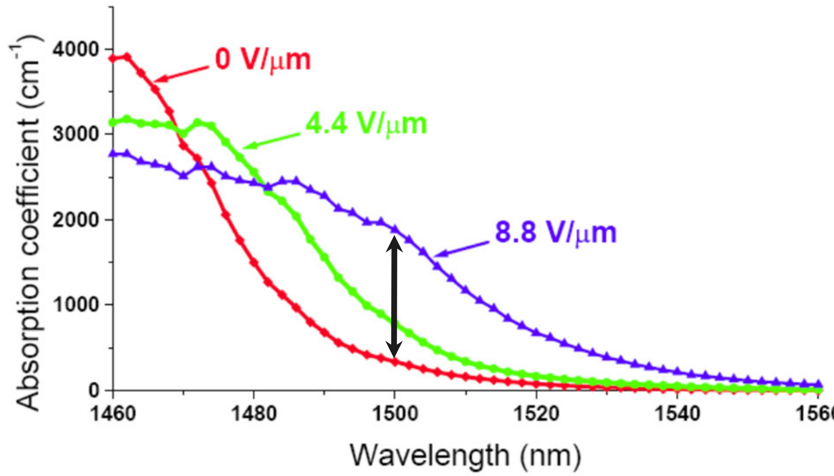


- Refractive modulator which splits incoming light into two paths, induces a voltage-controlled phase shift in the two paths, and recombines the light in or out of phase
- Long device (several mm) requires driver to drive low-impedance transmission line at potentially high swing ($5V_{ppd}$)
- While much higher power relative to RRM, they are less sensitive to temperature variations

Electro-Absorption Modulator (EAM)



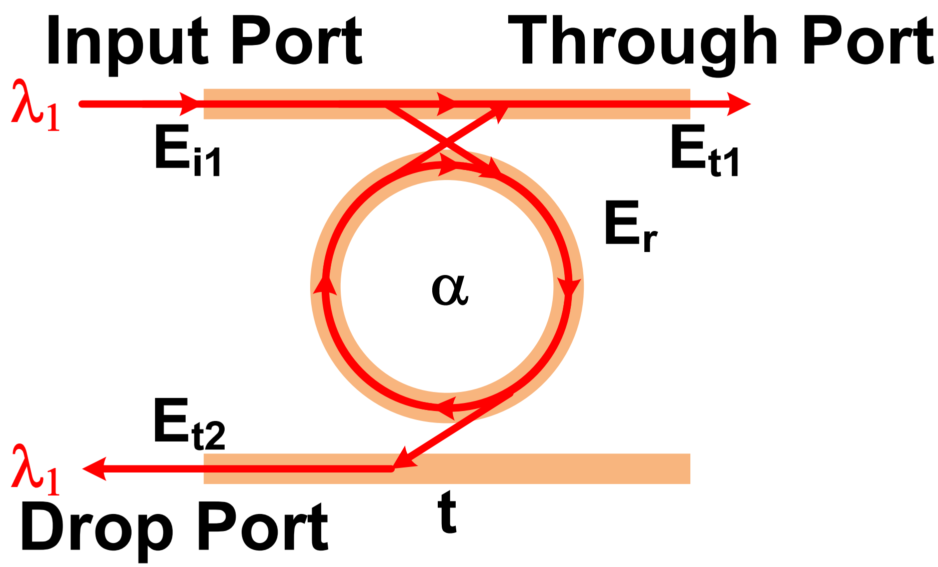
Waveguide EAM [Liu 2008]

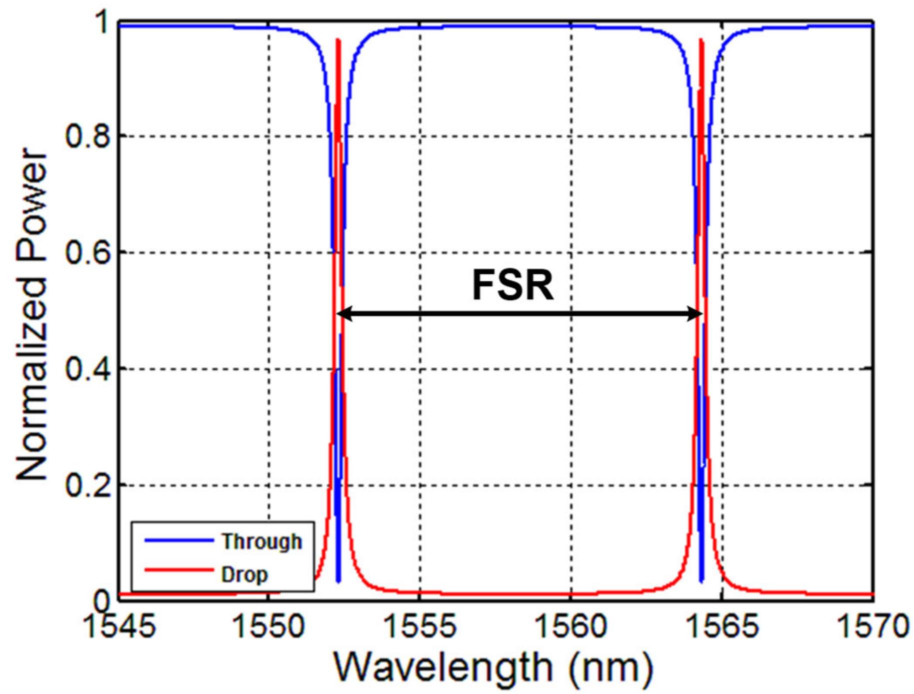


[Helman JSTQE 2005]

- 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

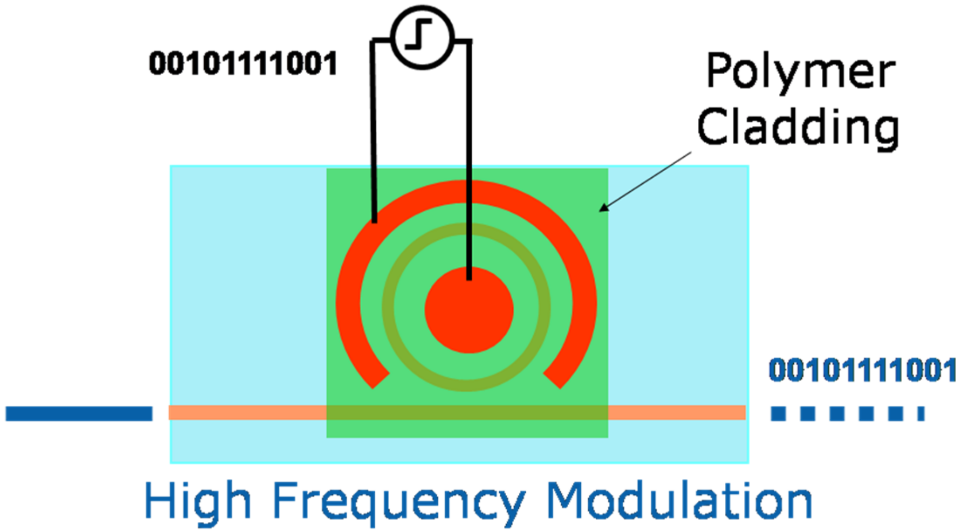
Ring Resonator Filter

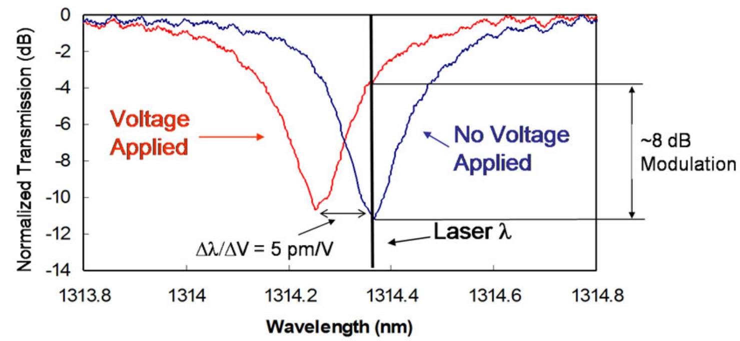


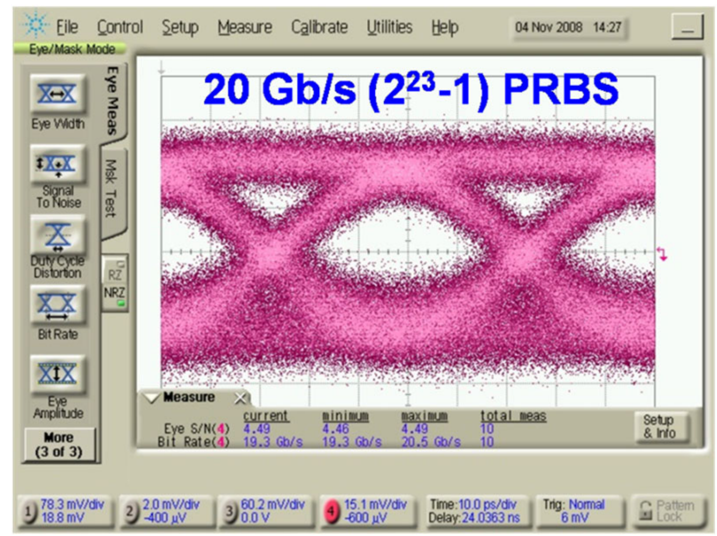


- Ring resonators display a high-*Q* notch filter response at the through port and a band-pass response at the drop port
- This response repeats over a free spectral range (FSR)

Ring-Resonator Modulator (RRM)





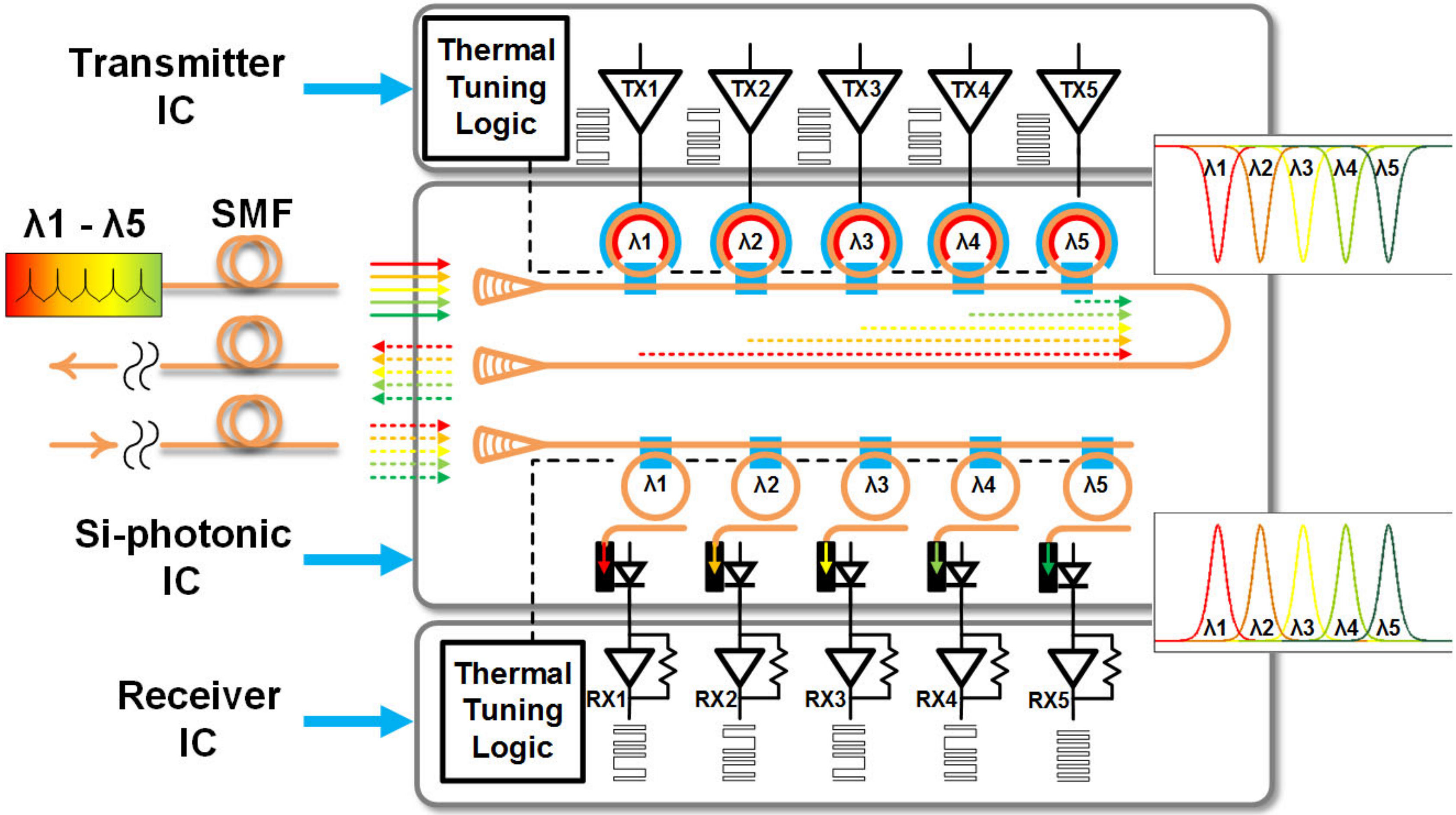


- Refractive devices which modulate by changing the interference light coupled into the ring with the waveguide light

- Devices are relatively small (ring diameters < 20μm) and can be treated as lumped capacitance loads (~10fF)

[Young ISSCC 2009]

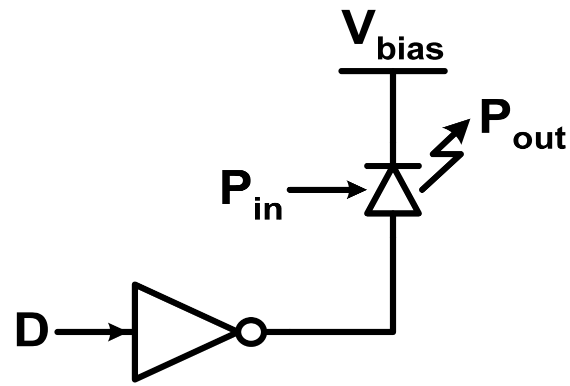
Wavelength Division Multiplexing w/ Ring Resonators



- 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 >100 waveguides, each modulated at more than 10Gb/s on a single on-chip waveguide

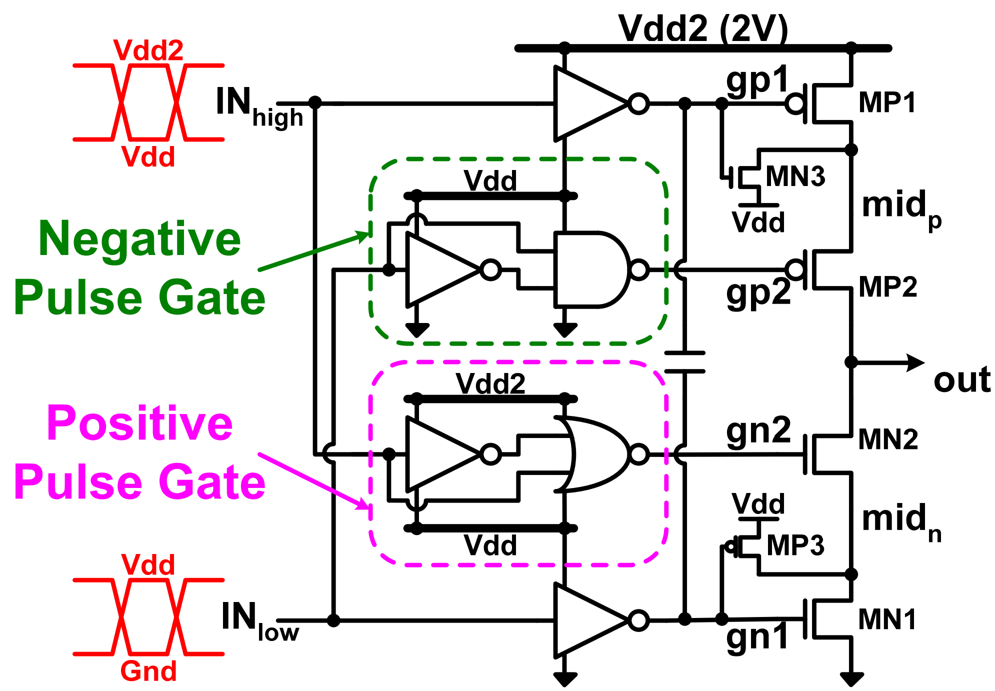
CMOS Modulator Driver

- Simple CMOS-style voltage-mode drivers can drive EAM and RRM due to their small size



- Device may require swing higher than nominal CMOS supply
  - Pulsed-Cascode driver can reliably provide swing of 2xVdd (or 4xVdd) at up to 2FO4 data rate

Pulsed-Cascode Driver



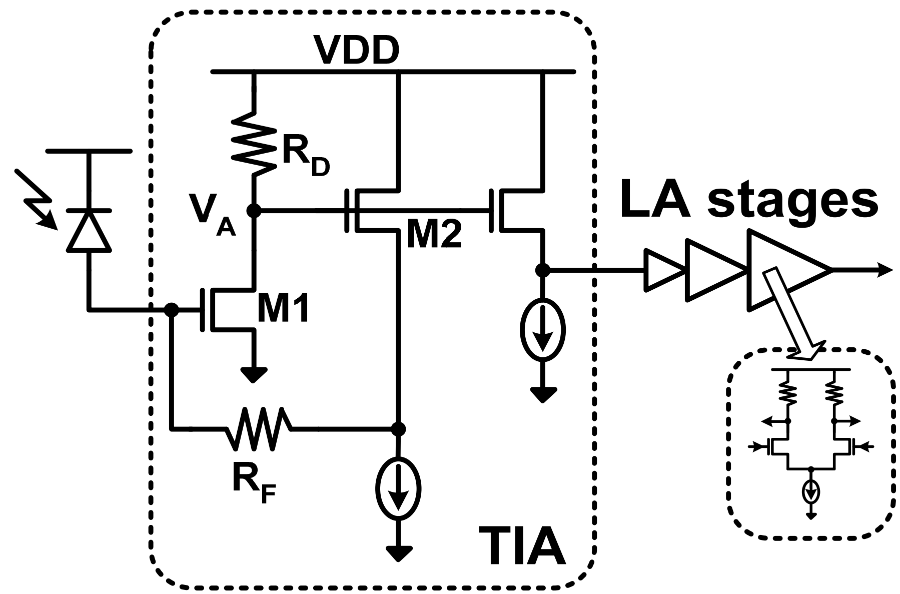
S. Palermo and M. Horowitz, "High-Speed Transmitters in 90nm CMOS for High-Density Optical Interconnects," *ESSCIRC*, 2006.

Optical Interconnects

- Electrical Channel Issues
- Optical Channel
- Optical Transmitter Technology
- Optical Receiver Technology
- Optical Integration Approaches

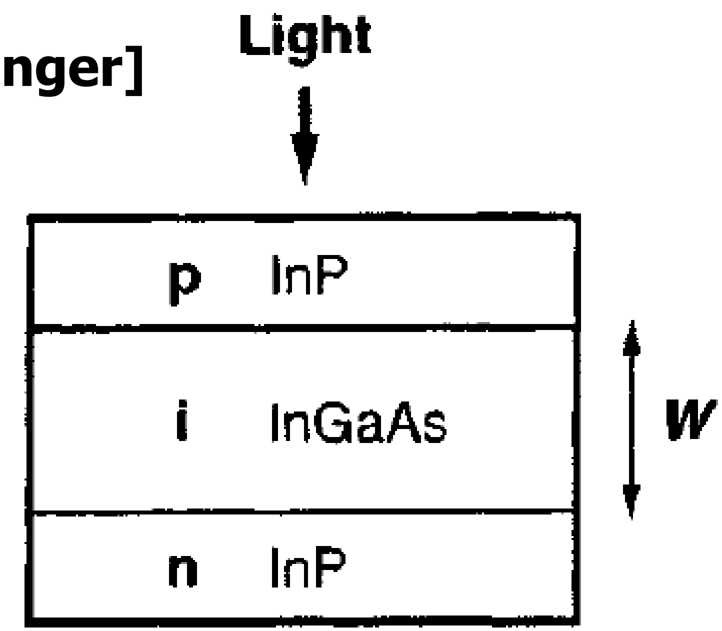
Optical Receiver Technology

- Photodetectors convert optical power into current
  - p-i-n photodiodes
  - Integrated metal-semiconductor-metal photodetector
- Electrical amplifiers then convert the photocurrent into a voltage signal
  - Transimpedance amplifiers
  - Limiting amplifiers
  - Integrating optical receiver



p-i-n Photodiode

[Sackinger]



Responsivity:

$$\rho = \frac{I}{P_{opt}} = \frac{\eta_{pd} \lambda q}{hc} = 8 \times 10^5 (\eta_{pd} \lambda) \quad (\text{mA/mW})$$

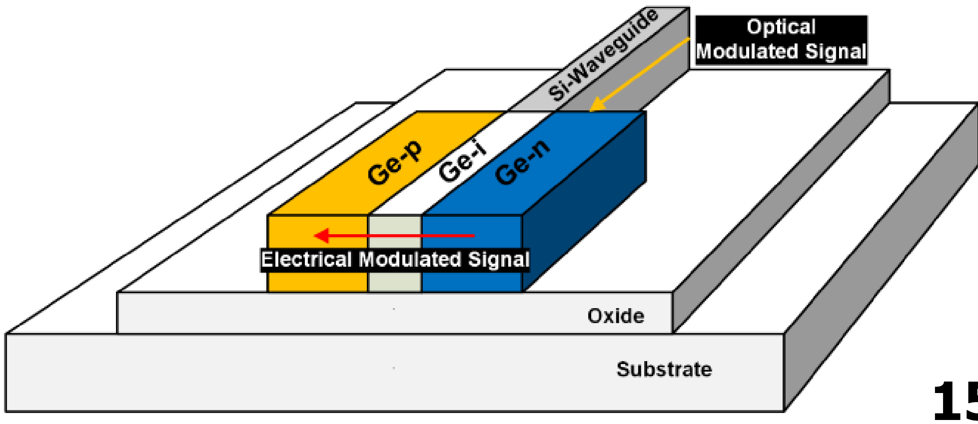
Quantum Efficiency: $\eta_{pd} = 1 - e^{-\alpha W}$

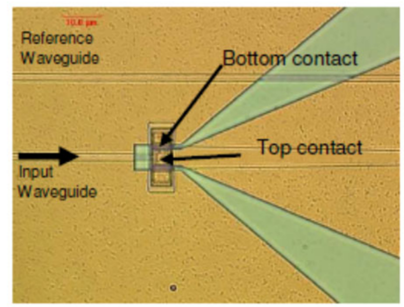
Transit-Time Limited Bandwidth:

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

- Normally incident light absorbed in intrinsic region and generates carriers
- Trade-off between capacitance and transit-time
- Typical capacitance between 100-300fF

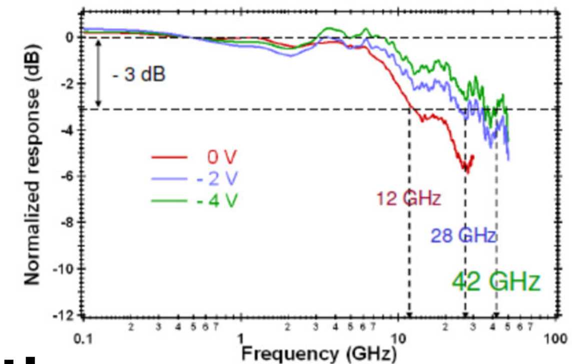
Waveguide p-i-n Photodetector





15μm detector length

[Vivien OptExp 2009]



- 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

Optical Interconnects

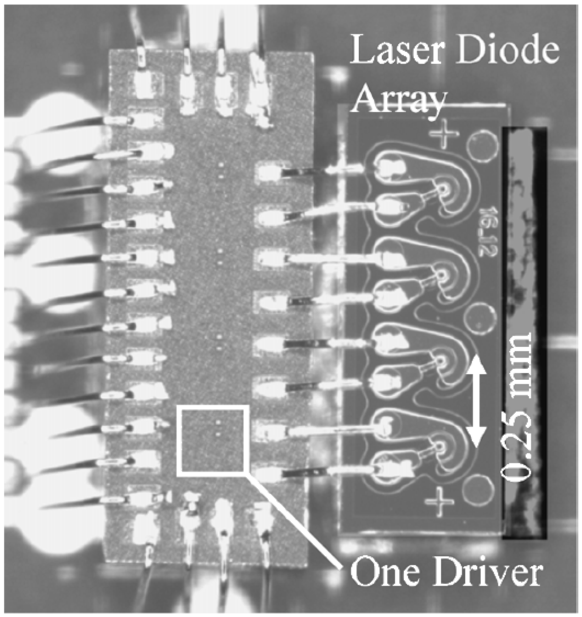
- Electrical Channel Issues
- Optical Channel
- Optical Transmitter Technology
- Optical Receiver Technology
- Optical Integration Approaches

Optical Integration Approaches

- Efficient cost-effective optical integration approaches are necessary for optical interconnects to realize their potential for improved power efficiency at higher data rates
- Hybrid integration
  - Optical devices fabricated on a separate substrate
- Integrated CMOS photonics
  - Optical devices part of CMOS chip

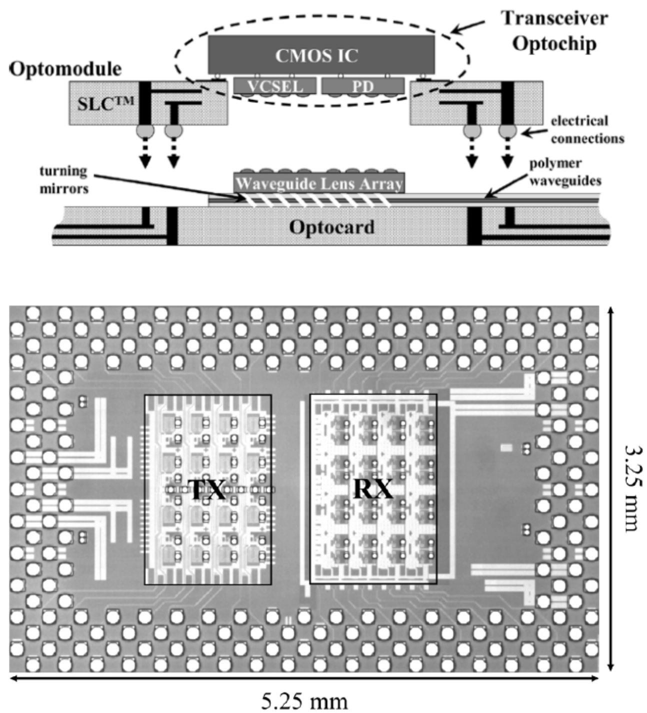
Hybrid Integration

[Kromer]



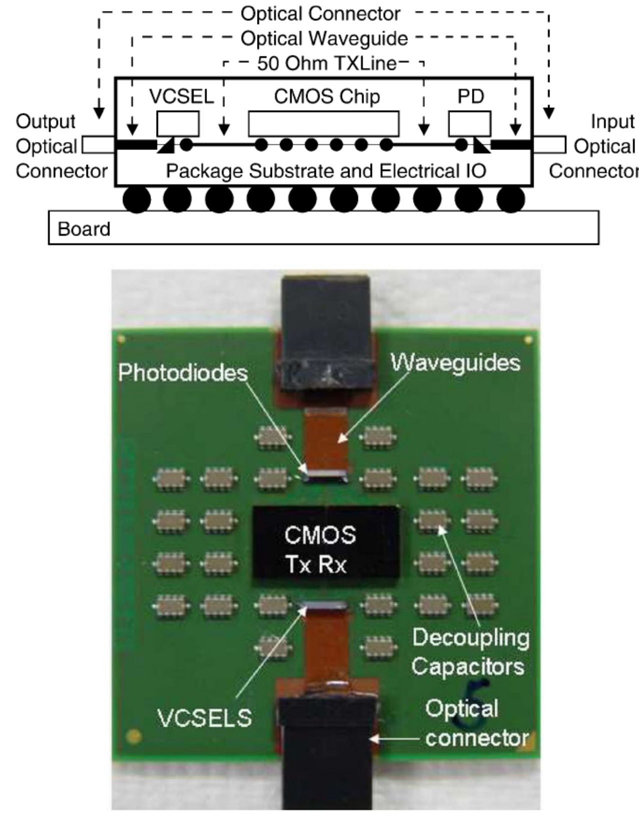
Wirebonding

[Schow]



Flip-Chip Bonding

[Mohammed]

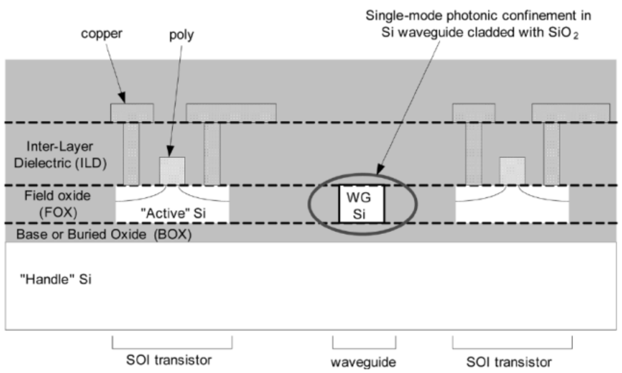


Short In-Package Traces

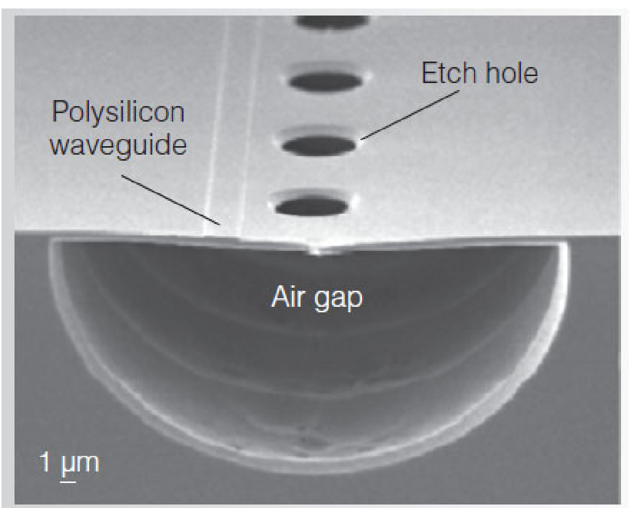
Integrated CMOS Photonics

SOI CMOS Process

[Analui]

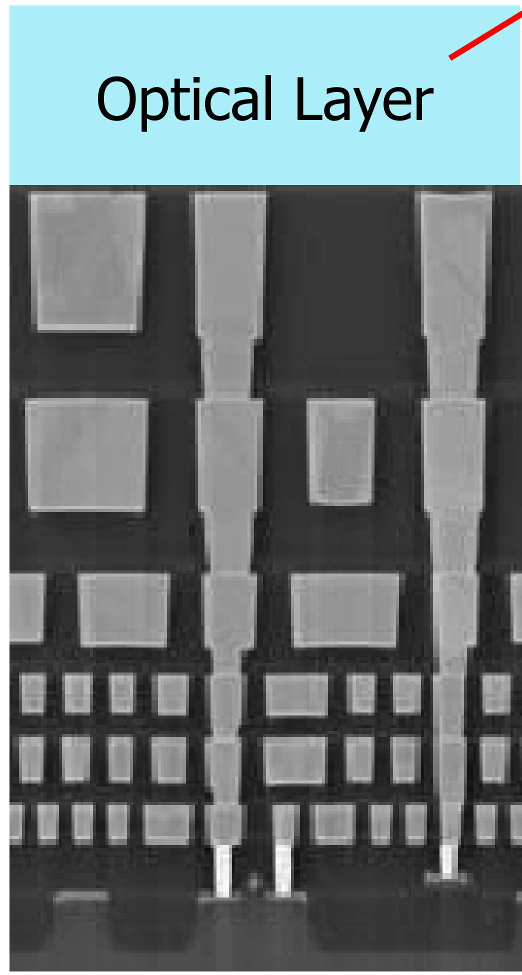


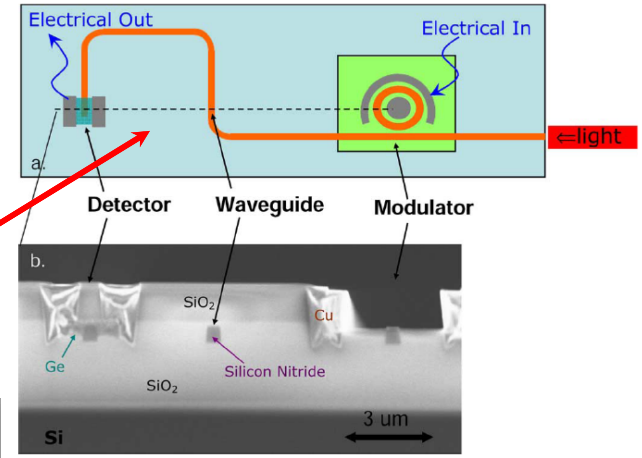
Bulk CMOS Process



[Batten]

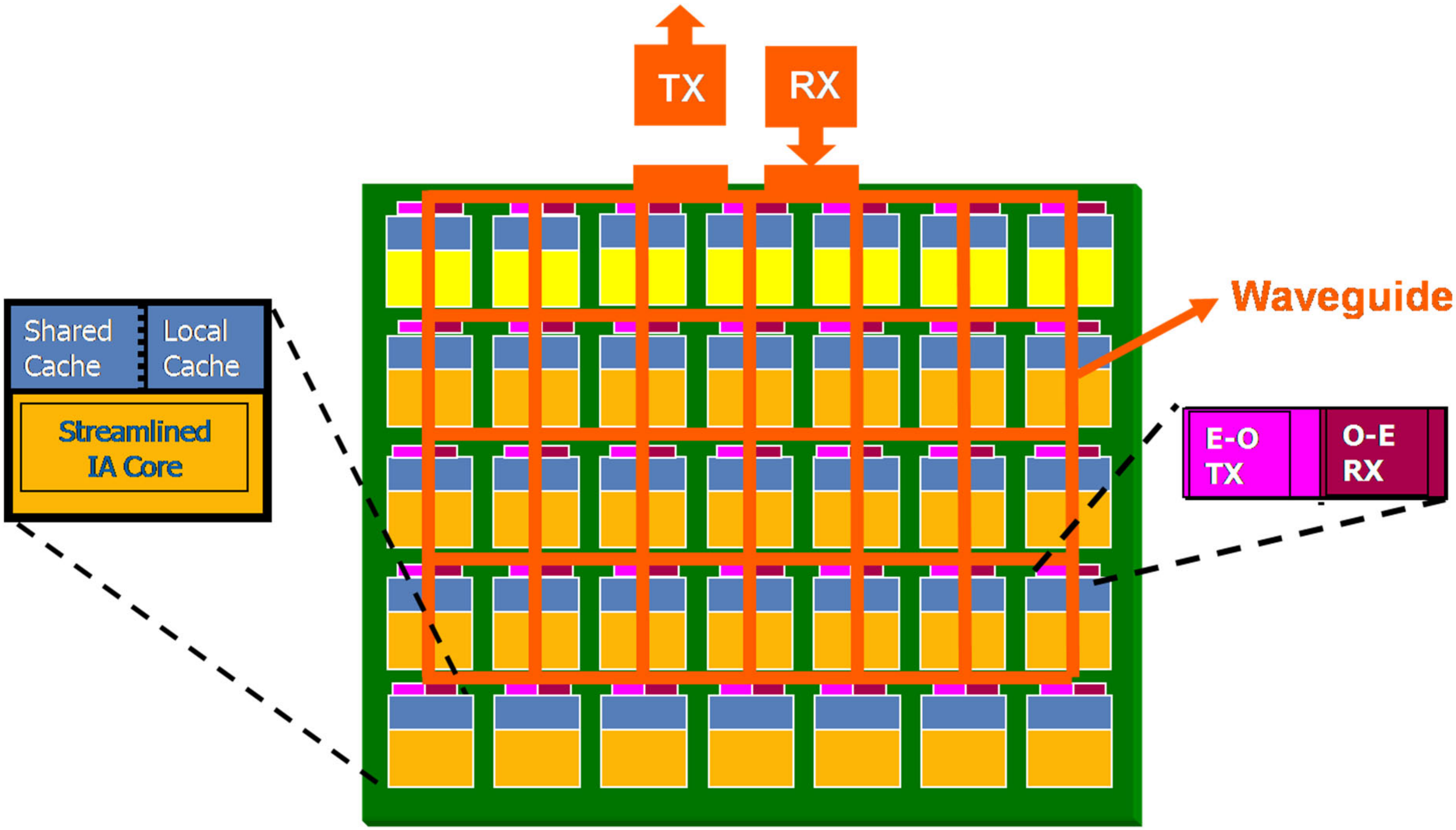
"Optics On Top"





[Young]

Future Photonic CMOS Chip



- Unified optical interconnect for on-chip core-to-core and off-chip processor-to-processor and processor-to-memory

I. Young, E. Mohammed, J. Liao, A. Kern, **S. Palermo**, B. Block, M. Reshotko, and P. Chang, "Optical I/O Technology for Tera-Scale Computing," *IEEE International Solid-State Circuits Conference,* 2009.

Next Time

- Optical Channels
  - Sackinger Chapter 2