ECEN720: High-Speed Links Circuits and Systems Spring 2023

Lecture 15: Optical I/O

Sam Palermo
Analog & Mixed-Signal Center
Texas A&M University

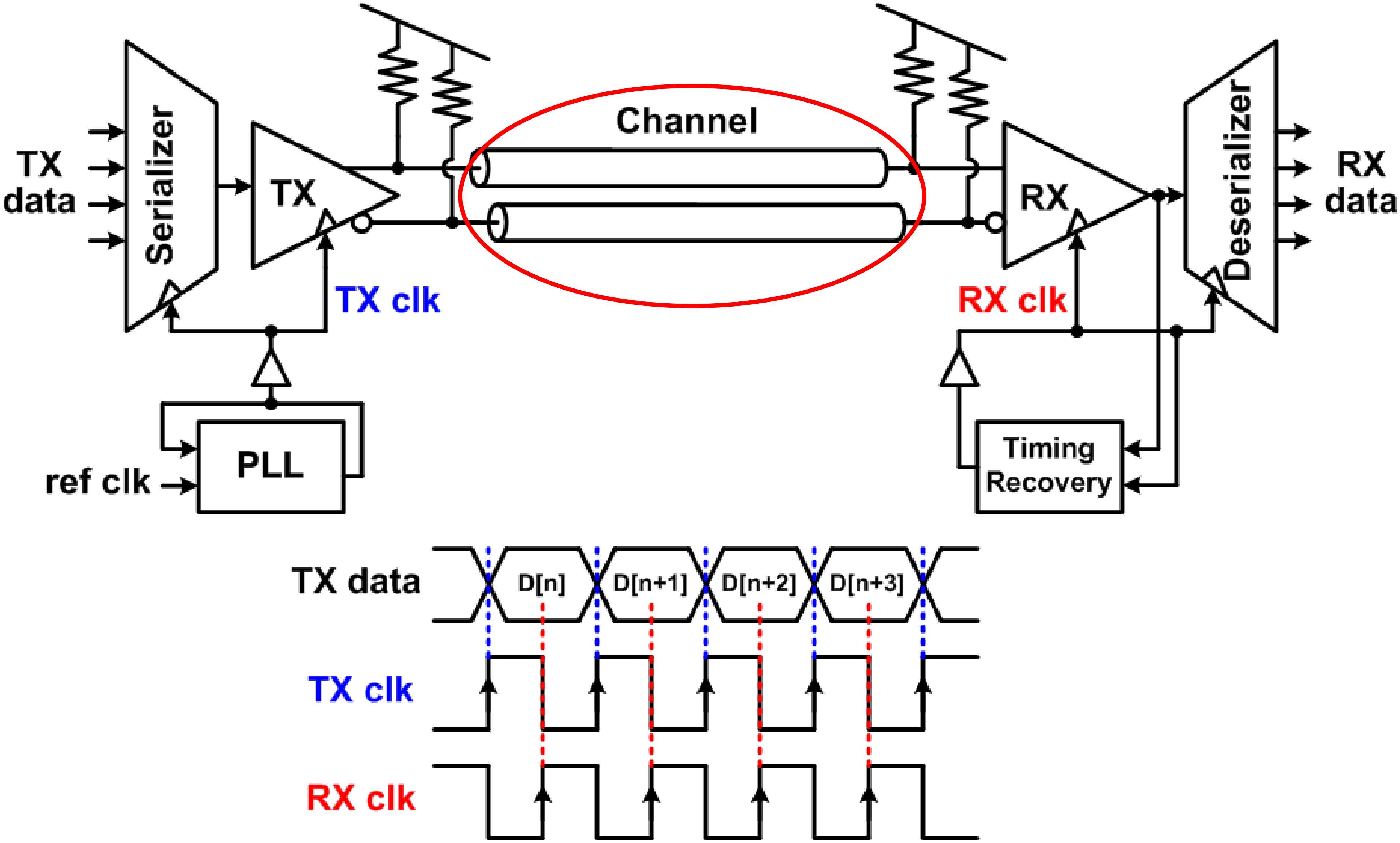
Announcements

- Exam 2 Apr 25
  - Focuses on material from Lectures 7-14
  - Previous years' Exam 2s are posted on the website for reference
- Project Final Report due May 2
- Project Presentations May 4 (12:30PM-2:30PM)

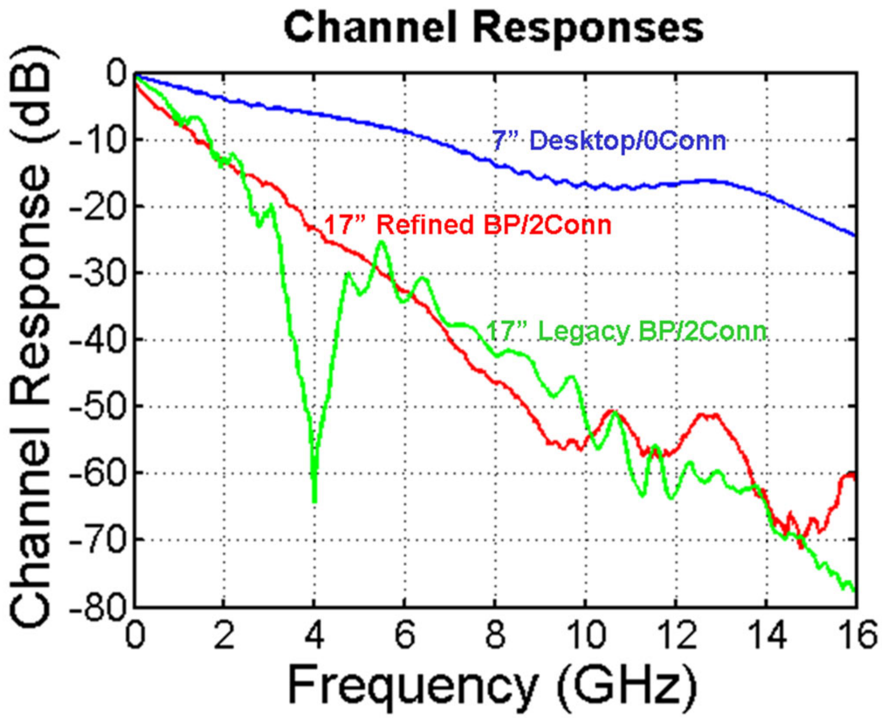
Optical Interconnects

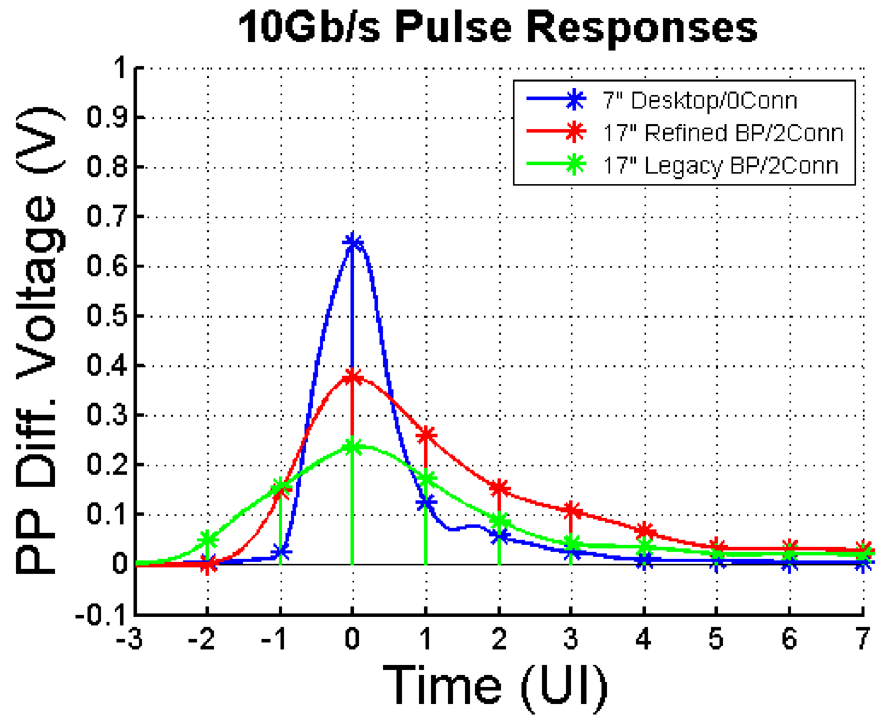
- Electrical Channel Issues
- Optical Channel
- Optical Transmitter Technology
- Optical Receiver Technology
- Optical Integration Approaches

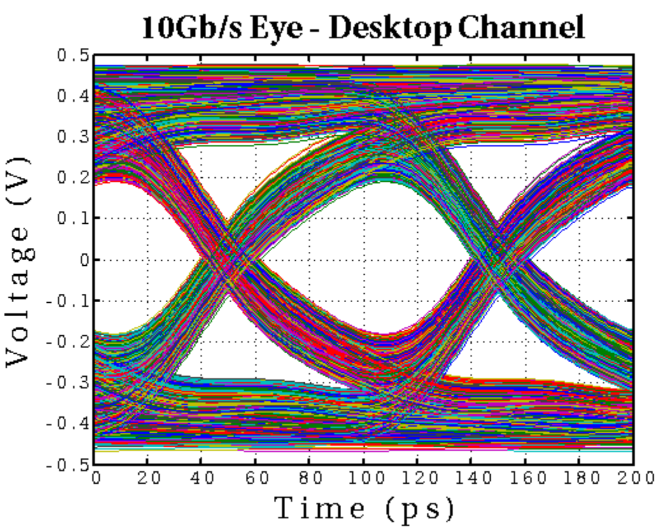
High-Speed Electrical Link System

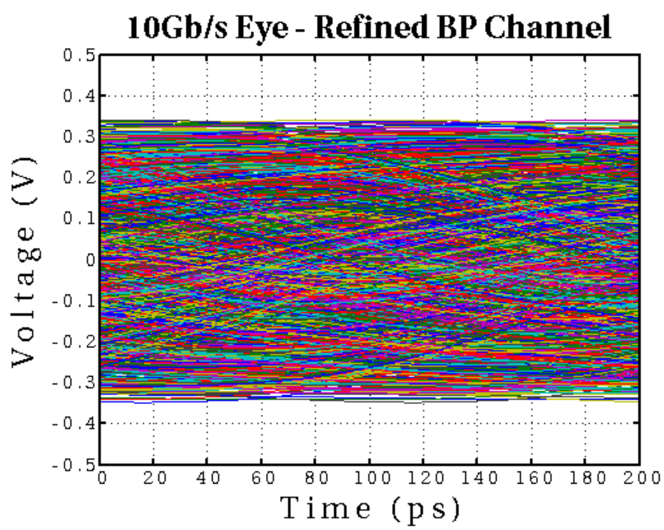


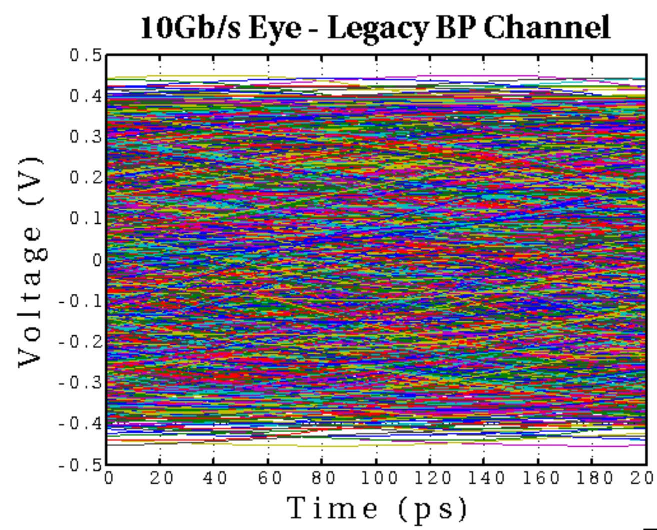
Channel Performance Impact



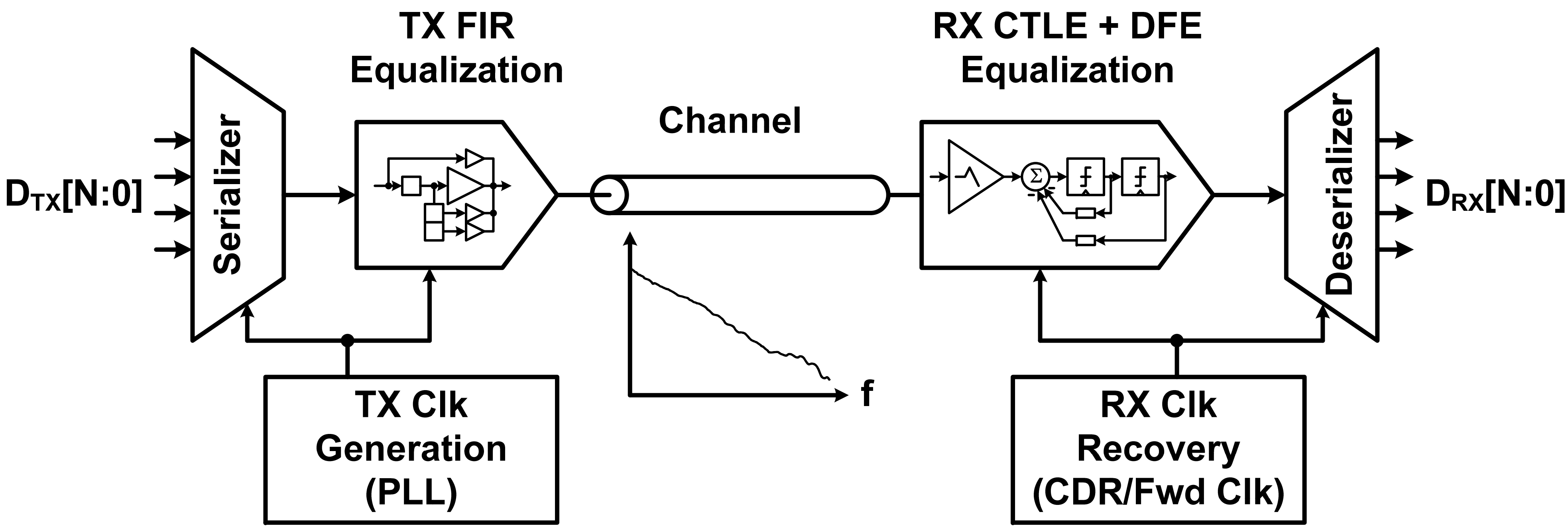




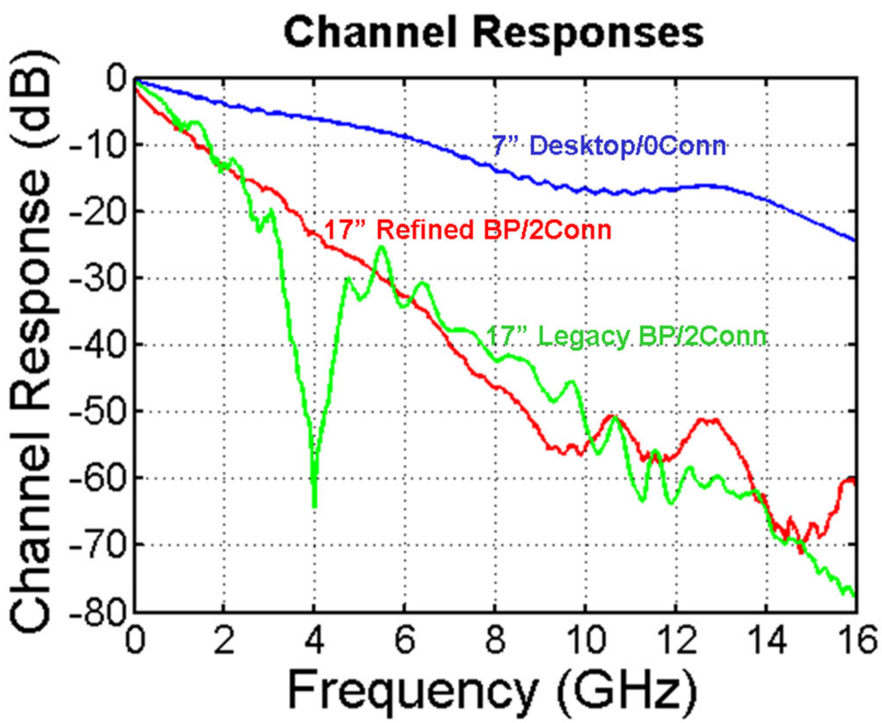


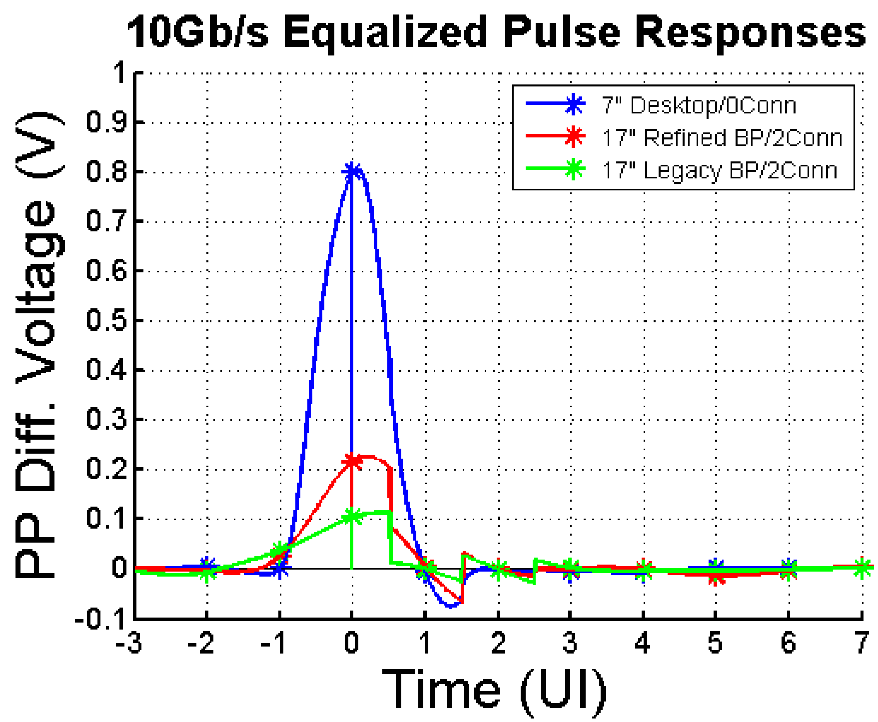


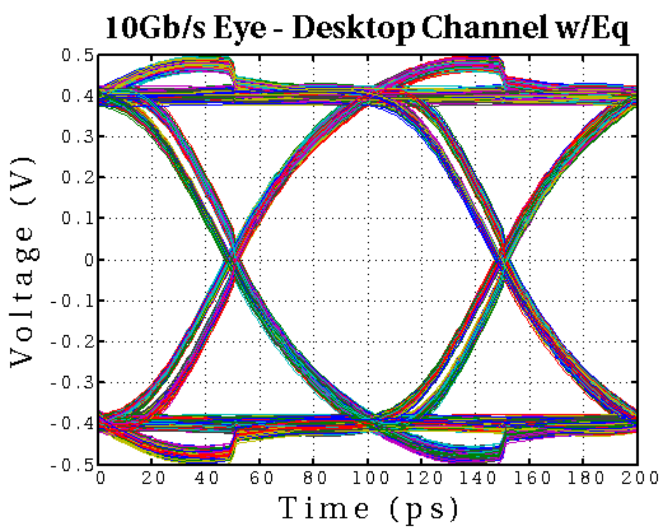
Link with Equalization

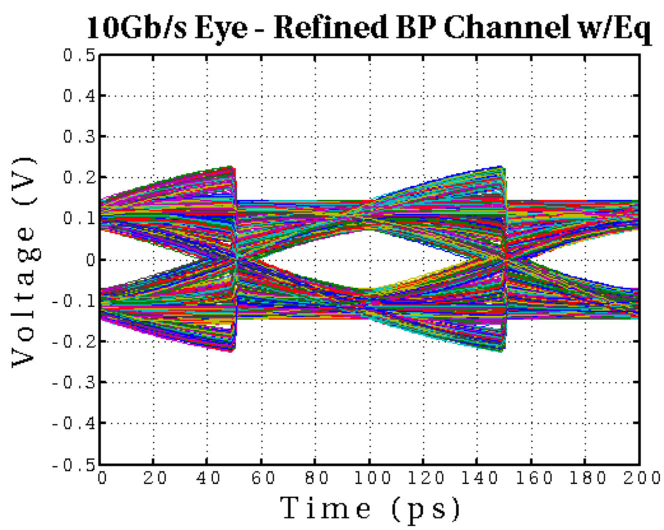


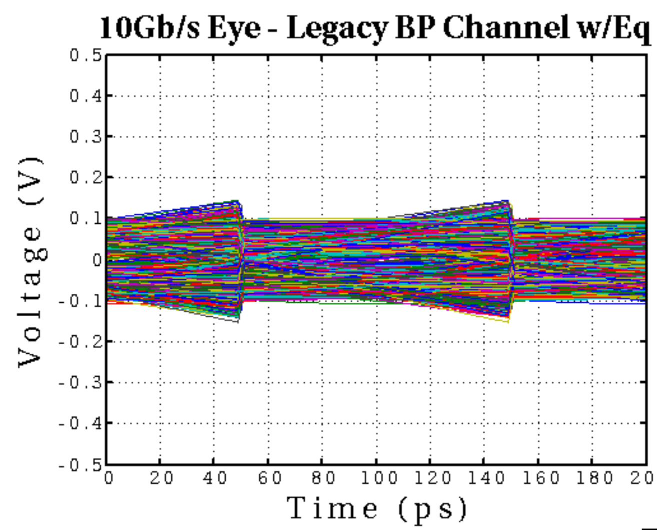
Channel Performance Impact



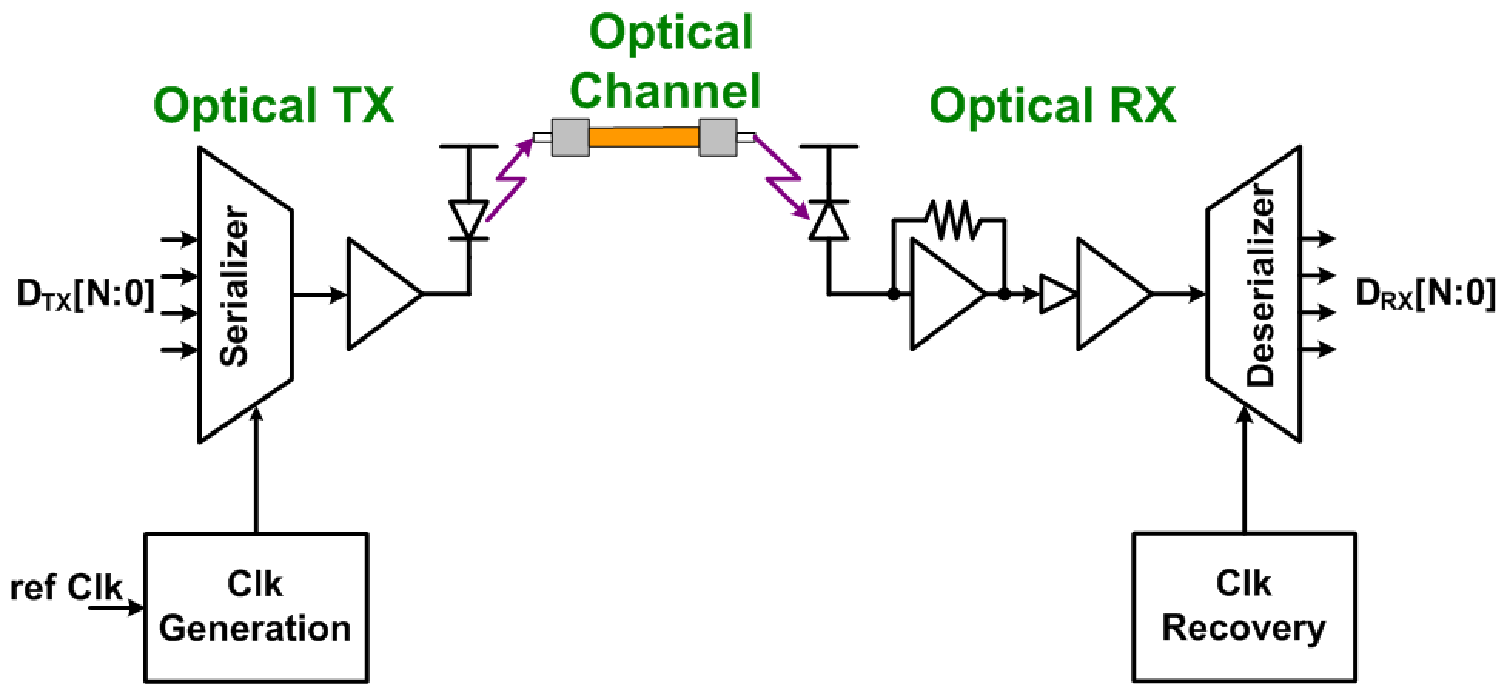




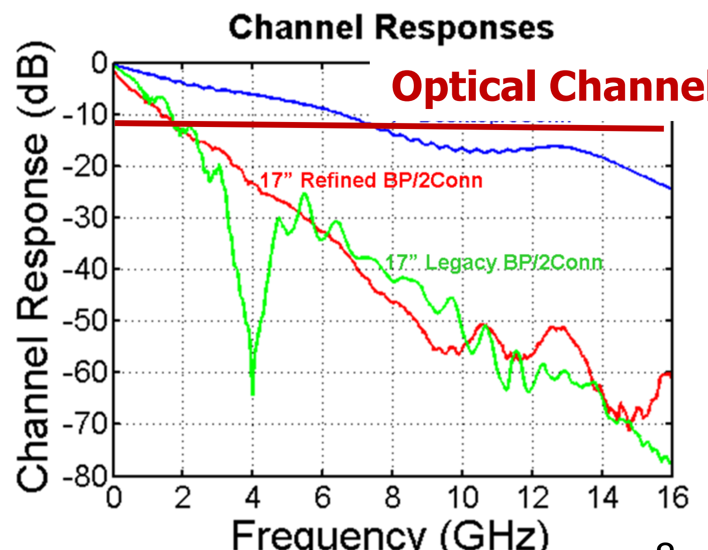




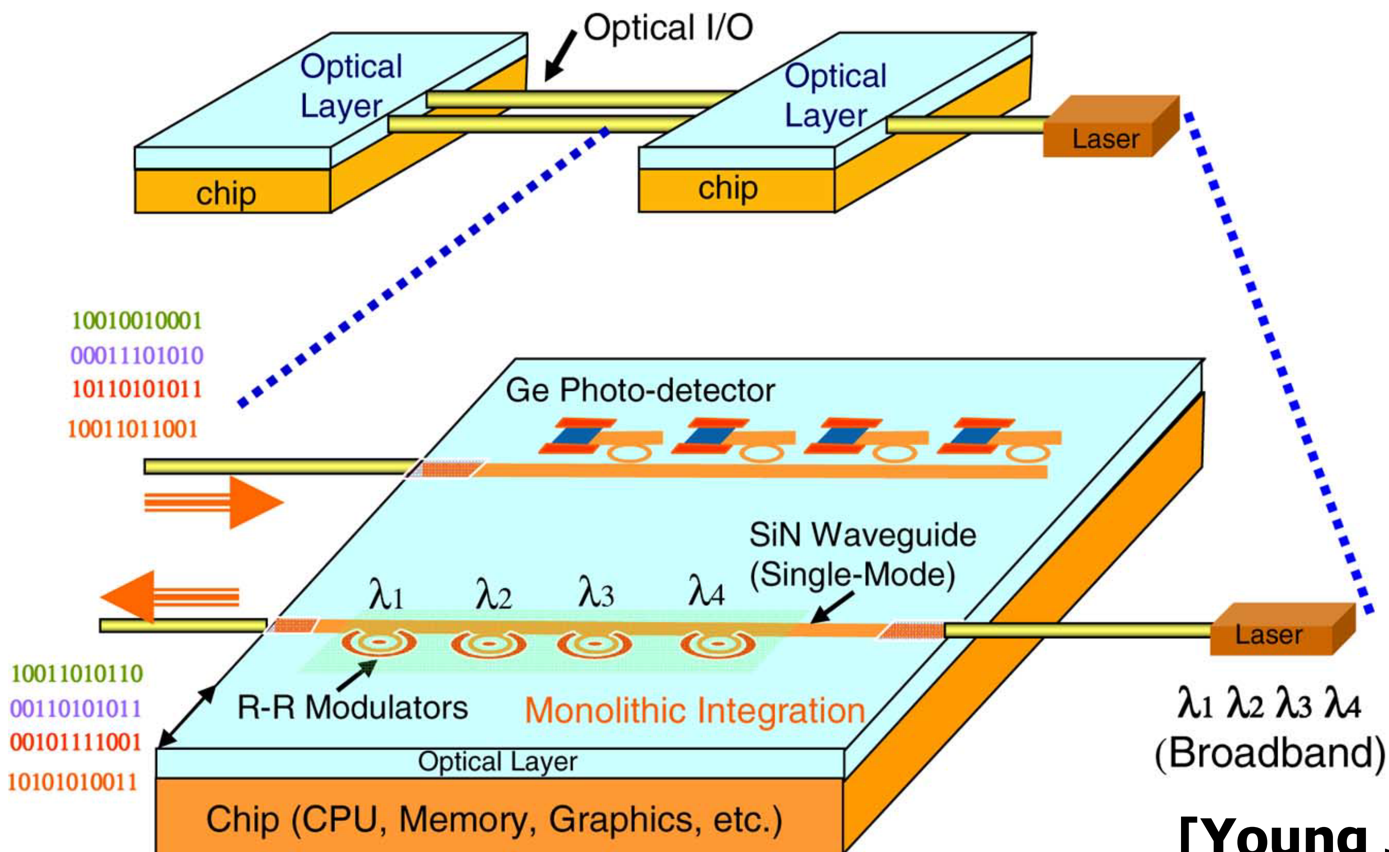
High-Speed Optical Link System



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



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

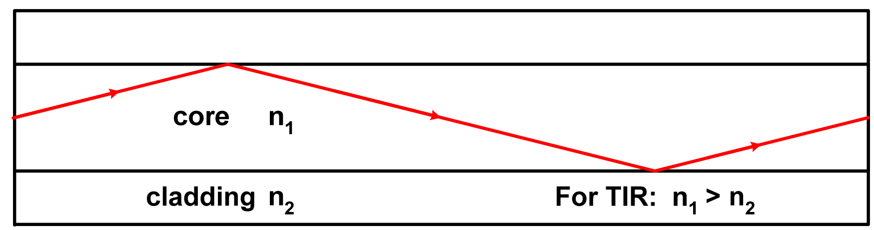
Optical Channels

- 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

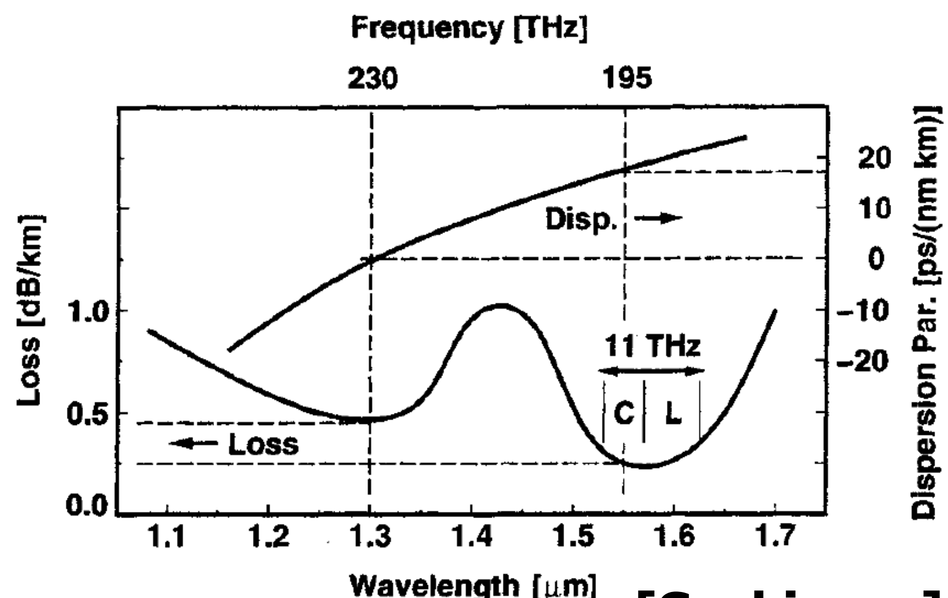
Waveguide (Fiber)-Based Optical Links

- 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



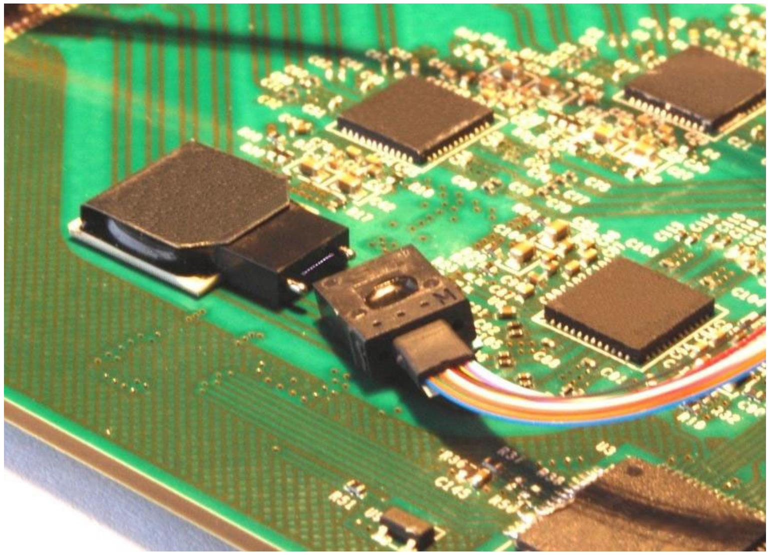
Single-Mode Fiber Loss & Dispersion



[Sackinger]

Inter-Chip Waveguide Examples

12-Channel Ribbon Fiber

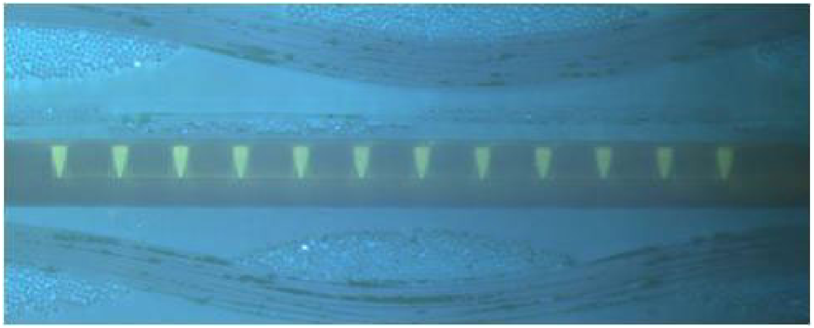


[Reflex Photonics]

12 channels at a 250μm pitch

10Gb/s mod. → 40Gb/s/mm

Optical Polymer Waveguide in PCB



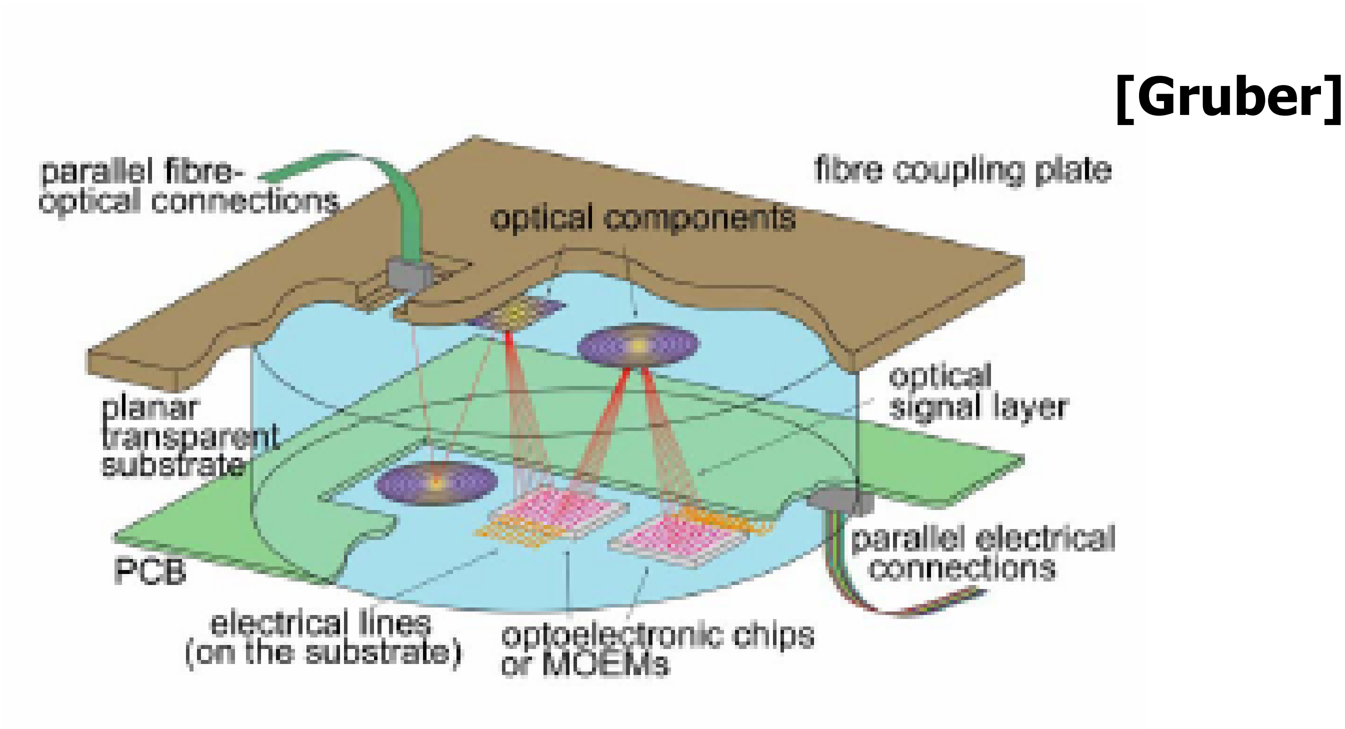
[Immonen 2009]

<100μm channel pitch possible

10Gb/s mod. → 100+Gb/s/mm

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

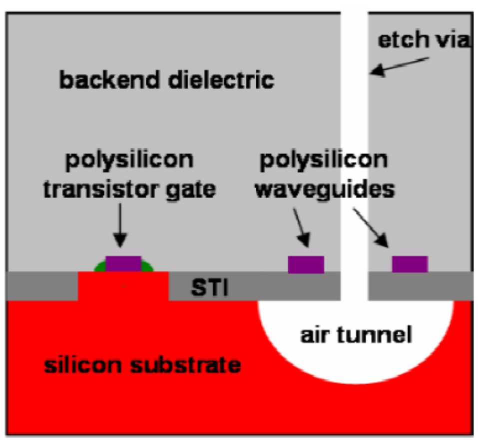
Free-Space Optical Links

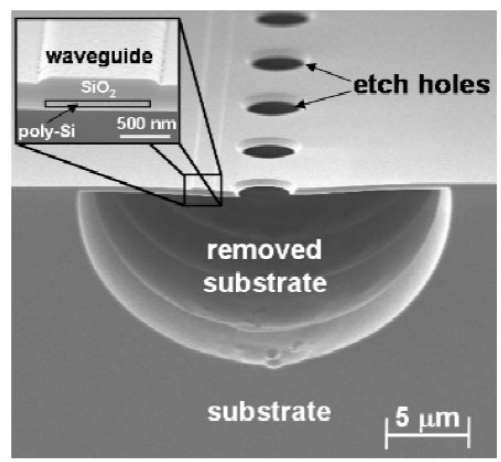


- Free-space (air or glass) interconnect systems have also been proposed
- Optical imaging system routes light chip-to-chip

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

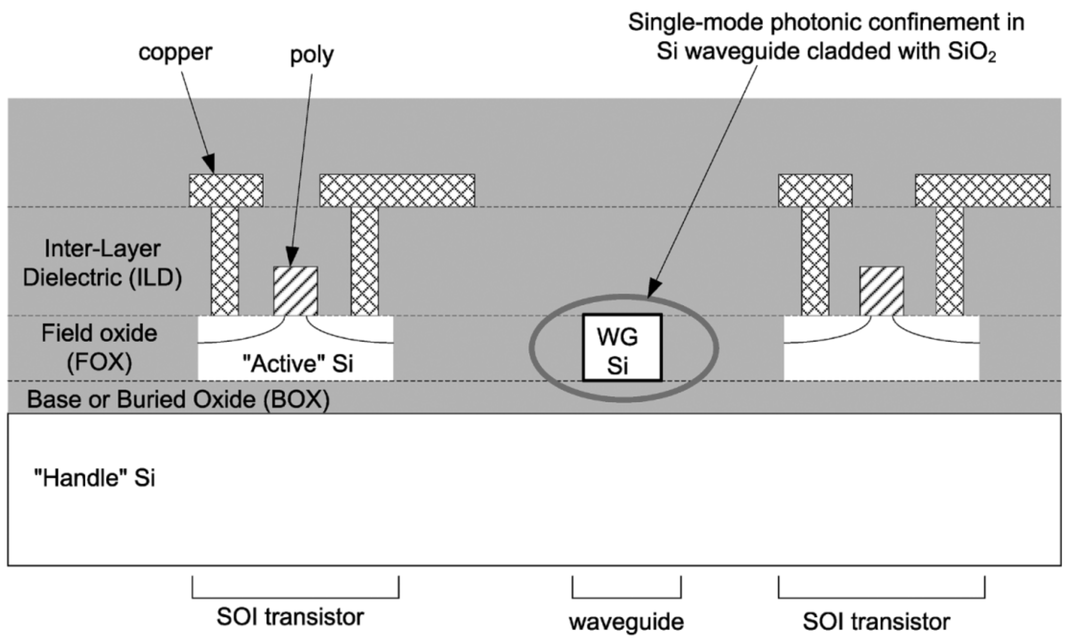




[Holzwarth CLEO 2008]

CMOS Waveguides – SOI

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

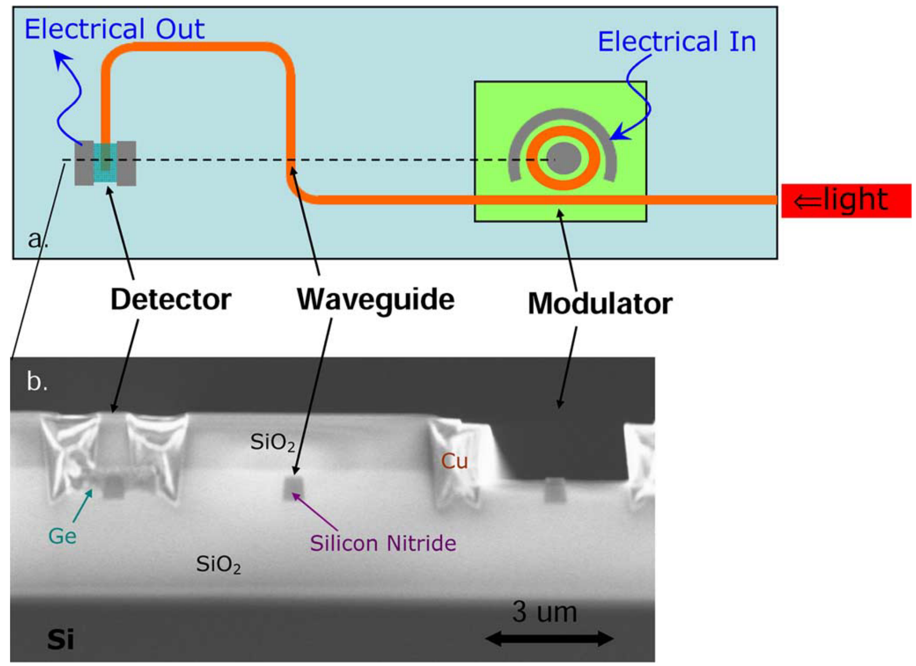


[Narasimha JSSC 2007]

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]

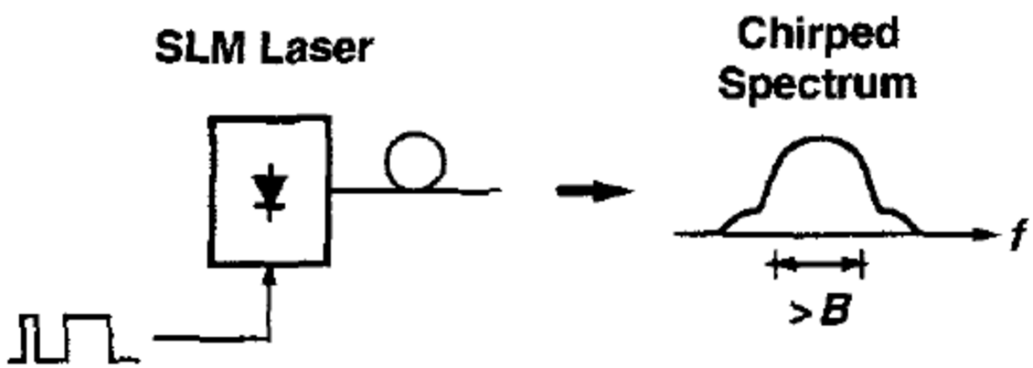


Optical Interconnects

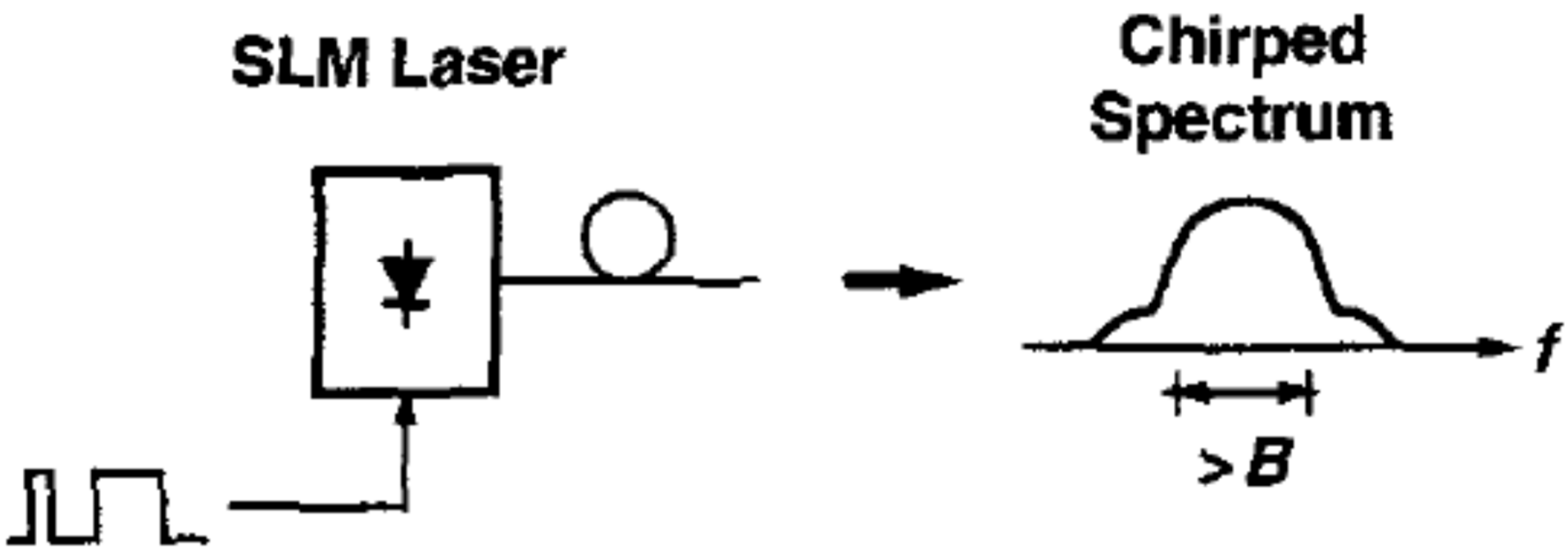
- Electrical Channel Issues
- Optical Channel
- Optical Transmitter Technology
- Optical Receiver Technology
- Optical Integration Approaches

Optical Modulation Techniques

- Due to it's narrow frequency (wavelength) spectrum, a single-longitudinal mode (SLM) laser source often generates the optical power that is modulated for data communication
  - This is required for long-haul (multi-km) communication
  - May not be necessary for short distance (~100m) chip-to-chip I/Os
- Two modulation techniques
  - Direct modulation of laser
  - External modulation of continuous-wave (CW) "DC" laser with absorptive or refractive modulators

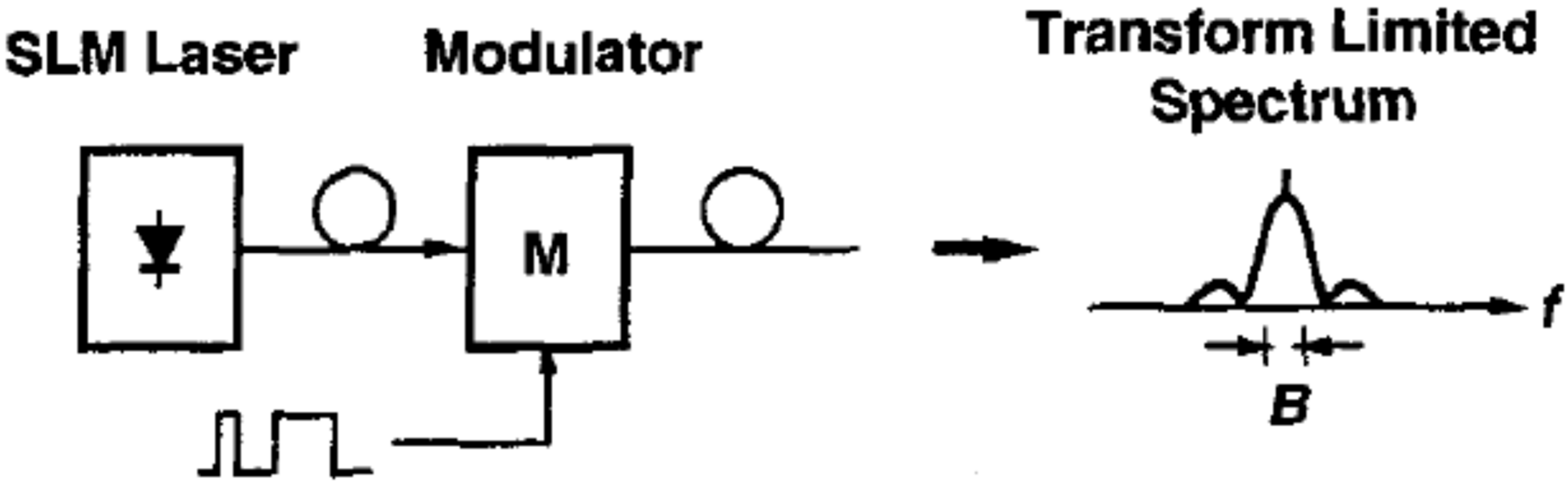


Directly Modulated Laser



- 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



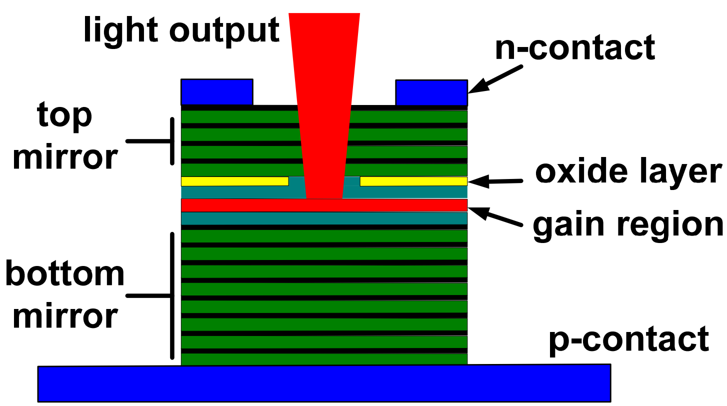
- External modulation of continuous-wave (CW) "DC" laser with absorptive or refractive modulators
  - Adds an extra component
  - Doesn't add chirp, and allows for a transform limited spectrum

Optical Sources for Chip-to-Chip Links

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

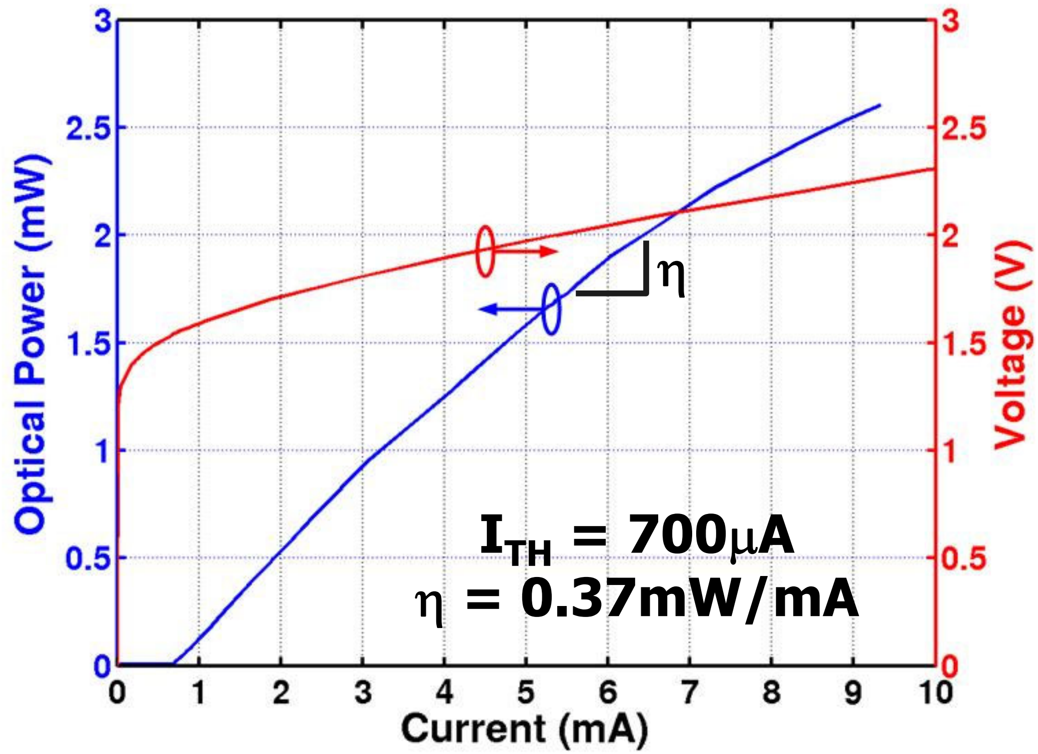
Vertical-Cavity Surface-Emitting Laser (VCSEL)

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

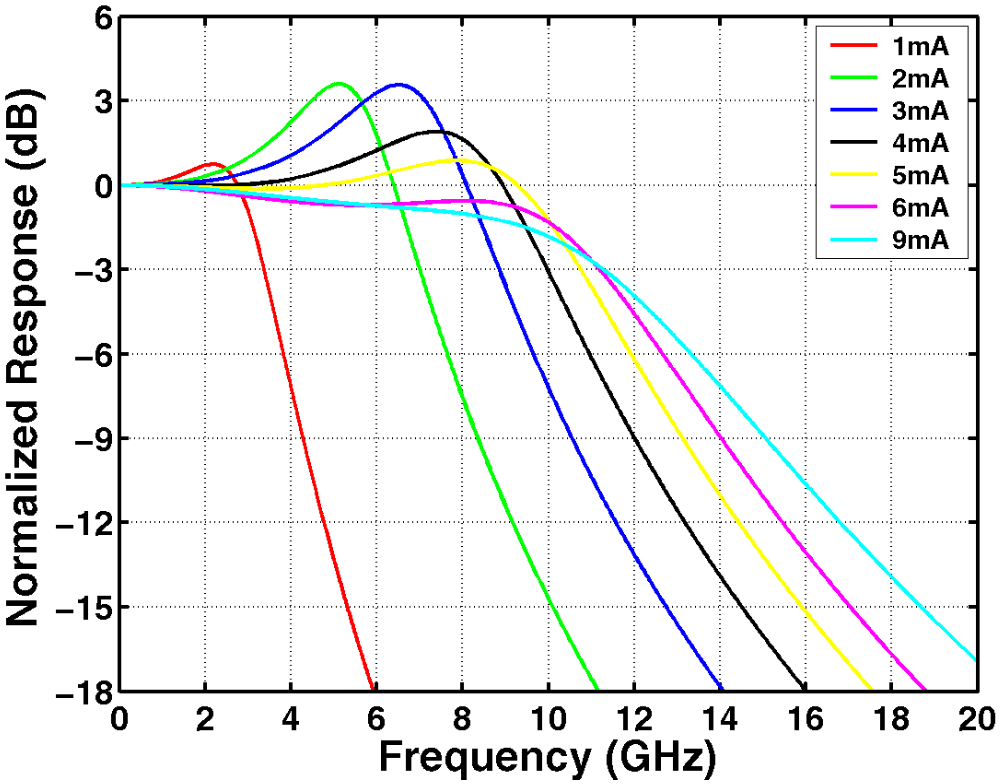


$$P_o = \eta\left(I - I_{TH}\right)$$

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

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

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

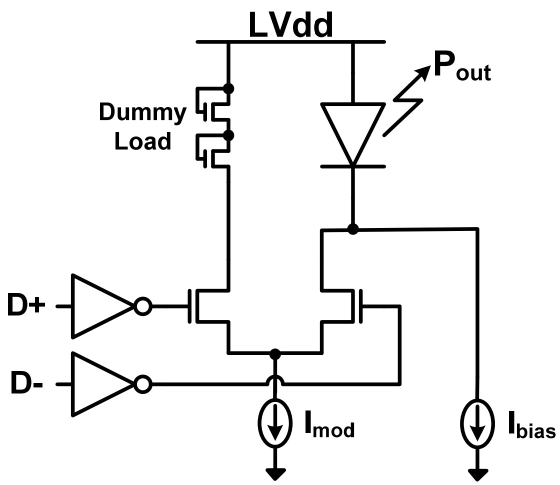
- Steep trade-off between bandwidth and reliability

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

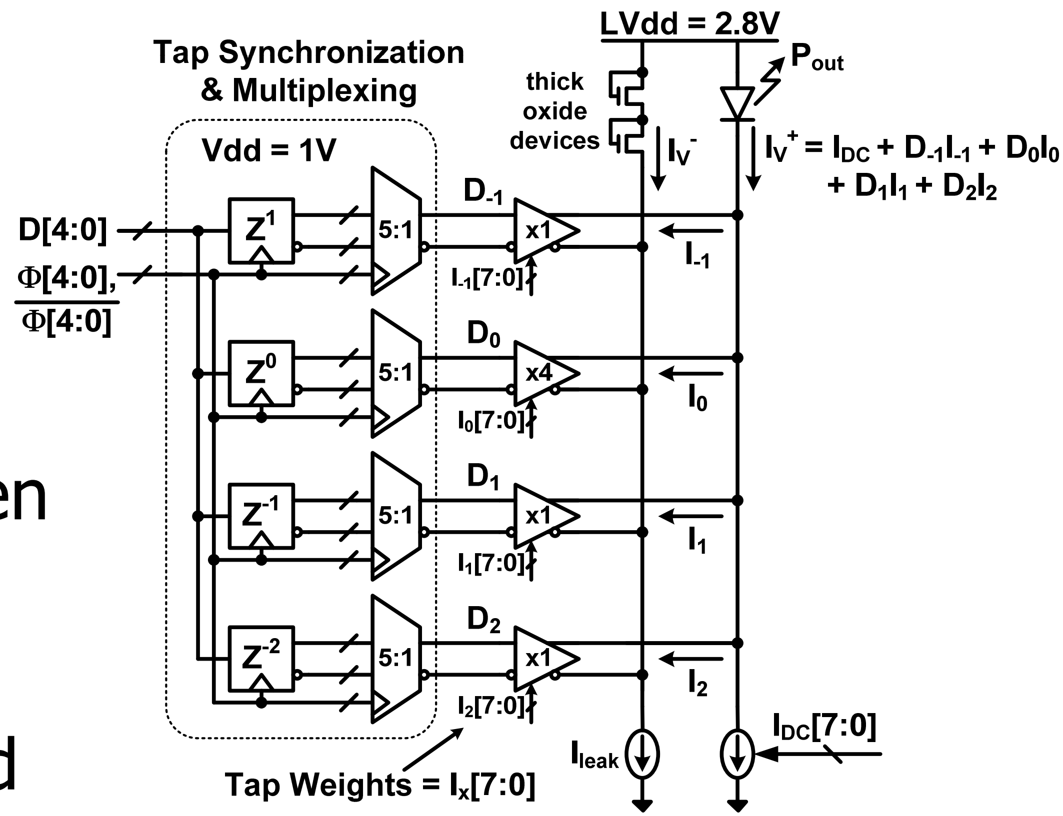
1. D. Bossert *et al*, "Production of high-speed oxide confined VCSEL arrays for datacom applications," *Proceedings of SPIE*, 2002.
2. M. Teitelbaum and K. Goossen, "Reliability of Direct Mesa Flip-Chip Bonded VCSEL's," *LEOS*, 2004.

VCSEL Drivers

Current-Mode VCSEL Driver



VCSEL Driver w/ 4-tap FIR Equalization

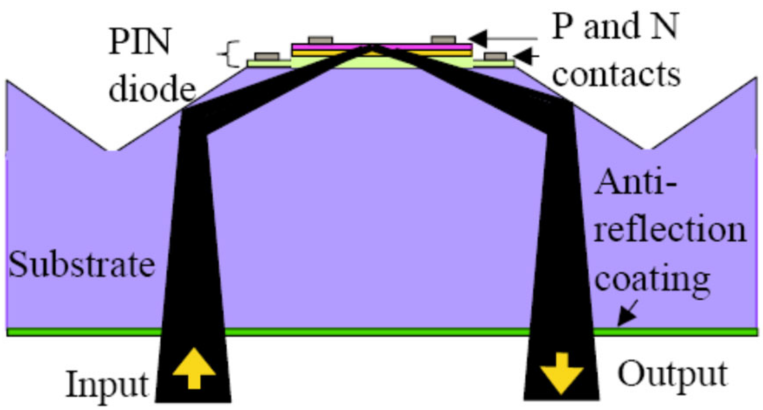


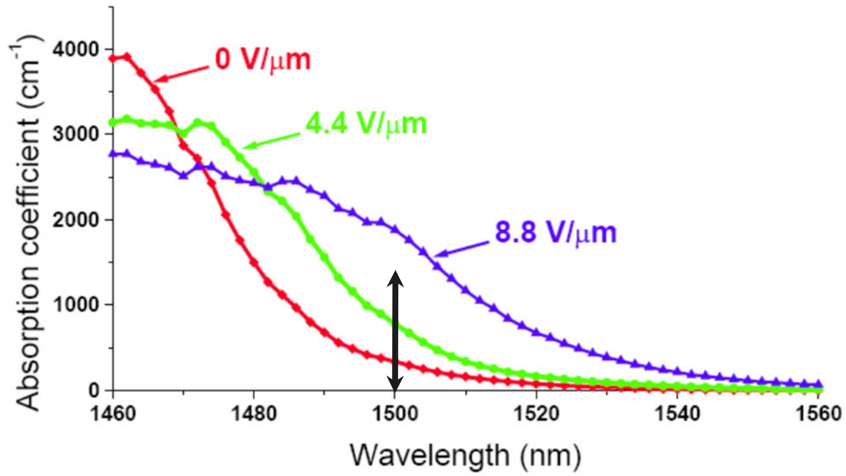
- Current-mode drivers often used due to linear L-I relationship
- Equalization can be added to extend VCSEL bandwidth for a given current density

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

Electro-Absorption Modulator (EAM)

QWAFEM Modulator*

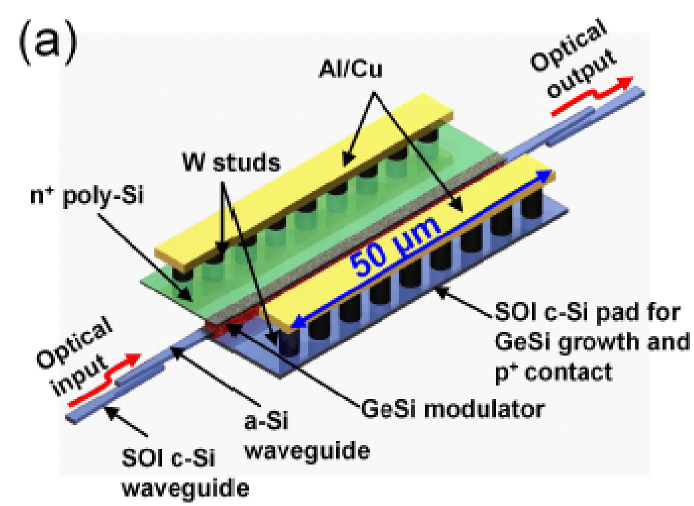




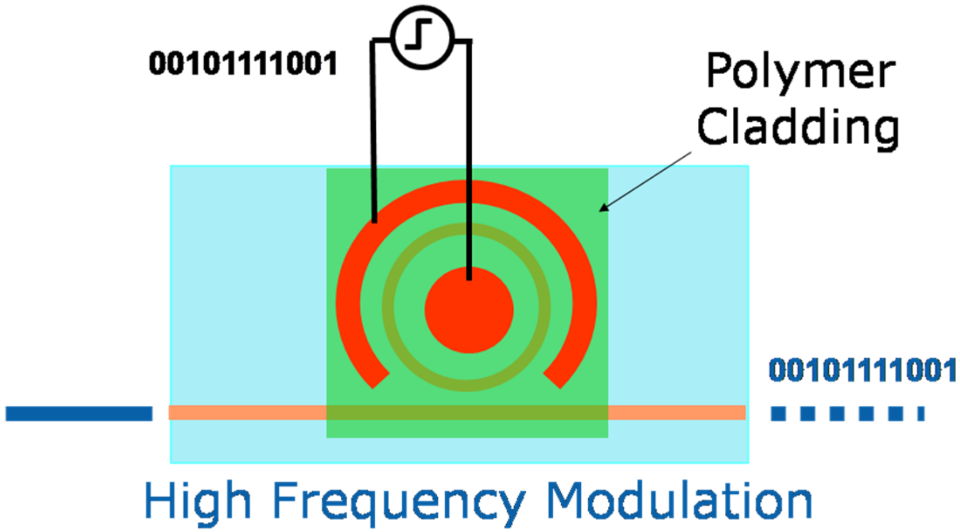
*N. Helman *et al*, "Misalignment-Tolerant Surface-Normal Low-Voltage Modulator for Optical Interconnects," *JSTQE*, 2005.

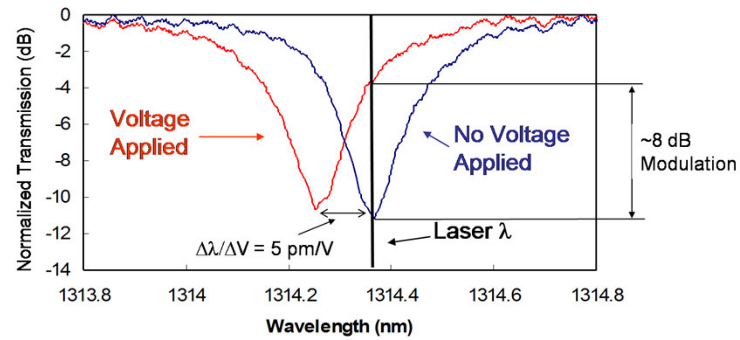
- Absorption edge shifts with changing bias voltage due to the "quantum-confined Stark or Franz-Keldysh effect" & modulation occurs
- Modulators can be surface-normal devices or waveguide-based
- Maximizing voltage swing allows for good contrast ratio over a wide wavelength range
- Devices are relatively small and can be treated as lump-capacitance loads
  - 10 – 500fF depending on device type

Waveguide EAM [Liu]

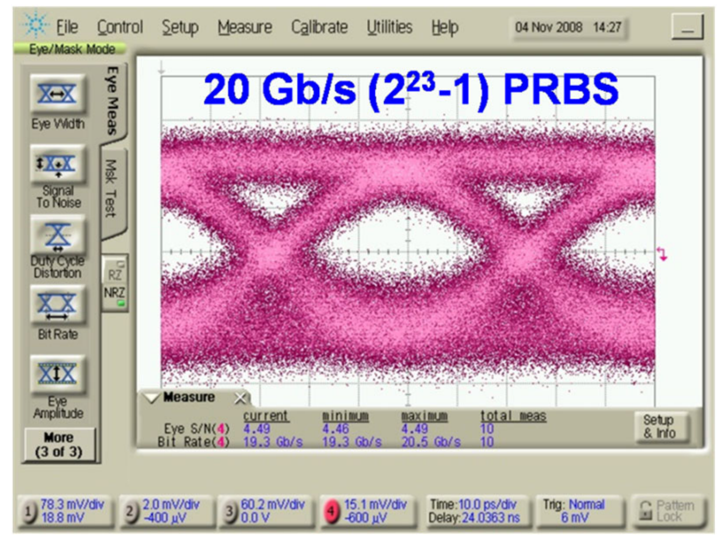


Ring-Resonator Modulator (RRM)



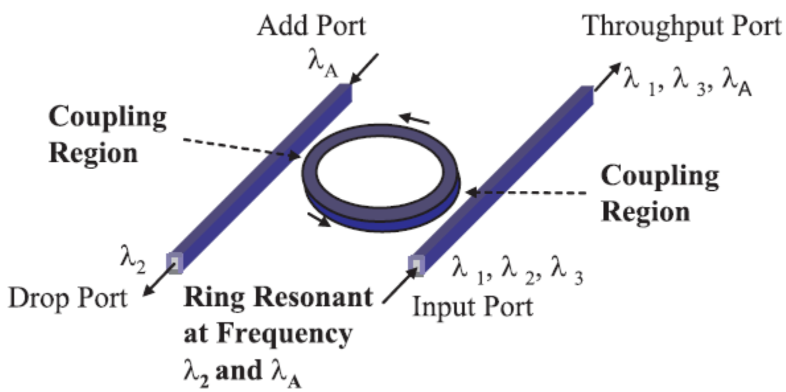


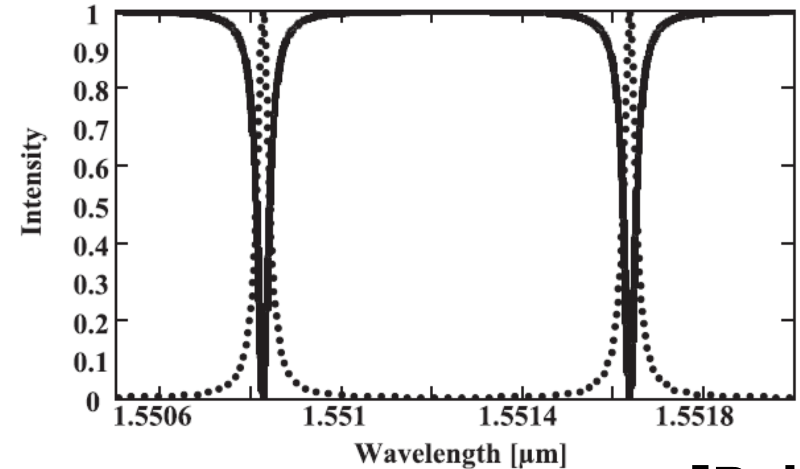
- Refractive devices which modulate by changing the interference light coupled into the ring with the waveguide light
- Devices are relatively small (ring diameters < 20μm) and can be treated as lumped capacitance loads (~10fF)
- Devices can be used in WDM systems to selectively modulate an individual wavelength or as a “drop” filter at receivers



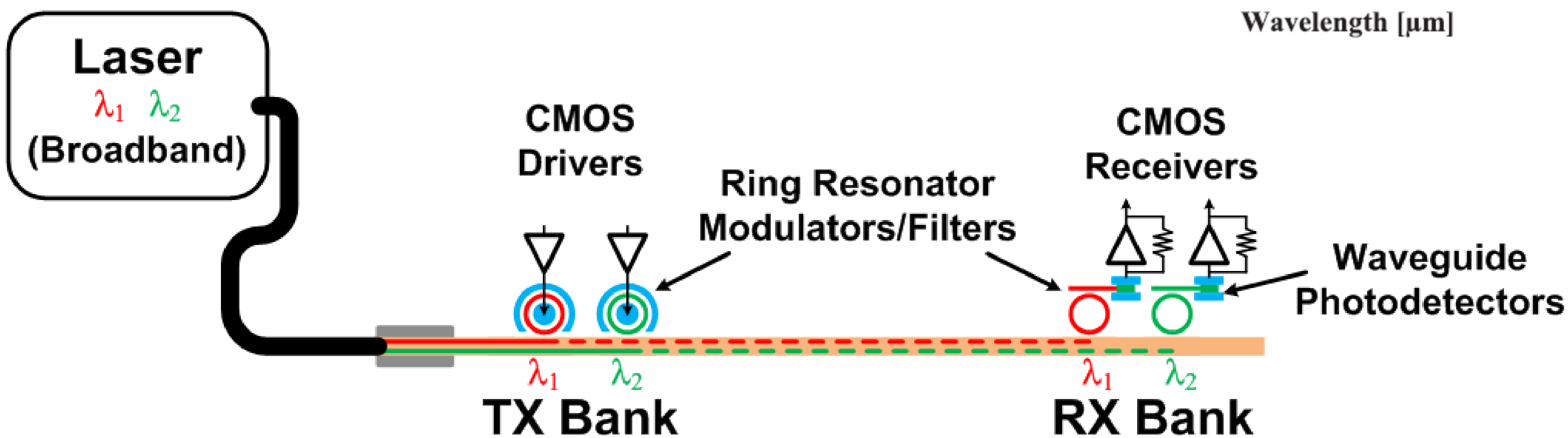
Optical Device Performance from: I. Young, E. Mohammed, J. Liao, A. Kern, **S. Palermo**, B. Block, M. Reshotko, and P. Chang, “Optical I/O Technology for Tera-Scale Computing," *ISSCC*, 2009.

Wavelength Division Multiplexing w/ Ring Resonators



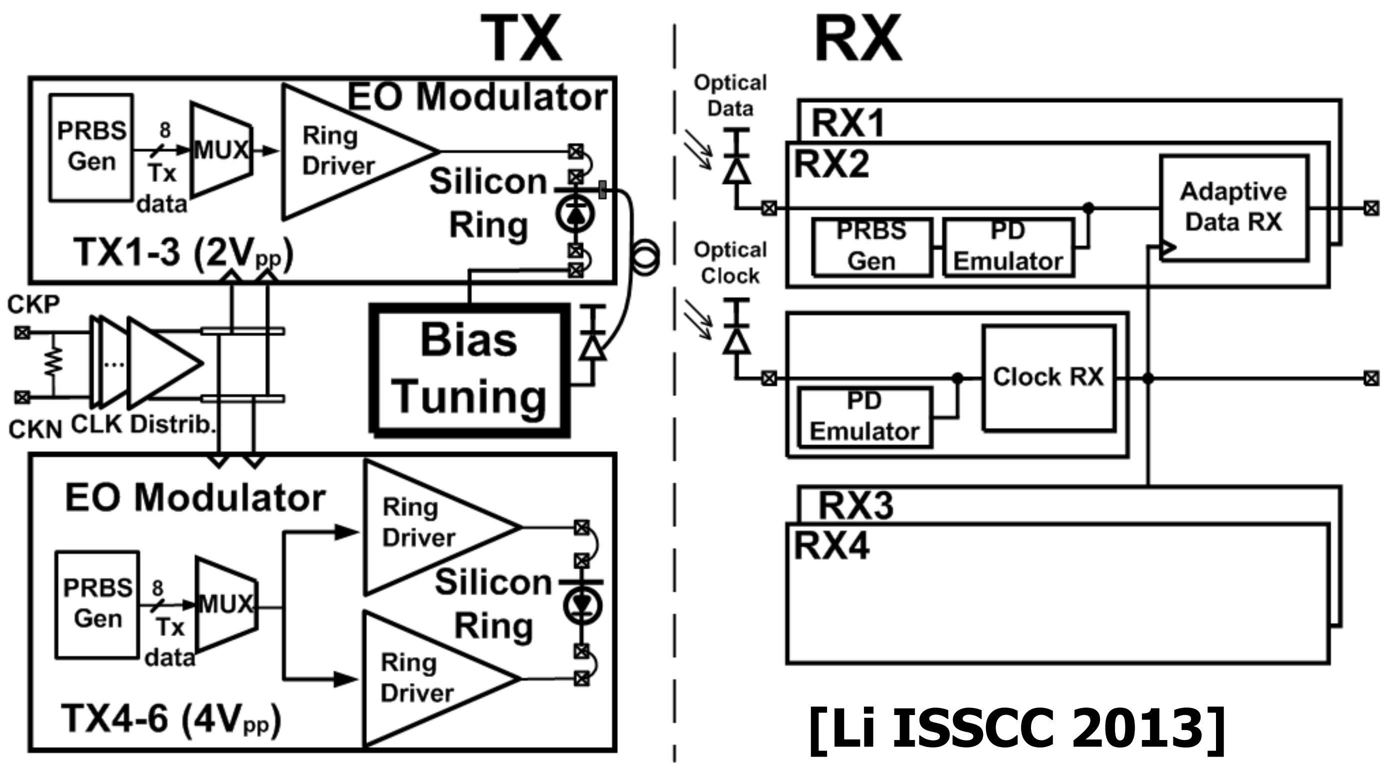


[Rabus]

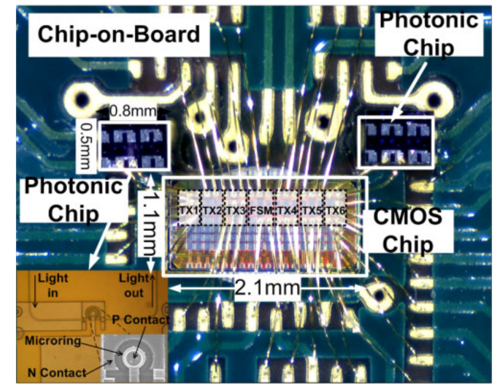


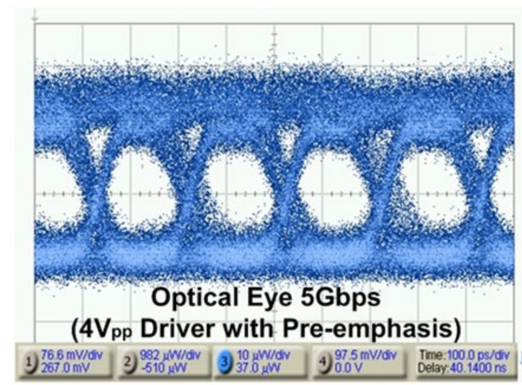
- Ring resonators can act as both modulators and add/drop filters to steer light to receivers or switch light to different waveguides
- Potential to pack >100 waveguides, each modulated at more than 10Gb/s on a single on-chip waveguide with width <1μm (pitch ~4μm)

Ring-Resonator-Based Silicon Photonics Transceiver



[Li ISSCC 2013]

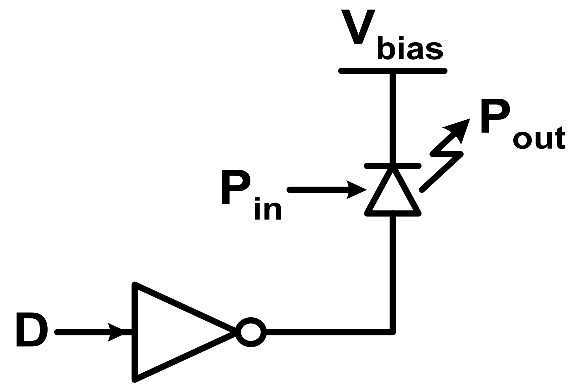




- High-voltage drivers with simple pre-emphasis to extend bandwidth of silicon ring-resonator modulators
- Forwarded-clock receiver with adaptive power-sensitivity RX
- Bias-based tuning loop to stabilize photonic device’s resonance wavelength

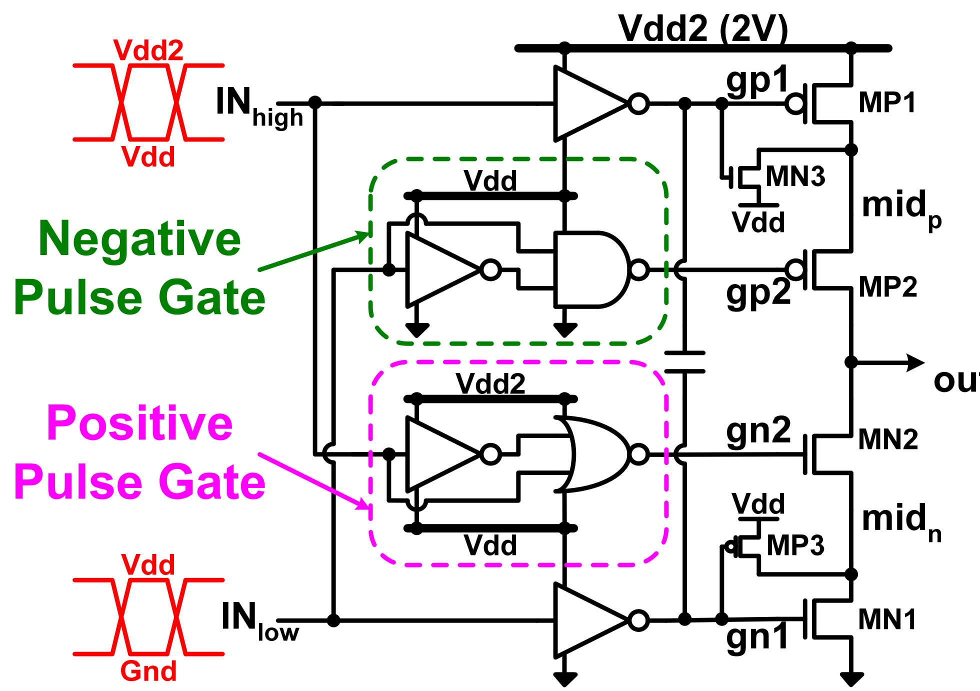
CMOS Modulator Driver

- 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

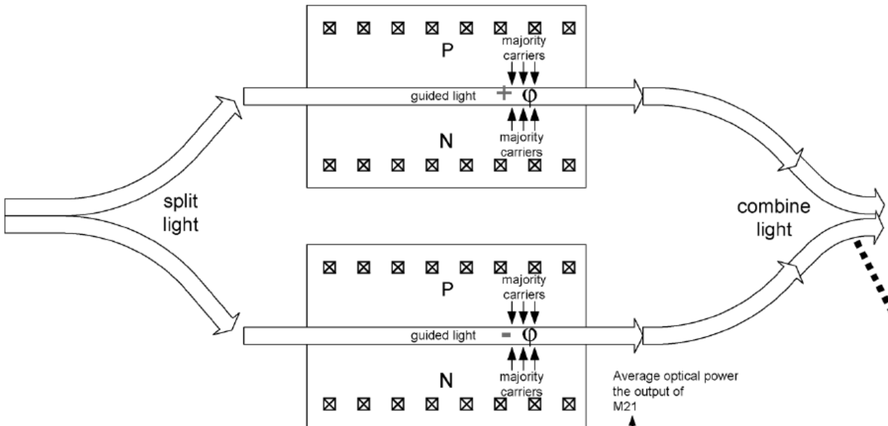
Pulsed-Cascode Driver



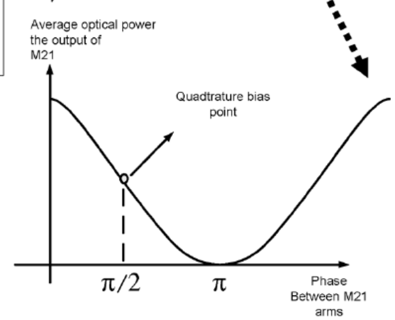
S. Palermo and M. Horowitz, "High-Speed Transmitters in 90nm CMOS for High-Density Optical Interconnects," *ESSCIRC*, 2006.

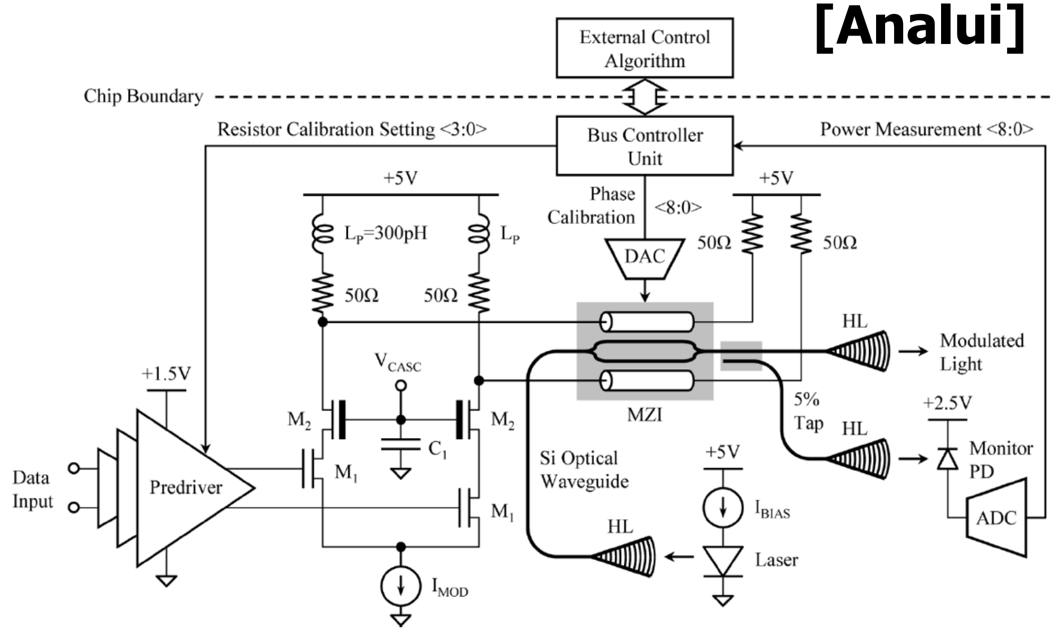
Mach-Zehnder Modulator (MZM)

[Analui]



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





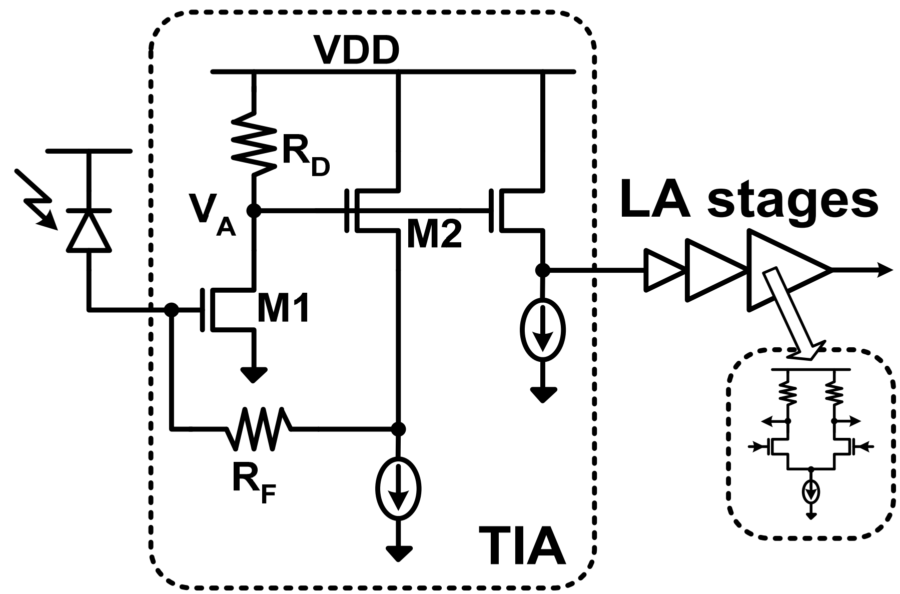
- Refractive modulator which splits incoming light into two paths, induces a voltage-controlled phase shift in the two paths, and recombines the light in or out of phase
- Long device (several mm) requires driver to drive low-impedance transmission line at potentially high swing ($5V_{ppd}$)
- While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

Optical Interconnects

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

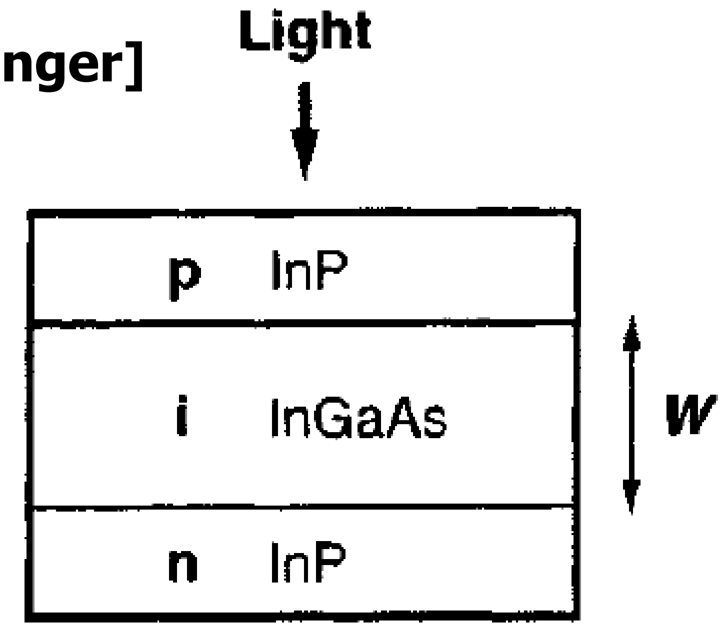
Optical Receiver Technology

- 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:

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

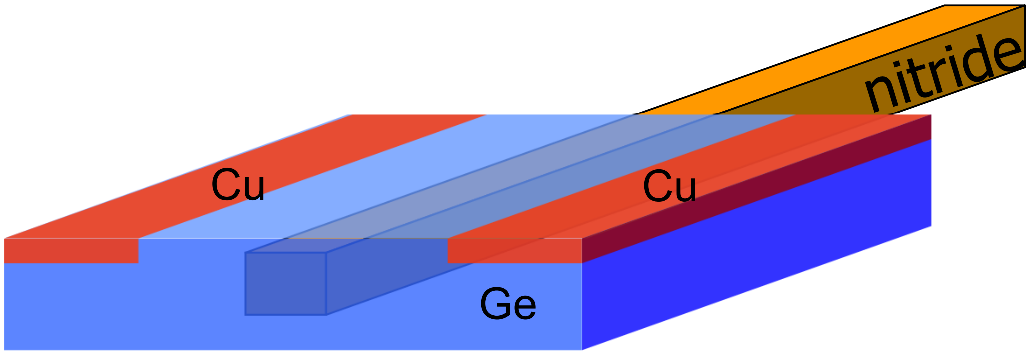
Quantum Efficiency: $\eta_{pd} = 1 - e^{-\alpha W}$

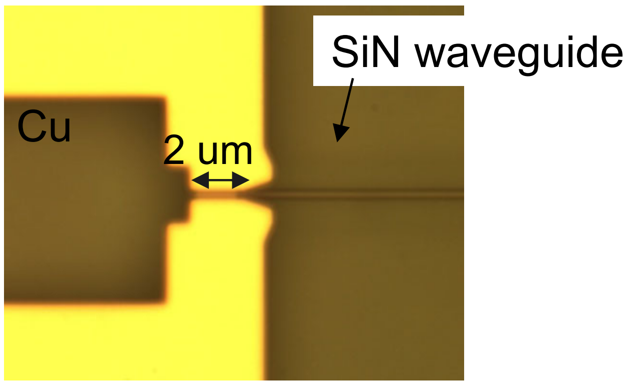
Transit-Time Limited Bandwidth:

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

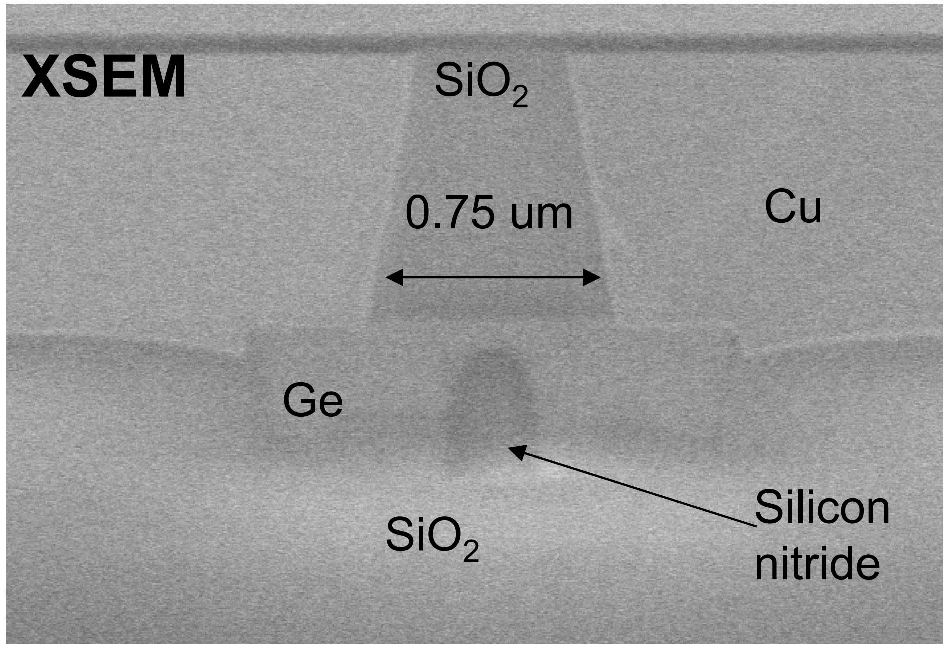
- Normally incident light absorbed in intrinsic region and generates carriers
- Trade-off between capacitance and transit-time
- Typical capacitance between 100-300fF

Integrated Ge MSM Photodetector





Detector



Very low capacitance: <1 fF
Active area: < 2 um^2

- Lateral Metal-Semiconductor-Metal (MSM Detector)
- Silicon Nitride Waveguide-Coupled
- Direct Germanium deposition on oxide

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 Journal of Solid-State Circuits*, 2010.

Optical Interconnects

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

Optical Integration Approaches

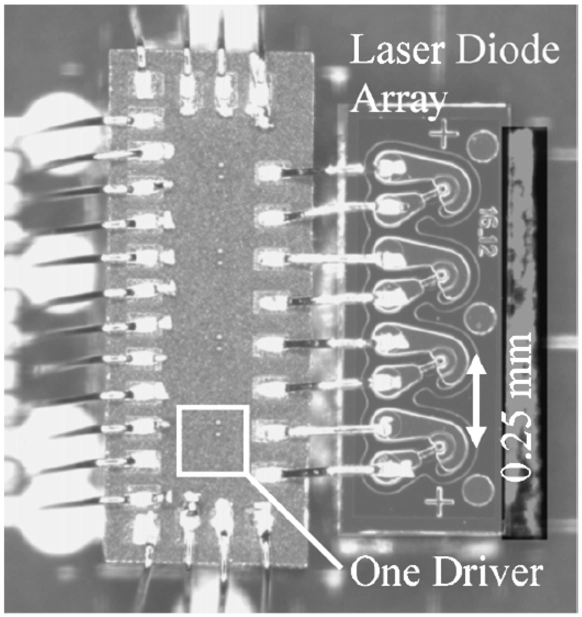
- Efficient cost-effective optical integration approaches are necessary for optical interconnects to realize their potential for improved power efficiency at higher data rates

- Hybrid integration
  - Optical devices fabricated on a separate substrate

- Integrated CMOS photonics
  - Optical devices part of CMOS chip

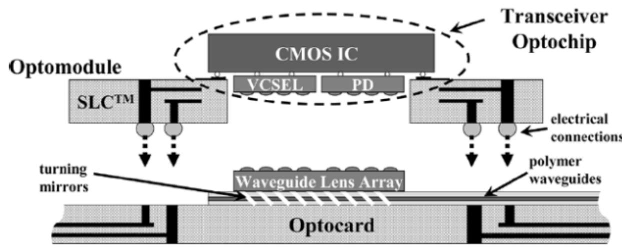
Hybrid Integration

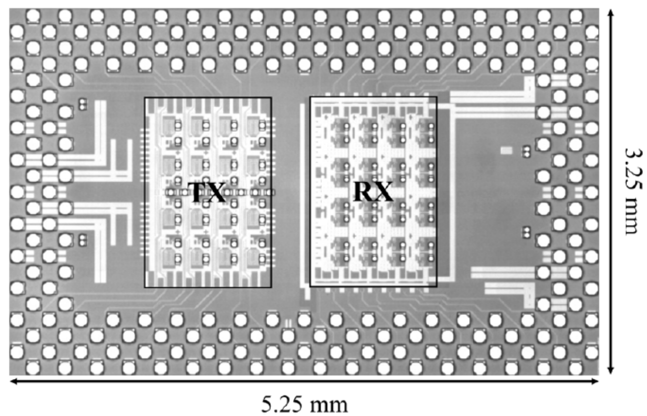
[Kromer]



Wirebonding

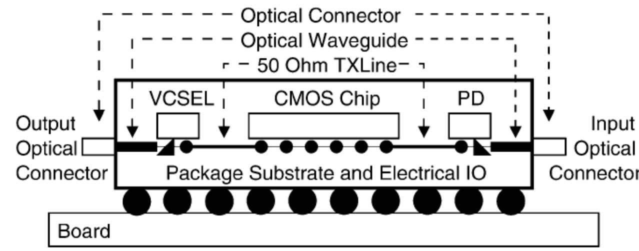
[Schow]

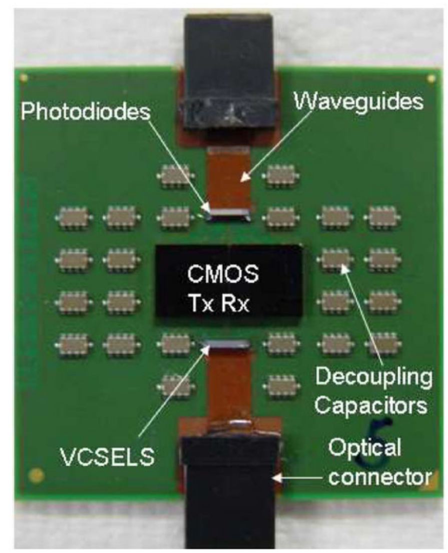




Flip-Chip Bonding

[Mohammed]



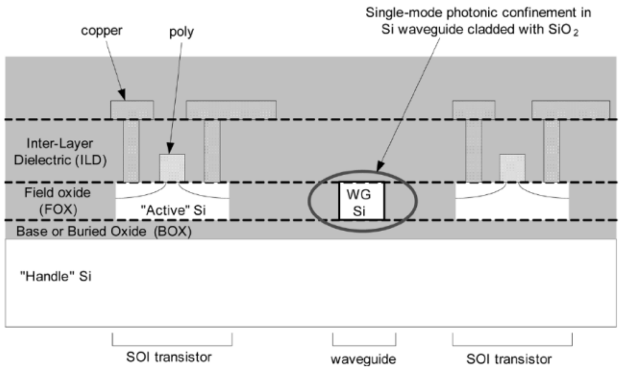


Short In-Package Traces

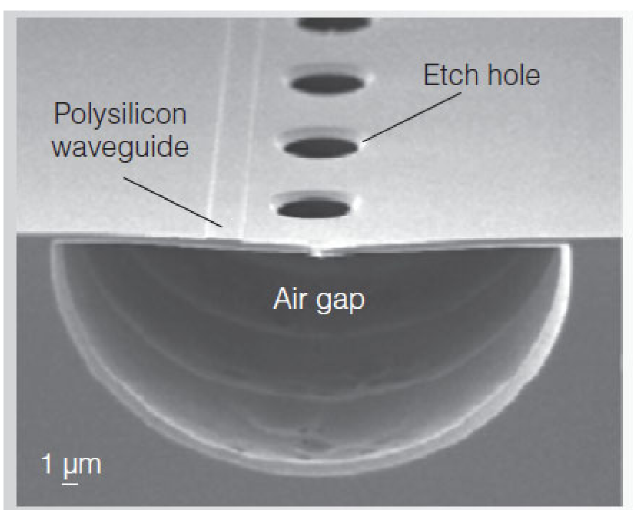
Integrated CMOS Photonics

SOI CMOS Process

[Analui]

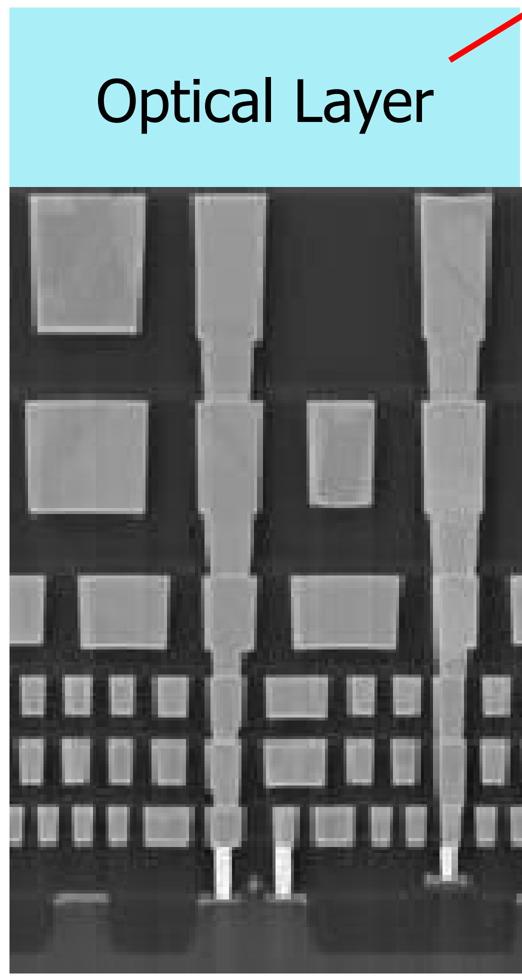


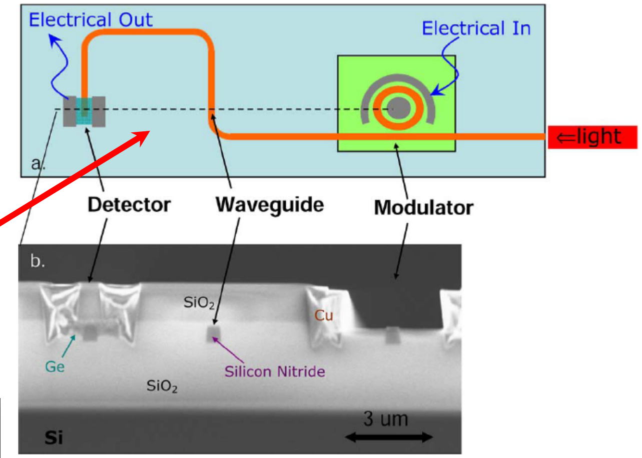
Bulk CMOS Process



[Batten]

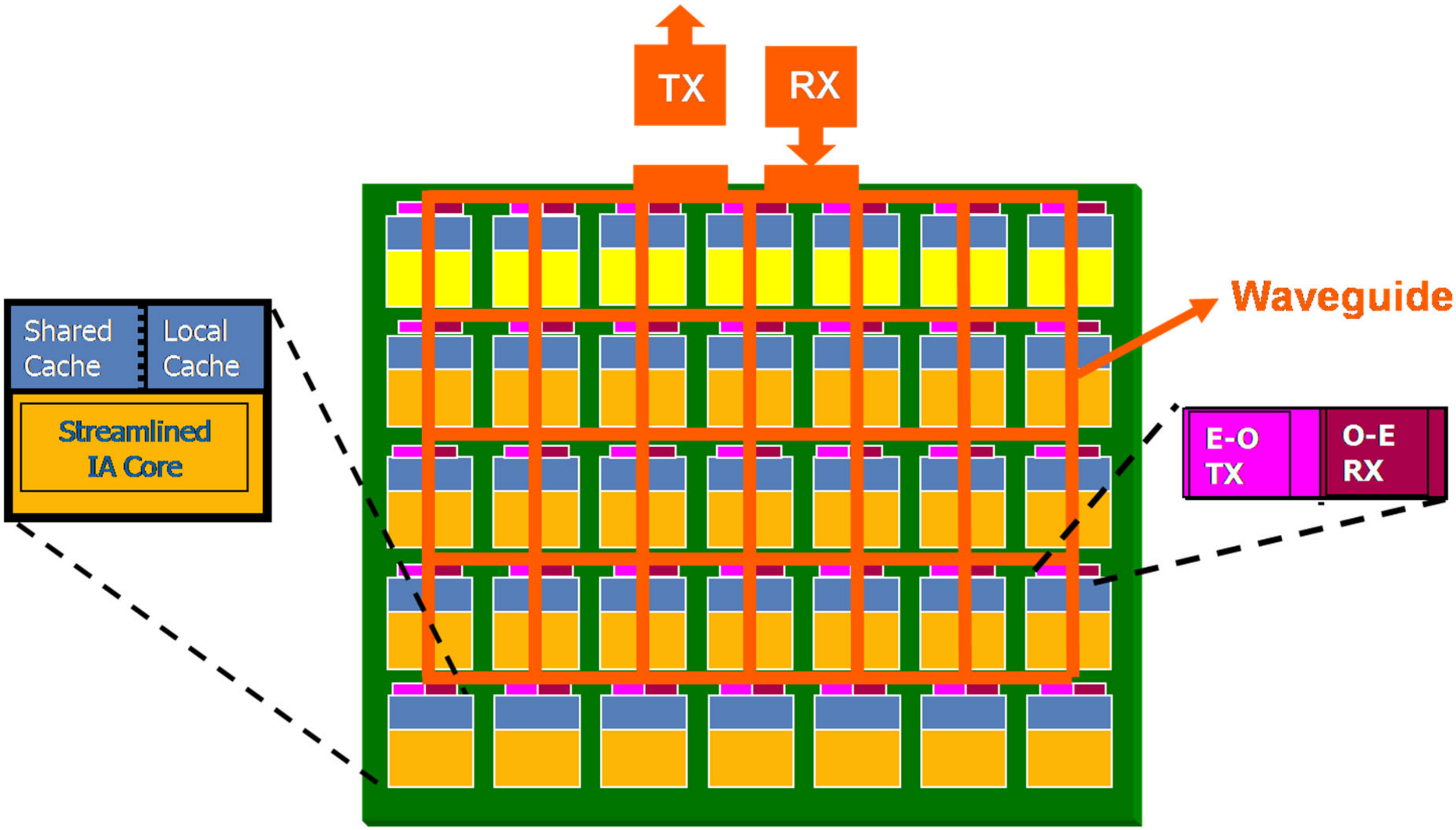
"Optics On Top"





[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.

Conclusion

- Thanks for the fun semester!