# ECEN689: Special Topics in High-Speed Links Circuits and Systems Spring 2010

## Lecture 33: Optical I/O

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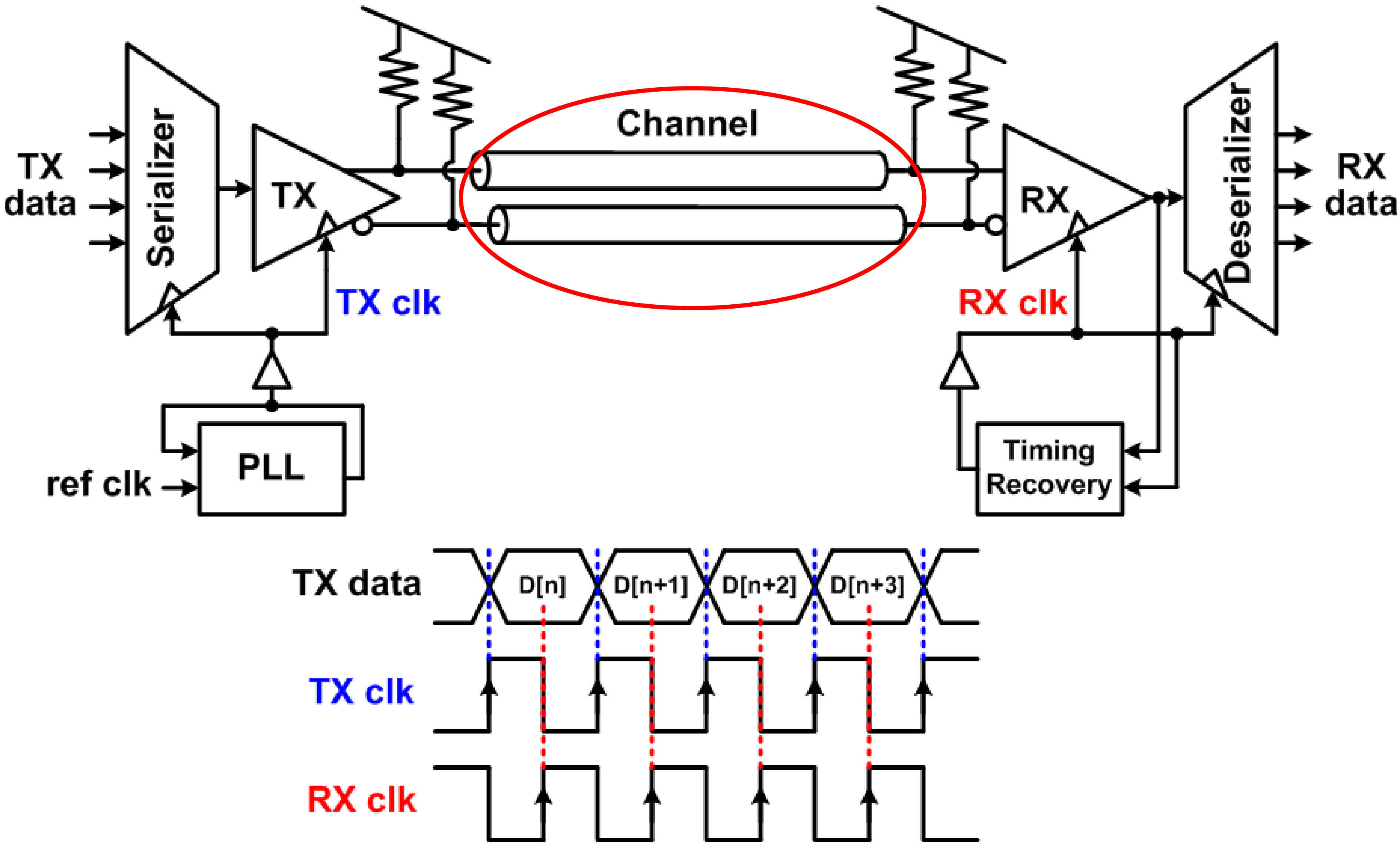
# Announcements

- Final Project Report Due Tomorrow by 5PM
- Project Presentations next Monday May 10, 8-10AM

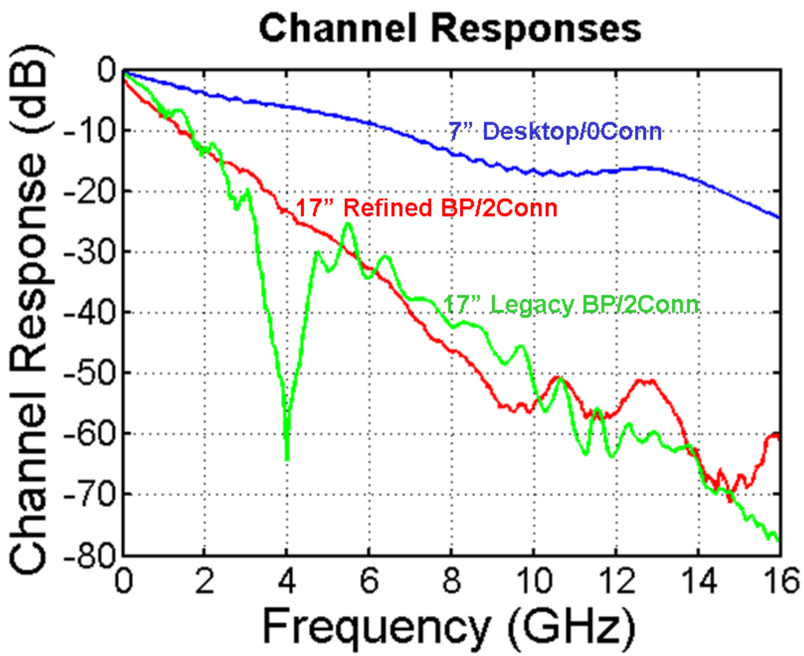
# Agenda

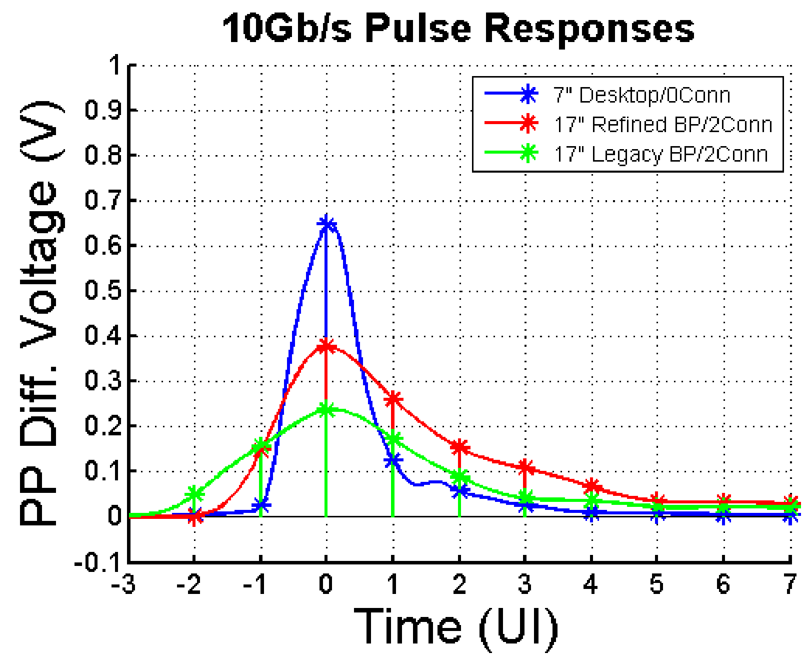
- Electrical Channel Issues
- Optical Channel
- Optical Transmitter Technology
- Optical Receiver Technology
- Optical Integration Approaches

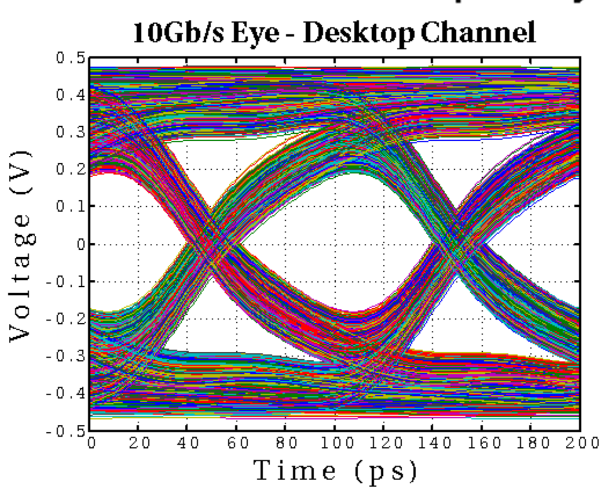
# High-Speed Electrical Link System

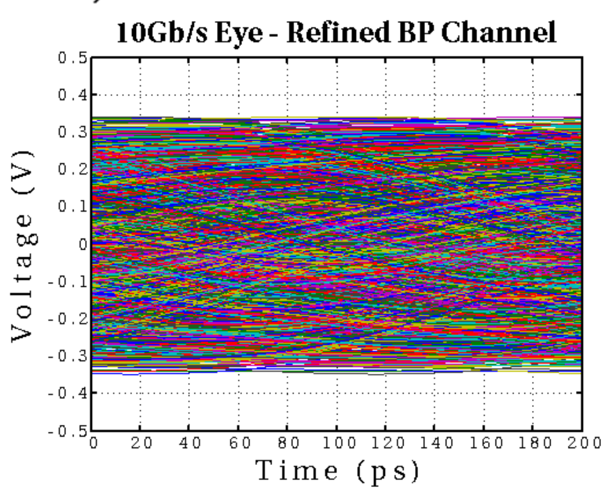


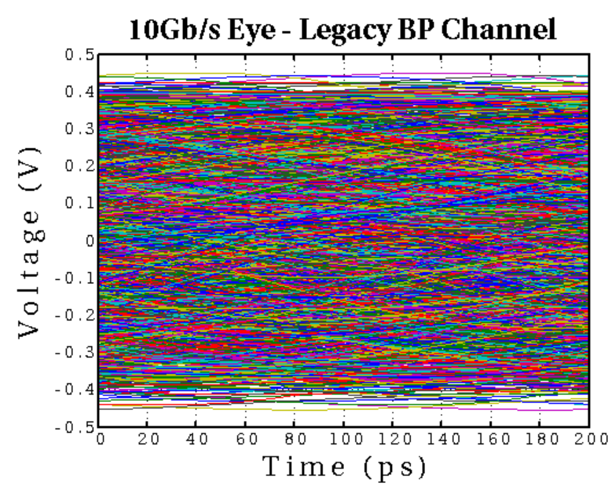
# Channel Performance Impact



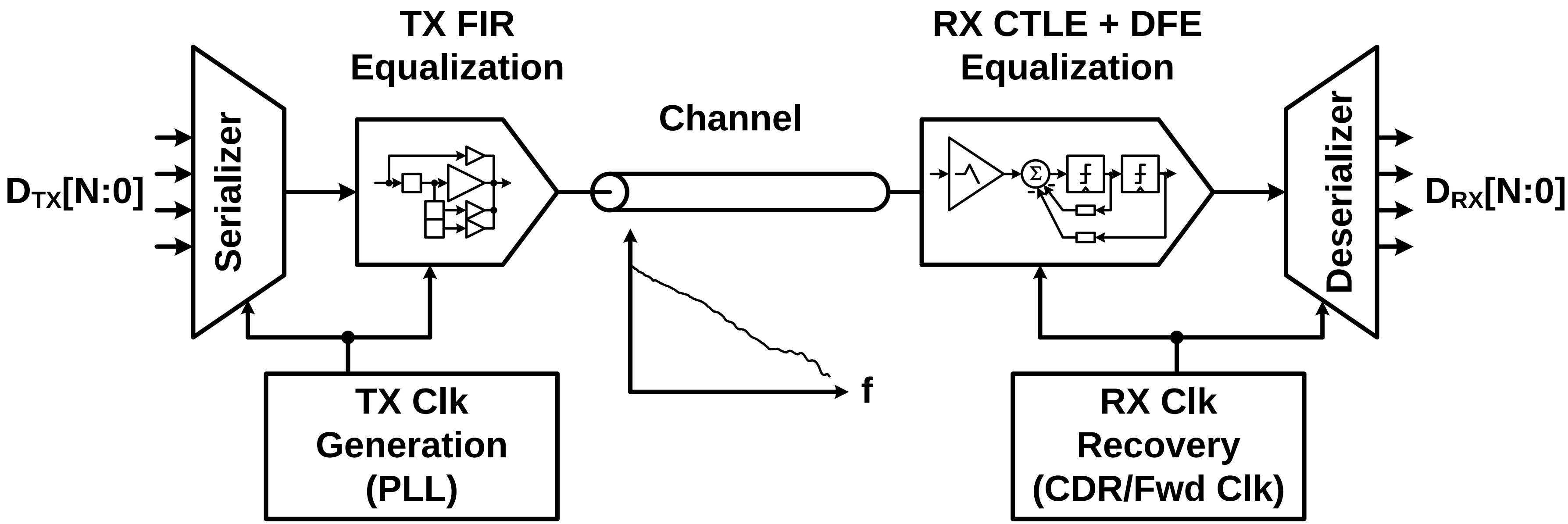



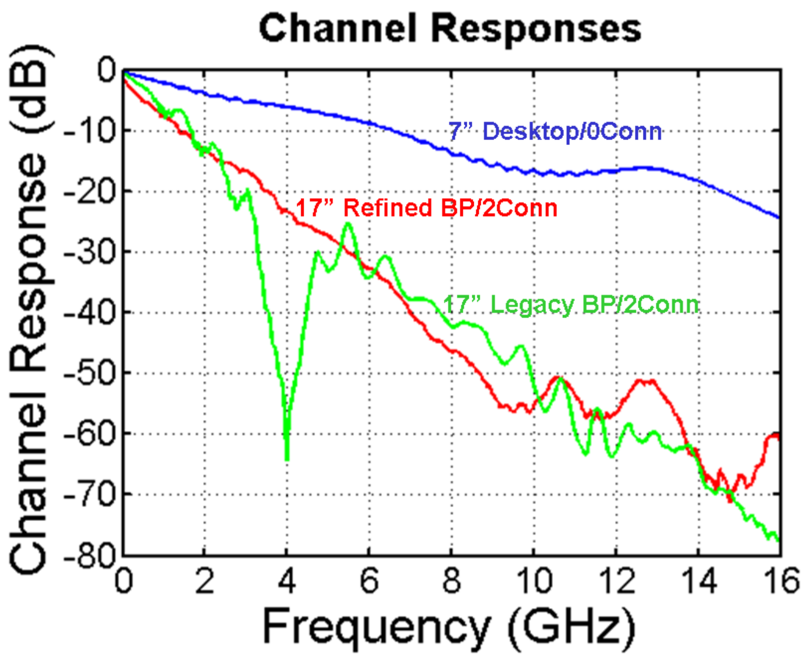



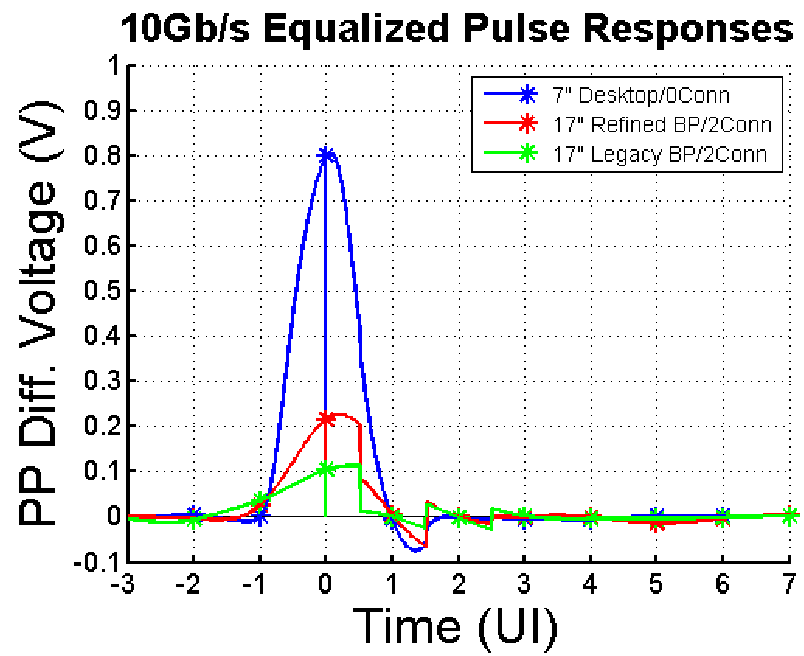



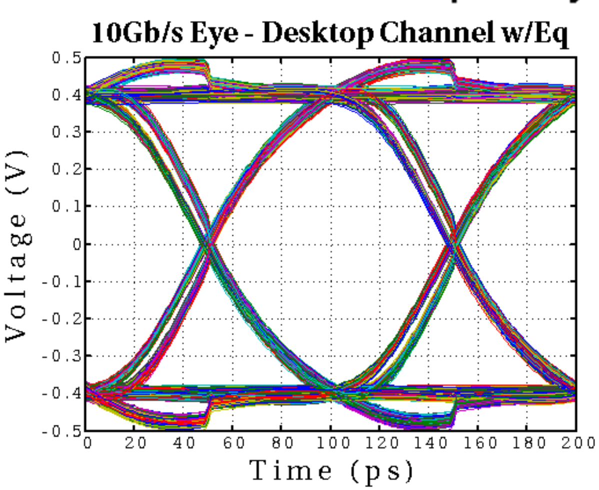
# Link with Equalization

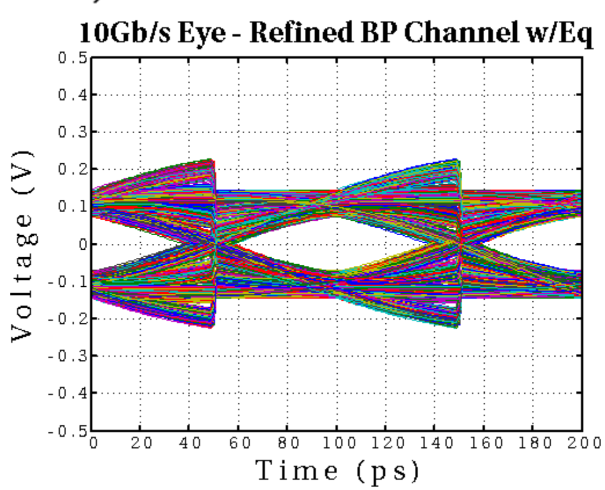


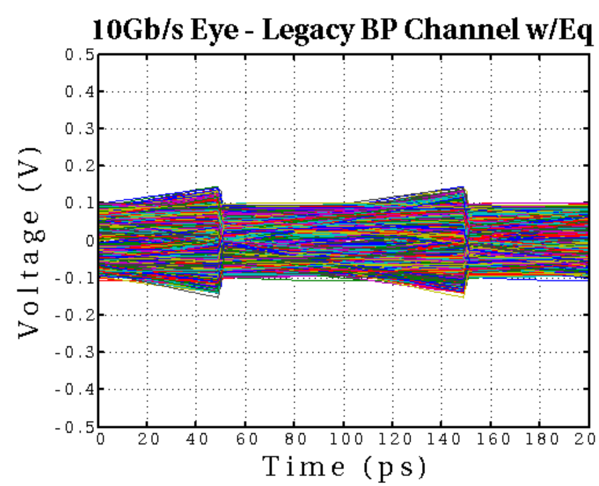
# Channel Performance Impact



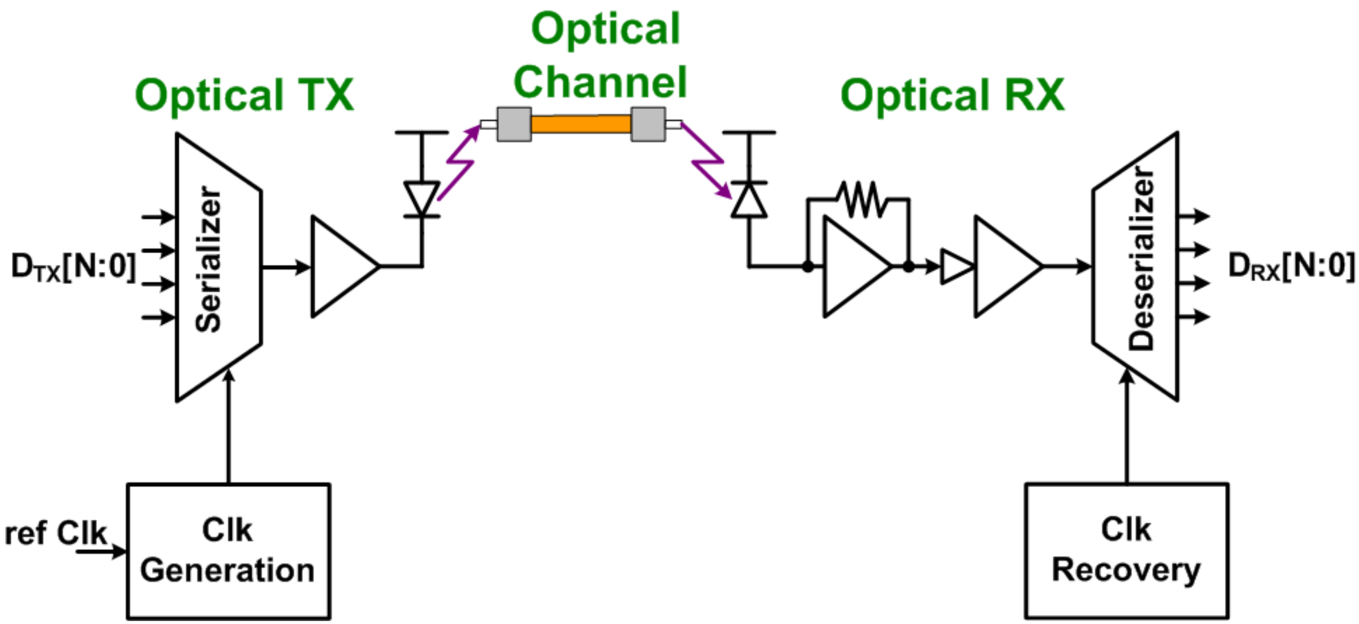



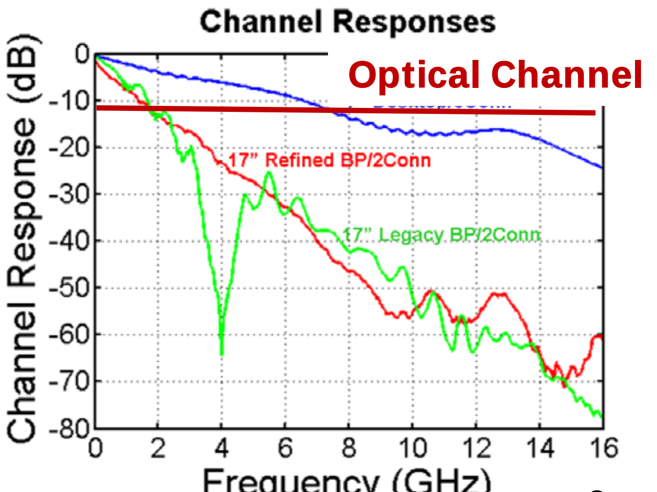



# High-Speed Optical Link System




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



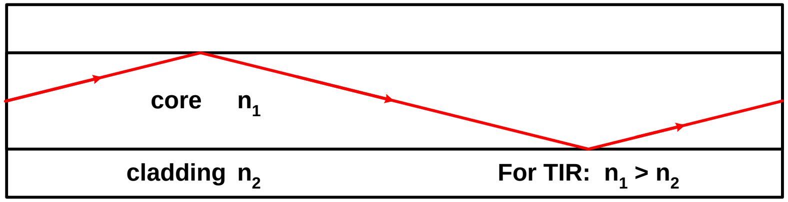
# Optical Channels

- 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

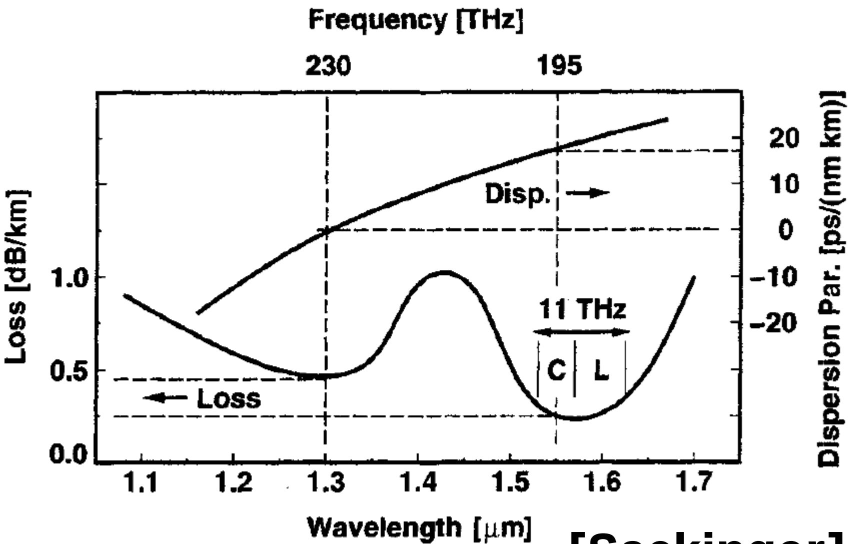
# Waveguide (Fiber)-Based Optical Links

- 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**



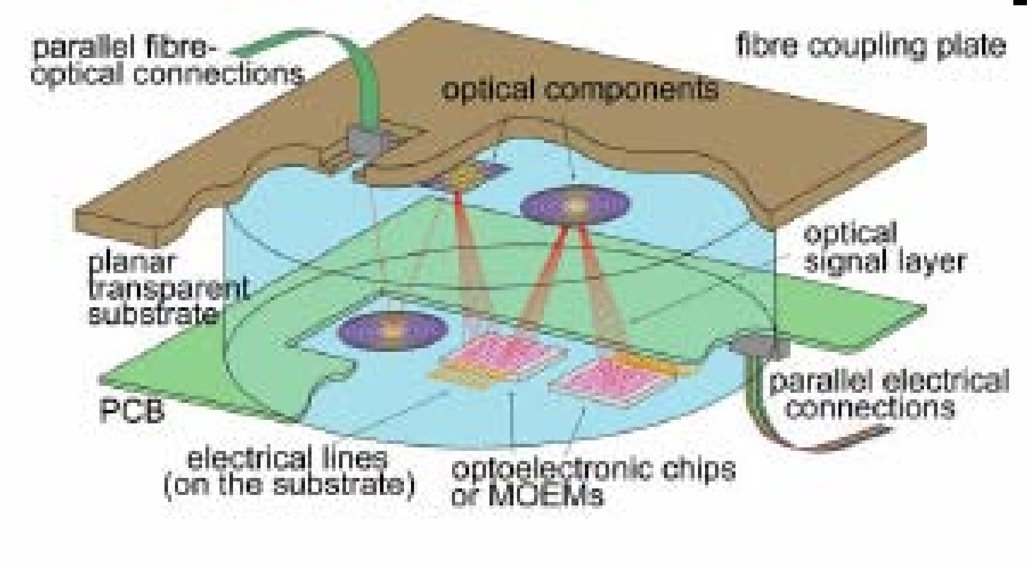

**Single-Mode Fiber Loss & Dispersion**




[Sackinger]

# Free-Space Optical Links

[Gruber]




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

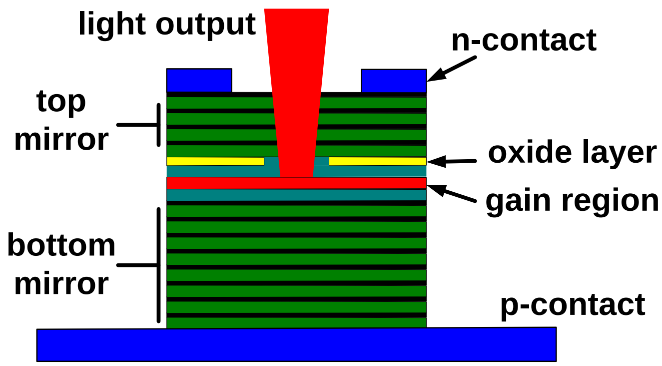
# Optical Transmitter Technology

- Optical modulation techniques
  - Direct modulation of laser
  - External modulation of continuous-wave (CW) “DC” laser with absorptive or refractive modulators

- 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)

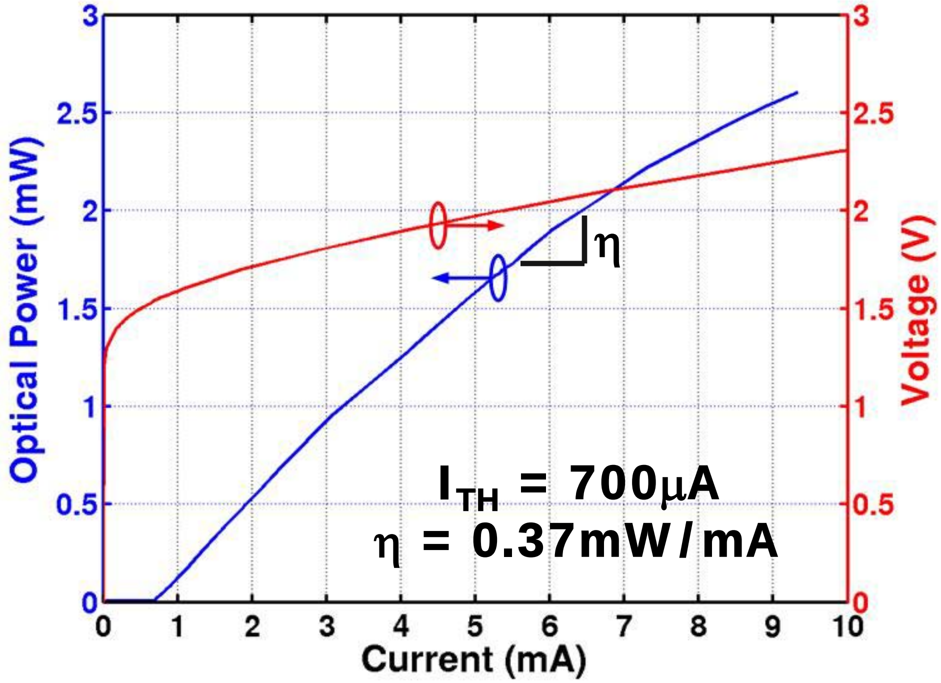
# Vertical-Cavity Surface-Emitting Laser (VCSEL)

**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**

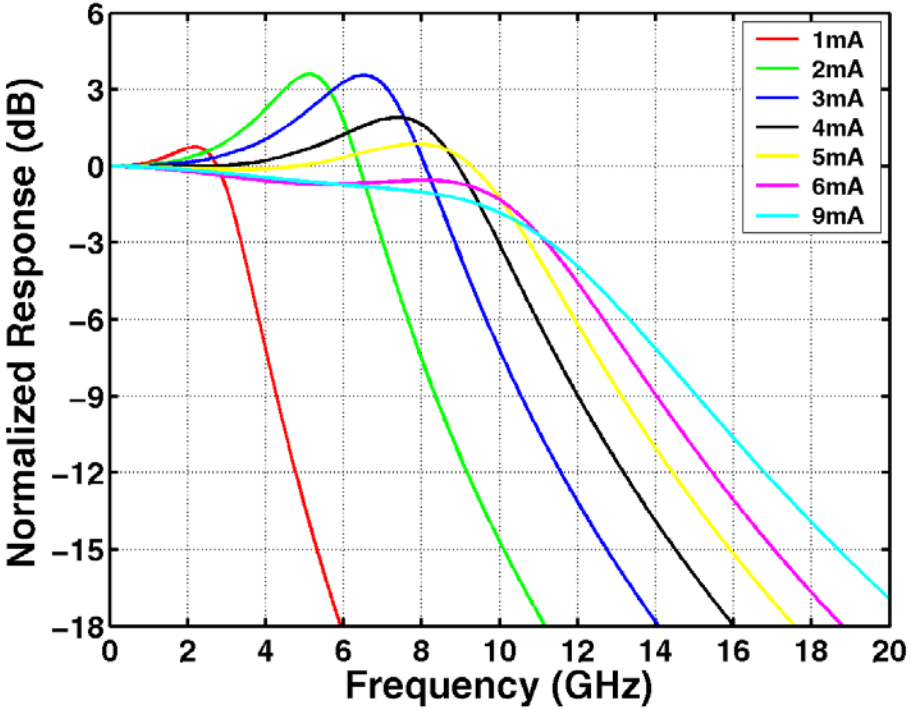



$$P_o = \eta\left(I - I_{TH}\right)$$

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

# 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

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

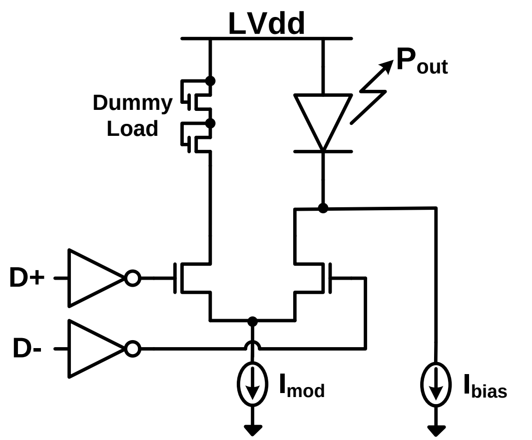
- Steep trade-off between bandwidth and reliability

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

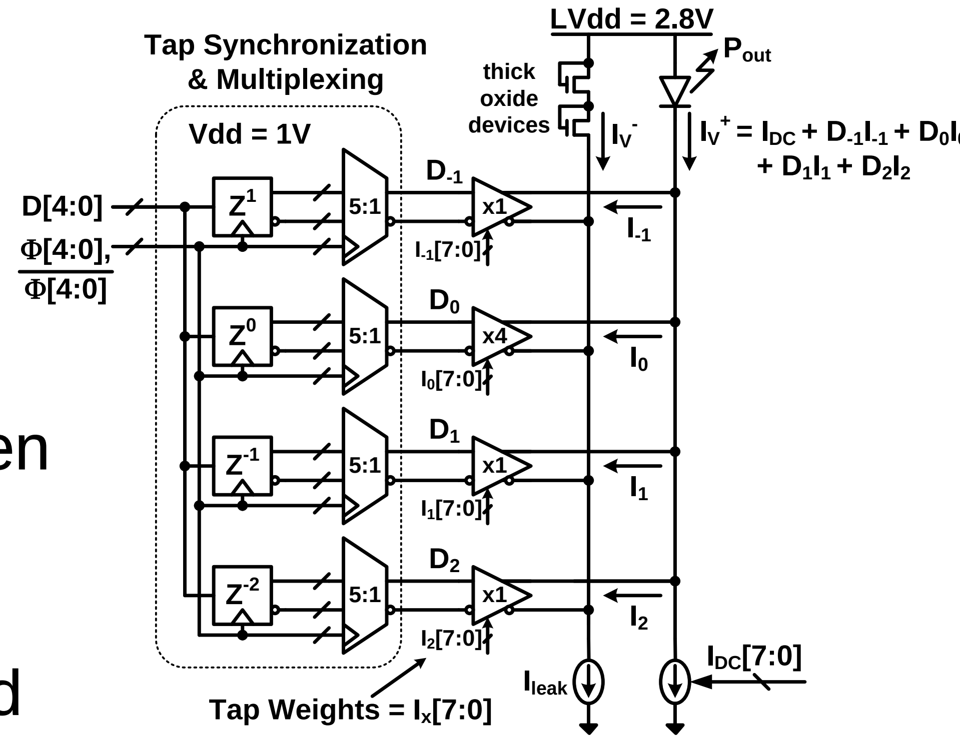

1. D. Bossert *et al*, "Production of high-speed oxide confined VCSEL arrays for datacom applications," *Proceedings of SPIE*, 2002.
2. M. Teitelbaum and K. Goossen, "Reliability of Direct Mesa Flip-Chip Bonded VCSEL's," *LEOS*, 2004.

# VCSEL Drivers

**Current-Mode VCSEL Driver**




**VCSEL Driver w/ 4-tap FIR Equalization**

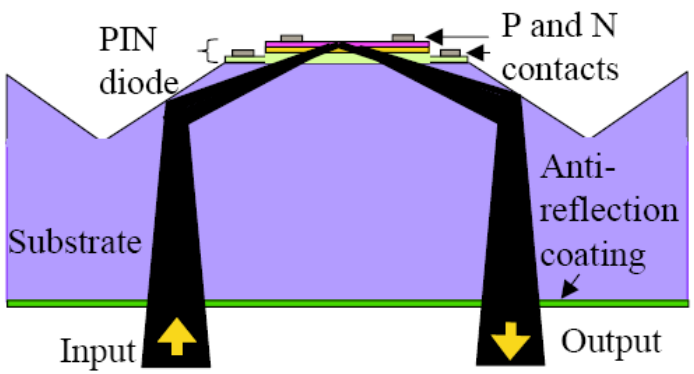


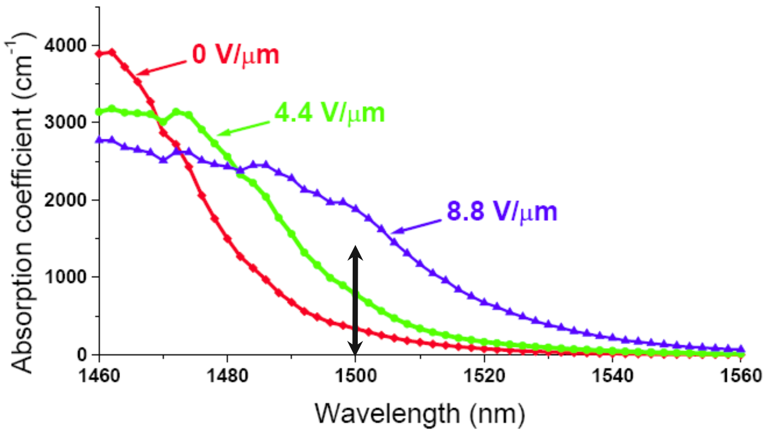

**S. Palermo** and M. Horowitz, "High-Speed Transmitters in 90nm CMOS for High-Density Optical Interconnects," *ESSCIRC*, 2006.

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

# Electro-Absorption Modulator (EAM)

## QWAFEM Modulator*

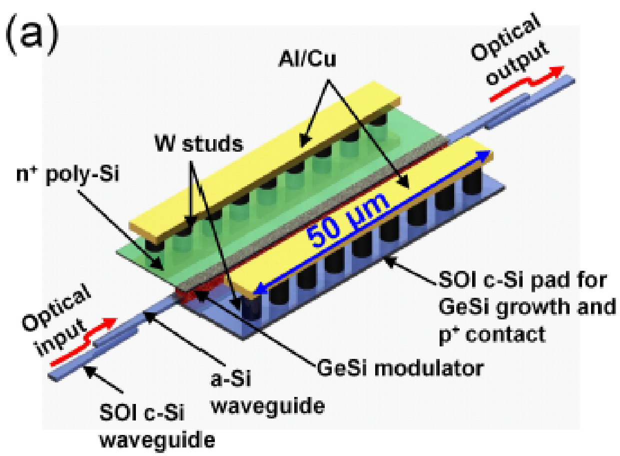


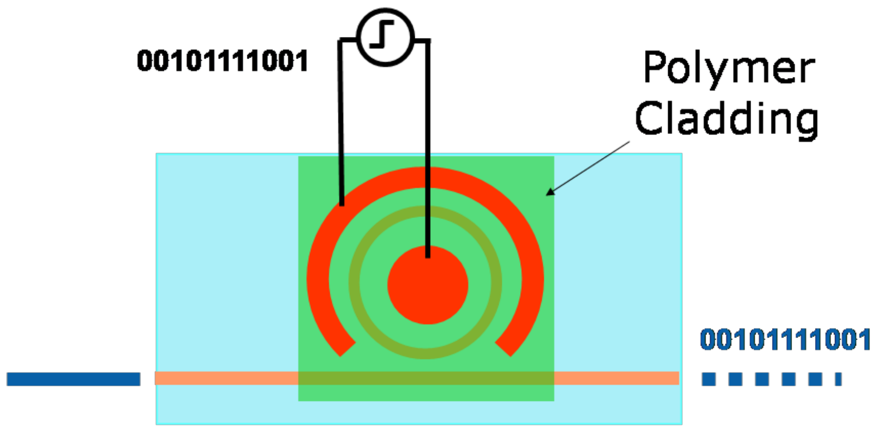

*N. Helman *et al*, "Misalignment-Tolerant Surface-Normal Low-Voltage Modulator for Optical Interconnects," *JSTQE*, 2005.

- 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

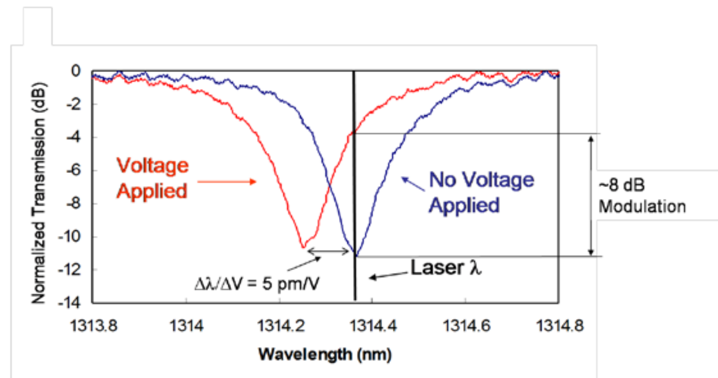
**Waveguide EAM [Liu]**

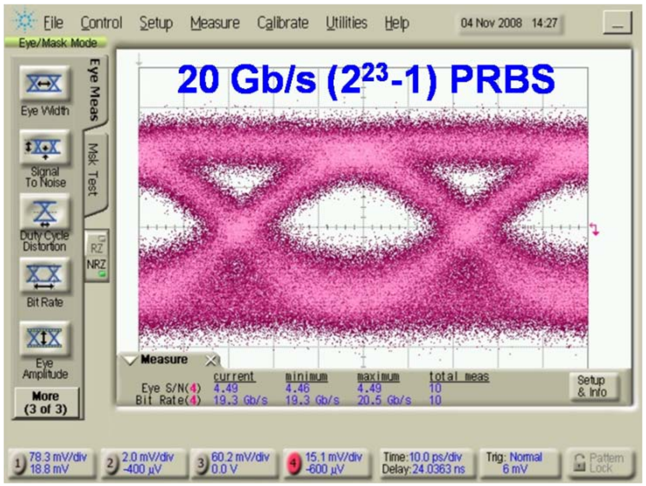


# Ring-Resonator Modulator (RRM)




High Frequency Modulation



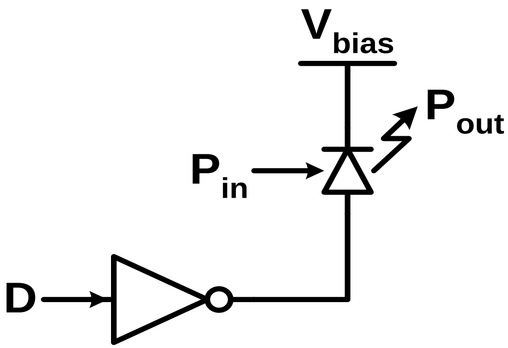




- Refractive devices which modulate by changing the interference light coupled into the ring with the waveguide light
- Devices are relatively small (ring diameters < 20μm) and can be treated as lumped capacitance loads (~10fF)
- Devices can be used in WDM systems to selectively modulate an individual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

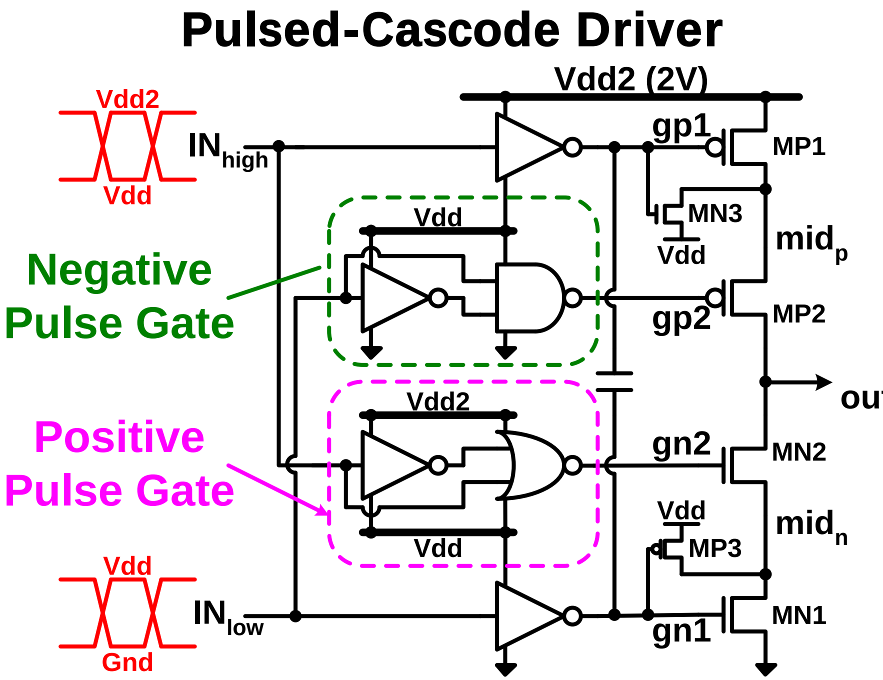
Optical Device Performance from: I. Young, E. Mohammed, J. Liao, A. Kern, **S. Palermo**, B. Block, M. Reshotko, and P. Chang, “Optical I/O Technology for Tera-Scale Computing," *ISSCC*, 2009.

# CMOS Modulator Driver

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



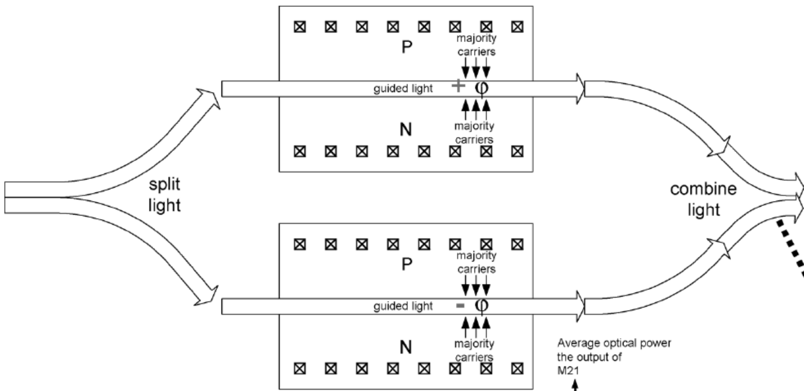

- Device may require swing higher than nominal CMOS supply
  - Pulsed-Cascode driver can reliably provide swing of 2xVdd (or 4xVdd) at up to 2FO4 data rate



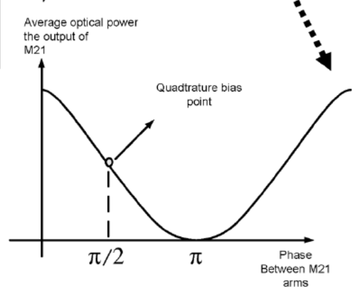

**S. Palermo** and M. Horowitz, "High-Speed Transmitters in 90nm CMOS for High-Density Optical Interconnects," *ESSCIRC*, 2006.

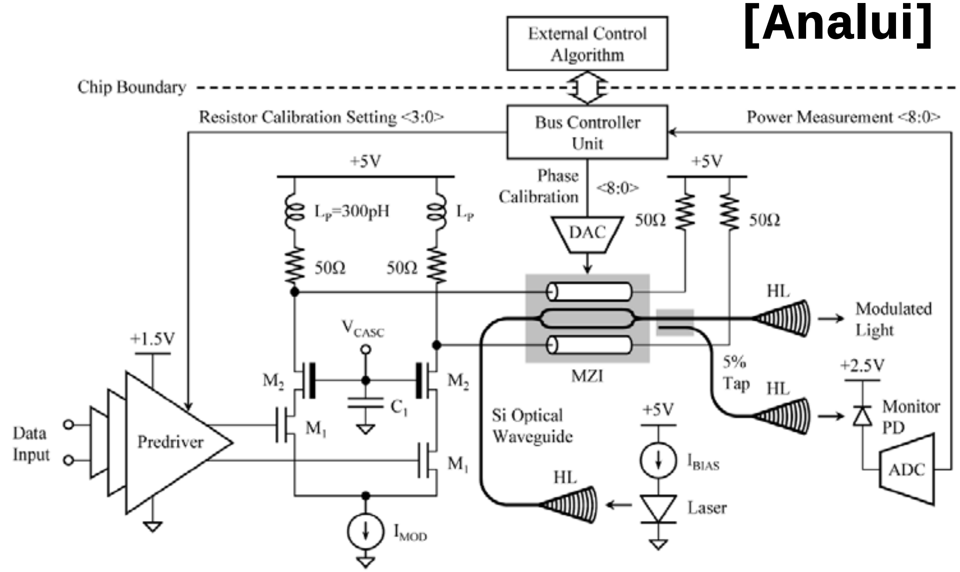
# Mach-Zehnder Modulator (MZM)

**[Analui]**




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

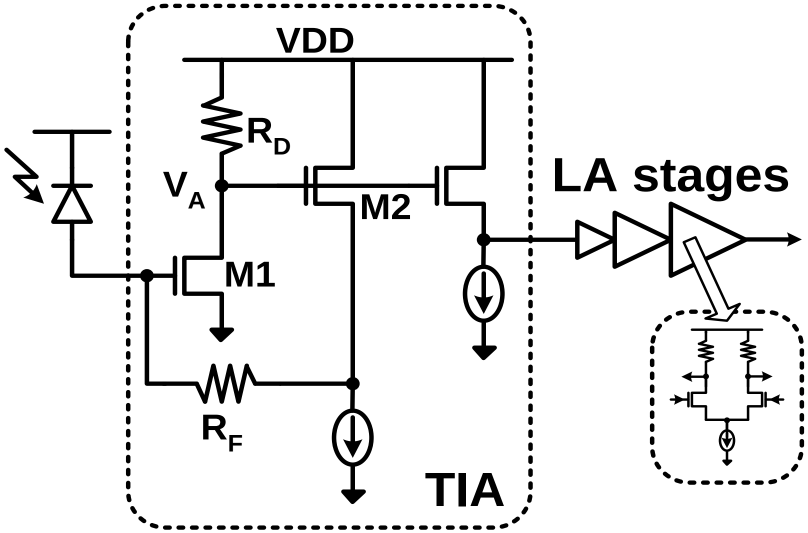



- Refractive modulator which splits incoming light into two paths, induces a voltage-controlled phase shift in the two paths, and recombines the light in or out of phase
- Long device (several mm) requires driver to drive low-impedance transmission line at potentially high swing ($5V_{ppd}$)
- While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

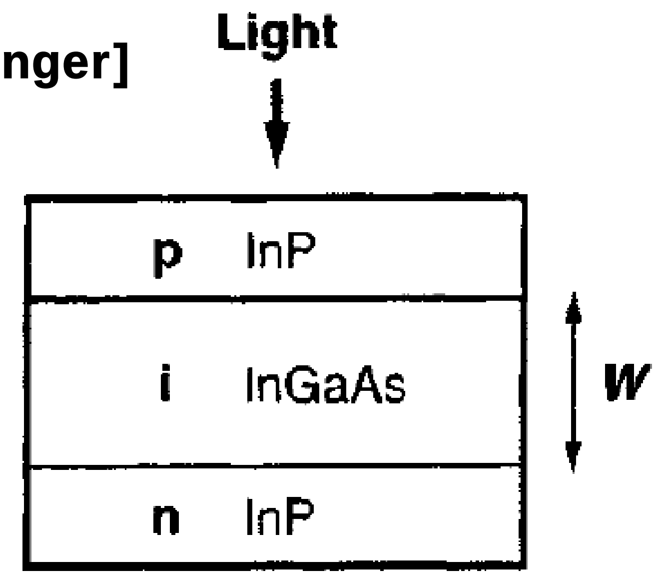
# Optical Receiver Technology

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

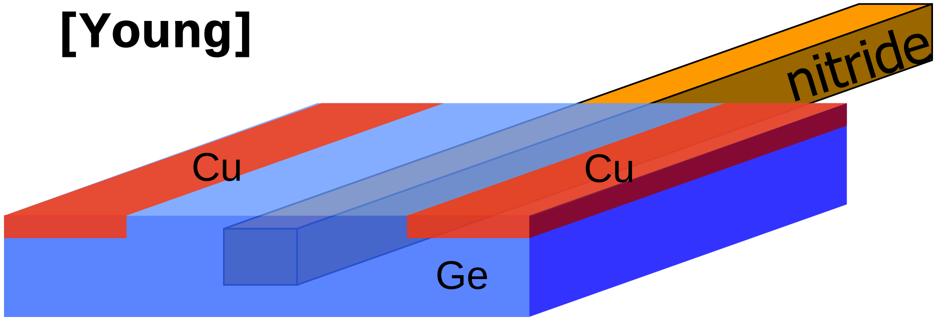
**Transit-Time Limited Bandwidth:**

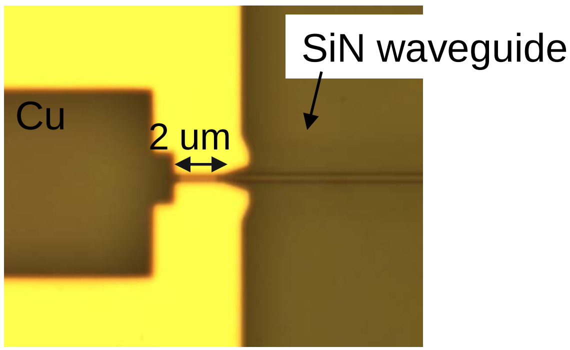
$$f_{3dBPD} = \frac{2.4}{2\pi\tau_{tr}} = \frac{0.45 v_{sat}}{W}$$

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

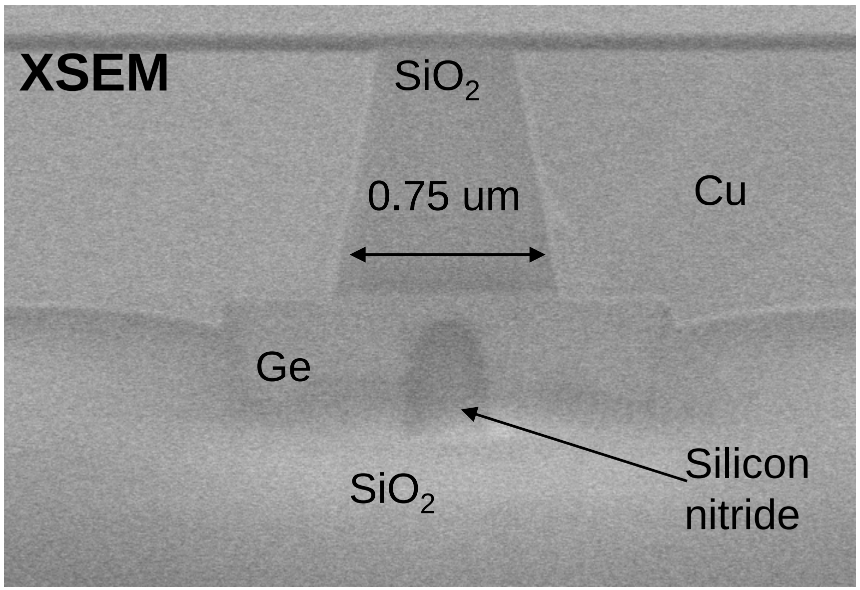
# Integrated Ge MSM Photodetector

**[Young]**




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

# Optical Integration Approaches

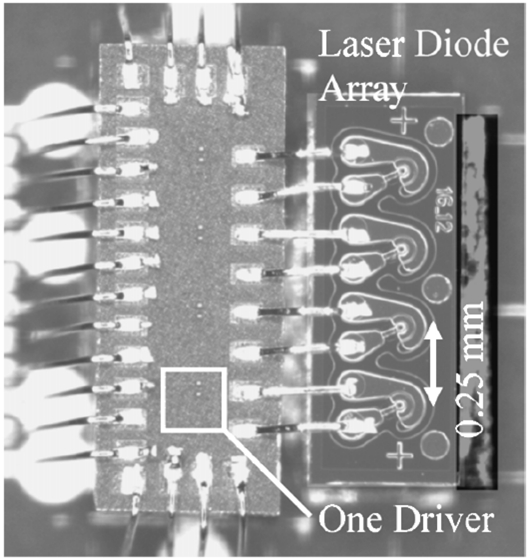
- Efficient cost-effective optical integration approaches are necessary for optical interconnects to realize their potential for improved power efficiency at higher data rates

- Hybrid integration
  - Optical devices fabricated on a separate substrate

- Integrated CMOS photonics
  - Optical devices part of CMOS chip

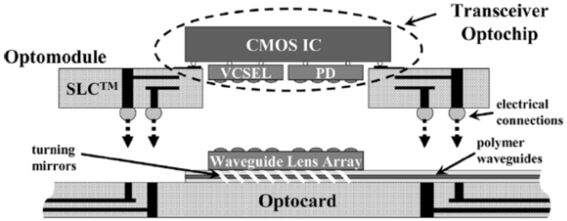
# Hybrid Integration

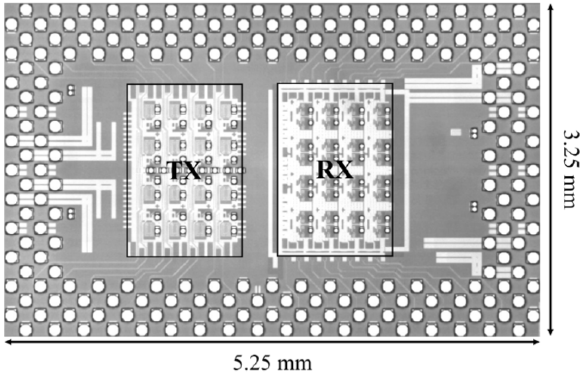
**[Kromer]**




**Wirebonding**

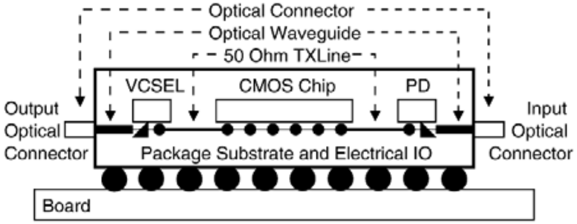
**[Schow]**

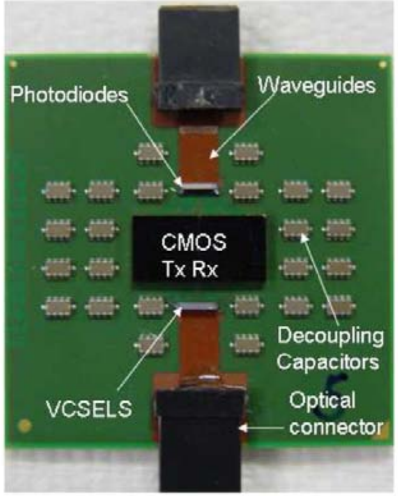



**Flip-Chip Bonding**

**[Mohammed]**

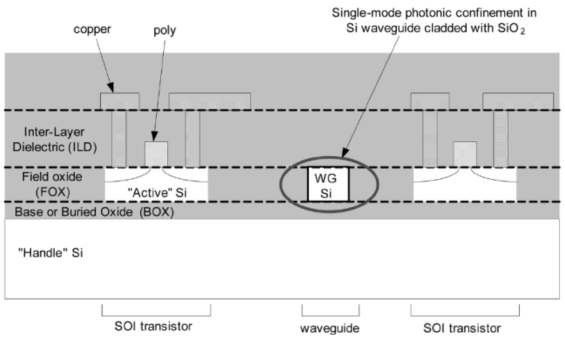


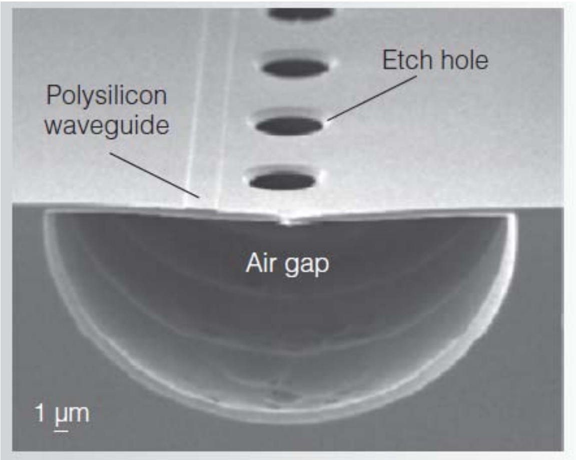

**Short In-Package Traces**

# Integrated CMOS Photonics

**SOI CMOS Process** **[Analui]**

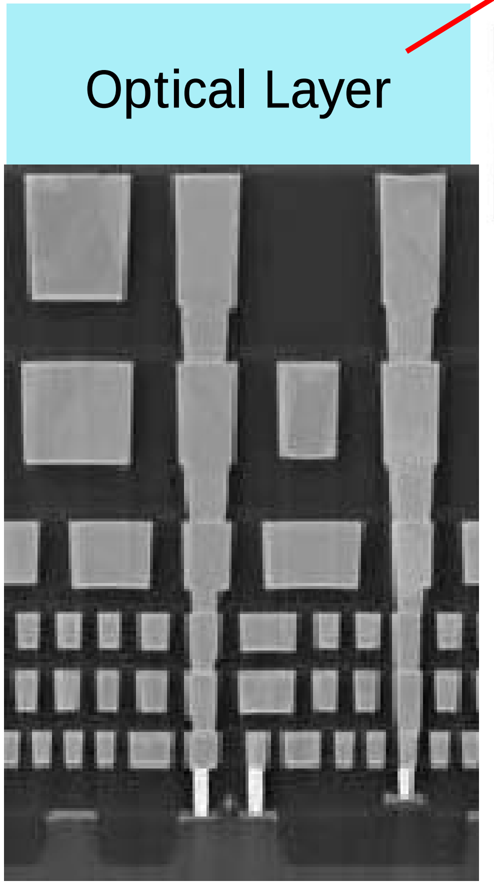


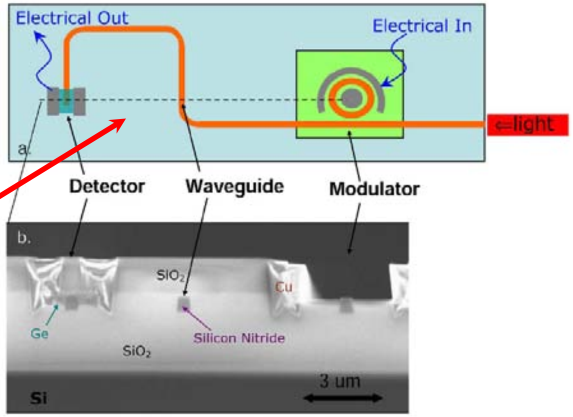

**Bulk CMOS Process**




**[Batten]**

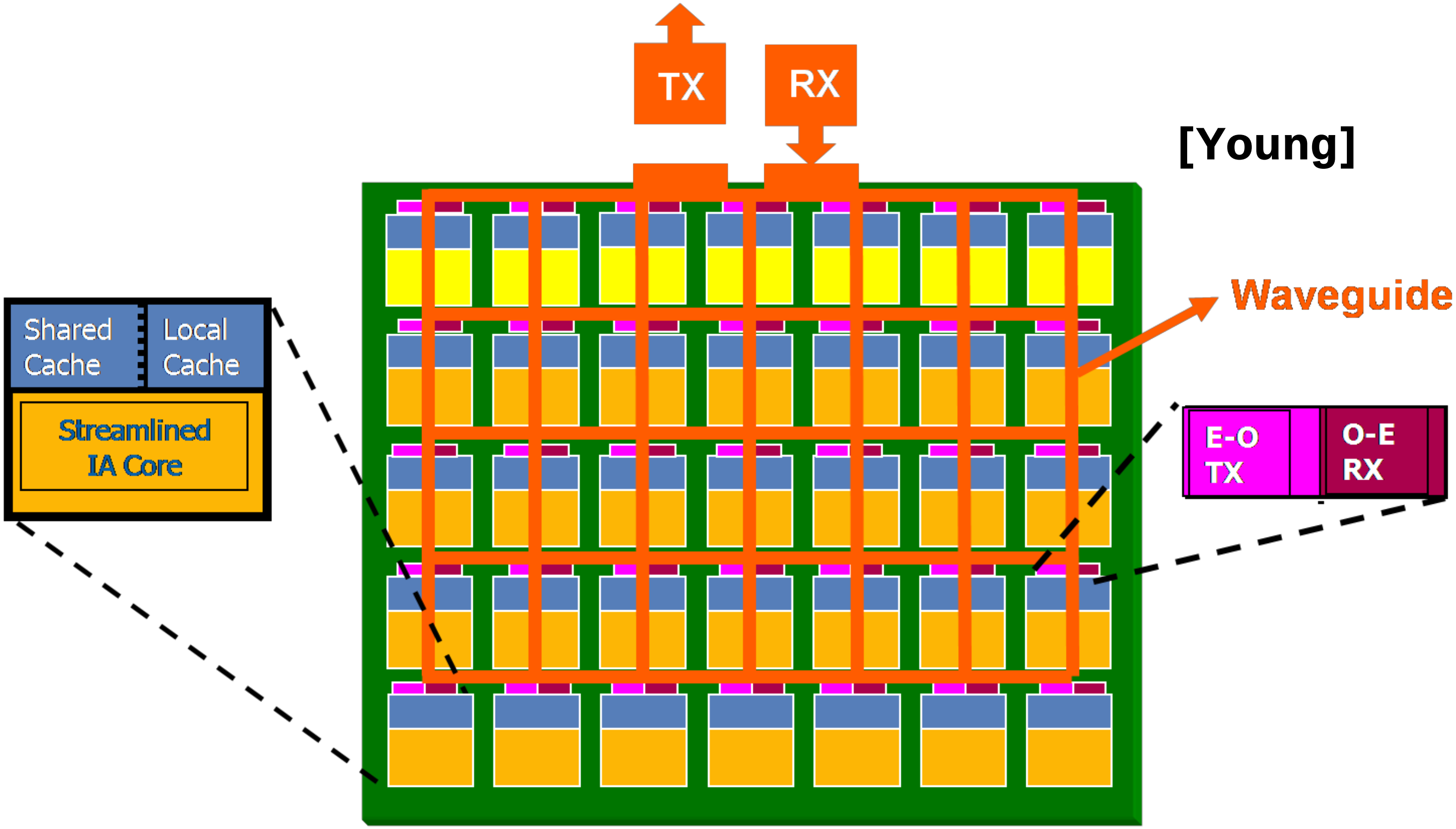
**"Optics On Top"**




**[Young]**

# Future Photonic CMOS Chip




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

# Conclusion

- Thanks for the fun semester!